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Estimation of Seasonal Irrigation Water Use

– *Method Development*

Prepared for Irrigation New Zealand Ltd

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TABLE OF CONTENTS

Page

List of Tables:

Page

List of Figures:

EXECUTIVE SUMMARY

Environment Canterbury (ECan) has included in its Proposed Natural Resources Regional Plan (PNRRP) Seasonal Irrigation Demand Standards that determine whether or not a specific use of water for irrigation requires a water use consent. These standards are listed in Schedule WQN9 of the PNRRP. It is reasonable to expect that these standards will become the "reasonable use" benchmark and that it will become difficult to obtain a consent to use more water than that ultimately allowed according to Schedule WQN9.

If the Seasonal Irrigation Demand Standards are too low, then farmers will be required to stop irrigating before the normal end of the irrigation season more often than the 1-year-in-5 that is the proposed "reliability" standard. There are potentially large adverse financial costs associated with this.

Many in the irrigation industry consider that the values in WQN9 are too low, and have challenged, through the PNRRP policy implementation process, the basis on which these values have been determined.

This project was commissioned to:

- Review ECan's approach to setting Seasonal Irrigation Demand Standards for inclusion in WQN9 of the PNRRP;
- Develop and demonstrate an alternative robust method for setting Seasonal Irrigation Demand Standards that take proper account of the main factors that determine irrigation water use;
- Provide ECan and the irrigation community with scientifically sound estimates of annual irrigation water use, for pasture, and the levels of risk associated with specific annual limits; and
- Provide ECan with the evidence it needs to adopt this more robust method and have it applied throughout Canterbury.

ECan's adopted method for determining the Seasonal Irrigation Demand Standard that is included in its PNRRP as Schedule WQN9 ("the WQN9 method") involves two phases:

- Determine the Seasonal Total Water Demand Standard; and
- Determine the Seasonal Irrigation Demand Standard for a specific farm.

The WQN9 method significantly underestimates plant water use, compared to internationally accepted standards methods, and therefore underestimates reasonable irrigation water use.

The WQN9 method provides estimated pasture water use (actual evapotranspiration) that trends downwards as profile available water increases, which is opposite to what would normally be expected, unless the adequacy of irrigation reduces significantly as profile available water increases.

The estimation error is likely to result from an accumulation of small errors introduced by the assumptions that must be made about the volume of water that

enters and is retained in the soil at each rainfall and irrigation event when applying the WQN9 method.

While the WQN9 method has used much data from many locations in Canterbury, the validation of this method at any site has not been reported.

The method erroneously calculates the 8-years-in-10 irrigation season water use by subtracting from an 8-years-in-10 irrigation season crop water demand value a 2-years-in-10 irrigation season rainfall value.

Aqualinc's approach to determining seasonal irrigation water use standards involves using the IrriCalc model. This approach:

- Is an application of an internationally accepted approach;
- Is scientifically robust;
- Is transparent – the assumptions that are made are clear and can be tested;
- Enables irrigation water use to be estimated for a range of irrigator types; and
- Can evolve as the prediction reliability of models increases.

The IrriCalc model was successfully validated using data collected by ECan at an irrigated lysimeter facility near Dunsandel.

IrriCalc was used successfully to calculate the seasonal irrigation water use of irrigators that are "policy compliant" (i.e. 80% application efficiency and 4-years-in-5 reliability), and those which are not.

Irrigator type, and how the irrigator is managed, have a major effect on seasonal irrigation water use. Variation in seasonal irrigation water use between irrigators is significant. The degree of variation is similar to that attributable to variation in rainfall. It is significantly more influential than variation in soil type.

Existing irrigation hardware typically does not allow the 80% irrigation application efficiency standard to be met.

Comparisons between the WQN9 seasonal irrigation demand standard and results from Policy Compliant IrriCalc simulations show that the WQN9 seasonal demands are significantly lower than the seasonal demands estimated by IrriCalc.

If the WQN9 standards become operative, it is highly likely that the NRRP's reliability standard of meeting irrigation needs four years in five will not be met.

IrriCalc provides a robust method for setting seasonal irrigation demand standards that is based on internationally accepted good practice, and it has been set up for Canterbury conditions and tested using Canterbury data.

1 INTRODUCTION

1.1 Background

Environment Canterbury (ECan) has included in its Proposed Natural Resources Regional Plan (PNRRP) Seasonal Irrigation Demand Standards that determine whether or not a specific use of water for irrigation requires a water use consent. These standards are listed in Schedule WQN9 of the PNRRP. Many in the irrigation industry consider that the values in WQN9 are too low, and have challenged, through the PNRRP policy implementation process, the basis on which these values have been determined. This project was commissioned to provide a defensible alternative to ECan's current methodology.

This project has developed a scientifically robust method for determining seasonal irrigation water use standards for pastoral irrigation, and applied it at three representative sites in Canterbury. In doing so, this project has:

- Identified significant technical shortcomings of ECan's approach to setting Seasonal Irrigation Demand Standards for inclusion in WQN9 of the PNRRP;
- Demonstrated to ECan and others a robust method for setting Seasonal Irrigation Demand Standards that take proper account of the main factors that determine irrigation water use;
- Provided ECan and the irrigation community with scientifically sound estimates of annual irrigation water use, for pasture, and the levels of risk associated with specific annual limits; and
- Provided ECan with the evidence it needs to adopt this more robust method and have it applied throughout Canterbury.

1.2 Objective

The objective of this project is to develop a robust method for determining the amount of water reasonably required to efficiently irrigate pasture and arable crops throughout their life cycle, using data that is readily available for the Canterbury region, and which can take account of the primary effects of irrigation system type.

Reasonable irrigation water use was assumed to be that incurred when:

- Irrigating to avoid yield loss due to soil water stress, to a defined reliability standard; or
- Irrigating according to a management regime that is practical for the irrigation equipment available on the farm in question.

The efficiency test is assumed to be met when best practice options are used to maximise irrigation efficiency subject to the constraints imposed by the existing irrigation equipment.

1.3 Overall Approach

The overall approach to the project is as follows:

a) Obtain from ECan the full length of record of raw, daily time series data for drainage from the irrigated lysimeter site operated by ECan, along with the daily rainfall plus irrigation time series for this site.

b) Obtain from Dr Tony Davoren the corresponding soil water content time series data built up by routine measurement of the soil water content at multiple depths using a neutron probe.

c) Complete a sanity check on the data, discarding datasets or parts thereof where it is clear there are errors.

d) Use the measured water inputs to, outputs from, and the change in soil water content of the soil column to directly calculate a crop coefficient time series for irrigated pasture.

e) Use this crop coefficient in a soil-plant-atmosphere model to simulate irrigation water use and soil moisture response over a 30+ year record of climate at three sites in Canterbury. The three sites were chosen to capture the effect that different seasonal rainfall amounts have on seasonal irrigation water use.

f) Determine from the modelled soil moisture and irrigation application time series data the annual allocation amounts required to meet specified levels of risk.

g) Compare these estimates of seasonal irrigation water use with ECan's Seasonal Irrigation Demand Standards, and explain any significant differences.

The soil water balance model used to model irrigation water use (see Section 6) is a straightforward representation of the conservation of mass principle.

2 OVERVIEW OF THE ECAN APPROACH

ECan's adopted method for determining the Seasonal Irrigation Demand Standard that is included in its PNRRP as Schedule WQN9 involves two phases:

a) Determine the Seasonal Total Water Demand Standard; and
b) Determine the Seasonal Irrigation Demand Standard for a specific farm.

This section describes the procedure adopted by ECan for determining the seasonal total water demand standard, explains the assumptions inherent in applying this method, and briefly describes how the seasonal irrigation demand standard for a specific farm is determined from the seasonal total water demand standard.

2.1 Estimation of Seasonal Irrigation Demand

ECan selected the 1998/99 season as a year expected to be representative of the 8-years-in-10 total water demand season. The method adopted by them to estimate the total water demand for this season involves the application of the following steps for each farm for which there is measured soil moisture, rainfall and irrigation:

1) Estimate the amount of effective rainfall over the soil moisture monitoring period by examining each rainfall event and making a judgement about how much of that rainfall event was retained in the depth of soil that supplies the pasture with water. The assumptions inherent in this process are described in Section 2.3.

2) Estimate the effective irrigation application depth over the soil moisture monitoring period by examining each irrigation event and making a judgement about how much of that irrigation event was retained in the depth of soil that supplies the pasture with water. The assumptions inherent in this process are described in Section 2.3.

3) Adjust the effective irrigation application depth by dividing it by 0.8 to reflect the PNRRP policy of basing irrigation water use limits on the assumption that irrigation application efficiency is 80%.

4) Calculate the change in the soil water content in the depth of soil that supplies the pasture with water between the first and last measurement for the 1998/99 season. If the final soil water content is less than the first, the change in soil water content has a positive value; otherwise, it has a negative value.

5) Calculate the total water demand (rain plus irrigation) over the measurement period by adding the effective rainfall (see step 1 above), the adjusted irrigation application depth (see step 3 above), and the change in soil water content (see step 4 above).

6) Estimate the effective rainfall between 1 October 1998 and the date of the first soil moisture measurement in the 1998/99 season. While not explicitly stated in Davoren & Scott (2005), it appears that this involved ignoring the

first 5 mm of each rainfall event and any rainfall event amounts in excess of 50 mm. If soil moisture monitoring commenced before 1 October, this amount has a negative value; otherwise, it has a positive value.

7) Estimate the effective rainfall between the date of the last soil moisture measurement in the 1998/99 season and 30 April 1999. If soil moisture monitoring finished after 30 April 1999, this amount has a negative value,; otherwise, it has a positive value.

8) Calculate the seasonal total water demand (rain plus irrigation) in 1998/99 by adding to the total irrigation demand over the measurement period (see step 5 above) the effective rainfall amounts estimated to have occurred between 1 October and the beginning of monitoring (see step 6 above), and between the end of monitoring and 30 April (see step 7 above).

9) Analysis of computer simulated seasonal total water demands for each of the farms for which monitoring data was available showed that the 1998/99 year was not the 8-years-in-10 total water demand year. An adjustment factor was calculated for each farm by dividing its total water demand in 1998/99 by the seasonal total water demand for the 8-years-in-10 total water demand specific to each farm. The computer simulated total water demand was obtained by using Scott's model with climate data from NIWA's virtual climate network and soils data from Davoren.

10) The 8-years-in-10 Seasonal Total Water Demand was calculated by dividing the seasonal total water demand in 1998/99 (see step 8) by the adjustment factor determined as described in step 9 above.

11) The 8-years-in-10 seasonal total water demand standard values were plotted against the estimated profile available water, as shown in Figure 2-1.

12) Various forms of envelop curve have been plotted across the top of these data points to define the Total Seasonal Water Demand Standard for a given value of Profile Available Water.

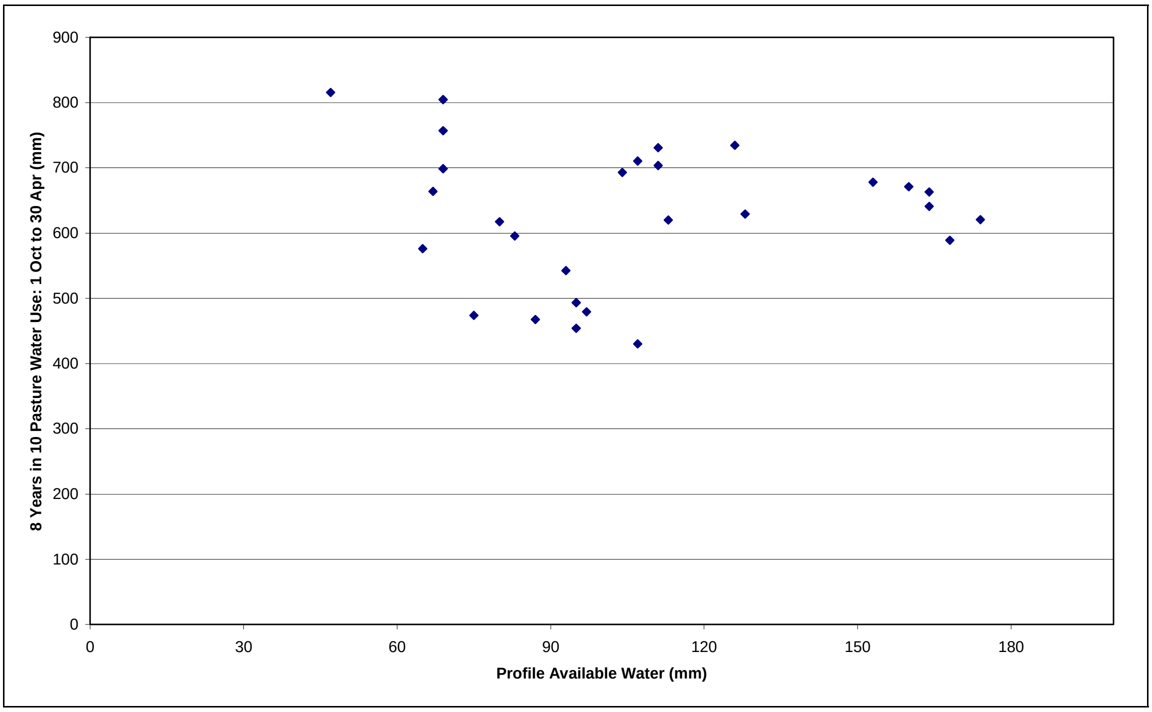

Figure 2-1: Irrigation Seasonal Total Water Demand values estimated for each farm using the WQN9 methodology

2.2 Determining the Seasonal Irrigation Demand Standard for a Specific Farm

Determining the Seasonal Irrigation Demand Standard for a specific farm using the WQN9 method involves the following steps:

1) Determine the profile available water for the soil type(s) on the farm.
2) For each profile available water, look up the Seasonal Total Water Demand Standard determined as described in Section 2.1.
3) Determine the 1-year-in-5 irrigation season effective rainfall for the farm.
4) Subtract the irrigation season effective rainfall from the seasonal total water demand standard.

ECan has estimated the effective rainfall for all potentially irrigable areas in Canterbury. The source data was NIWA's virtual climate network rainfall data. The first 5 mm of rainfall and any rainfall in excess of 50 mm per rain event was considered to be not effective.

The principal weakness of this part of the WQN9 method is the potential mismatch between the irrigation seasons having 1-year-in-5 effective rainfall and 4-years-in-5 total water demand – they need not occur in the same irrigation season.

Rainfall and total water (rainfall plus irrigation) time series are observations of one and the same climate pattern. To dissociate the rainfall time series from the total water time series (which is what happens when the 1-year-in-5 rainfall year is matched up with the 4-years-in-5 total water demand year) is to deny that the rainfall and total water time series come from the same climate. Clearly, this is incorrect.

A proportion of each rainfall and irrigation event is intercepted and does not reach the soil surface. The WQN9 method assumes that this amount is 5 mm. The WQN9 method further assumes that this amount of water is not effective in meeting the evapotranspiration demand, because it does not enter the soil. There is ongoing scientific debate about whether interception losses should be counted as a total loss from the evapotranspiration process, or whether it still contributes to meeting evapotranspiration demand.

Energy that is used to evaporate water droplets from a leaf surface cannot be counted as being available to also drive transpiration from that leaf. To do so would be to double count the energy used to evaporate water droplets. Evaporation of intercepted water from leaf surfaces must therefore reduce the evapotranspiration demand met from soil water. The actual reduction in soil water content on days when the leaf surface is wet will therefore be less than the evapotranspiration estimated using the Penman-Montheith method. Detection of this suppression would require high frequency soil water content measurement. Such data is not available for the lysimeter site used in this study.

If evaporation of water from leaf surfaces does suppress transpiration from the plant and evaporation from the soil surface, in effect the 5 mm of water assumed to be intercepted would actually participate in the soil water balance indirectly. It would therefore be effective.

The lack of high frequency soil water content data for the lysimeter site, and ongoing scientific debate about whether or not evaporation of intercepted water contributes to meeting the evapotranspiration load, marks this as an area of uncertainty with regard to estimation of seasonal irrigation water use.

2.3 A Comparative Evaluation of this Method

To test the effects of the assumptions inherent in this approach, it is informative to calculate the plant water use between 1 October 1998 and 30 April 1999 using the same data and assumptions used by Davoren & Scott (2005). Plant water use is synonymous with actual evapotranspiration (AET). Alternative methods are available for estimating evapotranspiration, so they provide a means of testing the WQN9 method.

Plant water use of the period 1 October to 30 April can be calculated by adding the effective rainfall (see Section 2.1, step 1 above), effective irrigation (see step 2 above), change in soil moisture (see step 4 above), and the effective rainfall amounts estimated to have occurred between 1 October and the beginning of monitoring (see step 6 above), and between the end of monitoring and 30 April (see step 7 above). The results are included in Appendix A.

Pasture plant water use (evapotranspiration) over this period should closely match the evapotranspiration estimated by the Penman-Monteith equation, with parameters appropriate for well watered pasture (assuming the pasture at the farm monitoring sites was well watered throughout the 1998/99 season).

Pasture water use over the period 1 October 1998 to 30 April 1999 for each of the farms used in this analysis is shown in Figure 2-2, along with Penman-Monteith estimates of pasture evapotranspiration that were made using climate data from Lincoln and Winchmore.

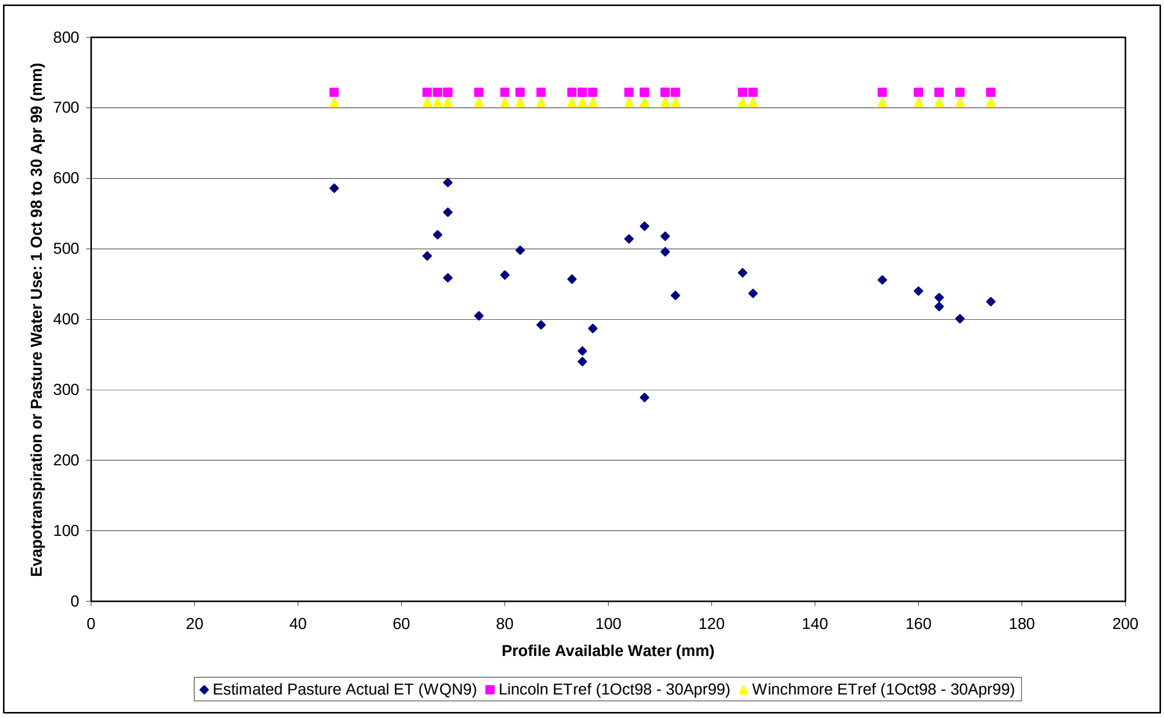

Figure 2-2: Comparison between pasture water use estimated using the method adopted by ECan and Penman-Monteith estimates of evapotranspiration

It is clear from Figure 2-2 that the pasture water use estimated using the WQN9 method is consistently significantly lower than the evapotranspiration estimated using the comprehensively tested and widely adopted Penman-Monteith method.

The wide scatter in estimated plant water use is surprising; it is expected that in reality the variation was not this great. If it were, there would most likely have been sufficient soil moisture stress to obviously reduce pasture production. The wide scatter and the significant difference between the WQN9 estimates of pasture water use and those made using Penman-Monteith could be attributed to the assumption inherent in the WQN9 method.

A downward trend in pasture water use with increasing profile available water is also evident in the results obtained using the WQN9 method. If the pasture has been adequately irrigated, it is highly unlikely that actual pasture water use would exhibit a trend with increasing profile available water. Under non-irrigated conditions an upward trend would be expected, as the amount of rainfall retained within the soil as plant-available water increases with increasing profile available water. If irrigation was not sufficient to maintain evapotranspiration at the potential rate, one would expect an upward trend against increasing profile available water. A downward trend against increasing profile available water under fully irrigated conditions is most unlikely. It is more likely that that the estimation process is generating the trend.

2.3.1 Conclusions Regarding the WQN9 Method for Determining Total Water Demand

If the pasture on the monitored farms has been adequately irrigated, the assumptions in the WQN9 method introduce errors in the estimated plant water use that accumulate over the irrigation season, and those errors appear to increase as profile available water increases. Errors in estimated plant water use translate directly into errors in the estimated Seasonal Total Water Demand.

If the pasture on the monitored farms has not been adequately irrigated, the data from them will not be suitable for the purpose of determining reasonable seasonal total water demand.

2.4 Estimation of Effective Rainfall or Effective Irrigation from an Event

Application of the WQN9 method requires the estimation of effective rainfall and effective irrigation for each rainfall and irrigation event on each of the monitored farms in the 1998/99 irrigation season.

Estimation of effective rainfall or effective irrigation due to a single rainfall or irrigation event is equivalent to estimating the water lost from the soil profile. Most of this is likely to be drainage. Without loss of generality in the following discussion, losses can be considered to be drainage.

Estimation of drainage from an irrigation or rainfall event can be based on the use of a single layer soil water balance model of the following form:

$$S_{t_2} = S_{t_1} + R_{(t_2-t_1)} + I_{(t_2-t_1)} - D_{(t_2-t_1)} - AET_{(t_2-t_1)} \qquad \text{(Equation 2-1)}$$

Where:

$AET_{(t_2-t_1)}$ = Actual evapotranspiration between time t_2 and t_1
$R_{(t_2-t_1)}$ = Rain between time t_2 and t_1
$I_{(t_2-t_1)}$ = Irrigation between time t_2 and t_1
$D_{(t_2-t_1)}$ = Drainage between time t_2 and t_1
S_{t_2} = Soil water content at time t_2
S_{t_1} = Soil water content at time t_1

Soil water content monitoring events at t_2 and t_1 bound the irrigation or rainfall event that is to be analysed.

The information used in the WQN9 method is measured soil water content (periodic) and daily rainfall, and measured or estimated irrigation amounts (each event).

Rearranging Equation 2-1 to place all of the measured data to the right of the equal sign, and all the unknowns to the left, results in:

$$D_{(t2-t1)} + AET_{(t2-t1)} = S_{t1} - S_{t2} + R_{(t2-t1)} + I_{(t2-t1)} \qquad \text{(Equation 2-2)}$$

It is clear from Equation 2-2 that there are two unknowns but only one equation. There is no unique solution to this equation.

Drainage, and therefore effective rainfall or effective irrigation, cannot be calculated unless AET has been measured.

AET cannot be calculated from the measured soil water contents, rainfall and irrigation data unless drainage is also measured.

If actual evapotranspiration is not measured:

- The estimated actual drainage, and therefore the effectiveness of rainfall or irrigation, depends entirely on the amount of AET assumed to have occurred.
- There is an infinite number of combinations of AET and drainage that satisfy the measured soil moisture contents and amounts of rainfall and irrigation.
- Over the course of an irrigation season there is no robust estimate of drainage or crop water use.

To apply this method to estimate crop water use over an irrigation season, ECan selected the 1998/99 season as a year expected to be representative of the 8-year-in-10 irrigation demand season.

Dr Tony Davoren, an experienced irrigation scheduling consultant, was engaged to apply the above method using soil water content, irrigation and rainfall measurements made by him at a number of farms on the Canterbury Plains. For each rain and irrigation event an assumption had to be made about the drainage or the AET. Having made this assumption, Equation 2-2 was used to calculate the actual evapotranspiration or the drainage (and thus effective rainfall or effective irrigation) that occurred between the successive measurements of soil water content. All such calculated values were then summed over the period 1 October 1998 to 30 April 1999 to give the effective rainfall, effective irrigation, and AET for that period.

While this method has used soil water content, rainfall and irrigation data from many locations in Canterbury, the method for using this data with the soil water balance model described by Equation 2-1 has not, to Aqualinc's knowledge, been tested or validated at any site. To do so would require use of either measured drainage or measured AET at one or more sites.

The conclusions in Section 2.3.1 suggest that the assumptions made in the analysis of the many rainfall and irrigation events that occur in an irrigation season result in errors that accumulate, over many events, to produce a significant underestimate of plant water use, and thus total water demand.

3 THE AQUALINC SEASONAL IRRIGATION DEMAND ASSESSMENT METHOD

3.1 Description of Method

Seasonal irrigation water use is primarily a function of plant water use and irrigation management. Soil hydraulic properties indirectly affect irrigation water use. Interactions between these soil properties, irrigation application system characteristics, and irrigation management determine how much of the applied water (including rainfall) is retained in the root zone of the soil, and thus how soon the next irrigation will be required.

The method used by Aqualinc to estimate irrigation water use is an implementation of the approach described by Allen *et al.* (1998). Aqualinc's implementation uses IrriCalc to simulate the day-to-day operation of an irrigation system to avoid yield loss due to water stress. A rule-based approach to irrigation management is simulated. Application of the irrigation management rule on a daily basis determines the timing of irrigation and the amount to be applied. The various components of the rule are described in Section 3.2.2. The result of applying the irrigation rule in concert with a daily water balance model is a daily time series of irrigation application depth. The total amount of irrigation water used over a user specified irrigation season is summed.

The time series of seasonal irrigation water use is then analysed to determine the seasonal irrigation water use that would avoid crop yield loss, to a specified level of reliability – such as eight years out of ten years on average.

Computer modelling of irrigation system operation is a transparent method for estimating seasonal irrigation demand, based on use of a validated soil water balance model, defined irrigation management rules, and climate data.

In particular, it is a method that preserves the correlation between daily rainfall and other daily climate data, and it avoids the need to make major assumptions about the effectiveness of rainfall and irrigation. The volume of drainage from each rainfall and irrigation event is an output – a result that depends on the soil water deficit at the time of the event and on the characteristics of the irrigation or rainfall event.

3.1.1 Summary of Key Assumptions

The key assumptions on which Aqualinc's method for estimating seasonal irrigation water use are:

a) The climate time series used with the soil-plant-atmosphere system model is representative of future climate;

b) The irrigation actions determined by the irrigation system model are practical;

c) Irrigation rules are consistently followed – for some rules, this implies that soil water content in the root zone is continuously monitored and used for irrigation decision making;

d) Water is always available for irrigation, at the rate required, when irrigation is required according to the decision rule being used;

e) Assumptions specific to the soil-plant-atmosphere model used (see Section 3.2.3 for assumptions pertinent to the IrriCalc model); and

f) Assumptions specific to the irrigation system model and irrigation management rules used (see Section 3.2.3 for assumptions pertinent to the IrriCalc model).

3.1.2 Information Required to Apply the Method

The information required to apply this method depend on the information requirements of the model(s) used. Section 3.3 describes the information required to use the IrriCalc model.

3.2 IrriCalc

3.2.1 Description of IrriCalc's Soil Water Balance Model

IrriCalc is a single-layer soil water balance model that uses the following equation to update the calculated soil water content on a daily basis given daily measurements or estimates of rainfall, irrigation, drainage and actual evapotranspiration.

$$S_{t_2} = S_{t_1} + R_{(t_2-t_1)} + I_{(t_2-t_1)} - D_{(t_2-t_1)} - AET_{(t_2-t_1)} \qquad \text{(Equation 3-1)}$$

Where:

$AET_{(t_2-t_1)}$ = Actual evapotranspiration between time t_2 and t_1

$R_{(t_2-t_1)}$ = Rain between time t_2 and t_1

$I_{(t_2-t_1)}$ = Irrigation between time t_2 and t_1

$D_{(t_2-t_1)}$ = Drainage between time t_2 and t_1

S_{t_2} = Soil water content at time t_2

S_{t_1} = Soil water content at time t_1

$AET_{(t_2-t_1)} = K_c \times f(S_{t_1}, a) \times ETref_{(t_2-t_1)}$

K_c = Crop factor applicable over time t_1 to t_2

$f(S_{t_1}, a)$ = Evapotranspiration reduction function

$ETref$ = Evapotranspiration for a well watered reference crop

The evapotranspiration reduction function is an empirical function that takes a value in the range 0 to 1, depending on the ratio of soil water content on day t_1 to the "field capacity" and the parameter "a". The parameter "a" is related to the volume of soil water that is readily available to the plant. The particular empirical function used in IrriCalc is described in Minhas *et al.* (1974), and has been used in New Zealand by Heiler (1981) and Bright (1986).

Drainage is assumed to occur whenever the soil water content is calculated to be greater than "field capacity". The volume of drainage is set equal to the volume required to reduce the soil water content to "field capacity", and it is assumed that drainage occurs within the same daily time period as the rainfall or irrigation that raised soil water content above "field capacity".

Reference crop evapotranspiration is calculated from daily climate measurements using the Penman-Monteith method (FAO-56), with parameters appropriate for estimating evapotranspiration from a well watered grass sward of 120 mm height.

Irrigation amounts are either calculated by an irrigation system model on each day of a defined irrigation season or are input as time series measurements. The irrigation system model is described in Section 3.2.2.

IrriCalc outputs each component of the soil water balance on each day of the simulation, along with a check-sum that indicates whether mass has been conserved and the accumulated volume of water used for irrigation.

3.2.2 Description of IrriCalc's Irrigation System Model

The irrigation system model enables key irrigation system design and irrigation management parameters or constraints to be specified. These are the depth and spatial uniformity of irrigation applications, the return period, the soil water level at which irrigation is triggered, the beginning and end of the irrigation season, and the maximum seasonal irrigation water use.

Table 3-1 shows the various combinations of irrigation system parameters that can be applied to replicate a wide range of irrigation systems and practices.

Table 3-1: Irrigation management options available in IrriCalc

	When to irrigate			
Application depth	Never	Every X days, where X = Return Period	Trigger on soil moisture, providing the days since the last irrigation equal or exceed the Return Period	User supplied time series
Zero	✓			
Fixed depth (user defined)		✓	✓	
Variable depth (return soil moisture to a specified level)		✓	✓	
User supplied time series				✓

Irrigation applications

These are either input as a time series of actual application depths or are determined by the application of irrigation management rules.

The application depth specified by the user, or calculated by the irrigation model, is the spatial average of the water depth applied across the wetted width and run length of the irrigation application device. The spatial uniformity of the irrigation application is specified by Christiansen's Uniformity Coefficient.

The amount of water that is retained in the soil due to an irrigation event is calculated using the method described in Bright (1986). Implicit in this calculation is the assumption that the spatial distribution of application depth can be represented by the Normal distribution. The amount retained, and thus the amount of irrigation water that drains, is a function of the soil water deficit at the time of irrigation, the average application depth, and the uniformity of irrigation application. The relationship between application efficiency (which is the ratio of volume of water retained to volume of water applied), average application depth, and uniformity is illustrated in the following figure:

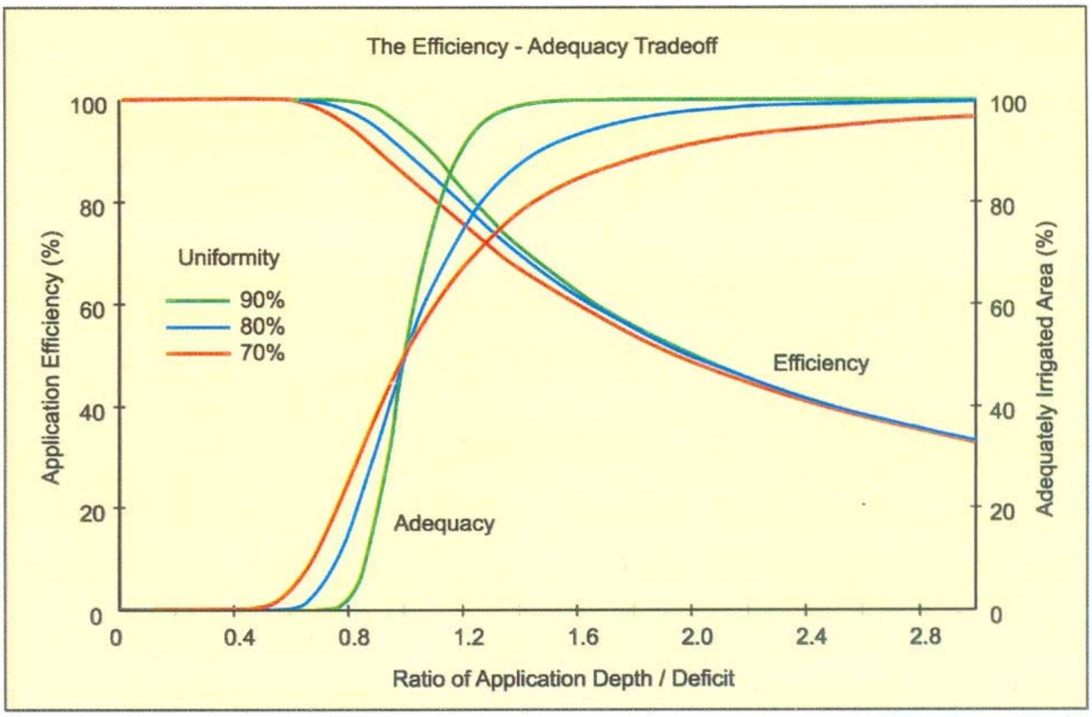

Figure 3-1: Relationship between application efficiency, application uniformity and application depth (source: Bright, 1986)

Application efficiency

Application efficiency is defined as the ratio of the volume of irrigation water retained in the root zone of the soil to the volume of irrigation water applied to the land surface. The application efficiency varies from application event to application event.

Application efficiency is not a direct output of an IrriCalc simulation, but can be calculated for each irrigation event by opening the IrriCalc output file in Excel and doing the calculation in Excel.

It is important to note that IrriCalc does not use any irrigation efficiency factors in its calculation of irrigation water use.

Irrigation system capacity

Irrigation system capacity is an implicit constraint in IrriCalc. The combination of application depth and return period constrains irrigation system capacity according to the following:

$$\text{Maximum flow rate} = (\text{Application depth} \times 10{,}000) \div (\text{Return period} \times 86{,}400)\ \ell/s/ha$$

Maximum seasonal irrigation water use

The total amount of irrigation water used in any irrigation season is constrained to be less than the user-specified maximum seasonal irrigation water use. If the specified maximum is reached during an irrigation season, then irrigation is prevented for the remainder of that season. No attempt is made, in this version of IrriCalc, to optimise the use of the limited volume of water. The total volume of irrigation water used is re-set prior to beginning of the next irrigation season.

To investigate how much irrigation water would have been used over a sequence of many years in the absence of a cap on total use, the specified maximum seasonal irrigation water use is simply set to a very large number.

3.2.3 Summary of Key Assumptions

a) The soil is free draining.

b) Crop canopy development is sufficiently consistent across years to enable use of a crop factor time series to transform evapotranspiration for a reference crop into evapotranspiration from the crop or pasture of interest. In east-coast New Zealand environments, crop factors developed for irrigated conditions should not be used for un-irrigated conditions, and vice versa.

c) All rainfall and irrigation intercepted and retained on leaf and stem surfaces is effective in meeting the evapotranspiration load.

d) The spatial distribution of irrigation application depth can be represented by the Normal Distribution.

3.3 Data Needed to Use IrriCalc to Estimate Seasonal Irrigation Demand

The information required to apply IrriCalc is summarised in the following sub-sections. The climate and soils data required are available throughout New Zealand, courtesy of fundamental databases maintained by the National Institute for Water and Atmospheric Research Ltd. and Landcare Research Ltd.

3.3.1 Climate, Crop and Soils Data Required

a) Daily time series for rainfall and potential evapotranspiration for the site of interest. These can be measured data or data from NIWA's virtual climate network.

b) Crop factor time series (one year). For irrigated pasture, the crop factor time series developed is as described in Section 4. For other crop factor time series, see FAO Publication 56.

c) Crop root depth (or depth of soil that supplies water to meet crop needs).

d) Water holding capacity of the soil to crop root depth (mm per mm of soil depth).

e) Dates the crop or pasture is sown and harvested.

3.3.2 Irrigation System Data Required

a) The type of irrigator to be modelled and some understanding of its operating requirements.

b) The maximum and minimum average application depth that is practical to apply for the particular irrigator.

c) The uniformity of irrigation applications (Christiansen's Uniformity Coefficient).

d) The length of the irrigation rotation (days).

e) The soil water content at which irrigation is initiated (if irrigation timing is determined by measured soil water content).

f) Maximum seasonal irrigation water use.

g) Beginning and end dates for the irrigation season.

4 DEVELOPMENT OF A CROP FACTOR FOR PASTURE

4.1 Development Method

Direct measurement of crop water use for broad acre crops and pasture has not been undertaken in New Zealand to the extent required for irrigation management and resource management.

Crop water use can be estimated from measurements of rainfall, irrigation, drainage and changes in soil water content over a soil depth greater than the depth that supplies the crop with water, using the following mass balance equation:

$$AET_{(t_2-t_1)} = R_{(t_2-t_1)} + I_{(t_2-t_1)} - D_{(t_2-t_1)} - \left(S_{t_2} - S_{t_1}\right) \qquad \text{(Equation 4-1)}$$

Where:

$AET_{(t_2-t_1)}$ = Crop water use between time t_2 and t_1

$R_{(t_2-t_1)}$ = Rain between time t_2 and t_1

$I_{(t_2-t_1)}$ = Irrigation between time t_2 and t_1

$D_{(t_2-t_1)}$ = Drainage between time t_2 and t_1

S_{t_2} = Soil water content at time t_2

S_{t_1} = Soil water content at time t_1

In this context, “crop water use” is the sum of water transpired from the crop and water evaporated from the soil.

In order to directly calculate crop water use, the value of all of the parameters on the right hand side of the equation must be measured, or be determined independently of each other.

ECan operates a lysimeter site near Dunsandel that is representative of irrigated intensive pastoral farms. Aqualinc obtained from ECan measured rainfall+irrigation, drainage and soil moisture data for this site. The soil moisture measurements were made by Dr Tony Davoren for ECan. Measured data for all parameters on the right-hand side of the above equation were obtained.

Actual evapotranspiration was calculated directly from these measurements using Equation 4-1.

Prior to the use of the data, the following processes were applied:

- Gaps in the rainfall record were filled by Leeston rainfall measurements.
- The rainfall and irrigation time-series was split into separate time series files by Dr Davoren. A period of missing irrigation record was filled by Dr Davoren by inference from his soil moisture data and drainage data from Lysimeter 2.
- Lysimeter 2 data was scaled by dividing it by 1.27 to produce estimated Lysimeter 1 drainage where it was necessary to fill gaps on the Lysimeter 1 record. This factor was obtained by averaging the ratio of Lysimeter 2 to Lysimeter 1 over a number of events prior to the gap in the Lysimeter 1 record.

Rainfall, irrigation and drainage were measured continuously and aggregated into daily totals. Soil water content was measured at irregular time intervals, varying according to the season. At the peak of the irrigation season, measurements were made once or twice per week.

Actual evapotranspiration between each successive soil water content measurement was calculated using Equation 4-1, providing there was zero drainage on the days on which soil water content was measured. If drainage occurred during a day on which soil water content was measured, there is uncertainty about whether the drainage occurred before, after or while the soil water content was being measured. To avoid the uncertainty in the calculated actual evapotranspiration that this would create, the time period over which the change in soil moisture was calculated was increased until zero drainage days coincided with days when soil water content was measured.

The total actual evapotranspiration calculated to have occurred over the measurement time period was divided by the potential evapotranspiration for the reference crop (100 mm high pasture) to get the crop coefficient value for that time period.

The reference crop potential evapotranspiration was estimated by NIWA using data from the Lincoln climate station for the period 1 July 1999 to 30 June 2001. This is referred to as the calibration period.

This two-year crop factor time series was split into two single years, referenced to 1 July, and averaged to provide a daily crop factor time series for irrigated pasture. This is shown in Section 4.2.

The use of a drainage lysimeter to measure drainage flux for this purpose implies the following assumptions:

- In the natural soil column there is no upward flux of water across a plain that is at the same depth as the base of the soil in the lysimeter;
- The creation of a zero tension plane (at the bottom of the lysimeter) does not significantly modify the soil water profile as experienced by the crop; and
- The lysimeter is deep enough to contain all of the crop roots.

These assumptions are reasonable for Canterbury Plains' shallow alluvial soils overlying coarse grained parent material (e.g. Lismore soils) if the lysimeter depth is substantially greater than the depth of soil, and the depth to the water table is greater than about 2 m.

4.2 Resulting Crop Factor for Pasture

The crop factor time series derived from field measurements for irrigated pasture using the method described in Section 4.1 is shown in Figure 4-1. The calculated time series was smoothed to reduce the number of step changes in value. The smoothed crop factor time series was then used as an IrriCalc input.

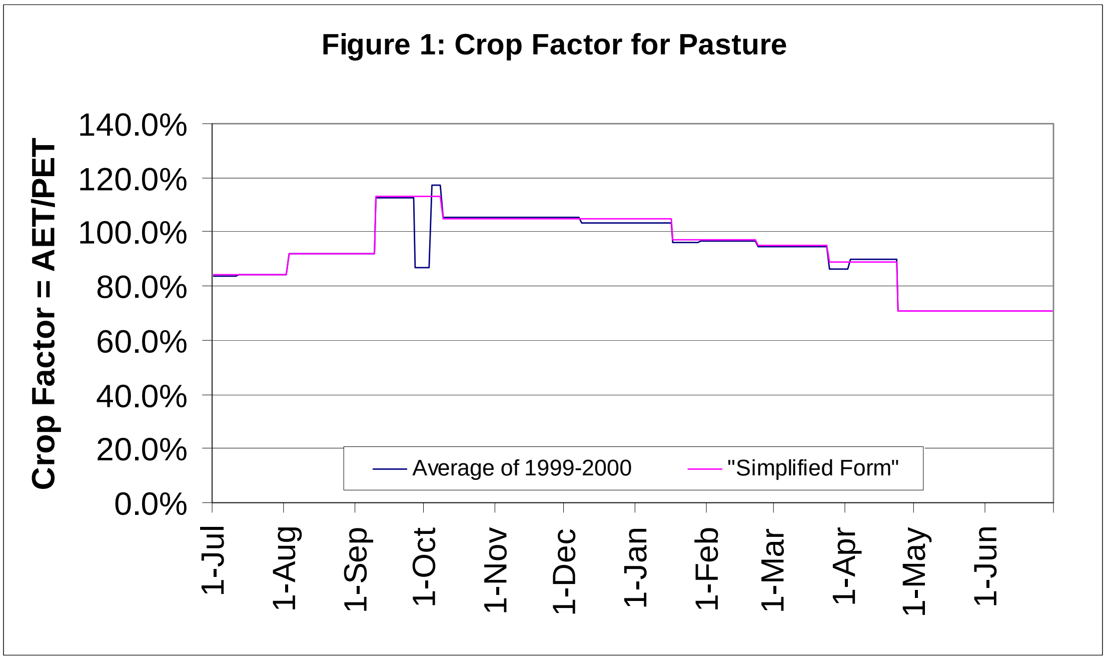

Figure 4-1: Derived crop factor for pasture in Central Canterbury

5 TESTING THE CROP FACTOR TIME SERIES WITH IRRICALC'S SOIL WATER BALANCE MODEL

5.1 Test Method

Testing of the pasture crop factor with IrriCalc was undertaken in two stages.

Stage 1 was simply to check the results of the crop factor calculation process, and to test the effects of the averaging and smoothing that occurred on the accuracy with which drainage (and thus actual evapotranspiration) is simulated. The measured inputs of rainfall and irrigation, along with potential evapotranspiration (PET) derived from the Lincoln climate station and the daily crop factor time series were used as inputs to Aqualinc's IrriCalc programme. The programme was run to produce a modelled drainage time series over the same time period used to derive the crop factor time series. The drainage time series was then compared to the measured Lysimeter 1 drainage time series. The results of doing so are shown in Section 5.2.

Stage 2 of the testing involved simulating drainage for time periods that were not used to derive the crop factor time series and comparing simulated drainage with measured drainage. The results of doing so are shown in Section 5.2.

5.2 Test Results

5.2.1 Comparison of Measured and Simulated Drainage for the Calibration Period

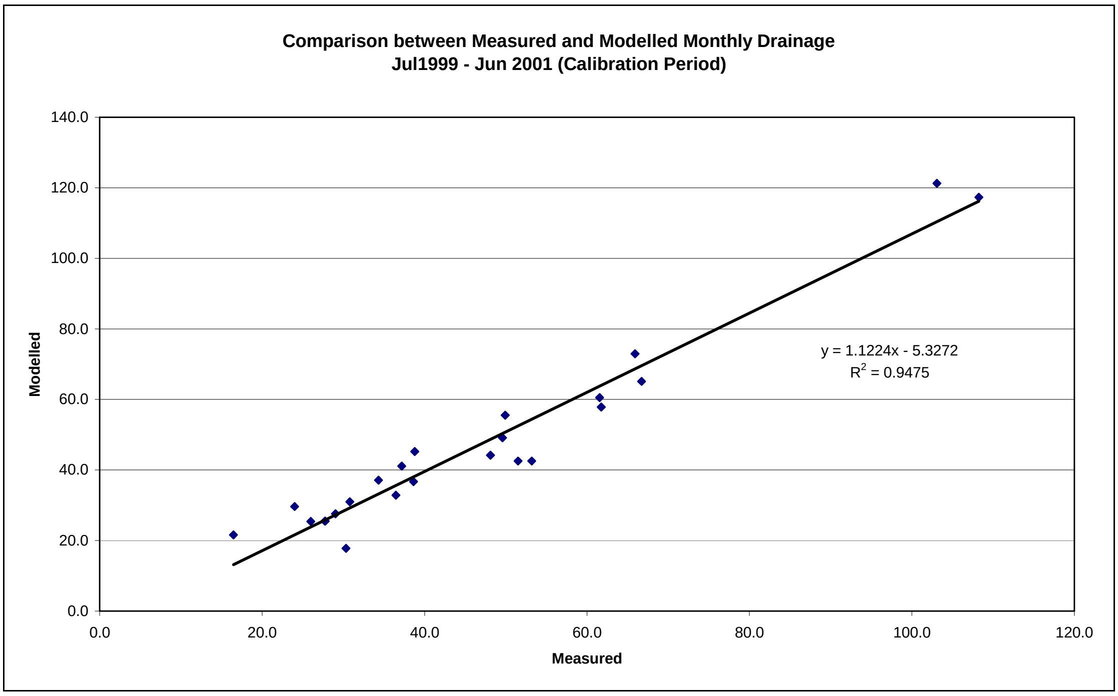

Figure 5-1: Comparison of modelled and measured drainage over the "Calibration Period"

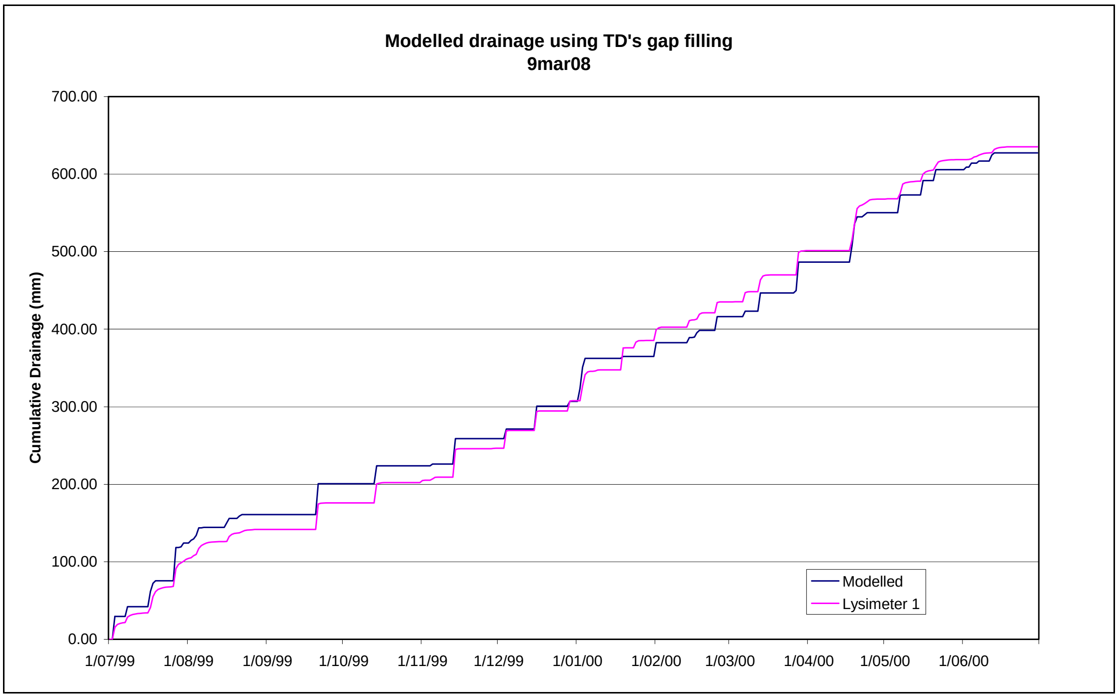

Figure 5-2: Comparison of modelled and measured cumulative drainage for 1999/2000

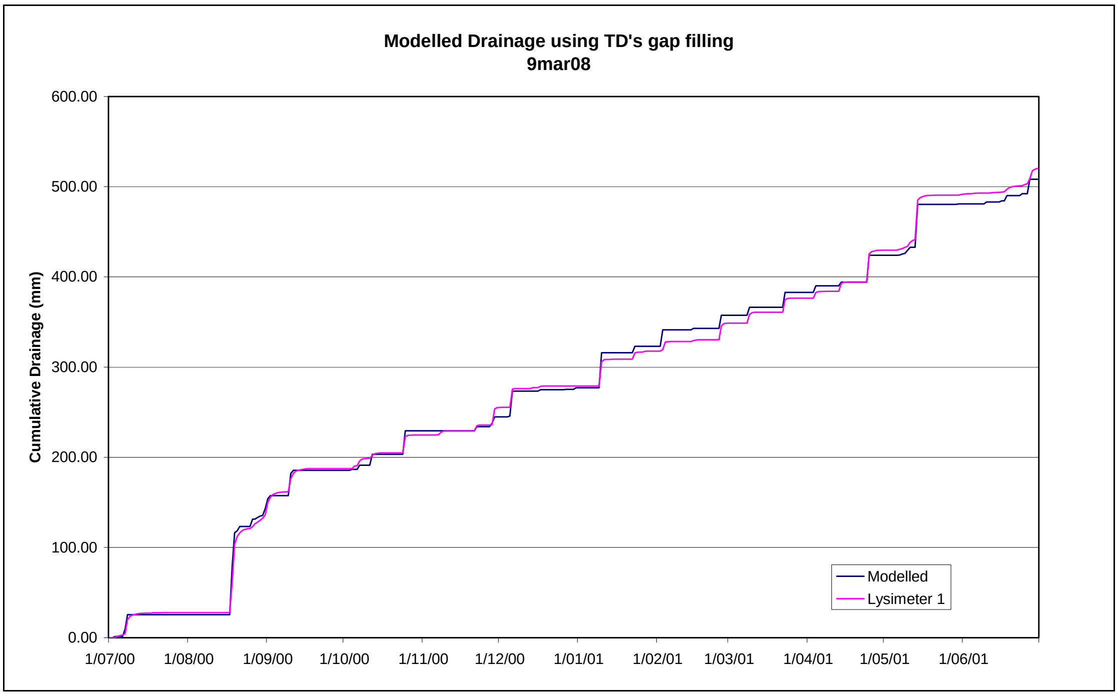

Figure 5-3: Comparison of modelled and measured cumulative drainage for 2000/01

5.2.2 Comparison of Measured and Simulated Drainage for the Validation Period

The 1998/99 year was not used for calculating the crop factor so has been used as a validation season. Comparison of the measured and modelled drainage for this year is shown in Figure 5-4 and Figure 5-5.

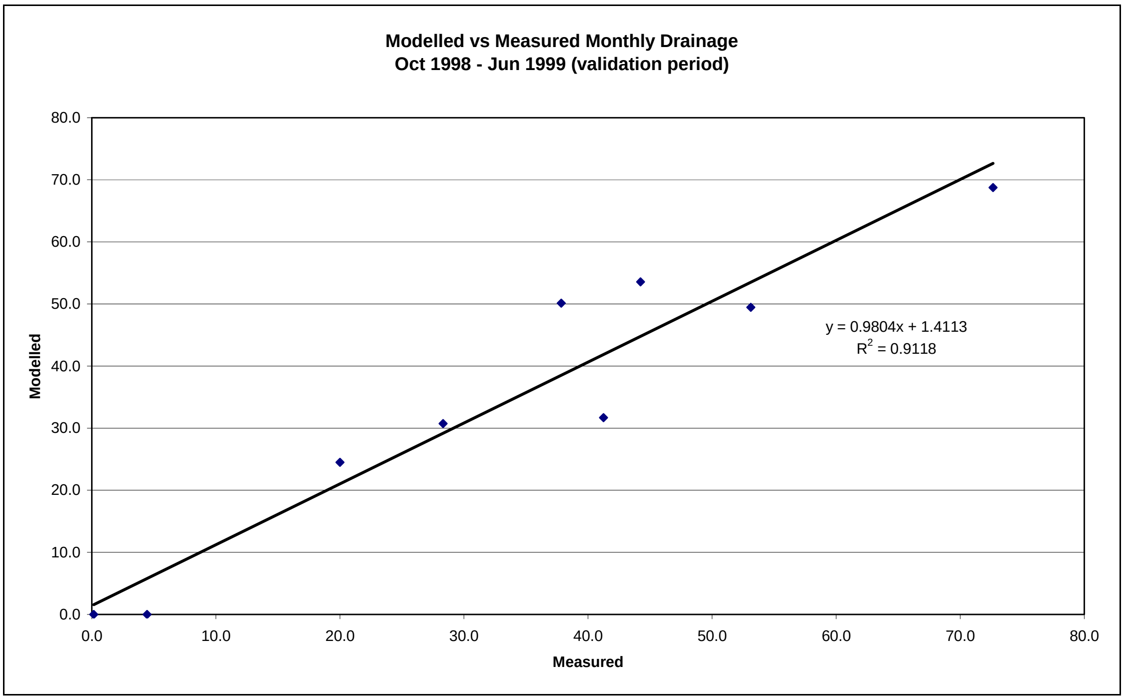

Figure 5-4: Comparison between measured and modelled drainage for validation period

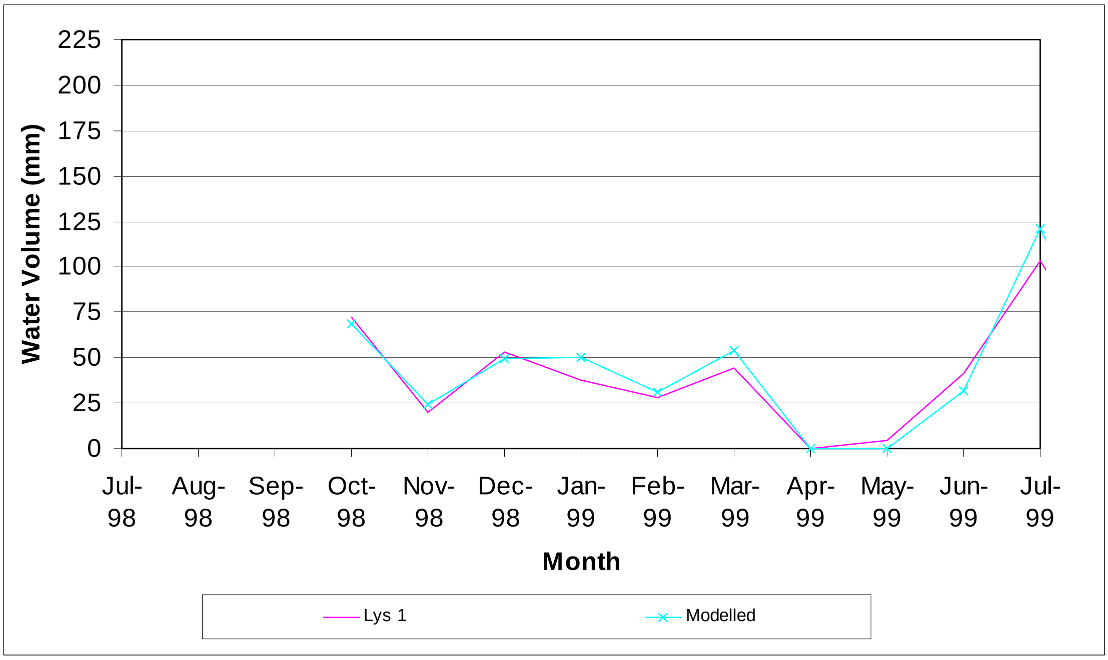

Figure 5-5: Comparison between measured and modelled drainage depths for 1998/99 irrigation season

Measurements of rainfall, irrigation, drainage and climate data were available for the period July 1998 to June 2005. IrriCalc was used to provide a modelled drainage time series for the whole of this period, which was then compared with the measured drainage time series.

The residuals (modeled drainage – measured drainage) are shown in Figure 5-6 below. A trend in the residuals is clearly evident. Figure 5-7 shows the modelled root-zone soil water content over the same period. It indicates that soil water deficits of sufficient magnitude to depress pasture growth (and thus leaf area index) increased in frequency and duration from mid 2001. As a result, actual evapotranspiration from mid 2001 is not expected to have occurred at the rate that occurred in the first three seasons. Measured actual evapotranspiration that is depressed relative to the modelled actual evapotranspiration results in the modelled drainage being less than the measured drainage (negative residual). The most likely reason for the increased frequency, duration and intensity of soil water deficits is changing groundwater level. During the period of measurement, groundwater levels steadily dropped, and the farmer was unable to operate his pump at its normal flow rate. Adjustments were made to the irrigator nozzles to reduce the flow rate and thus application depth, so as to prevent the pump tripping out on low water level. Consequently, the irrigation that occurred was insufficient to keep up with evapotranspiration losses and soil water deficits increased.

A key point is that the crop factor time series determined by this work is for well watered (but not perfectly watered) pasture for which leaf area development has probably not been significantly impeded by soil water deficits.

Use of this crop factor time series for un-irrigated pasture will lead to an underestimate of drainage in seasons where significant soil water deficits develop.

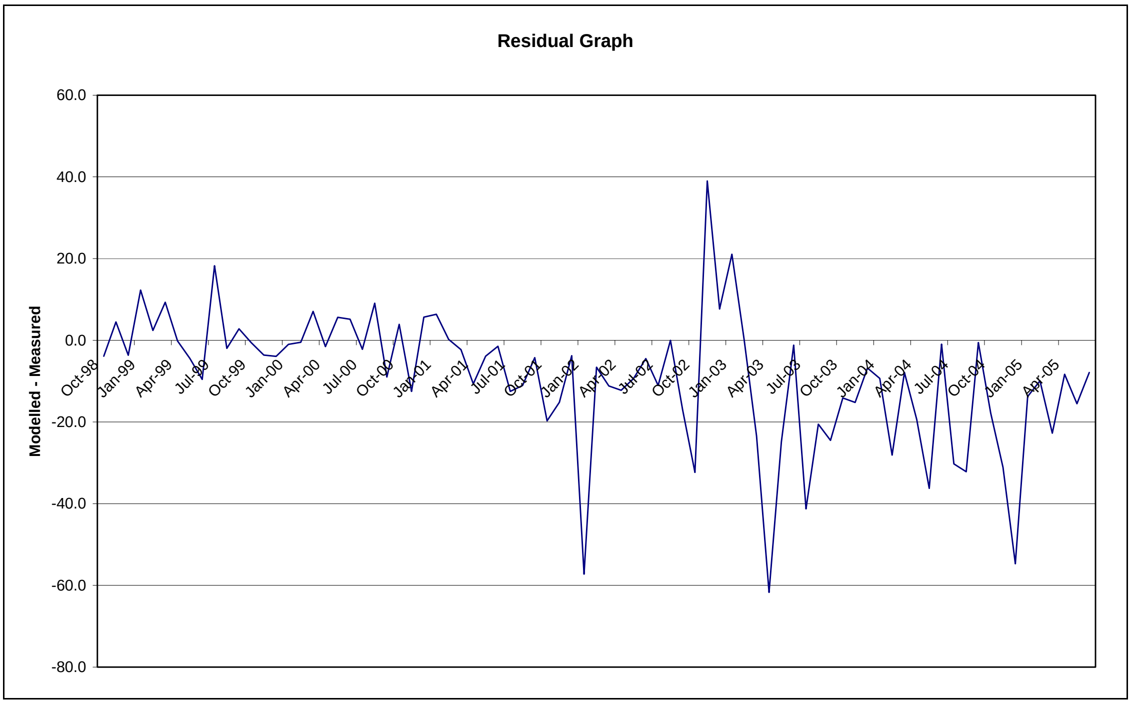

Figure 5-6: Residuals plot (modelled drainage – measured drainage)

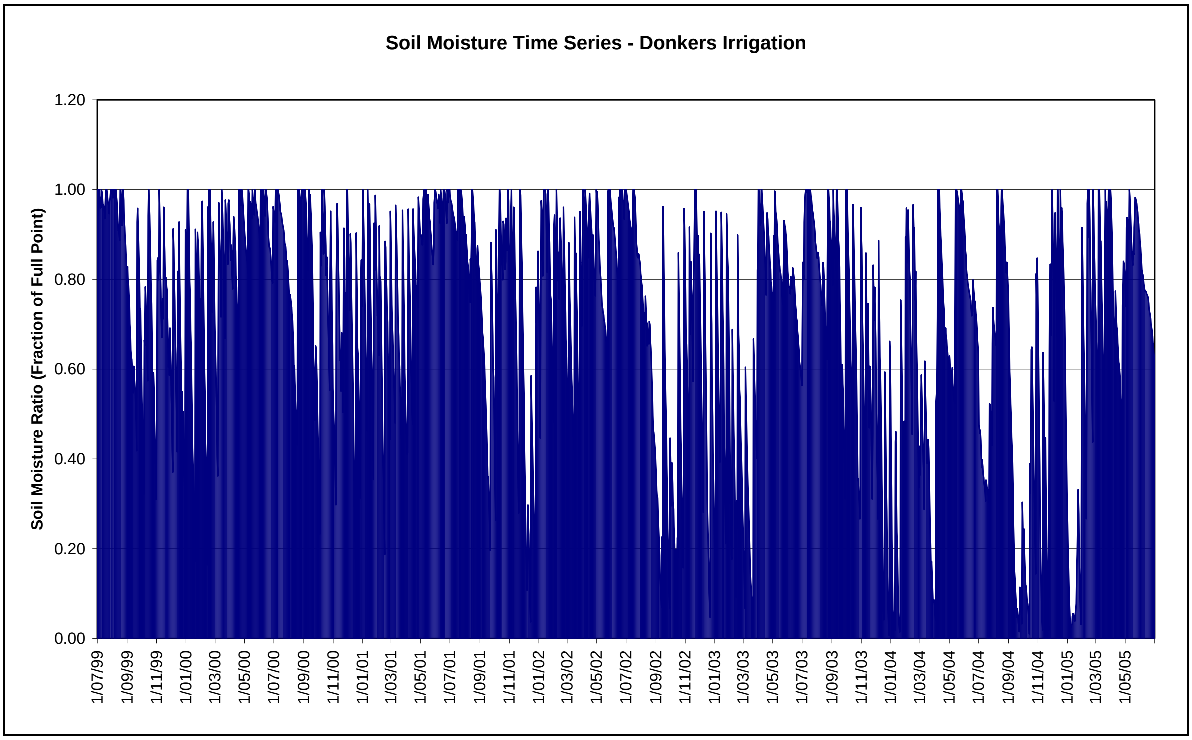

Figure 5-7: Modelled soil water

6 REPRESENTATIVE APPLICATIONS OF IRRICALC

The IrriCalc model has been used to simulate irrigation water use, for pasture, for a number of combinations of soils and rainfall stations, all with Lincoln potential evapotranspiration.

Three sets of irrigation systems have been evaluated for various combinations of soil and climate.

In the first irrigation system arrangement, the average application depth was adjusted, keeping the irrigation trigger point constant, to achieve an average application efficiency of 80%.

In the second irrigation system arrangement, the application depth was set having regard to the soils capacity to store plant available water (PAW_{cap}) and the normal range of application depths achievable with a rotating boom irrigator. The irrigation trigger point was adjusted to provide an average application efficiency of 80%, except when this would have resulted in an irrigation trigger point of less than 50% of the PAW_{cap} (to avoid significant soil water deficits).

In the third irrigation system arrangement, the operation of a centre-pivot or lateral-move irrigator was simulated.

In the simulations conducted for this project, a uniformity coefficient of 70% was used for all irrigators except pivots. For pivots, a uniformity coefficient of 90% was used. These parameter values are based on the results of tests of traveling irrigators conducted by John *et al.* (1985).

The results of these simulations are shown in tabular and graphical form in the following pages.

It should be noted that the irrigation application efficiency referred to in this report is the ratio of the volume of water retained in the depth of soil that supplies the plant with water to the volume of water applied to the land surface. Its value changes from irrigation event to irrigation event, depending on the soil water deficit at the time of irrigation, the depth of water applied, the uniformity with which it is applied, and whether it rains on the same day. In general, application efficiency is less than 80% for irrigation events that coincide with rain days and is higher than 80% (sometime significantly higher) when irrigation has been delayed by the return period constraint. Application efficiency values are reported in the following tables as averages over time of all irrigation application events.

6.1 Irrigator with an Average Application Efficiency of 80%

Table 6-1: Seasonal irrigation water use and AET for soils with 60 mm, 80 mm and 120 mm plant available water capacities

Rainfall station	Soil PAW_{cap} (mm)	Application depth (mm)	Return period (yr)	Average application efficiency (%)	Seasonal irrigation water use			Actual ET		
					80 percentile	**90 percentile**	**Average**	**80 percentile**	**90 percentile**	**Average**
Lincoln	60	40.5	8	80.1	729	770	613	813	854	769
	80	53	10	79.5	689	742	591	815	857	771
	120	78	15	79.9	702	741	557	815	858	771
Te Pirita	60	40	8	79.6	680	720	601	826	857	781
	80	52.5	10	79.9	683	735	580	829	859	783
	120	77	15	80.4	678	693	531	832	860	783
Hororata	60	39.5	8	79.8	592	632	507	814	855	770
	80	52	10	80.2	572	624	469	816	859	771
	120	77	15	80.1	539	539	426	816	859	772

Note: Plant available water capacity (mm) = Plant root depth (mm) × Soil water holding capacity (mm/mm)

The IrriCalc modelled plant available water time series shown in Figure 6-1 and Figure 6-2 illustrate how many irrigation applications are required to keep up with atmospheric water demand in a high irrigation demand season.

The 1998/99 irrigation season has the same seasonal irrigation water use as the 80 percentile year (1977/78) (in Figure 6-3). The 1997/98 irrigation season had the third highest seasonal irrigation water use over the 1928-2004 time period.

These figures illustrate that in 80 percentile demand years, and drier, there are a number of days on which the plant available water is below the 50% irrigation trigger point. This is indicative of the irrigation system having insufficient capacity to keep up at times of high evapotranspirative demand. In the scenarios analysed, the capacity has been set at a rate equivalent to about 5 mm per day.

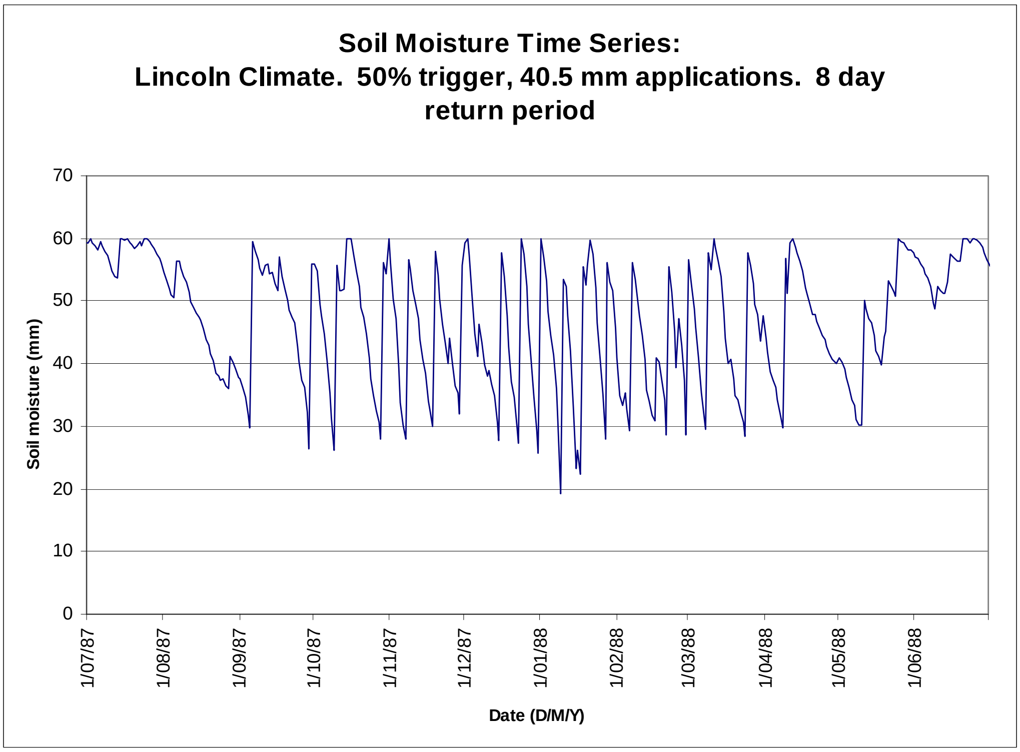

Figure 6-1: Soil moisture time series for the 1987/88 irrigation season (60 mm PAW_{cap})

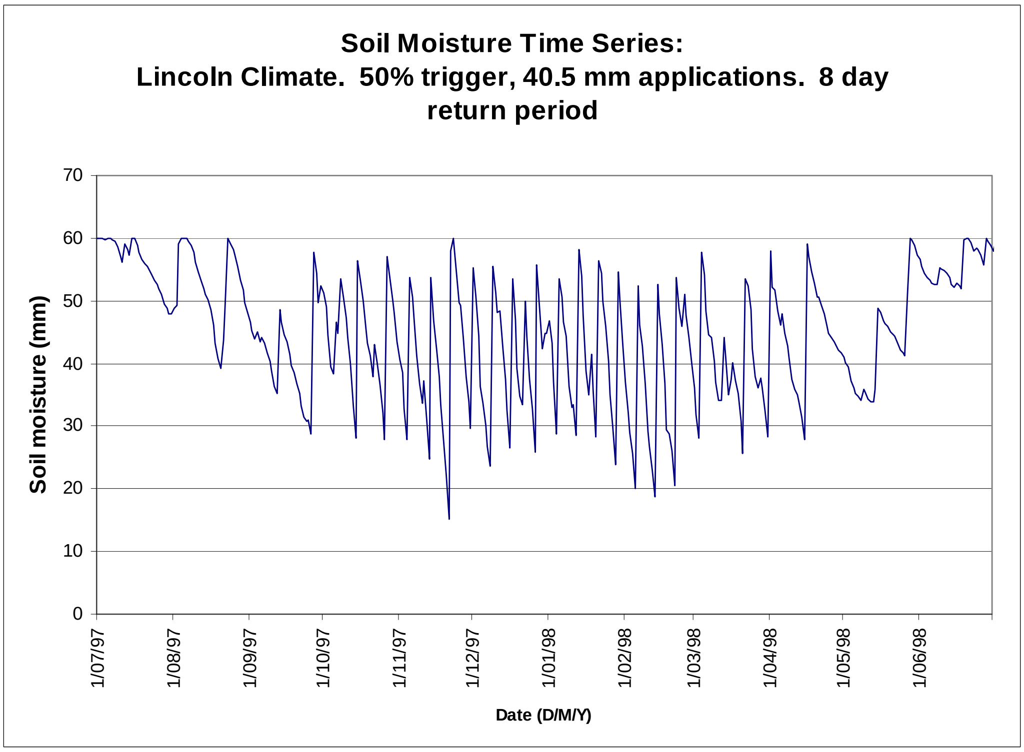

Figure 6-2: Soil moisture time series for the 1997/98 irrigation season (60 mm PAW_{cap})

In Figure 6-3 to Figure 6-5, the seasonal irrigation water use has been ranked to enable comparison between years and with the 80 percentile year.

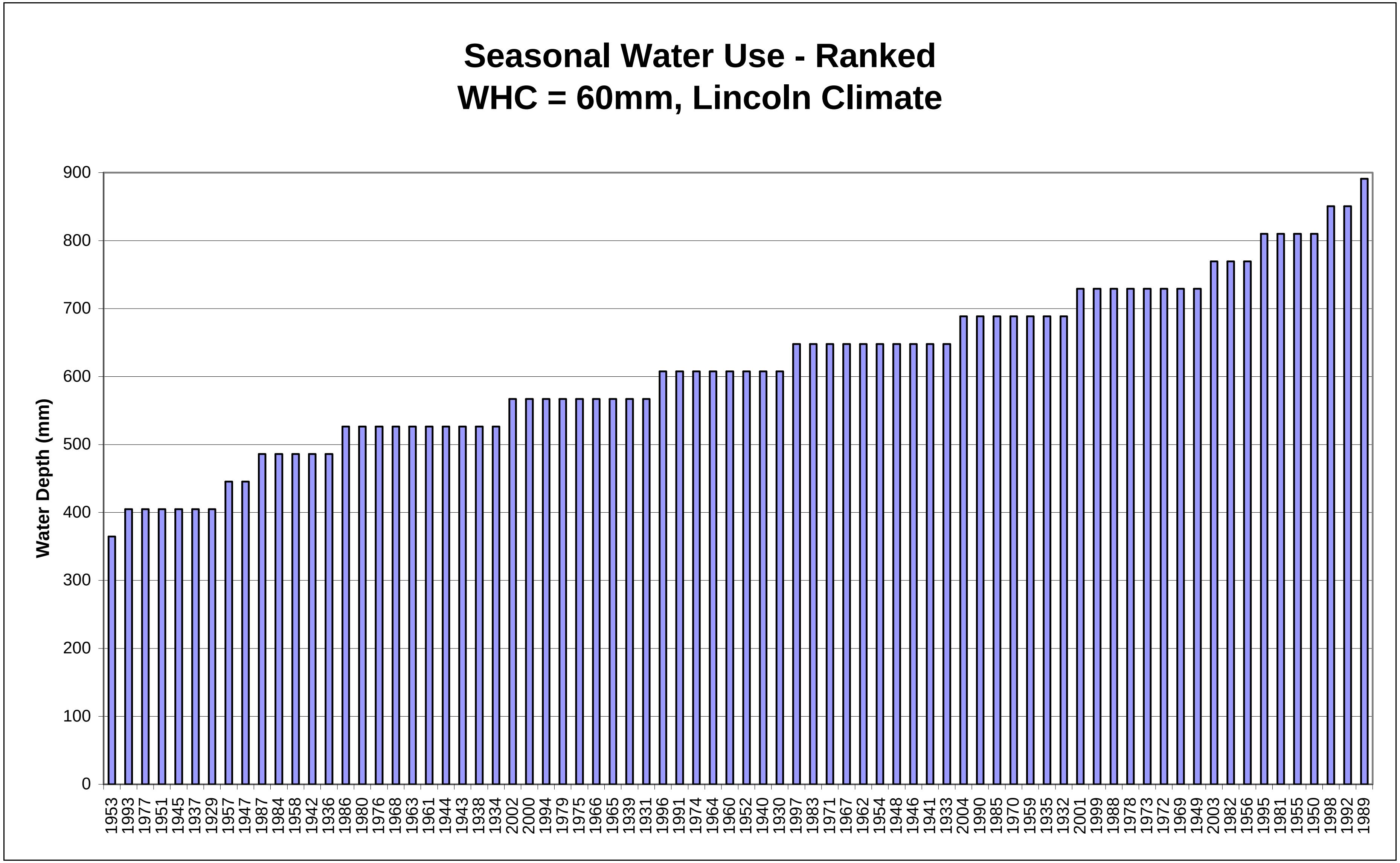

Figure 6-3: Ranked seasonal irrigation use at Lincoln for the period July 1928 – June 2004. Date label is 30 June YYYY.

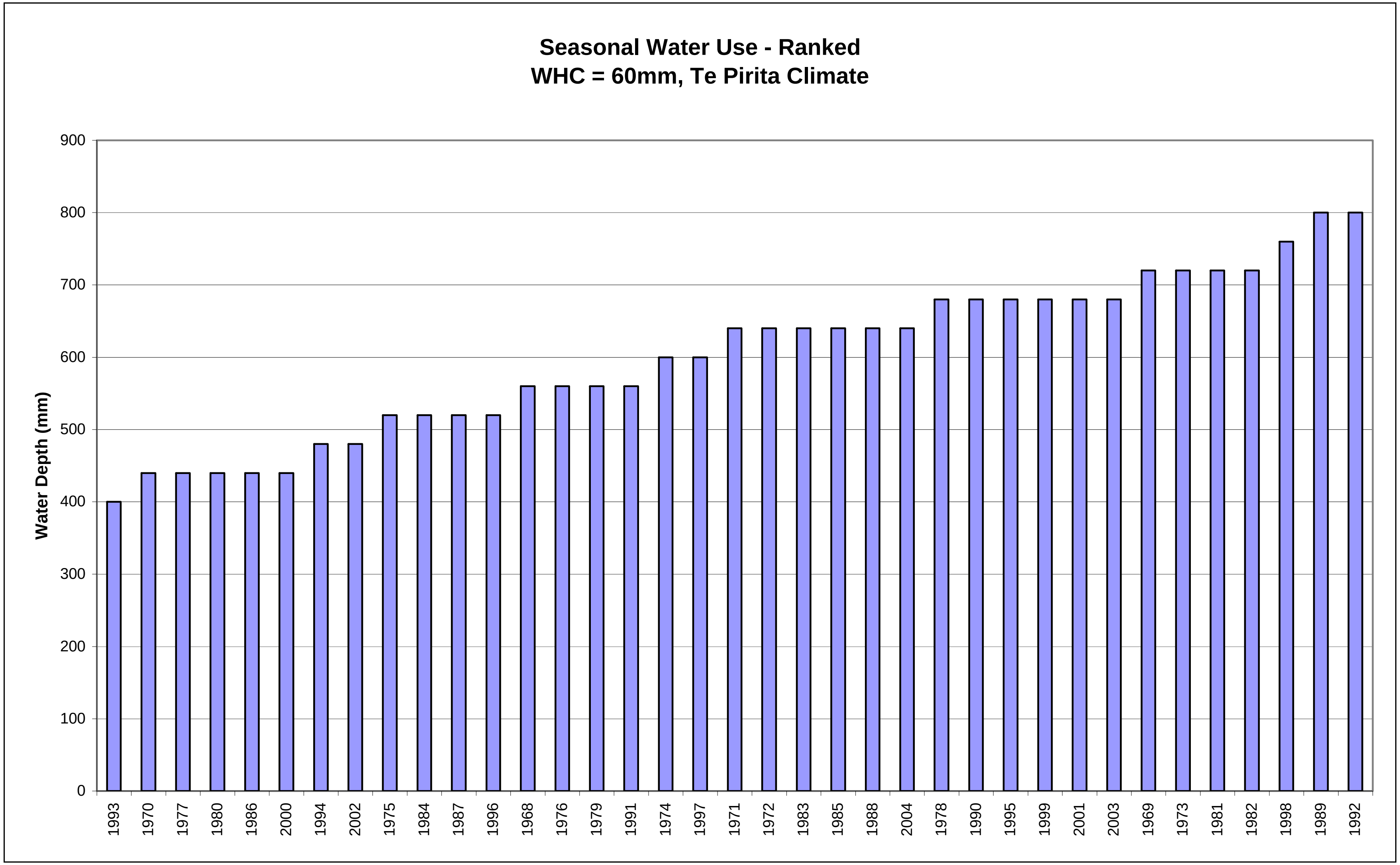

Figure 6-4: Ranked seasonal irrigation use at Te Pirita for the period July 1967 – June 2004. Date label is 30 June YYYY.

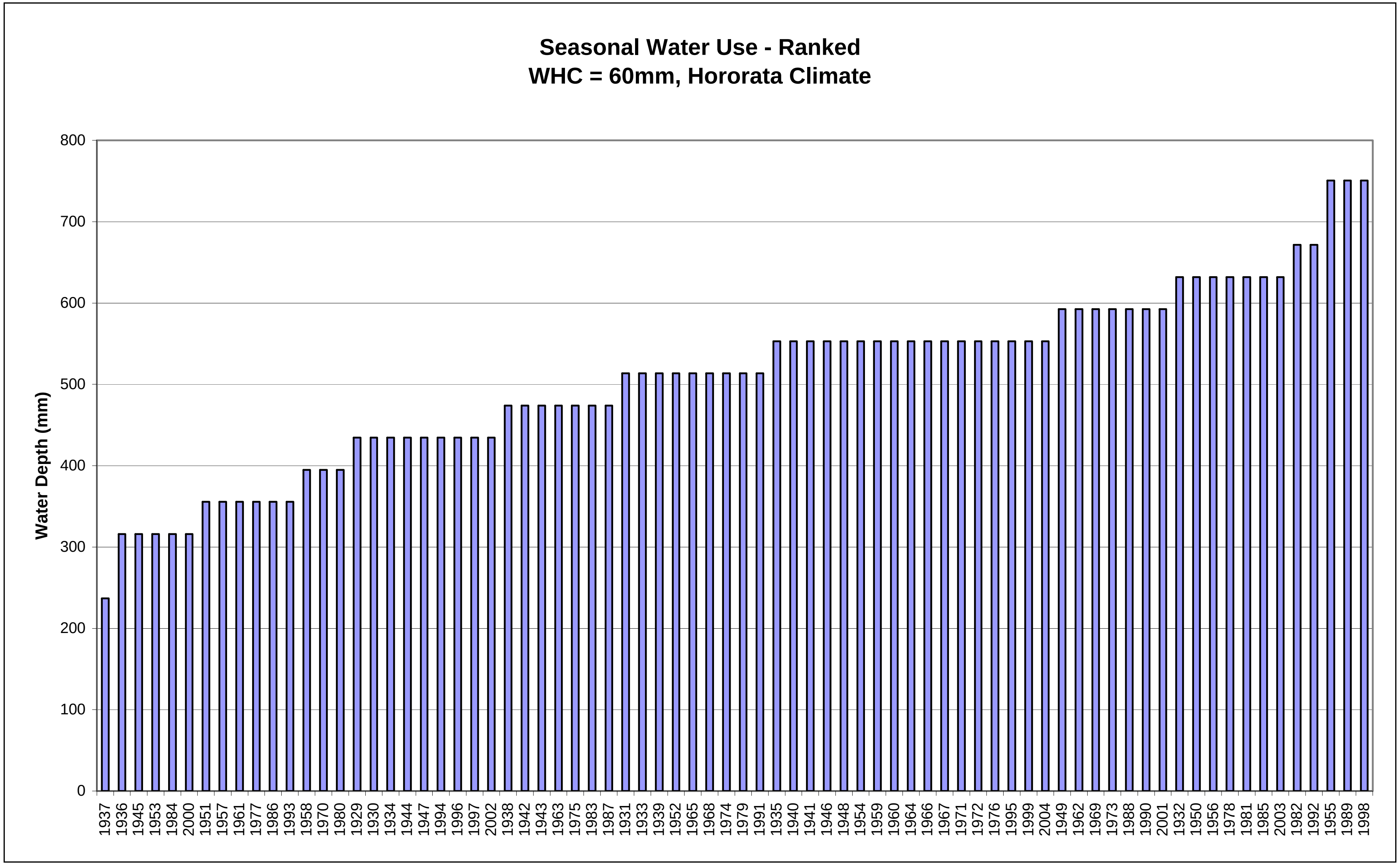

Figure 6-5: Ranked seasonal irrigation use at Hororata for the period July 1928 – June 2004. Date label is 30 June YYYY.

6.2 Rotating Boom Irrigators

Table 6-2: Seasonal irrigation water use and AET under a rotating boom irrigator

Rainfall station	Soil PAW$_{cap}$ (mm)	Application depth (mm)	Return period (days)	Soil moisture trigger point (%)	Application efficiency (%)	Seasonal irrigation water use (mm)			Actual ET (mm)		
						80 percentile	90 percentile	Average	80 percentile	90 percentile	Average
Lincoln	60	50	10	50	68.5	850	875	705	809	844	764
	80	55	11	50	77.8	715	770	606	814	854	770
	120	60	12	62	80.3	720	720	579	818	861	773
Te Pirita	60	50	10	50	67.4	800	850	697	820	854	777
	80	55	11	50	77.1	715	737	599	827	858	782
	120	60	12	62	79.7	708	720	576	834	862	785
Hororata	60	50	10	50	65.9	700	750	603	813	850	767
	80	55	11	50	76.9	605	660	491	815	857	771
	120	60	12	61.5	80.4	540	600	450	818	862	773

6.3 Centre-pivot and Lateral Move Irrigators

Table 6-3: Seasonal irrigation water use and AET under a centre-pivot or lateral move irrigation system

Rainfall station	Soil PAW$_{cap}$ (mm)	Application depth (mm)	Return period (days)	Soil moisture trigger point (%)	Application efficiency (%)	Seasonal irrigation water use (mm)			Actual ET (mm)			Average number of irrigation days per season
						80 percentile	90 percentile	Average	80 percentile	90 percentile	Average	
Lincoln	60	21	4	50	99.0	567	620	467	813	855	769	22.3
	80	26	5	60	98.9	572	624	476	817	860	772	18.3
	120	26	5	60	99.7	520	572	423	817	861	772	16.3
Te Pirita	60	21	4	50	98.8	542	588	460	749	759	720	21.9
	80	26	5	60	97.8	546	582	465	833	862	784	17.9
	120	26	5	60	99.9	515	546	410	833	862	784	15.8
Hororata	60	21	4	50	97.9	462	494	382	814	857	770	18.2
	80	26	5	60	97.5	468	507	388	817	861	773	14.9
	120	26	5	60	99.6	416	442	320	817	861	773	12.3

7 DISCUSSION

7.1 The Pasture Crop Factor

The Crop Factor is a plant structure parameter that defines the evapotranspiration of a plant population relative to a reference evapotranspiration.

Usually the reference evapotranspiration is that of a well watered pasture with canopy characteristics that are constant throughout the year. The key canopy characteristics are plant height, leaf area index, and the stomata resistance and the canopy resistance to vapour transport.

The assumption that the reference crop is "well watered" implies that there is a good store of water in the soil. It also implies that the form and hydraulic resistances of the plant's root system are such that the root system is capable of supplying water at the flow rate required to meet the atmosphere's capacity to evaporate and transport water away from the plant canopy.

The crop factor derived in this project varies throughout the year, as shown in Figure 4-1. The temporal variation in the crop factor was not unexpected because the height, leaf area index, and form of real pasture canopies change throughout the year.

In the absence of a locally derived crop factor, it is standard practice to assume a crop factor of between 0.9 and 1.0. The crop factor derived in this project has an average value of about 1.0 over the irrigation season. Therefore, it seems reasonable to continue to use a crop factor of 1.0 in Canterbury in the absence of a locally derived crop factor.

Recently reported field measurement of actual evapotranspiration from pasture near Ruakura, Hamilton, suggests that a crop factor of 1.13 is appropriate for well water pasture in Waikato during the winter-spring period (Kuske, 2009).

7.2 Application of IrriCalc

The following observations are made with reference to the results of using IrriCalc to simulate irrigation water use by an irrigator operated to be "policy compliant". That is, it meets the PNRRP requirements that irrigation applications be 80% efficient and that seasonal irrigation water use be limited to that required to meet demand eight years in ten, on average. The relevant results are presented in Table 6-1.

For all combinations of soil and rainfall characteristics modelled, the modelled pasture water use (actual evapotranspiration) varied less than 2%. This indicates that all scenarios modelled, irrigated the pasture equally well.

As the plant available water capacity of the soil increased there is a significant reduction in the number of irrigation events required (50%). However the depth of irrigation water applied per irrigation application increases so that the net result is a reduction in seasonal irrigation water use of only 10%, when comparing the shallowest soil against the deepest soil.

In contrast, there was a 19% to 23% reduction in seasonal irrigation water use between the driest site modelled (Lincoln) and the wettest (Hororata). The number of irrigation events reduced by a similar degree.

Irrigation water use is more sensitive to variation in irrigation season rainfall than to variations in the soils capacity to store plant available water.

Achieving 80% application efficiency on soil with a plant available water capacity of 60 mm requires an irrigator that can apply an application depth of 40 mm, and an irrigation system with an 8-day return period. Some commonly used irrigators will probably need to be run on a two shifts per day basis to achieve this. Most now operate on one 23-hour shift per day.

Comparison of the results presented in Table 6-1 to Table 6-3 enable the following observations to be made about the influence of irrigator type. Note that the modelled operation of each system results in the same standard of irrigation – there is minimal variation in the modelled pasture water use between irrigator types.

a) At the driest location (Lincoln) and on the shallowest soil:
The centre-pivot irrigator used about 22% less irrigation water per season than did the "policy compliant" irrigator. The rotating boom irrigator used about 17% more irrigation water than did the "policy compliant" irrigator.

b) At the wettest location (Hororata) and on the deepest soil:
The centre-pivot irrigator used about 22% less irrigation water per season than did the "policy compliant" irrigator. The rotating boom irrigator used the same amount of irrigation water as the "policy compliant" irrigator.

Variation in seasonal irrigation water use between irrigators is significant. The degree of variation is similar to that attributable to variation in rainfall. It is significantly more influential than variation in soil type.

Pivots consistently use less water than the "policy compliant" irrigator because they operate at much higher application efficiency. However, this is only achievable with pivots that are designed to have an instantaneous application intensity that is well matched to the soils infiltration capacity. This is most unlikely to be the case with current pivot designs if they are greater than about 600 m long.

Irrigator type, and how the irrigator is managed, have a major affect on seasonal irrigation water use.

7.3 Comparison Between IrriCalc Results and ECan PNRRP Schedule WQN9

The seasonal irrigation water use that meets demands with a reliability of eight years in ten, as shown in Table 6-1 to Table 6-3, are compared in Table 7-1 with the seasonal irrigation water use provided for by Schedule WQN9.

Additional irrigations in Table 7-1 were calculated by dividing the difference between the WQN9 and the IrriCalc values by the irrigation application depth. The additional days covered were calculated by multiplying the number of additional irrigations by the return period.

Centre-pivot irrigation that is well designed and well managed almost always requires a lower seasonal irrigation demand standard than that provided by WQN9, because application efficiency of greater than 80% is achievable.

The PNRRP policy compliant irrigator has higher seasonal water use than the WQN9 seasonal irrigation demand standard – the difference ranging from 72 to 188 mm.

Seasonal water use for rotary boom irrigators, which are most probably the most commonly used irrigators on the Canterbury plains, is always significantly higher than the WQN9 standard. The differences range from 100 to 235 mm. If farmers with rotary boom irrigators have to irrigate within the proposed WQN9 standard, it will mean that in an 8-year-in-10 irrigation demand year they will be prevented from irrigating on between 20 and 47 days, at least, depending on location and soil characteristics. The worst affected area would be Te Pirita. These shortfalls in irrigation days have been calculated assuming an irrigation design capacity of 5 mm per day.

The WQN9 standard clearly provides insufficient water to meet irrigation water use by an irrigation system that is designed and operated in compliance with the proposed NRRP policy standards of 80% application efficiency and a volumetric limit that meets reasonable use eight years in ten.

Use of the most commonly occurring irrigation systems will be significantly constrained because the WQN9 standard does not provide sufficient water to meet irrigation water consumption even when they are operated in a competent manner.

Table 7-1: Comparison between WQN9 seasonal irrigation demands and Aqualinc seasonal irrigation demands

		Irrigated Pasture									
		Seasonal irrigation demand via WQN9v3				**8-year-in-10 seasonal irrigation demand via Aqualinc method**					
	PAW class	**Plant available water**	**Total seasonal demand**	**Effective rainfall**	**WQN9 seasonal irrigation allocation**	**Centre pivot**	**80 % Efficient irrigator**	**Rotary boom**	**Additional water: 80% efficient irrigator compared to WQN9**	**Additional irrigations**	**Additional days covered**
	mm	**mm**	**mm**	**mm**	**mm**	**mm**	**mm**	**mm**	**mm**	**#**	**days**
Lincoln area	<70	60	815	190	625	567	729	850	104	2.5	20
	70-190	80	800	190	610	572	689	715	79	1.5	15
	70-190	120	740	190	550	520	702	720	152	1.9	28
Te Pirita area	<70	60	815	250	565	542	680	800	115	2.9	23
	70-190	80	800	250	550	546	683	715	133	2.5	25
	70-190	120	740	250	490	515	678	708	188	2.4	36
Hororata area	<70	60	815	300	515	462	592	700	77	1.9	15
	70-190	80	800	300	500	468	572	605	72	1.4	14
	70-190	120	740	300	440	416	539	540	99	1.3	19

7.4 Consequences of Using WQN9

The consequence of having a seasonal irrigation demand standard and a water metering for compliance monitoring is that in some seasons, irrigation will have to stop even though the plants require irrigation to achieve optimum growth.

Different seasonal irrigation demand standards result in differences in the date the first irrigation is missed and the total number of irrigations that are missed.

To illustrate the consequences of using the WQN9 standard for irrigation of pasture grown in a soil with 60 mm plant available water in the Lincoln area, the WQN9 limit was applied to the irrigation water use estimated by IrriCalc for the period 1 July 1928 to 30 June 2004, and the date of the first irrigation missed was recorded. The total number of missed irrigations was also recorded. These results indicate what would have happened on well managed, policy compliant, irrigated pastoral farms in the Rakaia-Selwyn zone over this 76-year period if the WQN9 Standard had been applied.

The following table summarises the result:

1 year in 2	Missed 1 or more irrigation events	
1 year in 3	Missed 2 or more irrigation events	
1 year in 4	Missed 3 or more irrigation events	No irrigation from about 8 Mar
1 year in 7	Missed 4 or more irrigation events	No irrigation from about 15 Feb
1 year in 10	Missed 5 or more irrigation events	No irrigation from about 7 Feb
1 year in 25	Missed 6 or more irrigation events	No irrigation from 20/2/92
1 year in 38	Missed 7 or more irrigation events	No irrigation from 10/2/98
1 year in 76	Missed 8 irrigation events	No irrigation from 8/1/89

WQN9 is intended to provide sufficient water to meet irrigation water use four years in five. This means that in four years in five, on average, there will be no missed irrigations.

The above table shows, however, that irrigation have to be missed (because the maximum volume of water use permitted by WQN9 has been reached) as frequently as every second year (one year in two). This means that Schedule WQN9 is not, in fact, allowing enough water use to meet the reliability standard stated in the proposed NRRP.

The consequences of adopting the IrriCalc determined, four years in five, seasonal irrigation demand standard for the same circumstances are summarised in the following table.

1 year in 7	Missed 1 or more irrigation events	No irrigation from about 26 Mar
1 year in 10	Missed 2 or more irrigation events	No irrigation from about 17 Mar
1 year in 25	Missed 3 or more irrigation events	No irrigation from 19/3/92
1 year in 38	Missed 4 or more irrigation events	No irrigation from 7/3/98
1 year in 76	Missed 5 irrigation events	No irrigation from 14/2/89

If IrriCalc is used to set the seasonal irrigation demand standard, irrigation will still have to cease prematurely in some years. Generally, this will be about the fourth week in March and one irrigation will be missed. Occasionally, irrigation will have to cease around mid March and two irrigations will be missed.

It is interesting to note that the worst case situation over the 76 years analysed would have occurred in the 1988/89 season. If WQN9 had been in force, irrigation would have to have stopped by 8 January 1989 and eight irrigations would have been missed. Even if IrriCalc seasonal irrigation demand standards have been in force, irrigation would have ceased in mid February 1989 and five irrigations would have been missed.

If the reliability standard was nine years in ten, the consequences of adopting the IrriCalc determined seasonal irrigation demand standard for the same circumstances would be as summarised in the following table:

1 year in 10	Missed 1 or more irrigation events	No irrigation from about 10 Apr
1 year in 25	Missed 2 or more irrigation events	No irrigation from about 30 Mar
1 year in 38	Missed 3 or more irrigation events	No irrigation from 24/3/98
1 year in 76	Missed 4 irrigation events	No irrigation from 25/2/89

The effect of raising the reliability standard from four years in five to nine years in ten, based on IrriCalc results, is to enable irrigation to continue for about an extra fortnight in the one year in ten when the seasonal irrigation demand standard is insufficient to enable full irrigation.

If future climate mirrors that of the past century, it is reasonable for farmers to expect to experience the results presented in the preceding paragraphs.

8 CONCLUSIONS

ECan's adopted method for determining the Seasonal Irrigation Demand Standard that is included in its proposed Natural Resources Regional Plan as Schedule WQN9 involves two phases:

- Determine the Seasonal Total Water Demand Standard; and
- Determine the Seasonal Irrigation Demand Standard for a specific farm.

The WQN9 method significantly underestimates plant water use, compared to internationally accepted standards methods, and therefore underestimates reasonable irrigation water use.

The WQN9 method provides estimated pasture water use (actual evapotranspiration) that trends downwards as profile available water increases, which is opposite to what would normally be expected, unless the adequacy of irrigation reduces significantly as profile available water increases.

The estimation error is likely to result from an accumulation of many small errors introduced by the many assumptions made when applying the WQN9 method.

While the WQN9 method has used much data from many locations in Canterbury, the validation of this method at any site has not been reported.

The method erroneously calculates the 8-years-in-10 irrigation season water use by subtracting from an 8-years-in-10 irrigation season crop water demand value a 2-years-in-10 irrigation season rainfall value.

Aqualinc's approach to using IrriCalc to determine seasonal irrigation water use standards:

- Is an application of an internationally accepted approach;
- Is scientifically robust;
- Is transparent – the assumptions that are made are clear and can be tested;
- Enables irrigation water use to be estimated for a range of irrigator types; and
- Can evolve as the prediction reliability of models increases.

The IrriCalc model was successfully validated using data collected by ECan at a lysimeter facility near Dunsandel.

Variation in seasonal irrigation water use between irrigators is significant. The degree of variation is similar to that attributable to variation in rainfall. It is significantly more influential than variation in soil type.

Irrigator type, and how the irrigator is managed, have a major affect on seasonal irrigation water use. IrriCalc was used successfully to calculate the seasonal irrigation water use of irrigators that are "policy compliant" (i.e. 80% application efficiency and four years in five reliability), and those which are not.

Existing irrigation hardware typically does not meet the 80% efficiency standard. Use of IrriCalc enables the setting of a Base volume for irrigation water use that is policy compliant, and a Supplementary volume that accommodates the lower efficiency of the existing irrigator fleet.

Comparisons between the WQN9 seasonal irrigation demand standard and results from Policy Compliant IrriCalc simulations show that the WQN9 seasonal demands are significantly lower than the seasonal demands estimated by IrriCalc.

If the WQN9 standards become operative, it is highly likely that the NRRP's reliability standard of meeting irrigation needs four years in five will not be met.

IrriCalc provides a robust method for setting seasonal irrigation demand standards that is based on internationally accepted good practice, and it has been set up for Canterbury conditions and tested using Canterbury data.

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Appendix A: Pasture water use calculations based on data from Daveron & Scott (2005)

Calculation of Policy Compliant Seasonal Water Demand - From Davoren and Scott (2005)																Pasture Water Use Estimated from Davoren and Scott data		Pasture Water Use Estimated from Climate Data using Penman-Monteith	
Crop	Effective Rain	Effective Irrigation	Adjusted Irrigation	Soil Moisture Difference	Total Water Demand (rainfall and irrigation)	Autumn Irrigation	Total Water Demand	Number of days of soil moisture monitoring	Freely Available Water	Estimated Profile Available Water	Effective Rainfall between 1 October & first soil moisture measurement	Effective Rainfall between last soil moisture measurement and 30 April	1 Oct 1998 to 30 Apr 1999 Season Total Water Demand	Demand Correction to give 8 yr in 10 value	Policy Compliant Seasonal Water Demand	1 Oct 1998 to 30 Apr 1999 Season Estimated Total Pasture Water Use	Policy Compliant Pasture Water Use 1 Oct - 30 Apr	Lincoln Potential Evapotranspiration 1 Oct 1988 - 30 Apr 1999	Winchmore Potential Evapotranspiration 1 Oct 1988 - 30 Apr 1999
	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10	Col 11	Col 12	Col 13	Col 14	Col 15	Col 16	Col 17	Col 18	Col 19
Pasture	165	365	456	-9	612	0	612	158	27	47	16	49	677	0.83	816	586	706	722	708
Pasture	232	360	450	6	688	0	688	225	54	69	-29	25	684	0.85	805	594	699	722	708
Pasture	298	185	231	13	542	0	542	169	40	69	44	12	598	0.79	757	552	699	722	708
Pasture	166	252	315	-93	388	0	388	150	85	126	0	141	529	0.72	735	466	647	722	708
Pasture	226	299	373	-28	571	0	571	206	64	111	21	0	592	0.81	731	518	640	722	708
Pasture	226	290	362	-14	574	0	574	218	62	107	-29	59	604	0.85	711	532	626	722	708
Pasture	226	299	373	-29	570	0	570	216	64	111	0	0	570	0.81	704	496	612	722	708
Pasture	205	176	220	3	428	0	428	172	40	69	75	0	503	0.72	699	459	638	722	708
Pasture	208	302	377	8	593	0	593	225	60	104	-29	25	589	0.85	693	514	605	722	708
Pasture	183	159	198	1	382	0	382	157	75	153	0	113	495	0.73	678	456	625	722	708
Pasture	223	202	252	22	497	0	497	216	78	160	-7	0	490	0.73	671	440	603	722	708
Pasture	176	207	258	42	476	0	476	145	52	67	0	95	571	0.86	664	520	605	722	708
Pasture	132	215	268	-45	355	0	355	150	80	164	16	113	484	0.73	663	431	590	722	708
Pasture	124	200	250	-39	335	0	335	153	80	164	24	109	468	0.73	641	418	573	722	708
Pasture	105	140	175	2	282	0	282	126	74	128	44	146	472	0.75	629	437	583	722	708
Pasture	125	114	142	-6	261	0	261	130	85	174	16	176	453	0.73	621	425	582	722	708
Pasture	98	125	156	21	275	0	275	126	65	113	44	146	465	0.75	620	434	579	722	708
Pasture	296	150	187	-7	476	0	476	200	65	80	0	24	500	0.81	617	463	572	722	708
Pasture	294	200	250	4	548	0	548	194	48	83	0	0	548	0.92	596	498	541	722	708
Pasture	210	95	118	-19	309	0	309	148	82	168	75	40	424	0.72	589	401	557	722	708
Pasture	179	160	200	-9	370	0	370	105	50	65	46	114	530	0.92	576	490	533	722	708
Pasture	282	170	212	5	499	0	499	194	54	93	0	0	499	0.92	542	457	497	722	708
Pasture	194	120	150	-7	337	0	337	196	55	95	0	33	370	0.75	493	340	453	722	708
Pasture	176	216	270	-3	443	0	443	165	56	97	-16	14	441	0.92	479	387	421	722	708
Pasture	229	125	156	-21	364	0	364	181	60	75	0	72	436	0.92	474	405	440	722	708
Pasture	209	155	193	-21	381	0	381	174	50	87	0	49	430	0.92	467	392	426	722	708
Pasture	91	126	157	4	252	0	252	105	55	95	-29	163	386	0.85	454	355	418	722	708
Pasture	127	100	125	-47	205	0	205	161	62	107	0	109	314	0.73	430	289	396	722	708

Notes:

Col 1: Input data - comes from event by event analysis of measured soil moisture, rainfall and irrigation time series, as described in Section 2

Col 2: Input data - comes from event by event analysis of measured soil moisture, rainfall and irrigation time series, as described in Section 2

Col 3: Col 2 divided by irrigation application efficiency of 80%, as proposed in ECan's NRRP

Col 4: Input data - comes from measured soil moisture time series. Equal to last measured soil moisture for season minus the first measurement for the season

Col 5: Col 1 + Col 3 + Col 4

Col 6: Input (not used for pasture irrigation - only for analysis of crops)

Col 7: Col 5 + Col 6

Col 8: Input - information not used in calculations within this table

Col 9: Input - derived from soil moisture measurements

Col 10: Input - derived from soil moisture measurements

Col 11: Input, estimated from rainfall time series by deducting first 5mm of each rainfall event and all rainfall in excess of 50mm per event

Col 12: Input, estimated from rainfall time series by deducting first 5mm of each rainfall event and all rainfall in excess of 50mm per event

Col 13 Col 7 + Col 11 + Col 12

Col 14: Input - a scaling factor to convert values for the 1998/99 season to the 8 year in 10 season, to meet NRRP policy standard

Col 15: Col 13 divided by Col 14

Col 16: Col 1 + Col 2 + Col 4 + Col 11 + Col 12

Col 17: Col 16 divided by Col 14

Col 18: Input - Pasture water use estimated from Lincoln climate data using Penman-Monteith

Col 19: Input - Pasture water use estimated from Winchmore climate data using Penman-Monteith method