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Groundwater REPORT

GROUNDWATER RECHARGE AND IRRIGATION DEMAND MODELLING

Ruamahanga Collaborative Modelling Project

PREPARED FOR
Greater Wellington Regional Council

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PREPARED BY
John Bright
Julian Weir

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Authors	John Bright, Julian Weir
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For more information regarding this document please contact

John Bright
Director: Research & Development
Aqualinc Research Limited
(03) 964 6521
j.bright@aqualinc.co.nz

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TABLE OF CONTENTS

1 MODELLING OBJECTIVES

The objective of the modelling described in this report was to develop irrigation and drainage time-series datasets for the 1972 to 2015 time period, across the whole of the Wairarapa Plains, and to provide these data for use in an integrated groundwater – surface-water flow model (MODFLOW/SFR) for this area.

2 CONCEPTUAL MODEL

2.1 Overview

Seasonal irrigation water use and drainage is primarily a function of rainfall, plant water use and irrigation management. Soil hydraulic properties indirectly affect irrigation water use. Interactions between these soil properties, rainfall, 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 much drainage occurs and how soon the next irrigation will be required.

The method used by Aqualinc to estimate irrigation water use is an implementation of the internationally accepted 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, in response to modelled soil water balance status, determines the timing of irrigation and the amount to be applied. The various components of the rule are described in Section 3.3. The result of applying the irrigation rule in concert with a daily water balance model is a daily time series of drainage volume and 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 fully meeting irrigation requirements 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 efficiency of 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.

2.2 Summary of Key Assumptions

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

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

- The irrigation actions determined by the irrigation system model are practical;
- 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;
- Water is always available for irrigation, at the rate required, when irrigation is required according to the decision rule being used (note that actual water availability can be used but for the purpose of estimating potential water demand 100% availability is assumed);
- Assumptions specific to the soil-plant-atmosphere model used (see Section 3.1 for assumptions pertinent to the IrriCalc model); and
- Assumptions specific to the irrigation system model and irrigation management rules used (see Section 3.3 for assumptions pertinent to the IrriCalc model).

2.3 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 describes IrriCalc model and the information required to use it.

3 MODEL DESIGN

3.1 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 3.3.

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 The Crop Factor

The Crop Factor is a plant structure parameter that specified 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 used in this project varies throughout the year. The temporal variation in the crop factor changes throughout the year because of changes in the height, leaf area index, and form of real pasture canopies.

3.3 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 1 shows the various combinations of irrigation system parameters that can be applied to replicate a wide range of irrigation systems and practices.

Table 1: Irrigation management options available in IrriCalc

Application depth	**When to irrigate**			
	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				✓

3.3.1 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:

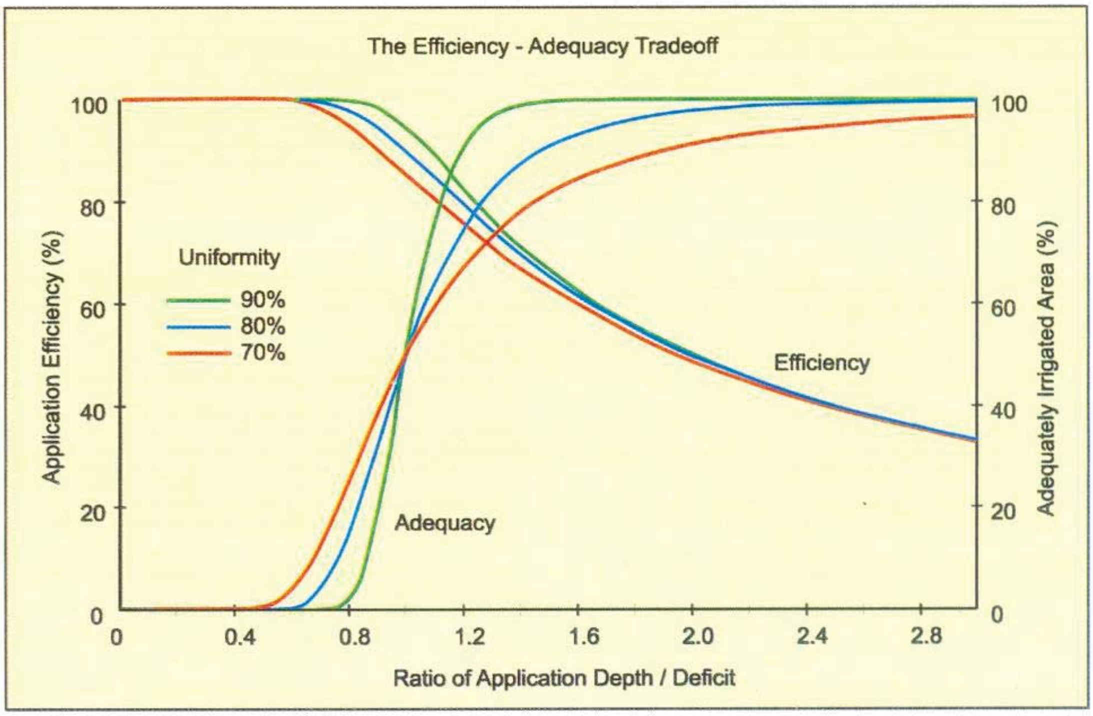

Figure 1: Relationship between application efficiency, application uniformity and application depth (source: Bright, 1986)

3.3.2 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.

3.3.3 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:

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

3.3.4 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.

3.4 Summary of Key Assumptions

- The soil is free draining.
- 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.
- All rainfall and irrigation intercepted and retained on leaf and stem surfaces is effective in meeting the evapotranspiration load.
- The spatial distribution of irrigation application depth can be represented by the Normal Distribution.

3.5 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.

3.5.1 Climate, Crop and Soils Data Required

- 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.
- Crop factor time series (one year). For irrigated pasture, the crop factor time series is based on Van Housen (2015). Crop factors for other crops are generally sourced from FAO 56.
- Crop root depth (or depth of soil that supplies water to meet crop needs).
- Water holding capacity of the soil to crop root depth (mm per mm of soil depth).
- Dates the crop or pasture is sown and harvested.

3.5.2 Irrigation System Data Required

- The type of irrigator to be modelled and some understanding of its operating requirements.
- The maximum and minimum average application depth that is practical to apply for the particular irrigator.

- The uniformity of irrigation applications (Christiansen’s Uniformity Coefficient).
- The length of the irrigation rotation (days).
- The soil water content at which irrigation is initiated (if irrigation timing is determined by measured soil water content).
- Maximum seasonal irrigation water use.
- Beginning and end dates for the irrigation season.

4 MODEL CALIBRATION

There are no data from the Wairarapa area that is suitable for calibrating the soil water balance model. The primary calibration parameter is the crop factor time series, followed by the capacity of the soil to store plant available water.

A crop factor time series has been calibrated for use in Canterbury, using data obtained from Canterbury Regional Council’s (CRC) lysimeter network (Van Housen, 2015). Figure 2 shows that the drainage modelled using this crop factor time series with IrriCalc matches closely that measured at CRC’s Methven lysimeter site. This crop factor has been used with IrriCalc to model irrigation water use and drainage for this project. The assumption is that the pasture species, growth rates and management used in the Wairarapa are the same as, or very similar to, those used in Canterbury.

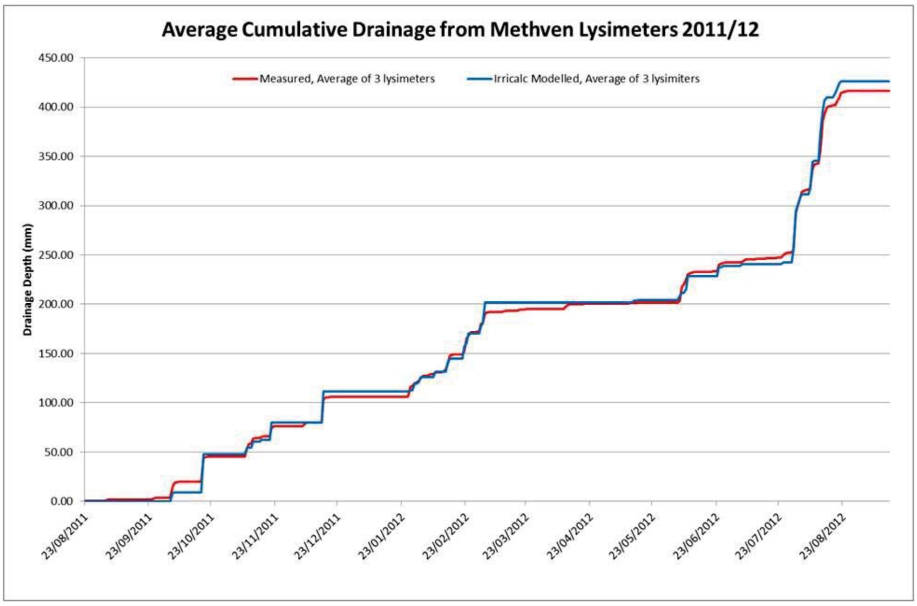

Figure 2: Comparison between measured and IrriCalc modelled drainage

5 MODELLING STATUS QUO

The Wairarapa Plains was divided up into 500m x 500m grid-squares based on the NIWA Virtual Climate Station grid. The area covered matches the area covered by the MODFLOW/SFR computational grid. Climate data for each grid square for the period 1 Jan 1972 to 31 December 2015 was supplied by NIWA from their Virtual Climate Station database.

The most prevalent soil type in each grid square was determined by intersecting this grid with a copy of S-Map provided by Landcare Research Ltd. for this area. The water holding capacity to 600mm depth was obtained for each of these soil types from S-Map.

IrriCalc was used to simulate changes in the soil water balance from day-to-day in response to rainfall, irrigation, actual evapotranspiration and drainage, for each grid-square over the period 1972 to 2015. The simulations were repeated assuming no irrigation so that for each grid-square three key time-series datasets were developed: potential irrigation demand, drainage under irrigated conditions, and drainage from unirrigated land.

The three key time-series datasets for each grid-square were provided to the MODFLOW/SFR modelling team as an input to their groundwater – surface water flow modelling.

Some results of the IrriCalc modelling are presented in summary form in the figures below.

Figures 3 and 4 illustrate the modelled average annual water flows into and out of the soil under dryland (i.e. unirrigated) and irrigated conditions for two areas on the Wairarapa Plain.

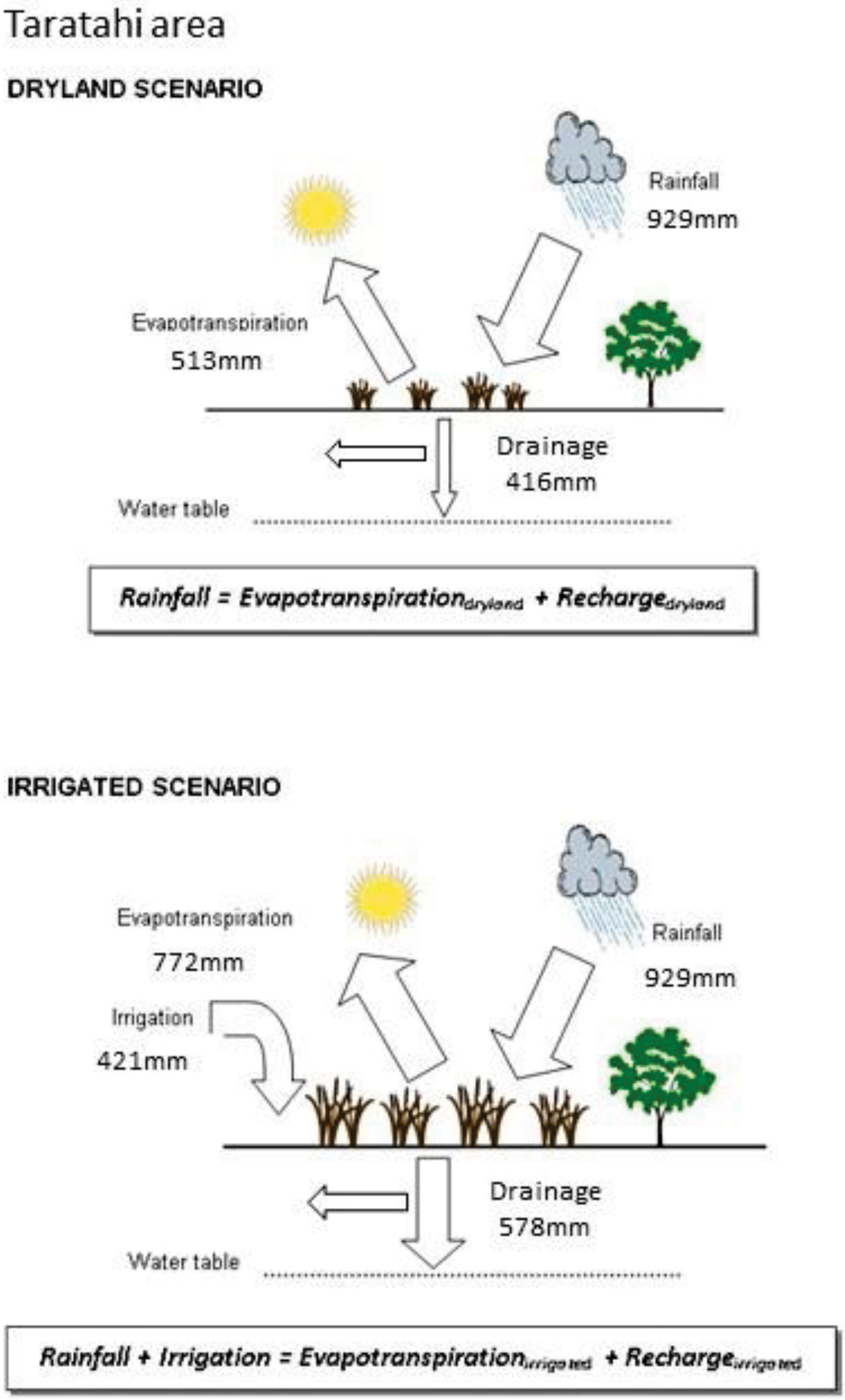

Figure 3: Average annual water inputs and outputs to soil in the Taratahi area

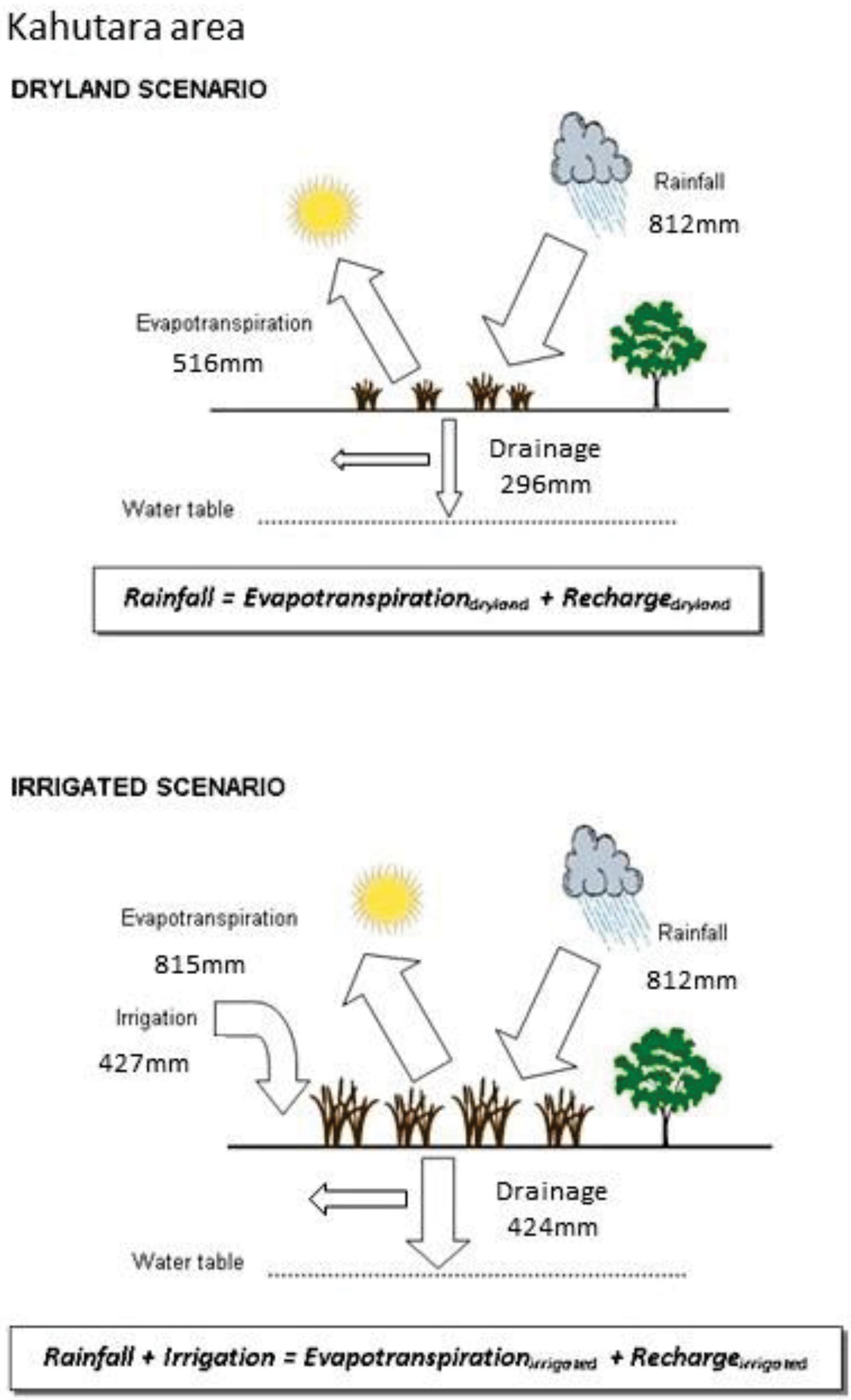

Figure 4: Average annual water inputs and outputs to soil in the Kahutara area

Not all of the amount of drainage shown in these figures goes to groundwater. A portion of the drainage moves laterally to rivers and streams, generally below the soil surface but at times as surface run-off. The partitioning of the drainage amount calculated by IrriCalc into groundwater recharge and near-surface lateral flow to streams is calculated separate from the IrriCalc modelling, as part of the MODFLOW/SFR calibration process.

Irrigation demand and drainage vary considerably from year to year. The following figures illustrate the degree of annual variation for the Taratahi and Kahutara areas, for irrigated pasture.

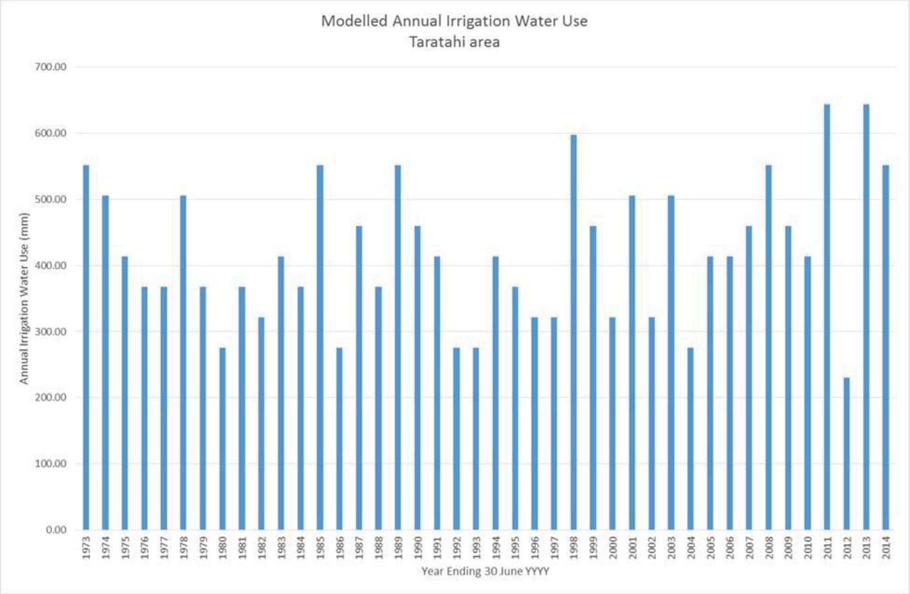

Figure 5: Modelled annual water use for irrigation of pasture in the Taratahi area

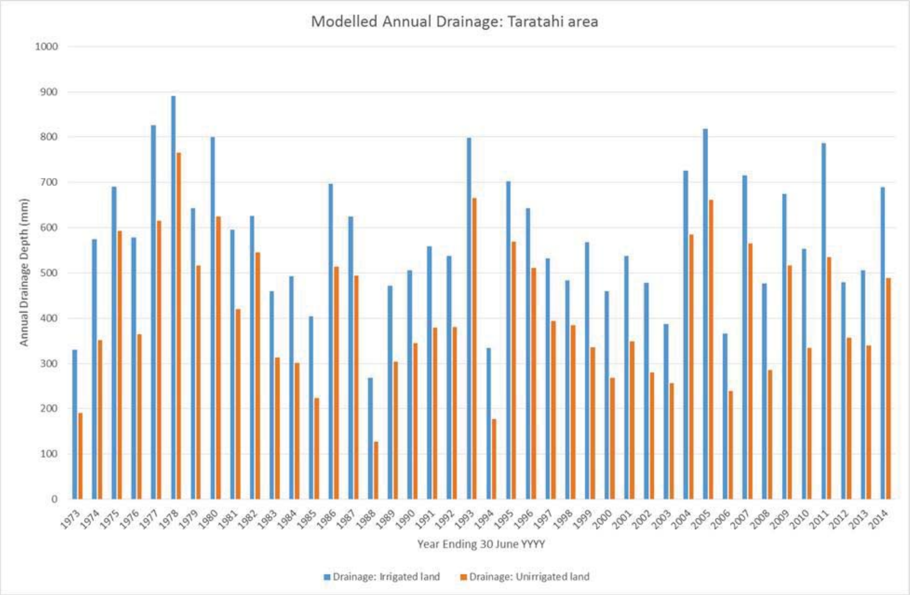

Figure 6: Modelled annual drainage depths under irrigated and unirrigated pasture in the Taratahi area

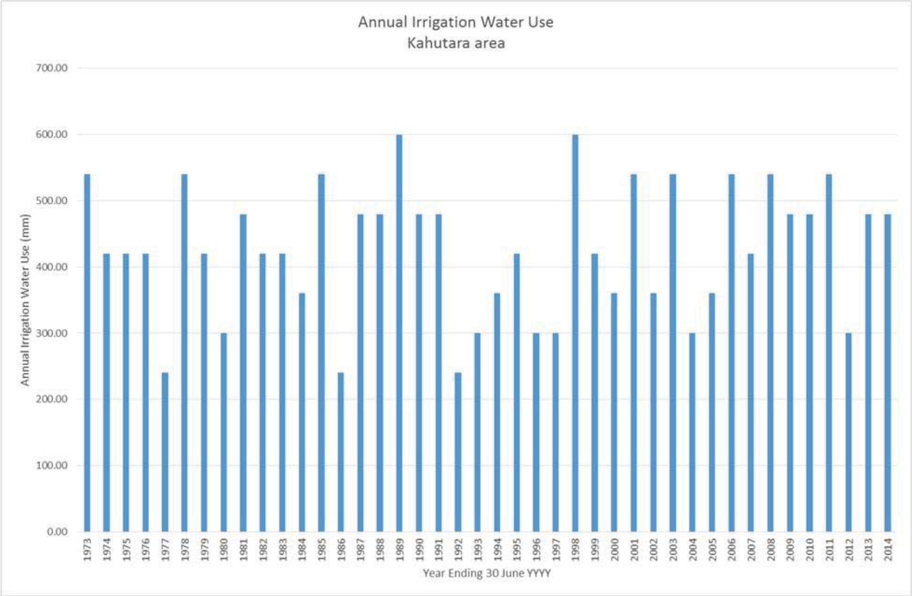

Figure 7: Modelled annual water use for irrigation of pasture in the Kahutara area

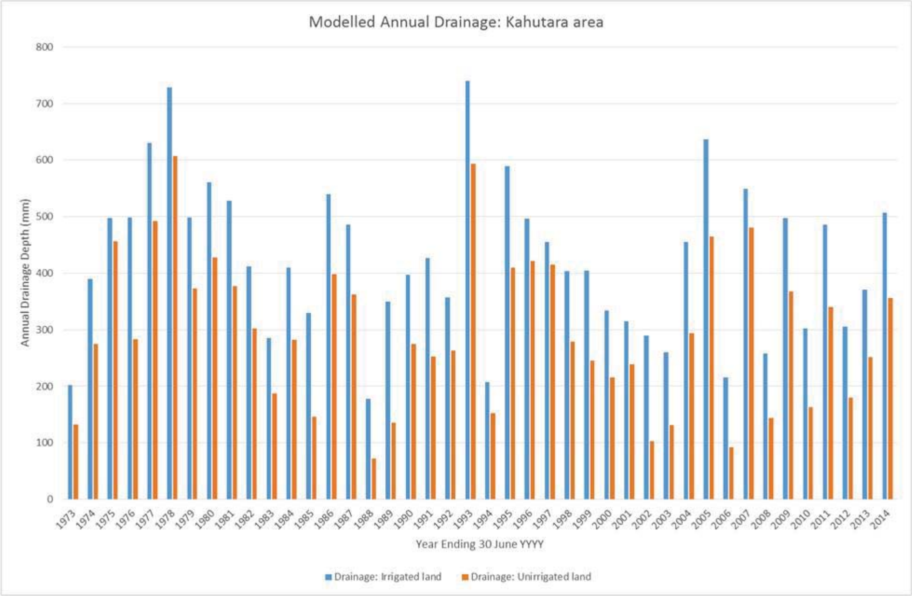

Figure 8: Modelled annual drainage depths under irrigated and unirrigated pasture in the Kahutara area

6 UNCERTAINTY ANALYSIS

A formal, mathematical uncertainty analysis of the soil water balance modelling is not possible because of the lack of relevant measurements.

There are two distinctly different areas of uncertainty in the modelling of irrigation water use and drainage. These areas are technical and behavioural. Uncertainties of a technical nature include measurement error, parameter uncertainty and the extent to which the conceptual model and associated mathematics deviate from the real world. Behavioural uncertainty exists because the model's irrigation decision making rule attempts to mimic farmer decision making about when to irrigate and how much to apply. The model assumes that irrigation decision making is based on information about the current soil water content. In practice other factors also play a part, but it's not yet practical to build these into a computer simulation model.

Recent research indicates that irrigation water use and drainage can be modelled to within 3% of true values for a specific farm if highly detailed information about that specific farm is available as model inputs (Van Housen, 2015). On the other hand, if generally applicable farm information is used to model irrigation and drainage for a specific farm then errors in the range 10% - 15% are to be expected (Van Housen, 2015). For studies involving scores of farms, modelling will very likely provide both over and underestimates of irrigation water use and drainage. In aggregate, errors of the order of 10% are likely.

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