Irrigation and Ecosystem Services

Development of an irrigation model for the LUCI ecosystem service framework

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Abstract

Poor water quality is currently a major environmental issue worldwide and in New Zealand, where reactive Nitrogen (N) and Phosphorous (P) lost from agricultural fields are significant drivers of water quality degradation in rural catchments. Irrigation application to crops is essential to agricultural production however irrigation inputs can increase N and P losses to waterways via drainage and/or overland flow directly and as a result of reduced soil capacity to buffer rainfall events. Indirect nutrient losses are also increased following irrigation implementation due to amplified farming intensity. Furthermore, irrigation applications represent the world's greatest consumptive use of water. Improving irrigation efficiency with regard to water use represents a synergistic opportunity for the improvement of a number of different ecosystem services including water quality, water supply, and food production.

Spatially explicit modelling of irrigation is needed to determine inefficiencies in water delivery and target these inefficiencies for management or mitigation at sub-field scales. A complimentary need exists for irrigation modelling within ecosystem service decision support tools so that nutrient and water movement can be accurately quantified in irrigated environments.

This thesis describes the development and implementation of SLIM – the Spatially-explicit LUCI Irrigation Model. SLIM adapts existing lumped hydrological and irrigation modelling techniques and practices to a fully distributed, spatially explicit framework, so that sub-field variations in water flows resulting from variable soil properties are accounted for. SLIM is generally applicable across New Zealand, using readily available national scale datasets and literature derived parameters. SLIM is capable of predicting irrigation depth and timing based on common management strategies and irrigation system characteristics, or can replicate irrigation applications where information is available. Outputs from SLIM are designed to assist irrigation management decisions at the field level, and to inform the hydrology component of the Land Utilisation and Capability Indicator (LUCI) ecosystem service assessment framework. Standalone SLIM outputs include time-series files, water balance plots, and raster maps describing the efficiency and efficacy of the modelled irrigation system.

SLIM has been applied in three different agroecosystems in New Zealand under surface, micro, and spray irrigation systems, each characterised by different levels of data availability. Results show that SLIM is able to accurately predict the timing of irrigation applications and provide usable information to inform irrigation application decisions. SLIM outputs emphasise the importance of soil variability with regard to water loss and risk of nutrient leaching. Opportunity exists for irrigation water use efficiency to be improved through targeted management at sub-field scales in New Zealand farming systems.

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Adequacy (irrigation) – A measure of the proportion of the target area of which the soil is restored to a target soil water content (see section 3.2.2).

Application efficiency – Average depth of irrigation contributing to target / average depth of irrigation applied (See equation 3.8).

Chemigation – Application of agrochemicals with irrigation water.

Drainage – Water losses below the rootzone of crops.

Ecosystem Services – The benefits mankind obtains from environmental processes.

ET_0 – Reference potential evapotranspiration.

ET_c – Adjusted potential evapotranspiration.

Evapotranspiration – Sum of evaporation and plant transpiration of water from the land to the atmosphere.

Fertigation – Application of fertiliser with irrigation water.

Field Capacity – Volume of water able to be stored in a given section of soil when capillary and gravitational forces are equal.

Gross application depth – The average depth over the field required so that the proportion of the field defined by the adequacy (section 3.2.2) receives at least the target depth.

IrriCalc – NZ developed lumped irrigation model as described in Bright (2009).

Irrigation efficiency – Volume of irrigation beneficially used / (volume of water applied – change in storage). See equation 3.7.

K_c – Crop coefficient.

Nr – Reactive Nitrogen.

Overseer - Overseer Nutrient Budgets, lumped nutrient budgeting software for NZ farming systems.

P – Phosphorous.

Permanent Wilting Point – Point where water is unable to be extracted from the soil. Generally estimated to occur at -1500kPa.

Plant Available Water – Water holding capacity of soil within the rootzone.

Readily Available Water – Volume of water able to be extracted and transpired by a plant without experiencing water stress.

Rootzone – Volume of soil able to be accessed by a plant root system.

Soil water content – Current volume of water stored in the crop rootzone/irrigation unit.

Soil moisture deficit – Difference between the soil moisture content and the water holding capacity.

Target application depth – Depth of water desired to be applied to an irrigated field. Usually equal to the soil moisture deficit at the time of irrigation.

Total Available Water – Total volume of water able to be extracted and transpired by a plant.

Water Holding Capacity – Volume of water held in a given section of soil able to be utilised by plants. Equivalent to field capacity less permanent wilting point.

Water Use Efficiency – Volume of water beneficially used / volume of water delivered to field. Includes rainfall inputs (See equation 3.6).

List of acronyms

AE – Application Efficiency

AET – Actual Evapotranspiration

CSA – Critical Source Area

CSV – Comma Separated Values

CU_c – Christiansen's coefficient of uniformity

DEM – Digital Elevation Model

DIN – Dissolved Inorganic Nitrogen

DM – Dry Matter

DRP – Dissolved Reactive Phosphorous

ESRI– Environmental Systems Research Institute

ET – Evapotranspiration

FAO – Food and Agriculture Organisation

FC – Field Capacity

FRP – Filterable Reactive Phosphorous

FSL – Fundamental Soils Layer

GUI – Graphical User Interface

ICID – International Commission for Irrigation and Drainage

IE – Irrigation Efficiency

LCDB – Land Cover Database

LUCI – Land Utilisation and Capability Indicator. Extension and implementation of the Polyscape framework described in Jackson et al. (2013)

NDVI – Normalised Difference Vegetation Index

NIWA – National Institute of Water and Atmospheric Research

NPS-FM - National Policy Statement on Freshwater Management

NRRP – Natural Resources Regional Plan

NSD – National Soils Database

NZLRI – New Zealand Land Resource Inventory

PAW – Plant or Profile Available Water

PET – Potential Evapotranspiration

PRAW – Profile Readily Available Water

PRD – Potential Rooting Depth

PWP – Permanent Wilting Point

RAW – Readily Available Water

SLIM – Spatially-explicit LUCI Irrigation Model

TAW – Total Available Water

VCN – Virtual Climate Network

VRI – Variable Rate Irrigation

WHC – Water Holding Capacity

WUE – Water Use Efficiency

1 Introduction

Agricultural ecosystems are essential to human wellbeing (Power, 2010). The recent expansion and intensification of agriculture has increased the provision of food, forage, bioenergy, and pharmaceuticals. However, the provision of other essential services has been degraded, such as the supply of clean water, pollination, and the regulation of air quality, climate, erosion, and pests (Millennium Ecosystem Assessment, 2005; Power, 2010; Tilman, 1999). In New Zealand, poor water quality is currently a major environmental issue, where reactive nitrogen and phosphorous lost from agricultural fields are significant drivers of water quality degradation (Dymond et al., 2013; Monaghan, Hedley, et al., 2007; Monaghan et al., 2007; Parliamentary Commissioner for the Environment, 2013).

Irrigation plays a critical role in global agricultural production, with some 40% of all crops produced by irrigated fields (FAO, 2014). Alongside fertiliser and pesticide use and improved crop genetics, irrigation has enabled global crop production to increase by a factor of 2.4 since 1950 (Oki & Kanae, 2006). Irrigation also represents a significant component of the hydrological cycle in irrigated catchments, and irrigation flows and infrastructure affect the provision of many ecosystem services, both beneficially and detrimentally (Droogers, Seckler, & Makin, 2001). In particular, water supply is impacted by withdrawals for irrigation and water quality is reduced where irrigation induced return flows transport nutrients and agrichemicals to waterways.

It is recognised that to improve both agricultural production and ecosystem service provision, large efficiency increases are essential in nitrogen, phosphorous, and water use (Monaghan et al., 2007; Tilman, 1999). For irrigated agroecosystems, improving water use efficiency represents a synergistic opportunity for improvement of clean water provision, agricultural production, and other connected ecosystem services. Tilman, et al. (2002) state that improving water and nutrient use efficiency is one of the greatest scientific challenges facing mankind, with substantial increases required in knowledge-intensive technologies that enhance scientifically sound decision making at the field level.

This thesis aims to aid improvements in water and nutrient use efficiency in irrigated environments through the development of an irrigation model within the Land Utilisation and Capability Indicator (LUCI) ecosystem service framework. LUCI is a physically based Geographic Information System (GIS) decision support tool that provides holistic and spatially explicit consideration of the impacts of land management on a variety of ecosystem services (Jackson et al., 2013). Because irrigation can be a major component of the hydrological cycle, irrigation consideration within the LUCI framework is essential for accurate ecosystem service accounting in irrigated agroecosystems. Where nutrient loss to waterways is an important driver of water quality degradation, as is the case in New Zealand, irrigation is especially important due to its control on the timing and volume of water inputs to- and losses from- agricultural fields. Integration of the model developed herein with the LUCI framework allows for the effects of irrigation to be viewed in a wider context and will enable the visualisation of trade-offs in ecosystem service provision that occur with changes in irrigation management and systems.

1.1 Ecosystem services

Ecosystem services are the benefits mankind obtains from ecosystem processes. The United Nations Millennium Ecosystem Assessment (2005) classifies ecosystem services into four categories: Provisioning Services, the products obtained from ecosystems; Regulating Services, the benefits obtained from the regulation of ecosystem processes; Cultural services, the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences; and Supporting services, those that are necessary for the production of all other ecosystem services. In New Zealand, an overview of the state of ecosystem service provision is provided in Dymond (2014).

The ecosystem service concept allows environmental systems to be viewed holistically, and encourages multiple benefits to be obtained from natural and disturbed landscapes. For agriculture, the primary ecosystem services produced are provisioning services; food, forage, bioenergy and pharmaceuticals. Agricultural systems also produce a variety of other ecosystem services, such as regulation of soil and water quality, carbon sequestration, support for biodiversity and cultural services (Power, 2010). In turn, agricultural systems rely on ecosystem services provided by natural ecosystems, including pollination, biological pest control, maintenance of soil structure and fertility, nutrient cycling and hydrological services (Power, 2010). Agricultural systems can thus be viewed as ecosystems that are modified to ensure or increase food production, and can be referred to as agroecosystems (Falkenmark et al., 2007).

It is increasingly recognised that several ecosystem services related to agriculture are in decline (Millennium Ecosystem Assessment, 2005; Tilman et al., 2002). Particularly noticeable are the worldwide declines in the supply and quality of fresh water, which can be traced to the expansion and intensification of agricultural systems. Primary impacts are the withdrawal of water from rivers and groundwater sources for irrigation, and reduced water quality from the flow of nutrients, sediments, and dissolved salts from agricultural lands (Dale & Polasky, 2007). Furthermore, agricultural expansion and intensification may also account for declines in air quality regulation, climate regulation, erosion regulation, pest regulation, and pollination (Millennium Ecosystem Assessment, 2005). Dale and Polasky (2007) state that a major concern is that the increased agricultural production over the past 50 years has come at the cost of the ecological sustainability that will be necessary to maintain productivity in the future.

Clearly, there exists a need for improved provision for a wide range of ecosystem services from agroecosystems. At the same time, increases in agricultural output are essential for global political and social stability and equity as world population increases by a predicted 50% by 2050 (Tilman et al., 2002). Solving the challenge of simultaneous improvement in agricultural production and the provision of a wide range of ecosystem services requires careful management of ecosystem processes and an increased understanding of the benefits and costs of different types of management practices (Dale & Polasky, 2007; Power, 2010). Ecosystem service based approaches to this challenge that encourage multiple benefits from agroecosystems can generate synergies that result in the wider distribution of benefits across more people and sectors (Falkenmark et al., 2007).

1.2 Nutrient and water management and regulation in NZ

In New Zealand, the primary focus of environmental management in agroecosystems concerns the quality of waterways. There is increasing public awareness of nutrient pollution of watercourses, and regulatory limits on nutrient losses are becoming more common and more stringent (Cichota & Snow, 2009). Water supply is also an issue in some areas (Jenkins, 2012), which is set to be exacerbated as competition for water resources increases from urban and commercial sectors (Hearnshaw, Cullen, & Hughey, 2010).

Irrigation is a key influence on both the supply and quality of water in agricultural catchments in New Zealand. Water use for irrigation is the primary water source of water extractions in New Zealand, accounting for 78% of total consumptive water use (not including the consumptive use of the Manapouri hydro-electric power station) (Ministry for the Environment, 2010). Water extracted for irrigation is then applied to fields, which increases the likelihood of nutrient and sediment transport to waterways. Furthermore, irrigation inputs allow increased production, and therefore greater stocking, fertilisation, and cultivation intensity and a subsequently increased risk of nutrient loss.

In 2011, the New Zealand government announced plans to increase support for regional irrigation projects at the same time as implementing a formal framework for improving the water quality of waterways. The Irrigation Acceleration Fund comprises a $35M package over five years to "unlock the economic growth potential of our primary sectors by developing more efficient and effective water infrastructure, such as storage and distribution" (Ministry for Primary Industries, 2011). Efforts to improve water quality directly were also funded, with the

Fresh Start for Fresh Water Clean-Up Fund providing $15M over two years to restore waterways affected by historical pollution (Ministry for Primary Industries, 2015). These two funds were accompanied by the National Policy Statement on Freshwater Management (NPS-FM), which aimed to create a consistent, nationwide regulatory framework for setting water quantity and quality limits to govern the allocation and use of freshwater. The NPS-FM, updated in 2014, requires regional councils to account for all water taken out of rivers, lakes and groundwater, and the sources and amounts of contaminants going into them. The statement also makes "ecosystem health" and "human health for recreation" compulsory national values which must be provided for everywhere (Ministry for the Environment, 2014).

1.3 Modelling environment

A number of computational tools have been developed to quantify nutrient and water flows to support land management decisions. Models have developed in part because of the difficulty in measuring environmental variables at sufficient spatial and temporal scales, as current measurement methods are generally time consuming, costly, and prone to large variability (Cichota & Snow, 2009; Tilman et al., 2002). Computational models can avoid some of these issues by simulating environmental and farming systems based on knowledge of the processes involved and augmented with measured data where available. For irrigation flows, predictive modelling is especially important because irrigation is rarely monitored; recent research shows that few farmers in New Zealand know how much water they use during an irrigation season, although this is changing rapidly (Lincoln Environmental, 2000a). Using environmental models, the possible impact of different land uses and management practices can be predicted (Cichota & Snow, 2009).

In New Zealand, Overseer Nutrient Budgets (Overseer) has become the de-facto tool for estimating nutrient use and loss from farms. Overseer is a lumped decision support farm model designed to simulate nutrient flows and greenhouse gas emissions on horticultural, arable and vegetable farming systems. Overseer is used by farmers, consultants, policy makers, scientists and local government bodies to model nutrient flows and inform management decisions (Wheeler & Shepherd, 2013). For irrigation water use, the IrriCalc model described in Bright (2009) has been developed to calculate the annual irrigation demand for farms on the Canterbury Plains. IrriCalc is an approved method of calculating seasonal irrigation allocations in Canterbury where the local government body, Environment Canterbury, has placed limitations on annual irrigation volumes under the Canterbury Natural Resources Regional Plan (NRRP) legislation. IrriCalc is planned to be deployed nationally by Irrigation New Zealand via a web interface in June 2015 (Irrigation New Zealand, 2015). The irrigation component of Overseer has been updated during the course of this thesis to follow a similar procedure to IrriCalc for determining irrigation inputs to farm systems ("Overseer expands for new demands," 2014).

Internationally, land management decision making is being increasingly aided by ecosystem service focussed decision support models that integrate ecology, economics, and geography to support multisectoral decision making (Daily et al., 2009). These tools vary in scope and complexity, but share a common goal of enabling replicable and quantifiable ecosystem service analyses (Bagstad et al., 2013). Well known ecosystem service decision support models include ARIES (Bagstad et al., 2011; Villa et al., 2011) and InVEST (Kareiva et al., 2011). LUCI is an ecosystem service decision support framework that has been used for ecosystem analyses in the U.K., New Zealand, Ghana, and Greece. LUCI is an implementation and extension of the Polyscape framework described in Jackson et al. (2013). In a review of 17 ecosystem service decision-support tools, Bagstad et al. (2013) recognised LUCI as the only tool capable of both landscape and site scale ecosystem service assessment.

1.4 LUCI framework

LUCI is a physically based, spatially explicit framework designed to allow visualisations of trade-offs between ecosystem services from sub-field to national scale. LUCI explicitly accounts for the spatial configuration and organisation of landscape features and their effect on a number of ecosystem services. Currently considered services include agricultural production, erosion risk and sediment delivery, carbon sequestration, flood mitigation, habitat connectivity and priority, nitrogen and phosphorous loss, and water quality.

LUCI operates as a series of toolboxes through ESRI's ArcMap GIS software. The model uses digital elevation, land use and soil data augmented by local stakeholder input to identify areas where change in land management can provide synergistic benefits to multiple ecosystem services. Outputs include 'traffic-light' maps that provide easy to understand recommendations of where ecosystem service provision can be improved or where provision currently exists. Specifically, LUCI is designed to facilitate (from Jackson et al., 2013):

1. Spatially explicit policy implementation;
2. Integration of policy implementation across sectors (e.g. water, biodiversity, agriculture and forestry);
3. Participation (and learning) by many different stakeholder groups.

The LUCI framework is the subject of on-going development, with a current focus on improving farm scale assessment of nutrient loss and water quality.

1.5 Research justification

It is recognised that to improve ecosystem service provision, spatially and temporally explicit frameworks are required to minimise trade-offs and maximise synergies between ecosystem services (Power, 2010). In the New Zealand context, nutrient management is likely to extend to encompass a wider consideration of resource use efficiency, including energy, water, and other environmental flows (Monaghan et al., 2007), which ecosystem service frameworks can enable. These frameworks are in the early stages of widespread use, and irrigation inputs are not a commonly included element, despite the known direct and indirect impacts water additions and extractions can have on hydrological flows and connected ecosystem services.

Similarly, few current irrigation models in widespread use are generally applicable and fully spatially explicit, which limits their ability to inform irrigation management decisions at field and sub-field scales. Neither Overseer nor IrriCalc are spatially explicit; agricultural fields are assumed to be homogenous in both models. There is an acknowledged need in the literature for generally applicable irrigation modelling frameworks to aid water use decisions (Bastiaanssen et al., 2007; Ragab, 2002). Hedley & Yule (2009) state that spatial decision support tools for precise irrigation scheduling are needed that are compatible with recent advances in irrigation technologies and can address the spatial and temporal variability of crop demand and soil water supply.

The need for irrigation consideration in ecosystem service decision support tools and the need for spatially explicit irrigation models are complementary and present the research focus of this thesis.

1.6 Research aim

This thesis aims to produce a physically based, spatially explicit irrigation model following accepted hydrological practice that can:

- Identify and communicate where gains in ecosystem service provision can be made by altering irrigation in space, time and volume;
- Enable LUCI existing tools to account for irrigation flows in their consideration of ecosystem services.

1.6.1 Objectives

Objectives to achieve the aim stated above can be categorised as either research or modelling focussed. The research objectives aim to develop an understanding of irrigation systems and their interaction with the physical environment. They are:

1. Summarise how irrigation impacts ecosystem services and identify where ecosystem service provision can be improved with regard to irrigation;
2. Gather data on typical irrigation systems and their management: how is water applied to an irrigated field?;
3. Identify important biophysical parameters that affect irrigation demand and water use efficiency in agroecosystems.

Modelling objectives aim to translate the research findings to a usable model that achieves the overall aim. They are:

4. Accurately predict irrigation events and replicate systems where irrigation event timing and depth are known;
5. Enable model application regardless of data availability;
6. Account for spatial variability in both soil properties and water application;
7. Enable rapid application without need for specialised software or hardware;
8. Produce outputs that can spatially communicate opportunities for ecosystem service improvement.

1.7 Thesis structure

This thesis consists of seven primary chapters:

1. **Introduction**

   Introduces the research topic and outlines thesis aims.

2. **Irrigation and ecosystem services**

   Chapter 2 situates irrigation within the concept of ecosystem services. The chapter outlines the beneficial and detrimental impacts of irrigation on various ecosystem services, with a focus on food production, water supply and water quality. Opportunities for improvement in ecosystem service provision with regard to irrigation systems and their management are identified. Chapter 2 focusses on achieving objective 1.

3. **Irrigation systems and management**

   Chapter 3 describes when, where and how much water is applied by irrigation systems. The chapter describes common irrigation systems and their parameters, defines measures of performance, and presents a method for calculating gross irrigation application depth based on the uniformity of the application system. Chapter 3 is focusses on achieving objective 2.

4. **Irrigation demand and physical properties**

   Chapter 4 provides an overview of soil properties, climate parameters, and crop water use, and outlines their consideration for a water balance framework. Chapter 4 focusses on achieving objective 3.

5. **Methods**

   Chapter 5 describes the irrigation model developed in this thesis. Data sources are discussed, the structure of the model is described, and a discussion on assumptions and potential sources of error is provided. Chapter 5 describes techniques used to achieve the modelling objectives (objectives 4 to 8).

6. **Case studies**

   Chapter 6 describes the application of the developed model to 3 locations in New Zealand: the Winchmore irrigation research station, an apple orchard near Nelson, and a hypothetical mixed farming operation near Leeston, Canterbury. The level to which the modelling objectives, 4 to 8, have been achieved is discussed.

7. **Discussion and Conclusions**

   Chapter 7 summarises the findings of this thesis. A discussion on model applicability and future development is presented. The degree to which the thesis aim has been achieved is addressed.

2 Irrigation and ecosystem services

Irrigation water withdrawals, storage, and application alter the quality, quantity, and timing of natural water flows. These alterations in the hydrological cycle associated with irrigation can change connected ecosystems capacity to produce ecosystem services, both positively and negatively (Molden, 2007). This section uses the ecosystem services concept to categorise irrigation impacts and identify where changes in irrigation management can benefit ecosystem service provision, with focus on food provision, water supply, and water quality.

2.1 Food provision

Global food production is reliant on irrigation. Approximately 250 million hectares of agricultural land is supplied by irrigation, representing 14% of the total agricultural area. This 14% produces 40% of all crops (Bos, et al., 2008; FAO, 2014). As world population increased from 2.5 billion in 1950 to 6.5 billion in 2007, the global irrigated area doubled and water withdrawals for irrigation tripled (Molden, 2007). Combined with increased fertilisation, cropping intensities, and improved crop genetics, irrigation expansion enabled food production to keep pace with growing food demand (see figure 2.1). Irrigation serves to improve crop production by supplying water to crops, although poorly managed irrigation inputs can in some cases reduce production through waterlogging, salt accumulation, and erosion.

Irrigation increases agricultural production by removing growth limitations that occur when plants become water stressed (plant stress and transpiration processes are discussed in chapter 4). While different crops and crop varieties exhibit different responses to water availability (Doorenbos et al., 1979), a linear response between evapotranspiration and yield has been reported for a wide range of crops and locations, and yield increases in response to irrigation are well established (De Juan et al., 1996). The drought day model developed in New Zealand by Rickard (1960) and Rickard & Fitzgerald (1969) suggests that yield for pasture and Lucerne is (negatively) linearly related to the number of days where soil moisture content is at or below

Permanent Wilting Point (PWP). Similarly, Sumanasena et al. (2011) found that increased irrigation frequency resulted in significantly more ryegrass and white clover production as a result of extended water availability to plants. Maintenance of Plant Available Water (PAW) through irrigation is therefore essential to agricultural yield where rainfall alone is insufficient.

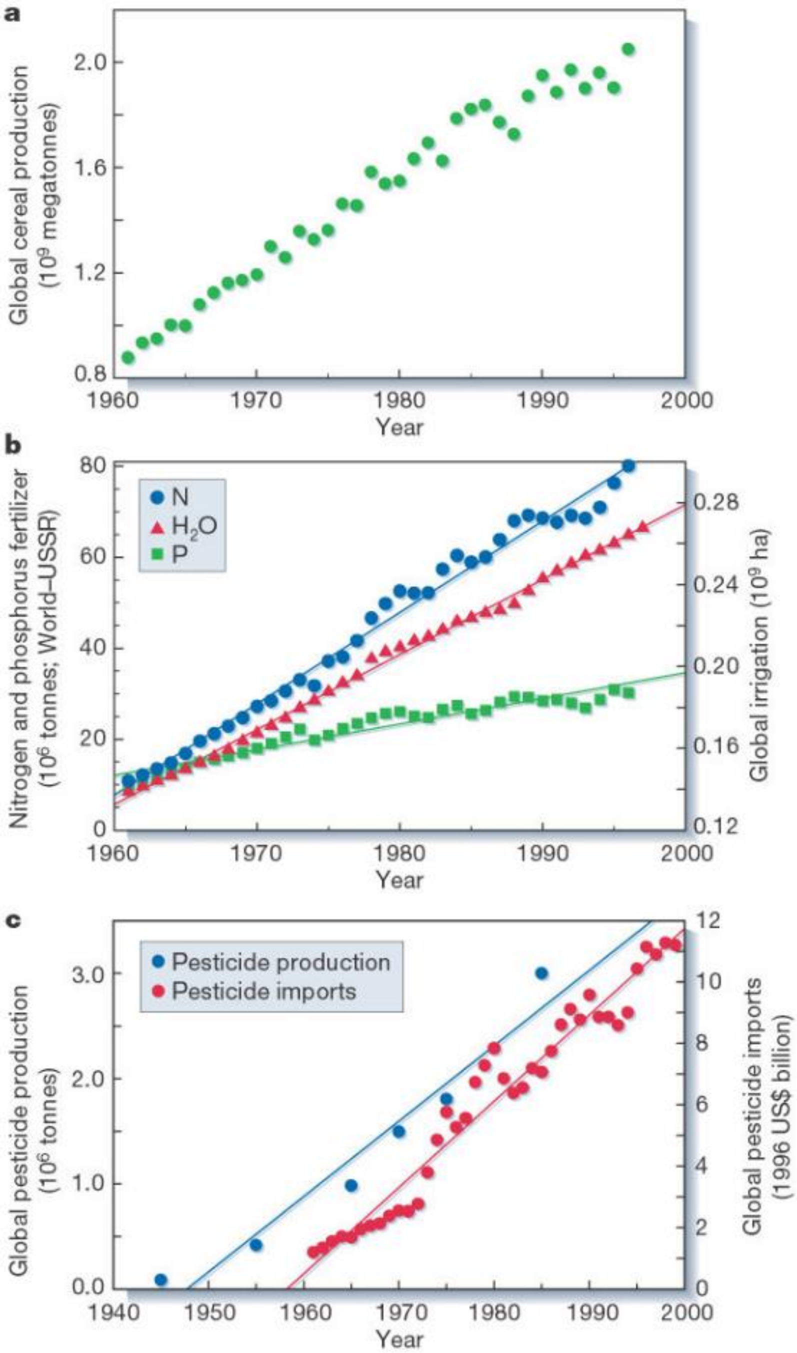


Figure 2.1

Agricultural trends over the past 40 years.

a: Total global cereal production;

b: Total global use of nitrogen and phosphorus fertilizer (except former USSR not included) and area of global irrigated land;

c: Total global pesticide production and global pesticide imports (summed across all countries)

From: Tilman et al., (2002).

Where irrigation application is poorly managed, waterlogging and salt accumulation in soils can decrease yields and reduce the sustainability of agroecosystems. Naylor (1996) estimates that 15 million hectares of crops have suffered reduced yields in developing countries as a result of water logging and saline soils. Waterlogging occurs where soils are inadequately drained or where water tables have risen to saturate the roots of plants, causing hypoxia and reducing growth (Barrett-Lennard, 2003). It is estimated that 10% of irrigated land globally suffers from waterlogging, reducing productivity by 20% in these areas (Stockle, 2002). Poorly drained soils can also result in salt accumulation which can compound production issues. Salt accumulation occurs where saline irrigation water is applied to fields and salts remain after water evaporates or is transpired by crops. Similarly, salts can remain in the crop rootzone where saline groundwater tables are raised. Technical problems that have led to irrigation induced salinity include poor on-farm water use efficiency, inadequate or lack of drainage infrastructure, and excessive seepage from poorly maintained or operated conveyance canals (Stockle, 2002). When irrigating fields prone to salt accumulation, applying water in excess of plant requirements can improve production by leaching salts from soils, so long as the underlying water table is not raised to within the crop rootzone (Bos et al., 2008).

In New Zealand, loss of production is more likely to occur as a result of erosion or soil compaction. Erosion results from the displacement of soil particles from rainfall, irrigation and wind energy. Erosion is estimated to remove 75 billion tons of soil globally each year, mostly from agricultural land (Pimentel et al., 1995). Erosion results in a loss of soil depth, degradation of soil structure, loss of fertility, and pollution of waterways with sediments and nutrients (Aqualinc, 2012; Pimentel et al., 1995). Erosion is of primary concern on cultivated land, where loosened, bare soils are more easily removed. Erosion can also be an issue for pasture production where fields are overgrazed or slopes are steep (Pimentel et al., 1995; Shaxson & Barber, 2003). The addition of irrigation water increases the potential for erosion to occur, especially where high intensity application is sufficient to break down surface soil structure (Aqualinc, 2012; McIndoe, 2001). Soil compaction can also degrade soil structure, and can cause reduced soil water storage and subsequently lower water supply to crops (McDowell, Nash, & Robertson, 2007). Houlbrooke et al. (2011) identify that soil compaction is often of bigger concern than erosion for pasture production. The authors found that the addition of irrigation water to a North Otago hill country pasture resulted in more soil compaction than an equivalent dryland system, with the timing of irrigation in relation to stock rotations a key determinant of compaction occurrence.

2.2 Water supply

Currently 70% of global freshwater withdrawals are estimated to be used for irrigation (ICID, 2014a). In many areas of the world demand for water now exceeds supply, with one fifth of the world's population, 1.2 billion people, living in areas of physical water scarcity where there is not enough water to meet everybody's needs (Molden et al., 2007). Many countries in a band from China through India, Pakistan, and the Middle East to North Africa either currently or will soon fail to have adequate water to maintain per capita food production from irrigated land (Seckler, Barker, & Amarasinghe, 1999). In the United States, approximately 20% of the irrigated area is supplied by groundwater pumped in excess of recharge, with similar concerns of excess groundwater withdrawals in China, Bangladesh (Tilman et al., 2002), Mexico, and Egypt (Molden, 2007). In the most extreme cases, consumptive water use and water diversions for irrigation and other uses have caused lakes to shrink, such as the Aral Sea in central Asia, resulting in wide-ranging impacts (Falkenmark et al., 2007). Similarly, consumptive water use and inter-basin transfers have transformed several of the world's largest rivers into highly stabilised, and in some cases only seasonally discharging channels (Meybeck & Ragu, 1997). In New Zealand, water extractions for irrigation account for 78% of total consumptive water use (not including the Manapouri hydro-electric power station) (Ministry for the Environment, 2010). National water allocations, predominantly for irrigation, increased by a third between 1999 and 2010, and the amount of land irrigated by consented water takes has increased by 82% over the same period (Ministry for the Environment, 2010). In Canterbury, which accounts for 70% of national irrigation by area, water extractions have reached sustainability limits where increased water use will require new storage infrastructure if environmental flows are to be maintained (Jenkins, 2012).

Abstraction of irrigation water from ground- or surface-water sources removes water from natural pathways, which can have a number of impacts of the water body concerned. The ability to provide habitat for riverine flora and fauna, support recreational activities, or assimilate waste are all reduced when water is extracted for use elsewhere (Doak et al., 2004). Maintaining environmental flows is an increasing priority in many catchments, and pressures on water resources are increased further as industrial and domestic water use, commercial freshwater fisheries, and hydro energy production all provide competition for water resources that were previously dedicated to agriculture (Tilman et al., 2002). Water demand from these sources is growing relative to agriculture, which is expected to receive a decreasing share of developed freshwater resources (Molden et al., 2007). This increased competition and declining groundwater reserves, coupled with rising food demand, higher energy prices, and climate change, necessitates that agricultural water use efficiency is increased so that more nutrition is produced for each drop of water used (Molden, 2007).

Minimising irrigation losses (i.e. maximising the proportion of applied water that is utilised by plants as transpiration) is generally beneficial to water provision for all users and pathways. In some instances however, return flows from excess irrigation applications can improve the provision of water through recharge of groundwater aquifers and maintenance of regular stream flows (Doak et al., 2004). Where return flows are able to be re-used downstream by another irrigator or user, or as environmental flows provided water is of sufficient quality, catchment scale water use efficiency can remain high. For example, the Waikakahi stream in Canterbury flows 4-9 times higher during summer than winter when runoff from border dyke irrigated fields augments natural flows (Wilcock et al., 2007). So long as sediment and nutrient load remain within limits, these flows have the potential to improve stream biodiversity through increased water provision, especially during drought periods. Work in Australia by Arthur, McGiness, & McIntyre (2011) found that increased water provision from irrigation affords benefits to native flora and fauna by creating artificial open-water habitats and raising water tables. Similarly, Richardson & Taylor (2003) found that irrigated Australian rice paddies provide habitat and foraging opportunities for Egrets and other wading birds, however both groups of researchers conclude that irrigated lands are not adequate substitutes for natural habitat.

Molden et al. (2007) and Oki & Kanae (2006) recognise that for much of the world, the pending water supply crisis is largely due to the mismanagement of water resources rather than a shortage of water. A number of methods for improving agricultural water use efficiency exist, including cultivating and developing crops with higher water use efficiencies and improving soil water holding capacity by increasing organic matter and reducing tillage (Tilman et al., 2002). For irrigation, matching irrigation inputs to the receiving crop demands and soil capacity and ensuring losses are minimised from non-uniform distribution, surface runoff, irrigation of non-cropping areas, and seepage from conveyance canals can all improve water use efficiency (Edkins, 2006). The rising demand for the finite amount of water available for pasture irrigation in New Zealand has resulted in increased interest in irrigation efficiency (Sumanasena et al., 2011).

2.3 Water quality

Water quality degradation from agriculture and other non-point sources is a major environmental issue worldwide and in New Zealand (Millennium Ecosystem Assessment, 2005; Power, 2010; Smil, 1999). In particular, losses of reactive Nitrogen (N) and Phosphorous (P) from agricultural fields to waterways are significant drivers of water quality degradation in rural catchments (Dymond et al., 2013; Monaghan, Hedley, et al., 2007; Monaghan, et al., 2007; Parliamentary Commissioner for the Environment, 2013). Irrigation enables greater farm productivity, but can also contribute to increased nutrient loss (McDowell, van der Weerden, & Campbell, 2011; Monaghan et al., 2007). Irrigation also increases losses of sediment, faecal bacteria, salt, and other chemicals which can adversely affect water quality downstream (Falkenmark et al., 2007; Stockle, 2002).

Nitrogen species can be divided into two groups: nonreactive and reactive. Nonreactive N is N_2, the bio-unavailable form that comprises the majority of the Earth's atmosphere. Reactive N (Nr) includes all biologically, photochemically, and radiatively active N compounds in Earth's atmosphere and biosphere. Nr includes inorganic reduced forms of N (e.g., ammonia [NH_3] and ammonium [NH_4+]), inorganic oxidized forms (e.g., nitrogen oxide [NO_x], nitric acid [HNO_3], nitrous oxide [N2O], and nitrate [NO_3−]), and organic compounds (e.g., urea, amines, proteins, and nucleic acids) (Galloway et al., 2003). Crop nitrogen requirements are supplied by indigenous sources of Nr in the soil, deposition of Nr from the atmosphere, biological N fixation, recycling of crop residues, animal manure, human waste, and by the application of synthetic Nr fertilizers (Galloway et al., 2003). It is estimated that 40% of the world's population is sustained by synthetic Nr fertilisers applied to crops (Smil, 1999).

Like Nitrogen, Phosphorous is essential for plant growth. Bio-available P normally occurs as phosphate (PO_4^{3-}) ions in soil and organic matter originating from parent rock and minerals. Phosphate rock is commonly mined and spread as fertiliser to boost indigenous soil P stocks so that maximum yields can be achieved. P fertilisers are estimated to account for 50-60% of all P supply in global agroecosystems (Smil, 2000). When soluble, such as in the form of superphosphate fertiliser, and where soil P retention properties are low, P can be leached from soils with percolating water. More commonly, P is insoluble and bound to soil particles as particulate P, and export occurs with runoff of eroded sediment (Hart, Quin, & Nguyen, 2004). The distinction between dissolved and particulate P is arbitrary, commonly determined by a filter size of 0.45 μm, and P can readily change between the two forms (Hart et al., 2004). The proportion of dissolved to particulate P in surface runoff or waterways is site specific and can change with time, depending on topography, stocking rates, crop type, intensity of rainfall or irrigation, and form and timing of fertiliser application (Hart et al., 2004). Increased soil erosion and runoff from fields, recycling of crop residues and manures, discharges of urban and industrial wastes, and applications of inorganic fertilizers have tripled natural P flows to the year 2000 (Smil, 2000).

Although essential elements to crop production, when Nr and P are transported to waterways a number of environmental issues can result. Aquatic impacts of nutrient loss from agroecosystems include eutrophication, increased frequency and severity of algal blooms, hypoxia and low oxygen conditions, and 'dead zones' in coastal marine ecosystems (Bouwman, Beusen, & Billen, 2009; Power, 2010; Tilman et al., 2002). Growth of nuisance aquatic flora, like agricultural crops, is determined by the limiting nutrient, so whether N or P levels are more important is site specific (in rare cases other elements tied to productivity such as Calcium, Carbon, Potassium, and Magnesium may also be limiting). A ratio of 15:1 Dissolved Inorganic Nitrogen (DIN) : Filterable Reactive Phosphorous (FRP) is commonly used to indicate whether a stream is N or P limited (White, 1983). Dissolved reactive phosphorus (DRP) and nitrate-N are the nutrients of most concern in New Zealand because they are immediately available to macrophytes and periphyton for growth (Dymond et al., 2013). Nr can also pollute groundwater reserves used for drinking supply. High concentrations of nitrate-N in drinking water can cause methaemoglobinaemia, to which infants and elderly are particularly susceptible. The World Health Organisation (2011) recommends nitrate-N levels are maintained below 11 mg/l to protect against methaemoglobinaemia in bottle-fed infants, although recognise that water sourced from wells often exceeds this concentration. Furthermore, once Nr is lost from agroecosystems, it enters a 'Nitrogen cascade' through natural ecosystems where it can be rapidly converted between Nr forms and can cause ecosystem service degradation in multiple locations over time (see figure 2.2) (Galloway et al., 2003). Nutrient loss is an economic burden on farmers as well as a driver of ecosystem degradation. Removed nutrients need to be replaced at cost, and a limited nutrient supply can reduce crop yields.

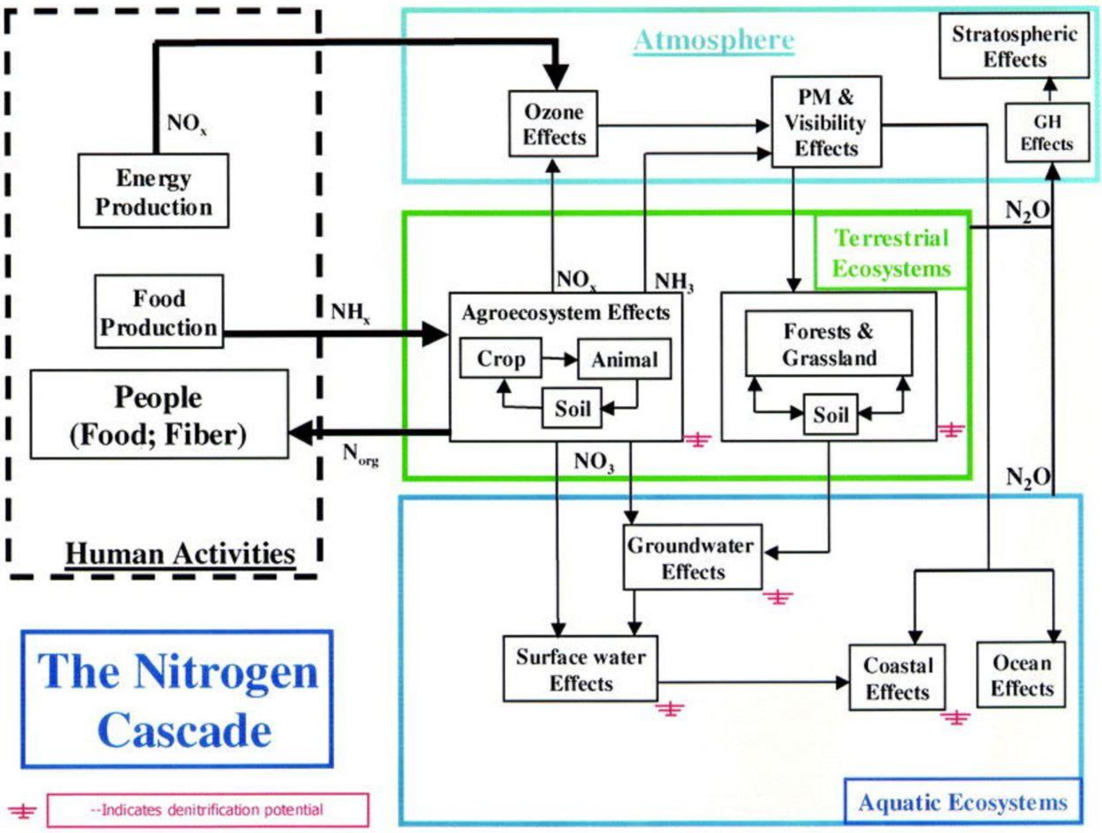


Figure 2.2 Nitrogen cascade showing the sequential effects that a single atom of N can have in various reservoirs after it has been converted from a nonreactive to a reactive form. Abbreviations: GH, greenhouse effect; NH3, ammonia; NO3–, nitrate; NOx, nitrogen oxide; N2O, nitrous oxide; PM, particulate matter. From: Galloway et al., (2003).

Irrigation increases nutrient loss potential by supplying more water to fields than otherwise received. Water draining beyond the rootzone or running off the field surface can transport nutrients outside field boundaries and into receiving streams or aquifers. A detailed discussion of irrigation loss pathways is given in section 3.4. Even where irrigation is perfectly matched to soil and crop requirements, increased drainage compared to dryland farming is inevitable as soil moisture content is kept nearer to field capacity, so increasing losses from rainfall events, especially summer storms and in early winter (Snow et al., 2007). Irrigation also increases nutrient loss potential indirectly by removing soil moisture limitations to growth and allowing greater farming intensity through higher inputs of fertiliser, increased stocking rates, and reduced crop rotation periods (Galloway et al., 2003; Monaghan, Hedley, et al., 2007). Figure 2.3 displays Nr flows between agroecosystems, humans, and the wider environment.

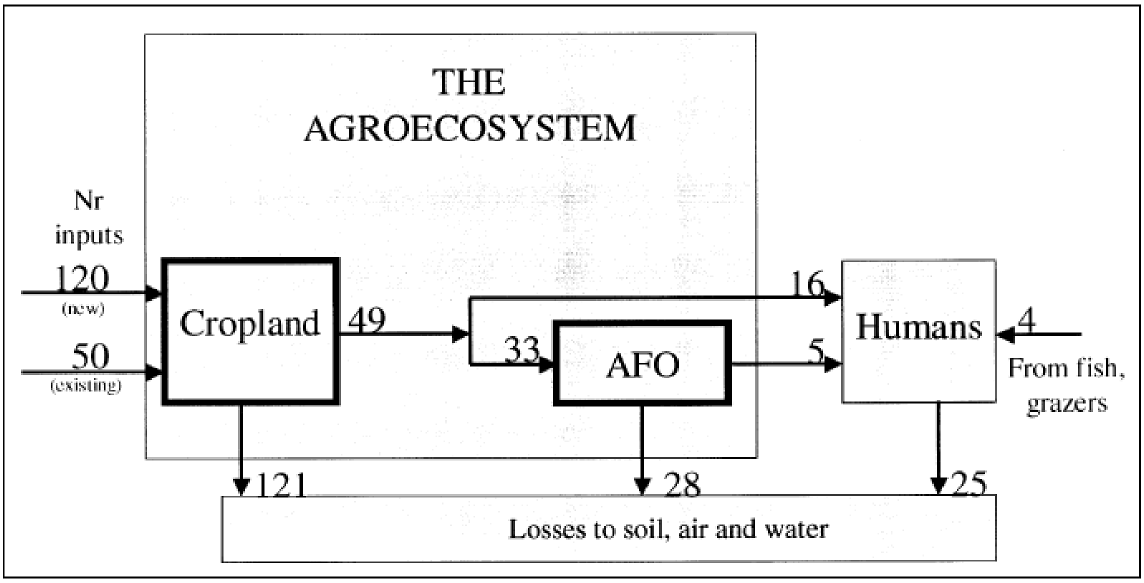


Figure 2.3 Major reactive nitrogen (Nr) flows in crop production and animal production components of global agroecosystems (teragrams of N/year). Reactive nitrogen inputs represent new Nr from fertilisers and from cultivation-induced biological nitrogen fixation, and existing Nr that is reintroduced in the form of crop residues, manure, atmospheric deposition, irrigation water, and seeds. Portions of the Nr losses to soil, air, and water are reintroduced into the cropland component of the agroecosystems. AFO: animal feeding operations**.** From: Galloway et al., (2003).

Nr loss generally occurs as leachate with drained irrigation and/or rain water. For seasonal crop production, Nr is lost from soluble fertilisers, crop residues and from recently tilled soils (Cameron et al., 1986; Jenkins, 2012). Globally, only 30–50% of applied nitrogen fertiliser is taken up by crops (Cassman, Dobermann, & Walters, 2002; Smil, 1999), and 20% is directly lost to aquatic pathways (Galloway et al., 2004). Vegetable production is especially vulnerable to Nr leaching due to their shallow rooting systems and typically large fertiliser applications (Cameron, Di, & Moir, 2003). Figure 2.4 displays reported Nr losses for different farming systems in New Zealand.

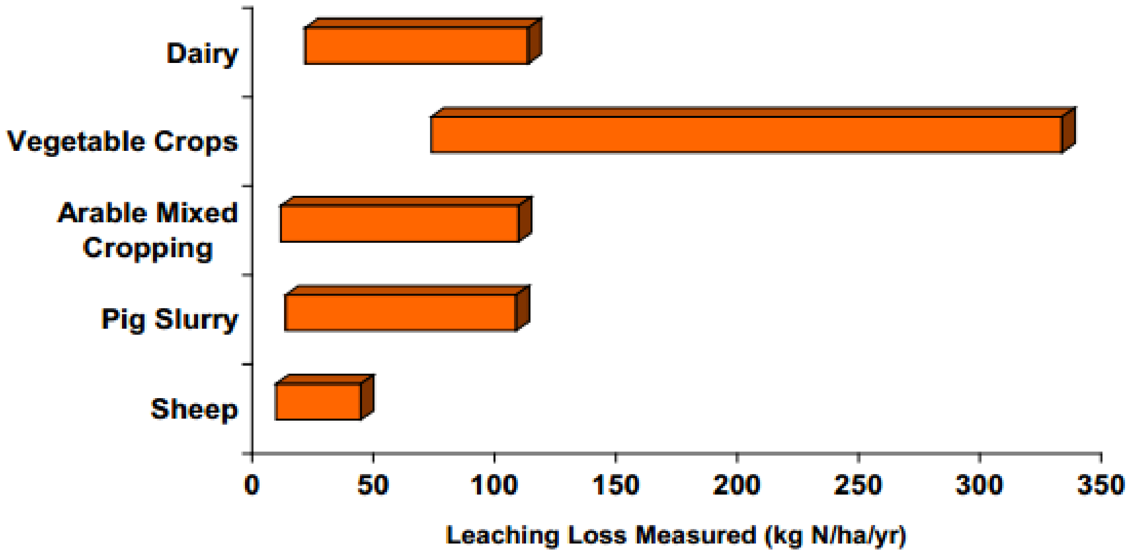


Figure 2.4 Range of Nitrate-N leaching losses recorded from different farm types in New Zealand. From Cameron, Di, & Moir (2003)

For livestock farming in New Zealand, direct losses of fertiliser are generally minimised (McDowell & Catto, 2005; Monaghan, et al., 2005), and the majority of Nr losses instead originate as dung or urine excreted by animals (Monaghan et al., 2007). Dairy cow urine contains between 500 and 1000 kg N/ha^{-1} (Ledgard, Penno, & Sprosen, 1999), with urine spread over just 3-5% of the field after one grazing event, or up to 25% of the field over one year (Cichota, Vogeler, & Snow, 2010). Animals therefore concentrate Nr into small patches where application rates are beyond the capacity of pasture to use, resulting in losses with percolating water. Cichota et al. (2010) applied 1000 kg N/ha^{-1} to the surface of lysimeters, and found that some 45–65% of the applied nitrogen (NH_4 and NO_3) was leached following 700 mm of irrigation and rainfall induced drainage over 8 months. Application of stored farm effluent also increases Nr concentrations in fields, which can be directly lost where volumes and timing of application are not correctly matched to soil storage capacity and crop nutrient demand. Regardless of the source of Nr or the farming system, Nr loss to waterways requires a transport mechanism. Irrigation therefore plays an important role in Nr leaching, with irrigation design and management recognised as a key factor for Nr pollution of waterways (Causapé, Quílez, & Aragüés, 2006).

P loss in many systems is thought to be governed largely by overland flow (McDowell et al., 2011). Soil P level is an important determinant of P concentration in overland flow (Carey, Drewry, Muirhead, & Monaghan, 2004), as is intensity of animal treading, grazing, and dung depositions, and type and quantity of applied fertiliser (Carey et al., 2004; McDowell et al., 2007). An analysis of 246,000 New Zealand Olsen phosphate samples from between 1988 and 2001 by Wheeler et al. (2004) showed that between 30% and 60% of dairy farms had Olsen P levels above the range required for near-maximum pasture production, indicating that there is scope to reduce P loss potential without reducing yield. A literature review by Hart et al. (2004) showed that recently applied fertilisers and manure can be significant event-specific sources of P in surface and subsurface runoff. Of the papers reviewed, the average Total P (TP) loss was 4.5 times greater, and Dissolved Reactive P (DRP) 6 times greater, for fertilised compared to unfertilised trials. Work by White et al. (2003) in the USA, Nash et al. (2004) in Australia, and Carey et al. (2004) in New Zealand show that high P losses can occur when soluble fertilisers such as superphosphate ($Ca[H_2PO_4]_2$), monoammonium phosphate ($NH_4H_2PO_4$), or diammonium phosphate ($[NH_4]_2HPO_4$) are applied prior to surface irrigation. White et al. (2003) measured a total reactive phosphorous load of 10.9 kg/ha^{-1} in runoff following irrigation, compared to a load of 0.6 kg/ha^{-1} for an unfertilised control field. The P load in the irrigation runoff from the monoammonium phosphate fertilised field accounted for 25.6% of the total applied P. Nash et al. (2004) found that the P load in border dyke irrigation surface runoff was 2.3 and 17.6 mg TDP/l for irrigations before and immediately after fertiliser application respectively. Carey et al. (2004) recorded a concentration of ~5mg P/l in border dyke outwash where soluble P fertiliser was applied 10 days previously, compared to an average concentration of 0.6mg P/l in previous unfertilised trials. The authors found that concentrations of P and N in irrigation run-off were consistently higher than the acceptable critical limits for water quality, even with in-stream dilution. Correlation between nutrient application to border-dyke irrigated fields and seasonal high P concentrations were also reported by Wilcock et al. (1999) in the Waikato, New Zealand. These findings emphasise the importance of irrigation timing in relation to fertilisation for P loss. Moreover, while it is well established that P losses are generated where overland flow is experienced, recent work suggests that losses of dissolved P with sub-surface drainage may be greater than previously thought (McDowell et al., 2014).

The quality and chemical composition of supplied irrigation water is also an important consideration in terms of water quality in agroecosystems. Untreated, often saline wastewater from residential, commercial, and industrial sources supplies irrigation water for millions of small scale farmers worldwide (Molden, 2007). Poor quality irrigation water requires careful management so that the health of people and crops are not adversely affected. While poor irrigation water quality is not common in New Zealand, a similar challenge is faced where effluent from animal milking and feeding areas is routinely applied to the land through irrigation systems. Furthermore, the nutrient load of irrigation water is an important factor for nutrient flows. Each milligram per litre of nitrate–N (or other nutrient) in irrigation water is equal to a 0.01 Kg/ha application for each millimetre of irrigation applied. There is little work in the literature regarding the nutrient content of irrigation water, however it follows that nutrients contained in irrigation water can be a significant nutrient source when irrigations are frequent and the nutrient concentration of irrigation water is high, as has been recorded in New Zealand. For example across Canterbury, nitrate-N concentrations in groundwater (a primary source for irrigation supply) generally vary within a range of 5 to 10 mg/L, with concentrations recorded above the Ministry of Health's maximum acceptable level of 11.3 mg/L in 27 of 97 tested wells sometime between 1996 and 2006 (Environment Canterbury, 2010). Each 1000 mm of irrigation with water containing 10mg/Nr/L represents an application of 100kg N/ha.

Given that hydrology is the most important factor in the transfer of nutrient from land to water (Hart, Quin, & Nguyen, 2004), limiting drainage is the primary means of reducing nutrient losses (Carey, Drewry, Muirhead, & Monaghan, 2004). The timing, volume, and composition of irrigation inputs with respect to rainfall, grazing patterns, and fertilisation is therefore an important influence on nutrient use efficiency and the extent of nutrient losses from fields (Carey et al., 2004; Causapé et al., 2006; Monaghan et al., 2007). A number of best management practices are recommended to minimise nutrient loss from farms. With regard to irrigation, these include matching inputs to soil storage capacity and maximising rainfall utilisation so that drainage and overland flow are minimised (Carey et al., 2004). It is also widely recommended to delay irrigation following fertiliser application. McDowell & Catto (2005) state that where P fertilisers are applied away from waterways and more than two weeks before irrigation or significant rainfall, direct losses of P from fertiliser are generally less than 10% of total P loss from pasture. Nexhip et al. (1997) recommend a more stringent best management practice of zero runoff for the first two irrigations after fertilisation and limiting runoff from remaining irrigations to 10% or less of the inflow volume for surface systems. Hart et al. (2004) conclude that a suitable delay between fertiliser spreading and irrigation is site specific and dependent on fertiliser solubility, soil characteristics, and timing and volume of irrigation and rainfall.

Management interventions that aim to improve water quality in agroecosystems are likely to be most successful when applied to areas of high runoff or drainage, high nutrient content, recent fertiliser application, or that have been recently grazed (Hart et al., 2004). These 'critical source areas' (CSAs), where nutrient source and transport factors coincide are thought to contribute the majority of nutrient losses, particularly P, from farmland (McDowell et al., 2004). Limiting CSAs is a primary goal of precision management techniques, which match temporal and spatial nutrient and water supply with inter- and intra-field variations in crop demand. Cassman et al. (2002) predict that the greatest gains in nutrient use efficiency and subsequent environmental protection will occur through increased precision management. Cassman et al., alongside Tilman et al. (2002), identify that precision management is possible for both large-scale agriculture in developed countries and small-scale farming in developing countries given the use of appropriate diagnostic tools.

2.4 Other ecosystem services

Figure 2.5 Fishing in an irrigation canal, California, USA. A number of ecosystem services are connected to irrigation systems. Photo: Matt Black (2015).

Alongside food provision, water supply and water quality, irrigation can have an impact on a number of other ecosystem services. The construction of irrigation water storage and conveyance infrastructure can alter the quantity, timing, variability, and composition of natural flows (Falkenmark et al., 2007). Impacts following alterations in catchment hydrology can be both positive and negative for ecosystem service provision. Impacts include changes in flood regulation (Lead et al., 2005), fragmentation and destruction of aquatic habitats, changes in the composition of aquatic communities, loss of species (Falkenmark et al., 2007), enhanced recreational opportunities (e.g. figure 2.5) (Doak et al., 2004), and changes in local community health. Globally, improved water availability for domestic needs from irrigation has allowed better nutrition, improved hygiene and reduced infections and diseases (Faures et al., 2007).

However health problems resulting from stagnant water are also common, with higher prevalence of malaria, schistosomiasis, and other waterborne diseases associated with irrigation infrastructure (Faures et al., 2007). Furthermore, changes in ecosystem services can have negative feedbacks for food and fibre production, through the reduction of pollinators and degradation of potential farmland (Falkenmark et al., 2007). Agricultural water use must therefore be viewed holistically, and at many scales (sub-field, farm, catchment) so that the most benefit can be derived from irrigation storage, conveyance, and application.

2.5 Irrigation and ecosystem services summary

Clearly, irrigation has wide-ranging impacts on ecosystem services. For food production, irrigation plays a major role in reducing yield loss associated with water stress and is a key contributor to global food production. Poor irrigation management however can reduce crop production through waterlogging, salt accumulation, erosion, and compaction. Irrigation also has a major impact on water supply, as water extractions for irrigation mean that less water is available for other users and environmental flows, which are essential for maintaining a suite of other ecosystem services. For water quality, irrigation can be a major driver of degradation where return flows transport nutrients, primarily N and P, to waterways. It is recognised that an important challenge for irrigation management is to acknowledge, account for, and mitigate the unavoidable alterations of ecological systems (Faures et al., 2007).

Increasing the efficiency of irrigation so that a greater proportion of applied water is utilised by crops and the volume of water lost as drainage or runoff is reduced allows improvement in food provision, water supply, and water quality. At the same time, on farm costs associated with electricity, labour, and water storage can be reduced (Ascough & Kiker, 2002). Aside from some rare instances where inefficient irrigation can leach salts from soils or provide beneficial recharge of streams or groundwater, increasing irrigation efficiency represents a strong opportunity for synergistic ecosystem service benefit.

3 Irrigation systems and management

In order to simulate irrigation processes and identify where and how improvement in ecosystem service provision can be made in irrigated agroecosystems, an understanding of irrigation systems and their management is required. This chapter identifies when, where, and how much water is applied by irrigation systems. Published literature, management documentation, and existing modelling frameworks are reviewed to identify important considerations for irrigation modelling. First, common irrigation systems are described. Management and system parameters are then discussed, with a focus on decision making regarding irrigation application and the distribution uniformity of irrigation systems. A method for calculating gross irrigation depth, adapted from Bright (1986), based on a target adequacy level and Christiansen's coefficient of uniformity is presented. Finally, measures of irrigation performance relevant to field scale water use and loss are discussed.

3.1 Irrigation systems

It is estimated that there are more than 300 million hectares equipped for irrigation globally (Bastiaanssen, et al., 2007; Siebert et al., 2013). Systems range from simply flooding a cropped basin to automated precision sprinklers that can alter application rates to match crop water demands. Irrigation in developing countries is dominated by traditional surface irrigation systems, while more energy intensive spray systems are preferred in New Zealand and other developed nations due to their greater precision, flexibility and water use efficiency (ICID, 2014a). Micro irrigation systems consisting of small sprinklers or drippers are commonly used to supply water to individual plants when producing high value tree crops such as in vineyards and orchards. Systems are often used together, with some combination of surface, spray, and micro systems commonly used within the same catchment or farm. Of the 721,740 ha equipped for irrigation in New Zealand, 80.3% is by spray, 13% is by flood, and 6.4% is by micro systems (Statistics New Zealand, 2013b). Dairy farming represents the greatest irrigated land use, accounting for almost half of irrigated land (48.8%), of which a higher proportion is irrigated with spray systems (87.8%), and less by surface (11.5%) and micro (0.7%) irrigation (Statistics New Zealand, 2013a). The type of irrigation system is a key determinant of application characteristics, such as the depth applied, interval between applications, and volume and pathway of water losses.

3.1.1 Surface irrigation

Surface irrigation is the oldest form of irrigation application, and remains the most widespread method used worldwide (ICID, 2014b). Surface systems, sometimes referred to as flood irrigation, range from simply planting crops on the regularly flooded margins of rivers to highly sophisticated multi-user schemes that use automated canal conveyance and laser levelled fields to supply water to crops. For all surface irrigation systems, surface- or extracted ground-water is diverted to the field where it infiltrates into the soil. Because of this application mechanism, soil characteristics of the irrigated field determine the rate at which water can infiltrate into the soil, rather than the co-dependence of infiltration rate and water application rate as in spray and micro systems. Soil characteristics are therefore the dominant factor in the efficiency of surface irrigation systems. Surface irrigation over light soils that allow water to percolate easily is not recommended as losses below the root zone will generally be high (Irrigation New Zealand, 2001). Where flood systems are used on unsuitable soils and infrastructure is not maintained or poorly designed, flood systems can be highly inefficient in terms of water use. With good design and suitable soils however, flood irrigation can be as efficient as other irrigation methods (Irrigation New Zealand, 2001). Surface irrigation systems can be divided into three major methods: basin, furrow and border dyke (border strip) (ICID, 2014b).

Basin irrigation describes flooded areas of flat land surrounded by low bunds (also called levees, dykes or ridges) to prevent water flowing off the target field. Basin irrigation is commonly used to grow rice on terraced hill slopes, although basins are also used to irrigate pasture, cereal and tree crops. Because water is ponded over the surface of the field, crops with low tolerance to prolonged water-logging (greater than 24 hours) are generally unsuited to basin irrigation (Brouwer et al., 1988). Water can be applied to basins either directly or cascaded through a series of fields. To achieve a high uniformity of water application, basins must be level and water must be applied quickly, although because the top of the basin is always irrigated for longer than the bottom, it is not possible to achieve a perfect match between the crop root zone and the wetted soil area. Figure 3.1 displays an ideal and an over irrigated basin. Poor water distribution can be caused by soil variations, a poorly-levelled surface, or applying too much or too little water (Brouwer et al., 1988). For rice production, it is desirable to maintain basins in a state of constant flooding, which serves to suppress weed growth and increase yield for many rice varieties (Brouwer et al., 1989).

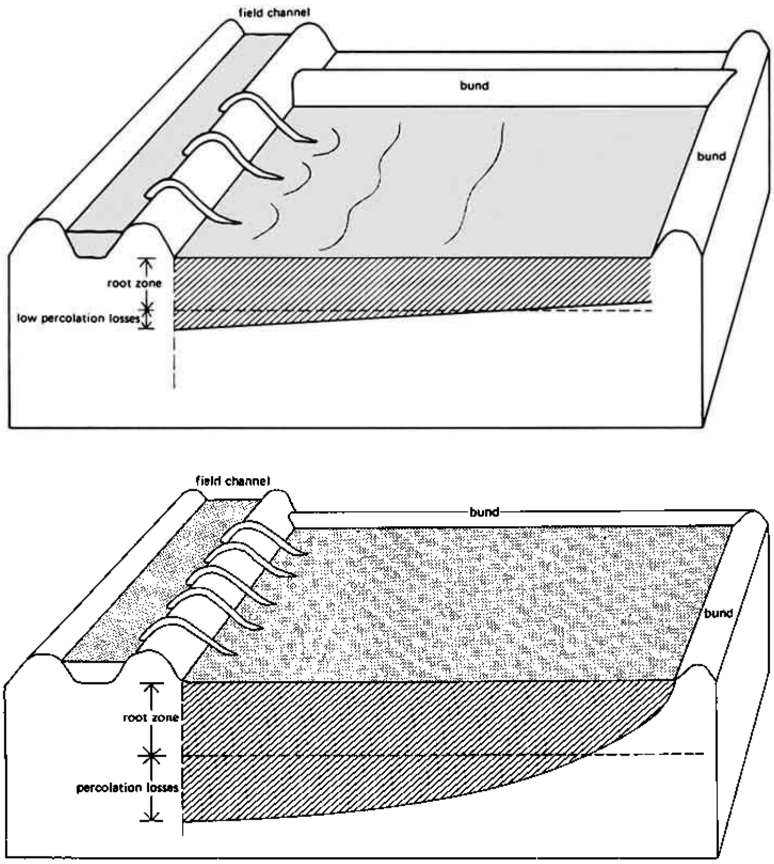
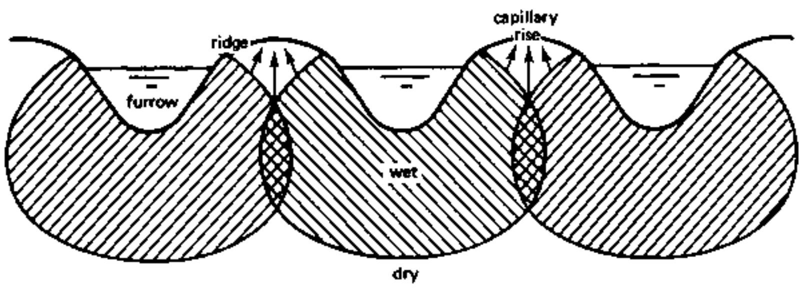


Figure 3.1 An ideally irrigated basin (top) and an over irrigated basin (bottom). There are over and under irrigated portions of the field for both scenarios. From: Brouwer et al. (1988).

Furrow and border strip methods of surface irrigation differ from basin irrigation by applying a timed water volume to the top of a sloped field, so that a consistent depth is targeted (although rarely achieved) for the whole field from a single irrigation event, and prolonged ponding over the surface is minimised. The depth of water that infiltrates into the soil depends on the characteristics of the soil, the slope and length of the field, the flow rate applied at the top of the field, the time the water is applied for, and the roughness of the field surface (Irrigation New Zealand, 2001). These parameters are largely reliant on system design, so once a system is built, it is difficult to change the depth of water applied with each irrigation event without also changing the proportion of the field that is irrigated.

Furrow irrigation utilises small channels to carry water between rows of crops in a field, with water infiltrating the soil into the root zone of crops planted on the ridges between channels. Furrow systems are used to irrigate crops planted in rows and those that are unsuited to the water inundation of basin systems. Furrows are recommended to maintain a flat or low slope topography (<0.5%), and should be contoured to match the slope if used on rolling terrain (Brouwer et al., 1988). Risk of soil erosion is high for furrow systems with an inclination greater than 3%, and where water flow down channels is rapid (>3.0 l/s) (Brouwer et al., 1988; Stockle, 2002). Furrow shape and spacing should be matched to the soil type so that an ideal volume is able to infiltrate into the crop root zone. Poor water distribution is caused by soil variations, uneven slope, poor furrow size and spacing, and applying too much, too little, or poorly timed water. Runoff from the ends of furrows can be 30% of inflow volume or higher, even under good irrigation conditions and management (Brouwer et al., 1988). Furrow irrigation is unique for surface systems in that only a fraction of the soil surface is irrigated.

Figure 3.2 Furrow irrigation cross section. From: Brouwer et al, (1988).



Border dyke irrigation utilises long, levelled fields divided by bunds which guide the water. Border dykes can be thought of as 'wide furrows' in their operation (Bos et al., 2008). Like all surface methods, border dyke systems should be matched to the correct soil type (medium infiltration rates), and topography (<2% slope) to allow effective irrigation to occur and reduce water losses and erosion (Brouwer et al., 1988). Because water flows over and off the field, the correct timing of water flows is required for border strip systems to achieve high efficiencies. Maximum efficiency from border dyke systems is achieved when water flow is stopped as it just reaches the end of the field, so that all but the last few metres of the field are restored to field capacity, and runoff is eliminated (Irrigation New Zealand, 2001). Various rules based on the infiltration rate of the soil are used to achieve correct timing, and application is typically automated in New Zealand using clocks or pneumatic control methods which turn off after a set period (Irrigation New Zealand, 2001). Excess irrigation from border dykes can occur due to incorrect timing, poor maintenance of borders and headrace, poor design, and gate and clock malfunctions (Carey et al., 2004). These issues are equally applicable to timed water application in furrow systems. Where excess runoff does occur, water can be captured and re-utilised as irrigation or can return to waterways to increase natural flows, although will carry an increased sediment and nutrient load.

Figure 3.3 Winchmore Irrigation Research Station and border dykes.

From: Te Ara - the Encyclopedia of New Zealand (2012).

Of the surface irrigation methods, border dykes are the only system capable of successfully irrigating intensive pasture, and are the traditional method used by most community irrigation schemes in New Zealand (McIndoe, 2001). While spray systems are generally preferred for modern irrigation investment, on suitable, homogenous soils and using modern technology such as laser levelling of fields, border dyke irrigation can achieve comparable efficiencies to spray systems and is attractive for its low labour requirements and long life (McIndoe, 2001).

3.1.2 Spray irrigation

Spray systems are the most common irrigation method in New Zealand, which are used over approximately 80% of the irrigated land (Statistics New Zealand, 2013b). Spray irrigators usually require additional energy to deliver water under pressure to sprinklers or guns which distribute the water over a field. There are a multitude of different spray irrigator types, which can be moveable or permanent, and which apply water at differing volumes, timing, intensity, and spatial extents. Spray systems typically irrigate at higher application efficiencies than flood systems (Edkins, 2006), although like flood systems, achieved efficiency depends on antecedent conditions, climate, soil, crop type, and system management.

McIndoe (2002) categorises spray systems commonly used in New Zealand as either travelling, manual move, or solid set. These are displayed in table 3.1. While spray systems can be grouped by physical appearance and method of operation, they are not easily differentiated by efficiency, even when applying water under identical conditions and management regimes due to differences in sprinkler type and water supply pressure. Other differences exist between systems in susceptibility to wind effects, labour requirements, capital and operational cost, ease of use, reliability, and flexibility to change the applied depth, timing, and irrigated extent during an irrigation season (McIndoe, 2001). For fixed and manual move systems, the depth of water applied relates to the time they are in operation. Travelling system application depth is determined by the speed of irrigator movement. System choice also determines the ability of the irrigation manager to apply water when desired. Large pivot or linear move systems may take multiple days to cover their irrigated area, so must be able to supply sufficient water so that crops are not stressed between irrigation events.

Table 3.1 Commonly used spray irrigation systems in New Zealand. From: McIndoe (2001).

	System	Sprinkler types
Travelling systems	Rotary boom	medium pressure
	Fixed boom	low pressure spray jets
		impact sprinklers
		multiple guns
		mini sprinklers
	Centre Pivot	low pressure pivot sprays &spinners
		rotating type pivot sprinklers
		impact sprinklers
	Linear move	low pressure pivot sprays & spinners
		rotating type pivot sprinklers
		impact sprinklers
	Hard hose gun	high pressure gun
		low-medium pressure boom
	Travelling gun	high pressure gun
Manual move systems	Hand shift / end tow	N/A
	Side roll	
	Long lateral & variants	
	K-line & variants	
Fixed systems	Solid set	small rotating sprinklers
		medium pressure impact sprinklers

For all spray systems, the rate of application and the depth of water applied should be matched to the receiving soil characteristics so that the applied water is maintained in the rootzone of the crop with minimal losses (Aqualinc, 2012; Greenwood et al., 2010; Irrigation New Zealand, 2013; Silva, 2007). These system parameters are discussed in section 3.3. Alongside depth and timing in relation to the water content of the receiving soil, the efficiency of spray systems is largely governed by the uniformity of water applied to the field. Uniformity is affected by the spacing and type of sprinklers or guns in the system, operating pressure, standard of maintenance, and is influenced by wind effects (McIndoe, 2001). Uniformity is discussed in detail in section 3.3.2. High winds can also blow water outside of the irrigated area, and can alter the speed (and therefore the applied depth) of travelling irrigators. High pressure systems such as big guns are usually most effected by wind, while low pressure systems with emitters close to the ground such as booms, centre pivots, long laterals or K-lines are generally least effected (McIndoe, 2001).

Figure 3.4 A travelling irrigator on the Canterbury plains. Photo: Ryan Evison (2015)

3.1.2.1 Precision application

Recent advances in irrigation technology have led to the development of Variable Rate Irrigation (VRI) spray systems. These systems supply different depths of water to different parts of the field, based on the variations in soil characteristics, crop water demand, or where irrigation is not wanted (roadways, houses, water storage infrastructure etc.) (Hedley & Yule, 2009). Most VRI systems are applied to Centre-Pivots or Linear move irrigators (Dukes & Perry, 2006; Hedley, Yule, & Bradbury, 2010), and use soil moisture monitoring either in real time using remote sensing techniques, or at the system design stage through electromagnetic

(EM) mapping of soil water holding capacity to determine management zones, each with a different target irrigation depth. VRI irrigators are equipped with a Global Positioning System (GPS), and are controlled by a software system and electronic solenoids that adjust the supply of water to emitters along their length. Water savings between 5% (Hedley et al., 2010) and 21% (Hedley, Yule, & Bradbury 2010) compared to uniform water application have been reported for VRI systems. Hedley et al. (2010) found that drainage and runoff was reduced between 19–55%, and cost savings were estimated at NZ$51–NZ$150 per hectare compared to uniform application. It follows that increasing use of VRI is likely, given increasing water use pressures discussed in chapter 2.

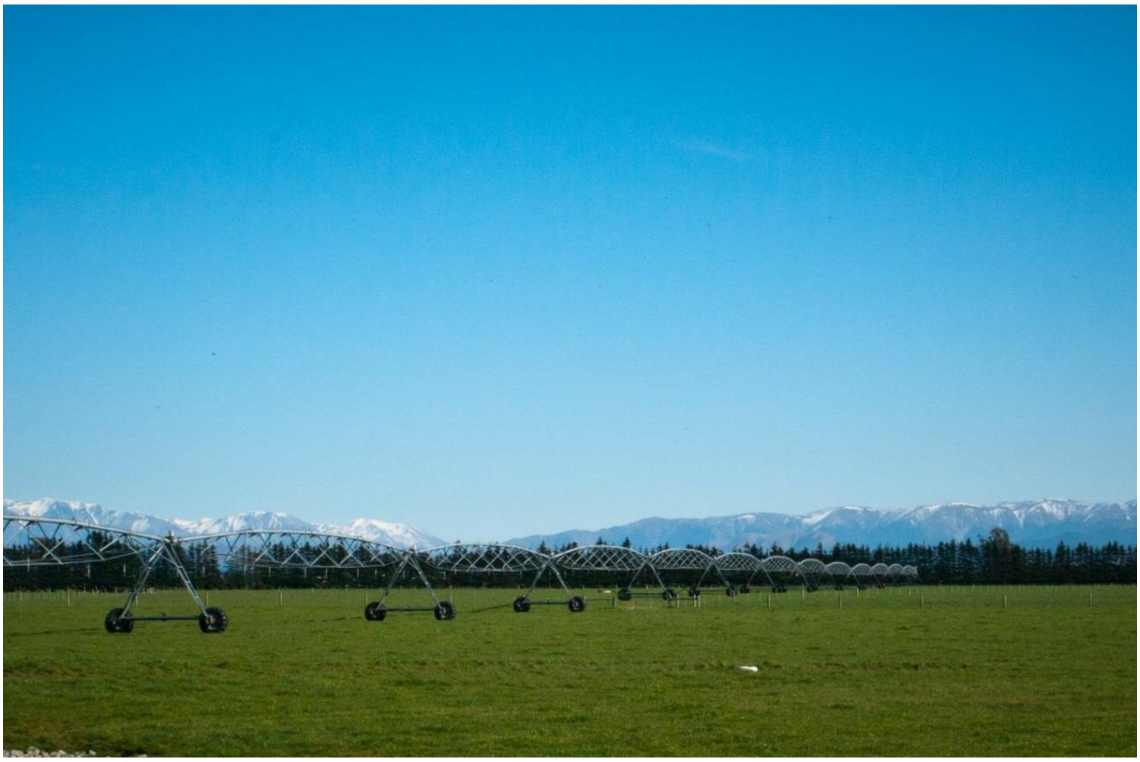


Figure 3.5 A Centre Pivot on the Canterbury plains. VRI technology is typically used with Centre-Pivot systems. Photo: Ryan Evison (2015).

3.1.3 Micro irrigation

Micro irrigation systems differ from other application methods by providing water directly to specific plants or trees, rather than the whole field. This enables a high level of control by the manager and usually provides improved application efficiencies over flood or spray systems (Edkins, 2006). Micro systems comprise of drippers or small sprinklers fed by small-diameter irrigation piping laid beneath rows of plants. Installation, maintenance and pumping costs are relatively expensive compared to other irrigation systems, and micro systems are unable to be used where animals graze or where fields are regularly cultivated (McIndoe, 2001). Their use is confined to high value and tree crops such as vineyards and orchards. Because micro systems apply water to only a portion of the field, calculating the water use of micro systems requires knowledge of the application footprint of the system.

3.2 Management parameters

Management parameters are those elements of an irrigation system that are readily adjustable during an irrigation season. The most commonly adjusted elements of an irrigation system are the interval between irrigation events and the depth (volume) of water applied (Aqualinc, 2012). Depth and return interval operate in tandem: the greater the applied depth (which requires an equivalent soil water holding capacity), the longer the interval can be until the next application, and vice-versa. The purpose of the irrigation and the proportion of the field targeted to receive the desired volume of water also influence the timing and volume of water applied. This section discusses adjustable irrigation parameters: irrigation purpose, spatial adequacy, return interval, and application depth. Their consideration for an irrigation modelling framework is identified.

3.2.1 Irrigation purpose

The purpose of irrigation is usually to maximise crop growth by removing water availability limitations. Irrigation can also be applied for frost protection, to leach salt from soils, or as deficit irrigation where water application only occurs during stages of crop development particularly sensitive to water stress.

For 'normal' irrigation, the management target is to maintain the soil in the crop rootzone at or near field capacity (Greenwood et al., 2010). Because applying extra water is usually only at a marginal extra cost to farmers compared to the potential yield loss that can occur with crop stress (Edkins, 2006), irrigation is often applied in excess of crop requirements as an insurance against soil moisture deficits (Greenwood et al., 2010; McDowell et al., 2011).

Unlike normal irrigation which aims to maximise plant growth, deficit irrigation aims to maximise water use efficiency by maintaining plant available water above critical levels only during water sensitive phenological stages (Kirda, 2002). While crops will usually experience some degree of water stress under deficit irrigation management, crop production can be improved by increasing the ratio of yield to water used (Zhang, et al., 1999) and allowing a greater area of land to be irrigated where limited water supplies are limited (ICID, 2014c). Nutrient leaching and fungal infection rates can also be reduced compared to normal irrigation management (ICID, 2014c). Supplementary irrigation is similar to deficit management and is a common management strategy in New Zealand. Supplementary irrigation management applies water only when rainfall is insufficient to maintain production at a desirable level, with irrigation serving as an insurance rather than a regular farm input (McIndoe et al., 2004). The distinction between 'normal' and deficit or supplementary irrigation is arbitrary, and irrigation application for all purposes can be described by differences in the depth and frequency of irrigation application (see sections 3.2.3 and 3.2.4).

Irrigation for frost protection is applied during periods of frost risk so that dew is unable to freeze and rupture cell walls in the crop. Frost protection is confined to overhead spray systems that apply water to the canopy of the crop. Predicting frost protection irrigation necessitates that temperature and crop frost susceptibility information is known; in the Overseer nutrient budgets irrigation component, the frost protection requirement is based on an irrigation rate of 3 mm/hr multiplied by the degree of frost (C°) for each hour the temperature is less than zero for 'orchard' crops (Wheeler et al., 2012).

Other irrigation purposes include applying water for crop germination, pest control, cooling the crop canopy (Clemmens & Burt, 1997; McIndoe, 2002), soil preparation, and maintenance of cover crops and wind breaks (Clemmens & Burt, 1997), and as an application mechanism for chemicals or fertiliser (chemigation and fertigation). Irrigations for these purposes generally apply relatively low volumes of water compared to irrigation for crop water supply, and require additional crop information beyond water demand to predict. Like normal irrigation, applying water for these purposes can be inefficient and result in non-beneficial losses of water.

3.2.2 Spatial adequacy

Irrigation New Zealand (2013) defines adequacy of irrigation as 'A measure of the proportion of the target area of which the soil is restored to a target soil water content'. This definition will be used here, and throughout this thesis. Irrigation systems apply water in a non-uniform manner, so the achieved adequacy for a given event will depend on the target depth, the mean depth of the actual irrigation event, the variation of water depths applied over the field, and the soil water deficit prior to irrigation (Lincoln Environmental, 2000b). If an irrigation system is highly non-uniform, achieving a high adequacy will result in portions of the field receiving excessive depths of water. The accepted adequacy level is a management decision, and may change with irrigation method, price of water and/or electricity, crop type, and season stage. Lincoln Environmental (2000b) suggest that a target adequacy level of 80% may be appropriate for pastoral agriculture (i.e., that 80% of a field receives at least the target volume), so long as uniformity is high enough so that large volumes are avoided for the portions of the field receiving the most water. The relationship between adequacy, distribution uniformity, and target depth is discussed more fully in section 3.3.2.

3.2.3 Return interval

The return interval describes the time period between irrigation events. The optimal return interval depends on the depth of water that an irrigator can apply, the irrigation purpose, irrigation adequacy, soil water holding capacity, crop water demand, rainfall, and evaporative demand of the atmosphere. The actual return interval is further influenced by the supply of water, system constraints, and the method of decision making used by the irrigation manager.

It is recognised that for many farmers globally, water application is often based on intuition and experience of what has given good results in the past rather than any objective assessment of crop water needs (Greenwood et al., 2010; Srinivasan & Duncan, 2011). In New Zealand, a survey by Lincoln Environmental (2000a) found that 68% of dairy farmers in New Zealand irrigate at the beginning of the season at least partly on the basis of on farm soil moisture monitoring, and that most farmers use a combination of methods when making irrigation application decisions. Survey responses are included in table 3.2.

Table 3.2 Responses to the question "how do you decide when to start irrigating at the beginning of the season?" Respondents could choose multiple answers. From: Lincoln Environmental (2000a).

Measure soil moisture	Scheduling service	Water budget	Inspect soil conditions	Inspect crops	Weather forecast	Watch neighbours	Other
23.7%	10.7%	4.9%	68%	41.5%	25.2%	5.2%	13.4 %

Crop demand for irrigation is commonly based on a 'trigger point' in irrigation models and scheduling services, which may be the lowest desired soil water level or a certain crop stress response. When the trigger point is reached, irrigation is initiated. For water balance modelling, the trigger point can be at any fraction of field capacity, and will depend on the irrigation purpose and system characteristics (e.g. deficit or normal – see section 3.2.1). Often, the trigger point is taken as the soil water content where actual evapotranspiration (AET) falls below potential evapotranspiration (PET), indicating crop stress and yield loss. For pastoral systems, it is commonly assumed that AET starts to decrease below PET once water content falls below half of field capacity, giving a trigger point of 0.5 (Monaghan & Smith, 2004; Scotter, Clothier, & Turner, 1979; Srinivasan & Duncan, 2012; Woodward et al., 2001). For modelling purposes, a trigger point of 0.55 is suggested by Allen et al., (1998), which is the figure used by Hedley & Yule (2009). In New Zealand, Overseer nutrient budgets (Wheeler & Rutherford, 2013) and the Irrigation Calculator (Martin et al., 2008) use a trigger point of 0.50, which is also the suggested value by the Foundation for Arable Research (2010).

Assuming that irrigation decisions are based on crop water demand that can be expressed as a trigger point, the return interval will vary within an irrigation season depending on the evaporative demand of the atmosphere, the volume of rainfall able to satisfy crop water demand, crop growth, and the characteristics of the irrigation system. When the irrigation system and water supply allow for a flexible return period, a manager is better able to maximise water use efficiency by delaying irrigation after rainfall or when rain is forecast. During dry periods characterised by high PET when regular irrigation is required, the frequency that a system is able to apply water to a field is determined by that system's minimum return interval. The minimum return interval for different irrigation systems is determined by the configuration and management of the farm as a whole. In general, solid set sprinklers and centre pivots can irrigate at relatively high frequencies (<1 day), while the minimum return period for travelling and manual move systems may be limited by labour requirements (McIndoe et al., 2004).

The return interval may also be influenced when water is supplied sporadically, unreliably, or under a set schedule. For much of the world, farmers receive inflexible water supplies that limit their ability to control the timing or volume of irrigation (Molden, 2007). In a constrained supply situation, if the return interval is fixed to a schedule, simulating irrigation timing requires only knowledge of the supply frequency. When supply is sporadic, irrigation prediction is difficult without integrating a water supply sub-model. Irrigation timing may also be influenced by labour constraints or where a single manual move irrigator is used across multiple fields.

3.2.4 Application depth

When irrigation is applied, the application depth describes the volume of water that is supplied to a given area. The amount of water applied by irrigation, like rainfall, is often measured in millimetres (mm) per unit area; each mm is equivalent to one litre per square metre of ground area. It is widely emphasised that irrigation depth should be matched to the water holding capacity of the receiving soil and rooting depth of the crop (Aqualinc, 2012; Greenwood et al., 2010; Irrigation New Zealand, 2013; Silva, 2007). Under normal irrigation management, the ideal irrigation depth is equal to the soil moisture deficit at the time of irrigation, which is the volume required to return the soil within the rootzone of the crop to field capacity. A large application depth will ensure that the soil water content is raised to or above field capacity, but can result in water losses via drainage below the rootzone or saturation excess overland flow where subsurface water movement is impeded (Aqualinc, 2012).

Drainage losses due to excessive irrigation depths, either over a whole field or in localised areas due to poor distribution uniformity of an irrigator, account for the greatest proportion of irrigation water losses (McDowell et al., 2011). Additionally, rainfall is poorly utilised when fields are maintained near field capacity, which can result in further drainage losses (Snow et al., 2007). Small application depths allow for greater rainfall utilisation, but may result in plant stress and reduced production if the return interval between irrigation events is too long (Bray, 1997; Hsiao, 1973). The optimum depth to apply is therefore a trade-off between application efficiency and risk of yield loss, and is highly dependent on the return interval of the irrigation system. In general, crop yield and insurance against water stress is prioritised over water use efficiency by irrigation managers (Lincoln Environmental, 2000a), however it is recognised that high frequency, low depth irrigation allows for high application efficiency without reducing yield (Clothier & Green, 1994).

When irrigating fields prone to salt accumulation, applying water in excess of plant requirements can improve production by leaching salts below the root zone of crops (Bos et al., 2008; Ragab, 2002). In this situation, deep percolation of irrigation water beyond the rootzone of crops is beneficial and target irrigation depths should account for an additional leaching volume. A number of complicated models have been developed to simulate salt/water/crop interactions such as SALTMOD (Oosterbaan, 2001) or SAHYSMOD (Singh & Panda, 2012). More simply, Bos et al., (2008) suggest that the total irrigation volume over a season be 10 - 20% (ideally 15%) greater than the amount of water transpired by the crop to ensure sufficient salt removal from soils.

Application depth can be adjusted by altering the time an irrigator operates for, the volume of water applied for flood systems, or the speed of movement for travelling irrigators. The range of applied depths can be limited for many systems, or may be fixed to a single volume (e.g. border dyke systems). The precise depth applied by an irrigator is often unknown, and different from the 'target depth' that a manager aims to apply due to the imprecise and variable nature of irrigation systems. Table 3.3 displays typical application depth ranges for common irrigation systems.

Table 3.3 Irrigation application depth ranges and application rates for common irrigation systems. Millimetre per hour values for drip systems depend on soil and crop properties. From: Rout (2003).

	Irrigation Method	Application Depth Range	Application Rate
Surface	Border Dyke	80 - 200 mm	N/A
	Contour flooding	50mm or higher	N/A
Spray	Hand shift, skid pans, end tow or angle tow	5 - 100 mm	7.5 - 15 mm/hr
	Sideroll / power roll	5 - 100 mm	7.5 - 15 mm/hr
	Hard hose reel and gun	10 - 100 mm	10 - 20 mm/hr
	Soft hose travelling gun	10 - 100 mm	15 - 20 mm/hr
	Fixed boom, soft hose	10 - 100 mm	20 - 50 mm/hr
	Rotary boom, soft hose	30 - 70 mm	15 - 25 mm/hr
	Linear move	10 - 100 mm	25 - 40 mm/hr
	Fixed centre pivot	5 - 100 mm	15 - 75 mm/hr
	Towable centre pivot	5 - 100 mm	15 - 50 mm/hr
	K-line, small impact sprinklers	50 - 80 mm	3 - 8 mm/hr
	Long lateral, impact sprinklers	35 mm or higher	15 - 25 mm/hr
Micro	Micro sprinklers	not given (wide range possible)	15 - 50 mm/hr
	Drip / Tape systems	not given (wide range possible)	0.5 - 4 litres/hr
	Subsurface drip	not given (wide range possible)	0.5 - 4 litres/hr

3.3 System parameters

System parameters are those elements of an irrigation system that are not readily changed during an irrigation season and can be considered fixed for an irrigator (non-VRI). Primary system parameters are the application rate and the uniformity of water application, which are key controls on the volume of water applied to a field and the subsequent performance of the irrigation system.

3.3.1 Application rate

Application rate is an important consideration for any spray or micro irrigation system. When water is applied at a rate greater than the infiltration rate of the soil, increased surface runoff and subsurface drainage through preferential flow pathways can occur, with a subsequent reduction in application efficiency (Clothier & Heiler, 1983). High intensity application can also induce erosion when water impact is sufficient to move and/or break down soil structure at the surface where crop cover is not 100% (McIndoe, 2001). For surface irrigation systems, a pond of free water is maintained on the soil surface, and water losses to runoff and subsurface drainage are subsequently greater than normally experienced under sprinkler systems (Clothier & Green, 1994). Because the application rate of an irrigator is not easily adjusted, it is recommended that the application rate is matched to the receiving soils infiltration rate when the system is constructed (Irrigation New Zealand, 2013).

It is generally thought that the risk of runoff and rapid drainage increases as irrigation application rate increases (Gjettermann et al., 1997; Jenkins, 2012; Kincaid, 2005; Silva, 2007). However, DeBoer & Chu (2001) and Powers (2012) indicate that surface runoff and drainage via preferential flow pathways experienced in practice is not as severe as has been predicted. Powers (2012) found that greater application rate, while inducing significantly faster infiltration into the soil profile, did not increase the fraction of water that drained from the bottom of the soil profile during field tests using lysimeters. Powers (2012) concluded that depth, duration, and antecedent soil moisture deficit had a greater influence on drainage than application rate, with the highest losses of water via preferential flow observed where lower application rates were applied for longer periods. DeBoer & Chu (2001) found that infiltration rates depend on sprinkler type and the rate of application. The authors state that surface runoff simulation based on a single infiltration relationship, independent of water application rates, does not accurately reflect soil infiltration and surface runoff relationships for variations in sprinkler technologies and can produce significant errors. It is recognised that significant gaps in knowledge exist on the relationship between soil infiltration rates and irrigation application intensities and the consequences for runoff and rapid sub-surface drainage (Aqualinc, 2012; Edkins, 2006).

3.3.2 Distribution uniformity

Distribution uniformity describes how evenly irrigation is applied to a field. Non-uniform application of water is a major cause of water loss beyond the root zone of irrigated crops (Edkins, 2006; Jensen et al. 1980; McIndoe et al., 2004; Snow et al., 2007), and is consequently a key determinant of irrigation application efficiency (Ascough & Kiker, 2002; Edkins, 2006; Letey, 1985; McIndoe, 2001). Expected water losses due to non-uniform application range between 5% and 30% of the total irrigation volume, with typical losses of 15% expected during a given irrigation event (Edkins, 2006). Accounting for the distribution uniformity of irrigation systems is therefore imperative for the accurate calculation of water inputs and losses in an irrigated field.

Irrigation uniformity is dependent on a number of factors, many of which can change between irrigation events. For spray systems, operating pressure (Clemmens & Solomon, 1997; McIndoe, 2001), sprinkler type, height, and spacing (McIndoe, 2001), as well as wind speed and direction (Burt et al., 1997; McIndoe, 2001) influence distribution uniformity. For surface irrigation systems important application variables are inflow rate, length of water run over the field, time of water shut-off, surface resistance to water flow, and field slope (Santos, 1996). A comprehensive list of system components that affect distribution uniformity for different irrigation systems is included in Burt et al. (1997).

While irrigation systems generally aim to apply water uniformly over a field, in practice this rarely happens. Some areas will receive more water than necessary to return to field capacity, while others will receive less than the target depth (Lincoln Environmental, 2000b). The parts of a field that receive less than the target depth will be susceptible sooner to depletion and water stress. Howell (1964), Seginer (1978), Stern & Bresler (1983), Solomon (1984), and Li (1998) have all shown that poor distribution uniformity can adversely affect crop yield due to localised areas of water stress. It must be noted that it is possible, and even likely, for an irrigation system with poor distribution uniformity to achieve high application efficiencies where the spatially average irrigation depth is significantly less than the water holding capacity of the crop root zone. In this situation, assuming a homogenous water holding capacity, all water applied may be used effectively, despite large areas of a field receiving less than adequate water volumes and at risk of stress and yield loss. It is only possible to achieve high application efficiencies (and therefore low water losses) with minimal under-irrigation if the distribution uniformity of the system is high (Ascough & Kiker, 2002; Burt et al., 1997).

The distribution of water within the soil is related to the distribution uniformity of the irrigation system, but also depends on soil and crop parameters such as infiltration rate, current water content, macroporosity, interception by crops in overhead systems, and surface micro-topography. Clothier & Heiler (1983) found that surface ponding and runoff, which activated preferential flow pathways, were the key contributors to non-uniform infiltration and spatial redistribution of otherwise evenly applied water under sprinkler applicators. Bright (1986) states that so long as surface ponding is avoided and the micro-topography of the field is flat in relation to the horizontal extent of the receiving plant's root system, then assuming the distribution of soil moisture is equivalent to the uniformity of application is reasonable for modelling spray systems. Where surface ponding is avoided, Cohen & Bresler (1967), Li (1998), Perrens (1984), and Li & Kawano (1996) show that the uniformity of soil moisture from a non-uniform application improves over time as pressure gradients redistribute water laterally within the soil matrix (assuming flat terrain). Given the difficulties in accounting for small scale soil variability and localised redistribution, irrigation models generally assume that no redistribution takes place, i.e. that the depth applied by the irrigator translates directly to the depth of water maintained and/or lost by the receiving unit of soil (e.g. Bright, 2009; Snow et al., 2007).

3.3.2.1 Measuring distribution uniformity

There are a number of statistical measures to describe the distribution uniformity of an irrigation system. The two most widely used measures in the literature are the lower quartile distribution uniformity introduced by Merriam & Keller (1978), and Christiansen's Coefficient of Uniformity (CU_c) (Christiansen, 1942). CU_c was the first uniformity measure introduced for evaluating sprinkler systems (Karmeli, 1978), and has become the most widely used and accepted criteria used to measure and report irrigation uniformity (Maroufpoor et al., 2010; Solomon, 1984; Zoldoske et al., 1994). Additionally, CU_c allows gross application depth to be estimated without need for further measurements following the technique described in Bright (1986), and adapted in the following section (3.4). CU_c is a measure of the variation of measured individual irrigation application depths from the mean irrigation depth over the entire field. The smaller the absolute average deviation from the mean, the higher the CU_c value, so that a CU_c of 100% represents a perfectly uniform irrigation. CU_c is defined as:

$$CU_c = 100\left(1 - \frac{\sum_{i=1}^{n}|x_i - \mu|}{\sum_{i=1}^{n} x_i}\right) \quad \textbf{Equation 3.1}$$

Where:

CU_c = Coefficient of uniformity, expressed as a percentage (%)

n = Number of depth measurements recorded

x_i = Measured application depth

μ = Mean application depth of all measurements

Measuring application depths to define a CU_c value for an irrigator is achieved using catch cans (for spray systems) or infiltrometers (for surface systems), distributed so that each measurement is representative of an equal area (Solomon, 1984). Zoldoske et al. (1994) give three warnings that should be considered when using CU_c as a measure of uniformity:

- The absolute difference between the measured and mean depth of application results in over- and under-irrigation is considered equally. Practically, deficient or excess water may be more or less critical than the other depending on the crop and/or management aim.
- The penalty assigned to each deviation is linearly proportional to the magnitude of the deviation.
- CU_c indicates how uniform the application depths are on average and does not give an indication of how different from the mean a particular area may be, or its size.

The Irrigation New Zealand design standards (Irrigation New Zealand, 2013) recommends that a CU_c of greater than 85% is achieved for modern spray systems and those systems applying fertilisers (fertigation), chemicals (chemigation), or wastewater, and above 90% for application to shallow rooted crops and for frost fighting. However, field measurements of irrigators have shown that typical CU_c values are often less than 85% (see table 3.4) (Edkins, 2006; Rout, 2003; Thomas et al., 2006), and a survey of dairy farmers conducted by Thomas et al. (2006) found that only 18% of farmers measure the distribution uniformity of their irrigators. Centre Pivots usually provide the most uniform application, and surface systems the least, although any kind of spray system is more susceptible to wind induced reductions in uniformity than surface methods. Because surface ponding is the means by which surface irrigation systems apply water to fields, the distribution uniformity for these systems is very difficult to measure, and largely influenced by soil properties, rather than system characteristics (Solomon, 1984). In general, irrigation systems that are well maintained and correctly operated are the systems that achieve high uniformity of application (Ascough & Kiker, 2002; McIndoe, 2001). Table 3.4 overleaf summarises CU_c measurements for common irrigation systems from New Zealand and international research.

Table 3.4 Collated CU_c measurements from literature and industry reports.

	Irrigation system	CUc (%)		NZ / International	Source
		Range (no.)	Average or single measurement		
Travelling Irrigators	**VRI (uniform mode) Centre Pivot**	-	93	International	Dukes & Perry (2006)
	VRI (uniform mode) Linear Move	73 - 94 (23) *	84		
	Centre-pivot	67 - 90 (4)	79	NZ	Edkins (2006)
		-	88	International	Ascough & Kiker (2002)
		85 - 85 (2)	85	NZ	Rout (2003)
	Long Lateral	57 - 67 (4)	62		
		-	96	NZ	John et. al (1985) in Edkins (2006) and McIndoe (2002)
	Low Pressure boom / fixed boom	84 - 84 (2)	84	NZ	Edkins (2006)
		-	92	NZ	John et. al (1985) in Edkins (2006) and McIndoe (2002)
	Linear boom	75 - 82 (unknown)	80		
		84 - 88 (2)	86	NZ	Edkins (2006)
	Rotary boom	75 - 84 (3)	80		
		-	75	NZ	John et. al (1985) in Edkins (2006) and McIndoe (2002)
	Travelling Guns	19 - 82 (unknown)	70		
		55 - 60 (3)	58	NZ	Rout (2003)
Fixed / Manual move	**K-line**	36 - 60 (3)	49	NZ	Edkins (2006)
		50-63 (2)	57	NZ	Rout (2003)
	Fixed sprinkler	-	55		
		-	70.8	International	Ascough & Kiker (2002)
Generic	**Generic Spray**	53 - 98 (12)	78	International	Li & Kawano (1996)
	Generic surface	37 - 67 (9)	50	International	Letey (1985)
Micro	**Drippers**	34 - 86 (4)	67	NZ	Edkins (2006)

3.3.2.2 Statistical distribution

Fitting a probability density function to the range of depths applied by an irrigator allows application depths to be estimated without requiring time and labour intensive in-situ measurement, and in some cases can improve parameter estimation over the use of raw data alone (Warrick et al., 1989). A number of studies have attempted to fit different statistical distributions to irrigation application depths. Early work by Hart & Reynolds (1965), Hart (1961), and Stern & Bresler (1983) assumed a normal (Gaussian) distribution of applied depths. Later analysis of catch can data fitted to normal, lognormal, uniform, and specialised power functions by Heermann et al. (1992) found that the normal distribution was most appropriate for describing the distribution of application depths under centre pivot irrigators.

Issues with using a normal distribution are that negative application depths can theoretically occur, and skewness that is normally present and expected in irrigation depth measurements is disregarded (Bright, 1986). For example the extremities of a centre pivot span or the upper and lower reaches of a surface system are likely to receive more water than other areas due to the mechanics of these systems, which may result in a better correlation to an asymmetric distribution function. Comparison of symmetric and asymmetric distributions by Seniwongse et al. (1972) to assess the significance of skewness however showed that the inclusion of a coefficient of skewness did not significantly affect the accuracy of depth estimates if the uniformity coefficient exceeded 75%. Elliott et al. (1980) concluded that the choice of distribution should be guided by its intended use and that for routine parameter estimation the normal distribution was suitable. Subsequently, a number of irrigation models have successfully assumed a normal distribution to calculate application depth(s) (e.g. Bright, 2009; De Juan et al., 1996; Li & Kawano, 1996; Mantovani et al., 1995). This thesis assumes that applied and infiltrated irrigation depths are distributed normally within a given field for all irrigation systems and parameter combinations.

3.4 Calculating gross irrigation depth

To account for distribution uniformity without knowing the specific spatial pattern of depths that are applied, some models use the concept of gross irrigation depth (Li, 1998). Gross depth represents the average depth over the field required so that the proportion of the field defined by the adequacy (section 3.2.2) receives at least the target depth. The target depth will change depending on the management and the operational parameters of the irrigation system, but is usually approximately equal to the soil moisture deficit at the time of application. The higher the desired adequacy level, the larger the required gross depth will be, although the distribution uniformity of the irrigation system is the most important parameter in determining gross depth and its degree of variation from the target depth. A perfectly uniform irrigator (CU_c = 100%) will achieve a 100% level of adequacy when applying a gross depth equal to the target depth. The method presented in this section to calculate gross irrigation depth is adapted from Bright (1986).

To estimate the gross depth necessary for an irrigation application of a given target depth, level of adequacy and CU_c, a normally distributed range of depths around the mean of the target depth can be calculated. This gives a distribution where half of the field receives less water, and half of the field receives more water than the target depth. To parameterise the Gaussian distribution, the standard deviation must be known. The standard deviation can be derived from the CU_c of an irrigator, which first requires the average deviation from the mean to be calculated. The average deviation is defined as:

$$Average\ deviation = \frac{1}{N}\sum_{i=1}^{N}|x_i - \bar{x}| \qquad \textbf{Equation 3.2}$$

Where:

N = Sample size

x = Distribution mean

The average deviation (equation 3.2) can be derived from a CU_c value by rearranging equation 3.1 to:

$$Average\ deviation\ =\ \mu(1 - CU_c/100) \qquad \textbf{Equation 3.3}$$

Where:

μ = Mean (taken as the target depth)

CU_c = Christiansen's coefficient of uniformity

Equation 3.3 assumes that the target depth is equivalent to the mean depth applied during CU_c measurement. From the average deviation, we can find the standard deviation following the relationship between average deviation and standard deviation established by Geary (1935):

$$\sigma = \frac{average\ deviation}{\sqrt{2/\pi}} \qquad \textbf{Equation 3.4}$$

Where:

σ = Standard deviation

Once the standard deviation and the target depth are known, a Gaussian (standard) deviation of simulated irrigation depths can be calculated:

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\,(x-\mu)^2 / 2\sigma^2} \qquad \textbf{Equation 3.5}$$

Where:

P(x) = Probability density function

μ = Distribution mean (target depth)

σ = Standard deviation (equation 3.4)

Using a probability density function (equation 3.5), the gross depth can be estimated to be the value of x at the percentile value equal to the adequacy level. The distribution mean represents the target depth, so that half of the irrigation depths in the field are greater than the target depth, and half are less. The depth (x) at the 80^{th} percentile represents the mean gross depth required to be applied so that at least 80% of the field receives a volume equal to or greater than the target depth (i.e. that an 80% adequacy ratio is achieved).

The method of gross depth calculation presented in this section allows for the explicit consideration of spatial variation of irrigation application for a modelling framework. The primary assumption of the method is that the CU_c value is applicable to the target depth being modelled. So long as the depth used for CU_c measurement and the target depth are within normal operational limits of the irrigator, this assumption is presumed to be justified. Python code used to replicate the process described in this section is described in chapter 5.

3.5 Irrigation performance

The performance of an irrigation system may refer to a number of different concepts and measures. Broadly, a high performing irrigation system can supply sufficient water to crops so that yield is maximised without unnecessary water losses. As well as water use efficiency, McIndoe et al. (2004) identify that farmers must consider energy use, labour, and capital cost when assessing the performance of irrigation systems. These considerations are undoubtedly important, however performance measures relevant to this project are confined to those that assess water use only. This section identifies water loss pathways that affect irrigation efficiencies, and describes measures of efficiency relevant to field and farm scale irrigation water use assessment.

3.5.1 Water losses

Up to 85% of irrigation water is lost during an irrigation event, with typical crop consumption rates between 40-65% of applied water (Johnson, 2008). Loss pathways and typical proportions of total irrigation volume lost for spray irrigation systems in New Zealand are given by Edkins (2006) and displayed in table 3.5.

Table 3.5 Expected losses for spray irrigation systems. The values were collated by Ian McIndoe from literature and published in Edkins (2006).

Source of loss	Range	Typical
Losses from open races	0 - 30%	10%
Leaking pipes	0-10%	<1%
Evaporation in air	0-10%	<3%
Blown away by wind	0-20%	<5%
Watering non-target areas	0-5%	<2%
Interception by plants	0-3%	<2%
Surface runoff	0-10%	<5%
Non-uniform application	5-30%	15%
Excessive application depth	0-50%	10%

Table 3.5 shows that the largest losses from an irrigation system are due to excessive application depths and non-uniform application. Non-uniform application is discussed in section 3.3.2 above. Excessive application depth can generally be attributed to inflexible system design or poor management (Edkins, 2006). The two sources of loss are also related: farmers may choose to apply an excessive depth so as to overcome poor distribution uniformity and ensure that an adequate proportion of the field receives a certain depth of water. Improving uniformity and better matching application depths to the receiving soil therefore represent the greatest potential for performance improvements.

Other water losses occur through wind effects, evaporation, and the watering of non-target areas. Wind serves to disrupt the uniformity and blow water onto non-target areas for spray irrigators, and increase evaporative losses for all irrigation systems. These losses are therefore dependent on weather conditions and are variable between irrigation events. Because these losses tend be low and difficult to quantify, they are not generally accounted for in irrigation models. Evaporation from plant surfaces following interception by the crop canopy also represent a loss pathway, however it can be assumed that crop transpiration is reduced by an equivalent volume resulting in no net change in water flux between the field and the atmosphere.

Losses from conveyance systems through leaking pipes and open races can be important factors in total system efficiency. Santhi et al. (2005) found that in the Rio Grande basin, conveyance losses were the next greatest water loss pathway after crop evapotranspiration. Conveyance losses depend on the canal or pipe type, maintenance, dimensions, and climatic variables, and so require site specific parameterisation.

3.5.2 Measures of efficiency

As a general term, irrigation efficiency describes the proportion of applied water that contributes to the irrigation aim. No single measure can fully describe the performance of an irrigation system (Burt et al., 1997), and there are more than 30 definitions of various measures of irrigation efficiency in the literature, each relevant to different system components and spatial or temporal scales (McIndoe, 2002). Many efficiency measures account for water losses in the extraction, storage and transport of water prior to irrigation application at the field level. Because this research is focused on generic modelling of field scale water flows, performance measures that account for water movement outside of field boundaries are not presented here. Broad measures of system performance are included in comprehensive reviews of irrigation efficiency measures given by Burt et al. (1997), Edkins (2006), and McIndoe (2002).

3.5.2.1 Irrigation efficiency

The traditional definition of irrigation efficiency (IE) given by the American Society of Civil Engineers in Kruse (1978) is:

$$IE = \frac{Volume\ of\ water\ beneficially\ used}{Volume\ of\ water\ delivered\ to\ field}$$ ***Equation 3.6***

This definition specifies the hydrological boundaries of the system (the field in question), accounts for rainfall inputs, and can be applied to any desired timeframe (McIndoe, 2002). The definition of beneficial water use will depend on the purpose of the irrigation (see section 3.2.1). The equation was modified by Burt et al., (1997) to account for soil water storage and with a focus on irrigation water use only:

$$IE = \frac{Volume\ of\ irrigation\ water\ beneficially\ used}{Volume\ of\ irrigation\ applied - \Delta\ storage\ of\ irrigation\ water}$$

Equation 3.7

While it is difficult to measure the precise volume of irrigation water applied and beneficially used for a given field, equation 3.7 is attractive because it is easy to communicate, widely used, and relatively simple to solve using a water balance modelling framework. For these reasons, equation 3.7 will be used as the definition of Irrigation Efficiency (IE) in this thesis. When consideration of rainfall inputs is required, equation 3.6 will be used and described as Water Use Efficiency (WUE). This is not to be confused with other measures also called water use efficiency that describe agricultural production per unit of water used.

3.5.2.2 Application efficiency

Application Efficiency (AE) is widely used as a performance measure to describe a single irrigation event. Like IE, there are a number of definitions in the literature for AE that account for different water inputs, aims, and areal boundaries. The definition to be used in this thesis, also from Burt et al. (1997), is:

$$AE = \frac{Average\ depth\ of\ irrigation\ contributing\ to\ target}{Average\ depth\ of\ irrigation\ applied}$$

Equation 3.8

This definition allows an estimate of the performance of a single irrigation event, even when the water applied has not yet been transpired by the crop. The advantage of this definition over some others is that the term 'contributing to target' can include water that provides a benefit beyond replacing soil moisture deficits (such as leaching salt). This AE equation is also attractive because all of its components are easily derived from a soil water balance model, and it can be applied to sub-field units of any size.

Irrigation New Zealand (2013) and McIndoe (2002) recommend that irrigation systems achieve average application efficiencies greater than 80%. For surface irrigation systems where losses to drainage have a quantifiable beneficial use, and where water supply is not limited, McIndoe (2002) indicates that an AE of 50% is sufficient. In practice, a number of researchers contend that actual achieved efficiencies are far lower than 80% for most systems (e.g. Edkins, 2006; Hedley & Yule, 2009; Lincoln Environmental, 2000b; Rout, 2003). The achieved AE of an irrigation event is primarily a function of the depth applied, the soil water content prior to irrigation and the ability of the soil to retain water (Lincoln Environmental, 2000b). Because these variables are all subject to change between irrigation events depending on atmospheric conditions and management, it follows that the AE will also change. It is therefore important that AE is treated as an output rather than an input into an irrigation model. Furthermore, application depth, water holding capacity and soil moisture deficit are often characterised by a considerable degree of spatial variability, which means that field scale predictions of application efficiency are likely to be uncertain, especially where soils are variable such as in the Canterbury Plains or other irrigated alluvial floodplains. Accounting for the spatial variability of soil characteristics within an irrigation model will therefore produce AE estimates that more accurately reflect field conditions.

Improving the AE of a system provides multiple benefits: water takes, application costs, drainage, and leaching potential are all reduced without necessarily impacting yield (Ascough & Kiker, 2002). Precision management techniques such as VRI that recognise spatial heterogeneity in soil and plant characteristics are increasingly used to improve AE. It should be noted that AE does not give an indication of the effectiveness of the irrigation: a high AE may be achieved without supplying sufficient water to crops. For example where return intervals are large, high application efficiencies are likely to be achieved due to correspondingly high soil moisture deficits, despite the increased likelihood of water stress experienced by the crop (Bright, 2009). Performance evaluations based on AE alone should therefore be treated with caution, and comparisons between systems are only valid where all other parameters are equal.

3.5.3 Irrigation performance visualisation

The following figures show the relationship between application efficiency (figure 3.6), adequacy (figure 3.7), and uniformity using the method described in section 3.4 to estimate gross application depth (assuming a target depth equal to the soil moisture deficit). Following Lincoln Environmental (2000), it is assumed that evaporative, drift, and run-off losses are negligible in their effect on application efficiency for these figures.

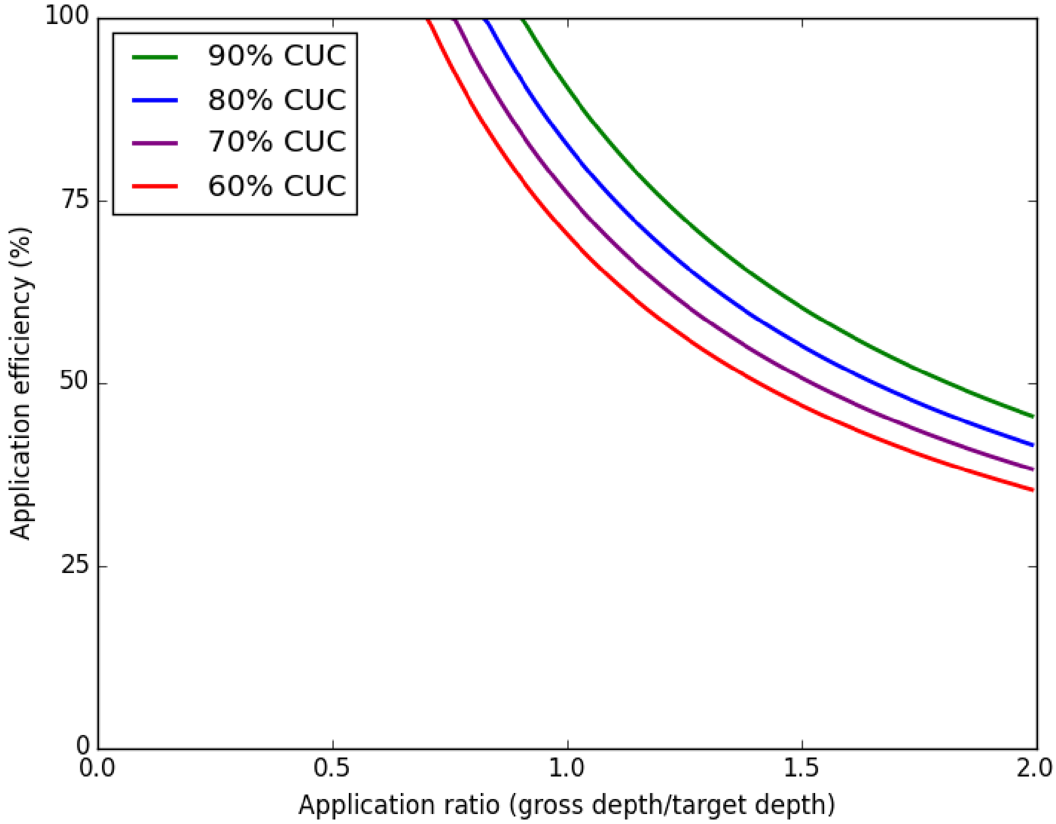


Figure 3.6 The effect of CUc on application efficiency for a range of target application depths for a hypothetical irrigation application where the target depth is equal to the soil moisture deficit.

Analysis of figure 3.6 shows a ~15% difference in application efficiency between an irrigator with a CU_c of 90% and an irrigator with a 60% CU_c where irrigation is applied at the target depth (application ratio is 1.0). Between the same two hypothetical irrigators, Figure 3.7 shows that to ensure that the target depth is applied over at least 80% of the field, more than 60% more water must be applied by the least uniform system.

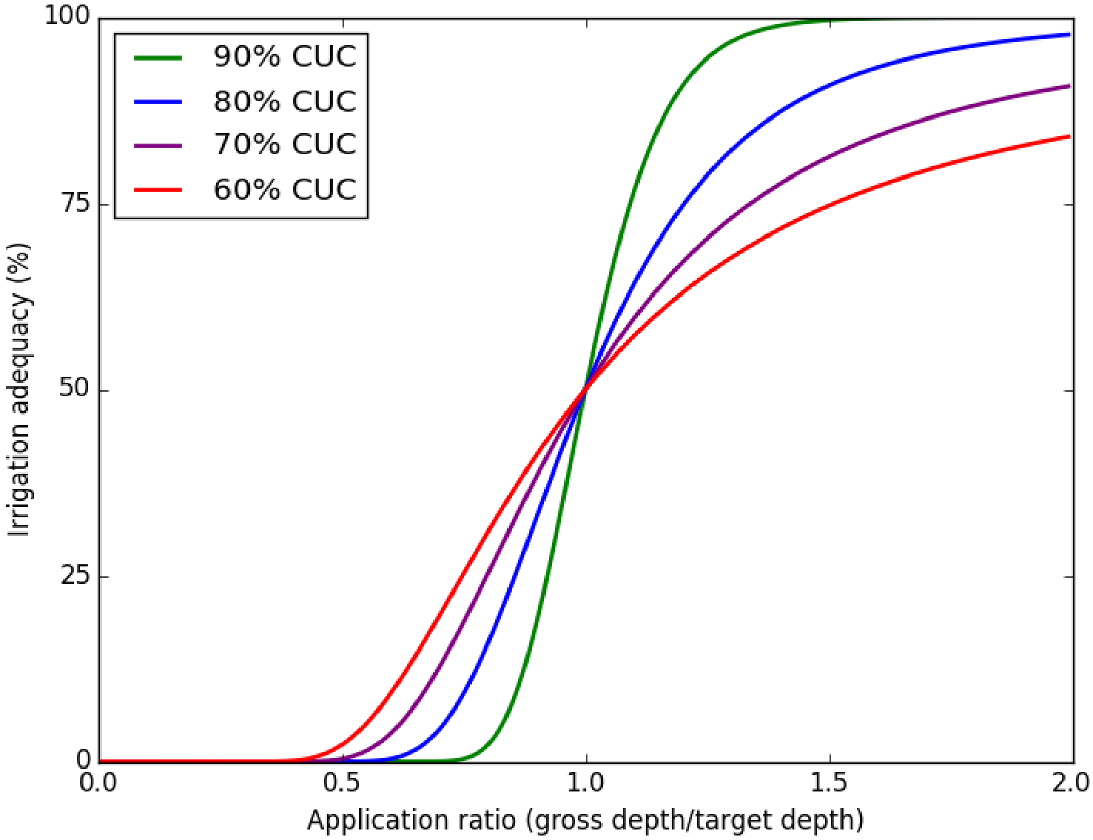


Figure 3.7 The relationship between application depth and adequacy for different CU_c values for a hypothetical irrigation application where the target depth is equal to the soil moisture deficit.

3.6 Irrigation systems and management summary

A wide range of different irrigation systems exist, which can be categorised as either surface, spray or micro. These categories define the method of water application. Management parameters determine the purpose, spatial adequacy, return interval, and depth of application, which are subject to change during an irrigation season. For the development of an irrigation model, management parameters should therefore be adjustable. Application depth and return interval operate in tandem and are especially important in determining irrigation timing and volume. System parameters are generally fixed, and define the application rate and distribution uniformity of the irrigation system. These parameters can be assumed to be static for a given irrigation system, and adequacy and uniformity values for common irrigation systems have been included in tables 3.3 and 3.5 respectively. Poor distribution uniformity is a key driver of poor application efficiency. The use of Christiansen's coefficient of uniformity to describe irrigation uniformity allows a distribution (assumed to be Gaussian) of application depths to be determined using a CU_c value and a target depth. Combined with a given level of adequacy, a gross application depth can be estimated. With regard to water use, the performance of an irrigation system can be described by the irrigation and application efficiencies, defined in equations 3.7 and 3.8 respectively. The achieved efficiency of an irrigation system is determined by the management and system parameters, and how the applied water interacts with the soil, crop and atmosphere (discussed in the chapter 4).

There are a number of other factors that influence irrigation application that have not been mentioned in this section, such as water restrictions, the reliability of water supply, and labour limitations. These considerations are undoubtedly important, however because this research is focused on field scale irrigation application and water loss, they have not been included in this thesis.

4 Irrigation demand and physical properties

Irrigation demand is dependent on soil properties, crop physiology, and atmospheric conditions, which must be accounted for in the development of a water balance model of an irrigated field. Specifically, the water holding capacity and depth of the soil, rainfall timing and volume, evaporative demand of the atmosphere, rooting depth of the crop and the ability of a crop to extract and transpire water will affect irrigation requirements and the performance of an irrigation system. This chapter provides an overview of these parameters and outlines their consideration for a water balance framework.

4.1 Soil properties

The soil in the rootzone of crops serves as the nexus between rainfall and irrigation inputs, rootzone storage, root uptake, and the drainage recharge of underlying aquifers and groundwater supplied waterways (Clothier et al., 2013). Various measureable properties of soil that relate to soil structure and its effect on the soil-water-plant system are described in the literature. These include field capacity, soil texture, bulk density, macropore volume, organic matter content, and water infiltration rate (Aqualinc, 2012; Bresler et al., 1984; Hillel, 1998; Saxton & Rawls, 2006). The primary soil characteristics relevant to irrigation management are water storage capacity, soil depth, infiltration rate and drainage characteristics (McIndoe et al., 2004). These properties provide critical controls on the supply of water to irrigated crops and the timing and volume of drainage and nutrient leaching (Clothier et al., 2013). A discussion of general soil properties is provided in this section. An overview of the specific soil types found in New Zealand can be found in Hewitt et al. (2013).

4.1.1 Soil water storage

The term 'Field Capacity' (FC) is used to describe the volume of water stored in a section of soil when capillary and gravitational pressures are equal. Field capacity is reached once excess water is drained following soil saturation. The concept was first introduced by Israelsen & West (1922) to inform irrigation decision making in the United States. Richards & Weaver (1944) found that FC for most soils corresponds to the water content held at a pressure potential of −33 kPa, although the precise point at which a given soil is at FC is dependent on the texture of the soil, the soil depth, and the point where drainage is determined to have ceased. FC is therefore imprecise by nature, although it is useful as a concept because it simplifies the estimation of the water storage capacity in the soil profile and the volume of water that may drain following the application of a given depth of water (Lincoln Environmental, 2000b).

The total volume of water that can be utilised in a given soil depth is referred to as Water Holding Capacity (WHC), which can be estimated as the difference between the soil water content at FC and the soil water content at Permanent Wilting Point (PWP). PWP is the point where water is no longer able to be extracted from the soil, and is generally estimated as the volume of water bound to the soil at a pressure potential of −1500 kPa (Beven & Germann, 1982). PWP and FC, and therefore WHC, are largely determined by soil texture; fine textured soils (i.e. those with a high clay content) tend to have a higher water holding capacity than coarser textured soils. Other factors that influence the WHC of soils are the organic matter content, soil biotic community (Power, 2010), and level of compaction (Aqualinc, 2012).

The volume of water held in a soil profile available to plants is referred to Plant or Profile Available Water (PAW) and is defined as the WHC of the soil within the rootzone of the crop. The depth of the rootzone is determined by plant physiology (see section 4.3) but can be limited where the soil depth is shallow and root growth is impeded (Houlbrooke et al., 2011; Letey, 1985). Agricultural soils able to store large volumes of water are better able to utilise rainfall, can go for longer periods without irrigation, and have the potential to enable more efficient irrigation application. In contrast, soils characterised by low PAW require more frequent irrigation, generally use irrigation and rainfall less efficiently, and require more irrigation water over a season to achieve the same level of effectiveness (Aqualinc, 2012; McIndoe et al., 2004).

Variation in soil water holding capacity can cause large differences in irrigation demand at regional, farm, or sub-field scales.

4.1.2 Water loss pathways

Irrigation and rainfall that enters the soil can be utilised by crops and removed as transpiration, or lost as evaporation, overland flow, or subsurface drainage below the rootzone. Evaporation and transpiration are discussed in section 4.2.2 in this chapter.

Subsurface drainage occurs when soils are wetted beyond field capacity and no impermeable layer exists to impede subsurface water movement. Drainage can also occur before field capacity is reached via macropore flow or other preferential pathways (e.g. drainage infrastructure) (Burt et al., 1997). Macropores represent the connected and continuous pathways within the soil matrix that can rapidly and preferentially transport water and dissolved nutrients and chemicals through and beyond the rootzone (Clothier & Green, 1994). Macropores can be defined as soil pores greater than 100μm or >-3.0 kPa capillary potential (Beven & Germann, 1982). Macroporosity is an indicator of the infiltration rate of a soil (Beven & Germann, 1982), and is an important consideration when estimating soluble nutrient leaching volumes. Increased macropore flow will reduce leaching of nutrients held outside of macropore channels within the soil matrix, while increasing the ability of exogenously applied nutrient (e.g. fertiliser or urine) to bypass the crop rootzone. The occurrence of macropore flow is dependent on the volume of macropores in the soil matrix and the application rate of irrigation or rainfall at the surface (Clothier & Green, 1994). Farm management practices that alter the level of soil compaction such as ploughing, vehicle traffic, or stocking density will affect the macroporosity of agricultural soils (Aqualinc, 2012).

Water lost across the soil surface occurs as either saturation excess or infiltration excess (Hortonian) overland flow. Saturation excess overland flow occurs when drainage of irrigation or rainfall inputs in excess of the storage capacity of the soil (at saturation point) is inhibited by an impermeable or reduced permeability layer, or where the groundwater table is raised to the surface. Impermeable layers may be naturally occurring or may result from subsurface compaction following high stocking rates, grazing during periods of high soil moisture content, or tillage practices in agricultural systems (Greenwood et al., 2010; Houlbrooke et al., 2011). Infiltration excess overland flow occurs when the application rate of rainfall or irrigation exceeds the infiltration capacity of the soil. The infiltration capacity of soil is influenced by the soil texture, bulk density, macroporosity, vegetation cover, hydrophobicity, topography, level of compaction, and level of saturation (Hillel, 1998; Silva, 2007; Aqualinc, 2012; Powers, 2012). In general, fine-textured and compacted soils tend to have slower infiltration rates than coarse textured soils. Water applied at a rate greater than is able to infiltrate into the soil may also result in increased macropore flow and reduced uniformity of infiltration (Clothier & Heiler, 1983; Clothier & Green, 1994; Hillel, 1998). Because the application rate of irrigation or rainfall and the infiltration rate of the soil both change in space and time, estimating the occurrence and volume of surface ponding or infiltration excess overland flow is difficult without site specific parameterisation (Scherrer et al., 2007). A discussion on the influence of irrigation application intensity on surface runoff and rapid subsurface drainage is given in section 3.2.

Topography is also an important consideration for water supply and loss in agricultural fields. A higher proportion of water applied in excess of the infiltration rate of soils will be lost to macropore flow in low slope areas, while steep slopes are more vulnerable to surface runoff (Aqualinc, 2012). Occurrence of sub-surface flow to and from fields also increases in steeper terrain (Allen et al., 1998). Irrigation New Zealand (2013) and Aqualinc (2012) recommend that irrigation application rates are reduced as field slope increases.

4.1.3 Soil variability

Soil properties are an important management consideration in irrigated farming systems because of their control on water storage and loss. Soil types can be highly variable within farms and within individual fields, resulting in spatial variation in crop production (Warrick &

Gardner, 1983), water requirements, and potential for environmental losses (Dennis et al., 2010; Hedley et al., 2009). Spatial variation in soil properties creates a major challenge for irrigators to supply sufficient water to crops while simultaneously achieving high irrigation efficiencies (Ahuja et al., 1990; Greenwood et al., 2010). However, spatial variability of soil properties is not generally taken into account by most irrigators, and irrigation design guidelines do not discuss how to manage soil variation (Aqualinc, 2012).

Recent work by Dennis et al. (2010); Hedley et al. (2010); Hedley et al. (2009); and Hedley & Yule (2009) has investigated the role of variable soils on irrigation efficiencies and subsurface drainage in New Zealand, and explored the potential of Variable Rate Irrigation (VRI) systems and soil mapping as methods of water saving. Hedley et al. (2010) reported water savings up to 21% for VRI over variable soils compared to uniform application, with a reduction in drainage and runoff between 19–55%, and cost savings estimated at NZ$51–150 per hectare per year. Dennis et al. (2010) report that developing management zones based on soil water holding capacity can save up to 6% of total water applied without any change to existing uniform rate irrigation infrastructure. Methods for improving water use efficiency over variable soils are likely to be increasingly investigated in New Zealand as competition for water supplies increase and nutrient-loss legislative limits are implemented. Explicit consideration of spatial variation in soil properties is a primary modelling objective of this thesis.

Soil variability in agricultural landscapes also occurs temporally, as various farm management practices affect soil properties. Fertilisation, drainage infrastructure, tillage, stocking intensity and timing can all affect the ability of soils to infiltrate and store water (Aqualinc, 2012; Lobb, 2011). Irrigation can also influence soil properties; Houlbrooke et al. (2011) found that irrigation implementation in North Otago caused increased soil compaction and reduced macro-porosity, and increased organic matter inputs to the soil via enhanced plant growth.

4.2 Climate

Irrigation demand is dependent on the supply and demand of water from the atmosphere - the very purpose of irrigation is to apply water to crops where natural precipitation alone is unable to satisfy crop water demands. Knowledge of evaporative demand and the timing and volume of precipitation is therefore essential for irrigation management and modelling to estimate irrigation timing, depth, drainage, and efficiency for a given system.

4.2.1 Precipitation

To estimate irrigation demand, the volume and timing of water provided by natural precipitation must be known. Rainfall is routinely measured, usually using rain gauges located on farm or provided by a local weather station and is generally reported in millimetres per unit area per unit of time, most often per day. Monthly or annual precipitation can be derived from historical averages and can be used to estimate approximate seasonal irrigation demand (Bos et al. 2008), but do not allow for the prediction of individual irrigation or rainfall events. Like irrigation inputs, rainfall can become unavailable to crops where the depth exceeds the soil moisture deficit of the soil, where the intensity exceeds the infiltration rate of the soil, or where water is lost to evaporation from the soil or plant surfaces. The proportion of rainfall that remains available to crops is called effective precipitation, which is specifically defined as "that part of total precipitation on the cropped area, during a specific time period, which is available to meet potential transpiration requirements in the cropped area" (Bos et al., 2008 pg. 81).

The least expensive form of water application is rainfall, so it is logical for farmers to maximise its use. The most efficient irrigation systems for utilising rainfall are those with a reliable water supply and a flexible return interval that can be managed in response to rainfall events or forecast rain. There is little published literature concerning water application in response to forecast rain, and irrigation modelling frameworks generally disregard changes in irrigation timing that may occur. The irrigation component of Overseer nutrient budgets (version 6) includes an active management option that delays irrigation application in response to forecast rainfall (Wheeler & Rutherford, 2013). On-farm irrigation application decisions in response to forecast rainfall are likely to be influenced by the reliability of the forecast, the magnitude of the predicted event, cost of application, and perceived risk.

4.2.2 Evapotranspiration

Evapotranspiration (ET) is the sum of evaporation and plant transpiration of water to the atmosphere. Evaporation is the process whereby liquid water is converted to water vapour (vaporisation) and removed from the evaporating surface. In agricultural fields evaporation of irrigation or rainfall occurs from plant surfaces and from the bare soil surface between vegetation. Transpiration describes the water taken up by plant roots that is vaporised from plant tissues, a process predominantly controlled by leaf stomata. Evaporation and transpiration are dependent on atmospheric demand, which is regulated by solar radiation, air temperature, humidity, and wind speed (Allen et al., 1998). Transpiration is further regulated by plant physiology, soil moisture conductivity, soil moisture content, salinity, and cultivation practices (Allen et al., 1998). Important plant characteristics for controlling transpiration are plant species, variety, and level of development which determine the crop height, roughness, reflection, surface cover and rooting depth. Knowledge of ET demand and the capacity of the plant and soil system to satisfy this demand is essential for determining irrigation requirements.

The atmospheric capacity to remove water as ET is known as Potential ET (PET). Where there is insufficient water available to meet PET, the Actual ET (AET) will be less than PET. A number of methods for calculating ET have been developed that use readily measurable atmospheric parameters to estimate evaporative demand (e.g. Hargreaves & Samani, 1985; Monteith et al., 1965; Penman, 1948; Priestley & Taylor, 1972). These estimations of PET can then be adjusted depending on PAW and crop characteristics to derive an estimation of AET (described in section 4.3). The most commonly used method of ET estimation is the modified Penman-Monteith method described in the Food and Agriculture Organisation's paper number 56 (FAO56) (Bos et al., 2008), which has been found to produce the closest estimates to measured ET compared to other ET estimation methods (Yoder, Odhiambo, & Wright, 2005).

The FAO56 Penman-Monteith method has become the standard practise for PET calculation in irrigation modelling because of its physical basis, flexibility around data requirements, and applicability to a number of different climates, soils and crop types (Bos et al., 2008). The FAO56 Penman-Monteith method calculates a reference PET, denoted as ET_0, based on measured climatic variables and properties of a hypothetical grass 'reference' crop. The reference crop is assumed to be fully covering the ground, not short of water, with a crop height of 0.12 m, a fixed canopy resistance of 70 s/m, and a canopy reflection coefficient of 0.23. Climatic data required for calculation of ET_0 are radiation, air temperature, air humidity, and wind speed information. The FAO56 Penman-Monteith equations can be applied to hourly and 24-hour time steps. 24 hour time-steps can use daily, weekly, 10-day, and monthly means for weather data (Bos et al., 2008). The required climate data are often measured at weather stations, and are available alongside a number of PET products for many locations in New Zealand through NIWA's CliFlo database system. A full description of the FAO56 Penman-Monteith method is given in that paper, which includes tools to aid ET_0 calculation (Allen et al., 1998). The use of a reference crop in the FAO56 Penman-Monteith method allows the estimation of PET for a number of different crop types, denoted as ET_c, by multiplying ET_0 by a crop coefficient (K_c) which accounts for physiological differences between the reference crop and the crop produced. Crop types, crop coefficients, growth stages, and the ability of crops to extract water from the soil are described in section 4.3.

4.2.3 Climate variability

Irrigation demand is primarily driven by the difference between effective rainfall and ET, defined as the water deficit for a given area (McIndoe et al., 2004). Spatial and temporal variation in precipitation and ET is therefore an important consideration for irrigation management and modelling. Accounting for temporal variation in climatic supply and demand of water is reliant on accurate measurement at an appropriate timescale. For irrigation scheduling or modelling, climate data must be at a daily time-step or less for the prediction of individual irrigation events and accurate estimation of system efficiency and drainage. For weekly, monthly, or annual data, only an approximate estimate of total irrigation demand can be made (Bos et al., 2008).

Precipitation and ET can also vary significantly in space. Figure 4.1 shows the variation in annual water deficit in New Zealand. Figure 4.1 shows a wide range of annual water deficit values across New Zealand, with the highest deficits corresponding to regions of high irrigation use (e.g. Canterbury, Central Otago, Nelson, Marlborough, Hawke's Bay, and the Manawatu). Climatic variation may also exist locally and may result in differences in water availability at sub-catchment scales. Sub-catchment climate variability is dependent on topography, aspect, vegetative shelter, and localised precipitation events (de Vries, Cochrane, & Galtier, 2010; Tetzlaff & Uhlenbrook, 2005). Localised variability has been shown to be a major source of error in investigations of rainfall-runoff processes in hydrological models that assume spatially homogenous climatic variables (O'Loughlin, Huber, & Chocat, 1996; Tetzlaff & Uhlenbrook, 2005). In New Zealand, Srinivasan & Duncan (2012) found that a strong soil moisture deficit gradient existed across the farms supplied by the Waimakariri Irrigation Scheme in Canterbury. They concluded that on average over the entire irrigation season, farms at the eastern side of the scheme could be receiving 100 mm less rainfall and losing 100 mm more to evapotranspiration than farms at the western side based on 37 years of data (1972–2008). To account for spatial variation of precipitation and ET, data should be representative of field conditions and preferably locally measured, with multiple measurement locations and/or interpolation techniques used where climate variables exhibit strong spatial variability.

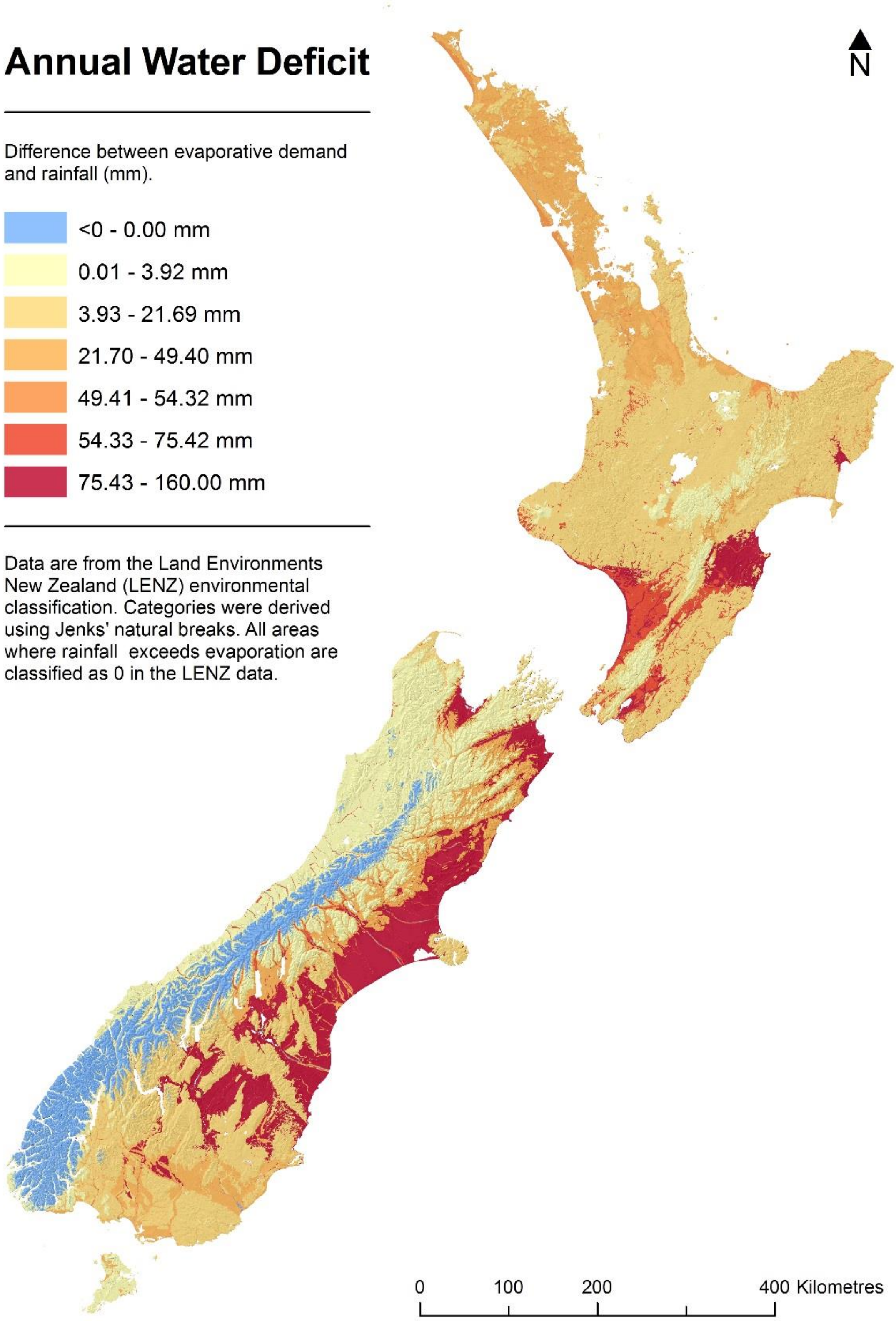


Figure 4.1 Annual water deficit in New Zealand. Data from LENZ environmental classification.

4.3 Crop water use

Other than climate and soil properties, crop water use is dependent on the transpirative capacity of the plant, the plants ability to extract water from the soil, and the volume of water able to be accessed by the plant's root system. Because plant water use is primarily of interest for irrigation modelling, rather than details of crop physiology and development, the relatively simple crop coefficient method developed over the last half century and formalised in FAO56 (Allen et al., 1998) has become ubiquitous for calculating AET in irrigation and soil water atmosphere plant (SWAP) modelling frameworks (e.g. Bos et al., 2008; Bright, 2009; Hornbuckle et al., 2005; Ragab, 2002; Steduto et al., 2009; Woodward, Barker, & Zyskowski, 2001). This section provides a description of the crop coefficient method given in Allen et al. (1998) and outlines data requirements for estimating ET for different agricultural crops.

4.3.1 Crop coefficients (K_c)

The use of a reference crop (ET_0) in the FAO56 Penman Monteith method allows the estimation of PET for a number of different crop types, denoted as ET_c, by multiplying ET_0 by a crop coefficient (K_c). Crop coefficients can be more or less than 1.0, and describe the transpirative ability of the crop in comparison to the reference grass surface by accounting for changes in ground cover, canopy resistance, albedo, leaf stomatal properties, and aerodynamic resistance between the two crops (Allen et al., 1998). Differences in evaporation and transpiration can be integrated into a single crop coefficient (K_c) or separated into a basal crop transpiration (K_{cb}) and soil evaporation (K_e) coefficient. For the single crop coefficient approach, the K_c value changes depending on the crop type, age, crop development during the growing season, the fraction of ground covered by the crop, and the moisture content of the soil surface. For PET estimation over a growing season, a single crop type may use more than one crop coefficient, combined in a crop coefficient curve, to account for changes in plant structure following growth and harvest. The PET for a given crop at a given time is calculated by multiplying ET_0 by the crop coefficient, K_c:

$$ET_c = K_c \times ET_0 \qquad \textbf{Equation 4.1}$$

where ET_c is crop potential evapotranspiration (mm d^{-1}), K_c is the crop coefficient (dimensionless), and ET_0 is the reference crop evapotranspiration (mm d^{-1}).

Methods for estimating the K_c for a given crop and conditions are included in the FAO56 document. FAO56 also includes a comprehensive table (Table 12) of crop coefficients for a wide variety of crops for different growth stages that can be used in modelling frameworks. This table is included in Appendix 9.2.2. In New Zealand, McIndoe, Attewell, & Engelbrecht (2004) adapted information from Standards New Zealand (1973) to produce approximate crop coefficients for eight crops shown in table 4.1. McIndoe et al. (2004) recommend to use a crop coefficient of 1.0 for mature crops where specific crop coefficients are unknown, or an average crop coefficient of 0.8 or 0.9 for calculating water use for seasonal crops. More robustly, Bright (2009) developed a crop coefficient curve for pasture in Canterbury using lysimeter and climate measurements. Bright (2009) notes that if a locally derived crop coefficient is unavailable it is reasonable to use a value of 1.0 in Canterbury given that the calculated crop coefficient curve had an average value of 1.0 during the irrigation season. Crop coefficients also can be calculated using sensors and Normalised Difference Vegetation Index (NDVI) using the linear relationship developed by Choudhury et al. (1994). In general, crop coefficients can be readily transferred between locations and regions with different climates, so long as the different climates do not effect stomatal functions and wind speeds are not substantially different, and these do not significantly affect leaf area development over time (Bos et al., 2008).

Table 4.1 Typical crop coefficients for crops grown in New Zealand. From: McIndoe et al. (2004).

Crop	Crop coefficient (Kc)
Pasture/seeds	1
Lucerne	1.2
Oats	1
Barley	1
Potatoes	1
Vegetables	1
Deciduous Orchard	0.85
Citrus Orchard	0.75

4.3.2 Crop development

Seasonal crop development is modelled in the crop coefficient approach described in FAO56 using three different crop coefficients and four growth stages for each crop for each season. The four growth stages, termed L_{ini}, L_{dev}, L_{mid}, and L_{end}, correspond to the number of days of the initial planting (from sowing to 10% ground cover), crop development (from 10% to ~70% ground cover), mid-season (including flowering and grain setting or yield formation), and late season stage (ripening and harvest), respectively (Bos et al., 2008). The length of each of these stages depends on crop and variety type and the climate, latitude, elevation and planting date (Allen et al., 1998). Local observations are recommended for determining the growth stage (Hornbuckle et al., 2005), however FAO56 includes a table (table 11) describing growth stage lengths for a wide range of crops and climates. This table is included in appendix 9.2.1.

The crop coefficient for a given stage of the season is determined by applying the three crop coefficients (Kc_{ini}, Kc_{mid}, Kc_{end}) to the four growth stages by constructing a crop coefficient curve. An example crop coefficient curve is displayed in figure 4.2. During the initial stage (L_{ini}), Kc is equal to Kc_{ini}; during the development stage (L_{dev}), Kc increases linearly from Kc_{ini} to Kc_{mid};

during the mid-season stage (L_{mid}) Kc is equal to Kc_{mid}; during the late season sage (L_{end}) Kc decreases linearly from Kc_{mid} to Kc_{end}.

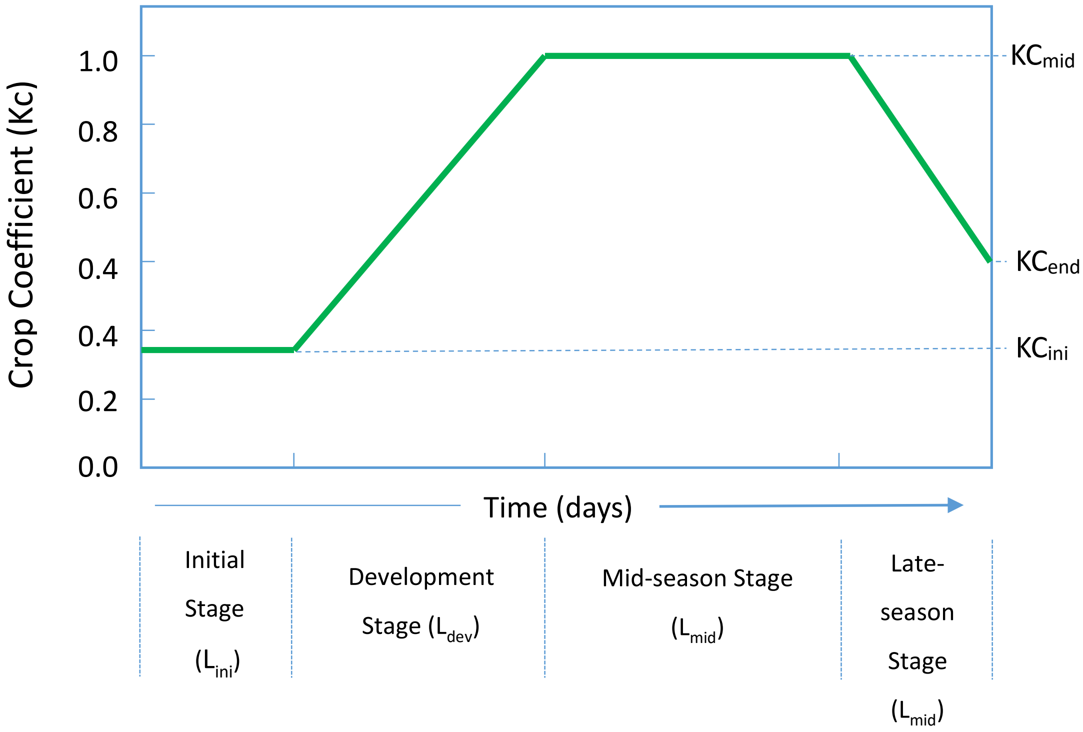


Figure 4.2 Crop coefficient curve using data for Cotton from FAO56 tables 11 and 12.

Of the four growth stages, the mid-season stage is generally the most sensitive to water shortages because it is the period of the highest crop water demand (Brouwer et al., 1989). The late season stage is least sensitive to water shortages. During any growth stage, the ability of a given crop to transpire the volume of water estimated by the crop coefficient approach ($ET_c = K_c \times ET_0$) is dependent on the volume of water available to the plant root system.

4.3.3 Rooting depth

The part of the soil from which the roots take water is named the effective rootzone. The depth of the rootzone for a given crop is governed by a combination of plant physiology and soil conditions and is an important control, alongside soil type, on PAW. The volume of water able to be held in the effective rootzone is equivalent to the FC of the soil to the depth of the plant roots.

For perennial crops, a static effective rootzone depth is generally assumed in water balance frameworks. For pastoral systems, a rooting depth of 600mm is consistently assumed in New Zealand (Bright, 2009; Martin et al., 2008; Wheeler & Rutherford, 2013). Rout (2003) assumes a reduced pasture rooting depth of 500mm. The potential rooting depth ranges for common agricultural crops are included in FAO56 table 22, included in appendix 9.2.3. For seasonal crops, root depth can be modelled dynamically to represent crop development over the season. Hornbuckle et al. (2005) follow a similar method to that used to calculate crop coefficients by assuming linear root development over the initial (L_{ini}) and development (L_{dev}) growth stages until the maximum rooting depth is reached at the beginning of the mid-season (L_{mid}) stage, where it remains until the crop is harvested.

For all crop types, root development may be limited by shallow soils (Houlbrooke et al., 2011), soil compaction or reduced soil water content (Greenwood et al., 2010), or where root growth is impeded by an impermeable layer (Letey, 1985). Clothier and Green (1994) showed that rooting systems can develop preferentially towards areas of frequent irrigation application. Greenwood et al. (2010) recognise that a drawback of water balance frameworks is their critical dependence on depth of rooting, which is often very difficult to estimate. The authors found that root penetration can vary by a magnitude of four for common agricultural crops over the normal range of soil resistances induced by compaction and by reduced soil water content. Where soil properties have been measured and the depth of an impermeable or resistant layer is known, the actual rooting depth of a crop can be assumed to be the lesser of the potential rooting depth and the depth of the impermeable layer. Like other soil properties, site-specific measurement of crop rooting depth will allow for the most accurate estimation of PAW.

4.3.4 Water stress

ET estimates made using the crop coefficient method described in section 4.3.1 above are equivalent to the upper limit of ET and represent conditions where no limitations are placed on growth or evapotranspiration due to water shortage. In practice, although water is theoretically available to, and utilised by, plants until wilting point is reached, plant water uptake begins to decrease well before soil moisture content in the root zone reaches wilting point. As soil moisture decreases, water becomes more difficult to extract as it becomes more strongly bound to the soil matrix. When soil water content reaches a critical value, soil water can no longer be transported quickly enough towards plant roots in response to transpiration demand and the crop begins to experience stress and subsequent yield loss (Allen et al., 1998). The fraction of Total Available Water (TAW) that a crop can extract before ET is reduced following water stress is called Readily Available Water (RAW). It is generally assumed in water balance frameworks that once RAW is depleted, crop ET declines linearly with a further decrease in available water until permanent wilting point is reached, when ET ceases (Allen et al., 1998; Lincoln Environmental, 2000b; Monaghan & Smith, 2004; Woodward et al., 2001).

The precise point at which growth is reduced depends on the crop species, age, growth stage, and soil type (Foundation for Arable Research, 2010; Lincoln Environmental, 2000b; Martin et al., 2008). For pastoral systems, it is commonly assumed that half (50%) of TAW is readily available, and a reduction in production will be experienced when soil water content falls below this point (Monaghan & Smith, 2004; Scotter, Clothier, & Turner, 1979; Srinivasan & Duncan, 2012; Woodward et al., 2001). Reported soil water content at which AET starts to decrease below PET in pastoral systems, expressed as a proportion of TAW, include 0.34 (Parfitt et al., 1985a), 0.41 (Parfitt et al., 1985b), 0.65 (Mcaneney et al., 1982), and 0.50 (Martin, 1990). For other crop types, Table 22 in FAO56 provides an estimate of the fraction of RAW to TAW, included in appendix 9.2.3.

Where soil water content is reduced below the RAW threshold, ET can be adjusted by multiplying the value given by the crop coefficient adjusted Penman-Monteith estimate of ET (ET_c) by an ET reduction function, K_s:

$$ET_{c\,adj} = K_s \times K_c \times ET_0$$ **Equation 4.2**

Where $ET_{c\,adj}$ is crop ET (mm d^{-1}), Ks is the ET reduction function (dimensionless), K_c is the crop coefficient (dimensionless), and ET_0 is the reference crop evapotranspiration (mm d^{-1}).

The ET reduction function (K_s) is determined by the volume of water remaining in the rootzone and is equal to the current water content divided by the water content at field capacity multiplied by the RAW fraction, as displayed in figure 4.3.

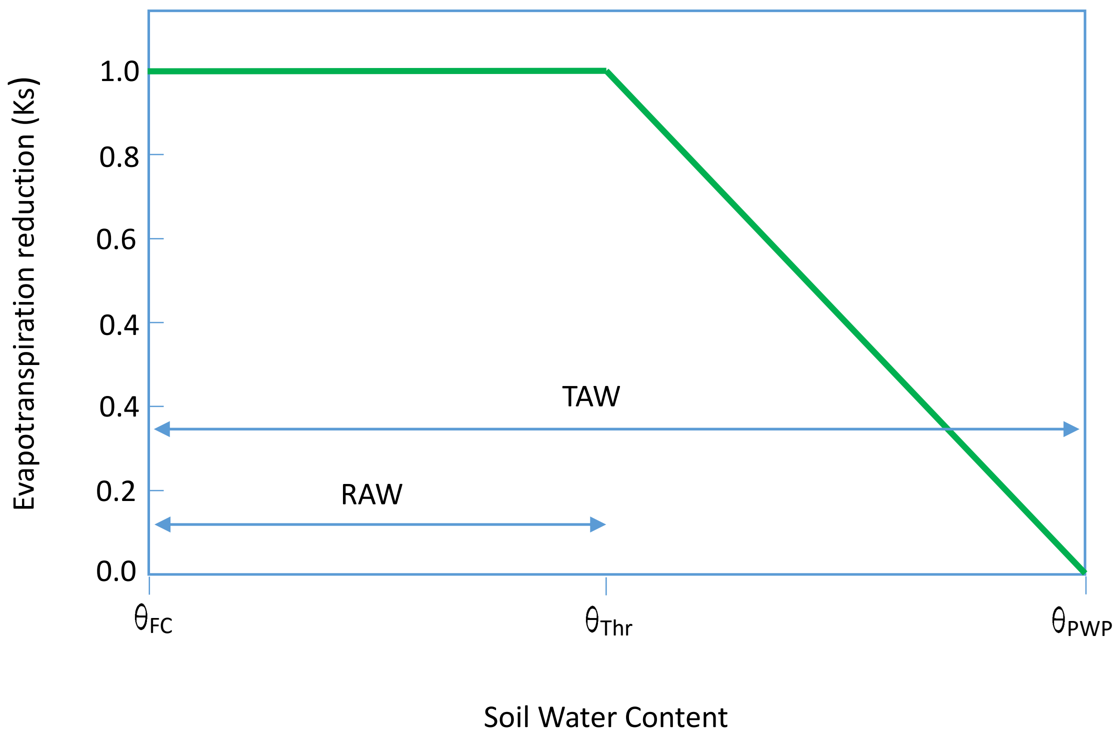


Figure 4.3 Evapotranspiration reduction function. ϴFC, ϴThr, and ϴPWP are the soil water content at Field Capacity, Reduction Threshold and Permanent Wilting Point. Adapted from Allen et al. (1998).

4.4 Irrigation demand and physical properties summary

Irrigation demand is determined by the supply of water from natural precipitation or previous irrigation, the soils capacity to store that water, and the utilisation of stored water by crops through evapotranspiration. Methods of consideration for rainfall, soil properties, and ET are well established in the literature and readily applicable to the soil water balance of an irrigation modelling framework. Rainfall information can be provided by recorded volumes, usually at a daily basis. Soil water storage is governed by the texture and structure of the soil in the rootzone of the crop and the capacity of the soil to retain water applied at the surface. Crop water use can be estimated by adjusting PET using a crop coefficient to account for different crop types and seasonal crop development, and an ET reduction function where RAW is depleted. All climate, soil, and crop variables exhibit variation in space and time. Spatial variation in these properties is not a standard consideration in irrigation models, although there is an increased interest in soil variability for precision management and variable rate irrigation systems.

5 Methods

This chapter describes the irrigation model developed in this thesis. To produce a physically based, spatially explicit irrigation model following accepted hydrological practice, irrigation system and physical field characteristics presented in the chapters 3 and 4 must be accounted for while considering issues of uncertainty, usability, speed of operation, and data coverage, availability, and quality. The model developed herein is called SLIM – the Spatially-explicit LUCI Irrigation Model. SLIM produces stand-alone irrigation outputs that describe the water use and efficiency of the modelled irrigation system, and is to provide hydrological information to other tools in the LUCI framework. The model can replicate an existing irrigation system where site specific data is available, and predicts the timing and depth of irrigation based on best management practice and typical New Zealand application methods in data scarce scenarios. For all model applications, irrigation efficiency maps and statistics regarding water use and leaching loss are produced. SLIM is designed to be generally applicable using national scale data that can be augmented where site-specific data is available, and can be applied at scales from a single field to a multi-field farm. SLIM models the water balance of an irrigated field in a spatially explicit manner by discretising each modelled field into 'irrigation units' based on the resolution of the input Digital Elevation Model (DEM). Each irrigation unit may have unique characteristics regarding soil properties, allowing for the impact of spatially variable soils to be accounted for and visualised with regard to application efficiency, irrigation efficiency, drainage volume, and crop stress.

SLIM exists as a Python script that functions as a toolbox through ESRI's ArcMap GIS software. Python and ArcMap were natural choices; ArcMap is the most common GIS system, and ArcMap spatial functions can be used in a Python script through the ArcPy programming library that is included with all installations of ArcMap. ArcMap is also the functional environment for existing LUCI tools. SLIM also utilises programming tools from NumPy, the fundamental package for scientific computing with Python, and MatPlotLib, a library for creating 2-dimensional plots using Python (Hunter, 2007). The first section in this chapter discusses the primary data sources for SLIM, before the model structure and code is described. A discussion of included and excluded elements is presented last.

5.1 Data

Data requirements for SLIM are soil information, climatic information (rainfall and evapotranspiration), a DEM, and irrigation system parameters. Datasets to fulfil these requirements, outside of irrigation system parameters which are usually system-specific, are readily available for New Zealand wide applications, and at the time of writing many were free to obtain online. A major limiting factor for environmental modelling approaches, like SLIM, is the lack of reliable and accurate data (Bastiaanssen et al., 2007; Hedley & Yule, 2009). Of the datasets reviewed here, there is little analysis of their accuracy or uncertainty in the literature. Consequently, it remains unclear as to whether national scale data is appropriate for field scale irrigation modelling. The primary advantage of the national scale datasets is the comprehensive coverage they provide, which facilitates rapid model application without the need for time consuming parameterisation. Data constraints, whether due to issues of accuracy or scarcity, are likely to always be an issue for any generally applicable environmental model. Data requirements in SLIM have consequently been designed to be flexible and allow site specific and locally derived data to be incorporated where available. This section reviews relevant national scale datasets available in New Zealand and identifies parameters used in SLIM.

5.1.1 Soil information

To simulate the water balance of an irrigated field, the plant available water (PAW), infiltration capacity, and the maximum rooting depth must be known. These soil properties are major determinants of irrigation demand and efficiency (see section 4.1), which necessitates that soil data be both accurate and spatially representative of field conditions. Because SLIM is designed to explicitly account for soil variations in space, input soil information is required to give the spatial distribution of soil types as well as soil properties. Two readily available datasets satisfy these requirements in New Zealand, the Fundamental Soils Layers (FSL) and S-map.

The FSL is a GIS product developed from the National Soils Database (NSD) that maps soil types, their properties, and their distribution as polygon features. The NSD is a legacy collection of geo-referenced soil profiles from more than 1500 sites in New Zealand, with associated information regarding the chemical and physical attributes for each site (Landcare Research, 2014). The NSD was supplemented with expert knowledge and applied to the polygons from the New Zealand Land Resource Inventory (NZLRI) to produce the FSL (Hewitt et al., 2013). The FSL is freely available online through the Landcare Research Information Systems (LRIS) data portal (https://lris.scinfo.org.nz/). The FSL is the only readily available soil dataset with complete New Zealand coverage, and has been used to determine soil hydraulic properties in prior modelling research (e.g. Cichota et al., 2013; Rout, 2003). Of the soil attributes included in the FSL, those of most utility to the water balance approach used in SLIM are profile available water and maximum rooting depth.

Two profile available water measures are attributed to each soil polygon in the FSL; Profile Available Water (PAW), and Profile Readily Available Water (PRAW). For both of these attributes, a minimum, maximum, and modal figure is given. PAW in the FSL is calculated as the volumetric water content difference between -10 kPa and -1500 kPa to a depth of 900mm or the maximum rooting depth, whichever is lesser. PRAW is different in that it is estimated as the volumetric water content difference between -10 kPa and -1500 kPa in the 0-0.4m layer, and between -10 kPa and -100 kPa in lower layers (to 900mm or the maximum rooting depth) (Landcare Research, 2008; Webb & Wilson, 1995). PAW and PRAW values are weighted averages over the specified profile section and are expressed in units of mm of water. The Potential Rooting depth (PRD) attributes in the FSL describe the minimum and maximum depths in metres to a layer that may impede root extension. An impeding layer may be defined by penetration resistance, poor aeration or very low available water capacity (Landcare Research, 2008). Like PAW and PRAW, 3 values for each soil polygon are given for the PRD:

a minimum, maximum, and the modal value for that soil type. Extended information on FSL PAW and PRD are included in appendix 9.1. As defaults, SLIM uses the modal PAW, and the maximum potential rooting depth value from the FSL as parameters from which the water holding capacity of each sub field area is calculated. For infiltration capacity, the FSL does not include a readily usable parameter. A 'permeability' attribute is included, which categorises soil permeability into slow, moderate and rapid categories. For water balance accounting, these categories do not provide sufficient detail; a better estimate of soil infiltration capacity is likely to be estimated from the particle size and macroporosity attributes. Deriving an infiltration capacity relationship to these parameters is beyond the scope of this thesis.

S-map is a new information portal for New Zealand spatial soil data developed by Landcare Research in conjunction with other crown research partners. S-map aims to improve the quality and availability of New Zealand soil information, fill gaps with new data, and upgrade soil information to meet a new national standard (Landcare Research, 2014). S-map data can be accessed online from http://smap.landcareresearch.co.nz/. While some information can be accessed, S-map was under development during this research, and comprehensive coverage of all New Zealand soils is not yet available. Soil characteristics, including PAW and PRD values, can be retrieved from S-map, however are limited to pdf 'factsheet' downloads, as S-map is not readily available in a GIS ready format. Attributes obtained from S-map factsheets can be used in place of existing FSL attribute data, although manual editing of FSL polygons is required.

As S-map is at the time of writing not available in a GIS-ready format, and does not yet have total New Zealand coverage, the FSL is used as the default soil dataset for SLIM. The accuracy and precision of the FSL is likely to be variable, given that soil parameter values are based on a limited number of soil profiles supplemented with expert knowledge. While prior hydraulic modelling has used the FSL (Cichota et al. 2013; Rout, 2003), there is little indication in the literature as to the suitability of FSL data for use in a water balance framework, where the maximum, minimum, or mode value is more appropriate, or in what situations the PAW or the PRAW measures should be used. Furthermore, Aqualinc (2012) question whether the spatial scale of the FSL, S-map, and similar databases is appropriate for farm-specific irrigation planning. Similarly, DeJonge et al. (2007), Hedley & Yule (2009), and Humphreys et al. (2008) acknowledge the importance of quality site-specific soil water data for crop modelling. While the FSL and S-map (where available) inputs ensure that soil information is provided for all potential model applications in New Zealand, it is acknowledged that site specific soil information should be used as a model input where available.

5.1.2 Climatic data

Rainfall and evapotranspiration are key determinants of irrigation demand (see section 4.2). Rainfall and Potential Evapotranspiration (PET) data for New Zealand are readily available online through CliFlo, the NIWA operated web portal for New Zealand's National Climate Database (http://cliflo.niwa.co.nz/). CliFlo provides access to data from ~6500 climate stations which have been operating for various periods since the earliest observations were made in the 1850. The database continues to receive data from over 600 stations that are currently operating (NIWA, 2015). CliFlo returns raw data and statistical summaries at daily, hourly, and up to ten minute frequencies for some stations, which can to be downloaded in a number of different formats. Rainfall and PET data are input into SLIM as simple comma separated value (CSV) files describing the date and depth of precipitation, and can be taken from the nearest climate station to the modelled farm system. Missing data is not uncommon when retrieving climate time-series from CliFlo, and all data should be checked for discrepancies. On-farm recording of rainfall is common for many farms and may give a more accurate estimate of actual rainfall than data provided through CliFlo. Provided the data is of sufficient quality, locally recorded rainfall can easily be used in place of CliFlo data where available.

A number of different methods exist to estimate PET, with each requiring a number of different climatic measurements that are rarely recorded by farmers. SLIM requires data to use the FAO56 Penman-Monteith method for PET estimates (see section 4.2.2). PET estimates are readily available through CliFLo for many climate stations, although the precise method used to produce the published PET values is unclear. Correspondence with NIWA has indicated that estimates using the Penman-Monteith method are available, however the CliFlo interface gives only Raised Pan, Sunken Pan, Open Water, Priestly-Taylor PET and Penman PET data options (NIWA, 2015). The CliFlo help files state that Penman PET estimates are calculated following the method published in Burman & Pochop (1994). A detailed comparison of PET calculation methods is beyond the scope of this research, and no other readily available sources of PET information exist in New Zealand. It is therefore assumed that Penman PET estimates accessed through CliFlo are equivalent to those produced using the FAO56 Penman-Monteith method, and that the application of literature derived crop coefficients to estimate Actual Evapotranspiration (AET) is appropriate for these data.

5.1.3 Land use

To model irrigation inputs in a spatially explicit manner, the location of irrigated fields and the crop types that are grown there must be known. Unfortunately, there is no national or regional scale data available in New Zealand that maps irrigation or specific crop types beyond non-spatial census statistics. For New Zealand applications, land use information for other LUCI tools is provided by the Land Cover Database (LCDB), which groups land use into broad categories and so is unsuitable to farm scale irrigation modelling. Because of this lack of data, it is necessary to define fields manually for SLIM operation by creating a shapefile or feature class polygon dataset that describes where irrigation is applied. This process is relatively simple through any GIS, and can be aided with satellite imagery to ensure correct field placement and extent. Similarly, crop characteristics such as rooting depth, growth stage lengths, and crop factor(s) are required to be input manually alongside irrigation system parameters. While it is recommended that crop characteristics are measured or derived locally, they can be taken from the data tables included in the FAO56 paper (Allen et al., 1998) where not otherwise available. Relevant tables from FAO56 include measurements for a wide variety of crops from a number of different climates and are included in the appendices of this thesis.

5.1.4 Digital elevation model

The DEM input to SLIM determines the size of the sub-field 'irrigation units' that are each modelled as individual soil buckets. A high resolution DEM will provide equivalently detailed output maps, however will also be more computationally expensive than a coarser dataset. A range of DEMs at different resolutions are freely available online through Koordinates (https://koordinates.com/) or the LRIS portal (https://lris.scinfo.org.nz/). The ideal resolution to use should adequately capture soil variations within the field and provide information at a usable scale to an irrigation manager should areas for ecosystem service improvement be identified, while minimising model runtimes. The appropriate resolution will depend on the soil characteristics of the field(s) and the extent of the model application, although a 15 - 25 metre resolution has provided a good balance during model testing and initial applications.

5.2 Model structure

SLIM is a fully distributed deterministic water balance model. This structure is attractive for its physical representation of the soil and relative simplicity compared to more complex models (e.g. those that solve Richards' equation), which allows SLIM to be applied using the national scale datasets discussed above without need for intensive site-specific parameterisation. Furthermore, a deterministic water balance approach can be applied to any spatial scale; either catchment, field, or sub field unit, and is used successfully by a number of existing irrigation models (e.g. Allen et al., 1998; Bos et al., 2008; Bright, 2009; Martin et al., 2008). A fully distributed water balance allows the variations in soil type that exist at sub-field scales to be accounted for, and fits well within the LUCI framework which produces outputs and models water flow in a fully distributed manner.

SLIM is not yet fully integrated into the LUCI framework, and is presented here as a stand-alone model. It is assumed in this thesis that all water additions (rainfall and irrigation) are able to infiltrate the soil, and a daily time-step is adequate to describe water flows. The methods described for SLIM are generalisable; it is anticipated that SLIM will be incorporated into the established (sub-daily time step) hydrology component of LUCI so that irrigation induced infiltration excess runoff is quantified and surface water flow is able to be routed according to surface topography.

This section describes the SLIM computational process, the various model components, and the outputs produced. The section is ordered following the SLIM code and user interface. Data inputs are listed first, then data manipulation and data structures are described before the irrigation application decision process and daily time-step calculations are shown. Model outputs are summarised last.

5.2.1 Input information

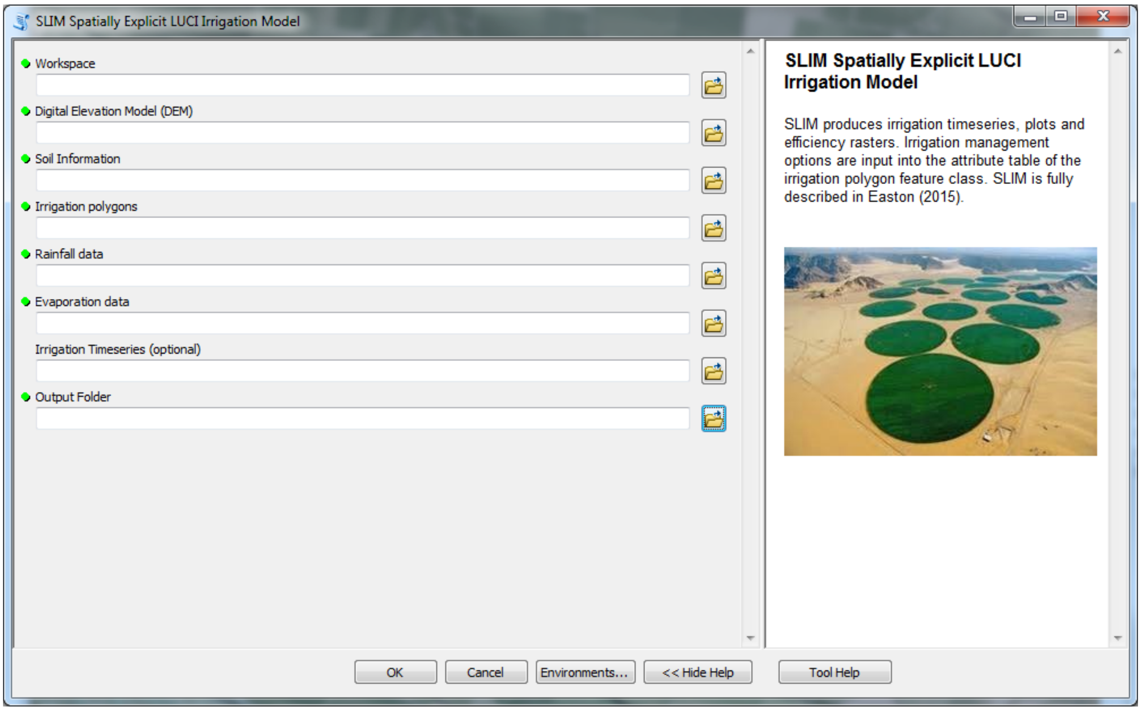


Figure 5.1 SLIM graphical user interface displaying data requirements

Inputs to SLIM are both GIS data layers and text parameters, most of which are optional depending on data availability and the irrigation system being modelled. The core datasets that are required for all model runs are a DEM, soil information, rainfall and climate time series, and a polygon feature class that describes the irrigated fields to be modelled. Irrigation system information is included with the irrigated area polygon feature class as attribute information which can be populated by a user. Otherwise default values are used. Similarly, the soil information dataset (default FSL) can be edited by a user where more accurate information is available. A geodatabase workspace and an output folder are also required to be defined, which give the geodatabase location where interim datasets are stored, and the folder where model outputs are saved respectively. The Graphical User Interface (GUI) with required inputs is displayed in figure 5.1. Sources for these required datasets are discussed in section 5.1.

Table 5.1 SLIM parameters applicable to each field/irrigator

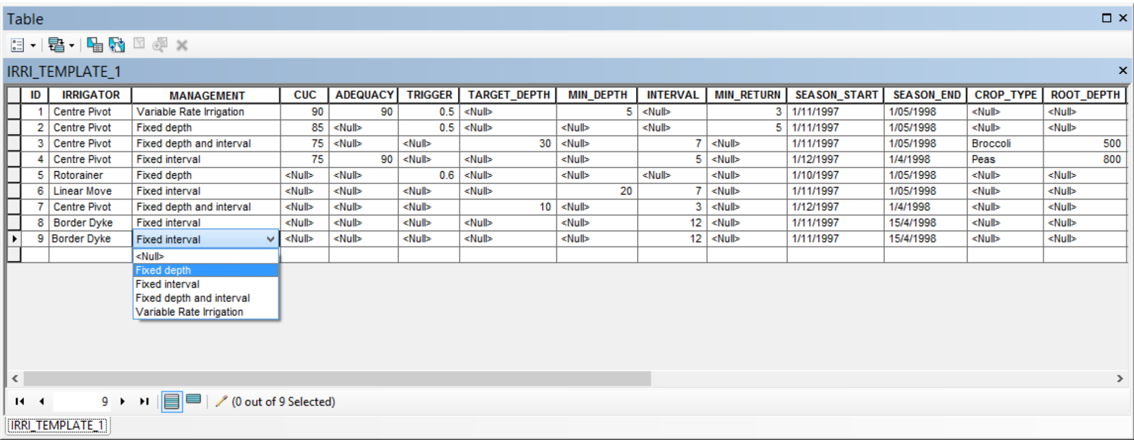
	Field	Data type	Default Value	Comment	Source
1	**ID**	Short Integer	**Null**	Unique identifier	User
2	**IRRIGATOR**	Text (domain restricted)	Generic Spray	Used to determine CUC and outwash ratio if not explicitly supplied	User
3	**MANAGEMENT**	Text (domain restricted)	Fixed Depth	Management decision for deciding when to irrigate	User
4	**TRIGGER**	Float	0.5	Proportion of FC when irrigation occurs for the variable interval management option	User
5	**TARGET_DEPTH**	Short Integer	FC - Trigger * FC	Determines target depth for the variable interval and fixed depth management options	User
6	**INTERVAL**	Short Integer	Null	Determines irrigation interval for variable depth and fixed interval management options	User
7	**CUC**	Float	See Table 5.3	Used to determine applied depth from target depth	User
8	**ADEQUACY**	Float	0.8	Specifies proportion of field that recieves at least the target depth	User
9	**MINIMUM RETURN PERIOD**	Short Integer	Null	Minimum number of days between irrigtaions for each field	User
10	**SEASON_START**	Text	Null	Date that irrigation can begin	User
11	**SEASON_END**	Text	Null	Date that irrigation season ends	User
12	**RAW**	Float	0.5	Defines the proportion of readily available water to total available water	User
13	**ROOT_DEPTH**	Short Integer	600	Maximum root depth in mm. Actual root depth is the lesser of this given root depth and the potential root depth from soils information layer	User
14	**CROP_TYPE**	Text	Null	Required only for output results for cropping scenarios	User
15	**PLANT_DATE**	Text	Null	Planting date for cropping scenarios (day/month) e.g. 1/10	User
16	**GS_INI**	Short Integer	Null	Number of days of the initial growth stage	User / FAO56
17	**GS_DEV**	Short Integer	Null	Number of days of the development growth stage	User / FAO56
18	**GS_MID**	Short Integer	Null	Number of days of the middle growth stage	User / FAO56
19	**GS_LATE**	Short Integer	Null	Number of days of the late growth stage	User / FAO56
20	**KC_INI**	Float	Null	Crop coefficient for the initial growth stage	User / FAO56
21	**KC_MID**	Float	Null	Crop coefficient for the middle growth stage	User / FAO56
22	**KC_END**	Float	Null	Crop coefficient for the late growth stage	User / FAO56
23	**SALINITY**	Boolean	No	Is field prone to salt accumulation Y/N	User

The irrigation polygon(s) describe the irrigated field or fields to be modelled. The data can be a shapefile or a geodatabase feature class. Because of limitations in the ArcGIS toolbox GUI, irrigation management and crop parameters are input into SLIM as attribute data linked to the irrigation polygons rather than through the toolbox interface. This allows for a less cluttered SLIM interface and facilitates data entry for multiple field simulations where each field has different irrigation and/or crop parameters. A full list of parameters that can be given as attribute data for each irrigated field (represented by a single polygon) is displayed in table 5.1. Of the parameters listed, only a unique field identification number is mandatory for SLIM to run, which allows model application regardless of data availability. Where no input information is given, the default parameters assume irrigation is applied to a perennial pasture block by a generic spray system that applies water at a fixed depth equal to half of field capacity.

Table 5.2 Domain restricted Irrigator and Management parameters

Field	Domain restricted options
IRRIGATOR	Centre Pivot
	Linear Move
	Rotorainer
	Travelling Gun
	K-line
	Fixed Sprinkler/Gun
	Border Dyke
	Micro system
MANAGEMENT	Fixed Depth
	Fixed Interval
	Fixed Depth & Interval
	Variable Rate Irrigation (VRI)
	Time series

Default inputs displayed in table 5.1 are based on common system management and recommended best management practices outlined in chapter 3. To aid parameter entry, a custom geodatabase and feature class template are provided with the SLIM script, so that all parameters in table 5.1 are provided to a user as attribute column headings. The irrigator type and irrigation management fields are domain restricted, which displays an option menu to a user rather than an open text entry field. This ensures that inputs are correctly parsed by the SLIM script and reduces potential errors. The domain restricted options for the irrigator type and management are shown in table 5.2. It is impractical to domain restrict the other fields due to their wide range of possible inputs and integer or floating point datatypes. An example of the template feature class for management parameter entry is shown in figure 5.2.



ID	IRRIGATOR	MANAGEMENT	CUC	ADEQUACY	TRIGGER	TARGET_DEPTH	MIN_DEPTH	INTERVAL	MIN_RETURN	SEASON_START	SEASON_END	CROP_TYPE	ROOT_DEPTH
1	Centre Pivot	Variable Rate Irrigation	90	90	0.5	<Null>	5	<Null>	3	1/11/1997	1/05/1998	<Null>	<Null>
2	Centre Pivot	Fixed depth	85	<Null>	0.5	<Null>	<Null>	<Null>	5	1/11/1997	1/05/1998	<Null>	<Null>
3	Centre Pivot	Fixed depth and interval	75	<Null>	<Null>	30	<Null>	7	<Null>	1/11/1997	1/05/1998	Broccoli	500
4	Centre Pivot	Fixed interval	75	90	<Null>	<Null>	<Null>	5	<Null>	1/12/1997	1/4/1998	Peas	800
5	Rotorainer	Fixed depth	<Null>	<Null>	0.6	<Null>	<Null>	<Null>	<Null>	1/10/1997	1/05/1998	<Null>	<Null>
6	Linear Move	Fixed interval	<Null>	<Null>	<Null>	<Null>	20	7	<Null>	1/11/1997	1/05/1998	<Null>	<Null>
7	Centre Pivot	Fixed depth and interval	<Null>	<Null>	<Null>	10	<Null>	3	<Null>	1/12/1997	1/4/1998	<Null>	<Null>
8	Border Dyke	Fixed interval	<Null>	<Null>	<Null>	<Null>	<Null>	12	<Null>	1/11/1997	15/4/1998	<Null>	<Null>
9	Border Dyke	Fixed interval	<Null>	<Null>	<Null>	<Null>	<Null>	12	<Null>	1/11/1997	15/4/1998	<Null>	<Null>

Figure 5.2 Example of SLIM parameter entry and domain restricted management options

5.2.2 Initialisation

When the script is run ('OK' is selected in figure 5.1), SLIM manipulates the input datasets to discretise each irrigated field polygon into sub field 'irrigation units' that are representative of the underlying soil information and equal in spatial extent to the resolution of the input DEM. The DEM and soil information are first clipped to the extent of the irrigation polygons. The DEM is then converted into a point feature class which returns the centroids of each DEM cell. The DEM centroids are spatially joined to the soil information and the irrigation polygons so that a dataset is created where each point feature is associated with the corresponding soil and management parameters according to its position. This dataset is then parsed to calculate the Water Holding Capacity (WHC) in millimetres (mm) for each point feature 'bucket'.

Because Plant Available Water (PAW) values in the FSL are calculated to 0.9 meters or to the crop rooting depth (whichever is lesser), a mm of water to mm of soil ratio (WHC mm/mm) is first calculated, then multiplied by the depth of the rootzone. The root depth is the smallest of the given depth (or modelled depth for seasonal crops) and the maximum rooting depth from the FSL. WHC is set to 'full' (field capacity) when irrigation units are initialised. A schematic of a single irrigation unit is displayed in figure 5.3.

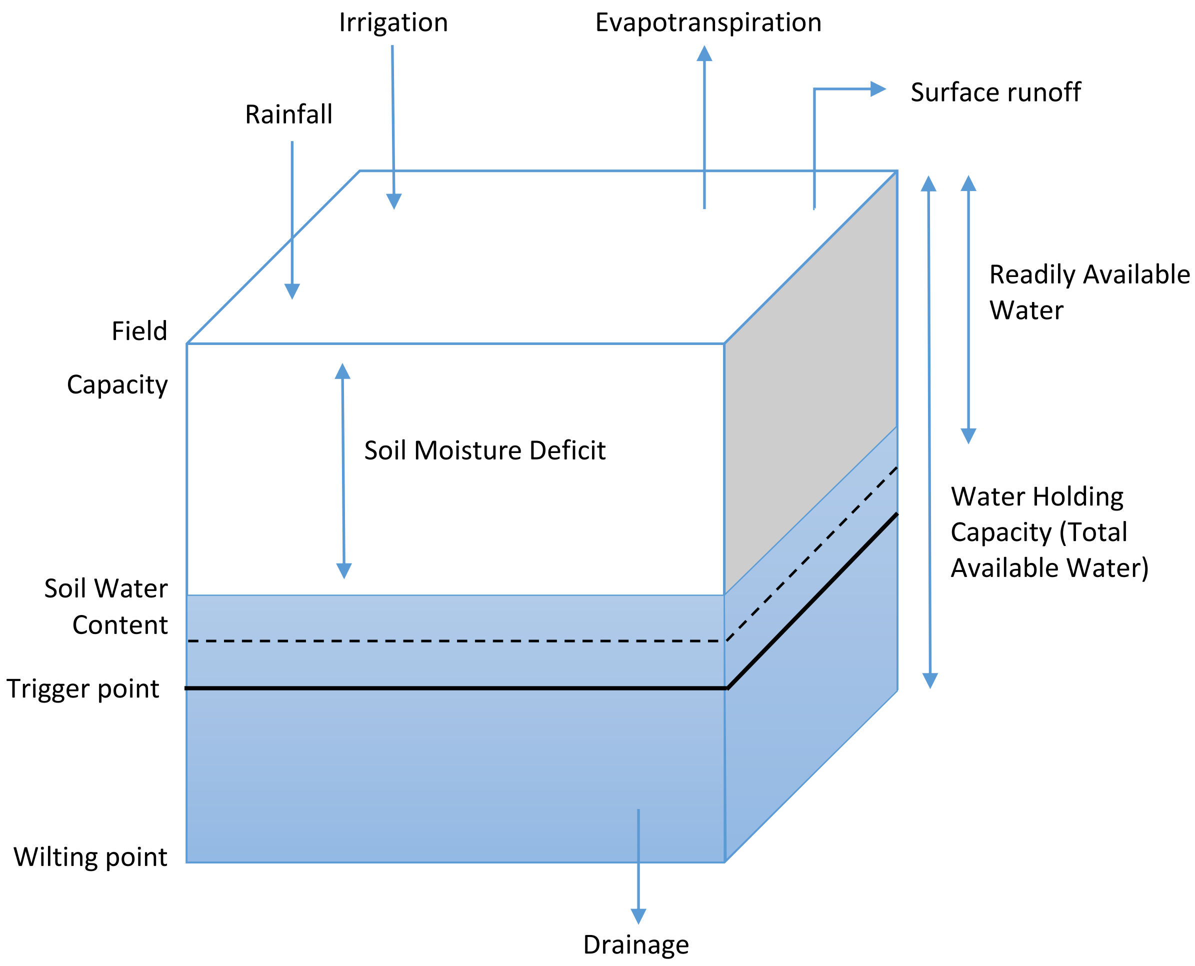


Figure 5.3 Schematic of a SLIM irrigation unit

The point feature class of irrigation units is then converted into two Numpy arrays for further processing. Numpy arrays are processed independently of ArcMap, and generally allow for significantly faster processing than feature datasets or shapefiles. This processing speed advantage makes Numpy arrays ideal for performing non-spatial operations iterated over large datasets. The first of the two arrays stores one irrigation unit for each irrigated field, with parameters equal to the driest portion of that field (i.e. the area with the lowest water holding capacity). This array determines the timing and depth of applications where irrigation is determined by a soil moisture trigger point. Choosing the portion of the field with the lowest water holding capacity as a 'command' irrigation unit replicates typical irrigation system management, which aims to maximise growth by applying irrigation to the field at the time when the portion of the field that is first depleted requires water (Bos et al., 2008). To ensure a reasonable proportion of the field is represented by the command unit, a limit of 10% coverage has been applied in SLIM: the water holding capacity of the command unit must be equal to or greater than at least 10% of the field represented. A 10% limit prevents the scenario where a small corner of a field characterised by a low WHC may prescribe irrigation inputs to a multi-hectare field. The precise figure is modifiable, and can be increased or decreased from 10% where appropriate. The second array stores all other irrigation units, which like the command array is updated at each time step following a simple water balance equation. Alongside the current water content, water holding capacity (at FC), current rooting depth, and Readily Available Water (RAW) parameters, each irrigation unit is associated with unique values for cumulative drainage volume, cumulative application efficiency, number of days where RAW is depleted, total volume of water delivered (including rainfall), and total volume of water used (cumulative AET). These values are updated each simulated day and are used to produce SLIM outputs.

5.2.3 Model process

The water content of each irrigation unit is updated for each day simulated in SLIM. Rainfall is added and AET is subtracted from the water balance according to the (adjusted) values that are given for that day in the input CSV files. Irrigation may be applied depending on the input management strategy and if the application requirements have been satisfied. Any water that remains above the field capacity of the irrigation unit is considered to drain from the soil profile at the end of the simulated day. The daily water balance equation for each irrigation unit is as follows:

$$S_{i+1} = S_i + R_i + I_i - D_i - AET_i \quad \textbf{Equation 5.1}$$

Where:

S_i = Soil water content at timestep i (mm)

R_i = Infiltrating Rainfall between timesteps i and $i+1$ (mm)

I_i = Irrigation between timesteps i and $i+1$ (mm)

D_i = Drainage between timesteps i and $i+1$ (mm)

AET_i = Actual Evapotranspiration between timesteps i and $i+1$ (mm)

t_i = timestep

5.2.3.1 Rainfall and Evapotranspiration

It is assumed in this thesis that the rainfall data provided is representative of the rainfall over the entire modelled extent, and that all rainfall can enter the irrigation units. Rainfall values are read from the input file and added to the water content of all irrigation units; rainfall lost to overland flow is not accounted for in the current version of SLIM and represents an avenue of future extension. The start date for any SLIM scenario is determined by the first date in the provided rainfall file; it is important that the input rainfall and ET files cover the same time period and missing data is avoided so that climatic variables are aligned.

After rainfall has been added, losses to evapotranspiration are calculated. For each irrigation unit, AET is considered equal to the PET multiplied by a crop factor (K_c). A crop factor of 1.0 (i.e. PET = AET) is assumed where no information is given. For seasonal crops, the input crop factor associated with the current growth stage is used. When RAW is depleted, a reduction factor is also applied. RAW is defined as a parameter with crop and irrigation system information (Table 5.1), given as a proportion of Total Available Water (TAW) (default 0.5).

The reduction factor simulates the increasing difficulty for plants to extract water as the soil water content approaches wilting point (see section 4.3.4). The reduction factor is expressed as a proportion of AET and is equal to the current soil water content divided by the volume of RAW. The proportion of AET to PET therefore reduces linearly as soil water content decreases below the 'stress point' indicated by RAW depletion (see figure 4.3). A python function to calculate the ET reduction factor (K_s) is called for each irrigation unit for each day:

```
>def get_ET_red(CWC, FC, RAW_prop):
>     if CWC < FC * RAW_prop:
>          ET_red = CWC / (FC * RAW_prop)
>     else:
>          ET_red = 1.0
>     return ET_red
```

Function 5.1

Function 5.1 returns an ET reduction factor (K_s) following the discussion in section 4.3.4. Given a PET value from the input data file, a crop coefficient (K_c) from input parameters, and an ET reduction (K_s), AET can be calculated:

$$AET = K_s \times K_c \times ET_0$$

Equation 5.2

Where AET is crop ET (mm d^{-1}), K_s is the ET reduction function (dimensionless), K_c is the crop coefficient (dimensionless), and ET_0 is the reference crop evapotranspiration (mm d^{-1}).

5.2.3.2 Irrigation application

The timing and depth of irrigation is dependent on the management option and the input irrigation system parameters. Irrigation management options, informed by section 3.2, are fixed depth (variable interval), fixed interval (variable depth), fixed depth and interval, Variable Rate Irrigation (VRI) (either fixed or variable interval), and input time-series (Table 5.2). Similar rule-sets have been employed for other irrigation models in New Zealand (Bright, 2009; Li, et al., 2007). Table 5.3 shows how irrigation depth and timing are determined depending on the management option selected for that field.

Table 5.3 Irrigation management options and application decision basis. SWC = Soil Water Content, WHC = Water Holding Capacity at Field Capacity, x = number of days entered in the return interval field.

		Return Interval	
		Fixed Interval	**Variable Interval**
Depth	**Fixed Depth**	Scheduled irrigation: fixed Target Depth applied every x days	Fixed Target Depth applied when SWC <= WHC * Trigger
	Variable Depth (between events)	Irrigation applied every x days. Target Depth = WHC - SWC	N/A
	Variable Rate Irrigation (within one event)	Irrigation applied every x days. Target Depth = WHC - SWC for each irrigation unit	Irrigation applied when SWC <= WHC * Trigger. Target Depth = WHC - SWC for each irrigation unit

For variable depth and variable interval options, the depth and return interval (respectively) are determined by the water content of the command irrigation unit which is representative of the portion of the field with the highest water demand. When a target depth is not given for the fixed depth options, it is assumed to be equal to the soil moisture deficit (WHC – Soil Water Content) at the trigger point given (default 0.5). For VRI options, the timing of the irrigation event is based on the portion of the field with the highest demand when a variable interval is also chosen, however VRI depth is always heterogeneous; the target depth applied at each irrigation unit is equal to the soil moisture deficit of that unit. For any non-VRI irrigation, the depth of irrigation is applied homogenously over the whole field. Variable interval options can be constrained by an input minimum interval: no irrigation can occur until this minimum interval is satisfied. Similarly, the target depth can be constrained for variable depth options by entering a minimum depth restriction. The minimum depth restriction prevents irrigation where the soil moisture deficit is less than the minimum depth the irrigator is able to apply.

Because there is no physically based irrigation prompt for a variable depth and variable interval scenario, simulation can only be achieved using an input irrigation event time series. The input time-series option requires a CSV file containing <date, depth> values. On the date specified, the depth given is applied to the field regardless of the soil water content.

SLIM also includes irrigation restrictions that are applied to all management strategies. When rainfall is to occur on the day that irrigation is scheduled, irrigation is delayed if the depth of precipitation is greater than 10mm. This rainfall delay seeks to replicate active irrigation management; it is not applied to time series simulation. Irrigation inputs may also be constrained by user entered irrigation season dates. The dates specify the beginning and the end of the irrigation season; no irrigation may take place outside of the given dates. For fixed interval options, the start date gives the date of the first irrigation, which will take place every day scheduled by the return interval until the end of the irrigation season is reached. Soil water content continues to be updated with rainfall inputs and ET losses outside of the irrigation season to allow pre-season calibration and multi-year simulations.

The actual depth applied (gross depth) for all irrigation decision methods is calculated following the procedure outlined in section 3.4. The gross depth is the required volume of water to be applied, given the uniformity of the irrigator, to ensure that the target depth is achieved over the proportion of the field given by the adequacy value. The target depth, adequacy, and Christiansen's coefficient of uniformity (CU_c) values may be entered by a user, or can be given by SLIM defaults. The default CU_c value is dependent on the irrigator type. CU_c values associated with different irrigators are stored as a dictionary by SLIM which has been informed by table 3.4 in section 3.3.2. These values are displayed below in table 5.4. Because the CU_c value is the primary determinant of the magnitude of difference between the target and gross irrigation depth, and is not always directly transferable between irrigators due to differences in wind effects, sprinkler types and operating pressure, values in table 5.4 are conservative estimates (i.e. may be higher than in practice) based on the range of values measured in the literature for each irrigator type. A default adequacy of 80% is used as suggested by Lincoln Environmental (2000).

Table 5.4 Default CUc values for different irrigators in SLIM

Irrigator	CU_c (%)
Centre Pivot	85
Linear Move	80
Rotorainer	75
Travelling Gun	70
K-line	60
Fixed Sprinkler/Gun	65
Border dyke	50
Micro system	90
VRI system	90

The gross depth is calculated for each field (or irrigation unit for VRI systems) when irrigation is applied by calling function 5.2. This function utilises the Python standard libraries' math package and the Scipy stats package to determine the gross depth, which is equal to the value at the percentile of the adequacy level for a probability range normally distributed about a mean value equal to the target depth. The input CU_c value determines the distribution's standard deviation, which defines the spread of values and hence the magnitude of difference between the target and gross depth. The gross depth is therefore always greater than the target depth for CU_c values less than 100%. In a situation where the applied depth is measured or precisely known, the CU_c value should be set to 100% so that the gross depth is equal to the target depth.

```
>def gross_depth_finder(target_depth, CUC, adequacy):
>     if CUC == 100.0:
>          return target_depth
>     CUC = CUC/100
>     adequacy = adequacy/100
>     a_dev = target_depth * (1- (CUC))
>     s_dev = a_dev/(np.sqrt(2/math.pi))
>     gross_depth = stats.norm(target_depth, s_dev).ppf(adequacy)
>     return gross_depth
```

Function 5.2

5.2.3.3 Crop growth

Irrigation demand for fields producing seasonal crops can be estimated in SLIM following the method outlined in FAO56 (Allen et al., 1998) and described in section 4.3.2. Input crop parameters describe the maximum rooting depth of the crop, the length of the different growth stages (L_{ini}, L_{dev}, L_{mid}, L_{end}), the crop coefficient for each growth stage (Kc_{ini}, Kc_{mid}, Kc_{end}), and the date when the crop is planted. The rooting depth is initially set to 50mm for all seasonal crops in SLIM, with root growth simulated linearly from the planting date until the end of the growth period (L_{dev}), when the given maximum rooting depth is reached. For perennial crops, the rooting depth is equal to the entered depth from the beginning. The input crop coefficients are applied to the PET prior to any reduction factor during each growth stage. For seasonal crops a crop coefficient curve is followed (see figure 4.2). The crop coefficient is static at the corresponding value for the initial and mid-season growth stages (L_{ini}, L_{mid}). The crop coefficient increases linearly between the initial (Kc_{ini}) and mid (Kc_{mid}) values during the development growth stage (L_{dev}), and decreases linearly between the mid (Kc_{mid}) and end (Kc_{end}) values during the late growth stage (L_{end}). Once the end of the combined growth stages is reached (i.e. the crop is harvested), Kc is equal to Kc_{end} and the irrigation season is deemed to be over.

5.2.3.4 Drainage

After rainfall or irrigation is added to the water balance of each irrigation unit, any water excess of field capacity is assumed to drain from the bottom of the rootzone. Irrigation units are considered independent of one another in SLIM; no water transfer is able to take place between adjacent units. For fields that are at risk of salt accumulation, drainage may improve production by leaching harmful salts from the soil profile. Where the salinity input Boolean is set to 'yes', an additional 15% is added to the target depth for all irrigations (see section 3.2.4). As stated earlier, for this thesis, infiltration excess overland flow is not simulated, nor is capillary rise of water into the rootzone. These flows are to be considered once SLIM has been fully integrated into the LUCI framework.

5.2.3.5 Outputs

SLIM produces a number of output data files. The first is a simple CSV time series file containing the date, volume of irrigation, and ID number of the irrigated field. This data file is designed to be able to be input into other hydrology models (spatially explicit or not) so that irrigation water flows can be accounted for in different frameworks. A series of charts plotting the water content for each field's command unit is also produced as a single PDF document. The charts are created using the Matplotlib Python library and are exported using the pdf pages module.

A series of raster maps are also produced by SLIM by converting the Numpy array of irrigation units into raster datasets. These maps allow for the visualisation of differences within and between fields of the average application efficiency (equation 3.8), drainage volume, total water use efficiency (equation 3.6), and the number of days where the crop experienced water stress over the modelled time period. These outputs are intended to be able to inform management interventions by identifying where improvements in ecosystem service provision can be made at sub-field scales. Chapter 2 showed that in general, ecosystem service provision can be improved by increasing the water use efficiency in irrigated fields. The application efficiency, drainage volume, and total water use efficiency raster maps are intended to visualise where water use efficiencies can be made. Drainage volume is calculated as the cumulative daily sum of water unable to be stored by the soil following rainfall and the application of the gross irrigation depth during the given irrigation season. For food provision, the 'stress day' raster can inform irrigation decisions regarding crop production by visualising the degree of water stress experienced by crops. Water stress is linearly related to crop production following the drought day model developed in New Zealand by Rickard (1960) and Rickard & Fitzgerald (1969) (see section 2.1).

5.3 Model discussion

For any generally applicable environmental model, biophysical processes must be abstracted to a series of computational operations which poses challenges associated with efficiency, accuracy, the appropriate level of detail, and the state of existing knowledge of the processes involved. This section discusses the various model components and inherent assumptions in the model process described above and identifies irrigation system elements that are not accounted for in SLIM currently.

5.3.1 Water movement

Surface runoff can be a significant loss pathway for both irrigation and rainfall, and is not currently accounted for in SLIM. Surface runoff is largely dependent on the relationship between the infiltration rate of the soil and the intensity of the rainfall or irrigation event. A discussion of these factors and how they interact is presented in section 3.3.1, where it was found that that significant gaps in knowledge exist on the relationship between soil infiltration rates and irrigation application intensities (Aqualinc, 2012; Edkins, 2006). Following this, it is currently assumed in SLIM that all rainfall and irrigation is able to infiltrate into the soil. For irrigation application, this is consistent with best management practice identified by Irrigation New Zealand (2013), and is standard practise for many irrigation models currently in use in New Zealand, including IrriCalc (Bright, 2009), Overseer (Wheeler & Rutherford, 2013), and the Irrigation Calculator (Martin et al., 2008). For future SLIM development and integration with LUCI hydrology, infiltration excess runoff is likely to be able to be accounted for using a sub-daily time step. This way an infiltration curve that describes the ability of a soil to receive water over time can be compared against the intensity and duration of rainfall and irrigation events. Predicted overland flow volumes could be routed according to the topography and infiltration capacity of downslope soils following the existing LUCI hydrology procedure.

SLIM currently assumes that soils are free-draining, and that no water transfer takes place between irrigation units. While the Fundamental Soils Layer includes a maximum rooting depth for all soils, this estimated boundary is not necessarily defined by a water impermeable layer. Without site specific parameterisation, it is consequently difficult to predict if and where drainage is impeded. It is also uncommon for irrigated fields to be characterised by inhibited drainage, and free draining soils are assumed for many irrigation models (Scotter et al., 1979; Woodward et al., 2001). The assumption of free-draining soils is therefore deemed reasonable; however care should be taken when interpreting results for sites prone to waterlogging. Similarly, lateral water movement is likely to influence irrigation unit water balance only in limited situations. Subsurface water movement between irrigation units is expected to occur in practise where fields are bounded by un-irrigated soils, where systems apply water to only a fraction of the field (e.g. micro sprinklers), or where the topography is steep enough to influence sub surface water movement (Allen et al., 1998). In these situations, a pressure gradient may result in sub-surface water redistribution. For these situations and field areas, SLIM estimations of drainage may be greater than what occurs in the field, although in general drainage estimates will be conservative due to the assumption of uniform wetting and disregard for macropore flow. The transfer of water into each irrigation unit through capillary flow (upward flux into root zone from underlying soils) is also not accounted for in SLIM. Capillary flow could be considered if groundwater information is known, however capillary rise is not a common element for many irrigation models (Hedley & Yule, 2009; Woodward et al., 2001) and has consequently not been included in SLIM development.

5.3.2 Evapotranspiration

Evapotranspiration consideration in SLIM uses the single crop coefficient approach outlined in FAO56 (Allen et al., 1998). This method requires crop coefficients to integrate the effects of both transpiration and evaporation over time. This is especially important during the initial (L_{ini}) and development (L_{dev}) crop growth stages for seasonal crops where the proportion of bare ground is most extensive. So long as crop factors correctly account for evaporative losses during these stages, then AET estimates can be assumed to be equivalent to field conditions provided that input PET data is accurate.

The linear ET reduction (K_s) applied once RAW is depleted is a standard method, included in FAO56 (Allen et al., 1998) and successfully used in irrigation modelling in New Zealand where a RAW proportion of 0.5 is commonly assumed (e.g. Martin et al., 2008; Monaghan & Smith, 2004; Woodward et al., 2001). For certain crop and soil types, a linear ET reduction may not accurately describe the ability of the plant to extract water from the drying soil. However given that common irrigation management applies water at trigger points at or around 50% of FC, it is likely that a linear reduction factor is sufficient for irrigation prediction under most scenarios.

Because SLIM irrigation units are single layer soil 'buckets', estimates of AET immediately following rainfall or irrigation application may under predict what occurs in practice. This under-prediction is because the top part of the soil profile containing the majority of the root mass tends to be wetter than lower parts of the profile following surface wetting (Woodward et al., 2001). The magnitude of this effect has not been analysed in the literature for other single layer irrigation models, although Woodward et al. (2001) suggest that a dual layer approach is used to account for ET immediately after rainfall and irrigation. Development of a secondary water balance layer represents an avenue for future SLIM development.

5.3.3 Irrigation application

SLIM applies irrigation at a calculated gross depth either at a fixed interval or when soil moisture reaches a trigger point (or following a timeseries). The use of soil moisture trigger points is ubiquitous in both irrigation modelling and scheduling services. SLIM uses a modifiable soil water trigger point with which irrigation application can be scheduled, so that different crop types and management aims can be accounted for. Where no information is available or input by a user, a value of 0.5 is assumed as a default trigger point. This trigger point is the same or similar to that used in a number of different models, and is consistent with farming 'rules of thumb' for pasture producing fields (Foundation for Arable Research, 2010). In some farming systems, the irrigation application rules may not adequately simulate on-farm decision making. For example, labour limitations or the turnaround time of manual move irrigators that irrigate more than one field may influence the timing of irrigation applications. In these circumstances, the precise timing of irrigation events may not be correctly predicted when a return interval based on a trigger point is used. Similarly, seasonal water restrictions may inhibit irrigation applications in some areas. While a simple water volume cap could be incorporated into SLIM, realistic simulation requires water use strategies to be included to account for prioritisation of certain fields or crops over others, the reduction of trigger points, or other water saving techniques that may be used by a manager. Outside of these exceptions, irrigation return intervals can be reasonably modelled using either a trigger point or a fixed return interval, with an additional minimum return interval constraint to account for system limitations.

Because surface water flows are not currently simulated in SLIM, surface irrigation systems are modelled in the same way as spray irrigation; all water assumed to enter the soil, which assumes best management practise is always followed (see section 3.1.1). To model surface irrigation dynamics explicitly, knowledge of the irrigation flow across the field as well as soil infiltration information is required. The flow of a surface irrigation event is described by the rate of advance of the wetting front and the rate of advance of the drying front (advance and recession curves).

Together these curves determine the opportunity time for infiltration, from which the depth applied to any point in the field can be calculated (Lincoln Environmental, 2000b). However, like the soil infiltration capacity, system flow is site-specific and cannot be estimated using national scale data. Because of these limitations, irrigation application for surface systems is assumed to be homogenous over the field at the gross depth determined in the same way as for spray and micro systems. This assumes then that the modelled surface systems are operated under best management practices where variability between applied depths within a field is low, and outwash of water from the end of the field is avoided. Reduced application efficiencies and increased drainage typical of surface irrigation compared to spray and micro systems are still expected to be predicted in SLIM where the target depth and CU_c (default 50% for Border dyke systems) is representative of field conditions.

Irrigation applications for the purpose of frost damage prevention, crop germination, pest control, cooling the crop canopy, soil preparation, maintenance of cover crops and wind, or as an application mechanism for chemicals or fertiliser are not explicitly accounted for in SLIM. Modelling for these irrigation aims requires site specific data and/or integration with crop growth models that are beyond the scope of this thesis. Where water application for these purposes has been recorded, they can easily be included with an input irrigation time series or approximated with a return interval during a simulation. While all water application can be inefficient and result in non-beneficial losses, these irrigation aims are limited to certain crop types and irrigation systems, and are of relatively low volume compared to irrigating for crop growth. It is therefore reasonable to ignore these application aims for the majority of SLIM simulations. Similarly, because SLIM models irrigation at the field scale only, losses during water conveyance are not considered.

For all systems except Variable Rate Irrigators (VRI), irrigation application in SLIM is assumed to be uniform over the entire field, at the volume of the calculated gross depth. Simulating uniform application in a spatially explicit framework is deemed to be reasonable as without sufficient knowledge of the spatial representation of existing CU_c measurements (i.e. catch can position and spacing), large assumptions and site specific knowledge are necessary to explicitly account for non-uniformity. Homogenous, irrigation applications based on a spatially averaged gross depth have been applied successfully in non-spatially explicit models by previous researchers to estimate irrigation demand (Bright, 2009; Li, 1998). Explicit consideration of the spatial pattern of application non-uniformity represents an avenue of exploration where irrigator specific data are able to be collected. The method of using a calculated gross depth to account for non-uniformity has the additional benefit of being readily applicable to VRI systems; each irrigation unit can receive a unique depth of water according to that unit's soil moisture deficit when irrigation is applied. Furthermore, the application efficiency of each irrigation event can be easily calculated as an output rather than a required input into the model. Accounting for the current water content of the soil at the time of irrigation provides a more realistic simulation of what occurs in the field than those models that assume a static application efficiency across all irrigation events (e.g. Santhi et al., 2005; Seginer, 1987).

Because distribution uniformity can change between irrigation events, the use of CU_c in this research assumes that the values obtained from the literature are applicable to all irrigation events applied by that system. This is reasonable so long as simulated target depths are within normal operating parameters of the modelled irrigators, and atmospheric disruption of the distribution pattern for spray systems remains low. Following the discussion of uniformity presented in section 3.3.2, irrigation depth estimates will be most uncertain for irrigators with low CU_c values (<75%) where skewness in the distribution of depths is likely to be of greater influence, and where modelled target depths are outside the range normally applied.

5.3.4 Crop growth

Crop growth simulation in SLIM governs the rooting depth and the crop coefficient, which influence plant available water and AET respectively. The crop coefficient approach relies on accurate crop coefficient values and growth stage lengths for accurate AET estimation. It is not established as to whether the crop coefficient and growth stage parameters from FAO56 are applicable to New Zealand crops. Root growth in SLIM is modelled as a linear progression from 50mm when the crop is planted to the input maximum root depth which is reached at the end of the initial and development growth stages (L_{ini} and L_{dev}). This approach is used by Hornbuckle et al. (2005), however the FAO56 paper (Allen et al., 1998) simulates root development over the development growth stage only. Including the initial stage in root development will result in more conservative estimates of drainage for irrigation applied during the initial growth stage than the FAO56 method. The 50mm initial rooting depth maintains conservative crop parametrisation, and may result in over prediction of application efficiency for early season irrigation application where the actual rooting depth of newly planted crops is lower. SLIM is currently unable to simulate a multiple crop scenario where two or more different crops are produced by a single field in a year without running the model twice with two different crop information data sets.

5.3.5 Climate spatial variability

While both rainfall and PET vary across space as well as time, they are considered to be homogenous for each day in SLIM simulations. This is computationally efficient and consistent with typical farm management practices where decisions are often based on information from a single rain gauge, however the variations in plant available water that may result from heterogeneous precipitation and evaporative demand are not captured. Until recently, spatially explicit PET and rainfall information was available through CliFlo in the form of the Virtual Climate Network (VCN) which gives estimates for a number of climatic variables in a New Zealand wide ~5km grid. VCN data has been used previously to estimate crop water demand (Jenkins, 2012) and to model nitrogen leaching (Cichota et al., 2013), however free public access to the VCN has unfortunately been revoked by NIWA during the course of this thesis. However, because SLIM is designed to be run at the field to farm level, spatial variation in rainfall and PET is unlikely to significantly affect irrigation demand at typical farm scales. So long as simulations are confined to farm scale, it is reasonable to assume that a single rainfall or PET value is representative of what is experienced over the entire modelled extent. Where spatial variation in PET and rainfall is experienced, SLIM can be run two or more times as required with different climate data inputs.

5.4 Model summary

SLIM applies a standard water balance method to sub-field irrigation units so that soil variation and its influence on irrigation demand, application efficiency, crop stress, and drainage can be estimated and visualised to inform management decisions. SLIM accounts for a wide range of irrigation systems and management techniques. Current irrigation systems modelled by SLIM are: Centre Pivot, Linear Move, Rotorainer, Travelling Gun, K-line, Fixed Sprinkler/Gun, Border Dyke, and Micro sprinklers. Irrigation application for these systems is determined by the management option, which can be fixed depth, fixed interval, fixed depth & interval, VRI, or time series. In general, assumptions in SLIM are conservative, and it can be expected that predictions of irrigation efficiency are likely to be higher than what is experienced in reality. Like all data-driven models, the quality of SLIM results is heavily reliant on the accuracy and precision of the input data.

6 Case Studies

This chapter applies SLIM in three locations in New Zealand to evaluate model performance and identify potential ecosystem service improvement for the modelled irrigation systems. The first case study assesses the predictive performance of SLIM against recorded data for border dyke irrigation over pasture at Winchmore, Canterbury. The second case study evaluates the irrigation performance of micro-sprinklers for the current (2014-2015) growing season for an apple orchard near Nelson. The third case study simulates a hypothetical spray irrigation system to investigate irrigation performance over spatially variable soils near Leeston in Canterbury. The Winchmore and Nelson sites were chosen because data was readily available for the irrigation systems used in these locations. The Canterbury site is characterised by highly variable soils and was chosen to showcase the spatially explicit nature of SLIM. The three sites are characterised by different irrigation systems, different management, and different levels of data availability.

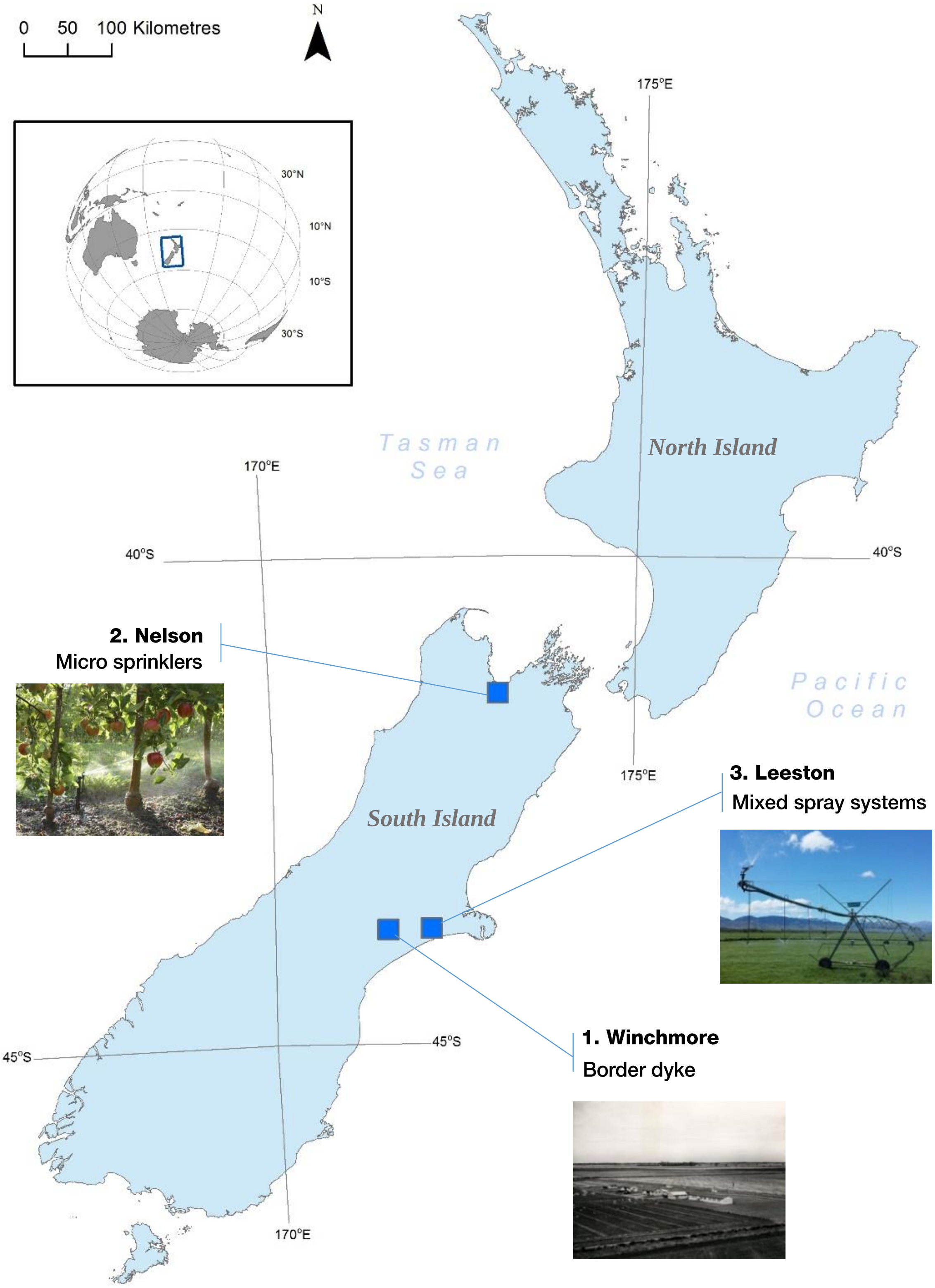


Figure 6.1 Case study locations

6.1 Winchmore, Canterbury

The Winchmore Irrigation research station was established in the late 1940s to investigate problems associated with the introduction of border dyke irrigation systems (Rickard & Moss, 2012). The site is situated 16km from Ashburton in mid-Canterbury, New Zealand, and is supplied by the Lyndhurst irrigation scheme. Field trials at Winchmore represent some of New Zealand's longest running scientific trials and are the longest running trials of grazed and irrigated pasture anywhere in the world (McDowell & Smith, 2012). Data from Winchmore have been used in nearly 500 publications (including peer-reviewed articles, conference papers, technical reports, and bulletins) investigating irrigation, pasture production, animal production, soil research, entomology, and other topics (Cousins & McDowell, 2012).

From the late 1950's, 5 replicate border dykes have operated under different irrigation regime 'trials' at Winchmore. Three border dyke trials are irrigated when the top 100mm of soil reaches 10%, 15%, and 20% moisture by weight respectively, one trial is irrigated every 21 days when required, and the final trial is not irrigated at all. The date of every irrigation event has been recorded up until 2002, and kindly provided for this project by Alister Metherell at Ravensdown. While the border dyke system used at Winchmore is not a system commonly installed in recent times in New Zealand (McIndoe, 2001), the very long record of irrigation applications and the physical basis of application decisions make the Winchmore trials an ideal dataset to evaluate the predictive performance of SLIM.

6.1.1 SLIM simulation

A series of SLIM simulations have been run for the 11 years between the 1990/1991 and the 2000/2001 irrigation seasons. These dates were chosen as they encompass the most recent decade of recorded irrigation at Winchmore, and provide a range of wet and dry seasons. Winchmore data shows that irrigation is applied from the beginning of October at the earliest during each irrigation season, and is not applied after April. These seasonal restrictions have been applied for each SLIM simulation. Each model run was simulated beginning in June of

1990, with Water Holding Capacity (WHC) set to full. Irrigation depth was set to 100mm, equal to the volume given in the provided data.

Climate data was taken from the Winchmore climate station accessed through the NIWA CliFlo database. Rainfall records are available back to 1958, however Penman PET information is only available from July 1971 onwards from this climate station. Penman PET information includes some data discrepancies; analysis reveals a data gap between June and October 1995 which also exists for nearby climate stations (e.g. the Ashburton and Methven stations). PET data for these months are instead taken from data recorded at Christchurch airport.

The soil at Winchmore is a homogenous Lismore stony silt loam on a thick bed of greywacke gravel and sand (Rickard & Moss, 2012). Plant Available Water (PAW) information for Winchmore is available from multiple sources; the NZFSL, S-map, samples taken by Peter Carey in 2002 (provided by Alister Metherell), and from Rickard & Moss (2012). This information is shown below in table 6.1**.** The variation in values reported in table 6.1 shows there is uncertainty as to the precise water holding capacity of the pasture rootzone at Winchmore. Because the model developed in this thesis requires a PAW figure in mm for the soil water balance, a PAW (mm) estimate was made from the volumetric and gravimetric percentages given in Rickard & Moss (2012) and measured by Carey (2002). An estimation of PAW (mm) can be made by subtracting the water content at Wilting Point (WP) from the water content at Field Capacity (FC), multiplied by the depth of the soil in the rootzone. Estimated PAW values are between 120mm (for 30% Mw at FC and 10% Mw at WP), and 162mm (37% FC, 10% WP) from the range of estimates in the Carey (2002) and Rickard & Moss (2012) data, assuming a pasture rooting depth of 600mm. Given the bulk density of 0.97 as measured by Carey (2002), assuming that gravimetric and volumetric measurements are roughly equivalent is justified (Woodward et al., 2001).

Table 6.1 Soil water holding capacity information for Lismore stony silt loam at Winchmore. Mw = Moisture weight (gravimetric), Mv = Moisture volume (volumetric).

Source	Field Capacity	Wilting Point	Plant Available Water (PAW)	Notes
Rickard & Moss (2012)	30 - 33% Mw	10% Mw	-	0 - 10cm in the soil profile.
Carey (2002)	33.9 - 35.7% Mv 35.2 - 36.9% Mw	-	-	0 - 5cm in the soil profile. 69 cores taken, reported here are the mean values for cores taken from 2 irrigated trial blocks under 15% and 20% treatment.
S-map	-	-	86.6 mm (to 60cm)	S-map reference: Lism_1a.1. Properties are representative of 75% of the map unit at the location of the Winchmore trials.
NZFSL	-	-	65 mm (to 41cm)	Modal PAW value taken. Rooting depth is restricted to 41cm in the NZFSL.

PAW estimates derived from the volumetric and gravimetric measurements from Carey (2002) are likely to be higher than what exists in reality because the samples are for the first 5cm of soil only, which is expected to have a greater water holding capacity than lower soil layers due to a greater proportion of soil organic matter (Clothier & Green, 1994). Higher organic matter content in the top section of the soil may be why data for the deeper estimates (10cm) in Rickard & Moss (2012) show a lower gravimetric water content at field capacity, and why the PAW values provided in S-map and the NZFSL (to 60 and 41cm respectively) are significantly lower than those estimated from extrapolation to the same depth using the data from Carey (2002). Soil organic matter at Winchmore is also likely to be higher compared to un-irrigated soils of the same type (Houlbrooke et al., 2011), which may also be a contributing factor to the lower estimates provided in the NZFSL and by S-map that encompass a large polygon feature of which Winchmore is but a small section.

The uncertainty in PAW at Winchmore provides an opportunity for sensitivity analyses on the role of PAW on irrigation timing for SLIM. Simulations have been run with PAW (mm) values of 167 mm, 120 mm, and 87 mm. These values are calculated from Carey (2002), Rickard & Moss (2012), and taken from S-map (rounded to the nearest mm) respectively.

Assuming a homogenous soil, trigger points equivalent to those used at three of the Winchmore trials (irrigation at 10%, 15% and 20% Mw) can be estimated in the same manner as used to estimate PAW (mm), then converted to a proportion by dividing by the PAW value used. For the 20% and 15% treatment fields, this gives trigger points of 0.34 and 0.19 respectively for the 162 mm PAW soil, and 0.5 and 0.25 for the 120 mm PAW soil. Trigger points of 0.5 and 0.25 were also used for the S-map derived 87mm PAW simulations. A trigger point of 0.0 is used for all simulations of the 10% treatment, replicating irrigation application at wilting point.

6.1.2 Winchmore results and discussion

The number of irrigations predicted by SLIM for different parameter combinations are displayed in table 6.2. Over the 11 year simulation period, there was 20, 37, and 54 irrigation events applied at Winchmore for the 10%, 15%, and 20% trials respectively. The best predictions by SLIM were when a PAW of 120mm was used, which predicted 0, 32, and 62 irrigation events for the 10%, 15%, and 20% trials respectively, using trigger points of 0, 0.25, and 0.5.

Table 6.2 Predicted and recorded irrigations at Winchmore from 1/10/1990 to 31/04/2001. *Irrigation was not applied according to soil water demand during the 1996/1997 season.

Border Dyke Trial		**10%**	**15%**		**20%**	
Trigger Point		**0**	**0.25**	**0.19**	**0.5**	**0.34**
PAW (mm)	**162**	0	23	17	43	32
	120	0	32	-	62	-
	87	0	45	-	87	-
Recorded Irrigation		**20**	**37**		**54***	

Whether SLIM over- or under-predicted the total number of irrigations for each trial was directly related to the PAW value used. The S-map 87mm PAW simulations resulted in SLIM over-predicting the total number of irrigations over the 11 year simulation period for all trials, and the 162mm PAW simulations under-predicted the total number of irrigation applications for all trials. Predictions were improved when the 162mm PAW simulations were repeated using trigger points of 0.25 and 0.5 for the 15% and 20% treatment border dykes respectively, but were still lower than the number of irrigations actually applied under both regimes.

The default SLIM simulations did not predict any irrigation events when a trigger point of 0.0 was used for any of the PAW values (i.e. soil moisture must reach 0 for irrigation to be applied). This is due to the linear reduction of Evapotranspiration (ET) that is applied when Readily Available Water (RAW) is depleted; the volume of water lost to ET becomes increasingly negligible as wilting point is approached, and is never reached in these scenarios before rainfall occurs. Following this, simulations were run without an ET reduction factor (i.e. AET = PET while there is water in the rootzone). These results are displayed in table 6.3 for all PAW and trigger point combinations. The results produced where an ET reduction factor was not used show a better prediction of total irrigation events for the 10% and 15% treatment border dyke trials. There is no change in the number of irrigation events predicted for the 20% treatment trials with a 0.5 trigger point whether or not an ET reduction function is used because irrigation is applied before RAW is depleted.

Table 6.3 Predicted and recorded Irrigations at Winchmore from 1/10/1990 to 31/04/2001, where no ET reduction factor was used. *Irrigation was not applied according to soil water demand during the 1996/1997 season. ** ET reduction factor was used, with AET limited to no less than 50% of PET.

Border Dyke Trial		10%	15%		20%	
Trigger Point		0	0.25	0.19	0.5	0.34
PAW (mm)	162	27	29	29	43	35
	120	30	40	-	62	-
	120**	11	32	-	62	-
	87	41	56	-	87	-
Recorded Irrigation		20	37		54*	

Predictions for the 10% treatment field (0.0 trigger) are the least accurate to the recorded irrigation data, and exhibited the most sensitivity to the presence or absence of the ET reduction function. Following this, a simulation was run using the existing ET reduction function, but limited so that AET could not fall below 50% of PET. This simulation produced the closest prediction of the total number of irrigations for the 10% treatment border dykes, with 11 irrigations predicted by SLIM for a 120 mm PAW soil compared to the 20 recorded irrigations for those treatments. There was no change in the number of irrigation events for the 15% treatment simulation compared to the standard reduction function which indicates that irrigation is triggered at or before AET falls to half of PET.

The large differences between the predicted and recorded number of irrigations over the 11 year time period for the 10% treatment Border Dykes shows the uncertainty of AET estimations when soil water content approaches permanent wilting point. A factor contributing to this uncertainty may be that irrigation applications at Winchmore are based on the water content in the first 100mm of soil. This upper section of the soil profile is likely to be more easily depleted than lower layers of remaining water as wilting point is approached due to the greater root density that is expected close to the surface of irrigated fields (Clothier & Green, 1994). Another factor may be that a linear ET reduction is inappropriate for pasture grown on Lismore stony silt loam; an exponential or other reduction function may better describe the ability of pasture to extract water when soil water content approaches wilting point. The most appropriate reduction function is likely to be soil and/or crop specific, and further investigation is outside of the scope of this thesis. More generally, the findings presented here suggest that a linear reduction in ET, as is commonly assumed in water balance frameworks, may be problematic and not representative of physical processes.

For the 15% and 20% treatments, SLIM predictions were closest to the recorded number of irrigations for simulations using a 120 mm PAW volume. Charts showing the number of predicted irrigation events and the cumulative irrigation volume for these simulations are displayed below. Figures 6.2 to 6.5 show that in general both the timing and number of irrigations per season was accurately predicted. There was only one irrigation season (1999/2000 for the 20% trials) where the number of events predicted was more than one event greater or less than what was recorded. For the 15% treatment, 37 irrigation applications were recorded in total, with 32 applications predicted when using the ET reduction function, and 40 predicted when no reduction function was used (figures 6.2 and 6.3). For the 20% treatment, 54 applications were recorded and 62 predicted (figures 6.4 and 6.5). The accuracy of this estimate is detrimentally affected by the 1996/1997 irrigation season, when problems at Winchmore resulted in only one irrigation being applied during that season despite soil moisture content falling below the trigger point. If these problems were avoided, the actual number of applications are likely to be closer to the SLIM prediction than this result shows. The effect of the missed irrigations can be clearly seen in figure 6.5.

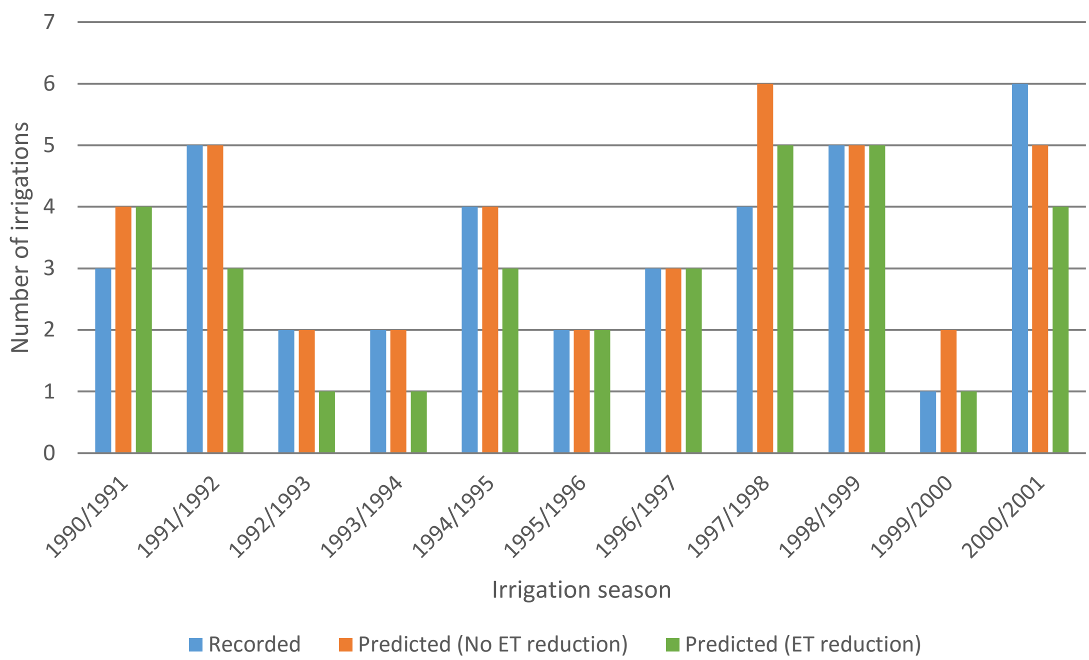


Figure 6.2 Number of irrigations for the 15% treatment Border Dyke trials at Winchmore over 11 years from 1990. Predicted estimates use a PAW of 120mm, and a trigger point of 0.25.

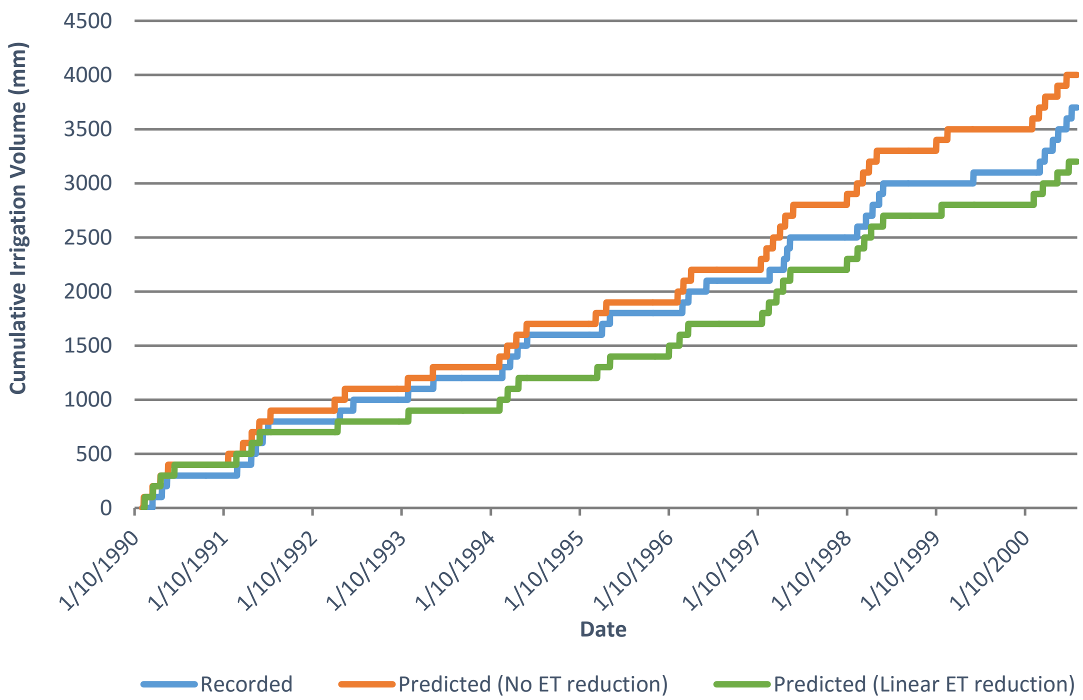


Figure 6.3 Cumulative irrigation volume for the 15% treatment Border Dyke trials at Winchmore over 11 years from 1990. Predicted estimates use a PAW of 120mm, and a trigger point of 0.25.

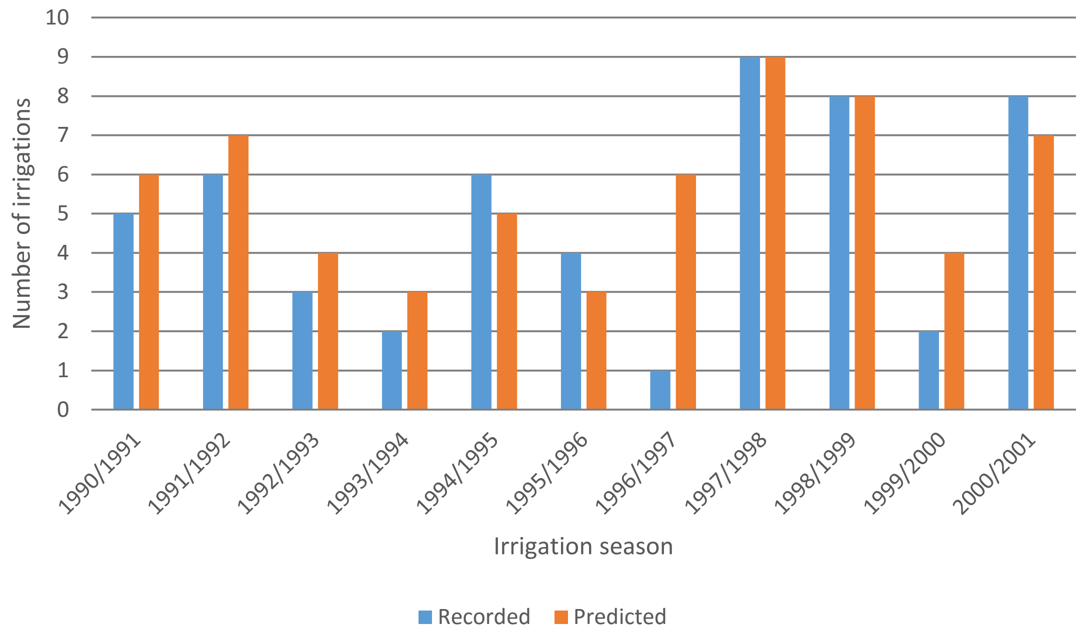


Figure 6.4 Number of irrigations for the 20% treatment Border Dyke trials at Winchmore over 11 years from 1990. Predicted estimates use a PAW of 120mm and 0.5 trigger point. Notice the irrigation that was only applied once during the 1996/1997 season.

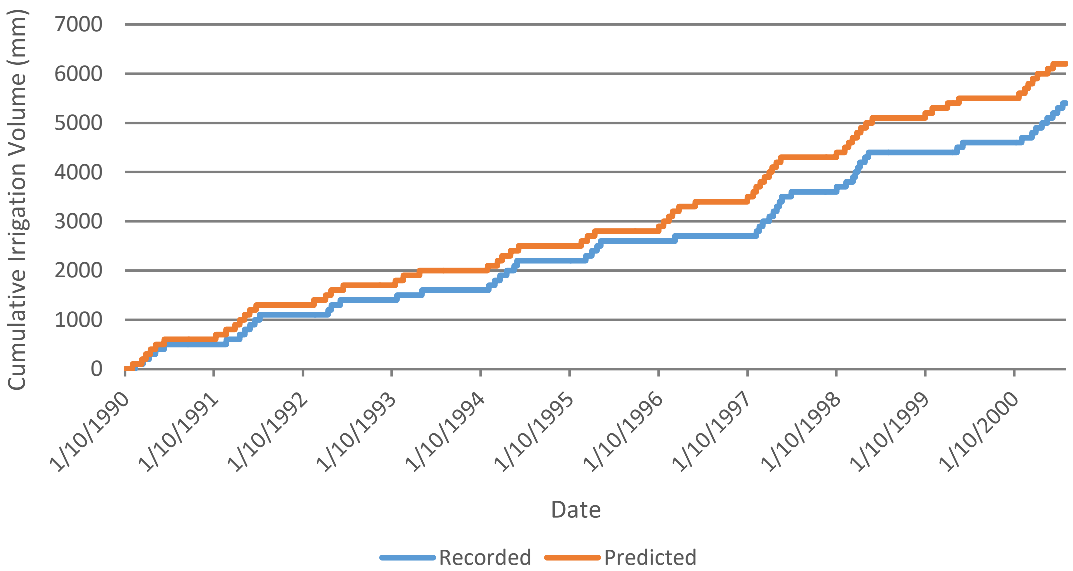


Figure 6.5 Cumulative irrigation volume for the 20% treatment Border Dyke trials at Winchmore over 11 years from 1990. Predicted estimates use a PAW of 120mm and 0.5 trigger point. Notice the irrigation that was only applied once during the 1996/1997 season.

Of the simulated irrigation regimes for Winchmore using a 120 mm PAW and no ET reduction function, application efficiency (volume retained in rootzone/volume applied) was highest on average over the simulated period for the 10% trials (trigger point at 0.0) while the 20% trials (trigger point at 0.5) were the least efficient. Over the 11 year simulation, average application efficiency was 100%, 92%, and 64% for the 10%, 15%, and 20% trials respectively. The poor application efficiency of the 20% trial simulations resulted in 3268mm of total irrigation season drainage over the 11 year period (~297mm/year), compared to 1066mm for the 15% trial (~97mm/year), and 222mm for the 10% trial (~20mm/year). The advantage from a farming perspective of applying water at a trigger point of 0.5, as was done to simulate the 20% treatment border dykes, is that PAW is maintained above half of field capacity (i.e. a constant supply of RAW is maintained), which is a commonly used approximation of potential crop stress and subsequent yield loss in pastoral systems.

To investigate the effect of the number of days where soil moisture is below the stress point of the pasture (i.e. where RAW is depleted), SLIM was run using the time-series of actual irrigation events applied at Winchmore and results compared to recorded Dry Matter (DM) pasture production. SLIM outputs predicted that the 20% treatment border dykes experienced 518 days where soil moisture was below half of field capacity during the irrigation season (October to April inclusive) over the 11 year simulation run compared to 784 days for the simulated 15% treatment border dykes and 1174 days for the 10% treatment fields. These 'stress days' for each year are plotted against the measured DM production for each trial at Winchmore in figure 6.6.

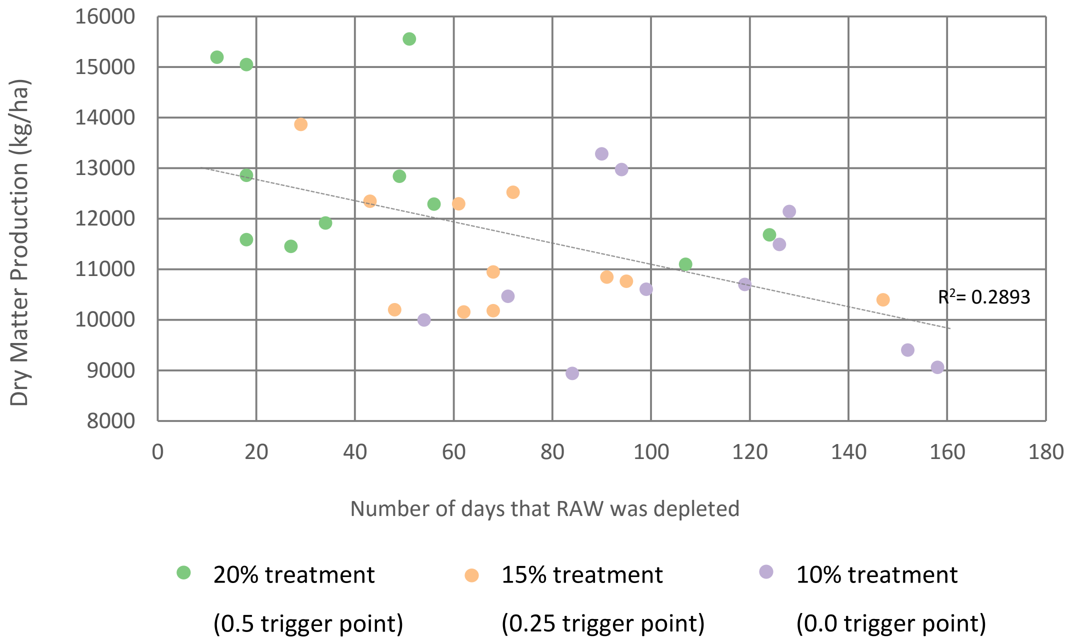


Figure 6.6 Measured Dry Matter production and number of days where PAW was less than half of field capacity for SLIM simulations using a 120mm PAW with a linear ET reduction using recorded irrigation dates.

Despite the 20% trials producing an average of 12867 kg DM/ha per year compared to 11321 and 10824 kg DM/ha per year for the 15% and 10% trials respectively, figure 6.6 shows no statistically significant correlation between the number of days where RAW was depleted (soil water content was below half of field capacity) and dry matter production. Over all the data points, an R^2 value of 0.2893 shows that pasture production at Winchmore is influenced by factors beyond the ability of the irrigation regime to maintain RAW, such as climate, fertilisation, harvest or stock rotation, crop genetics, or sensitivity to the timing of water stress. DM production for the dryland trials at Winchmore produced just 8568 kg DM/ha over the same time period which highlights the role of irrigation on pasture production in Canterbury, and indicates that deficit irrigation management similar to the 10% Winchmore trials can increase production even at low cumulative irrigation volumes.

6.1.3 Winchmore conclusions

Overall, SLIM predicted irrigation applications well over a long time period for the Winchmore irrigation trials. Both predicitons for the 15% treatment (with and without an ET reduction function), and the 20% treatment (with missing applications) were within 15% of the number of recorded irrigation applications over an 11 year period. This level of accuracy is deemed to be adequate and shows that the SLIM methodology can successfully predict irrigation applications under the irrigation regime used at Winchmore. Discrepancies are always likely, given uncertainties as to the precise PAW of the pasture rootzone, the correct ET reduction function, data accuracy, water restrictions, and unaccounted social factors that may influence irrigation applications.

The most uncertain predictions were for the Border Dykes with low trigger points, especially for the 10% treatment fields where irrigation was applied only once the soil was approaching permanent wilting point. This irrigation regime is highly uncommon in practise, given the yield loss associated with plant water stress (both measured and perceived). Measured data at Winchmore shows that the 10% treatment field produced 2 tonnes of dry matter per hectare less than the 20% treatment field over the 44 year trial period on average, a greater than 16% reduction in productivity. If irrigation regimes that apply water at trigger points close to wilting point are to be simulated using SLIM, care should be taken during parameterisation and when interpreting the timing of predicted irrigation applications. To ensure that predictions for application frequency are conservative, it is recommended that the linear ET reduction function be used when simulating low trigger point irrigation application.

Given that irrigation applications were not applied during the 1996/1997 season for the 20% treatment Border Dykes, it is not unreasonable to assume that irrigation was not always applied on the precise day when soil moisture reached the trigger point. During any irrigation season or over multiple seasons, any mistimed or missed irrigation application can potentially affect the timing of later irrigation, whether an irrigation predicted by SLIM or actually applied at

Winchmore. One factor that may have affected irrigation applications at Winchmore is water restrictions, as water availability is linked to the flow of the Rangitata river. Unfortunately, data describing the timing and severity of water restrictions was unavailable for the period simulated. Another influence on the timing of irrigation may be social or labour related factors, for example SLIM predicted that irrigations would occur for the 15% treatment Border Dykes on New Year's Eve (31st December) in 1996, 1997, and 1998 when a 120 mm PAW and trigger point of 0.25 were used, however no irrigation applications are recorded for any of the Winchmore trials on New Year's Eve over the 44 years of data available. It is likely that the timing of irrigation applications may be influenced by factors beyond the soil water content of the soil, and exact prediction of the number of irrigation events over multiple year periods may not be regularly achievable for most irrigation systems.

The number of different PAW values for the soil at Winchmore and their effect on the total number of irrigation applications emphasises the importance of accurate, locally derived soil information for irrigation predictions. The PAW values given by the NZFSL and S-map were much lower than that measured at Winchmore, and subsequently resulted in prediction of much higher frequency irrigation than what was actually applied. This indicates that irrigation predictions using these datasets in other areas may also be uncertain.

6.2 Easton Apples

Easton Apples' Bartlett Road block is an apple orchard irrigated by micro sprinklers. The orchard is located near Richmond on the Waimea Plains in the South Island, New Zealand. Irrigation at the orchard is scheduled based on crop demand and season stage, soil moisture content, and weather conditions. The irrigation regime is characterised by low depth, high frequency irrigation application during the growing season. Soil moisture levels at the orchard are monitored by neutron probe sites operated by Agfirst New Zealand to produce irrigation recommendation reports. Scheduling information recorded by orchard staff and access to Agfirst probe readings has been kindly made available by Elliot Easton. The provided data describes the rooting depth, PAW, daily rainfall, irrigation depth, and irrigation timing for the Bartlett New Eve (BNE) section of the Bartlett Road orchard (see figure 6.7 below).

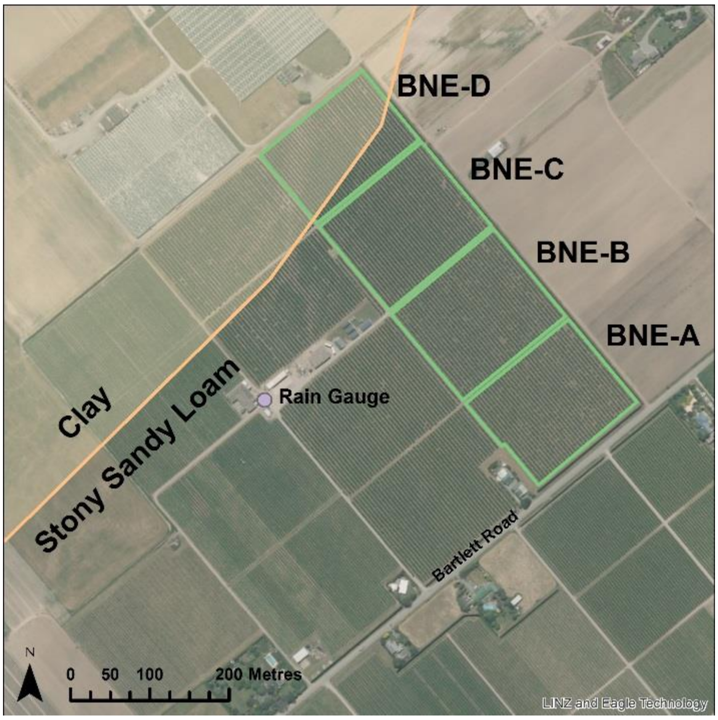


Figure 6.7 Easton Apples' Bartlett Road orchard.

BNE consists of 4 blocks of Mariri Red Braeburn apple trees, labelled A to D, totalling 9.32 hectares and approximately 8,273 individual trees. The sprinklers are spaced so that each provides water to two trees, giving approximately 444 sprinklers per hectare. BNE covers two different soil types, with 'Burt's bank' defining the boundary between a stony sandy loam and a heavier clay based soil. These two soils are called 'stones' and 'clay' respectively by the management at the orchard, and will be referred to as such here. The difference in water holding capacity between the two soils has resulted in previous mitigation measures adopted on the orchard. Irrigation was originally applied homogenously across BNE by 5mm/hr micro sprinklers, before taps were installed along the approximate soil boundary which transects BNE-D. On the clay side of the boundary, sprinklers were also replaced with lower depth 2mm/hr emitters. Because the irrigation pump does not have the capacity to apply water to all 4 BNE blocks simultaneously, the blocks are plumbed so that BNE-A and BNE-B receive water at the same time, and BNE-C and BNE-D receive water together. The installed taps allow BNE-

C and the portions of BNE-D that overlay the stones soil to be irrigated without applying water to the BNE-D trees on the clay soil. These measures were adopted in an effort to reduce the occurrence of root-rot and fungal infections associated with prolonged periods of soil saturation common on the clay soil. Irrigation to BNE is applied with added potassium fertiliser (fertigation). Potassium is applied to boost the potassium to nitrogen ratio in the fruit which improves apple storage. Previous year's crops had stored poorly, which was attributed to variable, and often very high (>30mg/litre) nitrate-nitrogen content in the irrigation water (sourced from an on-farm bore).

A SLIM simulation was run for the 2014/1015 irrigation season (up until 20th January) using recorded irrigation depth and timing information to estimate the application efficiency of the BNE irrigation regime, investigate the effectiveness of the mitigation measures applied, and evaluate SLIM performance for micro-irrigation systems.

6.2.1 SLIM simulation

SLIM was run using the recorded time series of irrigation events, on-farm rainfall records, and PAW from the Agfirst neutron probe estimations. The model was run on the 26th January, 2015 and encompassed all irrigation and rainfall events up until that date from the beginning of June 2014. The earliest irrigation was applied during October, with the simulation covering between 32 (BNE-D) and 45 (BNE-A and BNE-B) individual irrigation events. The extent of each irrigation unit was defined by a 15 metre resolution DEM produced by the Survey School of Otago University and obtained via koordinates.com.

Soil PAW was taken from the provided Agfirst reports which have been derived from neutron probe measurements to a depth of 900mm. Neutron probe measurements used to provide PAW values for the modelled scenario are taken from adjacent blocks over the same soils; a time-series of soil moisture measurements was unavailable for the modelled blocks. These PAW values, 320mm and 230mm for the clay and stones soils respectively, have been edited into the

NZFSL polygons. Discussion with the farm owner revealed that the rooting depth in BNE is likely to be significantly greater than the 900mm measured by the neutron probe array, as previous excavations of the same variety and rootstock combination revealed roots below 2 metres for trees grown in a stony sandy loam soil under drip irrigation. However because the actual rooting depth in BNE is unknown, and neutron probe measurements are to 900mm only, large assumptions would be required to extrapolate the measured PAW values to greater depths. The unaltered values given by the Agfirst measurements have been used in this exercise. The soil boundary has been edited from that displayed in the NZFSL so that the boundary more closely matches field conditions. The soil polygons have been moved approximately 100 metres towards the north-east under guidance from the management at Easton Apples (as displayed in figure 6.7). It is assumed that the soil boundary is exactly matched by the installed in-line taps that also mark the change in sprinkler type.

Rainfall is recorded at the Bartlett Road block on a daily basis during the irrigation season. This data was used during the SLIM simulation from October onwards, with data from the nearby Appleby climate station, approximately 3km from BNE, used during the calibration period from June until October. ET data is not recorded at Bartlett Road nor Appleby, with the closest recording climate station at Nelson, approximately 7.5km from BNE. These daily data were obtained through CliFlo.

6.2.2 Easton Apples results and discussion

SLIM output raster maps are displayed in figure 6.8. The results show that irrigation for BNE is generally efficient, with achieved average application efficiency upward of 75% for all BNE blocks. Drainage ranged between 0 and 264 mm, and only the portion of BNE-D over the clay soil was predicted to suffer from water stress during the modelled period.

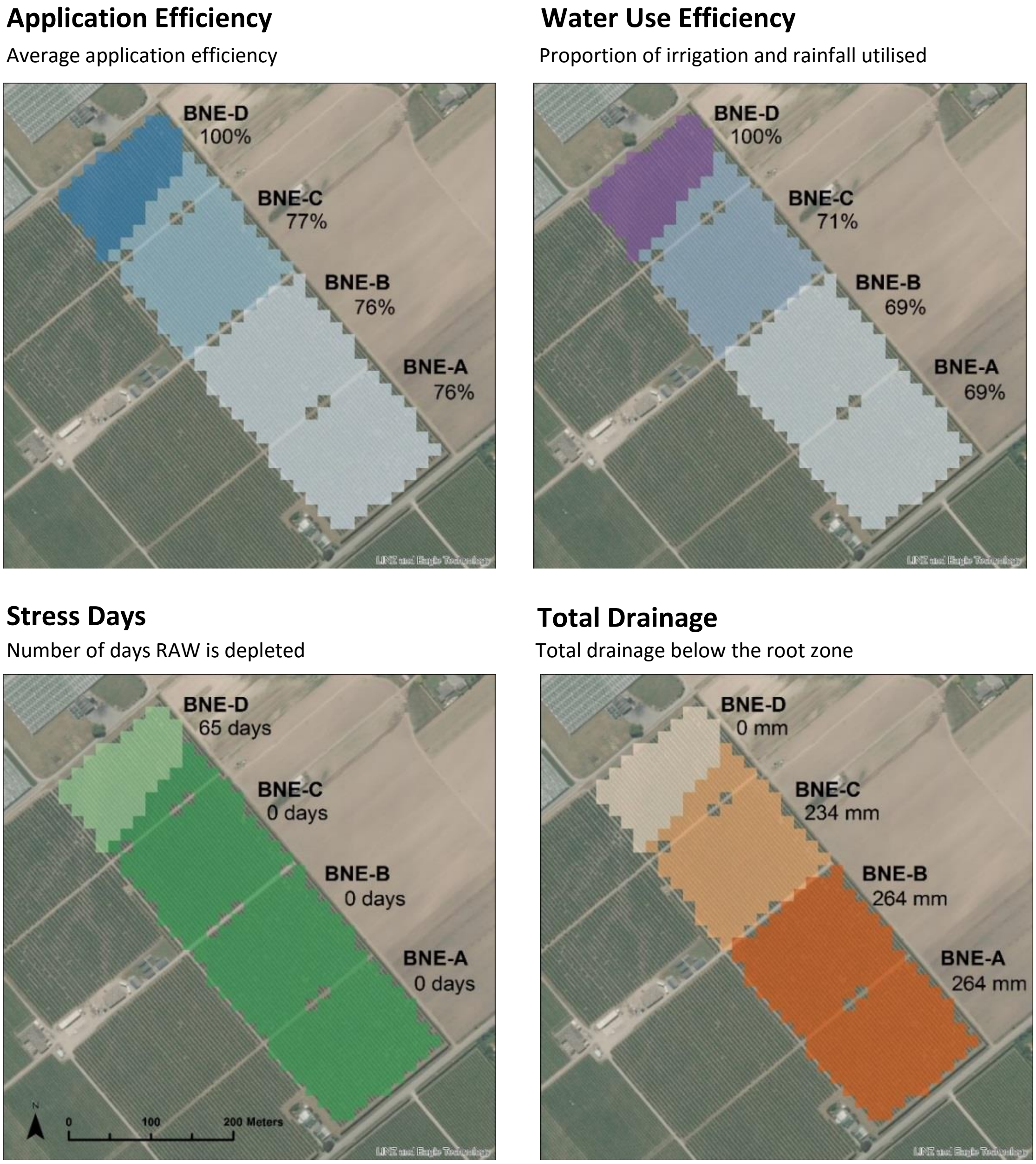


Figure 6.8 SLIM outputs for the BNE blocks at Easton Apples' Bartlett Road orchard for the 2014/15 season until 25/01/2015.

The most efficient irrigation and water use was in BNE-D over the clay soil as a result of the soil's increased ability to store water and the reduced depth and frequency of the applied irrigation compared to the other blocks. The clay area received fewer irrigations than the other blocks because the inline taps were turned off until the 14th of November. Once irrigation was initiated in BNE-D, each 3-hour application supplied just 6mm, compared to 15mm applied to BNE-A, B, and C due to the different sprinklers installed. The result was that application efficiency and water use efficiency achieved 100% in BNE-D, with no drainage beyond the rootzone predicted by SLIM. While the water-efficiencies were high for the section of BNE-D on the clay soil, it was the only block where RAW was depleted, which was predicted by SLIM to occur for 65 days over the modelled period. A plot of the modelled soil water balance is displayed in figure 6.9. RAW is equivalent to half of FC for apples (FAO56 table 22), indicating that water stress occurs when water content falls below 160mm for the clay soil in BNED (the orange line in figure 6.9). Figure 6.9 shows that soil water content is only raised above 160mm following significant rainfall, with irrigation alone not sufficient to replace water lost to ET. This suggests that irrigation should be applied for longer than the current 3 hour application time so that a greater irrigation depth is achieved and the soil moisture deficit is reduced.

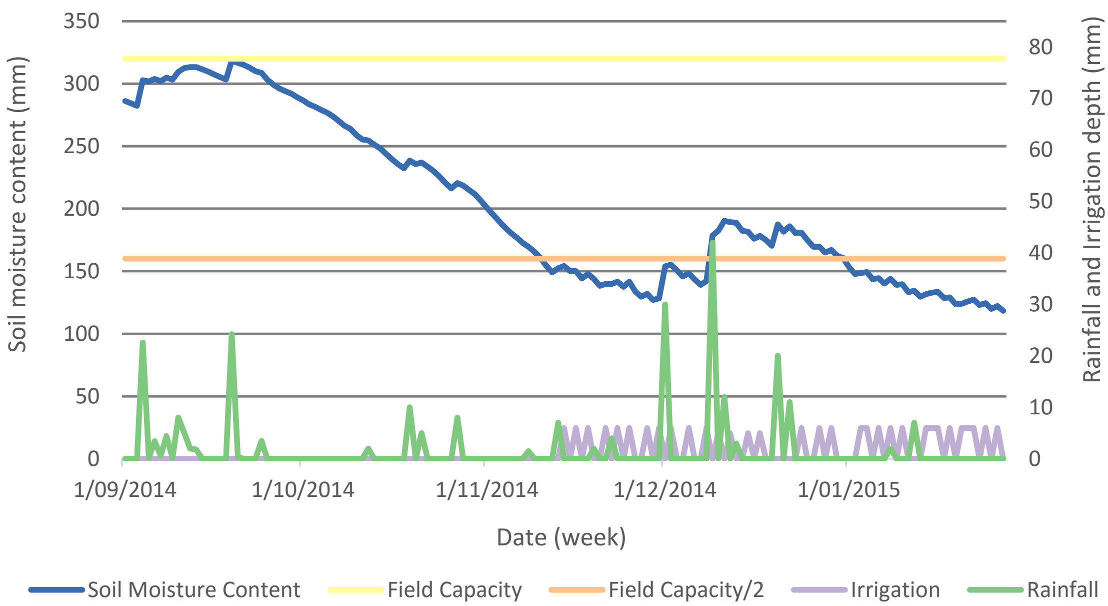


Figure 6.9 Soil Water Balance plot for BNE-D for the 2014/2015 irrigation season until 25/1/2015.

A discussion with the management team at Easton apples revealed that the water table beneath BNED was relatively high, with extended periods of surface ponding experienced in previous years following large rainfall events. Given that the rooting depth is likely greater than the modelled 900mm, it is probable that the Apple trees in BNE-D are either able to access groundwater directly, or groundwater capillary rise into the lower root zone occurs, reducing the likelihood of water stress as predicted by SLIM.

BNE-A, B, C, and the portion of D over the stones displayed lower application and water use efficiencies than the BNE-D clay, and experienced no days where RAW was depleted. Because BNE-A and B have the same soil type, sprinklers and irrigation regime, results are identical for these blocks. Irrigation to BNE-C is applied by the same sprinklers as in BNE-A and B, but under a different irrigation regime; irrigation is generally applied on opposite days to BNE-A and B, and only 43 events were recorded compared to 45 for BNE-A and B for the modelled season. The different timing of irrigation resulted in BNE-C achieving a marginally higher application and water use efficiency. Water use efficiency fell by 6% for BNE-C and 7% for BNE-A and B in comparison to the achieved application efficiency. This emphasises the importance of irrigation timing on overall water use, and suggests that rainfall utilisation could be improved for these blocks. Furthermore, the lower application efficiency (<80%) achieved over the season in BNE-A, B and C suggests that either the depth or frequency of irrigation can be reduced without effecting crop water availability. Analysis of the output time-series shows that the largest drainage events occurred when irrigation was applied immediately before or after rainfall events, or when irrigation was scheduled on consecutive days.

SLIM predicted 264mm of drainage over the modelled season for BNE-A and B, and 231mm for BNE-B. Because SLIM considers irrigation to be applied homogenously over each irrigation unit, when in reality only a fraction of the ground area is irrigated with micro sprinklers, estimates of drainage could be higher than that experienced in the field. As the centres of the orchard rows are not irrigated, it is expected that a sub-surface pressure gradient would develop and redistribute irrigation water laterally towards the row centre, reducing the volume of water transported vertically. Lateral sub-surface water redistribution is likely to reduce the leaching volume when compared to spray or surface irrigation systems that target to wet the entire field, although this effect is not likely to be significant on sandy soils where the unsaturated hydraulic conductivity is low. The actual leaching volume may also be less than predicted given that the rooting depth is likely to be greater than that modelled in the SLIM scenario; a greater rooting depth is better able to store irrigation inputs and buffer early season rainfall events.

To investigate the impact of the lower rate sprinklers installed on the clay and the in-line taps along the soil boundary, a SLIM simulation for BNE-D was run using the depth and timing information from BNE-C, replicating the original irrigation regime. The results found that application efficiency fell to 83% (figure 6.10), there was 92mm of drainage, and no days where RAW was depleted when simulating the original irrigation regime prior to intervention. The reduction in drainage between the original and current irrigation system in BNE-D shows that the interventions have been effective in reducing soil water content (and therefore susceptibility to root-rot and fungal infections) during the irrigation season, with the added benefit of increased water use efficiency and reduced irrigation volume.

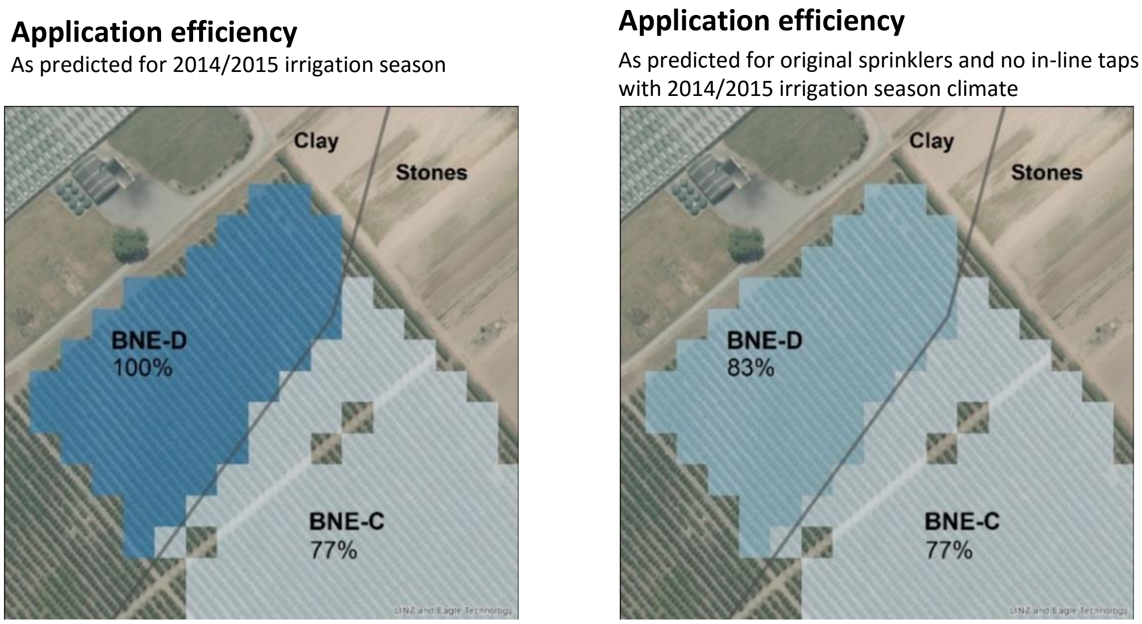


Figure 6.10 Comparison of average application efficiencies for BNE-D for the current irrigation systems (left) and the original system (right) for the 2014/2015 season until 25/01/2015.

6.2.3 Easton Apples conclusions

Overall, SLIM found that irrigation at the BNE block at the Bartlett Road orchard of Easton Apples is effective in maintaining soil water supply to the apple trees, and efficient in terms of water use. The intervention measures applied in BNE-D resulted in the most efficient irrigation from a water use perspective and were effective in reducing the number of days where the soil was saturated. The interventions in BNE-D show how irrigation systems can be effectively managed to account for differences in soil type and the use of taps and lower rate sprinklers provide an example for drainage-reducing mitigation measures that could be applied to other micro-sprinkler irrigation systems. The lowest estimated water use and application efficiencies (<80%) were predicted for BNE-A, B and C, where irrigation was applied with 15mm/hr sprinklers. The reduced efficiency suggests that irrigation frequency and/or volume could be reduced for these blocks and the timing of applications in relation to rainfall could be improved. However because sub-surface water redistribution and the full rooting depth of the trees has not been accounted for, actual application efficiency is likely to be higher than that predicted by SLIM. Furthermore, because irrigation was often applied for the purposes of potassium application rather than to satisfy crop water demand, especially following large rainfall events, the average application efficiency is likely to be reduced compared to previous years or what may be achievable if crop water supply alone was the irrigation purpose.

From a modelling perspective, this SLIM application showed that using recorded irrigation information can produce outputs that identify where mitigation measures could be targeted in the field. The results were shared with the management at Easton apples, with the information taken into consideration for irrigation scheduling for the remainder of the season alongside the Agfirst neutron probe readings, apple tree physiology, nutrient requirements and past experience. It was indicated that SLIM outputs were useful from a management perspective, especially for comparing irrigation efficiency and efficacy between blocks. SLIM results for the BNE-D scenarios (before and after mitigation measures where implemented) were especially interesting for the management team, who felt vindicated in their decision to invest in the sprinklers and labour used to reduce irrigation volumes to BNE-D. SLIM predictions of reduced soil water content in BNE-D following mitigation were supported by a reduction in observed instances of root infections.

Future improvements for modelling micro-irrigation systems should account for the partial wetting of the surface and subsequent subsurface water redistribution. This would require fine scale irrigation units matched to orchard row and sprinkler locations and explicit calculation of unsaturated sub-surface flow using Richards Equation (Richards, 1931). This extension is beyond the scope of this thesis and is likely to be computationally expensive, but represents an avenue for future development of SLIM or other spatially explicit irrigation models.

6.3 Leeston, Canterbury

Data has unfortunately not been available to include a SLIM performance evaluation for an existing spray system or arable cropping farm. A hypothetical irrigation regime has instead been applied to a farm in Canterbury by making assumptions based on satellite imagery and typical management practise. The created farm system is a mixed cropping and dairy operation, with parameters chosen to encompass a wide range of management practices rather than to closely resemble any farming system specifically. It is stressed that the results and discussion included in this section are not representative of or applicable to the actual farm at this location. The SLIM simulations examine sub- and between-field variability in irrigation performance as a result of different soil types, management techniques, and crops, and the advantages of VRI systems are explored briefly.

The simulated farm is located near Leeston in the Selwyn District in Canterbury, New Zealand. Ten irrigated fields have been created by tracing approximate boundaries visible from the satellite imagery. Each of the 10 fields is characterised by a different irrigation system, method of application decision making and/or crop. The fields total roughly 500 hectares combined.

The simulated farm system is displayed in figure 6.11. Fields 1, 2, and 3 are pasture blocks irrigated by Centre Pivots; fields 1 and 2 apply water at a fixed depth of 5mm, field 3 is irrigated every 3 days with a target depth of 15mm. Field 4 encompasses all of the 'corners' of fields 1, 2, and 3 which are irrigated by Fixed Sprinklers applying a fixed depth of 30mm. Field 5 is also producing pasture, and is irrigated by a Linear Move system applying water equal to requirement (i.e. fixed interval) with a minimum of 10mm applied every 7 days. Field 6 produces a maize crop planted on the 1st of November and irrigated by a Travelling Gun applying a fixed depth of 50mm. Field 7 is a pasture block irrigated by a K-line system applying 35mm every 7 days. Fields 8, 9, and 10 produce a Sugar Beet crop planted on 1st of October irrigated by a Rotorainer rotating boom system; the fields are irrigated every 7 days, offset by 2 days for each field which mimics a system where a single irrigator is used to irrigate all 3 fields. All depth and return interval ranges are based on table 3.3 in section 3.2.4. Christiansen's uniformity coefficient values are given as the default for each irrigator type (table 5.4, section 5.2.3). Crop parameters are derived from Tables 11, 12 and 22 from FAO56 (Allen et al., 1998). A full table of input parameters is given in tables 6.4 and 6.5.

Figure 6.11 Simulated farming system near Leeston, Canterbury

The soil information from the NZFSL is displayed in figure 6.12. Figure 6.12 shows that almost all of the fields contain multiple soil types, with many fields overlying three different soils. Large differences in the PAW and Potential Rooting Depth (PRD) figures between neighbouring soil types are evident. The 'Very Stony Sand and Very Stony Sandy Loam' is characterised by an especially low PAW (15mm) and PRD (0.44m). These highly varied soils are not uncommon for the Canterbury plains and other alluvial floodplains. Climate information was taken from CliFlo for the Leeston (Harts Creek) climate station for June 2011 to April 2012, representing the 2011/2012 growing season. These are the latest data recorded at the Leeston climate station available on CliFlo.

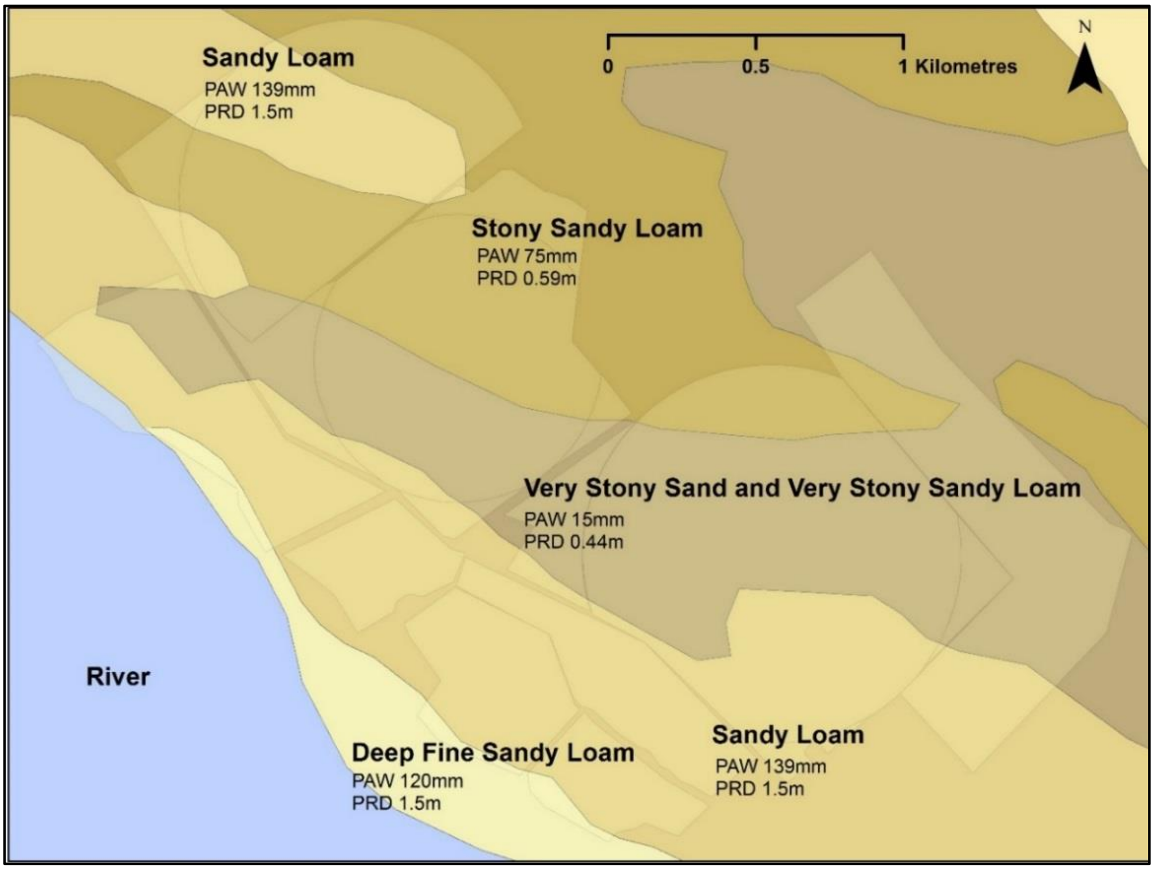


Figure 6.12 NZFSL soil information and field positions

Table 6.4 Irrigation parameters for the simulated farm system.

ID	IRRIGATOR	MANAGEMENT	TRIGGER	TARGET_DEPTH	MIN_DEPTH	INTERVAL	MIN_RETURN	SEASON_START	SEASON_END
1	Centre Pivot	FIXED_DEPTH	0.5	<Null>	5	<Null>	3	1/10/2011	1/04/2012
2	Centre Pivot	FIXED_DEPTH	0.5	<Null>	5	<Null>	3	1/10/2011	1/04/2012
3	Centre Pivot	FIXED_DEPTH_AND_INTERVAL	<Null>	15	<Null>	3	<Null>	1/10/2011	1/04/2012
4	Fixed Gun	FIXED_DEPTH	<Null>	30	5	<Null>	3	1/10/2011	1/04/2012
5	Linear Move	FIXED_INTERVAL	<Null>	<Null>	10	7	<Null>	1/11/2011	1/04/2012
6	Travelling Gun	FIXED_DEPTH	<Null>	50	<Null>	<Null>	<Null>	1/11/2011	1/04/2012
7	K-line	FIXED_DEPTH_AND_INTERVAL	<Null>	35	<Null>	7	<Null>	1/11/2011	1/04/2012
8	RotoRainer	FIXED_INTERVAL	<Null>	<Null>	30	7	<Null>	1/10/2011	1/04/2012
9	RotoRainer	FIXED_INTERVAL	<Null>	<Null>	30	7	<Null>	5/10/2011	1/04/2012
10	RotoRainer	FIXED_INTERVAL	<Null>	<Null>	30	7	<Null>	3/10/2011	1/04/2012

Table 6.5 Cropping parameters for fields 6, 8, 9, and 10.

ID	CROP_TYPE	ROOT_DEPTH	PLANT_DATE	GS_INI	GS_DEV	GS_MID	GS_LATE	KC_INI	KC_MID	KC_END
6	Maize (sweet)	1200	1/11/2011	20	25	25	10	0.3	1.15	1.05
8	Sugar Beet	1000	1/10/2011	25	35	50	50	0.35	1.2	0.9
9	Sugar Beet	1000	1/10/2011	25	35	50	50	0.35	1.2	0.9
10	Sugar Beet	1000	1/10/2011	25	35	50	50	0.35	1.2	0.9

6.3.1 Leeston results and discussion

The results show that the simulated systems varied widely in their performance, and that spatial variation in soil type contributes to large sub-field variations in application efficiency, water use efficiency, total drainage, and effectiveness in maintaining soil moisture above the stress point of crops.

The application efficiency raster output (figure 6.13) shows that the most efficient irrigation was achieved by the Centre Pivot systems over fields 1 and 2, which were both simulated to apply water when soil moisture reached half of field capacity. Because the soil with the lowest PAW within each field is used to determine the target depth where a depth is not defined, applications for field 2 were frequent and low depth (~8.7mm) due to the low PAW (15mm) in the very Stony Sand and very Stony Sandy Loam soil that intersects the field. Applications to field 1 were infrequent and much deeper (~43.4mm), as a result of decisions based on the higher PAW of the Stony Sandy Loam (75mm). A portion of field 1 is over the shallow very Stony Sand and very Stony Sandy Loam soil, but because the proportion is less than 10% of the total field area, decisions are instead based on the deeper Stony Sandy Loam. The section of shallow soil in field 1 subsequently achieved significantly lower average application efficiency (33%) compared to the portion of field 1 over the deeper soil (95%). The influence of soil properties and their proportion of the field on application decisions should be considered in future SLIM applications, and the 10% threshold altered where appropriate.

Some of the lowest application efficiencies were predicted for field 4 which encompasses the corner sections of the Centre Pivot irrigated fields. This is a result of the Fixed Gun system frequently applying a greater volume of water (30mm fixed depth) than the soil could store each time the very shallow Stony Sand and very Stony Sandy Loam soil reached its trigger point (half of FC). Improvements in efficiency could be readily made by managing each corner section separately (i.e. disaggregate the corner blocks into multiple fields in SLIM), even if the largely non-uniform Fixed Gun system (CU_c 65%) was retained. Similarly, there is opportunity for management intervention to improve application efficiency in fields 5, 6, 9, and 10 where sub-field differences in soil type resulted in sections of decreased average application efficiency. Comparing between fields shows that the highest application efficiencies are achieved by those systems that are able to apply water under either a flexible interval or at a flexible depth, where the timing or volume is determined by irrigation demand.

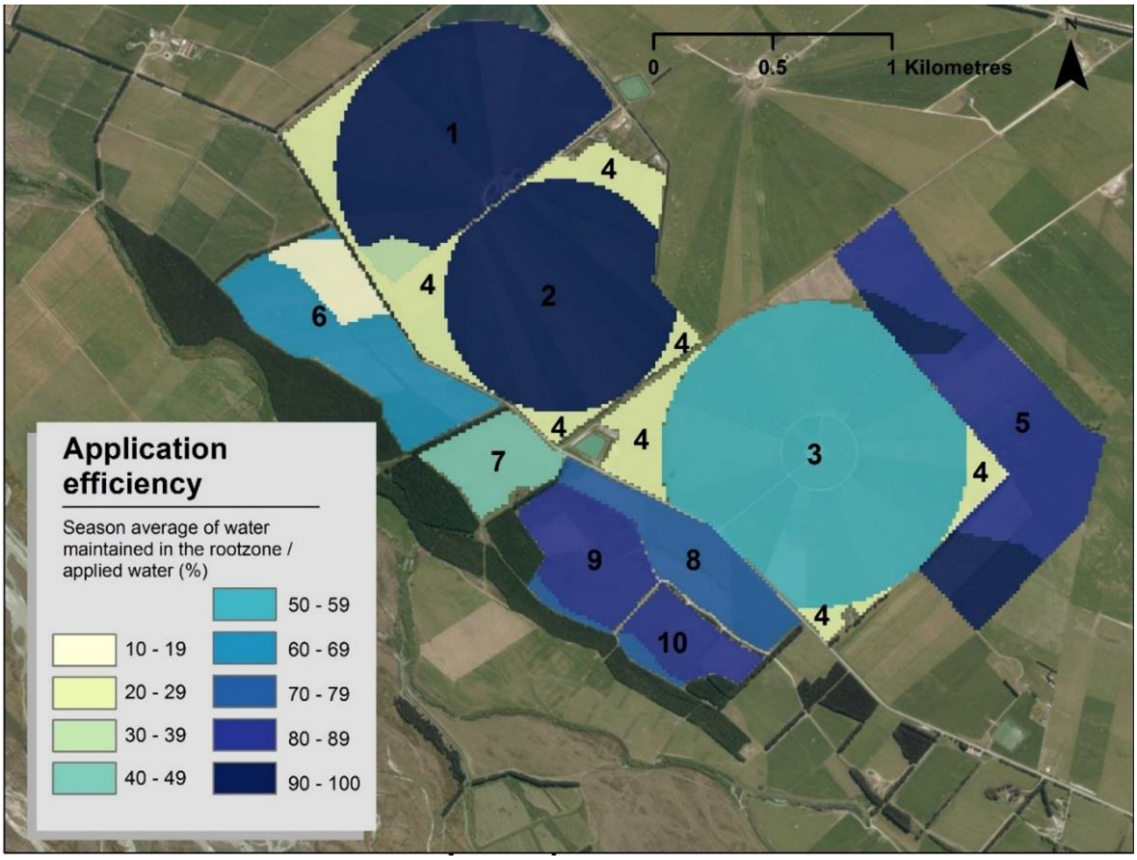


Figure 6.13 Average application efficiency predicted for the 2011/2012 growing season.

Total drainage and water use efficiency, like application efficiency, are characterised by large variation between and within fields. Figure 6.14 shows that soils with low PAW are particularly prone to large drainage volumes as they are unable to store large rainfall events, even when irrigation application is flexible and able to be delayed before or after the event. Inability to utilise all rainfall is reflected in the decreased Water Use Efficiency (WUE) (figure 6.15) compared to application efficiency for all fields in the simulation. For the sugar beet crop produced in fields 8, 9, and 10, the 2 day difference between the fields in the timing of the fixed interval irrigation resulted in total drainage volumes of 276, 168, and 175mm respectively (71%, 80% and 79% WUE), where all other parameters where equal. This emphasises the importance of irrigation timing in relation to rainfall for irrigated fields, and shows that temporal as well as spatial consideration of soil moisture variability is important for minimising the risk of nutrient leaching.

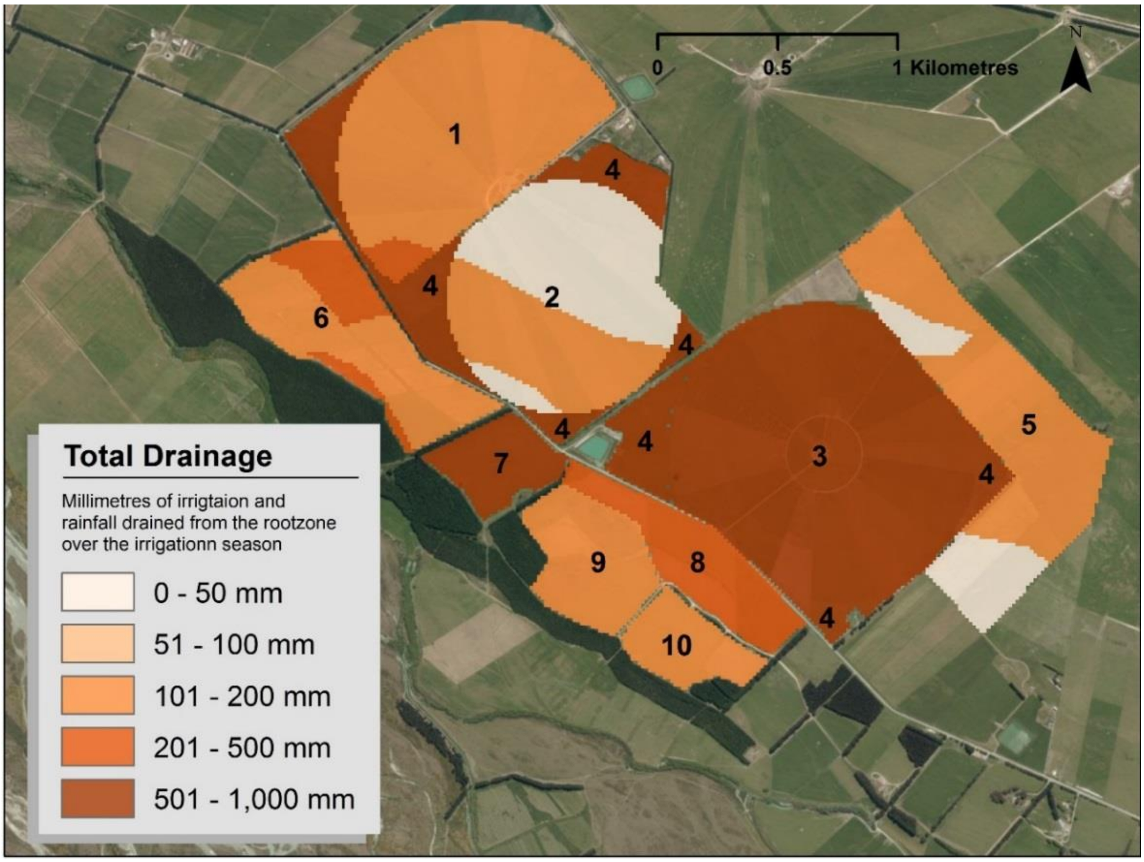


Figure 6.14 Total drainage predicted during the 2011/2012 growing season.

The lowest WUE was just 18%, which was predicted for the portion of field 6 (Maize crop) over the shallow Stony Sand and very Stony Sandy Loam soil. This is a result of the soil's inability to store rainfall and irrigation, which was exacerbated during the early season stage of the Maize development where rooting depth was only 50mm (depth), and PAW less than 10mm (water). The Travelling Gun system applied 50mm each irrigation, and significant drainage was experienced over the whole field during the crop development stage on all soil types in field 6. This highlights the sensitivity of arable crops to drainage in their early season stages, and indicates that achieving high application or water use efficiency is likely to be very difficult for most irrigation systems in rotational cropping situations.

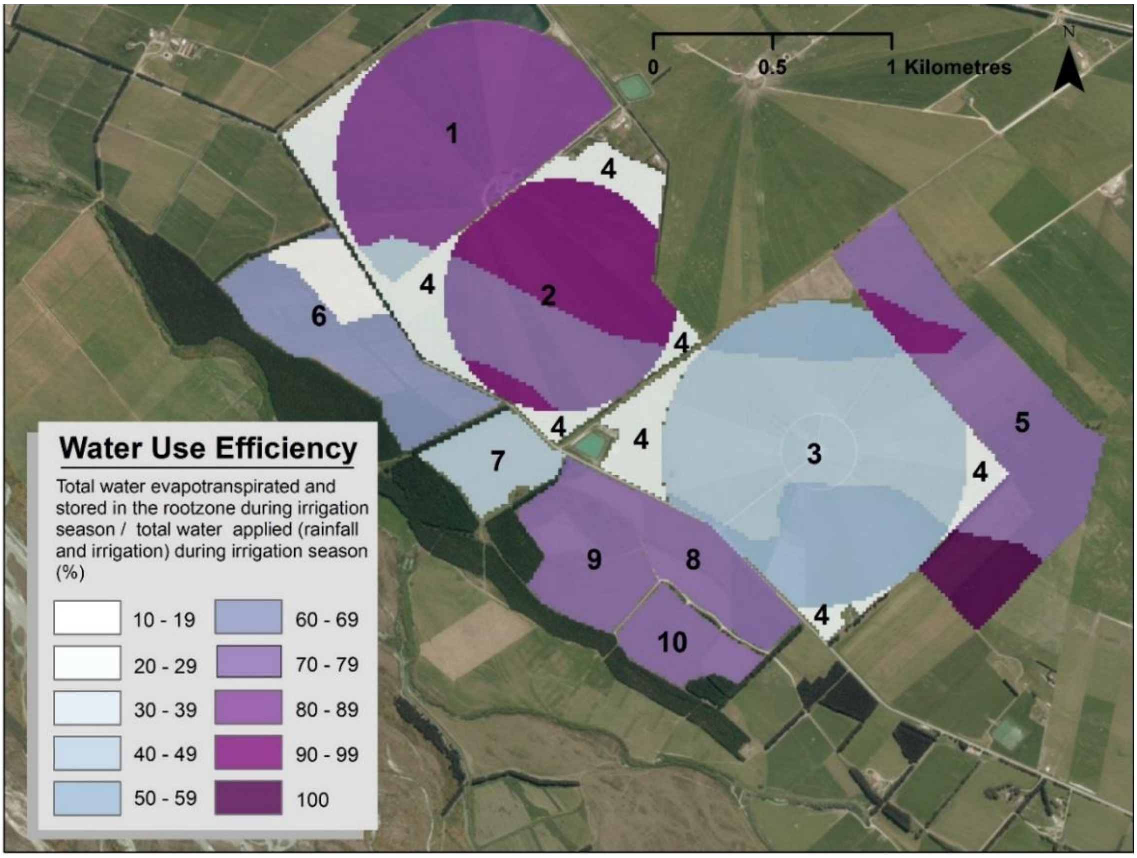


Figure 6.15 Water use efficiency predicted for the 2011/ 2012 growing season.

The Stress Day raster also shows sub-field variation in the number of days where soil moisture is less than the stress point of the crop as a result of soil variation. The stress point (i.e. the proportion of Total Available Water (TAW) that is not readily available) used in the simulation for pasture and the maize crop was 0.5, and 0.55 for the sugar beet crop as given in table 22 in FAO56 (Allen et al., 1998). Like water use efficiencies, figure 6.16 shows that soils with very low PAW result in poor performance for minimising crop stress. Similarly, systems that were unable to provide sufficient water to satisfy atmospheric demand resulted in more days of crop stress. For example, field 5 experienced 91 days where soil moisture was below the stress point (0.5) of the pasture in the portions of the field with deep soil (139mm PAW) due to a 7 day return interval and low application depth which were insufficient to maintain soil moisture above the crop stress point for prolonged periods. From a crop growth perspective, the best performing systems (i.e. those able to maintain soil moisture above the stress point) are those that apply water at a flexible interval or depth, which are able to compensate for increased atmospheric water demand by applying more water or water more frequently.

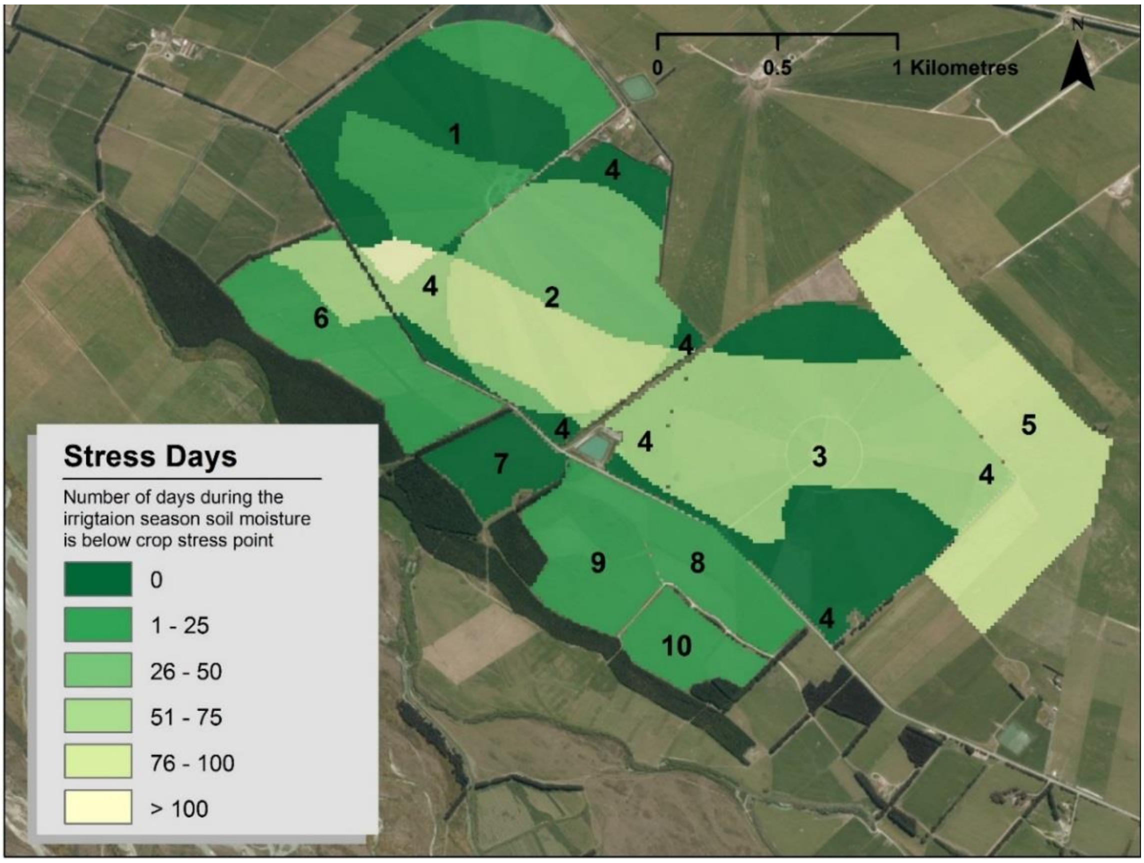


Figure 6.16 Number of days where water content is below the stress point of the crop predicted for the 2011/2012 growing season.

To investigate the effectiveness of Variable Rate Irrigation (VRI), a comparison was undertaken for fields 3 (Centre Pivot) and 5 (Linear Move) between the irrigation regime given for the scenario above and a scenario where the irrigators have been equipped with variable rate technology. The existing return interval (3 days and 7 days for the Centre Pivot and Linear Move respectively) and minimum depth (5 and 10 mm) parameters were retained for the VRI simulation.

The outputs for application efficiency, total drainage and stress days are displayed in Figure 6.17, which show that VRI was able to improve the performance of both irrigation systems. For the fixed interval Centre Pivot system, application efficiency was improved to 93% over the whole field, and total drainage reduced by 443mm for the shallowest soil during the simulated season. The improved efficiency is due to the VRI system applying water to satisfy the soil moisture deficit at the time of irrigation, where the original system applied 15mm regardless of the soil moisture content at the time of application. The outputs suggest that implementation of VRI technology represents an avenue for significant water savings for the Centre Pivot irrigated field. It should be noted that this comparison is intentionally simplistic, and does not account for the cost of implementation or likely management changes that could be implemented for both regimes.

Standard Irrigation

Centre Pivot: 15mm applied every 3 days
Linear Move: Irrigation applied every 7 days at a target depth equal to the deficit of the driest portion of the field

Variable Rate Irrigation

Centre Pivot: VRI applied every 3 days
Linear Move: VRI applied every 7 days

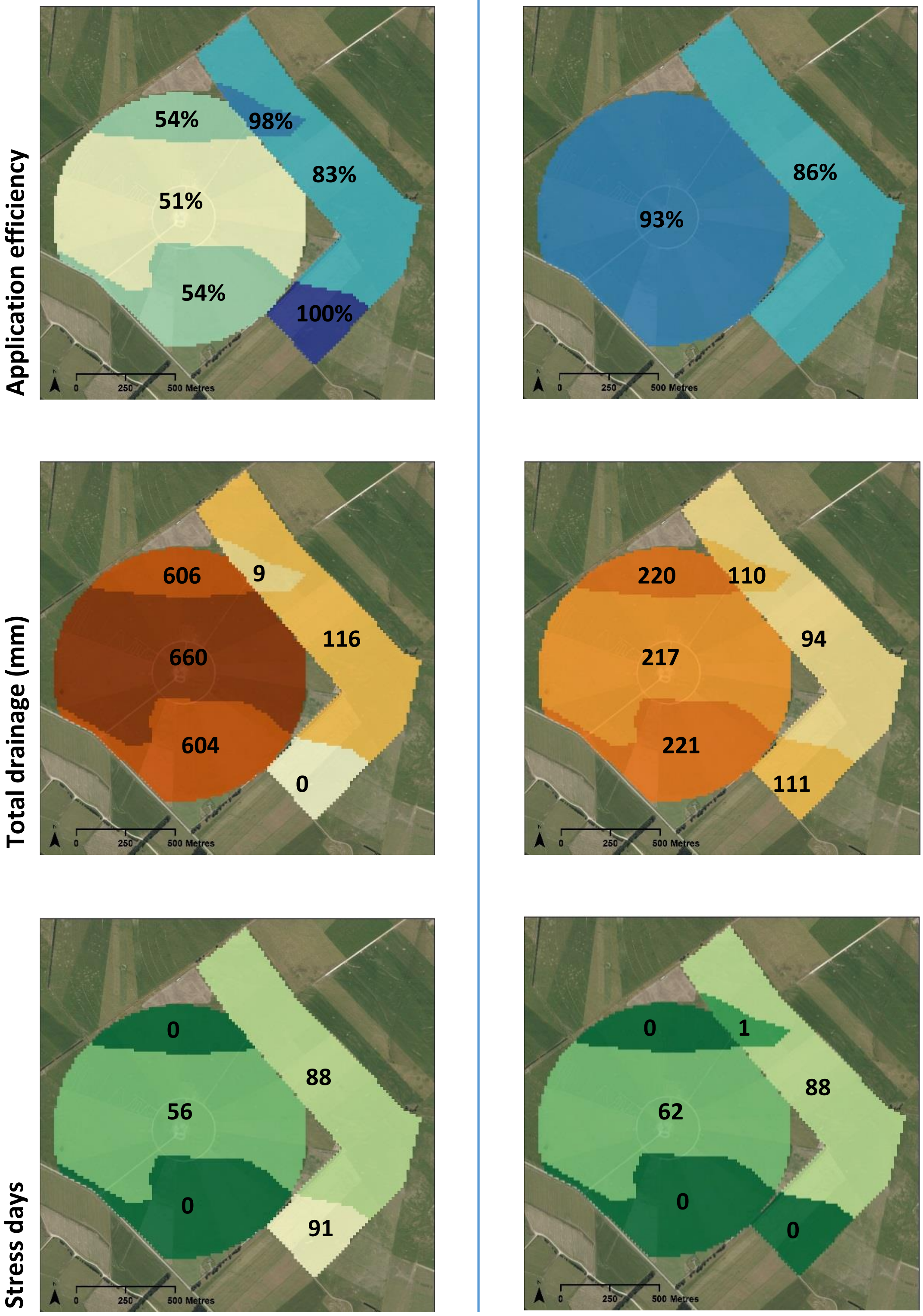


Figure 6.17 Comparison between a standard irrigation system (left) and a Variable Rate Irrigation system (right) for the 2011/2012 growing season.

The field irrigated by the Linear Move system experienced only marginal application efficiency improvement with VRI implementation, and the portions of the field over deeper soils actually experienced reduced application efficiency and increased drainage compared to the standard system. This is due to the low depths (~10mm) that were applied based on the requirements of the shallow soil in the field for the standard system. The low depths and 7-day return interval were efficient under the standard system, but resulted in a large number of days (88 and 91) where soil moisture was below the stress point of the pasture for the portions of the field over the deeper soils, compared to just 1 and 0 stress days predicted for the same soils under the VRI system which was able to apply water at a target depth equivalent to the soil moisture deficit at the time of irrigation. These results suggest that VRI implementation for the Linear Move system would most improve water supply to the pasture and would likely improve crop production significantly.

To determine the role of spatial and temporal variation of irrigation depth on efficiency, the scenario was run two more times. The first scenario, to test the impact of temporal variation in application depth, simulated VRI irrigators capable of supplying a spatially homogenous, but temporally variable depth of irrigation at each application. The target depth for each application is equal to the soil moisture deficit over the driest portion of the field at the time of irrigation. The second scenario tests the impact of spatial variability by simulating irrigators capable of varying their applications spatially, prescribed as a target depth equal to RAW over the corresponding soil type, but not temporally, i.e. the same volume is applied to each irrigation unit at each application.

For the first, temporally variable application depth scenario, achieved application efficiencies were between 86% and 89% for the Centre Pivot irrigated field, and 82% and 99% for the field irrigated with the Linear Move system. The spatially variable applications simulated in the second scenario exhibited a lower spatial variation in achieved application efficiencies, at 85% over the entire Centre Pivot irrigated area, and between 82% and 84% for irrigation units supplied by the Linear Move system. These results indicate that varying irrigation depth temporally can achieve higher application efficiencies than varying depths spatially, however at a reduced spatial consistency between soil types within a single field. Similar results were recorded between the temporal and spatially varied treatments for water use efficiency and drainage, with the temporally varied irrigation achieving slightly higher water use efficiency (65% - 86% against 63% - 73%) and lower drainage values (2mm – 276mm against 114mm – 283mm) over the two modelled fields, but exhibiting a greater spatial variation in results. The spatially varied treatment was better able to maintain soil moisture above the stress point of the pasture, with the number of stress days predicted between 0 and 83 over the different soil types, compared to between 0 and 88 for the temporally varied treatment.

For all measures, applications that were varied both temporally and spatially (page 143) were more efficient than varying application depth in either time or space individually. Whether spatial or temporal flexibility is more important in terms of efficiency and efficacy is likely to be site specific and dependent on soil properties, the weather regime, and the timing of irrigation. For the implementation of a new irrigation system, the choice of VRI system, either variable in space or time, could be aided by running similar comparison tests using SLIM. In general however, this examination of VRI irrigation indicates that the highest efficiencies are achieved by those irrigators with the greatest flexibility in both time and space.

6.3.2 Leeston conclusions

The SLIM simulation shows that variations in soil type are a major influence on irrigation system performance. The results showed that high application efficiencies where able to be achieved in fields containing variable soils through high frequency, low depth irrigation that is applied based on crop water demand. However very shallow soils were unable to be consistently maintained above the stress point of pasture, and were prone to drainage following rainfall events even where irrigation application efficiencies were high.

The SLIM outputs display the sub-field variation in system performance that result from changes in soil type that would not be accounted for in a general, non-spatial irrigation model. The outputs could readily inform farm management decisions regarding the irrigation regime, crop and stock rotations, field layout and potential infrastructure investment. While an experienced farmer will likely be able to better identify areas where irrigation performance for crop production can be improved, SLIM outputs may still provide useful information, especially regarding difficult to measure drainage volumes and irrigation efficiencies.

A challenge facing a spatially explicit model such as SLIM for predicting homogenous irrigation applications over heterogeneous soils is which soil type to base the depth and timing parameters when they are not given by a user. Knowledge of the model process and farming system is therefore important where SLIM is used to predict irrigations so that the minimum proportion limitation (default 10%) can be altered where appropriate.

6.4 Case studies summary

The three case studies presented in this chapter show SLIM was able to model a wide range of irrigation systems independent of data availability. Irrigation prediction for the border dyke irrigation at Winchmore showed good agreement with recorded data, while simulating actual irrigation events with time-series data at Easton Apples' Bartlett road block provided usable information for irrigation management for the remainder of the season. The results also emphasised the importance of quality input data. Winchmore results were highly sensitive to the PAW value used, and results at Easton Apples may have been erroneous due to an under prediction of the rooting depth of apple trees. The accuracy of the soil information from the Fundamental Soils Layer used for the Leeston simulations is not known.

SLIM is able to model surface, micro, and spray irrigation systems. There is scope for improvement in the consideration of surface and micro systems by accounting for system outflow and sub-surface redistribution respectively. SLIM operation and parameterisation was relatively simple, and was completed remotely on a desktop computer. Once data for each site was collated, SLIM runtimes were ~3 minutes for the 11 year simulation at Winchmore, ~20 seconds for the Easton Apples applications, and ~7 minutes for the 10 field, 500 hectare mixed farming system at Leeston.

Assuming the modelled systems are representative, SLIM outputs presented in this chapter show that there is scope to improve ecosystem service provision in irrigated landscapes in New Zealand. The simulations showed that those systems able to achieve high application- and water use-efficiencies while maintaining a constant supply of readily available water to crops were those that were flexible in their timing and/or application depth so that variations in the supply and demand of water from the atmosphere were able to be utilised and satisfied respectively. In general, high-frequency, low-depth application was the most effective irrigation regime, even over very shallow soils.

7 Discussion & conclusions

This section discusses SLIM assumptions, limitations, and utility. Opportunities for future extensions and improvements of SLIM are discussed, and final conclusions with regard to the thesis aim and objectives are presented. An in depth discussion on SLIM processes is provided in Chapter 5.

7.1 SLIM discussion

SLIM is physically based and follows accepted practice for estimating irrigation demand, application depth, and irrigation timing. SLIM is widely applicable, with 6 different spray irrigators, micro irrigation, border dyke systems, and Variable Rate Irrigation (VRI) currently able to be simulated. Data inputs are flexible and default values are informed by the literature, allowing SLIM application without need for site-specific parameterisation. Results presented in chapter 6 show that SLIM is able to accurately predict irrigation event timing and produce usable outputs that spatially identify where ecosystem service improvement can be made in irrigated agroecosystems.

It was beyond the scope of this thesis to fully integrate SLIM within the LUCI framework. However, the SLIM time-series output files describing irrigation timing and depth, combined with spatial polygons describing the irrigated area, can be readily input to LUCI to include irrigation flows in LUCI assessment of ecosystem services. Future full integration with LUCI will utilise existing LUCI hydrology algorithms to allow for surface runoff, topographical routing of water, and groundwater interactions, which are not currently accounted for in SLIM (see section 5.3). Simulating losses via surface runoff and subsequent water movement for irrigation and rainfall will result in changes in irrigation demand, especially on sloped fields and under high intensity irrigation systems. It is anticipated that SLIM will be readily and fully integrated into LUCI following the completion of this thesis.

7.1.1 Limitations and key assumptions

The primary assumptions in SLIM concern the movement and storage of water within the soil profile. Specifically, SLIM assumes that wetting following irrigation or rainfall is homogenous in the soil profile, and that irrigation units are free draining when water content exceeds field capacity (although overland flow will be incorporated in future versions). Assuming homogenous soil wetting is commonplace among water balance frameworks, but will likely result in an underestimation of drainage (and therefore overestimation of water use efficiencies) because rapid losses via macropore pathways are not accounted for (see section 4.1.2) (White, Johnson, & Snow, 2008). SLIM also assumes that losses from wind-drift, leaking pipes or canals, blocked sprinklers, or canopy interception are negligible in their effect on application depth to the soil profile. Where water losses from these sources are high, SLIM predictions for application depth may be erroneous. Other assumptions regard the method for estimating gross irrigation depth from Christiansen's coefficient of uniformity described in section 3.4. The primary assumption of this method is that data describing the uniformity (CU_c) and adequacy (default 80%) are applicable to the modelled system, and the distribution of application depths follows a Gaussian distribution. In regard to irrigation timing, SLIM assumes that water is always available to irrigate when required. Furthermore, influences on irrigation application outside of the field water balance are not accounted for, such as social factors, labour availability, weather uncertainties, price of electricity, other economic factors, or equipment malfunction.

In comparison to existing irrigation frameworks, SLIM provides some significant advantages in its consideration of an irrigated farming system. The primary point of difference for SLIM compared to existing models such as IrriCalc (Bright, 2009), Overseer (Wheeler & Rutherford, 2013), and the Irrigation Calculator (Martin et al., 2008), is an explicit consideration of spatial soil variability. Explicit consideration of soil variability allows for more accurate quantification of water flows in irrigated fields (provided input data are accurate), and provides outputs which allow for targeted management intervention. For estimates of efficiency, SLIM is able to account for the current water content of the soil, which allows for application and water use efficiencies to change between events and reflect management practise. Explicit consideration of the soil water balance provides a more realistic simulation of what occurs in the field than those models that assume a static application efficiency or inefficiency factor across all irrigation events (e.g. Santhi et al., 2005; Seginer, 1987; Wheeler & Rutherford, 2013).

The spatially explicit nature of SLIM also presents challenges not faced by lumped models. For SLIM applications in data scarce scenarios where soils are variable, an assumption must be made as to which soil type to base irrigation decisions (depth and timing). The current default is based on the area of the field with the lowest water holding capacity, so long as that area comprises at least 10% of the modelled field. This assumption means that predicted irrigation in data scarce scenarios may be applied more regularly, and application depths lower, than what is practical (where not constrained by a minimum target depth or return interval), due to the rapid water depletion of shallow soils. Frequent, low depth irrigation was predicted for Fields 2 and 3 in the Leeston simulations (section 6.3) for this reason, which resulted in very little drainage simulated anywhere within the field because the target irrigation depth was equal to the soil moisture deficit of the shallowest soil in the field (i.e. very low). Prediction of low application depths is likely to significantly under-estimate the drainage of typical systems, and may result in an underestimation of the utility of VRI systems in comparison to an existing system. Care should therefore be taken when predicting irrigation applications over shallow soils where irrigation system data are not available.

Water movement within irrigated fields is another consideration unique to a spatially explicit model. Currently, irrigation units in SLIM are considered to be independent of one another and no movement can take place. Accounting for sub-surface water movement requires lateral flows to be modelled which is computationally expensive, but represents an avenue for future extension to account for those systems that irrigate only a portion of the field (e.g. micro systems or furrow surface irrigation). Similarly, capillary rise, while not exclusive to spatial modelling, can act as a water source to plant root systems where water tables are high. As discussed earlier, it is anticipated that SLIM integration with the LUCI framework will allow groundwater interactions and subsequent capillary rise into the rootzone to be quantified, along with lateral flows. Additionally, LUCI integration will enable surface water exchange through topographical routing of water to be simulated within fields.

Like all data-driven models, the quality of SLIM results is heavily reliant on the accuracy and precision of the input data. SLIM has been designed to allow application even in data scarce scenarios, although the use of the Fundamental Soils Layer (FSL) represents a source of uncertainty, following the discrepancies between FSL estimates of PAW and those measured for the soils at Winchmore and Easton Apples (sections 6.1 and 6.2). Site-specific soil data should therefore be preferred where available. For any application, the input climate parameters are extremely important – SLIM outputs are only applicable to the irrigation season simulated as estimations of drainage, crop stress and water use efficiency are subject to change depending on the supply and demand of water from the atmosphere. Multi-year simulations will provide an understanding of the irrigation system performance for a range of climate types.

A further source of uncertainty for SLIM is that, like any water balance model, errors are cumulative and irrigation applications can become out of step with requirement (Greenwood et al., 2010). While SLIM estimation of soil moisture content can be assumed to be calibrated to the field at each recorded rainfall event that saturates the soil profile, differences in timing may be compounded between predicted and actual irrigation. Furthermore, where application decisions are influenced by labour restrictions, water supply, economics, or are based on intuition rather than the soil water balance, irrigation may be delayed or applied early in comparison to the timing predicted by SLIM.

7.1.2 SLIM utility

There are a number of applications where SLIM may be able to aid decision making processes. The primary focus for SLIM outputs is to aid on-farm irrigation decision making regarding ecosystem service provision by identifying areas where application efficiency, water use efficiency, drainage, and crop water supply can be improved. Decisions may relate to the timing or the depth of irrigation applied with an existing system, or to the design process for a new or upgraded irrigation system. Specific interventions will depend on the irrigation system, as some systems are more flexible than others in their ability to change application depth and timing. For spray and micro sprinkler systems, sprinklers may be replaced with higher or lower intensity emitters, as was done successfully at Easton Apples to account for different soil types (section 6.2). For travelling or manual move systems, interventions in response to SLIM outputs may involve changes in irrigator position or application extent. For the implementation of a new irrigation system, SLIM outputs could aid comparison between potential irrigators. For fixed depth or interval systems, SLIM can inform initial design by providing information regarding water losses and utilisation for a range of application depths or return intervals.

With regard to other farm inputs such as fertiliser, crop types, and stocking rates, SLIM outputs can aid the establishment of management zones. For example sub-field areas identified as prone to drainage may be fenced off, or areas characterised by high water use efficiencies could be targeted for effluent application. Furthermore, Woodward et al. (2001) identify that predictions of soil water content, as are provided by SLIM, can be used to support decisions for stock rotations, feed rationing, or supplementary feed purchasing for pastoral farms.

For scheduling irrigation applications and depths, SLIM utility is limited by available data. While George, Shende, & Raghuwanshi (2000) have identified a need for generally applicable, user-friendly irrigation scheduling models, Hedley & Yule, (2009) recognise that the utility of real time scheduling is heavily reliant on quality data which must include the effects of site-specific rainfall, rooting depth and compaction zones. Data at this level of precision has not been available during this thesis. Should such data become available, SLIM is well placed for adaption for real-time scheduling because sub-field variability in soil properties is accounted for. George et al. (2000) identified that barriers to adoption for irrigation scheduling models were their specialised hardware requirements, difficulty to use, and inability to simulate multiple fields simultaneously; SLIM has been designed with usability and utility in mind, and is not constrained by these limitations. More generally, Edkins (2006) acknowledged that communicating knowledge with stakeholders represents the largest barrier to irrigation efficiency improvement measures. While SLIM outputs have not yet been tested in depth with irrigation managers, the raster outputs provide a simple visualisation of irrigation performance that is likely to be relatable and easy to understand. SLIM outputs for Easton Apples (section 6.2) where deemed useful by the orchard management for informing irrigation decisions.

7.1.2.1 Opportunities for ecosystem service improvement

As found in Chapter 2, ecosystem service provision can (in general) be improved for food provision, water supply, and water quality by reducing the volume of non-beneficial water losses from irrigated fields.

The case studies (chapter 6) showed that there are irrigation specific strategies to improve ecosystem service provision in irrigated landscapes. The Winchmore case study (section 6.1) showed that even under deficit management for the 10% border dyke trials, where irrigation is not applied until the pasture was stressed (i.e. Readily Available Water [RAW] was depleted), production was still significantly higher than dryland fields. Applying irrigation after RAW has been depleted produces a greater soil moisture deficit that allows for increased application efficiency, and therefore reduced drainage. Even if individual irrigation events are inefficient due to poor uniformity, or the system is poorly designed and runoff is inevitable, the total volume of drainage will be significantly reduced under deficit irrigation management compared to more regular irrigation, as was found when comparing the three modelled border dyke trials at Winchmore. For the micro irrigation system at Easton Apples' BNE blocks, the use of inline taps and reduced intensity micro sprinklers showed a relatively simple modification to an existing irrigation system that was able to significant improve application efficiency and reduce drainage in response to variable soils.

For nutrient leaching, section 2.3 showed that as well as the volume of water lost as drainage, the timing of irrigation in relation to fertiliser inputs was an important determinant of the nutrient content of runoff and drained water. Active management and the flexibility of irrigation systems with regard to farm management and climate represents an opportunity for considerable reductions in drainage, and therefore nutrient loss. It was shown for the SLIM applications at Easton Apples and the Leeston farming system that those irrigators capable of irrigating in response to rainfall and changes in atmospheric demand (PET) were able to achieve high efficiencies, and therefore low drainage volumes, while maintaining soil moisture. Spatial flexibility is also important; SLIM outputs for Easton Apples and Leeston showed that irrigated fields over variable soils display large variability in efficiency and efficacy. Those irrigation systems able to be managed in response to changes in soil and crop demands will be far more effective for the provision of a suite of ecosystem services. Specific whole-farm management strategies for nutrient loss mitigation are discussed in Monaghan et al. (2007).

In general, low depth, high frequency irrigation can maintain adequate soil moisture while minimising drainage even over shallow and variable soils. For systems characterised by low depth application, it is critical that the application distribution uniformity is high. If the distribution uniformity is low, even if high application efficiencies are able to be achieved, the adequately watered area will be unacceptably low, and economic objectives will not be met (Lincoln Environmental, 2000b). Low depth, high frequency irrigation systems that apply water in a uniform manner therefore represent the ideal irrigation system for most farming systems, and are able to achieve, in general, the greatest net ecosystem service benefit.

7.1.3 Future extensions

SLIM is generalisable, and there are a number of possible extensions possible to improve and expand SLIM's consideration of irrigated agroecosystems.

A necessary development of the existing SLIM algorithm is an improved simulation of surface and micro irrigation systems. For surface irrigation, SLIM currently assumes best management practise is always followed: that all water applied infiltrates the soil within the field boundaries. In reality, many surface systems are prone to surface outwash, which can contribute significant volumes of nutrient to waterways (see section 2.3). Once SLIM has been integrated with LUCI, existing hydrology algorithms will allow surface irrigation dynamics to be simulated, with surface water routed across the field surface and an infiltration rate curve applied to determine the volume of water entering the soil profile. For micro systems, and those that apply water to only a fraction of the field, improved consideration is likely to require detailed, site specific data, and a high-resolution DEM so that irrigation units are able to be matched to the application area of the irrigation system. As discussed, LUCI integration will also provide opportunity to account for infiltration excess (Hortonian) and saturation induced overland flow for both rainfall and irrigation inputs.

For surface water flows to be modelled, a sub-daily time step is required, which presents further opportunities for expanding the irrigation purposes modelled for in SLIM beyond water application for crop growth (section 3.2.1). A sub-daily time-step, combined with detailed climatic measurements, can inform irrigation simulation for frost protection or crop canopy cooling. Other irrigation purposes such as for fertigation or chemigation may be predicted through integration with a specialised crop growth model, which may provide further opportunities to explicitly account for nutrient utilisation of crops. Increased crop growth detail may also allow for estimates of water-use to yield ratios to be obtained. SLIM is also readily expandable to predict applications of effluent for livestock farming systems. SLIM may be combined with Dairy New Zealand's effluent storage calculator (Dairy New Zealand, 2015) and stocking information to estimate effluent application requirements. Similarly, the nutrient content of irrigation water, as discussed in section 2.3, is an important consideration for nutrient utilisation and export from farming systems. It is anticipated that irrigation water chemistry will be included for LUCI reactive Nitrogen (Nr) and Phosphorous (P) export estimations in future.

There is also opportunity to improve SLIM's estimation of evapotranspiration (ET). Estimates of AET immediately following rainfall or irrigation may currently be under predicted by SLIM's single layer water balance structure because the top part of the soil profile containing the majority of the root mass tends to be wetter than lower parts of the profile following surface wetting (Woodward et al., 2001). A dual-layer water balance, where the upper layer represents a rapidly filled and depleted water store, is the suggested approach by Woodward et al. (2001) to improve estimation of ET immediately after rainfall and irrigation. Increased detail for PET estimation may also be attained by using the dual crop coefficient method described in FAO56. The dual crop coefficient approach estimates evaporation and transpiration separately, which, compared to the single crop coefficient approach, may provide a more accurate estimation of ET for row crops and during the initial growth stage of seasonal crops where there is a high proportion of bare soil (Allen et al., 1998). Data requirements however are much greater than what is needed for the single crop coefficient method currently used in SLIM.

For irrigation application, spatially explicit irrigation modelling provides an opportunity for highly detailed site specific simulation through consideration of specific uniformities of an irrigation system (e.g. catch can measurements). For surface systems, areas of the field prone to greater water application depths (i.e. at the head of the field for border dykes) may be simulated, or wind effects may be able to be accounted for during spray system simulations. SLIM's consideration of spatially variable soils may also be expanded to included climate parameters so that the effects of localised rainfall events, micro climates, and shelterbelts can be accounted for. Large scale spatial climate variability may be captured and utilised through NIWA's Virtual Climate Network (VCN), however farm and field-scale consideration is likely to require on-site instrumentation.

Integration with measurement devices or sensors represents a further opportunity for extension of SLIM. Soil moisture data, from neutron probe measurements or electrical-conductivity surveys may allow real-time calibration and provide sufficient accuracy to enable accurate and reliable irrigation scheduling. Accuracy of crop water use estimates may also be improved through Normalised Difference Vegetation Index (NDVI) sensors, which can provide a rapid measurement of the current crop coefficient following the linear relationship established in Choudhury et al. (1994).

Other extensions include accounting for the supply and conveyance of water to the irrigation system and including economic factors in SLIM assessment of irrigation systems. An irrigation supply limit could be implemented in SLIM to account for irrigation restrictions. Water restriction consideration also requires water use strategies to be included to account for prioritisation of certain fields or crops over others, the reduction of trigger points, or other water saving techniques that may be used by a manager. Water losses and sporadic supply due to conveyance infrastructure could be incorporated using an edge-node model as in Santhi et al. (2005), although site-specific data collection is necessary. Economic consideration in SLIM could include capital and operational costs compared against an estimated income based on crop yield and market prices.

Opportunities also exist for SLIM improvement with regard to data inputs and model structure. SLIM currently requires that irrigated areas be defined and parameterised, however for regional scale implementations of SLIM and/or LUCI tools, data collection and manipulation may be impractical. There is unfortunately no national New Zealand scale dataset of irrigated fields beyond non-spatial regional statistics. There exists an opportunity for prediction of irrigation implementation based on a combination of survey data, land use information, topography, and climate; datasets of which are all readily available at national and regional scales. SLIM data structures could also be modified to allow easier and faster model initialisation and runtimes. Specifically, the fully distributed nature of SLIM means that processing is computationally expensive as the water balance of each irrigation unit is manipulated for each time-step. Adapting the irrigation units into a semi-distributed framework where irrigation units with equal parameters are combined represents an opportunity for significantly faster processing times without a reduction in the precision or utility of the SLIM outputs. Additionally, SLIM outputs can be readily extended to include other measures beyond application efficiency, irrigation efficiency, drainage volume and crop stress by modifying the code. For example other definitions of irrigation efficiency, or total ET could be displayed for each irrigation unit.

7.2 Conclusions

The aim of this thesis was to produce a physically based, spatially explicit irrigation model following accepted hydrological practice that can produce standalone outputs capable of identifying where gains in ecosystem service provision can be made by altering irrigation in space, time and volume, and inform LUCI tools hydrology. The Spatially-explicit LUCI Irrigation Model (SLIM) satisfies the thesis aim. Building on research presented in Chapter 3 which describes important elements of irrigation systems, and Chapter 4 which describes physical properties of irrigated fields, SLIM was developed and described in Chapter 5. Chapter 2 found that (in general) ecosystem service provision for food production, water supply, and water quality can be improved by maintaining plant available water while minimising losses to drainage and runoff. These findings informed SLIM outputs, and the case studies presented in Chapter 6 showed where ecosystem service provision could be improved in three farming systems in New Zealand.

Objective 1 was to summarise how irrigation impacts ecosystem services and identify where ecosystem service provision can be improved with regard to irrigation. Chapter 2 achieved this objective. Chapter 2 showed that the primary impacts of irrigation with regard to ecosystem service provision are that food production is enhanced significantly, while water supply and water quality in irrigated catchments can be reduced, especially under poor management. Agricultural production is enhanced by maintaining plant readily available water to crops, which allows just 14% of the global agricultural area to produce 40% of crops. Increasing competition for water and recognition of the importance of environmental flows means irrigation efficiency (i.e. volume of water utilised/volume of water applied) is increasingly important. Improving efficiency results in a reduction in the volume of water lost to drainage and runoff, which improves the provision of clean water by reducing losses of nutrients to waterways. Improved irrigation efficiency can also reduce on-farm costs associated with labour and electricity. In most instances, improving irrigation efficiency represents an opportunity for synergistic ecosystem service benefit. However, each catchment and farm system should be viewed holistically and potentially beneficial return flows, costs, practicability, and farm management with regard to nutrient sources should be considered for any intervention strategy.

Objective 2 was to gather data on typical irrigation systems and their management and identify how water is applied to irrigated fields. Chapter 3 achieved this objective, however it was found that irrigation systems are complex and highly variable, and subsequently difficult to identify what typical management may be. A broad generalisation of a typical irrigation system is a spray irrigator that applies water at a volume equal to the water deficit at the time when Readily Available Water (RAW) is depleted, which is generally assumed to equal half of Plant Available Water (PAW) at Field Capacity (FC) for pasture (and a number of other crops). This 'typical' system defines the default irrigator in SLIM. Where data is available for a specific system, chapter 3 identified those management and system parameters that describe an irrigation system's application regime. Of most importance for management are irrigation depth and return interval, which may be either flexible or fixed. The system parameter of most importance is distribution uniformity, which determines a significant component of irrigation losses. Irrigation uniformity can inform the estimation of the gross irrigation depth following the process developed in Bright, (1986) utilised in IrriCalc (Bright, 2009), and adapted in section 3.4.

Objective 3 was to identify important biophysical parameters that affect irrigation demand and water use efficiency in agroecosystems. These parameters were identified, and established methods for their incorporation into a water balance framework were outlined in chapter 4. The use of time-series datasets for precipitation and Potential Evapotranspiration (PET) is ubiquitous in hydrological modelling, as are the crop coefficient and reduction factor adjustments used to determine Actual Evapotranspiration (AET) following the method described in FAO56. Soil parameters, especially PAW and rooting depth, are important parameters that define the storage capacity of an irrigated field or sub-field section. Soil properties are often highly variable in space, which translates to spatial variability in irrigation demand and leaching potential. Soil variations are a recognised challenge for irrigation management, and recent work has investigated the role of field-scale soil mapping and Variable Rate Irrigation (VRI) for improving water usage over variable soils.

The modelling objectives, numbers 4 to 8, were to: (4) accurately predict irrigation events and replicate systems where irrigation event timing and depth are known; (5) enable model application regardless of data availability; (6) account for spatial variability in both soil properties and water application; (7) enable rapid mode use without need for specialised software or hardware; (8) produce outputs that can spatially communicate opportunities for ecosystem service improvement. The degree to which these objectives were achieved was discussed in Chapter 6.

The Winchmore case study showed that SLIM was able to accurately predict irrigation that is applied on the basis of soil moisture content (objective 4), although different estimates of PAW produced a wide range in the number of irrigations predicted over an 11 year period. Additionally, there was uncertainty as to the applicability of a linear reduction of ET for soil moisture content approaching wilting point.

There was a range of data availability between the Winchmore, Easton Apples, and Leeston case studies simulated in chapter 6, and SLIM able to simulate all irrigation systems (objective 5). For Easton apples, the current irrigation season was able to be replicated as irrigation had been recorded, while the simulations at Leeston were able to be run using default, literature derived irrigation and cropping parameters. Soil information was able to be taken from on-site measurements (Winchmore and Easton Apples), from the FSL (Leeston), and from S-map (Winchmore).

Consideration of the spatial variation in soil properties was enabled through spatial data inputs (GIS layers) and the manipulation of that data as described in chapter 5 (objective 6). Spatially explicit consideration of soil properties is not common in generally applicable irrigation models. Results in chapter 6 showed that soil variability resulted in large differences in the drainage volume and crop water availability within and between fields at Easton apples and especially at Leeston. Consideration of non-spatially uniform irrigation application was enabled by the calculation of gross irrigation depth following the method described in section 3.4. Explicitly varying irrigation depth for a single application is not possible without large assumptions when only a single measure of uniformity (e.g. CU_c) is known.

SLIM applications were run on a standard laptop computer, and run-times of seconds (Easton Apples) to minutes (~7 minutes for the 500 hectare farm at Leeston) allow rapid model application that could be practically carried out in the field (objective 7). The primary control on SLIM runtime was the resolution of the input Digital Elevation Model (DEM) and the extent of the simulated farming system. Increased speed could be achieved using a coarser DEM (e.g. 80 metre resolution), which is likely to be sufficient to capture soil variations in large pastoral and cropping fields. SLIM calls for no additional software to the existing LUCI tools, although ArcMap is required which limits SLIM's general applicability for farm managers.

Following the research presented in chapter 2, outputs from SLIM were designed to inform management decisions regarding ecosystem service provision, specifically water use efficiency and crop production (objective 8). SLIM raster overlays display average application efficiency, water use efficiency, total drainage volume, and number of days where the crop is under water stress.

Tilman et al. (2002) state that improving water and nutrient use efficiency is one of the greatest scientific challenges facing mankind, with substantial increases required in knowledge-intensive technologies that enhance scientifically sound decision making at the field level. It is hoped that outputs produced by SLIM and the research included in this thesis are able to improve nutrient and water use efficiencies, and lead to the improvement of ecosystem service provision in irrigated landscapes. It is anticipated that recommendations of on-farm interventions will be most effective when LUCI tools that describe nutrient loss, agricultural production, habitat provision, flood mitigation, and other ecosystem services are combined with the irrigation specific outputs produced by SLIM. It is anticipated that SLIM will help enable improvements in ecosystem service provision in agroecosystems, however results are attained only through on-farm land management interventions.

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9 Appendices

9.1 NZFSL attributes

The following information is taken from the Landcare Resource Information System (LRIS) spatial data layers information book (Landcare Research, 2008).

9.1.1 Profile Available Water

Profile total available water:

PAW_CLASS is a classification of profile total available water for the soil profile to a depth of 0.9 m, or to the potential rooting depth (whichever is the lesser). Values are weighted averages over the specified profile section (0–0.9 m) and are expressed in units of mm of water. The classes originate from the work of Gradwell and Birrell (1979), Wilson and Giltrap (1982) and Griffiths (1985), and are described more fully in Webb and Wilson (1995). Profile total available water classes and their corresponding values are as follows:

PAW_ CLASS	***PAW_ MIN (mm)***	***PAW_ MAX (mm)***	***PAW_ MOD (mm)***	***Description***
1	250	350	Refer comment under 'Item values & Interpretation'	Very high
2	150	249		High
3	90	149		Moderately high
4	60	89		Moderate
5	30	59		Low
6	0	29		Very low

The ArcInfo 'world polygon' has a null value, otherwise all records contain values from the list above.

Profile readily available water:

PRAW_CLASS is a classification of profile readily available water for the soil profile to a depth of 0.9 m, or to the potential rooting depth (whichever is the lesser). Values are weighted averages over the specified profile section (0–0.9 m) and are expressed in units of mm of water. The classes originate from the work of Gradwell and Birrell (1979), Wilson and Giltrap (1982) and Griffiths (1985), and are described more fully in Webb and Wilson (1995). Profile readily available water classes and their corresponding values are as follows:

PRAW_ CLASS	*PRAW_ MIN (mm)*	*PRAW_ MAX (mm)*	*PRAW_ MOD (mm)*	*Description*
1	150	250	Refer comment under 'Item values & Interpretation'	Very high
2	100	149		High
3	75	99		Moderately high
4	50	74		Moderate
5	25	49		Low
6	0	24		Very Low

The ArcInfo 'world polygon' has a null value, otherwise all records contain values from the list above.

MOD values:

Values for _MOD are calculated for each record, as the estimated modal value for a particular class. These modal values are calculated using the class range and variability (_VAR) and are considered to approximate the most common value. The following formula is used to calculate the modal value for records where soil values decrease as class number rises (e.g. PAW, PRAW, MPORS, MPORD);

Mod = (Cn+Cx)/2 - (Vars ((Cx-Cn)/3))

Cn = Class minimum value

Cx = Class maximum value

Vars = Value of var not = 0 (i.e. 1+, 1-, 2+, 2-)

e.g. a PAW of class 3 with a _VAR value of 1- is calculated as follows:

Mod = (90+149)/2 - (-1 ((149-90)/3)

= 139.2

9.1.2 Potential Rooting Depth

Potential rooting depth:

Potential rooting depth describes the minimum and maximum depths (in metres) to a layer that may impede root extension. Such a layer may be defined by penetration resistance, poor aeration or very low available water capacity. These classes, described more fully in Webb and Wilson (1995), are as follows:

PRD_ CLASS	***PRD_ MIN (m)***	***PRD_ MAX (m)***	***PRD_ MOD (m)***	***Description***
1	1.2	1.5	Refer comment under 'Item values & Interpretation'	Very deep
2	0.9	1.19		Deep
3	0.6	0.89		Moderately deep
4	0.45	0.59		Slightly deep
5	0.25	0.44		Shallow
6	0.15	0.24		Very shallow

9.2 FAO56 Tables

The following tables are reproduced from FAO56 (Allen et al., 1998). They describe the lengths of crop development stages (table 11), crop coefficients (table 12), and rooting depth and depletion fraction (ratio of RAW to TAW) (table 22). The figures included in these tables can be used during SLIM parameterisation when locally derived information is unavailable.

9.2.1 Table 11 Crop Growth Stages

TABLE 11. Lengths of crop development stages* for various planting periods and climatic regions (days)

Crop	Init. (L_{ini})	Dev. (L_{dev})	Mid (L_{mid})	Late (L_{late})	Total	Plant Date	Region
a. Small Vegetables							
Broccoli	35	45	40	15	135	Sept	Calif. Desert, USA
Cabbage	40	60	50	15	165	Sept	Calif. Desert, USA
Carrots	20	30	50/30	20	100	Oct/Jan	Arid climate
	30	40	60	20	150	Feb/Mar	Mediterranean
	30	50	90	30	200	Oct	Calif. Desert, USA
Cauliflower	35	50	40	15	140	Sept	Calif. Desert, USA
Celery	25	40	95	20	180	Oct	(Semi) Arid
	25	40	45	15	125	April	Mediterranean

	30	55	105	20	210	Jan	(Semi) Arid
Crucifers[1]	20	30	20	10	80	April	Mediterranean
	25	35	25	10	95	February	Mediterranean
	30	35	90	40	195	Oct/Nov	Mediterranean
Lettuce	20	30	15	10	75	April	Mediterranean
	30	40	25	10	105	Nov/Jan	Mediterranean
	25	35	30	10	100	Oct/Nov	Arid Region
	35	50	45	10	140	Feb	Mediterranean
Onion (dry)	15	25	70	40	150	April	Mediterranean
	20	35	110	45	210	Oct; Jan.	Arid Region; Calif.
Onion (green)	25	30	10	5	70	April/May	Mediterranean
	20	45	20	10	95	October	Arid Region
	30	55	55	40	180	March	Calif., USA
Onion (seed)	20	45	165	45	275	Sept	Calif. Desert, USA
Spinach	20	20	15/25	5	60/70	Apr; Sep/Oct	Mediterranean
	20	30	40	10	100	November	Arid Region
Radish	5	10	15	5	35	Mar/Apr	Medit.; Europe
	10	10	15	5	40	Winter	Arid Region
b. Vegetables - Solanum Family *(Solanaceae)*							
Egg plant	30	40	40	20	130\1	October	Arid Region
	30	45	40	25	40	May/June	Mediterranean
Sweet peppers (bell)	25/30	35	40	20	125	April/June	Europe and Medit.
	30	40	110	30	210	October	Arid Region
Tomato	30	40	40	25	135	January	Arid Region
	35	40	50	30	155	Apr/May	Calif., USA
	25	40	60	30	155	Jan	Calif. Desert, USA
	35	45	70	30	180	Oct/Nov	Arid Region
	30	40	45	30	145	April/May	Mediterranean
c. Vegetables - Cucumber Family *(Cucurbitaceae)*							
Cantaloupe	30	45	35	10	120	Jan	Calif., USA
	10	60	25	25	120	Aug	Calif., USA
Cucumber	20	30	40	15	105	June/Aug	Arid Region
	25	35	50	20	130	Nov; Feb	Arid Region
Pumpkin, Winter squash	20	30	30	20	100	Mar, Aug	Mediterranean
	25	35	35	25	120	June	Europe
Squash, Zucchini	25	35	25	15	100	Apr; Dec.	Medit.; Arid Reg.
	20	30	25	15	90	May/June	Medit.; Europe
Sweet melons	25	35	40	20	120	May	Mediterranean
	30	30	50	30	140	March	Calif., USA
	15	40	65	15	135	Aug	Calif. Desert, USA
	30	45	65	20	160	Dec/Jan	Arid Region
Water melons	20	30	30	30	110	April	Italy
	10	20	20	30	80	Mat/Aug	Near East (desert)
d. Roots and Tubers							

Beets, table	15	25	20	10	70	Apr/May	Mediterranean
	25	30	25	10	90	Feb/Mar	Mediterranean & Arid
Cassava: year 1	20	40	90	60	210	Rainy	Tropical regions
year 2	150	40	110	60	360	season	
Potato	25	30	30/45	30	115/130	Jan/Nov	(Semi) Arid Climate
	25	30	45	30	130	May	Continental Climate
	30	35	50	30	145	April	Europe
	45	30	70	20	165	Apr/May	Idaho, USA
	30	35	50	25	140	Dec	Calif. Desert, USA
Sweet potato	20	30	60	40	150	April	Mediterranean
	15	30	50	30	125	Rainy seas.	Tropical regions
Sugarbeet	30	45	90	15	180	March	Calif., USA
	25	30	90	10	155	June	Calif., USA
	25	65	100	65	255	Sept	Calif. Desert, USA
	50	40	50	40	180	April	Idaho, USA
	25	35	50	50	160	May	Mediterranean
	45	75	80	30	230	November	Mediterranean
	35	60	70	40	205	November	Arid Regions
e. Legumes *(Leguminosae)*							
Beans (green)	20	30	30	10	90	Feb/Mar	Calif., Mediterranean
	15	25	25	10	75	Aug/Sep	Calif., Egypt, Lebanon
Beans (dry)	20	30	40	20	110	May/June	Continental Climates
	15	25	35	20	95	June	Pakistan, Calif.
	25	25	30	20	100	June	Idaho, USA
Faba bean, broad bean	15	25	35	15	90	May	Europe
	20	30	35	15	100	Mar/Apr	Mediterranean
- dry	90	45	40	60	235	Nov	Europe
- green	90	45	40	0	175	Nov	Europe
Green gram, cowpeas	20	30	30	20	110	March	Mediterranean
Groundnut	25	35	45	25	130	Dry	West Africa
	35	35	35	35	140	season	High Latitudes
	35	45	35	25	140	May May/June	Mediterranean
Lentil	20	30	60	40	150	April	Europe
	25	35	70	40	170	Oct/Nov	Arid Region
Peas	15	25	35	15	90	May	Europe
	20	30	35	15	100	Mar/Apr	Mediterranean
	35	25	30	20	110	April	Idaho, USA
Soybeans	15	15	40	15	85	Dec	Tropics
	20	30/35	60	25	140	May	Central USA
	20	25	75	30	150	June	Japan
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)							
Artichoke	40	40	250	30	360	Apr (1st yr)	California
	20	25	250	30	325	May (2nd yr)	(cut in May)
Asparagus	50	30	100	50	230	Feb	Warm Winter

	90	30	200	45	365	Feb	Mediterranean
g. Fibre Crops							
Cotton	30	50	60	55	195	Mar-May	Egypt; Pakistan; Calif.
	45	90	45	45	225	Mar	Calif. Desert, USA
	30	50	60	55	195	Sept	Yemen
	30	50	55	45	180	April	Texas
Flax	25	35	50	40	150	April	Europe
	30	40	100	50	220	October	Arizona
h. Oil Crops							
Castor beans	25	40	65	50	180	March	(Semi) Arid Climates
	20	40	50	25	135	Nov.	Indonesia
Safflower	20	35	45	25	125	April	California, USA
	25	35	55	30	145	Mar	High Latitudes
	35	55	60	40	190	Oct/Nov	Arid Region
Sesame	20	30	40	20	100	June	China
Sunflower	25	35	45	25	130	April/May	Medit.; California
i. Cereals							
Barley/Oats/Wheat	15	25	50	30	120	November	Central India
	20	25	60	30	135	March/Apr	35-45 °L
	15	30	65	40	150	July	East Africa
	40	30	40	20	130	Apr	
	40	60	60	40	200	Nov	
	20	50	60	30	160	Dec	Calif. Desert, USA
Winter Wheat	20[2]	60[2]	70	30	180	December	Calif., USA
	30	140	40	30	240	November	Mediterranean
	160	75	75	25	335	October	Idaho, USA
Grains (small)	20	30	60	40	150	April	Mediterranean
	25	35	65	40	165	Oct/Nov	Pakistan; Arid Reg.
Maize (grain)	30	50	60	40	180	April	East Africa (alt.)
	25	40	45	30	140	Dec/Jan	Arid Climate
	20	35	40	30	125	June	Nigeria (humid)
	20	35	40	30	125	October	India (dry, cool)
	30	40	50	30	150	April	Spain (spr, sum.); Calif.
	30	40	50	50	170	April	Idaho, USA
Maize (sweet)	20	20	30	10	80	March	Philippines
	20	25	25	10	80	May/June	Mediterranean
	20	30	50/30	10	90	Oct/Dec	Arid Climate
	30	30	30	103	110	April	Idaho, USA
	20	40	70	10	140	Jan	Calif. Desert, USA
Millet	15	25	40	25	105	June	Pakistan
	20	30	55	35	140	April	Central USA
Sorghum	20	35	40	30	130	May/June	USA, Pakis., Med.
	20	35	45	30	140	Mar/April	Arid Region
Rice	30	30	60	30	150	Dec; May	Tropics; Mediterranean
	30	30.	80	40	180	May	Tropics

j. Forages							
Alfalfa, total season [4]	10	30	var.	var.	var.		last -4°C in spring until first -4°C in fall
Alfalfa [4] 1st cutting cycle	10	20	20	10	60	Jan Apr (last - 4°C)	Calif., USA.
	10	30	25	10	75		Idaho, USA.
Alfalfa [4], other cutting cycles	5	10	10	5	30	Mar	Calif., USA.
	5	20	10	10	45	Jun	Idaho, USA.
Bermuda for seed	10	25	35	35	105	March	Calif. Desert, USA
Bermuda for hay (several cuttings)	10	15	75	35	135	---	Calif. Desert, USA
Grass Pasture [4]	10	20	--	--	--		7 days before last -4°C in spring until 7 days after first -4°C in fall
Sudan, 1st cutting cycle	25	25	15	10	75	Apr	Calif. Desert, USA
Sudan, other cutting cycles	3	15	12	7	37	June	Calif. Desert, USA
k. Sugar Cane							
Sugarcane, virgin	35	60	190	120	405		Low Latitudes
	50	70	220	140	480		Tropics
	75	105	330	210	720		Hawaii, USA
Sugarcane, ratoon	25	70	135	50	280		Low Latitudes
	30	50	180	60	320		Tropics
	35	105	210	70	420		Hawaii, USA
l. Tropical Fruits and Trees							
Banana, 1st yr	120	90	120	60	390	Mar	Mediterranean
Banana, 2nd yr	120	60	180	5	365	Feb	Mediterranean
Pineapple	60	120	600	10	790		Hawaii, USA
m. Grapes and Berries							
Grapes	20	40	120	60	240	April	Low Latitudes
	20	50	75	60	205	Mar	Calif., USA
	20	50	90	20	180	May	High Latitudes
	30	60	40	80	210	April	Mid Latitudes (wine)
Hops	25	40	80	10	155	April	Idaho, USA
n. Fruit Trees							
Citrus	60	90	120	95	365	Jan	Mediterranean
Deciduous Orchard	20	70	90	30	210	March	High Latitudes
	20	70	120	60	270	March	Low Latitudes
	30	50	130	30	240	March	Calif., USA
Olives	30	90	*60*	90	2705	March	Mediterranean
Pistachios	20	60	30	40	150	Feb	Mediterranean
Walnuts	20	10	130	30	190	April	Utah, USA
o. Wetlands - Temperate Climate							
Wetlands (Cattails, Bulrush)	10	30	80	20	140	May	Utah, USA; killing frost
	180	60	90	35	365	November	Florida, USA

Wetlands (short veg.)	180	60	90	35	365	November	frost-free climate

* Lengths of crop development stages provided in this table are indicative of general conditions, but may vary substantially from region to region, with climate and cropping conditions, and with crop variety. The user is strongly encouraged to obtain appropriate local information.

[1] Crucifers include cabbage, cauliflower, broccoli, and Brussel sprouts. The wide range in lengths of seasons is due to varietal and species differences.

[2] These periods for winter wheat will lengthen in frozen climates according to days having zero growth potential and wheat dormancy. Under general conditions and in the absence of local data, fall planting of winter wheat can be presumed to occur in northern temperate climates when the 10-day running average of mean daily air temperature decreases to 17° C or December 1, whichever comes first. Planting of spring wheat can be presumed to occur when the 10-day running average of mean daily air temperature increases to 5° C. Spring planting of maize-grain can be presumed to occur when the 10-day running average of mean daily air temperature increases to 13° C.

[3] The late season for sweet maize will be about 35 days if the grain is allowed to mature and dry.

[4] In climates having killing frosts, growing seasons can be estimated for alfalfa and grass as:

alfalfa: last -4° C in spring until first -4° C in fall (Everson, D. O., M. Faubion and D. E. Amos 1978. "Freezing temperatures and growing seasons in Idaho." Univ. Idaho Agric. Exp. station bulletin 494. 18 p.)

grass: 7 days before last -4° C in spring and 7 days after last -4° C in fall (Kruse E. G. and Haise, H. R. 1974. "Water use by native grasses in high altitude Colorado meadows." USDA Agric. Res. Service, Western Region report ARS-W-6-1974. 60 pages)

[5] Olive trees gain new leaves in March. See footnote 24 of Table 12 for additional information, where the K_c continues outside of the "growing period".

9.2.2 Table 12 Crop Coefficients

TABLE 12. Single (time-averaged) crop coefficients, K_c, and mean maximum plant heights for non stressed, well-managed crops in subhumid climates ($RH_{min} \approx 45\%$, $u_2 \approx 2$ m/s) for use with the FAO Penman-Monteith ET_o.

Crop	$K_{c\,ini}$[1]	$K_{c\,mid}$	$K_{c\,end}$	Maximum Crop Height (h) (m)
a. Small Vegetables	**0.7**	**1.05**	**0.95**	
Broccoli		1.05	0.95	0.3
Brussel Sprouts		1.05	0.95	0.4
Cabbage		1.05	0.95	0.4
Carrots		1.05	0.95	0.3
Cauliflower		1.05	0.95	0.4
Celery		1.05	1.00	0.6

Garlic		1.00	0.70	0.3
Lettuce		1.00	0.95	0.3
Onions				
- dry		1.05	0.75	0.4
- green		1.00	1.00	0.3
- seed		1.05	0.80	0.5
Spinach		1.00	0.95	0.3
Radish		0.90	0.85	0.3
b. Vegetables - Solanum Family *(Solanaceae)*	**0.6**	**1.15**	**0.80**	
Egg Plant		1.05	0.90	0.8
Sweet Peppers (bell)		1.05[2]	0.90	0.7
Tomato		1.15[2]	0.70-0.90	0.6
c. Vegetables - Cucumber Family *(Cucurbitaceae)*	**0.5**	**1.00**	**0.80**	
Cantaloupe	0.5	0.85	0.60	0.3
Cucumber				
- Fresh Market	0.6	1.00[2]	0.75	0.3
- Machine harvest	0.5	1.00	0.90	0.3
Pumpkin, Winter Squash		1.00	0.80	0.4
Squash, Zucchini		0.95	0.75	0.3
Sweet Melons		1.05	0.75	0.4
Watermelon	0.4	1.00	0.75	0.4
d. Roots and Tubers	**0.5**	**1.10**	**0.95**	
Beets, table		1.05	0.95	0.4
Cassava				
- year 1	0.3	0.80[3]	0.30	1.0
- year 2	0.3	1.10	0.50	1.5
Parsnip	0.5	1.05	0.95	0.4
Potato		1.15	0.75[4]	0.6
Sweet Potato		1.15	0.65	0.4
Turnip (and Rutabaga)		1.10	0.95	0.6
Sugar Beet	0.35	1.20	0.70[5]	0.5
e. Legumes *(Leguminosae)*	**0.4**	**1.15**	**0.55**	
Beans, green	0.5	1.05[2]	0.90	0.4
Beans, dry and Pulses	0.4	1.15[2]	0.35	0.4
Chick pea		1.00	0.35	0.4
Fababean (broad bean)				
- Fresh	0.5	1.15[2]	1.10	0.8
- Dry/Seed	0.5	1.15[2]	0.30	0.8
Grabanzo	0.4	1.15	0.35	0.8
Green Gram and Cowpeas		1.05	0.60-0.35[6]	0.4
Groundnut (Peanut)		1.15	0.60	0.4
Lentil		1.10	0.30	0.5
Peas				
- Fresh	0.5	1.15[2]	1.10	0.5

- Dry/Seed		1.15	0.30	0.5
Soybeans		1.15	0.50	0.5-1.0
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)	**0.5**	**1.00**	**0.80**	
Artichokes	0.5	1.00	0.95	0.7
Asparagus	0.5	0.95[7]	0.30	0.2-0.8
Mint	0.60	1.15	1.10	0.6-0.8
Strawberries	0.40	0.85	0.75	0.2
g. Fibre Crops	**0.35**			
Cotton		1.15-1.20	0.70-0.50	1.2-1.5
Flax		1.10	0.25	1.2
Sisal [8]		0.4-0.7	0.4-0.7	1.5
h. Oil Crops	**0.35**	**1.15**	**0.35**	
Castorbean (*Ricinus*)		1.15	0.55	0.3
Rapeseed, Canola		1.0-1.15[9]	0.35	0.6
Safflower		1.0-1.15[9]	0.25	0.8
Sesame		1.10	0.25	1.0
Sunflower		1.0-1.15[9]	0.35	2.0
i. Cereals	**0.3**	**1.15**	**0.4**	
Barley		1.15	0.25	1
Oats		1.15	0.25	1
Spring Wheat		1.15	0.25-0.4[10]	1
Winter Wheat				
- with frozen soils	0.4	1.15	0.25-0.4[10]	1
- with non-frozen soils	0.7	1.15	0.25-0.4[10]	
Maize, Field (grain) *(field corn)*		1.20	0.60-0.35[11]	2
Maize, Sweet *(sweet corn)*		1.15	1.05[12]	1.5
Millet		1.00	0.30	1.5
Sorghum				
- grain		1.00-1.10	0.55	1-2
- sweet		1.20	1.05	2-4
Rice	1.05	1.20	0.90-0.60	1
j. Forages				
Alfalfa Hay				
- averaged cutting effects	0.40	0.95[13]	0.90	0.7
- individual cutting periods	0.40[14]	1.20[14]	1.15[14]	0.7
- for seed	0.40	0.50	0.50	0.7
Bermuda hay				

- averaged cutting effects	0.55	1.00[13]	0.85	0.35
- Spring crop for seed	0.35	0.90	0.65	0.4
Clover hay, Berseem				
- averaged cutting effects	0.40	0.90[13]	0.85	0.6
- individual cutting periods	0.40[14]	1.15[14]	1.10[14]	0.6
Rye Grass hay				
- averaged cutting effects	0.95	1.05	1.00	0.3
Sudan Grass hay (annual)				
- averaged cutting effects	0.50	0.90[14]	0.85	1.2
- individual cutting periods	0.50[14]	1.15[14]	1.10[14]	1.2
Grazing Pasture				
- Rotated Grazing	0.40	0.85-1.05	0.85	0.15-0.30
- Extensive Grazing	0.30	0.75	0.75	0.10
Turf grass				
- cool season [15]	0.90	0.95	0.95	0.10
- warm season [15]	0.80	0.85	0.85	0.10
k. Sugar Cane	**0.40**	**1.25**	**0.75**	**3**
l. Tropical Fruits and Trees				
Banana				
- 1st year	0.50	1.10	1.00	3
- 2nd year	1.00	1.20	1.10	4
Cacao	1.00	1.05	1.05	3
Coffee				
- bare ground cover	0.90	0.95	0.95	2-3
- with weeds	1.05	1.10	1.10	2-3
Date Palms	0.90	0.95	0.95	8
Palm Trees	0.95	1.00	1.00	8
Pineapple [16]				
- bare soil	0.50	0.30	0.30	0.6-1.2
- with grass cover	0.50	0.50	0.50	0.6-1.2
Rubber Trees	0.95	1.00	1.00	10
Tea				
- non-shaded	0.95	1.00	1.00	1.5
- shaded [17]	1.10	1.15	1.15	2
m. Grapes and Berries				
Berries (bushes)	0.30	1.05	0.50	1.5
Grapes				
- Table or Raisin	0.30	0.85	0.45	2
- Wine	0.30	0.70	0.45	1.5-2
Hops	0.3	1.05	0.85	5
n. Fruit Trees				
Almonds, no ground cover	0.40	0.90	0.65[18]	5
Apples, Cherries, Pears [19]				
- no ground cover, killing frost	0.45	0.95	0.70[18]	4

- no ground cover, no frosts	0.60	0.95	0.75[18]	4
- active ground cover, killing frost	0.50	1.20	0.95[18]	4
- active ground cover, no frosts	0.80	1.20	0.85[18]	4
Apricots, Peaches, Stone Fruit [19, 20]				
- no ground cover, killing frost	0.45	0.90	0.65[18]	3
- no ground cover, no frosts	0.55	0.90	0.65[18]	3
- active ground cover, killing frost	0.50	1.15	0.90[18]	3
- active ground cover, no frosts	0.80	1.15	0.85[18]	3
Avocado, no ground cover	0.60	0.85	0.75	3
Citrus, no ground cover [21]				
- 70% canopy	0.70	0.65	0.70	4
- 50% canopy	0.65	0.60	0.65	3
- 20% canopy	0.50	0.45	0.55	2
Citrus, with active ground cover or weeds [22]				
- 70% canopy	0.75	0.70	0.75	4
- 50% canopy	0.80	0.80	0.80	3
- 20% canopy	0.85	0.85	0.85	2
Conifer Trees [23]	1.00	1.00	1.00	10
Kiwi	0.40	1.05	1.05	3
Olives (40 to 60% ground coverage by canopy) [24]	0.65	0.70	0.70	3-5
Pistachios, no ground cover	0.40	1.10	0.45	3-5
Walnut Orchard [19]	0.50	1.10	0.6518	4-5
o. Wetlands - temperate climate				
Cattails, Bulrushes, killing frost	0.30	1.20	0.30	2
Cattails, Bulrushes, no frost	0.60	1.20	0.60	2
Short Veg., no frost	1.05	1.10	1.10	0.3
Reed Swamp, standing water	1.00	1.20	1.00	1-3
Reed Swamp, moist soil	0.90	1.20	0.70	1-3
p. Special				
Open Water, < 2 m depth or in subhumid climates or tropics		1.05	1.05	
Open Water, > 5 m depth, clear of turbidity, temperate climate		0.6525	1.2525	

[1] These are general values for $K_{c\ ini}$ under typical irrigation management and soil wetting. For frequent wettings such as with high frequency sprinkle irrigation or daily rainfall, these values may increase substantially and may approach 1.0 to 1.2. $K_{c\ ini}$ is a function of wetting interval and potential evaporation rate during the initial and development periods and is more accurately estimated using Figures 29 and 30, or Equation 7-3 in Annex 7, or using the dual $K_{cb\ ini} + K_e$.

[2] Beans, Peas, Legumes, Tomatoes, Peppers and Cucumbers are sometimes grown on stalks reaching 1.5 to 2 meters in height. In such cases, increased K_c values need to be taken. For green beans, peppers and cucumbers, 1.15 can be taken, and for tomatoes, dry beans and peas, 1.20. Under these conditions h should be increased also.

[3] The midseason values for cassava assume non-stressed conditions during or following the rainy season. The $K_{c\ end}$ values account for dormancy during the dry season.

[4] The $K_{c\ end}$ value for potatoes is about 0.40 for long season potatoes with vine kill.

[5] This $K_{c\ end}$ value is for no irrigation during the last month of the growing season. The $K_{c\ end}$ value for sugar beets is higher, up to 1.0, when irrigation or significant rain occurs during the last month.

[6] The first $K_{c\ end}$ is for harvested fresh. The second value is for harvested dry.

[7] The K_c for asparagus usually remains at $K_{c\ ini}$ during harvest of the spears, due to sparse ground cover. The $K_{c\ mid}$ value is for following regrowth of plant vegetation following termination of harvest of spears.

[8] K_c for sisal depends on the planting density and water management (e.g., intentional moisture stress).

[9] The lower values are for rainfed crops having less dense plant populations.

[10] The higher value is for hand-harvested crops.

[11] The first $K_{c\ end}$ value is for harvest at high grain moisture. The second $K_{c\ end}$ value is for harvest after complete field drying of the grain (to about 18% moisture, wet mass basis).

[12] If harvested fresh for human consumption. Use $K_{c\ end}$ for field maize if the sweet maize is allowed to mature and dry in the field.

[13] This $K_{c\ mid}$ coefficient for hay crops is an overall average $K_{c\ mid}$ coefficient that averages K_c for both before and following cuttings. It is applied to the period following the first development period until the beginning of the last late season period of the growing season.

[14] These K_c coefficients for hay crops represent immediately following cutting; at full cover; and immediately before cutting, respectively. The growing season is described as a series of individual cutting periods (Figure 35).

[15] Cool season grass varieties include dense stands of bluegrass, ryegrass, and fescue. Warm season varieties include bermuda grass and St. Augustine grass. The 0.95 values for cool season grass represent a 0.06 to 0.08 m mowing height under general turf conditions. Where careful water management is practiced and rapid growth is not required, K_c's for turf can be reduced by 0.10.

[16] The pineapple plant has very low transpiration because it closes its stomates during the day and opens them during the night. Therefore, the majority of ET_c from pineapple is evaporation from the soil. The $K_{c\ mid} < K_{c\ ini}$ since $K_{c\ mid}$ occurs during full ground cover so that soil evaporation is less. Values given assume that 50% of the ground surface is covered by black plastic mulch and that irrigation is by sprinkler. For drip irrigation beneath the plastic mulch, K_c's given can be reduced by 0.10.

[17] Includes the water requirements of the shade trees.

[18] These $K_{c\ end}$ values represent K_c prior to leaf drop. After leaf drop, $K_{c\ end} \approx 0.20$ for bare, dry soil or dead ground cover and $K_{c\ end} \approx 0.50$ to 0.80 for actively growing ground cover (consult Chapter 11).

[19] Refer to Eq. 94, 97 or 98 and footnotes 21 and 22 for estimating K_c for immature stands.

[20] Stone fruit category applies to peaches, apricots, pears, plums and pecans.

[21] These K_c values can be calculated from Eq. 98 for $K_{c\ min} = 0.15$ and $K_{c\ full} = 0.75$, 0.70 and 0.75 for the initial, mid season and end of season periods, and $f_{c\ eff} = f_c$ where f_c = fraction of ground covered by tree canopy (e.g., the sun is presumed to be directly overhead). The values listed correspond with those in Doorenbos and Pruitt (1977) and with more recent measurements. The midseason value is lower than initial and ending values due to the effects of stomatal closure during periods of peak ET. For humid and subhumid climates where there is less stomatal control by citrus, values for $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ can be increased by 0.1 - 0.2, following Rogers et al. (1983).

[22] These K_c values can be calculated as $K_c = f_c K_{c\ ngc} + (1 - f_c) K_{c\ cover}$ where $K_{c\ ngc}$ is the K_c of citrus with no active ground cover (calculated as in footnote 21), $K_{c\ cover}$ is the K_c, for the active ground cover (0.95), and f_c is defined in footnote 21. The values listed correspond with those in Doorenbos and Pruitt (1977) and with more recent measurements. Alternatively, K_c for citrus with active ground cover can be estimated directly from Eq. 98 by setting $K_{c\ min} = K_{c\ cover}$. For humid and subhumid climates where there is less stomatal control by citrus, values for $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ can be increased by 0.1 - 0.2, following Rogers et al. (1983).

For non-active or only moderately active ground cover (active indicates green and growing ground cover with LAI > about 2 to 3), K_c should be weighted between K_c for no ground cover and K_c for active ground cover, with the weighting based on the "greenness" and approximate leaf area of the ground cover.

[23] Confers exhibit substantial stomatal control due to reduced aerodynamic resistance. The K_c, can easily reduce below the values presented, which represent well-watered conditions for large forests.

[24] These coefficients represent about 40 to 60% ground cover. Refer to Eq. 98 and footnotes 21 and 22 for estimating K_c for immature stands. In Spain, Pastor and Orgaz (1994) have found the following monthly K_c's for olive orchards having 60% ground cover: 0.50, 0.50, 0.65, 0.60, 0.55, 0.50, 0.45, 0.45, 0.55, 0.60, 0.65, 0.50 for months January through December. These coefficients can be invoked by using $K_{c\ ini} = 0.65$, $K_{c\ mid} = 0.45$, and $K_{c\ end} = 0.65$, with stage lengths = 30, 90, 60 and 90 days, respectively for initial, development, midseason and late season periods, and using K_c during the winter ("off season") in December to February = 0.50.

[25] These K_c's are for deep water in temperate latitudes where large temperature changes in the water body occur during the year, and initial and peak period evaporation is low as radiation energy is absorbed into the deep water body. During fall and winter periods ($K_{c\ end}$), heat is released from the water body that increases the evaporation above that for grass. Therefore, $K_{c\ mid}$ corresponds to the period when the water body is gaining thermal energy and $K_{c\ end}$ when releasing thermal energy. These K_c's should be used with caution.

9.2.3 Table 22 Rooting Depth and Depletion Fraction

TABLE 22. Ranges of maximum effective rooting depth (Z_r), and soil water depletion fraction for no stress (p), for common crops

Crop	Maximum Root Depth [1] (m)	Depletion Fraction [2] (for ET ≈ 5 mm/day) p
a. Small Vegetables		
Broccoli	0.4-0.6	0.45
Brussel Sprouts	0.4-0.6	0.45
Cabbage	0.5-0.8	0.45
Carrots	0.5-1.0	0.35
Cauliflower	0.4-0.7	0.45
Celery	0.3-0.5	0.20
Garlic	0.3-0.5	0.30
Lettuce	0.3-0.5	0.30
Onions		
- dry	0.3-0.6	0.30
- green	0.3-0.6	0.30
- seed	0.3-0.6	0.35
Spinach	0.3-0.5	0.20
Radishes	0.3-0.5	0.30
b. Vegetables - Solarium Family *(Solanaceae)*		
Egg Plant	0.7-1.2	0.45
Sweet Peppers (bell)	0.5-1.0	0.30
Tomato	0.7-1.5	0.40
c. Vegetables - Cucumber Family (*Cucurbitaceae*)		
Cantaloupe	0.9-1.5	0.45
Cucumber		
- Fresh Market	0.7-1.2	0.50
- Machine harvest	0.7-1.2	0.50
Pumpkin, Winter Squash	1.0-1.5	0.35
Squash, Zucchini	0.6-1.0	0.50
Sweet Melons	0.8-1.5	0.40
Watermelon	0.8-1.5	0.40
d. Roots and Tubers		
Beets, table	0.6-1.0	0.50
Cassava		
- year 1	0.5-0.8	0.35
- year 2	0.7-1.0	0.40
Parsnip	0.5-1.0	0.40
Potato	0.4-0.6	0.35
Sweet Potato	1.0-1.5	0.65
Turnip (and Rutabaga)	0.5-1.0	0.50
Sugar Beet	0.7-1.2	0.55[3]

e. Legumes *(Leguminosae)*		
Beans, green	0.5-0.7	0.45
Beans, dry and Pulses	0.6-0.9	0.45
Beans, lima, large vines	0.8-1.2	0.45
Chick pea	0.6-1.0	0.50
Fababean (broad bean)		
- Fresh	0.5-0.7	0.45
- Dry/Seed	0.5-0.7	0.45
Grabanzo	0.6-1.0	0.45
Green Gram and Cowpeas	0.6-1.0	0.45
Groundnut (Peanut)	0.5-1.0	0.50
Lentil	0.6-0.8	0.50
Peas		
- Fresh	0.6-1.0	0.35
- Dry/Seed	0.6-1.0	0.40
Soybeans	0.6-1.3	0.50
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)		
Artichokes	0.6-0.9	0.45
Asparagus	1.2-1.8	0.45
Mint	0.4-0.8	0.40
Strawberries	0.2-0.3	0.20
g. Fibre Crops		
Cotton	1.0-1.7	0.65
Flax	1.0-1.5	0.50
Sisal	0.5-1.0	0.80
h. Oil Crops		
Castorbean *(Ricinus)*	1.0-2.0	0.50
Rapeseed, Canola	1.0-1.5	0.60
Safflower	1.0-2.0	0.60
Sesame	1.0-1.5	0.60
Sunflower	0.8-1.5	0.45
i. Cereals		
Barley	1.0-1.5	0.55
Oats	1.0-1.5	0.55
Spring Wheat	1.0-1.5	0.55
Winter Wheat	1.5-1.8	0.55
Maize, Field (grain) *(field corn)*	1.0-1.7	0.55
Maize, Sweet *(sweet corn)*	0.8-1.2	0.50
Millet	1.0-2.0	0.55
Sorghum		
- grain	1.0-2.0	0.55
- sweet	1.0-2.0	0.50
Rice	0.5-1.0	0.20[4]
j. Forages		
Alfalfa		

- for hay	1.0-2.0	0.55
- for seed	1.0-3.0	0.60
Bermuda		
- for hay	1.0-1.5	0.55
- Spring crop for seed	1.0-1.5	0.60
Clover hay, Berseem	0.6-0.9	0.50
Rye Grass hay	0.6-1.0	0.60
Sudan Grass hay (annual)	1.0-1.5	0.55
Grazing Pasture		
- Rotated Grazing	0.5-1.5	0.60
- Extensive Grazing	0.5-1.5	0.60
Turf grass		
- cool season [5]	0.5-1.0	0.40
- warm season [5]	0.5-1.0	0.50
k. Sugar Cane	1.2-2.0	0.65
l. Tropical Fruits and Trees		
Banana		
- 1st year	0.5-0.9	0.35
- 2nd year	0.5-0.9	0.35
Cacao	0.7-1.0	0.30
Coffee	0.9-1.5	0.40
Date Palms	1.5-2.5	0.50
Palm Trees	0.7-1.1	0.65
Pineapple	0.3-0.6	0.50
Rubber Trees	1.0-1.5	0.40
Tea		
- non-shaded	0.9-1.5	0.40
- shaded	0.9-1.5	0.45
m. Grapes and Berries		
Berries (bushes)	0.6-1.2	0.50
Grapes		
- Table or Raisin	1.0-2.0	0.35
- Wine	1.0-2.0	0.45
Hops	1.0-1.2	0.50
n. Fruit Trees		
Almonds	1.0-2.0	0.40
Apples, Cherries, Pears	1.0-2.0	0.50
Apricots, Peaches, Stone Fruit	1.0-2.0	0.50
Avocado	0.5-1.0	0.70
Citrus		
- 70% canopy	1.2-1.5	0.50
- 50% canopy	1.1-1.5	0.50
- 20% canopy	0.8-1.1	0.50
Conifer Trees	1.0-1.5	0.70
Kiwi	0.7-1.3	0.35

Olives (40 to 60% ground coverage by canopy)	1.2-1.7	0.65
Pistachios	1.0-1.5	0.40
Walnut Orchard	1.7-2.4	0.50

[1] The larger values for Z_r are for soils having no significant layering or other characteristics that can restrict rooting depth. The smaller values for Z_r may be used for irrigation scheduling and the larger values for modeling soil water stress or for rainfed conditions.

[2] The values for p apply for $ET_c \approx 5$ mm/day. The value for p can be adjusted for different ET_c according to

$p = p_{\text{table 22}} + 0.04\,(5 - ET_c)$

where p is expressed as a fraction and ET_c as mm/day.

[3] Sugar beets often experience late afternoon wilting in arid climates even at $p < 0.55$, with usually only minor impact on sugar yield.

[4] The value for p for rice is 0.20 of saturation.

[5] Cool season grass varieties include bluegrass, ryegrass and fescue. Warm season varieties include bermuda grass, buffalo grass and St. Augustine grass. Grasses are variable in rooting depth. Some root below 1.2 m while others have shallow rooting depths. The deeper rooting depths for grasses represent conditions where careful water management is practiced with higher depletion between irrigations to encourage the deeper root exploration