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Irrigation Scheduling: a Soft Adaptor to Weather Uncertainties and Irrigation Efficiency Improvement Initiatives

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Abstract of a thesis submitted for a degree of Doctor of Philosophy

Abstract

Irrigation Scheduling: a Soft Adaptor to Weather Uncertainties and Irrigation Efficiency Improvement Initiatives

by

Birendra K.C.

Expanding dairy farming around the world including the Canterbury region of New Zealand is causing increasing demand for irrigation, placing more pressure on already stressed water resources. The challenge for New Zealand dairy farming is to maintain an appropriate equilibrium between pasture production and environment protection, achievable through the proper management/utilization of agricultural water, for which application and expansion of carefully identified and evaluated irrigation scheduling can play a key role.

The focus of this research was, therefore, to contribute to the development of irrigation scheduling to determine the irrigation range within the soil water holding capacity taking into consideration precipitation (P), evapotranspiration (ET), plant available water (PAW) and crop coefficient (K_c). This was achieved through estimating K_c of pasture at different grazing rotations by field measurements and analysing irrigation and deep percolation under a range of PAW-based irrigation triggers by applications of mathematical modelling of irrigation scheduling. A farmers' survey has been carried out with 32 dairy farmers in Canterbury, New Zealand to collect information on current irrigation practices, particularly in relation to PAW and grazing rotation.

The experiments were conducted at Lincoln University Dairy Farm (LUDF), South Island, New Zealand during the period August 2014 to March 2016. A network of 20 non-weighing lysimeters and an Aquaflex installed on LUDF were utilized for the study. Pasture height, precipitation, irrigation application, deep percolation and change in soil moisture in the lysimeters were measured throughout the study period. Time Domain Reflectometry (TDR) probes with 200, 500 and 900 mm lengths were installed vertically adjacent to the Aquaflex and lysimeters for improving soil moisture determination in the lysimeters without disturbing natural water flux inside the lysimeters. To account for climatic variability, available 16 years of climatic data were collected from Broadfield

weather station. Irrigation and deep percolation have been estimated using two soil-plant-atmosphere mathematical models (IrriCalc and CropWat 8) under a range of irrigation management strategies, including those identified in the farmers' survey, and commonly applied crop coefficient values in addition to those estimated in this research.

Based on reference and actual evapotranspiration, K_c of pasture was estimated for different grazing rotations. Analysing the relationship between K_c and crop canopy represented by pasture's height (h in cm) showed that a linear fit simulates well this process. Aquaflex soil moisture (SM) readings resulted in a value of 0.43 for the coefficient of determination (R^2) for the $K_c - h$ relationship, which increased to 0.66 when Aquaflex SM measurements were adjusted for each lysimeter using corresponding TDR readings. This signifies the importance of accurate soil moisture determination to improve irrigation planning. The estimated values of K_c just after and before grazing were 0.6 and 1.0 for corresponding pasture heights of 10 cm and 30 cm. Average K_c for one grazing rotation was estimated at 0.7. This implies conventional irrigation planning with a constant pasture crop coefficient of 1.0 would provide "on average" 30% more water compared to the actual water demand of pasture under grazing condition. This significant amount of water saving can contribute to conserve water and reduce leaching of nutrients.

During the shoulder seasons (September – October and March – May) current irrigation strategy leaves sufficient space for potential rain. However, during the peak irrigation season (November - February), the majority of farmers apply irrigation to fill soil up to 100% of the Field Capacity (FC), which is prone to cause deep percolation if rainfall follows an irrigation event. Analysis of the irrigation and deep percolation predicted for 14 irrigation seasons indicated that a minimum soil moisture level to start irrigation at 55 and 60 % of PAW, respectively on the shoulder and peak irrigation seasons, and stopping irrigation correspondingly at 80 and 90 % of PAW were optimal for this case study. This would allow for rainfall harvesting and thus, reduce net irrigation requirement and deep percolation losses.

These results will make important contributions towards improving irrigation scheduling. Such irrigation scheduling can serve as soft adaptor to cope with weather uncertainty. The proposed irrigation scheduling contributes to agricultural water management, eventually supporting the sustainable development of dairy farming industries in New Zealand and around the world. In addition, it would also decrease water pollution by reducing nutrient leaching from pastoral farms to water resources.

KEY WORDS: Crop coefficient, grazing rotation, pasture, Time Domain Reflectometry, Aquaflex, soil moisture, plant available water, survey, irrigation scheduling, rainfall harvesting

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Abbreviations and Symbols

ABBREVIATIONS

ET	Evapotranspiration
FAO	Food and Agriculture Organisation
FC	Field capacity
GDP	Gross domestic product
GPS	Global Position System
L21	Lysimeter 21
L22	Lysimeter 22
LUDF	Lincoln University Dairy Farm
N	Nitrogen
NIWA	National Institute of Weather and Atmospheric Research
PAW	Plant Available Water
PM	Penman-Monteith method
PMFAO	FAO-Penman-Monteith method
RG	Ryegrass
RAW	Readily available water
RPM	Rising plate meter
SMC	Soil moisture content
TAW	Total available water
TDR	Time domain reflectometry
TDT	Time delay transmission
WP	Wilting point

SYMBOLS

<i>AET</i>	Actual evapotranspiration (mm)
<i>CR</i>	Capillary rise (mm)
<i>D</i>	Deep percolation (mm)
<i>DM</i>	Dry matter (t/ha, kg/ha)
<i>e_a</i>	Actual vapour pressure (kPa)
<i>e_s</i>	Saturation vapour pressure (kPa)
<i>ET</i>	Evaporation (mm)
<i>ET_a</i>	Actual crop evaporation (mm/day)
<i>ET_r</i>	Reference crop evaporation (mm/day)
<i>G</i>	Soil heat flux density (MJ/m ² /d)
<i>h</i>	Pasture canopy height (cm)
<i>I</i>	Irrigation (mm)
<i>K_c</i>	Crop coefficient
<i>K_s</i>	Water stress coefficient
<i>P</i>	Precipitation (mm)
<i>RH</i>	Relative humidity (%)
<i>R_n</i>	Net radiation (MJ/m ² /d)
<i>R²</i>	Coefficient of determination
<i>RO</i>	Runoff (mm)
<i>SF</i>	Surface flow (mm)

t	time (d, min, s)
T	Air temperature ($^{\circ}\text{C}$)
T_{min}	Minimum daily air temperature ($^{\circ}\text{C}$)
T_{max}	Maximum daily air temperature ($^{\circ}\text{C}$)
u_2	Wind speed at 2 m (m/s)

GREEK SYMBOLS

Δ	Slope of the saturation vapour pressure temperature relationship ($\text{kPa}^{\circ}\text{C}^{-1}$)
θ	Volumetric water content (v v^{-1})
ρ_b	Dry bulk density of the soil (kg m^{-3})
ρ_w	Density of water (kg m^{-3})
γ	Psychrometric constant ($\text{kPa}^{\circ}\text{C}^{-1}$)

Chapter 1

Introduction

1.1 Background of the research

Increasing pressure on water resources and the degrading environmental conditions such as water quality, salination, waterlogging, are posing special challenges to improve irrigation efficiency for sustainable food production (Tal, 2016; Zhang et al., 2015). Globally about 70, 20 and 10% of the annual water withdraw goes to agriculture, industries and domestic sectors, respectively (Bekchanov et al., 2015; Food and Agricultural Organisation (FAO), 2014). With increasing world population and standard of living, the water demand for domestic and industrial sectors is also rising. Consequently percentage share of agricultural water is declining (International Water Management Institute (IWMI), 2015; Kumar et al., 2011). In addition, relying only on more intensive use of irrigation would exacerbate precarious water scarcities situation in many parts of the world (Springer & Duchin, 2014; Tal, 2016). This requires the irrigation sector to produce more food with less water by improving performance of the existing irrigation schemes (Zhang et al., 2015).

Inefficient irrigation management results in under/over irrigation. Under-irrigation creates water stress for crop, and in turn has the potential to reduce yield. Over-irrigation wastes large volumes of water through surface runoff and deep percolation and limits water availability for other water users. In fact, over-irrigation is not only wasting our precious water resource, power (for pressured irrigation) and nutrients (Bolan et al., 2009), but also causing contamination of the environment, especially water quality through increased deep percolation and in turn nutrient leaching. In addition, poor agricultural water management is lowering water table due to over-exploitation of groundwater (George et al., 2000; Thomas & Morini, 2005). Therefore, in addition to the main source of food production, inefficient irrigated agriculture is also considered the root cause of water pollution (Aragüés & Tanji, 2006; Di & Cameron, 2002; Zonderland-Thomassen & Ledgard, 2012).

Various irrigation performance studies indicate a substantial potential for improvement in the prevailing irrigation efficiency level (Fernández et al., 2007). Improved irrigation can have a positive impact on both sustainable food production and environment protection (Skhiri & Dechmi, 2012). In fact, the conservation of the natural resources and sustainable increment in agricultural production are equally important objectives (Skhiri & Dechmi, 2012). Hence, the challenge of irrigated cultivation is to maintain appropriate equilibrium between food production and environment protection (Skhiri & Dechmi, 2012).

The situation is even worse in pasture based dairy farming all over the world including New Zealand. The New Zealand dairy industry is a world leader, and dairy farming is an important pillar of the country's economy (DairyNZ, 2013). New Zealand is focussed on boosting dairy farming to be the food bowl of Asia, where prevailing dairy demand is higher than the production (Australia and New Zealand Banking Group Limited (ANZ), 2012). Within New Zealand a large proportion of arable land and water is being transformed into dairy farming (Statistics New Zealand, 2012). However, expanding dairy industry is causing a huge pressure on water resources along with various adverse effects on the environment (Jay, 2007; Van Housen, 2015). Nitrate leaching from agricultural farms is contaminating the quality of groundwater and surface water sources (Cameron et al., 2012; Thomas & Morini, 2005).

When a call to boost dairy farming is raised, major concerns connected with dairy farming are emerging in parallel. Growing competition for limited water resources and challenges to obtain access to resources are major concerns in New Zealand (Van Housen, 2015). In summary, efficient utilization of water resources for maximizing pasture yield without the environmental deterioration, for addressing the issues of water scarcity and quality are key concerns for the dairy farming industry in New Zealand (DairyNZ, 2013).

Within New Zealand, Canterbury region is the largest water user accounting for more than half of the country's total allocated water (Tait, 2010). Irrigated pasture accounts for around 75% of the total irrigated area within Canterbury, and the region is facing ever increasing pressure to conserve water and environment (Tait, 2010). This calls for improving irrigation efficiency in the dairy farms to address both water quantity and quality problems (Van Housen, 2015).

To address the issue along with other concerning agencies, farmers, scientists and researchers in New Zealand are keen to explore the options for improving irrigation efficiency and environmental integrity (DairyNZ, 2013). Irrigation water management can be improved by using available water more efficiently (Pereira et al., 2002). Several initiatives such as accounting for potential precipitation in irrigation planning and periodic measurement of soil water content on the farm, have been undertaken around the world to improve agricultural water management (Skhiri & Dechmi, 2012). Around 20% irrigation water can be saved through proper irrigation scheduling that deals with when and how much to irrigate a crop (George et al., 2000; Mannini et al., 2013).

Accuracy of any irrigation scheduling can be improved greatly through the use of a more accurate crop coefficient (K_c) (Benli et al., 2006; Hamlyn, 2004; Tyagi et al., 2000). In addition, soil moisture measurement and water balance monitoring in the plant root zone play a vital role to develop quantitative irrigation scheduling (George et al., 2000). Real time irrigation scheduling should account for weather uncertainty by leaving sufficient storage of water in the soil. This will help

minimise under/over-irrigation while maintaining adequate soil moisture level in plant root zone to make efficient use of available water for securing potential yield without the environmental deterioration (Rawnsley et al., 2007).

However, the most common irrigation scheduling method for pasture production in New Zealand is purely based upon plant available water (PAW), with no regard for the influence of the plant canopy (Van Housen, 2015) or the climate. The irrigation requirement is estimated, mostly based on a constant K_c of 1.0. Due to the rotational grazing system, pasture canopy is constantly changing across the paddock, requiring a variable K_c values for irrigation scheduling. K_c of pasture estimated based on the grazing rotation is still lacking in New Zealand and around the world. In addition, scientific consideration of threshold soil moisture limits to start and stop irrigation is not well addressed, resulting in often over irrigation, and in turn wasting our valuable water resource (DairyNZ, 2011; Orloff et al., 2001; Rout, 2003b).

This thesis, therefore, aims to investigate optimal minimum soil moisture limits to start irrigation and optimal maximum soil moisture limits to stop irrigation by incorporating historical climatic data. K_c have been derived based on grazing rotation to match actual crop water demand. Two soil-plant-atmosphere models IrriCalc and CropWat 8 are utilized to investigate optimal irrigation range for rotational grazing systems. The findings raise hope to make important contribution towards improving irrigation efficiency, eventually supporting the sustainable development of the dairy farming industries in New Zealand and around the world. In addition, it would also point to ways to decrease water pollution by reducing nutrient leaching from dairy farming.

1.2 Context of New Zealand dairy farming

New Zealand's dairy farming started in 1814 with the first cattle, a bull and two heifers, imported by early European settler Samuel Marsden (a missionary) from New South Wales, Australia (Biotechnology Learning Hub 2014; Fonterra, 2014). In the beginning, cows used to be milked by hand in sheds and dairy production was mostly aimed at the domestic markets (The Agribusiness Research and Education Network (AREN), 2008). Slowly export to Australia developed with first dairy export in 1846 (Dairy Companies Association of New Zealand (DCANZ), 2014; Fonterra, 2014).

The first dairy co-operative, a cheese company was established in Otago Peninsula in 1871 (Dairy Companies Association of New Zealand (DCANZ), 2014). Once refrigerator technology was available, New Zealand started exporting refrigerated dairy products to a wider distance (The Agribusiness Research and Education Network (AREN), 2008). The first refrigerated shipment of butter was exported in 1882 from Dunedin to London which remained the largest export market until 1970 (Dairy Companies Association of New Zealand (DCANZ), 2014).

Since 1970 there has been a huge diversification in dairy production and marketing (Fonterra, 2014). The dairy farming has become a significant pillar and a growing contributor of the national economy which produces 20% of New Zealand's gross export revenue and directly accounts for 2.8 percent of GDP (Fonterra Co-operative Group et al., 2003; Schilling et al., 2010).

New Zealand is a key stakeholder at global dairy markets which produces enough milk to supply dairy products for 165 million people (DairyNZ, 2013; International Union for Food (I.U.F), 2011). New Zealand exports more than 95% of its total dairy production, while at global level around 95% of the dairy products is consumed in the area of production and only about 5% is exported abroad. Today, United States and several Asian countries including China and Japan has outnumbered the export share of the United Kingdom (Dairy Companies Association of New Zealand (DCANZ), 2014).

The success of the New Zealand dairy farming lies behind low cost clover-based system and the country's favourable climate enabling cows to graze pastures almost all year around (Monaghan et al., 2008). Pasture based dairy farming has provided an opportunity to produce milk with substantially low investment compared to global trends (Bolan et al., 2009). Apart from suitable environment, New Zealand also has technological and business savvy farmers for sustainable dairy farming (The Agribusiness Research and Education Network (AREN), 2008).

During the sixteen years' time period starting 2000, total number of dairy cattle increased by 53%, reaching 5.0 million by 2015. Over the same time span, the average herd size (cows in one group) increased by more than 75%, and average number of cows per hectare increased by 13% reaching 2.87 by 2015 (Livestock Improvement Corporation (LIC) & DairyNZ, 2015). Increasing demand for dairy products is promoting conversion of non-dairy farming land into dairy farming (Statistics New Zealand, 2012). A large proportion of sheep farming land and forestry is being converted in dairy farming as comparative return from dairy farming is higher.

However, since a few years back milk price is declining constantly. For example, in 2014 average farm gate milk price was NZ\$ 8.93 per kg of milk solids (MS), which reduced to NZ\$ 4.4 by 2015 and NZ\$ 3.9 by March 2016 (Fonterra, 2016). For the season (2015/016) Fonterra forecasted 4% decline in New Zealand milk production compared to previous season (2014/015 of 21.3 billion litres of milk) as farmers are reducing herd size and feeding significantly less supplementary in response to the ongoing low milk prices (Fonterra, 2016; Livestock Improvement Corporation (LIC) & DairyNZ, 2015).

The US which has been one of the major export destinations for New Zealand, is now emerging as net exporter as a consequence of drastic improvement in its dairy farming industry (National Milk Producers Federation (NMPF), 2012). In addition, some South American countries including Argentina and Brazil are also emerging as significant exporters at global milk market (The

Agribusiness Research and Education Network (AREN), 2008). This has threatened the international competitiveness of the New Zealand dairy industry (Greig, 2006).

1.3 Current situation of irrigation systems in New Zealand dairy farms

Agricultural land which is not blessed with abundant rainfall can be made productive by different irrigation systems (Pacific Crest, 2014). Commonly, surface (border-dyke) and sprinkler irrigation methods are being adopted for pasture production in New Zealand. Compared to sprinkler irrigation system, border-dyke irrigation wastes water, contributes to low crop yields and nutrient losses to river systems (Austin, 1998; Bethune, 2004). Therefore, pressurised irrigation methods such as centre pivot systems are seen as the better option for increasing productivity from the limited water resources.

Therefore, in New Zealand, irrigation systems have been shifting from the old border dyke system to centre pivot spray irrigation. On average, surface irrigation decreased nationally by 16,400 ha (17% less) and sprinkler irrigation (spray irrigation) expanded nationally by 122,800 ha (21% increase) during the period 2008 to 2012 (Statistics New Zealand, 2012). Until 2000, travelling irrigators were the most frequently used irrigation application method in New Zealand (Lincoln Environmental, 2000b). However, currently the most popular irrigation system, particularly on dairy farms, is centre pivot as it supplies water with the required application depth more uniformly (McIndoe, 2013). In addition, centre pivot can also be used for steeper terrain and requires less labour.

Many dairy farmers have adopted center pivot irrigation system to take advantage of low application rates, short return intervals, low labour requirements and higher pasture production than other irrigation systems (Rout, 2003a). For example, in the Lincoln University Dairy Farms (LUDF), Canterbury, New Zealand, almost 80% of the total 160 ha dairy farm area is being irrigated by centre pivot (South Island Dairying Development Centre (SIDDC), 2013).

Centre-pivot irrigation which is also called circle irrigation is a method of crop irrigation in which equipment rotates around a pivot and crops are watered with sprinklers (Mader & Kan, 2010; Omary et al., 1997). The center pivot system consists of a main water delivery pipe of relatively large diameter supported above the ground by towers (Food and Agricultural Organisation (FAO), 2007). One end of the water delivery pipe is connected to a pivot at the center of the command area. Sprinklers or spray nozzles are connected along the water delivery pipeline to apply water. The circular area under centre-pivot irrigation is centred to the pivot, when viewed from sky, which is also called crop circles (Gray, 2012).

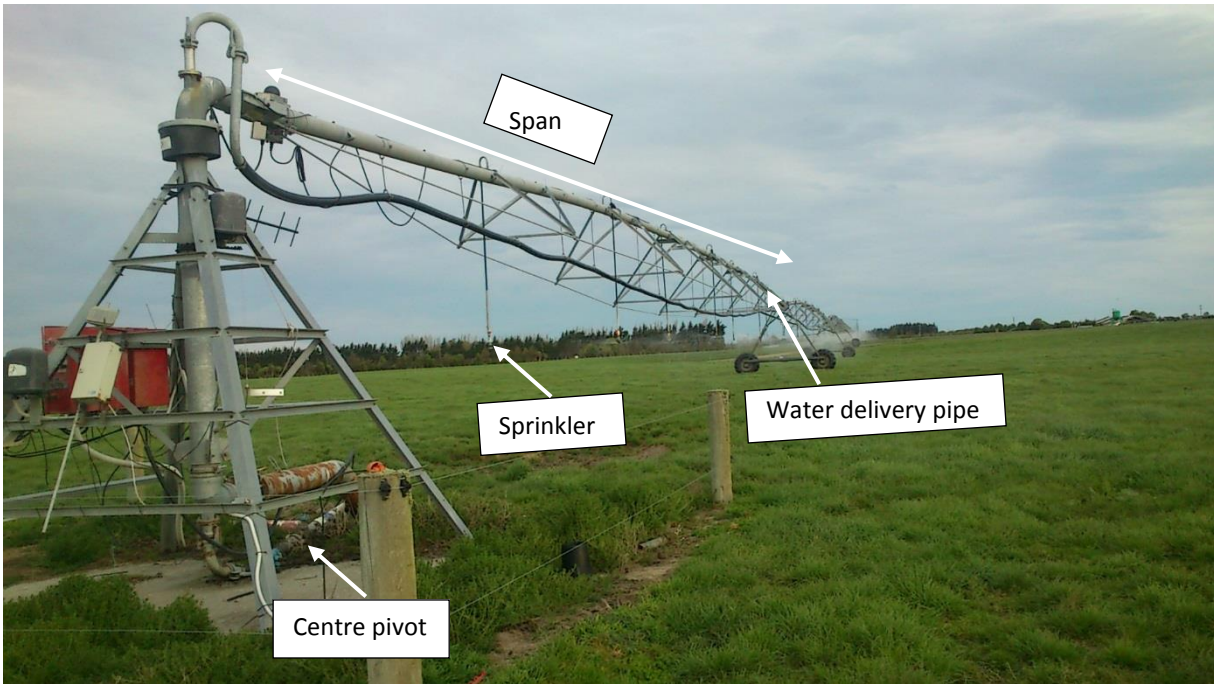


Figure 1-1: Centre pivot irrigator system

The application rate of the water emitters varies from lower values near the pivot to higher values towards the outer end by the use of small and large size of nozzles along the water delivery pipe line accordingly, to account for the areas served by these emitters (Food and Agricultural Organisation (FAO), 2007).

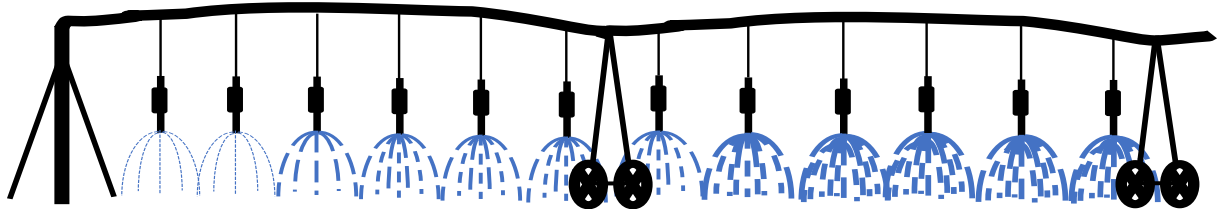


Figure 1-2: Irrigation application rates through emitters in a centre pivot irrigator system

In some cases, to capture the corners in a field, a swing arm can be added to the basic centre pivot system. At the end of the swing arm an end gun is attached which is run by Global Position System (GPS) located on the end tower. The coordinates of the field are programmed into the GPS software based on which the swing arm adjusts its path automatically to be oriented to irrigate the full extent of the field (Pacific Crest, 2014).

1.4 Main issues in New Zealand dairy farming irrigation

1.4.1 Irrigation demand

New Zealand dairy farming is dominated by pasture-based open grazing system (Monaghan et al., 2008). In many countries around the world, forage provides only around 40-70% of the required nutrients of the cows while in New Zealand pasture provides almost 100% of the needed nutrients (McGuffey & Shirley, 2011).

In many dairy farming areas in New Zealand, including Canterbury, pasture evapotranspiration, especially during spring, summer and autumn is higher than rainfall (Figure 1-3). Thus, irrigation is a must to ensure pasture production for sustainable dairy farming. It has been estimated that, with irrigation, pasture production in Canterbury can be increased by more than 5,000 kg DM/ha/year, which is almost two-fold compared to the un-irrigated production (ROCKPOINT, 2012).

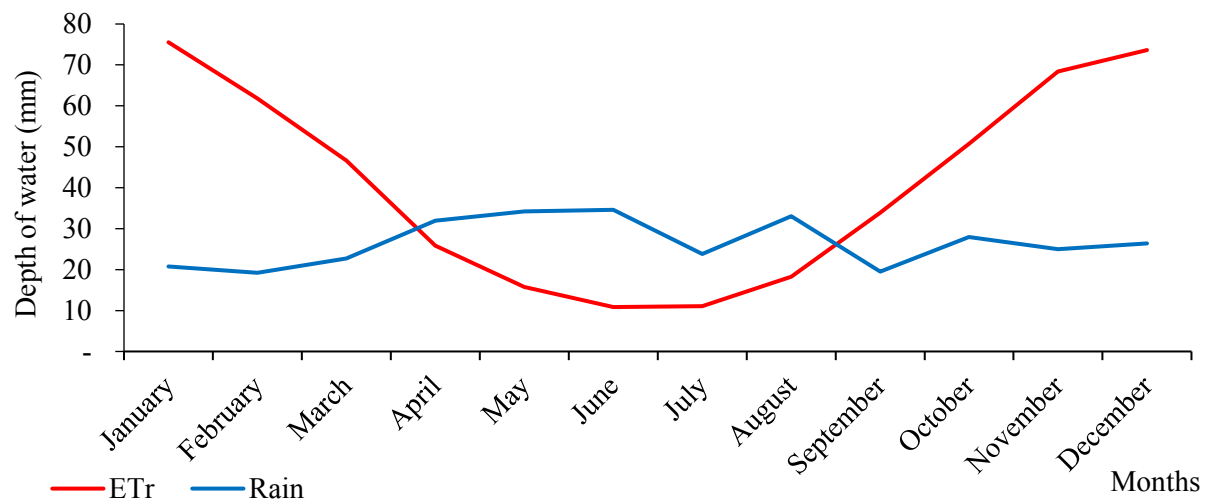


Figure 1-3: Average monthly reference evapotranspiration (ETr) and rainfall data based on 16 years (2000 – 2015) values recorded at Broadfield weather station

1.4.2 Irrigation efficiency

A large proportion of farmers have little idea about when to start irrigation and how much water to apply based on Plant Available Water (PAW) to satisfy actual crop water demand. Increasing pressure on water and environment are posing special challenge to make it mandatory to account for soil moisture in irrigation planning (Heiler, 2012). Many farmers recognise the need to measure soil moisture available in root zone, but fewer than 10% farmers use the measured value in their irrigation planning (ROCKPOINT, 2012). Only about 20% of the total irrigated land in New Zealand is irrigated based on soil moisture consideration (Heiler, 2012).

Though, irrigation efficiency improvement technologies are available, farmers use them rarely (ROCKPOINT, 2012). Due to rotational grazing system pasture height differs across the paddocks, however, irrigation is applied uniformly regardless of actual plant canopy. Therefore, in many irrigation schemes, current irrigation efficiency is below the potential limit.

1.4.3 Water quality

Chemical fertilizer, animal manure and effluents used for agriculture production cause nutrient leaching to the water bodies, if water application is more than crop water requirement and exceeds the soil's storage capacity of the root zone. In addition, nutrients from the urine of the grazing animal further exacerbate water quality issues (Di & Cameron, 2002). In fact, urine is the main source of nitrogen (N) that results in nitrate (NO_3^-). The N loading rate under a urine patch is about 1,000 kg N ha^{-1} (Di & Cameron, 2002) which is more than pasture's absorption capacity (Haynes & Williams, 1993; Jarvis et al., 1995). Therefore, pasture cannot utilize all available N and the surplus N, when converted to NO_3^- is prone to leach if there is excess of water.

In New Zealand, intensification of dairy farming is causing considerable negative impact on water quality due to N leaching (Hamill & McBride, 2003; Jay, 2007; Ledgard et al., 1999; Vant, 2001). Therefore, on-going intensification of New Zealand dairy farming requires irrigation efficiency improvement to reduce N leaching by reducing deep percolation and surface runoff from the agricultural farm and thereby improve water quality.

1.5 Motivation for irrigation efficiency improvement

Water is one of the most important natural resources and its sustainable management is essential (UNESCO, 2003). Although, 70% of our earth is covered by water almost 97% is saline, hence unsuitable for agriculture, and only 3% of global water is fresh (United Nation's Environment programme, 2008; United State's Geological Survey Science for a changing world (USGS), 2008; World Water Council, 2008). It is not economically and environmentally viable option to go for new water resource development (George et al., 2000). According to International Water Management Institute (IWMI) (2007) the era for new water resource development is over. Thus, increasing water demands from different sectors: irrigation, domestic, municipal, industrial, and environmental, have to be addressed by improving performance of the existing water resources (Food and Agriculture Organization of the United Nations (FAO), 2008; George et al., 2000; Kumar et al., 2011; Schultz et al., 2009).

At global level only half of the water diverted from water sources is used productively by crops and the remaining proportion of the initial water ends up in aquifers and rivers (Food and Agriculture Organization of the United Nations (FAO), 2003). In New Zealand up to two thirds of the applied

water in surface irrigation scheme are lost through deep percolation (Martin et al., 2006). Even in pressurised irrigation methods current efficiency levels are below the potentials. Therefore, an efficient use of water resource by adopting proper irrigation management strategies is essential (International Water Management Institute (IWMI), 2007; Kumar et al., 2011).

In fact, efficient use of the available water leads to more food, income, better livelihoods and ecosystem (Molden et al., 2010). To conserve present ecosystem and biodiversity, productivity improvement of the existing irrigation schemes by the improvement of irrigation efficiency is the best option (Bekchanov et al., 2015). The risk of not maintaining a productive agriculture is a strategic mistake (Schultz et al., 2009). It is the promise and the challenge to make proper use of precious water resources to contribute sustainable food production and environment protection (International Water Management Institute (IWMI), 2006).

1.6 Irrigation efficiency

Irrigation efficiency is an outcome of how farmers manage their irrigation systems on a day to day basis (Lincoln Environmental, 2000b). The scheme irrigation efficiency includes conveyance efficiency, distribution efficiency and field application efficiency (Food and Agricultural Organisation (FAO), 1989). Conveyance and distribution efficiencies measure the efficiency of canal/pipe networks to transport water from the source and distribute it into the irrigation systems. The efficiency of water application in the farm is termed as field application efficiency, which measures the fraction of the applied water into the farm that is actually used by the crop (Food and Agricultural Organisation (FAO), 1990). Thus, scheme irrigation efficiency implies how effectively irrigation volume taken from source is being used by the plant.

The field application efficiency does not include water losses between the source and water application point at the farm. For pressure irrigation systems, conveyance and distribution losses are generally low which makes field application efficiency almost close to or equal to the system efficiency (Rout, 2003a). Therefore, for pressure irrigation systems, field application efficiency is commonly used to assess efficiency of the irrigation system. Maximising irrigation efficiency will significantly contribute to minimising the net irrigation requirements along with adverse environmental impacts of water abstraction and deep percolation (Rout, 2003a).

Irrigation efficiency can be improved by adopting prudent irrigation scheduling strategies that deal with when and where to apply irrigation to minimise yield reduction due to water shortage and deep percolation due to water excess (Evans et al., 1996). In other words, irrigation scheduling improvement is extremely important management practice for improving irrigation efficiency (Evans et al., 1996).

1.7 Options to improve irrigation scheduling

1.7.1 Crop canopy monitoring

Variations in the plant heights across the paddocks under rotational grazing system means differences in crop water needs, because crop height impacts on crop canopy (Benli et al., 2006; Cambridge University Press, 1998) and thus crop-water requirements (Allen, 2003; Food and Agriculture Organization (FAO), 1998; Hanson & May, 2006). Therefore, adequate knowledge of crop coefficient to match actual crop canopy on the paddock is essential to estimate correct crop irrigation requirements, to improve irrigation scheduling, and thus increase on-farm irrigation-efficiency levels (Levidow et al., 2014; Morris, 2006).

1.7.2 Soil moisture monitoring

Soil moisture measurements make sure that plants are only watered when they need irrigation. Accurate soil moisture readings help to promote yield by ensuring that the soil is neither too wet nor too dry (The Energy Efficiency and Conservation Authority (EECA), 2009).

Irrigation application without considering soil moisture levels can cause under/over-irrigation. Over irrigation wastes our valuable water and results in an increased nutrient leaching. Therefore, identification of the proper soil moisture levels to start and stop irrigation is essential, to improve irrigation scheduling, and thus improving irrigation efficiency and crop yield (Cabelguenne et al., 1997; Gheysari et al., 2009; Howell & Meron, 2007). This implies, irrigation based on soil moisture monitoring contributes greatly to conserve water, optimize yields, and minimise water pollution (Morris, 2006).

1.7.3 Water balance monitoring

The soil water balance approach is essential to estimate the amount of water available in the crop root zone at a given time, based on which next irrigation is decided. In the water balance approach, soil water budgeting in the root zone is considered to develop irrigation scheduling (Camp et al., 1988; Feddes et al., 1974; Foroud et al., 1992; George et al., 2000; Kincaid & Heermann, 1974; Rowse et al., 1983; Smith, 1992). The water balance approach estimates current soil water deficit by accounting for all water additions and subtractions within the root zone (Colorado State University, 2011). This approach contributes to irrigation scheduling improvement by manipulating irrigation application based on estimated soil water deficit (George et al., 2000).

1.7.4 Accounting for weather uncertainty

Efficiency of any irrigation planning greatly depends on the accuracy of weather consideration (Cabelguenne et al., 1997; Rochester & Busch, 1972; Saleem et al., 2013). Rainfall in semi-humid

environments can contribute a significant proportion of irrigation needs and only the remaining needs should be applied through irrigation (Brown et al., 2010). Irrigation supply without considering future rainfall may create over/under irrigation (Azaiez & Hariga, 2001; Leenhardt et al., 1998).

The use of future rain in irrigation scheduling was recommended about 40 years ago (Rochester & Busch, 1972). Variability in weather and available water resources, and the impact of intensive irrigation on the environment, especially on water quality are further pressing the need to incorporate future rain in irrigation planning (Cabelguenne et al., 1997).

To cope with weather uncertainty two types of adaptation measures are recommended: hard adaptation (improvement in irrigation infrastructures) and soft adaptation (improvement in knowledge of irrigation application methods and technique) (Mishra et al., 2013; World Bank, 2010). Soft adaptation measures are preferred options as they require low investment compared to the hard adaptation measures (World Bank, 2010).

1.8 Research objectives and methods

The overall research objective of the study was to contribute to the improvement of agricultural water management by enhancing irrigation scheduling. This was achieved by incorporating correct pasture water requirement due to the grazing rotation and accounting for long term climatic variability in the choice of the starting and ending soil moisture contents for irrigation scheduling. In this context the following inter-related specific objectives were identified as sub objectives that together addressed the main research objective:

1. To develop correct crop coefficient (K_c) of pasture that matches actual pasture water needs

To achieve this objective, water use in the 20 non-weighing lysimeter was studied during the period August 2014 to July 2015 at Lincoln University Dairy Farm (LUDF), South Island, New Zealand. Pasture growth dynamics on the lysimeters were monitored over the same time period. Precipitation, irrigation application and deep percolation through the lysimeters were measured for the same time period. Aquaflex soil moisture readings were adopted to estimate change in soil moisture in the lysimeters. Application of the water budget equation to the lysimeters data enabled actual evapotranspiration (ET_a) calculation. Reference evapotranspiration (ET_r) was estimated using Penman Monteith equation using, for which weather data were collected from Broadfield weather station that lies 3 km north east of LUDF. Crop coefficient of pasture (K_c) was developed by dividing ET_a by ET_r at different grazing stages and a linear relationship between K_c and h has been derived.

2. To couple Time Domain Reflectometry (TDR) and Aquaflex soil moisture (SM) readings to improve soil moisture determination in non-weighing lysimeters for improving water balance studies for crop coefficient (K_c) development

The second objective was addressed to improve the developed K_c - h relationship to address the first objective. Three different lengths (200, 500 & 900 mm) of TDR probes were installed beside the lysimeters and Aquaflex. Soil moisture content (% vol) was measured during the period June 2014 to December 2015 covering the field capacity down to the critical point. That led to investigate the spatial and temporal distribution of soil moisture during different wetting and drying events. Results of the experiments were analysed and investigated to identify a strong linear relationship between TDR and Aquaflex soil moisture readings. Based on the developed relationship, Aquaflex soil moisture values, which were available before the installation of the TDRs, were converted to lysimeters' moisture content. Application of Aquaflex soil moisture readings, adjusted based on TDR measurements, demonstrated the improvement in the water balance study of the lysimeters.

3. To investigate irrigation and deep percolation from current irrigation strategies adopted in Canterbury, New Zealand dairy farm

This objective was met by conducting a pastoral survey to the Canterbury, New Zealand dairy farmers during the period September 2014 to June 2015. A questionnaire was prepared and 32 dairy farmers were interviewed via telephone that helped to understand farmer's current irrigation management strategies during different seasons, particularly in relation to pasture growth dynamics and plant available water. IrriCalc model was used to predict irrigation and deep percolation under prevailing irrigation management strategies to investigate the opportunities for irrigation scheduling improvement.

4. To identify optimal soil moisture range to start and stop irrigation for improving irrigation scheduling

Two Soil-Plant-Atmosphere models IrriCalc and CropWat 8 were used to estimate irrigation and deep percolation for a range of irrigation management scenarios and crop coefficient values. Analysis of the IrriCalc and CropWat 8 results was carried out to identify the minimum soil moisture content to start irrigation and the maximum soil moisture content to stop irrigation for assessing optimal irrigation range that accounts for potential rain and therefore, reduce net irrigation requirement and deep percolation losses.

1.9 Conceptual framework

Irrigation scheduling improvement by developing a new formula for pasture crop coefficient based on grazing rotation, and identifying the optimal soil moisture range for irrigation to minimise deep percolation losses over a long period by accounting weather uncertainties is the main concept behind this research. The conceptual framework developed for the study is presented in Figure 1-4. As shown in the conceptual framework, crop canopy, soil moisture and water balance monitoring are the main focus of this study, which constitute different sub-objectives of the overall research, which are addressed in various self-contained chapters.

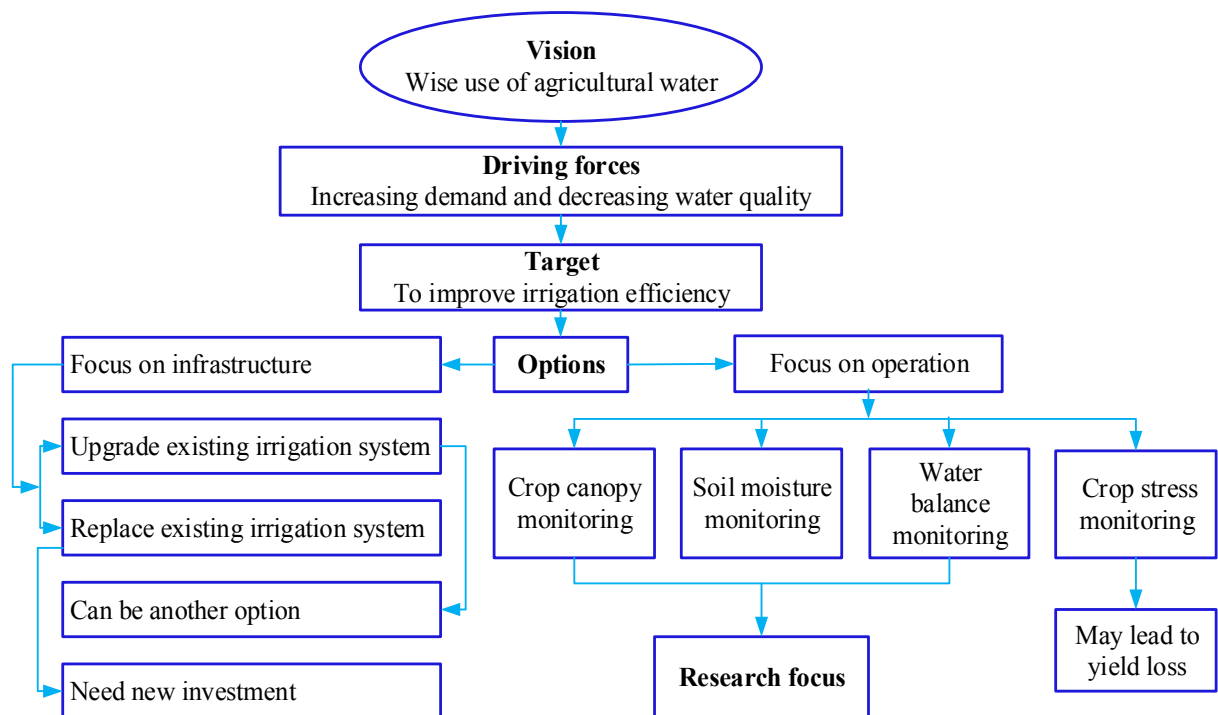


Figure 1-4: Conceptual framework developed for the study

The study used multiple methods and analytical techniques. The detailed methodologies are discussed in each self-contained chapter. The study was primarily based on field data sets measured at Lincoln University Dairy Farm (LUDF) and climatic data sets collected from Broadfield weather station. Detailed description, sources and properties of data are mentioned in each individual chapter.

1.10 Chapters overview

This thesis consists of six chapters, including four articles, focussed on identifying four specific objectives. These objectives, constituting a particular practical element of irrigation scheduling, are developed to answer the overall research objective.

Chapter 1 (this chapter) provides background of the study and dairy farming in New Zealand. This chapter also identifies main issues in New Zealand dairy farming irrigation sector, highlights the need to improve irrigation efficiency and discusses the options for improving irrigation scheduling. The thesis objective, research framework, chapter overview, and original contributions are also presented at the end of this chapter.

Chapters 2 to 5 are self-contained essays written in journal article style.

Chapter 2 **Manuscript 1: Impact of Rotational Grazing Systems Upon the Pasture Crop Coefficient for Irrigation Scheduling.** This chapter reviews different contemporary approaches to quantify actual and reference evapotranspiration for crop coefficient development of pasture (K_c). Primarily the chapter focuses on a Lysimetry based water balance approach for estimating actual evapotranspiration (ET_a), and calculating reference evapotranspiration (ET_r) by applying Penman Monteith method by using CropWat 8 model. The key question answered is: What is the relationship between K_c and pasture's height (h in cm)? The "newly" derived $K_c - h$ relationship was essential to estimate K_c for different grazing rotations to meet Objective 1.

Chapter 3 **Manuscript 2: Understanding Spatio-Temporal Variability of Soil Moisture Measurement with Aquaflex and Time Domain Reflectometry.** This chapter was designed to improve the $K_c - h$ relationship, which was developed in Chapter 2, by installing Time Domain Reflectometer (TDR) beside the lysimeters and Aquaflex and analysing their measurements of soil moisture data. Chapter 3 examines spat-temporal variability of soil moisture contents beside the lysimeters and Aquaflex, and identifies a strong relationship between soil moisture measured from these two soil moisture sensors. TDR installed beside the lysimeters and Aquaflex helped to convert Aquaflex soil moisture values, which were available before the installation of the TDR, to the corresponding lysimeters to improve water balance studies in the lysimeters. With adjusted Aquaflex soil moisture values, based on TDR values, an improved $K_c - h$ relationship was derived. Outcomes of Chapter 3 address Objective 2.

Chapter 4 **Manuscript 3: Current Irrigation Strategies for Rotationally Grazed Pasture in New Zealand and their Impacts on Irrigation Efficiency.** Knowledge of existing irrigation management strategies is a key to analyse their impact on irrigation efficiency and to propose irrigation scheduling improvement alternatives. This chapter identifies different irrigation strategies adopted by Canterbury, New Zealand dairy farmers, particularly in relation to grazing rotation and soil water holding capacity, based on the survey. Identified irrigation strategies were applied to LUDF to estimate and analyse irrigation and deep percolation using IrriCalc model, to assess the impact of prevailing irrigation strategies on water use to meet Objective 3. This chapter also describes current grazing scenarios and pasture production status in Canterbury, New Zealand.

Chapter 5 **Manuscript 4: Determining the Optimal Irrigation Strategy for Rotational Grazing Systems.** In this chapter commonly applied crop coefficient value of 1.0 in addition to those “newly” estimated in Chapter 3 and a range of irrigation management strategies, including those identified in Chapter 4, are utilized to estimate irrigation and deep percolation using two soil-plant-atmosphere models (Irricalc and CropWat 8). Analysis of the estimated irrigation and deep percolation for 14 irrigation seasons (2001/02 to 2014/015) under different irrigation management scenarios and crop coefficient values guided to identify threshold soil moisture limits to start and stop irrigation. Outcomes of the study proposes new irrigation scheduling methodology to address Objective 4.

Chapter 6 draws overall conclusions and discusses relevant policy implications of the study. The overview contained in this chapter includes: crop coefficient of pasture and its relationship with pasture height, role of soil moisture determination in water balance study, current irrigation management strategies adopted by Canterbury dairy farmers, and threshold soil moisture limits to start and stop irrigation. Based on the study some suggestions for irrigation scheduling improvement in irrigated dairy farming and recommendations for further research are summarized.

1.11 Original contributions

The principal original contribution of this research is the development of a robust relationship between two interrelated variables: crop coefficient of pasture (K_c) and pasture’s height “ h ” (Manuscripts 1 & 2). The next contribution include: improving current irrigation strategies to address weather uncertainty for enhancing irrigation efficiency (Manuscripts 3). Another contribution is: identification of optimal irrigation strategy for efficient use of water on rotational grazing pasture farms (Manuscripts 4). In the current context, when the most common irrigation scheduling for rotational grazing pasture is dominated by soil moisture monitoring and a constant crop coefficient of 1.0, the proposed $K_c - h$ relationship and optimal irrigation range is an addition to the literature in the route to improve irrigation efficiency.

Other contributions includes:

1. Developing a new relationship between pasture’s height and days after grazing;
2. Investigating a relationship between Aquaflex and TDR soil moisture readings;
3. Examining optimal root depth for pasture’s water uptake using dry-down experiment; and
4. Identifying current irrigation strategies in relation to grazing rotation and plant available water.

Chapter 2

Impact of Rotational Grazing Systems upon the Pasture Crop Coefficient for Irrigation Scheduling

Abstract

Due to rotational grazing systems, pasture height in a dairy farm varies greatly across the paddocks requiring for variable crop coefficients (K_c) to match actual pasture height (h). However, irrigation planning in New Zealand dairy farms is based on a constant K_c of 1.0. The aim of this study was to understand the impacts of grazing rotations upon the K_c for ryegrass pasture (*Lolium perenne*) using non weighing percolation lysimeters. The experiments were conducted on Lincoln University Dairy Farm, New Zealand during the period August 2014 to March 2016. FAO Penman-Monteith equation was used to estimate the reference evapotranspiration (ET_r) using daily weather data. A water balance approach was applied to 20 lysimeters' data to calculate actual evapotranspiration (ET_a). Based on ET_a and ET_r , K_c was estimated for the different pasture growth stages of a grazing rotation.

There was a significant variation in deep percolation through the lysimeters, which are installed just 1.0 m apart. Over the study period, total deep percolation measured from first group of 10 lysimeters installed in a silty loam soil ranged from 0.14 mm to 186 mm. For the same period, total deep percolation measured from the second group of 10 lysimeters installed in a sandy loam soil ranged from 130 mm to 323 mm. Pasture height measured on each of the 20 lysimeters also showed great variation, just before and just after grazing. However, average pasture height on 20 lysimeters just before and after grazing was comparable to the corresponding pasture height on wider paddock number seven (N7).

The results showed that K_c and h can be modelled by a linear relationship. Pasture heights pre and post grazing were typically 30 cm and 10 cm, for which estimated K_c values were 1.1 and 0.7 respectively. The average K_c for one grazing rotation of 30 days was estimated at 0.8. This implies that the conventional irrigation scheduling using a K_c of 1.0 would provide "on average" 20% more irrigation than the actual water demand of grazed pasture. Irrigation scheduling that incorporates a more accurate K_c will lead to more efficient water use and importantly less deep percolation. This will reduce leaching of nutrients, perhaps the biggest environmental challenge for pastoral irrigators in New Zealand, without impacting upon productivity.

KEY WORDS: irrigation; crop coefficient; pasture; grazing; lysimeter, evapotranspiration.

2.1 Introduction

To address global hunger and increasing food demand, crop yield needs to increase by at least 1% per year (Grafton et al., 2015). However, relying only on more extensive use of irrigation would exacerbate water scarcities (Springer & Duchin, 2014). This necessitates judicious use of agricultural water for sustainable food production, especially in water-scarce regions like many Asian and African countries (Food and Agriculture Organization of the United Nations (FAO), 2008; Global Research, 2014; Kumar et al., 2011; Schultz et al., 2009). Many regions in New Zealand are also facing water shortage. For example in Canterbury, due to increased water demand from different sectors, including dairy farming, many water resources are at or are approaching their allocation limits (Tait, 2010).

Irrigated pasture is the dominant fresh water consumer in Canterbury and accounts for around 75% of the total irrigated area (Van Housen, 2015). The Canterbury climate can vary dramatically from season to season, with a high probability of long dry spells in the summer frequently causing drought conditions (Saunders & Saunders, 2012). Evapotranspiration in the region is generally higher than rainfall during summer, irrigation is therefore essential to enable more intensive pastoral land use (Martin et al., 2006). Today the Canterbury region is not only the largest water user but also the region with the highest dependency on irrigation. Almost 58% of all water allocated for consumptive use in New Zealand is within Canterbury which faces mounting pressure to conserve water (Tait, 2010).

Water management can be improved greatly through the use of a more accurate crop coefficient for irrigation scheduling (Benli et al., 2006; Tyagi et al., 2000). However, irrigation scheduling on pastoral farm in New Zealand is purely based upon plant available water (PAW), with no regard for the influence of the canopy (Van Housen, 2015). In fact, irrigation scheduling based on plant growth stages under local weather conditions has largely been ignored universally, including in the technologically advanced USA (United States Department of Agriculture (USDA), 2015). It is claimed the dynamic nature of grazing rotations makes it difficult to schedule irrigation based on actual crop coefficient (Snyder et al., 2008). Subsequently the irrigation requirement is estimated, mostly based on a constant pasture coefficient of 1.0 or the crop coefficient values recommended by FAO, due to lack of locally adapted K_c values (Kisekka et al., 2010).

A dairy farm consists of several small blocks called “paddocks” designed for grazing management. Cows are grazed rotationally in different paddocks resulting in a variation in pasture height across a farm. Rout (2003b) found a notable difference in pasture heights before and after grazing, with respective values of approximately 30 cm and 10 cm, over a 20-days grazing rotation. Over the course of the grazing rotation the crop coefficient varies with the changes in ground cover (Allen et

al., 1998). This highlights the need to use a variable crop coefficient of pasture for irrigation scheduling with rotational grazing system.

2.1.1 Crop coefficient: concept and estimation process

Actual evapotranspiration (ET_a) refers to the amount of water that is actually removed from a surface or a soil profile through combined processes of evaporation and transpiration under specific soil and plant conditions. Evapotranspiration from a hypothetical reference crop with specific characteristics, not short of water, independent of soil factors is called reference evapotranspiration (ET_r), which depends only on climatic parameters and can be computed from weather data (Allen et al., 1998).

During the last five decades many scientists and specialists have developed numerous techniques for ET_a estimation (Kumar et al., 2011; Najafi, 2007). For field measurement of ET_a , simple mass balance methods, such as lysimetry approach are preferable (Jong & Bootsma, 1996; Najafi, 2007; Rickert et al., 1984; Samani, 2000; Woodward et al., 2001). There are several approaches for ET_r estimation based on climatic data (Hasegawa & Sakayori, 2000; Łabędzki et al., 2011) which are described in Pereira et al. (2015).

Plant height, leaf area, amount of soil shaded, available stomata for evaporation and soil wetness beneath the canopy affect, up to certain extent, the amount of ET_a (Allen et al., 1998). For the estimation of ET_a , effects of all these parameters are lumped into a single parameter called K_c (Allen et al., 1998). The K_c is ratio of ET_a to the ET_r (Jensen, 1968). In other words K_c is the factor that relates ET_a to ET_r (The United States Department of Agriculture (USDA), 1993).

Single and dual crop coefficient approaches have been used to estimate K_c (Majnooni-Heris et al., 2012). In dual crop coefficient approach, evaporation is separated into crop transpiration and soil evaporation. When the ground is fully covered by grass, evaporation from soil is not a large component of evaporation, and therefore use of a single crop coefficient approach is recommended (Allen et al., 1998).

Different approaches of ET_r , ET_a and K_c estimation are also described in Allen et al. (2011). Among various methods on ET_r estimation, the FAO Penman-Monteith method has become one of the most cited publications in the field of crop water relationship (Pereira et al., 2015). Details about the FAO Penman-Monteith's equation is summarized among others in Allen et al. (1998). The FAO Penman-Monteith method follows the principle of conservation of energy, and uses meteorological data, such as maximum and minimum temperature, maximum and minimum relative humidity, wind speed, and solar radiation to estimate ET_r .

Two types of hypothetical reference crops used to define ET_r include: (1) 0.12 m tall clipped, cool-

season grass with a fixed surface resistance of 70 sm^{-1} and an albedo of 0.23" as suggested in FAO-56; and (2) 0.5 m tall full-cover alfalfa (Lucerne) having surface resistance of 45 sm^{-1} as introduced by ASCE (2005). Compared to grass reference, the alfalfa reference is taller, has a higher leaf area, represent low surface resistance and has higher tolerance to reduced soil water content which in turn produces higher rates of ET than for grass, particularly under dry, hot, and windy conditions (Irmak et al., 2008; Walter et al., 2000). In general, the tall (alfalfa) reference is superior to the clipped grass due to the closer similarity of alfalfa reference to the agricultural crops in terms of height, leaf area and stomatal conductance (Allen et al., 2011).

However, in humid and semi-humid climates under full grass cover status, the use of the tall (alfalfa) reference or the clipped grass gives similar results for ET_r (Allen et al., 2011). In this research ET_r for 0.12 m tall clipped grass is used as CropWat 8 and IrriCalc, which are applied in this study for analysing irrigation planning, require grass reference. CropWat 8 and IrriCalc are the computerised crop water management models that utilises FAO Penman-Monteith equation to estimate ET_r .

2.1.2 Pasture crop coefficient estimation in New Zealand

Four different stages (measured in days) of crop growth, initial, development, mid-season and late-season, and corresponding crop coefficient values for a large variety of crops are presented in Doorenbos and Pruitt (1977) and Allen et al. (1998). However, Allen et al. (1998) and follow on publications have recommended the development of crop coefficient based on local weather, crop variety and cultural practices. In addition, it is a challenge to distinguish different growing stages for perennial pastures that have been established for several years, and that are grazed several times each year.

In New Zealand, there are very few studies on correct crop coefficient estimation of pasture (Kienzle & Schmidt, 2008; Landcare Research, 2004; Van Housen, 2015). Researchers who estimated the pasture crop coefficient in New Zealand, include Rout (2003b), Bright (2009) and Van Housen (2015). In this previous work, monthly average and daily time series of pasture crop coefficients for the whole year have been developed. However, crop coefficient estimations of pasture based on grazing rotations are still lacking (Van Housen, 2015). Crop coefficients that match actual plant canopy are essential to develop proper irrigation scheduling (Moriondo et al., 2015; Moriondo et al., 2013; Vanino et al., 2015).

2.1.3 Available relation between crop coefficient and plant height

Assuming constant relative humidity and wind speed, Rout (2003b) has proposed the following relationship between pasture crop coefficient (K_c) and pasture height 'h' (h in cm).

$$K_c = \frac{h^{0.3}}{3} \quad (2-1)$$

However, wind speed and relative humidity vary with seasons. For example daily wind speed and relative humidity recorded at Broadfield weather station (43°35'53", 172°28'12"), Canterbury, New Zealand during 2014/015 irrigation season (September 2014 to April 2015) varied from 1.5 to 7.7 m s⁻¹ and 43 to 99%, respectively. Both daily minimum and maximum wind speeds were observed during September 2014. The daily minimum relative humidity was recorded during November 2014 and the daily maximum relative humidity was recorded during April 2015. Both wind and relative humidity affect the value of K_c (Allen et al., 2011; Scotter & Heng, 2003). This necessitates further refining of the above relation to estimate correct crop coefficient for different grazing stages.

The main objective of this research was to estimate the crop coefficient for pasture through the different stages of a grazing rotation, to better represent the actual water needs of pasture based on its canopy. Using the estimated values of ET_r and ET_a , respectively from FAO Penman-Monteith method and lysimeter data, K_c for pasture was developed for different growth stages to produce a relationship between K_c and pasture height 'h' (h cm). The K_c values developed through this study provide useful guidelines for improving irrigation scheduling in pastoral farm. This, in turn, will help to conserve water and improve environmental performance, minimise deep percolation events and reduce nutrient leaching losses.

2.2 Material and Methods

2.2.1 Site description

The study area, Lincoln University Dairy Farm (LUDF), (40° 38' 40.26" and 172° 26' 35.86") is located in Canterbury, South Island, New Zealand. The LUDF has 160 ha of irrigated pasture land which forms the dairy farm milking platform. Pasture is the collective name of sown or naturally grown plants for grazing animals (The Encyclopedia of New Zealand, 2014). Perennial ryegrass pasture (*Lolium perenne*) is the grass sown on the LUDF which is the main pasture grass for providing major nutrients to dairy cows in New Zealand (Lee et al., 2010; Monaghan et al., 2008).

The LUDF consists of two blocks; north block with 11 paddocks; and south block with 10 paddocks. The north paddocks are denoted as N and the South paddocks are denoted as S, followed by respective paddock number. Thus, first paddock in north block is denoted as N1 and so on.

Average annual rainfall and reference evapotranspiration for the study area recorded at Broadfield weather station that lies 3 km north east of LUDF were 609 and 939 mm, respectively. An average 450 mm of irrigation is supplied per annum by three different irrigation systems: centre-pivot, long laterals and k-lines (spray-lines which are based on a sprinkler pod system). Two centre-pivots, with

basic pivot length of 402 m, irrigate almost 80% of the farm followed by long lateral (15%) and k-lines (5%). The pivots take 20.8 hours to complete one full rotation at 100% maximum speed. Irrigators take water from a 90 m deep well and supply to the farm at a rate of 5.5 mm of water per day.

Centre pivot is the most popular irrigation system, particularly on dairy farms in New Zealand, as it supplies water with the required application depth more uniformly (McIndoe & Curtis, 2012). Long lateral and k-lines are also widely used for areas where the centre pivots cannot cover such as corners of the paddock. Irrigation applications under long lateral and k-lines are higher than pivot due to longer irrigation return interval of long lateral and k-lines.

Generally, soils in the north block are silty loam to sandy loam with stones and therefore free draining, while on the south block soils range from silty clay loam to clayey and are poorly-drained. Based on these different soil textures, four soil moisture sensors (Aquaflex) are installed in paddocks N2, N7, S6 and S9 to monitor volumetric percentage of soil moisture content to inform irrigation decision making. The installed Aquaflex (SI.95-10-C) on the farm was manufactured by Streat Instruments Christchurch, New Zealand. In addition, paddock N7 has 20 lysimeters (non-weighing) installed for monitoring nutrient leaching through deep percolation losses. These 20 lysimeters and the Aquaflex soil moisture sensor installed in paddock N7 were utilised for a detailed study of the impact of grazing rotation on the crop coefficient of pasture.

Twenty lysimeters used for the study are installed in two groups with 10 lysimeters in each group. Distance between adjacent lysimeters is 1 m, and distance between the two groups of lysimeters is 50 m. Aquaflex is 100 m away from the first lysimeter in the second group, see Figure 2-1.

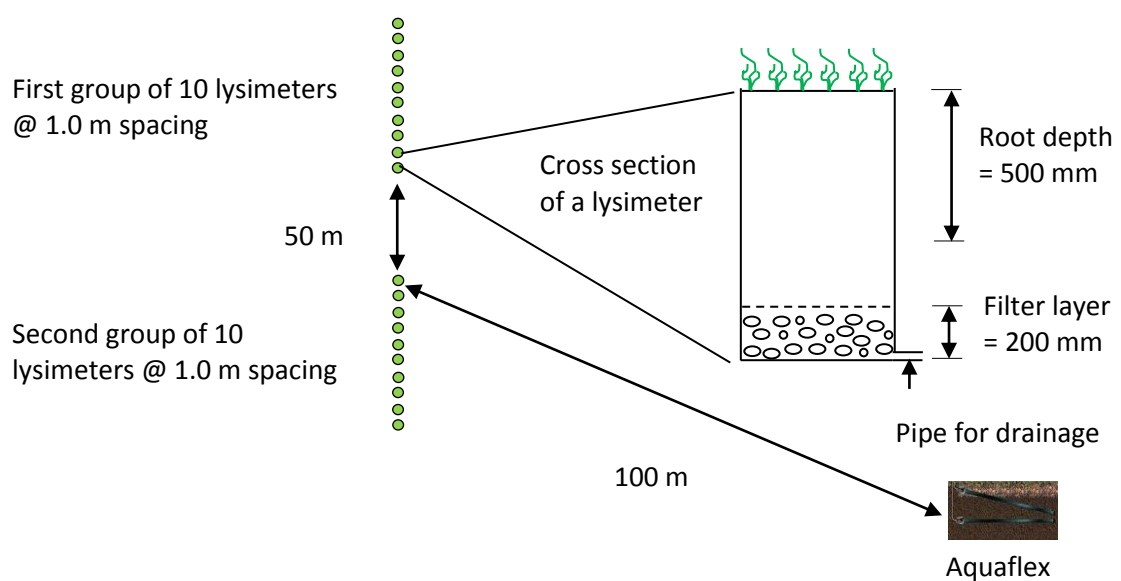


Figure 2-1: Equipment set-up in the field (LUDF) with cross-sectional view of a lysimeter

The non-weighing lysimeters (also called percolation or deep percolation lysimeters) used for the study are circular shaped with diameter 500 mm and height 900 mm. Each lysimeter is connected to an individual container through a separate pipe at the bottom to collect gravity driven free deep percolation. The lysimeters have been installed on site, such that the soil (monoliths) inside them is undisturbed and its characteristics are the same as the paddock. The soil level inside and outside the lysimeters is the same to ensure inside and surrounding areas receive the same amount of sunshine and rainfall plus irrigation. A 200 mm filter layer (sand, coarse sand, gravel) is placed at the bottom of the lysimeters with very low water holding capacity. This filter layer provides a natural disturbance to free vertical flow so that the soil above the filter layer will be near saturation before water will move from the soil to the sand and gravel filter. To prevent wall flow, the gap between the soil core and the lysimeter casing has been sealed using petroleum jelly (liquid Vaseline). All lysimeters are open to grazing, while containers for deep percolation collection are stored in an underground room.

Aquaflex consists of a 3 m long dual-core wire which is joined at the end to form two complete loops for signal transmission (Charlesworth, 2005). Both ends of the wire are connected with the Aquaflex sensor which sends electrical pulse along the first transmission line that returns back through the second transmission line. Aquaflex works based on the time delay transmission (TDT) principle to measure soil moisture (Charlesworth, 2005). The more water molecules around the sensor the longer is the time taken by the pulse to travel through the sensor cable. Aquaflex sensors are installed near the fence line to minimize disturbance from animals which is the common way of sensor installation in New Zealand dairy farms. Aquaflex is comprised of two sensors installed 90 degrees from the fence line: the top inclined sensor measures average soil moisture content of the top 200 mm soil depth and the bottom horizontal sensor measures soil moisture of the soil at 500 mm depth, see Figure 2-2.

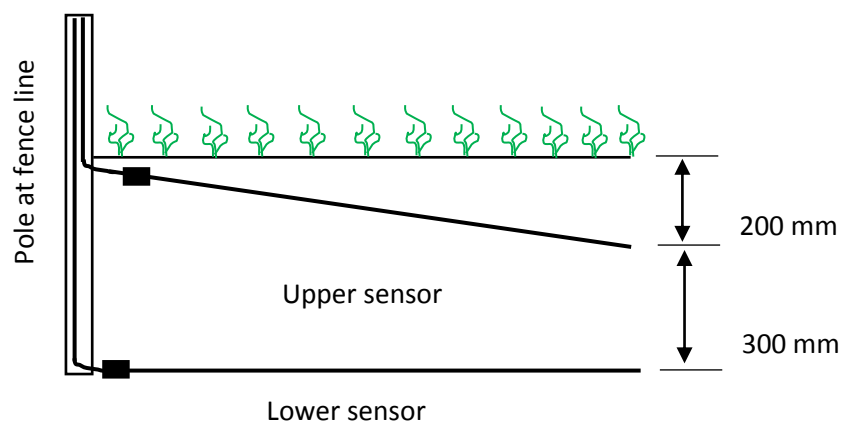


Figure 2-2: Schematic representation of an Aquaflex installed on LUFD

2.2.2 Estimation of reference evapotranspiration

FAO Penman Monteith's equation for ET_r estimation is given as:

$$ET_r = \left\{ \frac{0.408 \Delta (R_n - G)}{[\Delta + \gamma (1 + c_d u_2)]} \right\} + \left\{ \frac{c_n \gamma}{[\Delta + \gamma (1 + c_d u_2)]} \cdot \frac{u_2 (e_s - e_a)}{(T + 273)} \right\} \quad (2-2)$$

Where ET_r = reference evapotranspiration (mm day^{-1}), Δ = slope of saturation vapour pressure curve ($\text{kPa } ^\circ\text{C}^{-1}$) at observed air temperature, R_n = net radiation at the crop surface ($\text{MJ m}^{-2} \text{day}^{-1}$), G = soil heat flux density ($\text{MJ m}^{-2} \text{day}^{-1}$), γ = psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), T = mean daily air temperature at 2 m height ($^\circ\text{C}$), U_2 = wind speed at 2 m height (m s^{-1}), e_s = saturation vapour pressure (kPa), e_a = actual vapour pressure (kPa), $e_s - e_a$ = saturation vapour pressure deficit (kPa) and C_n and C_d are constants used to change reference crop type and time step. Values of C_n and C_d for different reference crops and time steps are available in Zotarelli *et al.* (2014).

For this research CropWat 8, one of the decision support soil-plant-atmosphere models, was used to estimate ET_r . CropWat 8 uses the FAO Penman-Monteith equation with respective values of $C_n = 900$ and $C_d = 0.34$, as it considers daily time step and grass as the reference crop. Thus Equation (2-2) becomes:

$$ET_r = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{(T + 273)} u_2 (e_s - e_a)}{[\Delta + \gamma (1 + 0.34 u_2)]} \quad (2-3)$$

This study used local climatic data: daily temperature ($^\circ\text{C}$), daily relative humidity (%), and wind speed (m/s) collected from the Broadfield weather station ($43^\circ 35' 53''$, $172^\circ 28' 12''$ and altitude of 18 m) 3 km NE from the LUDF. The Broadfield weather station records hourly relative humidity (RH) therefore, average daily RH was calculated as the average of the recorded 24 hourly values. FAO Penman-Monteith equation uses wind speed measured at 2 meters above the ground, while at Broadfield weather station wind speed is measured at 10 m above the ground. Therefore, the following logarithmic Equation (2-4) proposed by Allen *et al.* (1998) was used to adjust wind speed data obtained from Broadfield weather station.

$$U_2 = U_Z \frac{4.87}{\ln(67.8 Z - 5.42)} \quad (2-4)$$

Where U_2 = adjusted wind speed for 2 m above the ground, U_Z = wind speed measured at Z meters above the ground (10 m in this case), \ln = natural log.

Solar radiation data is not measured at the Broadfield weather station and has instead been taken from the nearest station, Christchurch Aero. Scotter and Heng (2003) stated that if data for sunshine hours, temperature or daily solar radiation, are not available for the site of interest, they can be

taken from a station within 100 km or within 1 degree latitude. The distance between the study area and Christchurch Aero is approximately 15 km.

Pasture cover on the study area is always in full cover status (> 1400 kg DM/ha). In such a situation, evaporation from the soil has no significant contribution to total evapotranspiration. Previous researchers such as McAneney et al. (1982) also indicated that evaporation from bare soil can be neglected for pasture. Therefore, a single crop coefficient approach was used for ET_a estimation. In addition, this farm has an irrigation system in place, which is expected to keep soil moisture above the critical point. Thus, pasture is unlikely to face water shortage making the choice of 1.0 for the water stress coefficient (K_s) applicable.

2.2.3 Estimation of actual evapotranspiration

A non-weighing lysimetry approach was used to apply the water budget for estimating actual evapotranspiration (ET_a), as this was the only available equipment in the study area. In the mass balance equation, ET_a is estimated from measurements of rainfall, irrigation supply, deep percolation and changes in soil water content within the lysimeter (Bright, 2009; Hasegawa & Sakayori, 2000). To apply the principle of conservation of mass in a lysimeter for ET_a calculation, the following standard water balance equation was applied over a time step Δt :

$$ET_a = P + I - RO - D + CR - \Delta SF - \Delta SM \quad (2-5)$$

Where, ET_a = actual evapotranspiration, P = precipitation, I = irrigation supply, RO = runoff, D = deep percolation, CR = capillary rise, ΔSF = change in subsurface flow, and ΔSM = change in soil moisture content during the time interval (one day in this case). Units of all variables of Equation (2-5) are in mm.

Lysimeters consist of a soil profile completely contained in a non-permeable chamber, therefore, subsurface flow and capillary rise will have no impact on the water budget of the lysimeter. Field observations indicate no surface runoff from the study area, therefore, RO was also considered negligible in the mass balance equation. These 'valid' assumptions simplify the above mentioned water balance Equation (2-5) to:

$$ET_a = P + I - D - \Delta SM \quad (2-6)$$

2.2.4 Precipitation, irrigation application and deep percolation measurement

Two rain gauges were installed, one outside the irrigated area to measure daily precipitation (P) and one inside paddock N7 to measure daily precipitation (P) and irrigation supply (I) on the lysimeters. Only centre pivot irrigation was measured as all the lysimeters considered for the water balance

study are under the pivot system. The gauge for irrigation was installed in a protected area, about 10 m², which provides access to the ground room which has the containers for deep percolation collection of the lysimeters. It is not feasible to have other gauges in the paddock at the lysimeters as cows are present and grazing. The rain gauge installed outside the irrigated area was located away from vertical obstructions as suggested by (Howell, 1996). Precipitation was recorded regularly to minimise the impact of evaporation losses. Precipitation was also collected from the Broadfield weather station for the comparative study. The volume of daily deep percolation (D) was also measured during the study period.

2.2.5 Soil moisture measurement

Weighted mean of the Aquaflex top and bottom sensor readings were utilized to estimate soil moisture of the soil mass considered in water budget equation for the lysimeters data. The depth of the vertical soil column, considered in the water budget equation, affects the soil water content and thus affects the measurement of ET_a (Young et al., 2000). ET_a was calculated by considering 500, 600 and 700 mm vertical soil depth in the mass balance equation. The 200 mm filter layer placed at the bottom of the lysimeters does not have any significant role in the water balance for the lysimeter, as its holding capacity is low and it is expected to be at field capacity all the time. The following weighted relationship was used to estimate soil moisture (θ) of a 500 mm deep soil column.

$$\theta_{500} = \theta_1 \times \frac{d_1}{500} + \theta_2 \times \frac{d_2}{500} \quad (2-7)$$

Where θ_{500} = soil moisture of 500 mm soil column based on Aquaflex top and bottom sensor readings, d_1 = top soil depth covered by the top sensor reading (θ_1), and d_2 = bottom soil depth covered by the bottom sensor reading (θ_2). To estimate soil moisture of 500 mm soil column $d_1 = 350$ mm and $d_2 = 150$ mm were applied in Equation (2-7). Likewise, to estimate soil moisture of 600 mm soil column $d_1 = 350$ mm and $d_2 = 250$ mm, and to estimate soil moisture of 700 mm soil column $d_1 = 350$ mm and $d_2 = 350$ mm were used.

Previous studies such as Paige and Keefer (2008) also calculated total profile soil moisture content using weighted mean of different sensors installed at various depths. They estimated soil moisture for 0-600 mm soil profile from the weighted mean of four sensors horizontally installed at 50, 150, 300 and 500 mm depths with weights 1/6, 1/6, 1/3 and 1/3 respectively.

2.2.6 Establishing relationship between crop co-efficient and plant height

The single crop coefficient approach for crop coefficient estimation gives the relationship between crop coefficient (K_c), actual evapotranspiration (ET_a) and reference evapotranspiration (ET_r) as follows:

$$ET_a = K_c \times ET_r \quad (2-8)$$

Since crop coefficient varies with crop growth stages, K_c was estimated at different grazing stages. This produced a relationship between K_c and pasture height for different grazing rotations. Pasture height (h in cm) was measured on each of the 20 lysimeters on a daily basis using simple ruler. Among various methods of pasture height measurement, the use of ruler is the simplest method (Rayburn & Lozier, 2003).

2.3 Results and Discussions

2.3.1 Precipitation and irrigation application

For the comparative analysis, available sixteen years climatic data for the period 2000 to 2015 were collected from Broadfield weather station. Measured total precipitation over one year period (August 2014 to July 2015) was 417 mm on the LUDF, which is only 6% higher than the 395 mm recorded at the Broadfield weather station. Likewise, total precipitation measured on LUDF during the irrigation season (September 2014 to April 2015) was 283 mm, against 260 mm recorded at the Broadfield weather station “9% higher”. Based on the sixteen years’ data, average precipitation was estimated as 609 mm, indicating the study year to be drier than long-term average by 192 mm of precipitation which is 31.5% less than the average. Particularly during January and February 2015, precipitations were respectively 67% and 42% less compared to the sixteen years’ average values, see (Figure 2-3).

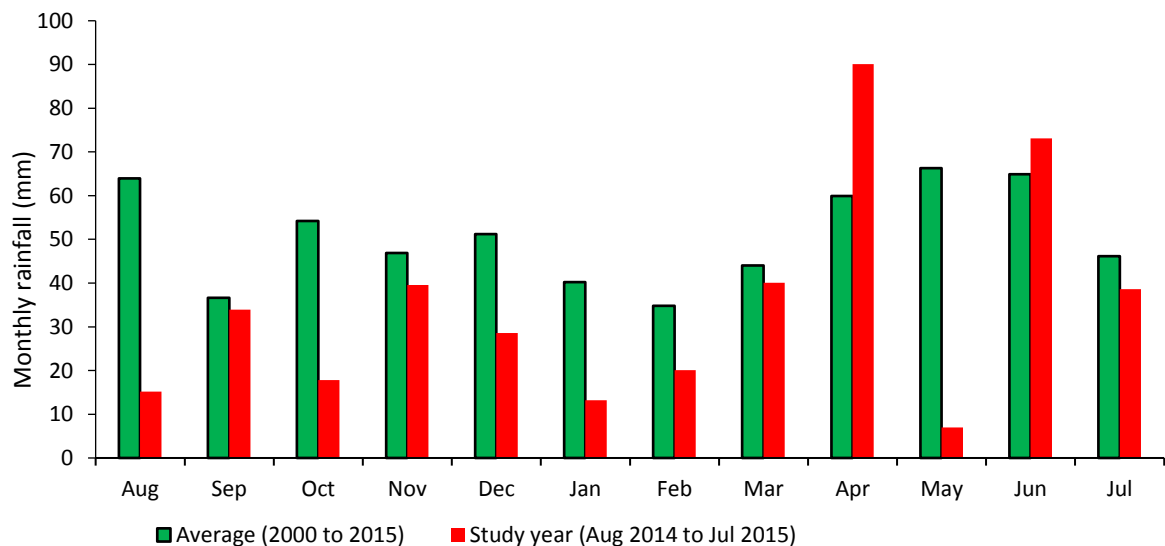


Figure 2-3: Sixteen years’ (2000 to 2015) average and August 2014 to July 2015 values of total monthly rainfall recorded in Broadfield weather station and measured in the study area (LUDF), respectively

Irrigation requirement was analysed by comparing rainfall input into the farm and water losses from

the farm. Figure 2-4 compares the amount of rainfall received per month (P) and losses due to ET_a . It shows that except for the three months: April, June and July (June and July are in non-irrigation season) there was less rainfall than what was required to meet estimated ET_a . This suggests supplementary irrigation is needed to meet ET_a requirement for different seasons.

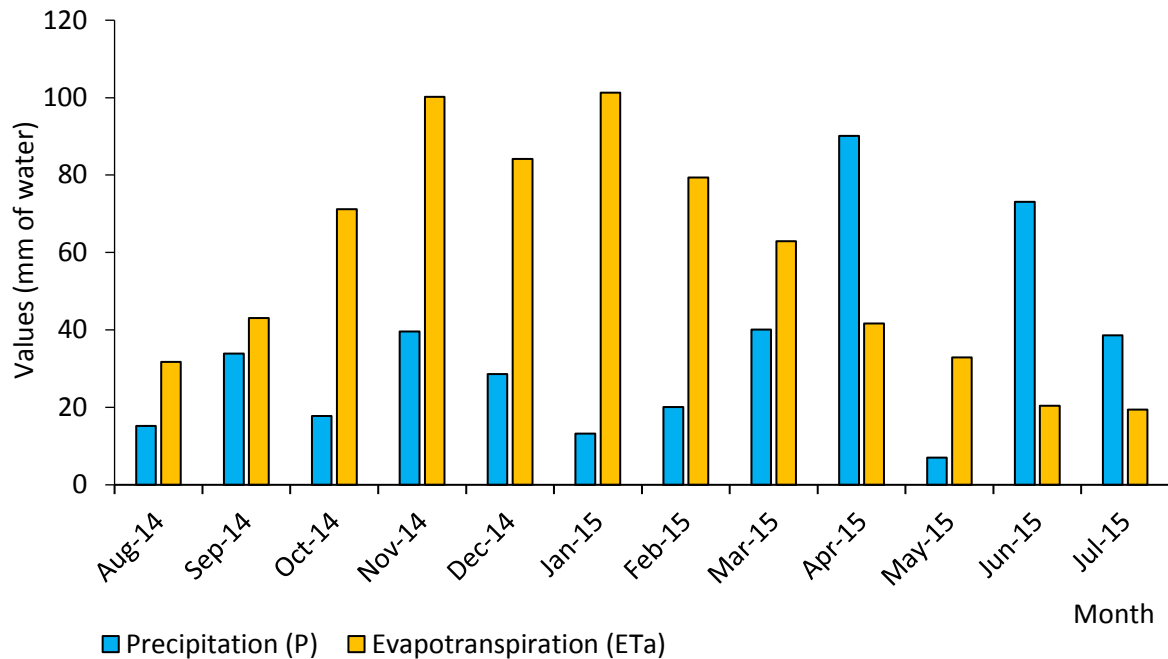


Figure 2-4: Monthly precipitation (P) and Evapotranspiration (ET_a) in the study area (LUDF) during the period August 2014 to July 2015

In New Zealand, irrigation season generally extends from September to April, with September – October and March – April known as shoulder seasons, and November – February known as peak irrigation season. The dry weather during the study period had clear impact on irrigation supply over the peak irrigation season. Irrigation per application of around 3 mm during February and March 2015 was almost half of the system capacity. The reduced rates of irrigation application in February and March 2015 were attributed to a lack of water availability in the well. In fact, by February 2015 groundwater level had declined to a level where the pumping system was unable to pump the required flow rate of water.

During October to January there was more rainfall plus irrigation than actual ET_a requirement. However, soil moisture contents on the farm were always maintained above the management allowable deficit to protect potential yield. Providing irrigation water at this level maintains soil moisture in the root zone at readily available soil moisture range which minimizes plant water stresses that could reduce yield (United States Department of Agriculture (USDA), 1997). Therefore, seasonal variations in irrigation application are not expected to have impacted on the outcomes of the study.

2.3.2 Deep percolation

Deep percolation was measured during the period August 2014 to July 2015. Figure 2-5 shows annual deep percolation recorded during no irrigation, shoulder and peak irrigation seasons.

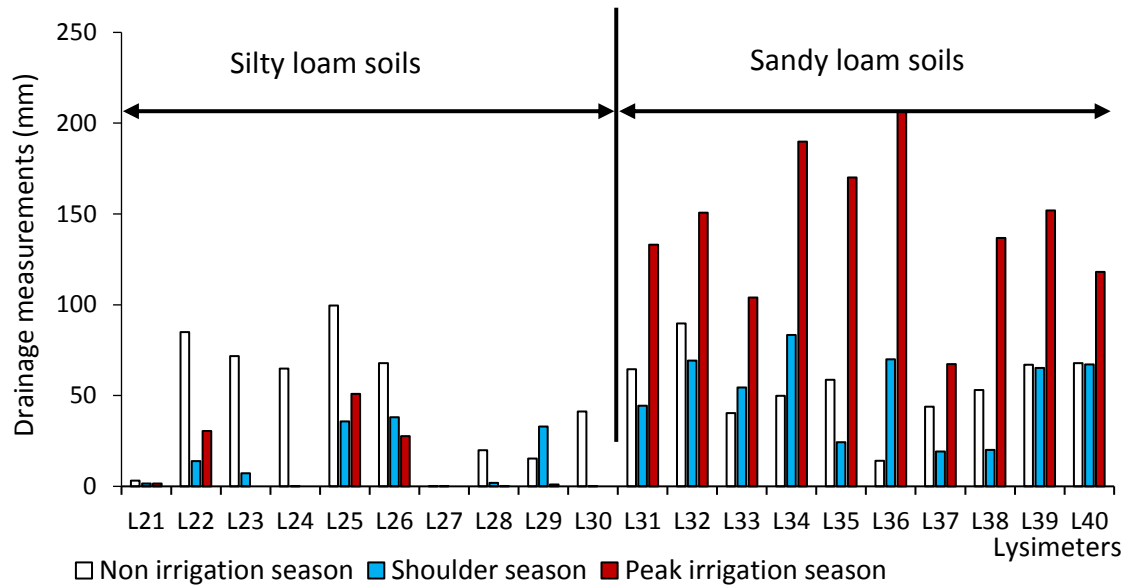


Figure 2-5: Total deep percolation during no irrigation, shoulder and peak irrigation seasons through 20 lysimeters in the experimental plot N7 over the period August 2014 to July 2015

Lysimeters 21 to 30 are in one field (first group) within the silty loam soil area, and lysimeters 31 to 40 are in another field (second group) within the sandy loam area. Annual (August 2014 – July 2015) average deep percolation from 10 lysimeters installed in the silty loam soils was 71 mm with minimum deep percolation from lysimeter 21 (6.4 mm) and maximum deep percolation from lysimeter 25 (186 mm). Over the same time span, average deep percolation from the 10 lysimeters installed in the sandy loam soils was twofold more (250 mm) than silt loam soils. In the second group, the minimum deep percolation was 130 mm from lysimeter 37 and the maximum deep percolation was 323 mm from lysimeter 34.

In New Zealand, there is a common understanding that deep percolation occurs only during winter season. However, this study indicates deep percolation losses occur throughout the year. Considering the fact that this study period was drier than average conditions, it is expected that deep percolation would be higher in wetter years, if irrigation scheduling is not managed properly to capture potential rainfall. Moir et al. (2007) measured 34 mm of average deep percolation during 2005/06 (233 mm rainfall) against 230 mm during season 2006/07 (426 mm rainfall) based on 60 lysimeters including 20 of the lysimeters used in this study.

There was a high variation in daily deep percolation through the lysimeters even though they were installed beside each other just 1.0 m apart. The deep percolation variation was noticeable from lysimeter to lysimeter and month to month. Particularly, in sandy loam soil, deep percolation loss was far greater during irrigation season than non-irrigation season.

For many agricultural farms soil moisture values can be different within 1.0 m distance (Allen et al., 2011). This might have caused discrepancy in deep percolation. Non-uniform water input or holding capacity at different locations would result in a different deep percolation (Beven & Germann, 1982; Clothier & Heiler, 1983; Kincaid et al., 1969; Powers, 2012). However, 10 lysimeters are under one span of the centre pivot irrigator and the remaining 10 lysimeters are under the adjacent span. In addition, the farm management unit conducts a performance assessment test of the centre pivot irrigators on an annual basis to ensure distribution uniformity. Therefore, non-uniform irrigation supply is unlikely to be the cause of uneven deep percolation, and varying holding capacity of the soil is more likely.

During peak irrigation season, farmers do not like to take the risk of yield reduction due to soil moisture depletion and therefore, irrigation supply aims at maintaining soil moisture content almost close to the field capacity. This situation favours preferential flow if macropores are present in the soil profile (Clothier & Green, 1994; Hillel, 1998). To make solid conclusions, more rigorous research is required to investigate macropore flow, which was not the scope of this study. However, keeping soil moisture near the field capacity decreases the storage ability of the soil and increases the potential of deep percolation due to rainfall.

2.3.3 Pasture growth dynamics

Over the study period (August 2014 to July 2015) there were ten grazing rotations with an average grazing return interval of 22 days during spring and summer (Sep to Feb) and 40 days during autumn (Mar to Apr). Pasture was not grazed during June and July 2015. An average grass height on the farm was 30 cm just before grazing and that was reduced to 10 cm just after grazing. Pasture height on each lysimeter showed a great variation, both just before and just after grazing. For example, during March 2015, pasture height just before grazing was 12 cm on lysimeter 21 while on lysimeter 38 pasture height was almost two fold (22 cm), and even higher on some other lysimeters. During April 2015, pasture height just after grazing was 4 cm on lysimeters 21 while on lysimeter 38 pasture height was almost three fold (11 cm), and even higher on some other lysimeters.

A null hypothesis (H_0) was tested to confirm average pasture height on 20 lysimeters just before and after the grazing is comparable to the corresponding pasture height on paddock number seven (N7). Total sample size (N) of 10 (10 grazing cycles) implies a degree of freedom of 9 (N-1) for each pre and

post grazing conditions. The t value needed for rejection of null hypothesis at the degree of freedom of 9 and confidence level of 95% is 2.2 which is greater than the calculated t value of 1.4 for pre grazing condition. Similar procedure was applied for post grazing condition. In both cases two tailed statistic test result failed to reject the null hypothesis. In other words pre and post grazing pasture heights on lysimeters are equivalent to the corresponding pasture height measured on the paddock number seven (N7).

Average pasture height 'h' (h in cm) measured on 20 lysimeters versus time in days after grazing (d) were fitted in linear, exponential and power curves to identify the best fit. For every grazing cycle linear relationship was the best-fitting among the three curves tested. Figure 2-6 demonstrates the pasture growth dynamics during different growing seasons. Each series of data represents an individual grazing cycle, which was in a different season. As can be seen, growing patterns of pasture are dependent on the grazing season, as climate conditions differ with seasons. In general, rate of pasture growth was very slow just after grazing for 1-2 days followed by a linear increase up to pasture height of 30 cm.

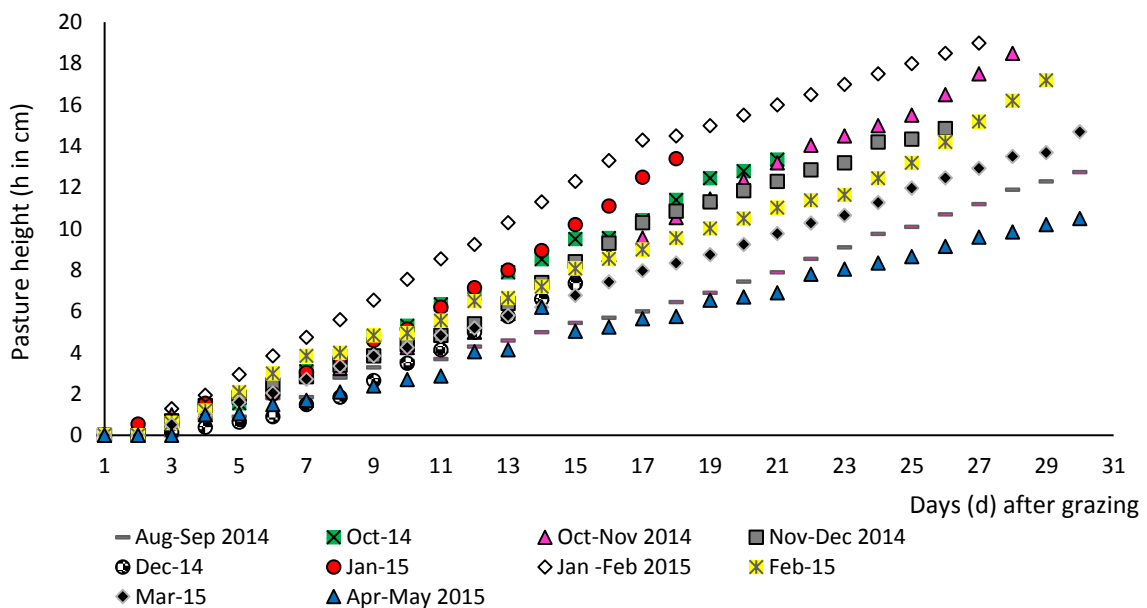


Figure 2-6: Linear relation between pasture height and days after grazing for ten grazing cycles

As the rate of pasture growth for 1- 2 days after grazing was almost negligible, we split the data into two series: 1) data from grazing date to 2 days after grazing; and 2) data measured beyond 2 days after grazing. As can be seen in Table 2-1, strong linear relations were observed between pasture height “h” and days after grazing “d” after 2 days of grazing, with the coefficient of determination R^2 above 0.98 for all grazing cycles. The rate of increase of h with d “slope” should “consistently” increase from spring to summer and reaches its peak in summer. However, this study did not indicate this type of relation between h and d.

Table 2-1 Linear relationships between pasture height (h cm) and days after grazing (d) during various grazing seasons (h₀ = pasture height just after grazing in cm)

Grazing period	Equations		h ₀	R ²
	0 ≤ d ≤ 2	2 < d ≤ length of grazing rotation		
Aug-Sep 2014	h = h ₀	h = 0.4537 d - 1.2369	7	0.99
Oct-14		h = 0.7429 d - 1.9999	10	0.99
Oct-Nov 2014		h = 0.7348 d - 2.6575	10	0.98
Nov-Dec 2014		h = 0.659 d - 1.7088	9	0.99
Dec-14		h = 0.6615 d - 2.9263	11	0.98
Jan-15		h = 0.8784 d - 3.039	10	0.98
Jan -Feb 2015		h = 0.7528 d - 0.0015	11	0.98
Feb-15		h = 0.5763 d - 0.7366	13	0.99
Mar-15		h = 0.5115 d - 0.893	10	0.99
Apr-May 2015		h = 0.3803 d - 0.7718	9	0.98

2.3.4 Relationship between crop coefficient and pasture height

Daily crop coefficient of pasture (K_c) was developed over a one-year period (Aug 2014 to July 2015) focussing on individual grazing rotation. This was undertaken by dividing actual evapotranspiration (ET_a) by reference evapotranspiration (ET_r). Individual lysimeter measurements are point measurements, representing measurements of ET_a at only one location in the farm from 0.2 m² surface areas. It might not be justifiable to extrapolate the result from one lysimeter to large areas. Therefore, daily K_c were estimated at lysimeter group level. To identify the relationship between K_c and pasture height 'h' (h in cm) we tested linear, power and exponential curve fittings using daily K_c and h values under the following three scenarios:

- **SCENARIO I: CROP COEFFICIENT BASED ON FIRST GROUP LYSIMETERS.** In this scenario, to represent similar soils, deep percolation and pasture cover 10 lysimeters installed in the first group were considered as one group. All the data measured for the 10 lysimeters over the ten grazing periods were lumped together to represent annual average scenario. Linear, power and exponential relationships were developed between K_c and h. Those relations were used for estimating K_c for different h (h in cm). In the equation, h was the independent variable, while K_c was the dependent variable. The K_c estimated showed increasing trend through different growth stages;
- **SCENARIO II: CROP COEFFICIENT BASED ON SECOND GROUP LYSIMETERS.** Similar to SCENARIO I, 10 lysimeters installed in the second group were considered as one group. All the data

measured for the 10 lysimeters over the ten grazing periods were lumped together. Linear, power and exponential relationships were again developed between K_c and h . Similar to SCENARIO I, the K_c estimated showed increasing trend with the pasture's height;

- SCENARIO III: CROP COEFFICIENT BASED ON LUMPING ALL 20 LYSIMETERS' DATA TOGETHER. In this scenario, all the data measured for the 20 lysimeters over the ten grazing periods were lumped together as one group. Other steps were the same as explained in SCENARIOS I and II. Estimated K_c increased with the pasture height, and produced a very close trend to the trends obtained from SCENARIO I and II.

Results from one group of lysimeters represent one particular field characteristics. K_c estimated under the above mentioned SCENARIO III may be a better representation of conditions representing the whole field. Under SCENARIO III, crop coefficients were estimated by applying the soil moisture data of the Aquaflex to the top 500, 600 and 700 mm soil depth in the lysimeters, and assuming the deeper soil in the lysimeters to be at field capacity. For all three scenarios (500, 600 and 700 mm), the linear relation was a preferred option for the fitted $K_c - h$ relationship among the three curves tested.

Figure 2-7 (a) represents the linear relation between K_c and h developed based on 500 mm soil depth with regression coefficient ($R^2 = 0.43$). Figure 2-7 (b) demonstrates the linear relation between K_c and h developed for soil depth of 600 mm with regression coefficient ($R^2 = 0.35$). Figure 2-7 (c) shows the linear relation between K_c and h developed for 700 mm soil depth with regression coefficient ($R^2 = 0.24$).

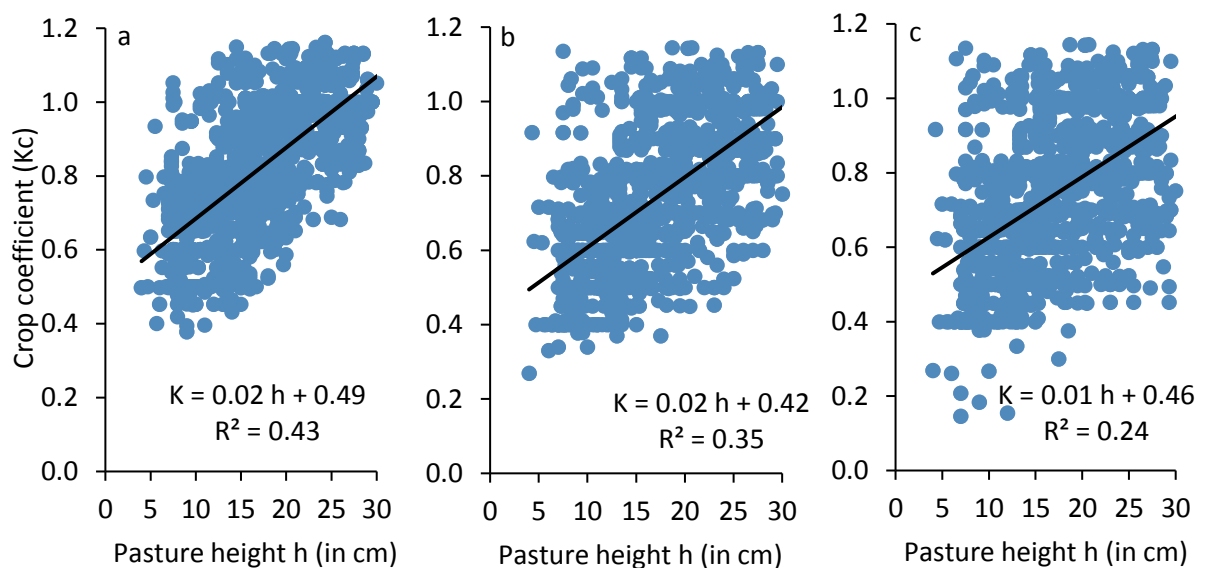


Figure 2-7: Linear relation between crop coefficient and pasture height for SCENARIO III, (a) under 500 mm soil depth, (b) under 600 mm soil depth and (c) under 700 mm soil depth

Linear, power and exponential curve fittings were also tested for individual lysimeter level with linear relationship fitted well among the tested three fitting cases. There was a high variation in R^2 values for each lysimeter ranging from 0.30 to 0.70. The low R^2 is attributed to the effect of soil moisture in the water budget equation. For all 20 lysimeters the same Aquaflex soil moisture information was applied as it was the only available option. In fact, such constraints are obvious upon many irrigated farms.

R^2 was affected when different depths of soil were considered in the water budget equation. When the 500 mm soil depth was considered R^2 for the $K_c - h$ relationship improved. This indicates that ET for irrigated lands occurs “mainly” in the top 500 mm soil. These R^2 values are expected to improve by installing devices to measure soil moisture contents for each lysimeter separately for the sake of its water budget calculations. This research intended to produce a relationship between K_c and h based on existing field condition and Aquaflex soil moisture measurements to capture real field scenario.

Disparity in pasture heights, deep percolation and soil moistures in different lysimeters meant variations in ET_a measurements for each lysimeter over the same grazing period resulting in a varied K_c . However, the results clearly support a linear relationship between actual water needs of pasture, represented by the crop coefficient, and the pasture height after grazing.

The generalised crop coefficient curve consists of three K_c values: (1) very small K_c value shortly after planting of annuals crops or emergence of new leaf for perennials crops after cutting/grazing; (2) the initial K_c values increase almost linearly until it reaches maximum K_c value during plant development stage and remains constant for mid-season stage; and (3) after mid-season stage the K_c values begin decreasing until it reaches a lower value at the end of growing stage (Allen et al., 1998). However, in a grazing system, pasture is grazed once it reaches a ceiling yield because after that stage no further dry matter will accumulate (Lee, 2011). This implies, under rotational grazing system, pasture consists of only the plant development stage for which K_c values increases with pasture growth, represented in its height, which is consistent with the above shown results.

Over the irrigation season (September 2014 to April 2015) the Aquaflex bottom soil moisture sensor showed small fluctuations in water content measurements compared to the top sensor (Figure 2-8). This indicated that the pasture take up water mostly from the top 500 mm of the soil profile. This was also supported by the fact that the irrigation application on the farm aims at sustaining soil moisture content, and ET_a occurs mainly in the top layer of the soil. In addition, frequent deep percolation through the lysimeters indicated that soil moisture level of the bottom soil in the lysimeters reached field capacity so that deep percolation occurs.

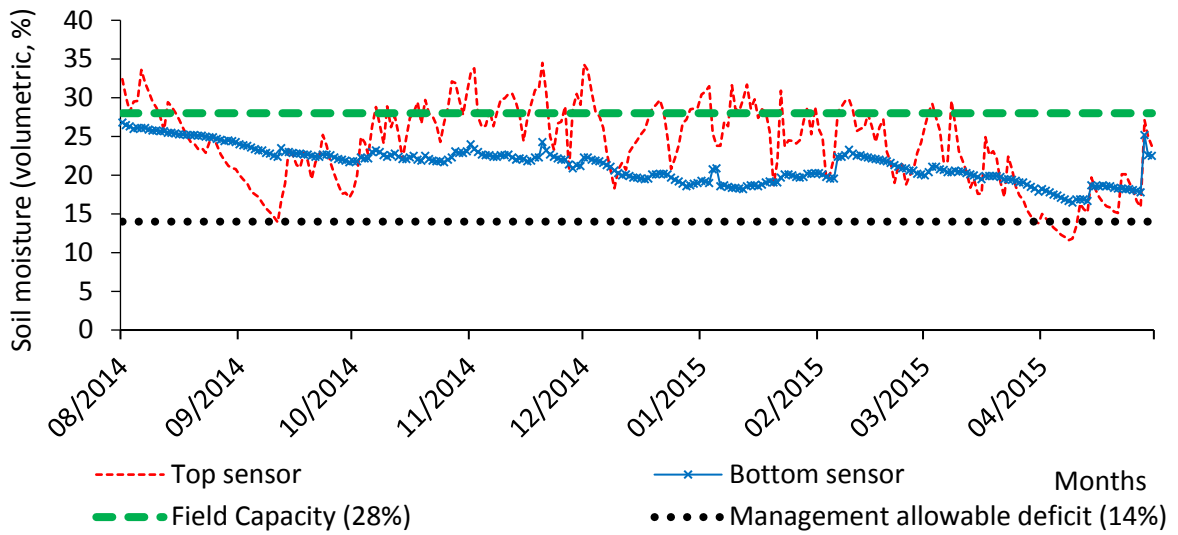


Figure 2-8: Soil moisture trend based on Aquaflex top and bottom sensor readings during August 2014 to July 2015

Based on the Aquaflex soil moisture readings, soil moisture of the soil mass below 500 mm depth can be assumed to be at field capacity, and does not have any significant role in the mass balance inside the lysimeters. Thus, the moisture data measured from the Aquaflex should apply only to the top 500 mm of the lysimeters for the water budget calculations. Thus, results from 500 mm soil depth indicate crop coefficients and pasture heights can be correlated through linear relations to represent field condition as:

$$K_c = 0.02 h + 0.49 \tag{2-9}$$

Rout (2003b) proposed a non-linear relationship between K_c and h (h in cm) as shown in Equation (2.1). Nonlinear curve fitting was used with the least squared method, which did not match well for our data, see Figure 2-9.

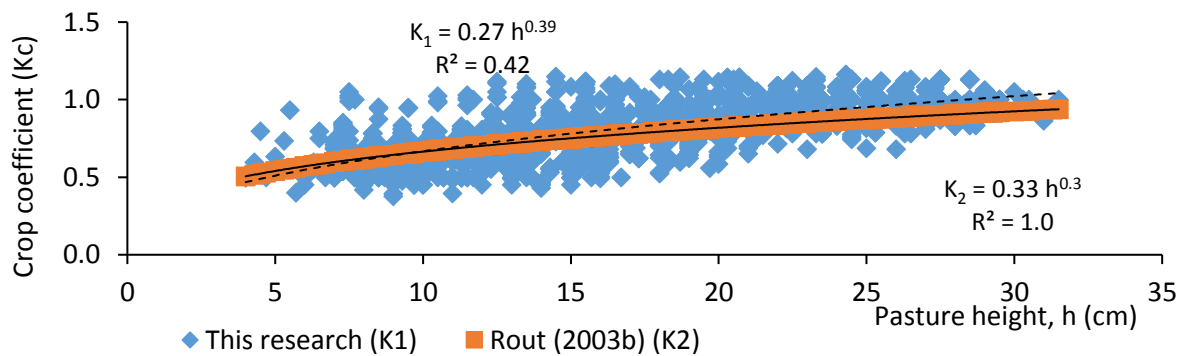


Figure 2-9: Curve fitting for the crop coefficients and pasture heights based on Rout (2003b) and this research (using power relation) under SCENARIO III

Crop coefficients estimated at different pasture heights based on the equations developed for 500, 600 and 700 mm soil depth, and Rout (2003b) are shown in Table 2-2. Under grazing pasture, crop coefficient should range from 0.85 -1.05 for corresponding pasture heights of 15 and 30 cm (Allen *et al.*, 1998). Crop coefficients estimated for the 500 mm soil depth are comparable with the recommended values.

Table 2-2 Crop coefficients of pasture estimated for different growth stages of a grazing rotation

Equations	Crop coefficient (K_c) at following pasture height						Remarks
	'h' (h in cm)						
	5	10	15	20	25	30	
$K = 0.02 h + 0.49$	0.6	0.7	0.8	0.9	1.0	1.1	500 mm depth soil
$K = 0.02 h + 0.42$	0.5	0.6	0.7	0.8	0.9	1.0	600 mm depth soil
$K = 0.01 h + 0.46$	0.5	0.6	0.6	0.7	0.7	0.8	700 mm depth soil
$K = 0.33 h^{0.3}$	0.5	0.7	0.7	0.8	0.9	0.9	Rout (2003)

Daily grass heights measured for an average grazing rotation of 30 days was applied to Equation (2.9) to estimate average crop coefficient for a single grazing rotation at 0.8. This implies conventional irrigation planning with a constant crop coefficient of 1.0 would provide 20% more irrigation compared to actual crop water needs under grazing conditions.

2.4 Conclusions

The analysis of LUDF field experiment data showed the crop coefficient of pasture (K_c) and pasture height h (in cm) can be modelled through linear relationships. The regression coefficient (R^2) for a $K_c - h$ linear relationship derived in this study was not very strong. However, despite low R^2 , the results clearly support a linear relationship between $K_c - h$ relationship, but with higher variability around the mean trend. This is significantly different from the one previously produced by Rout (2003b).

Integrating this relationship in water balance models for irrigation scheduling will contribute to a better estimation of crop water requirements to match actual water needs of ryegrass pasture (*Lolium perenne*) under a grazing rotation. Typically grass heights pre and post grazing were 30 cm and 10 cm for which estimated K_c values were 1.1 and 0.7. This implies a difference in irrigation demand of 40% to meet actual crop water needs at the start and end of the grazing rotation.

Average K_c estimated for a grazing rotation was 0.8. Many researchers have suggested to use a K_c of 1.0, however, this would supply, on average, 20% more water compared to the actual pasture water demand. The results from this study show that, due to variations in the pasture height at different

grazing stages, the use of a single crop coefficient value of 1.0 is erroneous.

The K_c values proposed herein can serve as useful guidelines for estimating more accurate irrigation applications to match the actual water demand of grazing rotation on pastoral farms, resulting in significant savings in water, and reduced deep percolation. It is also recommended that the soil water content of the lysimeters in the field be directly monitored, as possible, to improve the water content values used in the water budget equation to further improve the K_c – h relationship.

Chapter 3

Understanding Spatio-Temporal Variability of Soil Moisture Measurement with Aquaflex and Time Domain Reflectometry

Abstract

Despite subtle variation in soil moisture across a farm, irrigation planning in New Zealand dairy farm is solely based on the soil water content monitored at one location. The objectives of this study were: (1) to understand spatio-temporal variability of soil moisture (SM) measurements using multiple length time domain reflectometry (TDR) and Aquaflex soil moisture sensors; and (2) to couple TDR and Aquaflex SM readings to improve SM determination in non-weighing lysimeters for improving water balance estimation for crop coefficient (K_c) development, and in turn improving the estimation of actual crop water needs. The experiments were conducted at Lincoln University Dairy Farm (LUDF), South Island, New Zealand. Multiple TDR probes with 200, 500 and 900 mm lengths were installed vertically adjacent to the Aquaflex and lysimeters for monitoring SM contents (% vol) without disturbing natural water fluxes in the lysimeters.

Both TDR and Aquaflex responded to simulated wetting and drying events, with varying SM observed both vertically and horizontally, due to variations in soil textures at different locations. The amplitude of the daily fluctuations in SM measurements were noticeably higher for 200 mm TDR and Aquaflex top sensors with slightly lower fluctuations for 500 mm TDR and Aquaflex bottom sensors. However, 900 mm TDR showed only minor fluctuation in average SM values indicating evapotranspiration on LUDF dominates in the top 500 mm soil profile. This signifies the importance of multiple lengths TDR to assess root water uptake for improving irrigation management.

Twenty lysimeters and an Aquaflex located about 125 m away from the lysimeters within different soils were utilized to derive a relationship between K_c and plant canopy (represented by height “h” in cm). When the original Aquaflex soil moisture values were used in the water budget equations for 20 lysimeters data, the coefficient of determination (R^2) for $K_c - h$ relationship was 0.43., which increased to 0.66 when Aquaflex SM values were adjusted for each lysimeter using corresponding TDR readings. For rotational grazing systems, K_c derived from the TDR improved $K_c - h$ relationship would save on average 10% irrigation compared to the K_c derived based on only the Aquaflex SM readings. This confirms that improved monitoring of SM at different locations in the farm is essential to improve the water balance estimation for quantifying actual crop water requirements.

KEY WORDS: soil moisture; lysimeters; water balance; crop coefficient; pasture; irrigation

3.1 Introduction

Soil moisture is the key component of the soil water balance, both on a small and large agricultural farm (Cape, 1997; Tromp-van Meerveld & McDonnell, 2006). Therefore, proper assessment of soil moisture availability is extremely important for studies involving agricultural water management (Brazil, 2015). Particularly, in farming soil moisture can contribute substantially to crop yield and the availability of nutrients (Cape, 1997).

Therefore, maintaining soil water levels in the root zone is a practical strategy that helps water conservation and improves agricultural production (FAO, 2000; George et al., 2000; Pimentel & Pimentel, 2008; SSSA, 1997). Soil-moisture driven irrigation planning contributes to improve irrigation effectiveness (Srinivasan & Duncan, 2011). This necessitates proper soil moisture information for estimating actual crop water needs (Cape, 1997; Chandler et al., 2004; Van Housen, 2015), for which monitoring of soil water status in the root zone is essential (Miyamoto et al., 2001).

Irrigation planning greatly depends on spatio-temporal variability of soil moisture and its measurement (Young et al., 2000). Spatial variability of soils and the spatial and temporal variability of water content in the soil is a reality throughout farms (Paige & Keefer, 2008). Spatial variability of soil moisture content is attributed to differences in vegetation, topography, soil type and non-uniform water input (Allen et al., 2011; Beven & Germann, 1982; Clothier & Heiler, 1983; Kincaid et al., 1969; Powers, 2012). In fact, soils are a physically and chemically heterogeneous complex porous medium (Seyfried & Murdock, 2001). This indicates that soil moisture measured at one location might not always represent water content of another location, or represent the whole farm. Therefore, several measurements of soil moisture at different locations across the farm are essential to capture average soil moisture in the field or the determining the benchmark point (Jacobs et al., 2004).

On farm, soil moisture sensors are positioned either within the soil type with the highest Plant Available Water Holding Capacity (WHC) to make efficient use of water at the risk of decreased yield, or within the soil type with the lowest WHC to maximize the yield (Irrigation Association, 2011). Therefore, soil moisture measured at a point with lowest WHC (relatively coarse particles) underestimates the field average soil moisture values, while those measured at locations with highest WHC (relatively fine particles) overestimate the average soil moisture contents on the farm. Occasionally, soil moisture sensors are placed in an area which receives the least amount of water from the irrigation system, to decide irrigation onset based on when that area becomes dry. Satisfying the driest part of the field ensures sufficient water for all plants and thus, leads to potentially increased production, but this would also result in more water use and in turn more deep percolation in areas which are not that dry.

With increasing water scarcity and pollution problems associated with over irrigation and waterlogging, the issue of proper soil moisture sensor placement to better represent given soil characteristics is also increasing (Evelt, 2016). Aquaflex is one of the widely used soil moisture measurement devices in New Zealand dairy farm. It consists of 3 m long dual-core wires which are joined at the end to form two complete loops for signal transmission. By calculating the pulse delay time (time delay transmission- TDT) of an electrical signal sent along the transmission line installed in soil, the dielectric constant is estimated based on which average soil moisture content around the Aquaflex length is measured.

Time domain reflectometry (TDR) is another tool for measuring soil water content in the field. TDR determines soil water content from the dielectric properties of soils (Jones et al., 2002; Skierucha et al., 2012). Based on the travel time of an electromagnetic signal passing through parallel probes buried in soil, the bulk dielectric constant¹ is estimated, which is then converted to water contents (Blonquist Jr et al., 2005; Chandler et al., 2004). TDR has been accepted as a practical technique for non-destructive, repetitive and in-situ measurement of soil water content in the profile (Robinson et al., 2003; Skierucha et al., 2012).

A combination of short and long TDR probes is needed to determine spatio-temporal variability of soil water content in a farm (Miyamoto et al., 2001; Young et al., 2000). Installing different soil moisture sensors at one location can help to evaluate and compare the responses of the different sensors to variable wetting and drying events (Paige & Keefer, 2008). Young et al. (2000) used 200, 400, 600 and 800 mm TDR and came to a similar conclusion “a combination of short and long probes improves the estimate of field deep percolation”. Field experiments by Miyamoto et al. (2001) with 100, 200, 300, and 450 mm TDR probes, installed vertically from soil surface, also demonstrated that the TDR technique with multiple length probes is an effective method for measuring soil water distributions at different depths. However, very few studies have directly compared the performance of different sensors under field applications (Paige & Keefer, 2008). Plauborg et al. (2005) compared the performances of the TDR with Aquaflex (Streat Instruments., Ltd, Christchurch, NZ) sensor installed in sandy soil only. In this study the performance of the TDR was compared with Aquaflex reading installed in silty loam and sandy loam soils which are dominantly available at Lincoln University Dairy Farm (Landcare Research, 2015).

On farm soil moisture measurement practices

On farm profile soil moisture is monitored based on soil moisture sensors installed at one or two or three different depths (Irrigation Association, 2011). The depth at which a sensor should be placed

¹ The dielectric constant is the capacity of a non-conducting material to transmit electromagnetic waves or pulses (Charlesworth, 2005).

depends on the crop rooting depth, however, in one monitoring depth technique soil moisture sensor is installed at 200 mm – 300 mm depth, covering sufficient root zone. Two monitoring depth approach consists of two sensors, one is located within the active root zone (100 mm – 300 mm), and the other is located below active root zone (400 mm – 700 mm) to control deep percolation. In three monitoring depth approach, the first soil moisture sensor is installed closest to the surface (100 mm – 200 mm), second sensor is installed at mid-depth (300 mm – 400 mm) and third sensor is installed at deeper depth (450 mm – 900 mm) for monitoring deep percolation.

In most New Zealand dairy farms, two monitoring depth approach are used, with the top sensor measuring average soil moisture of the top 200 mm - 300 mm soil profile and the bottom sensor measuring soil moisture horizontally at 450 mm - 500 mm depth. Soil moisture readings from top sensor are used to decide irrigation trigger points and soil moisture readings from the bottom sensors are used to judge over-irrigation (trend up) or under-irrigation (trend down).

On New Zealand dairy farms, Aquaflexes are installed at the fence line to minimize disturbance from animals. Lysimeters installed for monitoring nutrient leaching are located at the middle of a paddock. Thus, differences in soil moisture beside the Aquaflex and lysimeters are expected, because in agricultural farms both subtle and sharp changes in soil type across the farm and down the soil profile are common. In fact, soil moisture changes even within 1.0 m distance (Allen et al., 2011). Therefore, water budget done in the lysimeters by adopting Aquaflex soil moisture values may not yield satisfactory result and therefore, could have potential to mislead irrigation planning.

The objectives of this research were (1) to evaluate and compare the spatio-temporal variability of volumetric soil moisture using multiple length TDR probes and Aquaflex; and (2) to improve the determination of the soil moisture content in the lysimeters by coupling TDR and Aquaflex readings for rising accuracy of water budget studies, and in turn more accurate estimation of actual water needs. TDR probes with 200, 500 and 900 mm length were installed vertically beside the Aquaflex and lysimeters for the spatial and temporal variability of soil moisture measurements without disturbing natural water fluxes in the lysimeters. The weighted relationships between Aquaflex and TDR soil moisture readings were used to convert Aquaflex soil moisture values to corresponding lysimeters for improving water budget studies in the lysimeters.

3.2 Material and Methods

3.2.1 Site description

This is the same site which has been detailed in section 2.2.1, Chapter 2

3.2.2 Experiment set-up in the field

The Aquaflex installed on the experiment plot is located at the fence line that divides adjacent paddocks (fence between N6 and N7), which is the common way of soil moisture sensor installation in NZ dairy farms. This minimizes disturbance by the animal and equipment. Twenty non-weighing lysimeters used for the study are installed at the middle of paddock N7. First group of 10 lysimeters (L-21 to L-30) are installed within silty loam soils and second group of 10 lysimeters (L-31 to L-40) are installed within sandy loam soils. Aquaflex is within sandy loam soils containing some stones.

Three sets of TDR probes with 200, 500 and 900 mm lengths and 5 mm diameter, with each set consisting of two parallel stainless steel rods having the same length, were installed vertically from the soil surface beside each of the lysimeters and the Aquaflex. Vertical probe installation was chosen to minimize soil disturbance on the farm. Each set of probes were installed at 100 mm spacing, with individual probes in one set being 50 mm apart. Distance between adjacent lysimeters is 1.0 m, and distance between a lysimeter and its corresponding TDR probes was 1.0 m, see Figure 3-1.

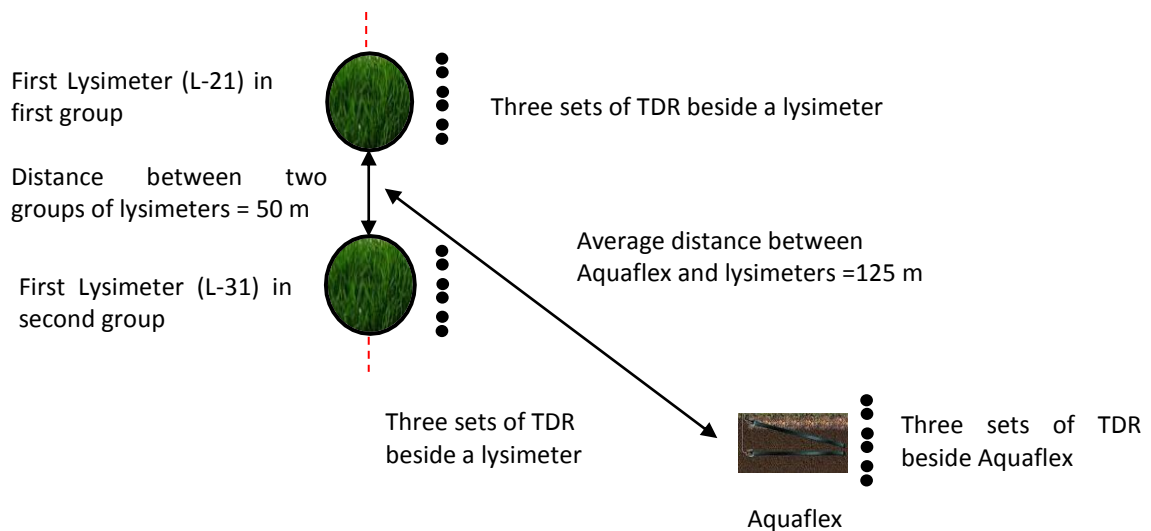


Figure 3-1: Schematic representation for equipment set-up in the field

3.2.3 Relationship between Aquaflex and TDR soil moisture readings

Based on the Aquaflex soil moisture readings and analysis of the crop coefficient results (details in section 2.3.4, Chapter 2), soil moisture of the soil mass below 500 mm depth was assumed to be at field capacity, and had no any significant role in the mass balance inside the lysimeters. Therefore, to estimate ET_a only the top 500 mm soil depth was considered in the mass balance equation.

Since Aquaflex and lysimeters are within different soils, Aquaflex soil moisture readings need some adjustments to be utilized in the water budget equations of the lysimeters data. A step-wise

approach was developed to determine soil moisture content in the lysimeters based on Aquaflex and TDR readings. In the first step, Aquaflex top and bottom sensors readings were used to estimate soil moisture of 500 mm soil column (θ_{500}). In the second step θ_{500} was used to investigate the relationship with 500 mm TDR readings. To test which soil depth is most representative for Aquaflex top and bottom sensor readings, the 500 mm soil depth considered for water budget studies was split into two depths, in three different combinations ($d_1 = 200$ mm & $d_2 = 300$ mm, $d_1 = 300$ mm & $d_2 = 200$ mm, $d_1 = 350$ mm & $d_2 = 150$ mm, see Figure 3-2).

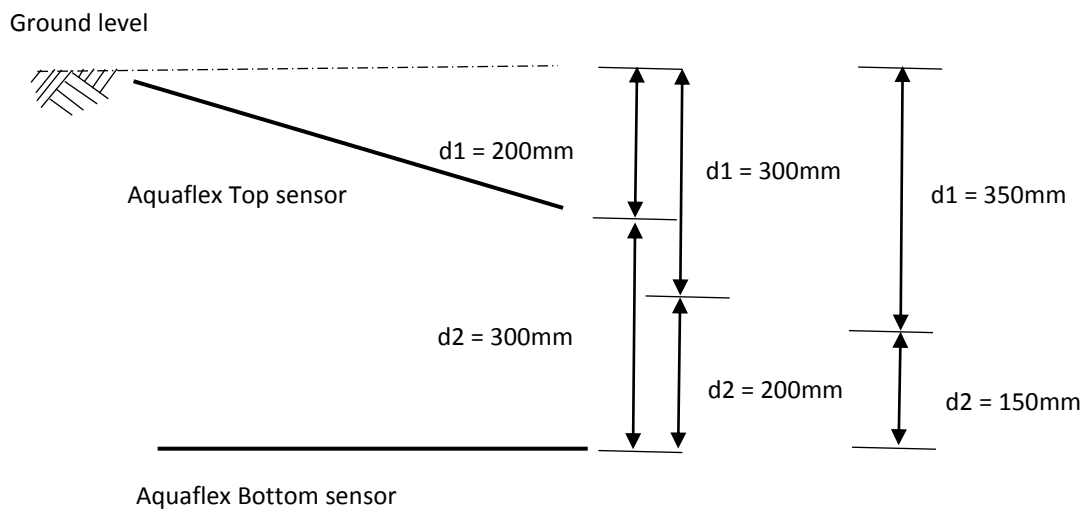


Figure 3-2: Schematic representation of the top and bottom soil moisture sensors in Aquaflex, and 500 mm soil depth considered for water budget study divided into two parts under three combinations

Under each combination, θ_{500} was estimated using the weighted relationship as expressed in Equation 2.7. As can be seen in Figure 3-3, θ_{500} under all three combinations of 500 mm soil depth produced strong linear relationships with 500 mm TDR readings. There was no significant difference among the relationships developed for θ_{500} and 500 mm TDR readings with P-values under all three conditions being far below the α level i.e. 0.05. Comparatively the third combination ($d_1 = 350$ mm and $d_2 = 150$ mm) produced better correlation with the highest coefficient of determination ($R^2 = 0.87$) and the lowest P-value (9.4×10^{-21}). Therefore, the regression equations of the trend lines, based on the third scenario were used to convert Aquaflex soil moisture values for each lysimeter. In the regression equations, Aquaflex soil moisture values (x) were independent and TDR readings (y) were dependent variables.

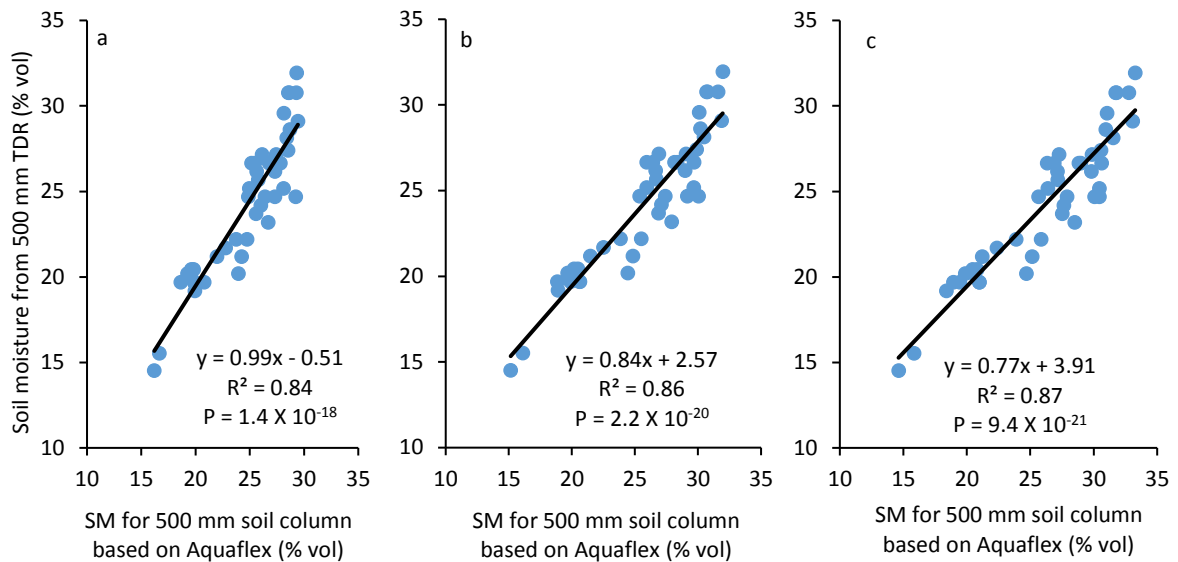


Figure 3-3: The relationship between soil moisture (SM) for 500 mm soil column based on Aquaflex and 500 mm TDR readings measured over 29 May 2015 to 10 Oct 2015 on LUDF: (a) when $d_1 = 200$ mm and $d_2 = 300$ mm, (b) when $d_1 = 300$ mm and $d_2 = 200$ mm, (c) when $d_1 = 350$ mm and $d_2 = 150$ mm

3.2.4 Water budget study

Individual soil moisture value was generated for each of the 20 lysimeters using weighted relationships between Aquaflex and corresponding 500 mm TDR readings. Generated soil moisture values were applied to the water budget equations developed for the 20 lysimeters to calculate ET_a . $K_c - h$ relationships were derived following a similar procedure as described in Chapter 2. $K_c - h$ relationships developed in this Chapter and in Chapter 2 were compared to investigate the significance of proper soil moisture determination in water balance estimation in irrigation planning.

3.3 Results and Discussions

3.3.1 Dry down experiment

Soil moisture sensors need to be evaluated over a range of conditions including natural wetting and drying sequences (Paige & Keefer, 2008). To determine how different probes respond under no water input regime, a dry down experiment was performed for thirteen days starting 26 Sep 2015 before the irrigation season started, as daily water input (irrigation and precipitation) complicates the soil moisture drainage process (Young et al., 2000).

Same length of probes installed at different locations showed high variations in soil moisture measurement, both vertically and horizontally. The surface soil became drier sooner than the deeper soil as shown in Figure 3-4.

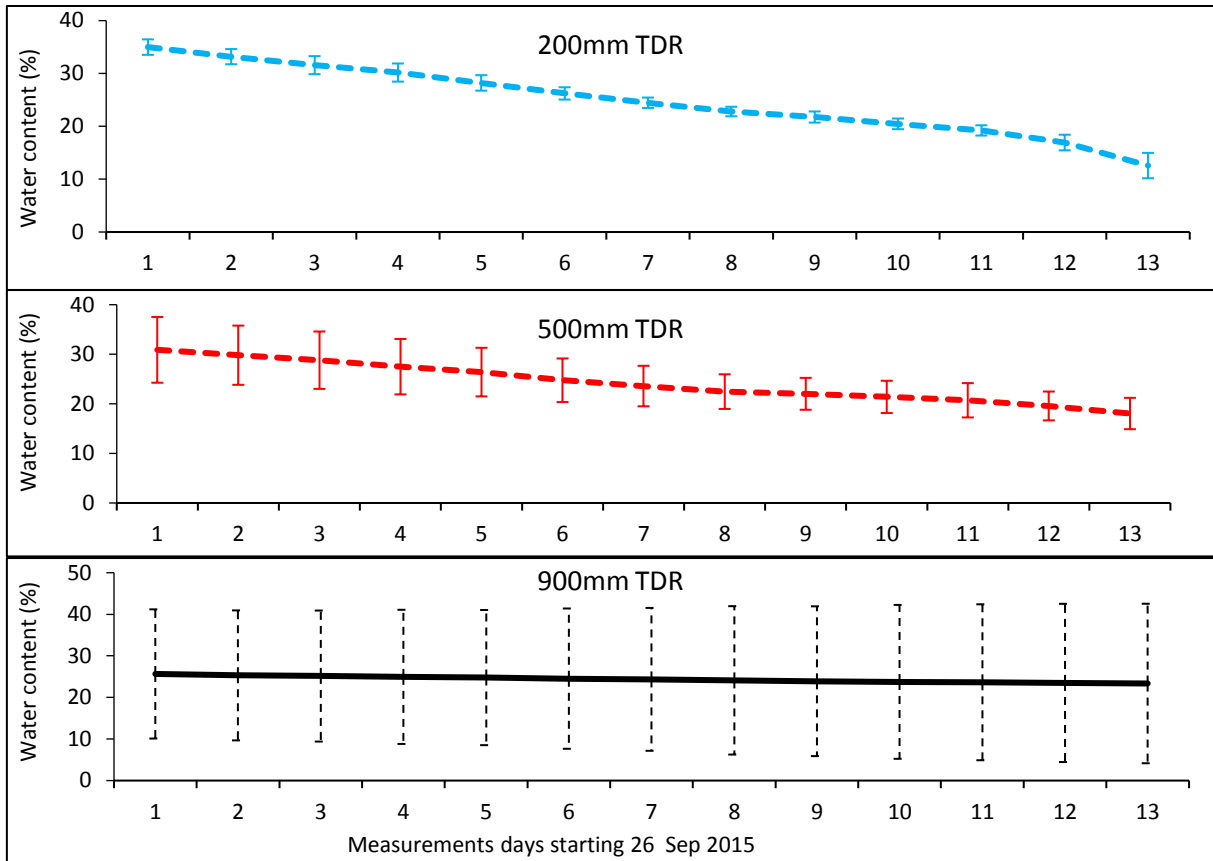


Figure 3-4: Changes in average soil moisture readings from 200, 500 and 900 mm TDR installed beside the lysimeters over 13 days dry down experiments commencing from 26 September 2015

Over 13 days' time period, average water content (% Vol) from 200 mm TDRs showed 22% reduction, from 35% at the beginning of the dry down experiment to 13% by the end of the experiment. The top sensor of the Aquaflex (200 mm) also showed similar reduction in average water content (% Vol), with 21% reduction over the experiment period, from 35% to 14%. Over the same time period, average water content (% Vol) from 500 mm and 900 mm TDRs reduced by 13% and 3%, from respective water content (% Vol) of 31% and 26% at the beginning of the dry down experiment to 18% and 23% by the end of the experiment.

The cumulative water loss calculated for all vertical probes showed a high variation. During the 13 days period, average water loss measured with the 200 mm probes was 45 mm (an average of 3.4 mm per day), compared to 64 mm (an average of 4.9 mm per day) measured with 500 mm probes. Daily water loss was uniform from the deeper probes (500 mm and 900 mm), while the loss rate from the 200 mm probes and Aquaflex top sensor (200 mm) decreased with time. Soil moisture reduced from soil layer less than 500 mm depth might be attributed to evapotranspiration. Small (3 %) reduction in soil moisture through 900 mm TDR might be the result of soil moisture change in top soil layer and deep percolation.

Standard error bars indicate that the variability in soil moisture measurements across the farm increases with soil depths. Among the three TDR probes tested, the 200 mm TDR showed the least variability in soil moisture measurement across the farm with slightly higher variability for 500 mm TDR. However, 900 mm TDR showed noticeably high variability in soil moisture measurement indicating significant differences in bottom soil texture across the farm.

To examine soil moisture status in three different soil profiles (0 mm - 200 mm, 200 mm - 500 mm, 500 mm - 900 mm) total storage of soil moisture available in each profile was calculated. Soil moisture recorded by 200 mm TDR was deducted from 500 mm TDR readings to get profile soil moisture for 200 mm - 500 mm. Difference between soil moisture recorded by 900 and 500 mm TDR produced profile soil moisture for 500 mm - 900 mm.

Among three different soil profile, total soil moisture losses was highest for 0 mm - 200 mm followed closely by 200 mm - 500 mm. Total soil moisture losses from 500 mm - 900 mm soil profile was minimal, suggesting a larger percentage of water lost from the soil was taken up from the 0 mm - 500 mm soil profile. Over the dry down period, out of the total water lost through the 0 mm - 500 mm soil profile, 69% was lost from 0 mm - 200 mm and 31% was lost from 200 mm - 500 mm soil profile.

The result indicates that once the shallower layers are dried out, the plant take up water from deeper layers. Young et al. (2000) also found similar trends, during 6 days dry down experiment water was taken up from the deeper layer once the top soil dried out. The results indicate that vertical TDR probes of different lengths can be useful in determining changes in root water uptake with time and depth.

3.3.2 Relationship between Aquaflex and TDR soil moisture readings

To investigate sensor's responses at different levels of soil moisture content, soil water measurements were carried out intermittently, over 29 May 2015 to 10 Oct 2015, to cover various soil moisture levels from the field capacity down to the critical point. To compare the seasonal variations of the water content profile, soil moistures were continuously measured at the same points. To enable comparison, TDRs were installed beside the Aquaflex so that both sensors are within the location. As Aquaflex measures average soil moisture over 3 m length, three sets of TDR were installed covering 3 m length and average soil moistures obtained from the three sets of TDR were compared with the Aquaflex values. Aquaflex top sensor (200 mm) readings were compared with 200 mm TDR values as both measure average soil moisture of top 200 mm soil profile. Soil moisture estimates for 500 mm soil column using Aquaflex top and bottom sensor readings were compared with 500 mm TDR readings.

Aquaflex top sensor and 200 mm TDR probes installed beside the Aquaflex: In dry conditions (<20% vol), 200 mm TDR produced slightly higher readings than Aquaflex, while in wet conditions (>30% vol) Aquaflex top sensor produced slightly higher values than 200 mm TDR, see Figure 3-5 (a). This variation in soil moisture measurement might be attributed to the differences in soil moisture measurement principle of two sensors and soil spatial variability. TDR is point measurement technique therefore, small wetting and drying events around its rods can impact greatly on the soil moisture reading. Aquaflex measures average soil moisture over 3 m length and therefore, if water content along the sensor is not uniform it may not affect the final results significantly. In other words, soil moisture changes at one point along Aquaflex sensor will have minor impact on the average soil moisture content from Aquaflex. A strong linear relationship was observed between soil moisture recorded by Aquaflex top sensor and 200 mm TDR probes, see Figure 3-5 (a).

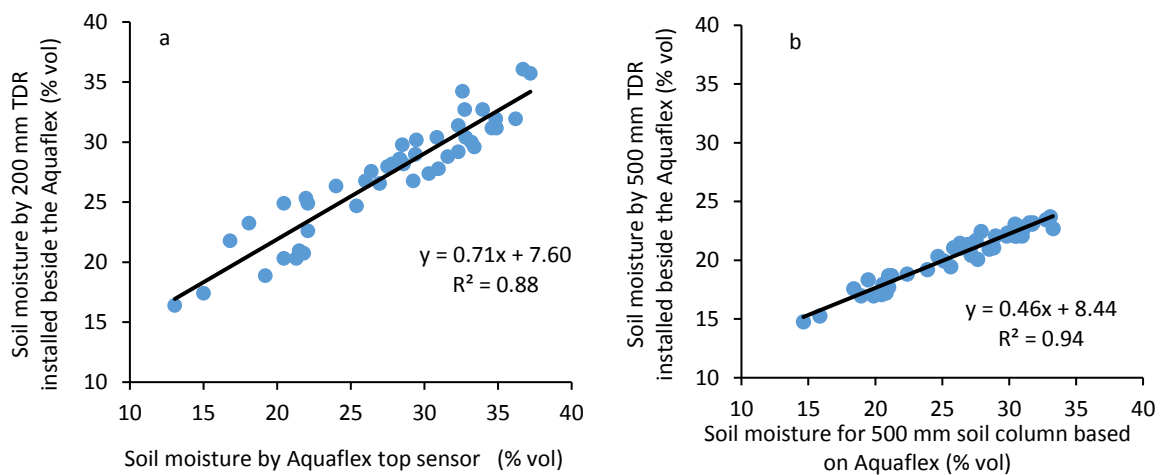


Figure 3-5: (a) Relationship between soil moisture (% vol) by 200 mm TDR installed beside the Aquaflex and Aquaflex top sensor reading, (b) Relationship between soil moisture (% vol) by 500 mm TDR installed beside the Aquaflex and soil moisture (% vol) for 500 mm soil column based on Aquaflex top and bottom sensor readings

500 mm TDR readings installed beside the Aquaflex and soil moisture for 500 mm soil column based on Aquaflex top and bottom sensor readings: For soil moisture <15% vol, 500 mm TDR produced higher readings than soil moisture estimates for 500 mm soil depth. While for soil moisture >15% vol, soil moisture estimates for 500 mm soil column based on Aquaflex was higher than 500 mm TDR readings. This difference in soil moisture measurement might be attributed to the differences in soil moisture measurement technique of two sensors and soil spatial variability. A strong linear relationship was observed between soil moisture estimates for 500 mm soil depth and 500 mm TDR probes readings, seen Figure 3 5 (b).

Aquaflex readings were also compared with soil moistures obtained from TDR installed beside the lysimeters. As can be seen in Table 3-1 the linear relationships between soil moisture measured by

the Aquaflex and TDR showed good agreement with strong coefficient of determination (R^2) and very small P-values (i.e. $\alpha \ll 0.05$). The high R^2 and low P-values indicate that there is a significant correlation between soil moistures measured from the aquaflex and TDR.

Table 3-1: Coefficient of determination (R^2) and P-values for the relationship between Aquaflex and TDR readings

TDR installed beside	R^2 and P-values for the following relationships			
	Aquaflex top sensor and 200 mm TDR readings		soil moisture for 500 mm soil column based on Aquaflex and 500 mm TDR readings	
	R^2	P	R^2	P
L-21*	0.87	2.4×10^{-20}	0.88	2.0×10^{-21}
L-25	0.80	2.3×10^{-16}	0.88	1.8×10^{-21}
L-30	0.83	2.7×10^{-18}	0.82	6.8×10^{-18}
L-31	0.82	1.0×10^{-17}	0.84	8.6×10^{-19}
L-34	0.87	2.5×10^{-21}	0.85	1.8×10^{-19}
L-40	0.87	5.7×10^{-21}	0.87	9.4×10^{-21}
Aquaflex	0.88	2.0×10^{-21}	0.93	2.8×10^{-28}

*L-21 indicates for lysimeter number 21 and so on

Due to soil spatial variation soil moisture recorded by 900 mm TDR probes installed beside each other showed good agreement compared to the 900 mm probes installed further apart. For example, relationship between soil moisture recorded by 900 mm TDR probes installed beside lysimeters 21 and 25 (4 m apart) showed strong coefficient of determination with $R^2 = 0.88$, while the relationship between soil moisture recorded by 900 mm probes installed beside the Aquaflex and lysimeter 40 (100 m apart) produced weak relation with $R^2 = 0.49$. The coefficient of determination further weakened when probes installed longer distances apart were considered.

3.3.3 Spatial and temporal variability of soil water content

This assessment incorporated analysing soil moisture within profile and between sites, and the sensor response variability of Aquaflex and TDR. Soil water content measured by 3 sets with 200, 500, 900 mm length of TDR probes installed vertically at different locations are shown in Figure 3-6. In the figures L-21 means soil moisture recorded by the TDR installed beside Lysimeter 21 and so on, TDR-A means soil moisture recorded by the TDR installed beside the Aquaflex. In Figure 3-6 (a) Aquaflex implies soil moisture reading from Aquaflex top sensor while in Figure 3-6 (b) Aquaflex implies soil moisture estimated for 500 mm soil column using Aquaflex top and bottom sensor readings. All TDR probes and Aquaflex responded to individual water input, especially the shorter probes and Aquaflex top sensor responded well compared to longer probes and Aquaflex bottom sensor. Two large rainfall events at measurements no. 10 and 29 are clearly reflected in TDR and Aquaflex values. After measurement no. 36 there was no water input (rainfall and irrigation) and therefore, soil moisture recorded by all TDRs and the Aquaflex sensor continued its down trend.

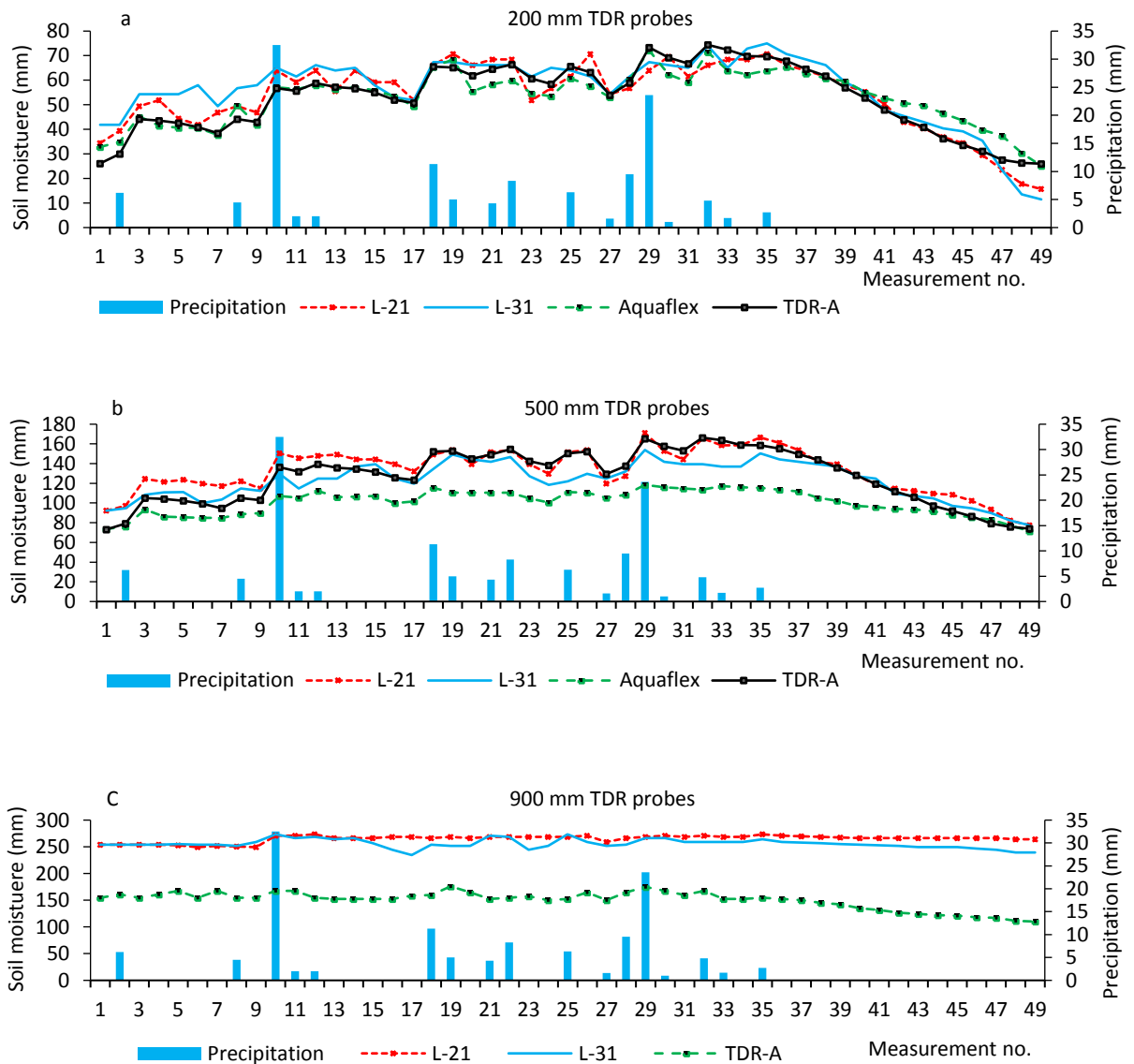


Figure 3-6: Soil water content (SWC) measured from TDR installed at different locations during a period 29 May 2015 to 10 Oct 2015: (a) for 200 mm TDR (b) for 500 mm TDR (c) for 900 mm TDR

The amplitude of the daily fluctuations in water content measurement from different length of probes were noticeably higher for shorter probes (200 mm) and Aquaflex top sensor than those recorded by the longer probes (500 and 900 mm) and Aquaflex bottom sensor. In other words, the top soil surface was recharged and depleted in a short period of time. This indicates more root activity in the top soil and in turn higher water use from top soil than deeper soil, which is also supported by Parry (1994); Young et al. (2000). The result indicates soil moisture changes in this farm due to ET usually take place in the upper part of the soil. Daily variations in soil moisture content recorded by the longer probes might be the result of the change in soil moisture in the top soil profile and deep percolation. Water holding capacity of top 200 mm soil profile over the

experimental plot showed less variations, with average soil moisture measured from 200 mm TDRs showing similar results ranging from 26 to 31% over four months measurement period. Over the same time period, average soil moisture recorded by 500 and 900 mm probes ranged from 21 to 28 % and 17 to 30 %, respectively.

Spatial and vertical variability in soil's bulk density and water holding characteristics creates disparity in soil moisture measurements at different locations (Allen et al., 2011). Cracks, rocks, pore size, plant roots, and texture layers are not homogenous over a cropped field which affects soil's water content (Charlesworth, 2005). Different soil types beside the TDR mean variations in infiltration capacity, which creates differential spatial wetting of soil leading to local spatial variation in soil moisture measurement.

TDR probes can only sample points in a paddock so, identification of representative location (benchmark point) for sensor installation is critical. Relying on inadequately placed equipment for soil water measurement may create over or under-irrigation conditions. Soil moisture monitoring requires detailed assessment of soil water dynamics at different locations and time to select the best sensor position for irrigation onset (Hedley & Yule, 2009). Despite high linear relationship, water content measured by 500 and 900 mm TDRs installed beside the Aquaflex was consistently lower than the soil moisture measured beside the lysimeters due to variation in soil texture. Therefore, for the water budget in the lysimeters, soil moisture recorded by Aquaflex needs to be adjusted.

3.3.4 Water budget study

With TDR adjusted aquaflex soil moisture values, a relationship between K_c and h was derived under SCENARIO III as described in section 2.3.4. in Chapter 2. Linear, power and exponential relationships were tested to select the best fit which showed the linear relation was a preferred option for the fitted $K_c - h$ relationship. When the original Aquaflex soil moisture values were used in the water budget equation for the lysimeters data, the coefficient of determination (R^2) for $K_c - h$ relationship was 0.43 (section 2.3.4. Chapter 2), which improved to 0.66 when TDR adjusted Aquaflex soil moisture values were utilized for corresponding water budget equations, see Figure 3-7.

However, there was no significant difference between the $K_c - h$ relationships developed under two conditions with calculated P-values of 0.0 being less than α level i.e. 0.05. Still the result suggests the importance of proper soil moisture determination for water budget estimation in irrigation planning.

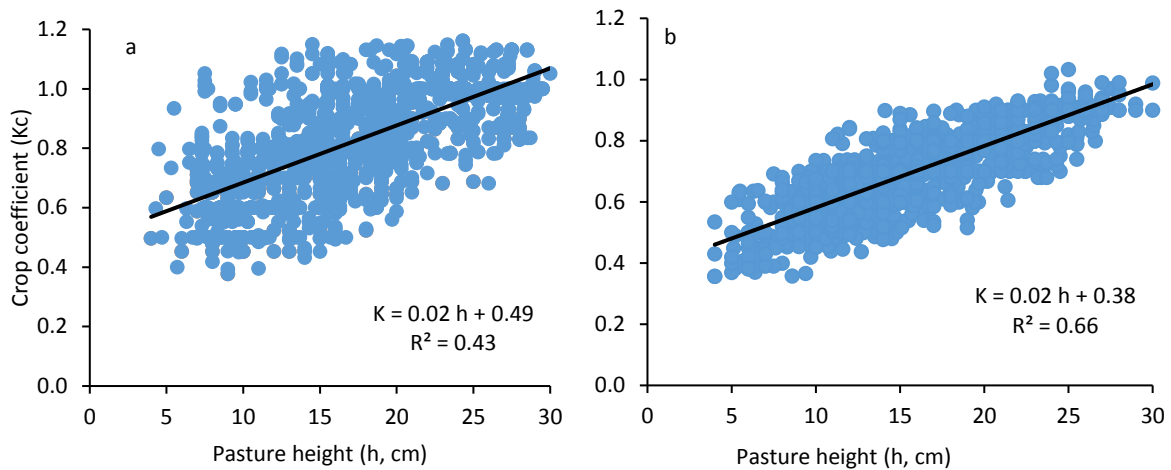


Figure 3-7: Linear relationship between crop coefficient and pasture height: (a) based on Aquaflex soil moisture without adjustment (b) based on TDR adjusted Aquaflex soil moisture

Improvement in $K_c - h$ relationship confirms the capacity of multi-length and multiple placements TDR to assess the spatio-temporal variability of soil moisture measurement in the field.

With the original Aquaflex soil moisture values, a relationship between K_c and h was produced as:

$$K_c = 0.02 \times h + 0.49 \quad (3-1)$$

With the TDR adjusted Aquaflex soil moisture values, the relationship between K_c and h was improved to:

$$K_c = 0.02 \times h + 0.38 \quad (3-2)$$

Crop coefficients' estimates at different pasture heights based on Equations (3.1 & 3.2) are shown in Table 3-2. Crop coefficient estimates with TDR adjusted Aquaflex soil moisture would consistently save 10% irrigation water than adopting only Aquaflex soil moisture values without adjustment. Average K_c estimated for one grazing rotation of 30 days with TDR adjusted Aquaflex soil moisture was 0.7. Results from this research indicate that conventional irrigation planning with crop coefficient of 1.0 would provide "on average" 30% more irrigation compared to actual crop water needs under grazing condition.

Table 3-2: Crop coefficients of pasture (K_c) estimated for different growth stages of a grazing rotation

Equations	Crop coefficient (K_c) at following pasture height "h" (h in cm)						Remarks
	5	10	15	20	25	30	
$K_c = 0.02 h + 0.49$	0.6	0.7	0.8	0.9	1.0	1.1	Aquaflex SM
$K_c = 0.02 h + 0.38$	0.5	0.6	0.7	0.8	0.9	1.0	TDR adjusted SM

3.4 Conclusions

This study demonstrated the effectiveness of using multi-length TDR probes placed in multiple locations for monitoring spatio-temporal variability of soil moisture in the farm. All TDR probes and Aquaflex responded effectively to rainfall and dry events with shorter probes and Aquaflex top sensor showing more responsive readings compared to longer probes and Aquaflex bottom sensor. However, high variability in soil moisture measurements within a short horizontal distances means there is complexity to figure out representative locations for soil moisture monitoring.

Application of a dry down experiment enabled us to assess the rate of soil moisture depletion in pasture root zone, as recorded by different lengths of TDR probes. Over 13 days of a dry down experiments average water content measured from 900 mm TDR were almost constant, while 200 and 500 mm TDR readings reduced significantly, indicating pasture water use is dominated in the upper soil depth. Based on the dry down experiment, it is concluded that the soil profile below 500 mm soil profile in the lysimeters has a minor role in the water mass balance.

The adjustments made on Aquaflex soil moisture values using TDR raised the accuracy of the water budget estimation in the lysimeters and consequently improved the relationships between the crop coefficient of pasture (K_c) and plant height “h” (cm). This indicates that installing more soil moisture sensors beside the lysimeters can adequately improve evapotranspiration estimation and thus improve K_c estimation in irrigation planning. This also signifies the importance of soil moisture monitoring at different locations in the farm, not only in one location.

Adopting the more accurate K_c in irrigation scheduling based on the developed equations of this research would save “on average” 30% of irrigation water compared to when applying the most commonly used crop coefficient value of 1.0. This significant saving in irrigation water can conserve water and reduce the negative impact of irrigation on the environment without deteriorating potential yield.

Chapter 4

Current Irrigation Strategies for Rotational Grazing Pasture in New Zealand and Their Impacts on Water Quantity

Abstract

Understanding pastoral irrigation, particularly in relation to grazing rotation and plant available water (PAW) is lacking in Canterbury, New Zealand. To support irrigation efficiency improvement, it is essential to identify the major limitations to irrigation management. The aims of this study were: 1) to investigate prevailing irrigation management practices on pastoral farms during different irrigation season in Canterbury, New Zealand; and 2) to analyse irrigation and deep percolation from identified irrigation strategies to explore irrigation efficiency improvement opportunities. Thirty two dairy farmers in Canterbury, New Zealand were interviewed during the period September 2014 to June 2015. A water balance model IrriCalc was used to estimate irrigation and deep percolation from irrigation strategies obtained from the survey.

Due to rotational grazing systems, pasture canopy varies across the paddocks, but irrigation application is uniform regardless of pasture growth dynamics. Producers have practiced different irrigation strategies during shoulder seasons (September to October and March to April) and peak irrigation season (November to February), which differs greatly from farmer to farmer. During shoulder seasons the majority of farmers start irrigation at 50% of PAW and stop irrigation at 80% of PAW. During peak irrigation season producers mostly start irrigation at 70% of PAW and fills soil up to 100% of PAW. Results showed that over the 14 irrigation seasons (2001/02 to 2014/015) this irrigation strategy would have produced a range of deep percolation per irrigation season between 40 and 550 mm. If the same irrigation strategy adopted for shoulder season was applied for whole irrigation season it would save 13% irrigation water and reduce 22% deep percolation compared to applying two distinct irrigation scenarios for shoulder and peak irrigation season.

Results demonstrate there is a high potential to optimise current irrigation strategies. Better utilization of rainfall during the irrigation season, would minimise irrigation requirements and deep percolation losses. This would help to address the issues of nutrient losses and relieve the pressure on water resources.

KEY WORDS: pastoral farming; grazing rotation; survey; IrriCalc; irrigation

4.1 Introduction

Dairy consumption is increasing around the world with increasing global population and standard of living (Mekonnen & Hoekstra, 2012; van der Lee et al., 2013). Particularly in many booming Asian countries, the dairy consumption rate is higher than the country's production capacity (Australia and New Zealand Banking Group Limited (ANZ), 2012). However, the increasing demand for dairy products is likely to put further pressure on already stressed water resources because the water footprint of any animal product is higher than the water footprint of crop products for the same calories (Mekonnen & Hoekstra, 2012).

In New Zealand, total numbers of dairy cattle increased by 53% during sixteen years' period, from 3.3 million in 2000 to 5.0 million by 2015. Over the same time period the average number of cows per hectare increased by 13% reaching 2.87 by 2015 (Livestock Improvement Corporation (LIC) & DairyNZ, 2015). Intensification of dairy farming is greater in the South Island than in the North Island, especially in the Canterbury region (South Island Dairying Development Centre (SIDDC), 2014; The Encyclopedia of New Zealand, 2014).

In New Zealand dairy farming is dominated by pasture based system (Monaghan et al., 2008). Naturally grown or sown field plants for grazing animals are collectively called forage plants or pasture (The Encyclopedia of New Zealand, 2014). In New Zealand dairy farming, perennial ryegrass (*Lolium perenne*) is the main pasture grass for providing major nutrients to dairy cows (Lee et al., 2010; Monaghan et al., 2008). Usually sown pasture contains one or a mixture of more grasses. In addition, pasture contains one or more legume species. Legumes, such as white clovers fix nitrogen from the atmosphere, add nutrients to the soil, and reduce crop demand for additional nitrogen fertilizer supply (Martinson & Peterson, 2014).

A dairy farm consists of several small blocks called "paddocks". Each paddock is grazed rotationally on a regular interval which is primarily based on "3-leaf" principle as described in Lee (2011). The "3-leaf" principle, to graze before fourth live leaf emerges, fits well for New Zealand conditions to ensure optimal pasture growth and quality (Lee, 2011). As the fourth leaf emerges, the first leaf starts decaying. Therefore, to balance pasture growth and grazing stage, pasture should be grazed between 2- and 3-leaf stages (Chapman, 2014). When 3rd leaf is fully grown, pastures will reach a ceiling yield after which no further dry matter will accumulate, and pasture quality will decline (Chapman, 2014).

Pasture is analogous to a solar panel, which absorbs energy from the sun, and converts that to feed for animals (Pasture Renewal Charitable Trust, 2008). To achieve maximum grass yield, the ground should always maintain a full cover by removing animals from the grazing paddock before the

exposure of bare ground. Pasture cover of 1400 kg DM/ha represents full cover status (Pasture Renewal Charitable Trust, 2008). To assess grass cover on a dairy farm for deciding when and where to graze the animals, dairy farmers monitor grass cover regularly using Rising Plate Meter (RPM), which is a widely used farm management tool for pasture cover measurement in New Zealand (DairyNZ, 2008).

Within New Zealand, two distinct pasture production systems are in practices: (1) rainfed system in North Island, Southland and South Otago, as generally rainfall in these regions is reliable during pasture growth season (spring, summer and autumn); and (2) irrigated system in Canterbury and Otago, where pasture evapotranspiration during pasture growth season exceeds rainfall inputs. Expanding dairy industry is promoting an irrigated area increase for pasture production. Comparatively the irrigated area expansion is highest in Canterbury than other regions of New Zealand (Srinivasan & Duncan, 2011; Van Housen, 2015).

Expanding dairy industry is promoting an irrigated area increase for pasture production. Comparatively the irrigated area expansion is highest in Canterbury than other regions of New Zealand (Srinivasan & Duncan, 2011; Van Housen, 2015). Between 2007 and 2012 the irrigated area in New Zealand increased by 102,400 ha resulting in a total irrigated area of 721,700 ha by 2012, with nearly 59% (60,000 ha) of total increment from Canterbury, see Table 4-1.

Table 4-1: Irrigated area increase between 2007 and 2012, Source: (Statistics New Zealand, 2012)

Regions	Total irrigated area ('000 ha)			
	2007	2012	Increase	% of national increase
New Zealand	619.3	721.7	102.4	
Canterbury	385.3	445.3	60.0	58.6

Approximately two-thirds of New Zealand’s total irrigated land is located in the Canterbury region, which shares 58% of all water allocated for consumptive use in New Zealand (Saunders & Saunders, 2012). Out of 340,000 ha irrigated area planned to expand in New Zealand, almost two-thirds is expected to be added in Canterbury (Carrick et al., 2013).

In Canterbury, with an increase in irrigated area, especially from irrigated dairy farms, water diversion from water sources is also increasing, causing water stress for other water users (Maskey et al., 2006; Miller & Veltman, 2004). Many water sources are becoming, or already considered fully

allocated (Maton et al., 2005). It is very hard for new schemes to get consents for water use (ROCKPOINT, 2012).

The dairy industry in Canterbury New Zealand is facing mounting pressure to improve irrigation efficiency without compromising potential yield (Edkins, 2006; Horizon Research Limited, 2014; Jay, 2007; Maskey et al., 2006; Miller & Veltman, 2004; ROCKPOINT, 2012; Van Housen, 2015). In general, prevailing practices for irrigation management are inadequate to address increasing water demand (Canterbury Water Management Strategy (CWMS), 2009; Ford et al., 2009).

Irrigation efficiency improvement technologies are available in New Zealand but farmers use them rarely (Ford et al., 2009; ROCKPOINT, 2012). Some farmers have little idea about when to start irrigation and how much water to apply. Soil moisture and crop growth monitoring make significant contributions to improve irrigation efficiency (Hamlyn, 2004; Heermann, 1990; Irrigation New Zealand, 2010; Vanino et al., 2015). However, many Farmers do not use measured soil moisture values in their irrigation planning (ROCKPOINT, 2012; Saunders & Saunders, 2012).

Inefficient irrigation not only waste water but also reduce yield by leaching valuable nutrients away from the root zone (Martin et al., 2006). If the production potential is not reached, nutrient use by the plants is also not optimal, which leaves more nutrients free to leach. Nutrient leaching induced by inefficient irrigation practices is causing adverse impacts on the environment, especially on water quality (Jay, 2007). Around 74% of the New Zealand public blame expanding dairy farming as the root cause of deteriorating water quality in New Zealand streams, lakes and rivers (Horizon Research Limited, 2014).

Improvement in irrigation efficiency ensures more precise water use and minimises negative impacts on the environment by reducing deep percolation events (Cabelguenne et al., 1997). Irrigation efficiency is a measure of how effectively an irrigation system is performing (McIndoe & Curtis, 2012). To support irrigation efficiency improvement, it is essential to identify the major limitations to agricultural water management (Lincoln Environmental, 2000a; Rout, 2003a).

Previous researchers including Srinivasan and Duncan (2011), highlighted key information gaps in the New Zealand irrigation sector. Researchers who conducted surveys to investigate challenges in irrigation sector in New Zealand, include Payne and Stevens (2010), Srinivasan and Duncan (2011) and Horizon Research Limited (2014). Payne and Stevens (2010) surveyed dairy farmers to determine producer's understanding and perceptions of water use efficiency in regards to their irrigation system. They found that nearly 50% of surveyed farmers didn't monitor or measure water supply on their farm for improving irrigation efficiency. Srinivasan and Duncan (2011) conducted a survey to dairy farmers to explore irrigation water use measurement status. They indicated a need to monitor

soil moisture and crop water requirement for scheduled irrigations. Horizon Research Limited (2014) conducted a survey to explore the view of New Zealanders on dairy farming and its impact on the environment. Above two thirds of the respondents blamed increasing dairy farming to be the root cause of deteriorating water quality in NZ water sources. Surveys carried out by these researchers have provided important insights into irrigation practices used by dairy farmers in New Zealand (Saunders & Saunders, 2012).

Irrigation planning based on grazing rotation and plant available water (PAW) would contribute significantly to conserve water and the environment (Hamlyn, 2004; Heermann, 1990; Irrigation New Zealand, 2010; Vanino et al., 2015). However, there have been very few studies to understand dairy farmer's irrigation strategies, particularly in relation to grazing rotation and PAW. The main objectives of this study were: (1) to understand current irrigation strategies adopted by the Canterbury dairy farmers during various irrigation seasons by considering grazing rotation and PAW; and (2) to estimate irrigation and deep percolation under identified irrigation strategies to investigate the opportunity for reducing net irrigation requirement and deep percolation events.

4.2 Material and Methods

4.2.1 Mixed-mode survey approach

A survey approach that incorporates two or more survey methods to collect data, termed as mixed-mode surveying method was used in this study (Baum et al., 2012). The mixed-mode survey methodology used for this study consisted of emailing copies of the questionnaire at first, so farmers are aware of the questions, and then completing the survey by asking the questions over the phone. The questionnaire used was prepared to target irrigation practices by farmers, seeking specific answers, therefore, live telephone conversation was the most appropriate approach for the surveying.

The Canterbury region was selected for the study as it accounts for about two-thirds of total irrigated area and shares 58% of total annual fresh water withdrawal in New Zealand. As focus was researching methods for the better management of irrigated pasture, the conditions for participation were to be irrigated pasture based dairy farming. Sprinkler irrigation is the dominant irrigation system in New Zealand, therefore growers with border dyke were excluded (McIndoe, 2013).

A questionnaire was sent to 40 farmers, whose email addresses were obtained from Irrigation New Zealand, asking them to take part in the survey. Irrigation New Zealand is a national level industry body focussed on addressing challenges and opportunities of the irrigation sector in New Zealand. A total of 32 dairy farmers who agreed for the survey were interviewed during the period August 2014 to June 2015.

The initial questionnaire was improved step by step by consulting with several scientists, relevant experts at Lincoln University, and other organization including Irrigation New Zealand, South Island Dairy Development Centre (SIDDC), Aqualinc Research Limited and the National Institute of Water and Atmospheric Research Limited (NIWA). Before conducting the final survey, the survey questionnaire was pre-tested by some selected farmers. This pre-tested survey data (pilot study) was not included in the final data set. To conduct the survey, approval was received from the Human Ethics Committee, at Lincoln University, Christchurch, New Zealand.

The multiple choice questions were designed to make the interview process more convenient. The survey consisted of five main sections: 1) general information about the farm; 2) grazing strategies; 3) farm characteristics; 4) irrigation system; and 5) irrigation process. The questionnaire used for the survey has been attached in Appendix B.

The information received in each questionnaire was coded and entered into a database and excel spreadsheet for subsequent analysis. Descriptive statistical analysis was carried out for both individual farm level and sub-groups which represent similar characteristics.

4.2.2 Irrigation and Deep percolation estimates using IrriCalc

IrriCalc is a water balance model developed by Aqualinc Research Limited New Zealand (Environment Canterbury, 2010). Detailed information about IrriCalc can be found in Bright (2009). IrriCalc estimates net irrigation requirement as a difference between actual crop water need and effective rainfall. Actual crop water need is equivalent to the multiplication of reference evapotranspiration (ET_r) and crop coefficient (K_c). ET_r was estimated from daily weather data using FAO Penman-Monteith method.

Effective rainfall refers to that proportion of total rainfall which is stored in root zone i.e. the difference between total rainfall and deep percolation losses, assuming no surface runoff. The amount of total rainfall/irrigation that exceeds field capacity in daily soil water balance is accounted for as deep percolation losses, as surface runoff due to overland flow was assumed to be negligible.

IrriCalc evaluates daily changes in the root zone's soil water content in response to daily rainfall, irrigation, evapotranspiration and deep percolation events using the following soil water balance equation:

$$S_{t_2} = S_{t_1} + P_{t_2-t_1} + I_{t_2-t_1} - D_{t_2-t_1} - AET_{t_2-t_1} \quad (4-1)$$

Where S_{t_2} = soil water content at time t_2 , S_{t_1} = soil water content at time t_1 , $P_{t_2-t_1}$ = rain between time t_1 and t_2 , $I_{t_2-t_1}$ = irrigation between time t_1 and t_2 , $D_{t_2-t_1}$ = deep percolation between time t_1 and t_2 ,

$AET_{t_2-t_1}$ = actual evapotranspiration between time t_1 and t_2 . Equation (4-1) was applied for one day intervals and therefore units of all variables of Equation (4-1) are in mm.

IrrCalc calculates daily soil moisture status over the simulation period and if soil moisture drops to the user defined refill point, a user specified amount of irrigation is applied. Different options are available in the models to regulate irrigation planning. This study adopted the option that regulates irrigation application based on user defined soil moisture limits i.e. irrigation start and stop points as certain percentages of PAW.

Irrigation management strategies as reported by the surveyed farmers were applied to Lincoln University Dairy Farm (LUDF) to investigate the impacts of these strategies on irrigation and deep percolation. For which pasture and soil data were measured at LUDF. A pasture root depth of 500 mm as per field observation was used. Field capacity at 28% volume and critical depletion at 14% volume were used as estimated for the experimental plot.

Various researchers such as Moir et al. (2007) suggested to estimate a multi-year average deep percolation values to make proper irrigation planning which accounts for variation in annual deep percolation due to annual climatic and irrigation variability. To account for temporal variability, daily time series of climatic data available for a 16 years period (2000 to 2015) were collected from Broadfield weather station lying 3 km NE from the LUDF. Irrigation and deep percolation were calculated by modifying irrigation start and stop points as certain percentages of PAW based on the values given by the surveyed farmers.

4.3 Results and Discussions

4.3.1 General information

The surveyed farmers represented different locations in 6 out of 9 districts of Canterbury region of New Zealand. They covered a wide range of irrigation management strategies adopted in Canterbury dairy farms. There was high variation in farm size with a minimum of 55 ha to a maximum of 700 ha, resulting in high variability of paddock numbers on each farm, ranging from 10 to 80. Similar to farm size, paddock size also varied greatly ranging from 3 to 39 ha.

4.3.2 Rainfall, evapotranspiration and irrigation application

On each surveyed farm evaporation was higher than rainfall amount indicating a need for irrigation see Figure 4-1.

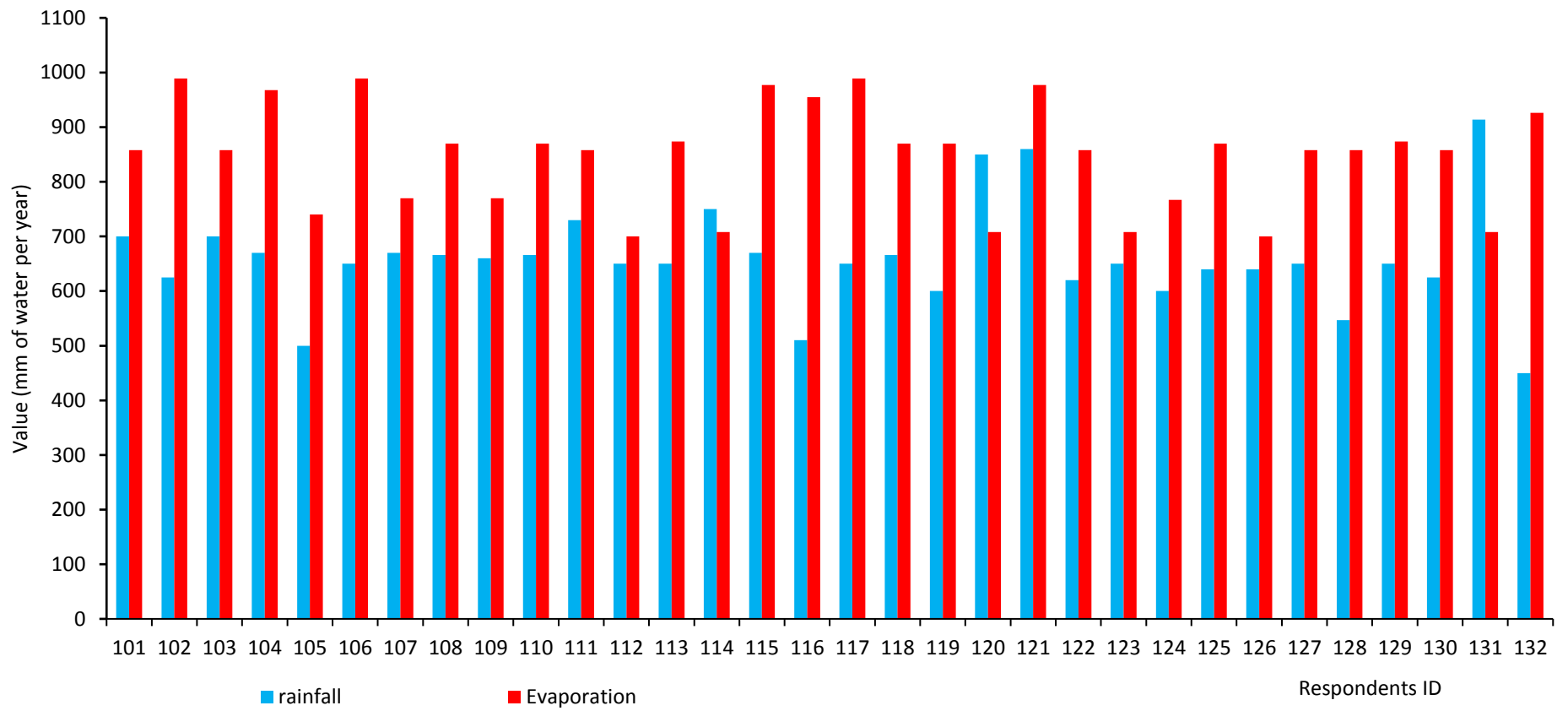


Figure 4-1: Rainfall and Evapotranspiration as reported by farmers under survey

To compare the average values, rainfall on each farm were summed and divided by total numbers of interviewees. Same procedure was followed for evapotranspiration and irrigation applied. This produced average annual rainfall at 659 mm and evapotranspiration at 849 mm, which indicates average annual rainfall deficit of 190 mm. However, average annual irrigation applied on the surveyed farms was 463 mm, which is nearly two and half fold more than the rainfall deficit. Occasionally rainfall occurrences and irrigation demands might not have been at the same time. Yet, irrigation strategies as reported by the surveyed farmers indicated lack of proper consideration for potential rain in irrigation planning.

Farmers have no long-term information about rainfall, evapotranspiration and irrigation application for their farms. To assess more closely whether irrigation management is proper or not, rainfall, evapotranspiration and irrigation data are needed at least at the weekly level. If weekly evapotranspiration exceeds weekly rainfall, that confirms the need for irrigation. Comparing weekly data for the whole irrigation season gives an indication of how many weeks irrigation was really needed. If there are weeks with rainfall exceeding evapotranspiration then irrigation supply during such week will contribute to deep percolation. Proper irrigation planning should try to avoid such incidents.

Rainfalls were also collected from the NIWA’s weather stations lying near the surveyed forms and compared with the respective values obtained from the survey. This comparative study was undertaken to assess the validity of survey data. Results showed good agreement between the rainfall values collected from these two independent sources with coefficient of determination (R^2) at 0.67, see Figure 4-2. The low value for R^2 might be attributed to the spatial variation in rainfall occurrence. This test results confirmed that the information reported by the farmers included in the survey represents well their farm condition.

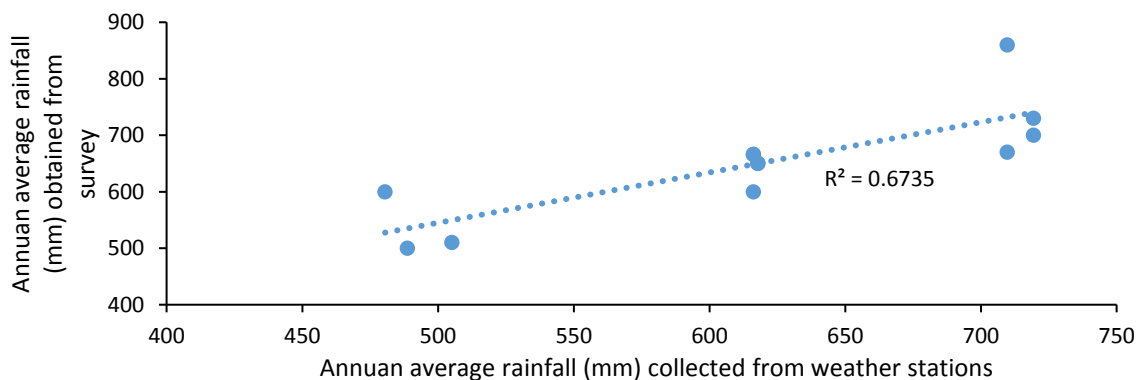


Figure 4-2: Relationship between rainfall data collected from the NIWA’s weather stations near the surveyed farms and obtained from the survey

4.3.3 Irrigation systems

Many surveyed farmers reported more than one type of irrigation systems, with centre pivot being the dominant one which covered 58% of the total irrigated area under the survey (Figure 4-3). The system capacity of almost 84% of the centre pivot irrigators was between 4 and 5 mm/day with the remaining pivots having their system capacity of less than 4 mm/day. Other irrigators such as rotary boom, long lateral and k-line were also used for areas where the centre pivots could not cover.

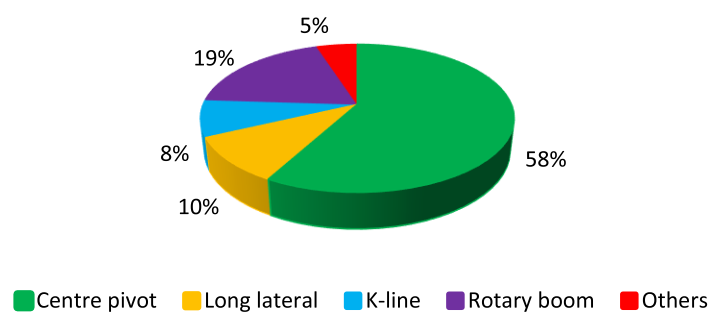


Figure 4-3: Percentages of total irrigated areas under survey covered by different irrigation systems

With many of the currently used irrigation systems such as rotary boom, long lateral, k-line, it is hard to achieve reliable distribution uniformity of the irrigated water. Domination of centre pivot irrigation in the studied region meant an opportunity to improve irrigation efficiency as it can apply irrigation more flexibly by adjusting speed of the irrigator. However, currently centre pivot irrigation systems are also performing below their potential levels. For example performance assessment test of six newly established centre pivot irrigators, conducted under the supervision of Irrigation New Zealand in different parts of Canterbury, showed less than 75% distribution efficiency, which is poor for this type of irrigation system. This indicates a big space for the irrigation efficiency improvement.

4.3.4 Soil types

In New Zealand, local soil names, such as Barrhill, Lismore, Rangitata, Rakaia etc, are commonly used, and farmers identify soils with this classification. These soils are further divided into numerous sub-divisions. For example Barrhill has 19 sub-divisions, such as Barrhill deep fine sandy loam, Barrhill moderately deep silt loam etc. Likewise, Lismore has 8 sub-divisions, such as Lismore very stony silt loam, Lismore shallow silt loam etc. Correlation between these local soil names and soil taxonomy is available on S-map fact sheets in Landcare Research (2015). For example Lismore very stony silt loam has a texture profile of silty loam.

Lismore, Eyre, Templeton, Waimakaririr were the most commonly reported soils by the farmers. Almost all interviewees reported different soils on their farms ranging from stony soils to heavy clayey. Soil types varied even within the same farm. For example, in Lincoln University Dairy Farm

(LUDF) there are six different soils: Wakanui deep, Wakanui deep (slow), Templeton deep, Templeton deep (slow), Paparua deep, Eyre shallow. However, all the farmers reported that they don't control irrigation applications depths based on soil types on their farms.

4.3.5 Root depth

Variations in soil types on the surveyed farms have affected pasture root depth. Reported root depth ranged from 90 to 500 mm with majority of respondents (79%) having root depth in the range of 100 to 300 mm (Table 4-2).

Table 4-2: Classification of effective rooting depth (ERD) obtained from the survey

Root depth (R, mm)	Percentage of the respondents (%)
$0 < R \leq 100$	6.9
$100 < R \leq 200$	58.6
$200 < R \leq 300$	20.7
>300	13.8

4.3.6 Plant available water (PAW)

PAW refers to available soil moisture between wilting point and field capacity. There was high variations in PAW in different farms, ranging from 18 mm to 225 mm. Half of the farms included in the survey have PAW greater than 60 mm, 38% of the farms have PAW between 30 and 60 and 12% of the farms have PAW less than 30 mm (Figure 4-4). PAW between 30 mm - 60 mm is considered low and that below 30 mm is very low (Webb & Wilson, 1995). For a farm with low PAW, longer irrigation return interval with higher amount of irrigation application at one time is prone to create deep percolation.

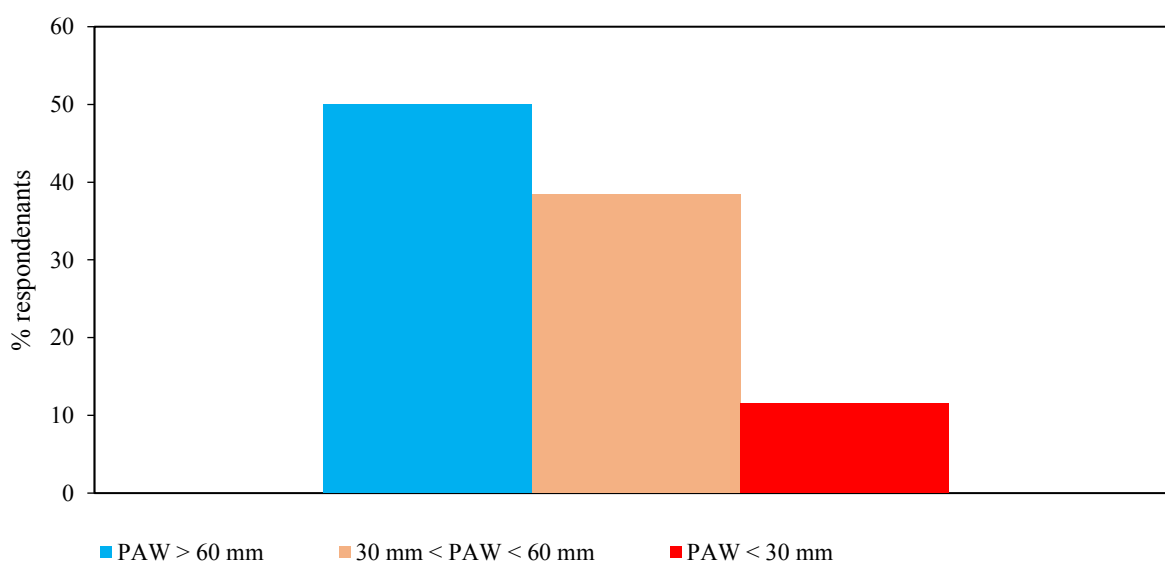


Figure 4-4: Percentages of respondents with different plant available water (PAW) on their farm

4.3.7 Irrigation strategy during different seasons

In Canterbury, irrigation season generally extends from September to April. The irrigation season from September to October (Zone-1) and March to April (Zone-3) are known as shoulder seasons, and November to February (Zone-2) termed as peak irrigation season.

Almost all interviewee reported that irrigation starting dates at the beginning of the irrigation season and irrigation stopping dates at the end of the irrigation season are mostly determined by three main factors: soil moisture, soil temperature and weather forecast. Either soil moisture less than 50% PAW or soil temperature $>10^{\circ}$ can drive irrigation starting dates while the opposite is true for irrigation stopping dates. However, approaches for deciding irrigation starting and stopping dates differ from farmer to farmer. For example: about 55% of the respondents said that they determine irrigation starting and stopping dates solely based on soil moisture status. Nearly 21% producers said that they consider both soil moisture and soil temperature, and 24% farmers said that they consider all three factors (soil moisture, soil temperature and weather forecast) to decide irrigation starting and stopping dates.

Distinct irrigation approaches are adopted for shoulder seasons and peak irrigation season due to weather variations (Table 4-3 and Table 4-4). However, even within the same irrigation season farmers are adopting different trigger soil moisture levels to start and stop irrigation. More interestingly, farmers with same irrigation starting strategies have quite different irrigation stopping approaches. For example, during shoulder seasons 57% of the respondents start irrigation when PAW is depleted by 50%, of which respectively 50, 37.5 and 12.5% of farmers stop irrigation correspondingly at 80, 90 and 100% PAW, see Table 4-3, first column.

Table 4-3: Irrigation starting and stopping strategies based on plant available water (PAW) during shoulder season

Irrigation starting point		Irrigation stopping points (% of respondents who stop irrigation at the following % of PAW)			
at % of following PAW	% of respondents	70% PAW	80% PAW	90% PAW	100% PAW
50	57	0	50	37.5	12.5
60	14	50	50	0	0
70	29	0	37.5	25	37.5

Similar to shoulder seasons, farmers' irrigation approaches vary also in peak irrigation season (Table 4-4). During shoulder season majority of irrigators start irrigation at 50% of PAW while in peak irrigation season mostly irrigation starts before soil moisture depleted by 50% of PAW. To maintain full pasture production, there is a rule of thumb that soil moisture levels should be above 50% of PAW (United States Department of Agriculture (USDA) 1997). All the respondents reported that they

have maintained soil moisture level above 50% of PAW, indicating farmers' concern to secure full production.

Table 4-4: Irrigation starting and stopping strategies based on plant available water (PAW) during peak irrigation season

Irrigation starting point		Irrigation stopping points (% of respondents who stop irrigation at the following % of PAW)			
at % of following PAW	% of respondents	70% PAW	80% PAW	90% PAW	100% PAW
50	36	0	20	30	50
60	21	0	33	0	67
70	43	0	17	25	58

Waiting for soil moisture to drop 50% of PAW to start irrigation can be risky especially in hot weather as it may push soil moisture below stress level leading to yield losses (United States Department of Agriculture (USDA) 1997). The situation further exacerbated if irrigation system fails and crop cannot be watered. Therefore, irrigation start before soil moisture drops to 50% of PAW might be essential to address evapotranspiration uncertainty and irrigation system's reliability risk.

To make efficient use of limited water resource it is wise to utilize precipitation as effectively as possible (Ngigi et al. 2005). During shoulder seasons, the majority of farmers irrigate in a way leaving sufficient space for potential precipitation. However, during peak irrigation season, majority (57%) of farmers fill soils up to 100% PAW, leaving no space for potential precipitation. Irrigation up to 100% PAW is not justifiable, because that way farmers can't take advantage of any rain events which might occur (United States Department of Agriculture (USDA) 1997). As such, if precipitation follows the irrigation event there is a high possibility of deep percolation. This would leach nutrients away from the root zone leaving less for plant, consequently reducing crop yield and deteriorating the environment, especially water quality.

Differences in irrigation strategies among farmers are mostly attributed to farmers' lack of knowledge about proper soil moisture consideration in irrigation planning (Srinivasan & Duncan, 2011). However, in some cases differences in irrigation strategy was also related to soil types and available water. Some farms with heavier soils (clayey) had higher trigger points as their actual stress points are also higher. But, the proportion of farmers who considered different triggers based on soil types was very small (less than 10%). Likewise, about 5% of the interviewee reported that they fill soil moisture below the field capacity as their consented volume of water is not sufficient to fill soil moisture up to 100% PAW.

Irrigation efficiency and pasture production can be improved by developing irrigation scheduling based on soil moisture measurement rather than intuition (Srinivasan and Duncan 2011). However,

20% of the farms included in survey are not equipped with soil moisture sensors. By far the largest proportions of the respondents who have installed soil moisture sensor have installed Aquaflex (61%), followed by TDR probe (20%) and dig hole (19%).

During the survey, some farmers said that they start and stop irrigation based on guessing. Some farmers said that they start and stop irrigation as per their more experienced neighbours who have similar soil and crop. Srinivasan and Duncan (2011) also found that many farmers had soil moisture sensors, but were not using the data for irrigation scheduling and management as soil moisture sensors are not installed at proper location. In New Zealand dairy farms Aquaflex which is dominantly used soil moisture monitoring sensor are installed at the fence line to avoid the disturbance from animal which may not represent actual soil moisture on the paddock. ROCKPOINT (2012) indicated that in New Zealand only about 10% of the farmers consider soil moisture in their irrigation planning.

During shoulder seasons, all farmers rely on weather forecasts to make irrigation planning while, during peak irrigation season producers mostly keep irrigating regardless of weather forecast. Very few farmers (25%) said that they cease or reduce irrigation application rate, during peak irrigation seasons, only after heavy rainfall (>15mm/day). However, if daily rainfall forecast is less than 15 mm/day farmers keep irrigating as if there is no rain. Peak irrigation season is the season of peak grass production (Rickard 1968). Almost all respondents said that they do not like to take the risk of yield reduction, during peak grass production season, due to soil moisture stress. Therefore, the majority of farmers apply irrigation almost on a daily basis. During field visits, several occasions were observed when some farmers were still irrigating while it was heavily raining.

4.3.8 Grazing strategy

Cows are grazed in different paddocks on rotational basis. The grazing interval differed greatly with pasture growing seasons. The average grazing return interval was 22 days during spring and summer (September to February) and 40 days during autumn (March to April). Based on the "3-leaf" principle, different grazing intervals are proposed for different seasons under the 2- and 3-leaf stages grazing (Lee, 2011; Macdonald et al., 2010). In general, grazing scenarios reported by the farmers were within the "3-leaf" principle (Figure 4-5). Farmers are mostly grazing before 3-leaf stage. However, during spring and summer some farmers are grazing slightly before 2-leaf stage. For example 54% of the farmers reported that they are grazing before 2-leaf stage during summer, meaning that they are losing whole production from the third leaf. In other words 54% of farmers are unable to capture full production during summer.

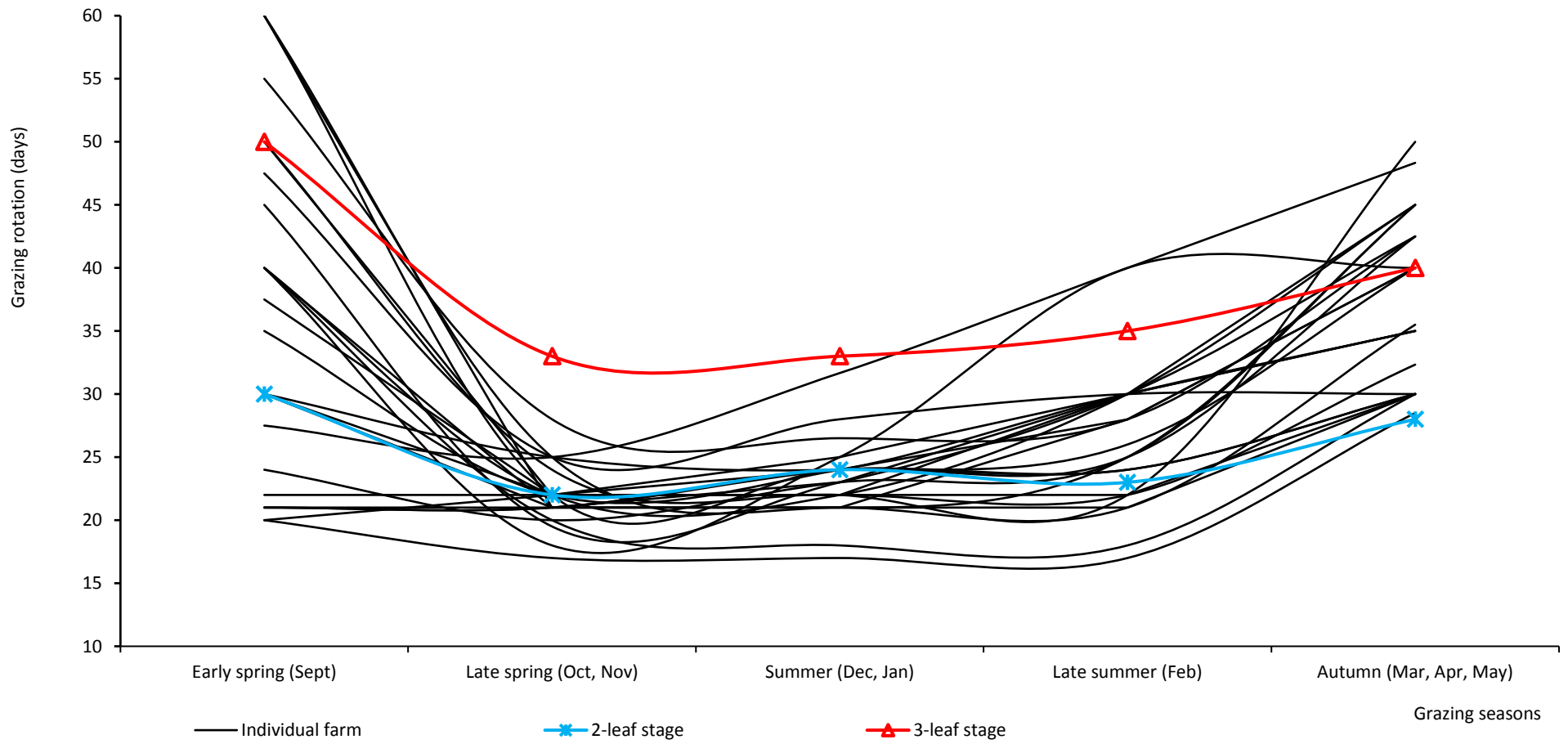


Figure 4-5: Grazing strategies adopted by surveyed farmers during different seasons in comparison with recommended scenarios

Pasture cover just before and after the grazing on the majority of farms included in the survey were comparable to the corresponding recommended ranges of 2600-3200 kg DM/ha and 1400-1600 kg DM/ha, with more than 80% of the interviewees reported to have pasture cover in this range (Table 4-5).

Table 4-5: Pre and post grazing pasture covers as reported by surveyed farmers, Sources: (Chapman, 2014; DairyNZ, 2014; Lee, 2011; Pasture Renewal Charitable Trust, 2008)

Description	Just before grazing			Just after grazing		
	lower	recommended	high	lower	recommended	high
kg DM/ha	< 2600	2600-3200	>3200	< 1400	1400-1600	>1600
% total respondents	11	89	0	0	82	18

Leaving post grazing pasture cover less than 1,400 kg DM/ha may reduce plant re-growth and leaving post grazing pasture cover higher than 1,400 kg DM/ha reduces pasture quality in subsequent rotations (Chapman, 2014; Lee, 2011). Eleven percent of surveyed farmers were grazing before grass grows to the recommended level, which does not allow the third leaf to fully grow (Chapman, 2014; Lee, 2011). Eighteen percent of the surveyed farmers were leaving higher pasture than recommended values, the quality of such pasture can be questionable. Differences in pre- and post-grazing pasture covers clearly indicate variations in crop water requirements at pre and post grazing conditions. However, all the respondents reported that they apply irrigation uniformly regardless of grazing rotation.

4.3.9 Pasture production

Historically, New Zealand dairy farmers have succeeded in improving the yield (Glasse et al., 2010). For example, annual pasture production on the average dairy farm was 4,000 kg DM/ha in 1935 (Holmes, 1989) which increased to 11,700 kg DM/ha by 2007 (Rawnsley et al., 2007). This study indicates a similar trend, with 42% of surveyed farmers producing annual dry matter (DM) at high level, and 21% of the interviewee yielding even above the high level (Table 4-6). However, still 37% respondents are producing at or below average level recommended for Canterbury.

Table 4-6: Classification of annual pasture yields as reported by surveyed farmers, Sources: (Glasse, 2007; Holmes, 2007; Macdonald et al., 2008; Rawnsley et al., 2007)

Description	Low	Average	High	Above high
kg DM/ha	<11,700	11,700 - <15,000	15,000-17,500	>17,500
% of total respondents	4	33	42	21

4.3.10 Irrigation estimates using IrriCalc

Both irrigation and deep percolation depths varied with irrigation management practices. The higher the irrigation application aimed to fill soil moisture, the higher was the deep percolation. Irrigation estimates from IrriCalc model for two irrigation management strategies, over 14 irrigation seasons (2001/02 to 2014/15) are shown in Figure 4-6. Over the 14 irrigation seasons, if the same irrigation strategy which was adopted for shoulder season which provides space for potential rainfall was applied for the whole irrigation season, it would save 13% irrigation water compared to applying two distinct irrigation scenarios for shoulder and peak irrigation season. This highlights a need for the improvement in current irrigation strategies especially adopted for peak irrigation season to account for potential rainfall.

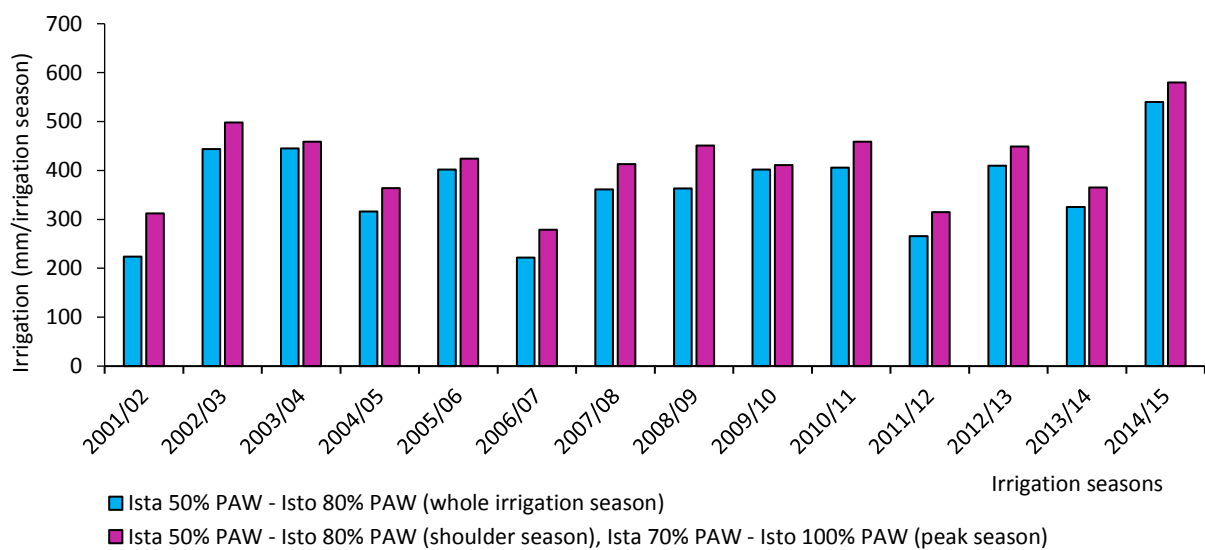


Figure 4-6: Irrigation estimates from Irricalc for 14 irrigation seasons (2001/02 to 2014/015) under two irrigation management strategies (Ista stands for irrigation starting and Ista stands for irrigation stopping points as percentages of PAW)

4.3.11 Deep percolation estimates using IrriCalc

Figure 4-7 shows IrriCalc predicted deep percolation for two irrigation management strategies during 14 irrigation seasons (2001/02 to 2014/15). Over the 14 irrigation seasons, if the same irrigation strategy which was adopted for shoulder season was applied for the whole irrigation season, it would reduce 22% deep percolation compared to applying different irrigation scenarios for shoulder and peak irrigation seasons. Over the 14 irrigation seasons current irrigation strategy would have produced 3287 mm of deep percolation, which is equivalent to an average deep percolation of 235 mm/irrigation season. Over the 14 irrigation seasons IrriCalc estimated deep percolation per irrigation season ranged between 40 and 550 mm.

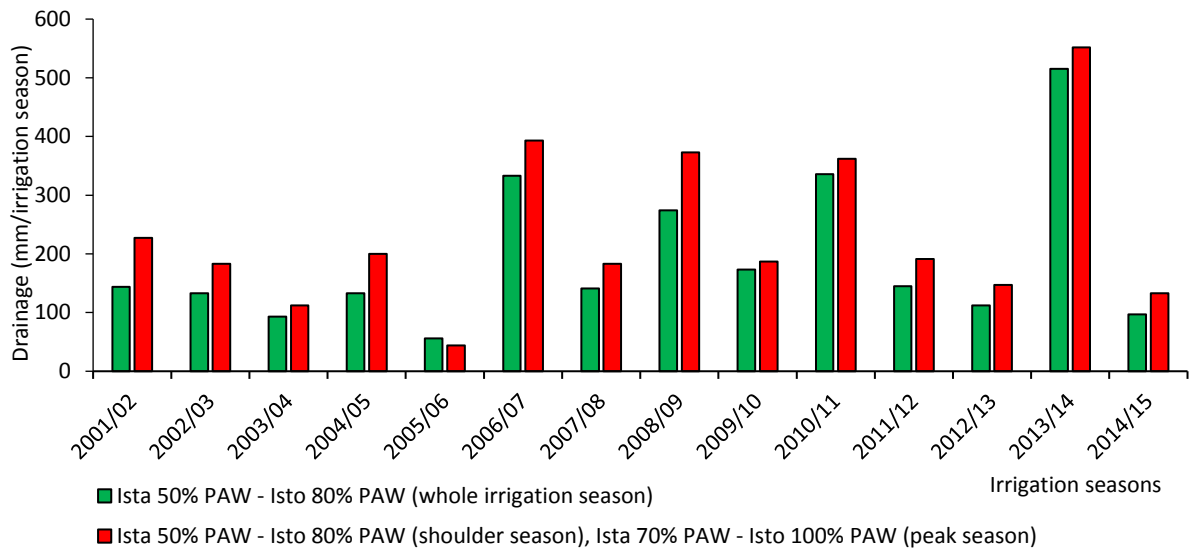


Figure 4-7: Deep percolation estimates from Irricalc for 14 irrigation seasons (2001/02 to 2014/015) under two irrigation management strategies (Ist a stands for irrigation starting and Ist o stands for irrigation stopping points as percentages of PAW)

Irrigation and deep percolation varied with irrigation management strategies and years. Yearly differences in irrigation and deep percolation were attributed to differences in annual rainfall amount and distribution. For example 2014/015 season with total rainfall 394 mm resulted in less deep percolation (44 mm) and high irrigation (580 mm). In contrary 2006/07 season with rainfall totalling 669 mm resulted in high deep percolation (393 mm) and application of less irrigation (279 mm). This confirms the need to derive an irrigation strategy which accounts for rainfall variability.

4.4 Conclusions

This survey provided insights into Canterbury, New Zealand dairy farmers’ grazing and irrigation management strategies during various seasons. All farmers measure pasture cover on their farms to decide when and where to graze cows. Farmers follow “3-leaf” stage grazing principle, maintaining pre- and post-grazing pasture cover within the recommended range of 2,600 – 3,200 kg DM /ha and 1,400 kg DM/ha, respectively. Average annual pasture production reported by two third interviewees was greater than 15,000 kg DM/ha, which is equivalent to high performing dairy farm production in New Zealand.

While most farmers recognised the need to base irrigation planning on soil moisture and climatic variability, they did not consider irrigation strategies based on long-term climatic/rainfall variability. Irrigation management strategies to keep soil moisture between field capacity and refill points are similar amongst farmers while irrigation ranges differ from farmer to farmer even within same types of soil.

During shoulder seasons (Sep-Oct and Mar-Apr) majority of farmers start irrigation at 50% PAW and stop at 80% PAW. While, during peak irrigation season (Nov-Feb) mostly irrigation is started at 70% PAW and stopped at 100% PAW without leaving any space for potential rainfall, which is risky for both yield reduction and environmental deterioration.

Over the simulated 14 irrigation seasons (2001/02 to 2014/015) if the same irrigation strategy which was adopted for shoulder season was applied for the whole irrigation season, it would save 13% irrigation water and reduce 22% deep percolation compared to applying two distinct irrigation scenarios for shoulder and peak irrigation season. Over the 14 irrigation seasons the current irrigation strategies would have produced a range of deep percolation per irrigation season between 40 and 550 mm due to variations in annual climate. This study indicates the importance of implementing the proper irrigation scheduling to reduce deep percolation losses over the long term, thus minimising the impact of farming on water quantity and quality.

Recommendations

- Identify the optimal soil moisture level to start irrigation for incorporation of evapotranspiration uncertainty to limit crop yield losses.
- Establish a clear soil moisture limit to stop irrigation to accommodate for potential precipitation in irrigation planning based on previous weather forecast to improve irrigation efficiency.

Chapter 5

Determining the Optimal Irrigation Strategy for Rotational Grazing Systems

Abstract

The threshold soil moisture content start and stop points, more commonly known as irrigation trigger points, for rotationally grazed pasture are largely remains ambiguous and imprecise. The objective of this study was to determine the irrigation range within the soil water holding capacity taking into consideration rainfall and evapotranspiration uncertainties. The experiments were conducted at the Lincoln University Dairy Farm (LUDF), Christchurch, New Zealand during the period August 2014 to March 2016. Two soil-plant-atmosphere models, IrriCalc and CropWat 8, were used to analyse the impacts of different crop coefficients (K_c) of pasture and soil moisture triggers upon the irrigation required and subsequent deep percolation losses over a long-term period. Various K_c values considered in this study included 1.0 as most commonly applied for planning pastoral irrigation in New Zealand, and variable K_c values comprising 0.6 and 1.0 corresponding to post and pre grazing conditions, as derived in this research. Under each K_c option net irrigation requirements and drainage losses were estimated for 49 irrigation strategies: irrigation starting at 50, 55, 60, 65, 70, 75 and 80% of PAW and stopping for each starting trigger at 70, 75, 80, 85, 90, 95 and 100% of PAW. Irrigation requirement for a constant K_c of 1.0 was found to be 40% more compared to when adopting variable K_c values. Therefore, conventional irrigation planning with a standard K_c of 1.0 places more abstractive pressure on the water resource, and also produces more deep percolation events leading to the environmental deterioration. The results showed a trigger point to start irrigation at 55 and 60% of plant available water (PAW), respectively on the shoulder (September to October and March to April) and peak (November to February) irrigation seasons, and stopping irrigation correspondingly at 80 and 90% of PAW were optimal for this case study. Adopting this irrigation strategy would allow for rainfall harvesting and thus, reduces net irrigation requirement and deep percolation losses. Maximising effective rainfall during the irrigation season as well as minimising deep percolation will help irrigators better balancing the growing tension between water use for agricultural production and the environment.

KEY WORDS: Plant Available Water, Irrigation, deep percolation, Crop Coefficient, IrriCalc, CropWat 8, Irrigation requirement, Rainfall Harvesting

5.1 Introduction

Applying the right amount of water at the correct time is essential to minimize deep percolation and thus, water pollution (Belaqziz et al., 2014). Especially in areas where available water is limited, proper irrigation scheduling is crucial to rectify over irrigation supply during wet period and efficient utilization of the limited water in average or dry period to ensure potential yield (Gowing & Ejieji, 2001; International Water Management Institute (IWMI), 2007). Appropriate irrigation scheduling can save water by regulating when and where to irrigate (George et al., 2000; Mannini et al., 2013). Thus, proper irrigation scheduling offers many advantages including water saving to environmental protection without yield losses (Bergez et al., 2001; Nazeer, 2009).

Knowledge of crop characteristics including crop coefficients is a key to estimate actual crop water demand (Saleem et al., 2013). Similarly, irrigation supplies without considering soil moisture and water balance in plant root zone contribute to under/over irrigation (Azaiez & Hariga, 2001; Leenhardt et al., 1998). Over-irrigation not only wastes water and nutrients but also causes waterlogging, and suffocates the plant and leads to root death (Thomas & Morini, 2005). In addition, over-irrigation leaches nutrients away from the root zone “where it is needed” which eventually will reach the groundwater and/or nearby streams.

Conversely, less irrigation compared to Crop Water Requirement (CWR) adversely affects plant growth, as it cannot meet crop evapotranspiration needs and in turn decreases crop yield and even leads to crop failure if the water stress hits in a critical stage of plant growth (Liu et al., 2006). It necessitates maintaining appropriate soil moisture levels in plants’ root zone for minimizing soil moisture related yield losses and deep percolation events.

5.1.1 Irrigation scheduling: concept, development and practices

Settled agriculture started about 10,000 years ago and farmers have been practicing controlled irrigation for over 6,000 years (Postel, 1999). However, irrigation efficiency was studied only in mid-twentieth (Israelsen, 1944). Until 1970 farmers used to supply irrigation based on fixed volume and fixed rotation regardless of climatic variations and therefore, there was no considerable improvement in irrigation scheduling practices (Jensen et al., 1970).

Irrigation scheduling was first defined by Jensen (1981). Today’s definition of irrigation scheduling still follow the basic view of Jensen (1981). Irrigation scheduling is an irrigation plan that determines the time and volume of next irrigation (Almiñana et al., 2010; Howell & Meron, 2007; Saleem et al., 2013).

Around two decades ago Howell (1996) felt lack of comprehensive irrigation scheduling that addresses changing weather and crop water demands. One decade ago Callan et al. (2004) recognised the same issue of irrigation scheduling. There has been an increasing awareness to vary the amount of water applied based on crop demands and soil moisture variability (Hedley & Yule, 2009). However, despite having several ways to measure soil-water-plant-atmosphere parameters, there is still a lack of irrigation scheduling that accounts for precipitation and evapotranspiration uncertainties which greatly impacts on net irrigation requirement (Belaqziz et al., 2014).

Irrigation strategies adopted by a majority of Canterbury, New Zealand dairy farmers for pasture production are insufficient to address grazing rotations and weather uncertainty (for more detail refer to Chapter 4). Nutrients leaching through deep percolation and surface runoff is probably the biggest environmental issue for irrigated farming in New Zealand (Cameron et al., 2012).

Site specific data including rainfall, evapotranspiration, soil water holding capacity and root depth are essential to produce correct irrigation scheduling (DeJonge et al., 2007; Hedley & Yule, 2009; Humphreys et al., 2008). The greater the rainfall used to meet crop water demand, the higher the irrigation efficiency (Snow et al., 2007), and the lesser the deep percolation (Rawnsley et al., 2009) and nutrient leaching (Moir et al., 2007). When deep percolation losses were reduced by about 4 times (from 135 to 34 mm/year) the nutrient leaching reduced nearly by 6 times (from 55 to 10 kg N ha⁻¹ yr⁻¹) (Moir et al., 2007). This implies nutrient leaching can be reduced significantly by minimizing deep percolation losses. It calls for investigating optimal irrigation strategy to match actual crop water needs by considering correct crop coefficient, soil moisture and water balance in plant root zone to capture potential rainfall thereby, reduce irrigation requirement and deep percolation losses.

5.1.2 Irrigation scheduling considering soil moisture limits

In order to develop proper irrigation management strategies, various researchers such as Gheysari et al. (2009); Rawnsley et al. (2009); Snow et al. (2007); Wheeler and Bright (2015) have studied the impact of irrigation variability on deep percolation events. Rawnsley et al. (2009) conducted an experiment during seven months period for examining the effect of different irrigation management strategies on deep percolation. He studied five irrigation strategies: irrigation applied up to 100, 80, 60, 40 and 0% of the rainfall deficit (potential evapotranspiration minus rainfall), at which respective deep percolation was calculated as 182, 116, 92, 68, and 21 mm. This indicated the greater the rainfall is used to meet crop water demand, the lesser the lost through deep percolation.

Snow et al. (2007) tested impacts of two different irrigation schedules on deep percolation development. In the first schedule, irrigation was applied in 7 days interval to fill up to the field capacity. In the second schedule, irrigation was applied in 21 days interval with the same volume of

irrigation as applied in the first schedule. The result indicated that irrigation variability impacts greatly on deep percolation development. This implies irrigation water can be saved by controlling irrigation applications more accurately.

However, there have been very few studies that estimate irrigation and deep percolation under a range of irrigation management strategies and crop coefficients using long term climatic data to account for climatic variability. Trigger points to start and stop irrigation for rotationally grazing systems are not well addressed.

The objective of this research was to determine the optimal irrigation trigger points for a given soil's water holding capacity taking into consideration seasonal variations in rainfall and evapotranspiration, and accounting for actual pasture water requirement under a grazing rotation. The adoption of an optimal irrigation strategy will make an important contribution towards improving irrigation scheduling and agricultural water management for rotational grazing systems in New Zealand and around the world. In addition, it would also decrease water pollution by reducing nutrient leaching from pastoral farms to water resources.

5.2 Material and Methods

5.2.1 Site description

It is the same site which has been detailed in section 2.2.1, Chapter 2

5.2.2 Data collection

Crop data were obtained based on field experiments (Chapter 2 & 3). Soil data were collected based on field experiments, S-map fact sheets and South Island Dairy Development Centre's (SIDDC) website. S-map provides detailed information about predominant soil and its attribute in New Zealand. SIDDC's website contains background information about the study area. To account for climatic variability a daily time series of climatic data available for 16 years during the period 2000 – 2015 was collected from Broadfield weather station (data source, NIWA; 43°35'53", 172°28'12" and altitude of 18 m).

5.2.3 Irrigation and Deep percolation estimates using Irricalc and Cropwat 8

An overabundant amount of software tools and technologies for irrigation scheduling have been developed in the last 30 years (Inman-Bamber et al., 2005; Mannini et al., 2013). Researchers such as Fessehazion (2011) has advised the use of a tool which is locally known by farmers instead of introducing another new tool. IrriCalc (also called Aqualinc's Irrigation Calculator), a daily water balance model developed by Aqualinc Research Ltd, New Zealand, was used in this research. IrriCalc

is well known by New Zealand dairy farmers. Detailed information about IrriCalc is described in section 4.2.2, Chapter 4.

The two key parameters used by IrriCalc that vary spatially are the PAW and K_c (Bright, 2009). IrriCalc has been tested and validated using lysimeter data installed in a number of pastoral farms in Canterbury, including Camden Farm (224 ha) in Dunsandel, which is representative of irrigated pastoral farms in the region (Bright, 2009). The distance between Camden Farm and LUDF is 25 km and both have similar climates and soils resulting in a similar pasture growth dynamics. Van Housen (2015) tested the accuracy of irrigation demand and deep percolation depths determined using a soil water balance model (equivalent to IrriCalc) with an average K_c determined from nine lysimeter datasets located at three sites across the Canterbury Plains (i.e. very different climates and soils) and found that modelled results were within 10% of measured deep percolation. In addition, IrriCalc has been set up for Canterbury conditions and therefore the model can be used to predict irrigation demand and deep percolation depth without further validation.

Models based on local calibrations can have limited global validity (Allen et al., 1998). Therefore, CropWat 8 which is one of the globally used irrigation planning tool, was also used in this research. Primarily all calculation procedures used in both models are based on the FAO guidelines as described in the publication No 56. However, in daily water balance calculation, the two models account for rainfall differently. CropWat 8 has three options to input rain data: daily, 10-days, and monthly. If daily rainfall data are supplied, CropWat 8 first totals 10-days rainfall values and generates equal rain events on 3rd and 7th day of the 10-day periods. If 10-days rainfall data is applied the model directly generates equal rain events on 3rd and 7th day of the 10-day periods.

If monthly rain data are adopted, CropWat 8 first divides monthly rain data equally into three 10-days periods, and to reproduce the non-continuous distribution of rainfall events, 10-days total rainfall values are equally divided to generate rain events on 3rd and 7th day of each of the 10-day periods. Unlike CropWat 8, IrriCalc requires daily rainfall data and uses the input data as it was supplied without any modification. In addition, IrriCalc requires daily time series of crop coefficient values for one year period while, CropWat 8 uses crop coefficient values for four different growing stages.

Like IrriCalc, CropWat 8 follows the same procedure for modelling irrigation and deep percolation (detailed in section 4.2.2, Chapter 4). To enable the comparison similar soil and crop data sets and irrigation management rules were adopted for both models. A pasture root depth of 500 mm as per field observation was used. PAW at 28% volume and readily available water (RAW) at 14% volume were used for the calculation as estimated for the experimental plot. Irrigation and deep percolation were estimated separately for shoulder and peak irrigation seasons based on two K_c alternatives:

variable K_c values comprising 0.6 and 1.0 correspondingly for post and pre grazing conditions as derived in this research (Chapter 3) and the most commonly used constant value of 1.0. Under each K_c option 49 irrigation strategies were adopted: irrigation starts at 50, 55, 60, 65, 70, 75 and 80% of PAW and stops for each starting trigger, at 70, 75, 80, 85, 90, 95 and 100% of PAW correspondingly. Estimated irrigation and deep percolation values were analysed to investigate the optimal irrigation range for rotational grazing pasture.

5.3 Results and Discussions

5.3.1 Rainfall and evapotranspiration

Average monthly reference evapotranspiration (ET_r) and precipitation (P) recorded at Broadfield weather station over the 16-year period (2000 to 2015) indicate the need for irrigation as ET_r usually exceeds P during spring, summer and autumn (September to May), see Figure 5-1. Total ET_r estimated for the period 2000 to 2015 was 15030 mm which is 1.5 times more than total rainfall occurrence of 9745 mm over the same time period. Maximum daily ET_r over the 16 years period was 7 mm during shoulder season and 10 mm during peak irrigation season, while maximum daily rainfall was 48 mm during shoulder and 74 mm during peak irrigation season. This indicates, several occurrences of daily rainfall were greater than ET_r , suggesting a need for flexible irrigation strategies to capture maximum rain water for storage in the root zone and thus reducing deep percolation losses.

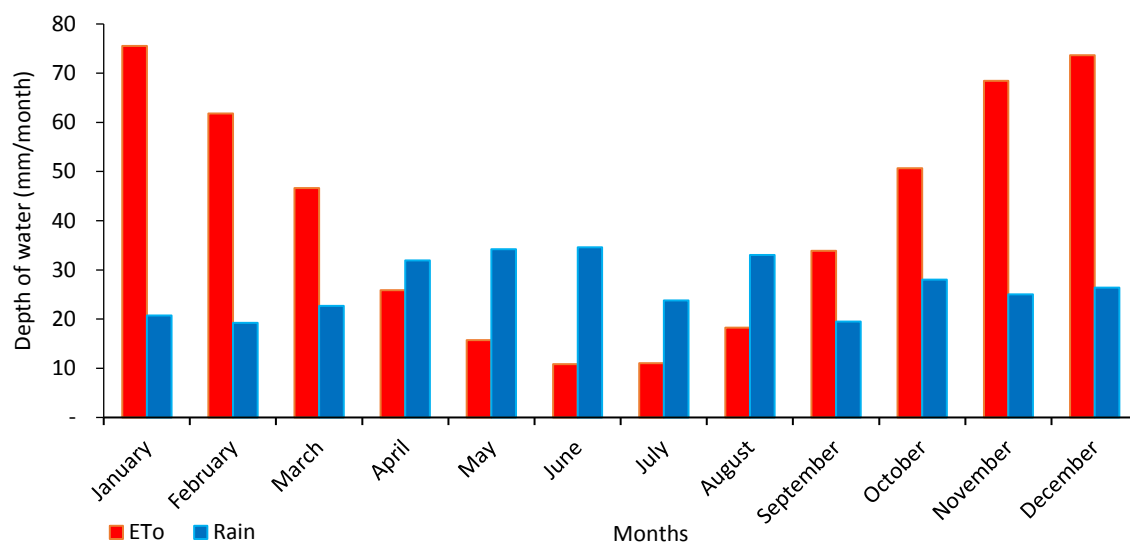


Figure 5-1: Average monthly reference evapotranspiration and rainfall based on 16 years' data (2000 to 2015) recorded at Broadfield weather station

Irrigation planning should ensure double targets: (1) leave enough space in the root zone to store potential rain; and (2) maintain soil moisture above critical depletion to avoid moisture stress which

can cause yield loss. In dry soils, plants require more effort, and in turn are under more stress, to absorb water from the root zone, while in wet soils plants can extract water without any stress (Food and Agriculture Organization (FAO), 1998). If soil moisture falls below a certain threshold level called critical level, the plant experiences water stress which adversely affects plant growth and in turn crop yield. So, irrigation should be applied whenever soil water level reaches the critical limit to optimize yield (Food and Agriculture Organization (FAO), 1998).

If rain is predicted, it will be desirable not to fill the soil profile to field capacity but leave some room to utilize the forecasted rainfall (Broner, 2005). If irrigation is applied to fill soil profile up to field capacity without leaving any space for future rainfall, we may lose not only precious water resources but also a proportion of investment made for fertilizer through surface runoff and deep percolation. In addition, surface runoff and deep percolation are expected to pollute our water resources through their high level of nutrients. However, if no rain is expected it may be wise to refill the soil profile to field capacity to extend irrigation interval which may reduce the cost for irrigation.

5.3.2 Irrigation estimates

Figure 5-2 compares the average annual irrigation estimates from IrriCalc under the two K_c alternatives and 49 irrigation scenarios. Over the 14 irrigation seasons (2001/02 to 2014/015) irrigation requirement for a constant K_c of 1.0 was “on average” 40% higher compared to varying K_c values that range from 0.6 to 1.0 respectively from post to pre-grazing conditions.

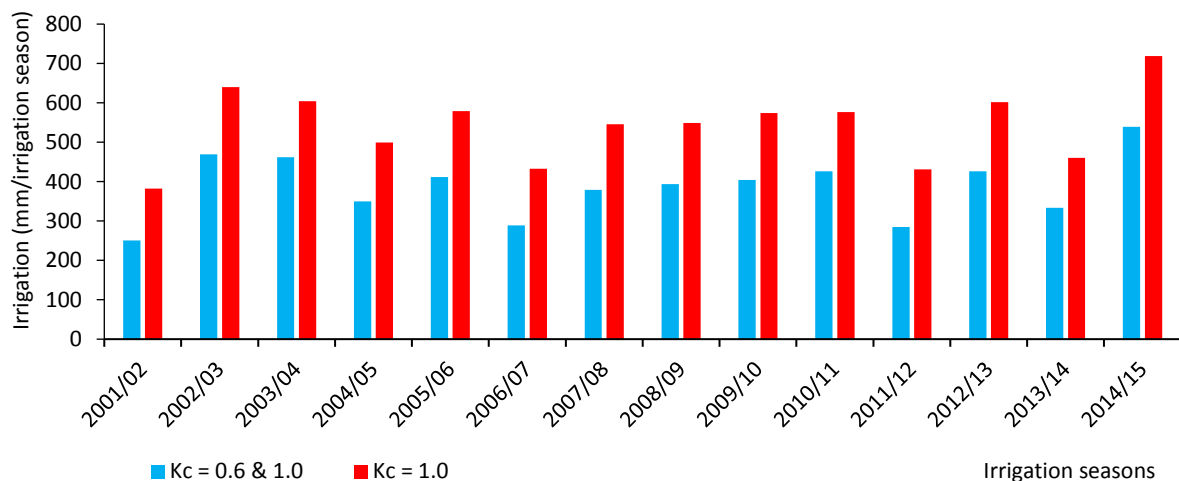


Figure 5-2: Average irrigation estimates from IrriCalc for 14 irrigation seasons (2001/02 to 2014/015) under 49 irrigation management strategies and two crop coefficient values: (a) when applying variable K_c values comprising 0.6 and 1.0 respectively for post and pre grazing conditions, (b) when applying a constant $K_c = 1.0$

For the detailed analysis variable crop coefficient values comprising 0.6 and 1.0 respectively for post and pre grazing conditions and seven irrigation strategies were considered: irrigation starting at 50, 55, 60, 65, 70, 75 and 80% of PAW and stopping correspondingly at 70, 75, 80, 85, 90, 95 and 100% of PAW. Irrigation requirement was estimated separately for shoulder and peak irrigation season. This test was undertaken to investigate net irrigation requirements when irrigation aimed to fill the same soil moisture depth at different triggers.

Annual irrigation estimates varied significantly with adopted irrigation management strategies. In general, irrigation estimates for both peak and shoulder irrigation seasons showed similar trends with the higher the PAW based irrigation trigger points, the higher irrigation requirements. Figure 5-3 shows the combined irrigation estimates for both peak and shoulder irrigation period over 14 irrigation seasons. Compared to the first (irrigation starts at 50% of PAW and stops at 70% of PAW), the last irrigation strategy (irrigation starts at 80% of PAW and stops at 100% of PAW) consistently produces significantly higher annual irrigation volume (or depth) which differs greatly from year to year. For example, during 2006/07 season, irrigation requirement under the last irrigation strategy was 100% more than the first, during 2014/015 it was higher only by 19%.

There was no specific link of wet and dry years with differences in irrigation requirement under a different irrigation strategy. For example, rainfall during two irrigation seasons 2001/02 (650 mm) and 2005/06 (645 mm) were similar. However, during 2001/02 irrigation requirement under last irrigation strategy was 106% more than the first, during 2005/06 it was higher only by 33%. Rather than total rainfall amount during irrigation season, patterns of individual rain events would have impacted on irrigation estimation. For example, any rainfall event that occurs before soil moisture drops to irrigation trigger levels minimises the irrigation requirement. However, if rainfall follows irrigation events, it will have no impact on irrigation estimation, especially if irrigation fills 100% of PAW. In general, irrigation requirements increase significantly when irrigation replenished the soil moisture above 80 and 90% of PAW, respectively during shoulder and peak irrigation season.

Irrigation requirement was also estimated using CropWat 8 model to compare with IrriCalc results. To enable comparison between irrigation estimates from two models, the same crop coefficient value of 1.0 and seven irrigation strategies: irrigation starting at 50, 55, 60, 65, 70, 75 and 80% of PAW and stopping correspondingly at 70, 75, 80, 85, 90, 95 and 100% of PAW, were applied. As can be seen in Figure 5 4, total irrigation estimates for 14 irrigation seasons by both models demonstrate similar trend, with the higher the PAW based irrigation trigger points, the higher irrigation requirements.

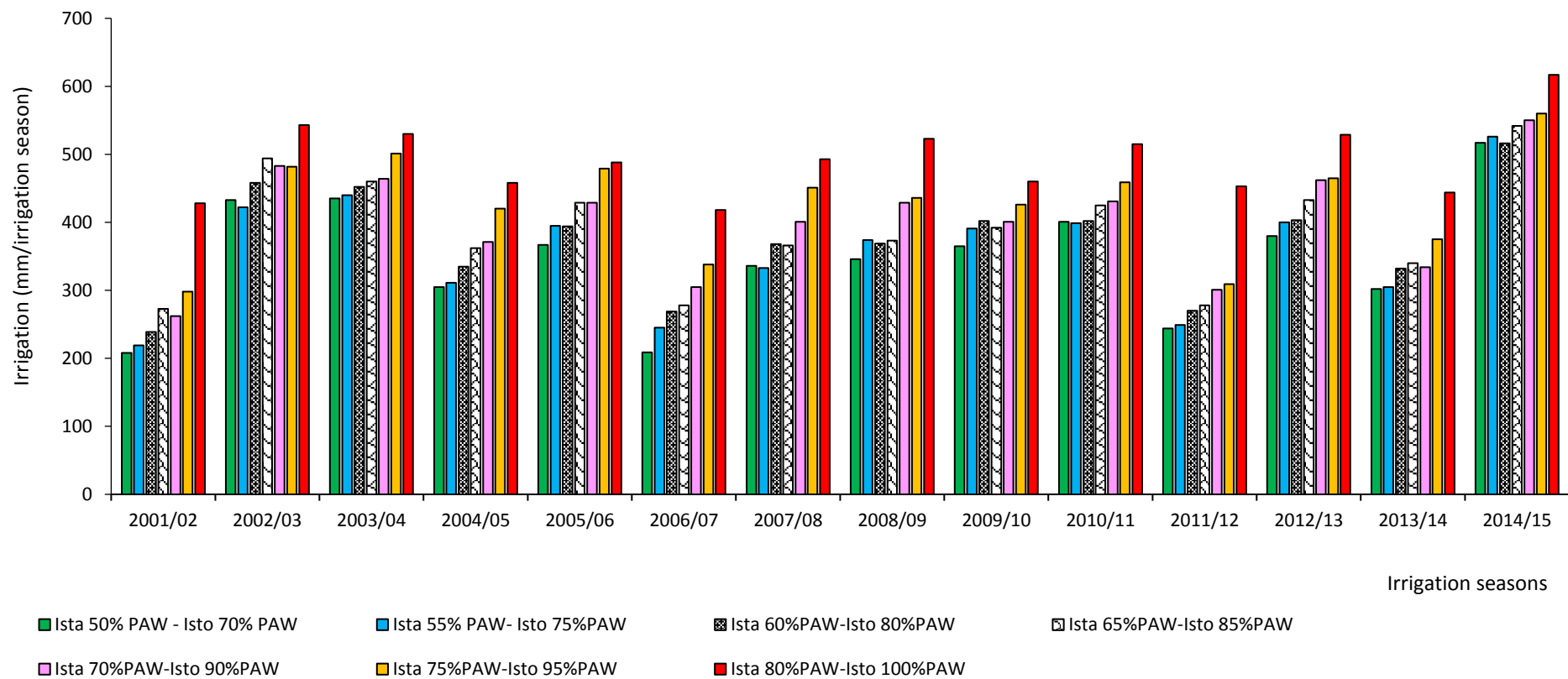


Figure 5-3: Irrigation estimates from IrriCalc over 14 irrigation seasons (2001/02 to 2014/015) under different seven irrigation management strategies (Ista stands for irrigation starting and Isto stands for irrigation stopping points as percentages of PAW)

IrriCalc predicted irrigation was 24% lower for first irrigation strategy (irrigation starts at 50% of PAW and stops at 70% of PAW) compared to the last (irrigation starts at 80% of PAW and stops at 100% of PAW). Similarly, CropWat 8 predicted irrigation was 13% lower for first irrigation strategy compared to the last. For first five irrigation strategies, CropWat 8 predicted around 7% more irrigation than IrriCalc. In contrary, for the last irrigation strategy (Irrigation starts at 80% PAW and stops at 100% PAW) IrriCalc predicted 7% more irrigation than CropWat 8. This variation in irrigation estimate might be attributed to the differences in rainfall modelling methodology by the two models (for more detail see section 5.2.3).

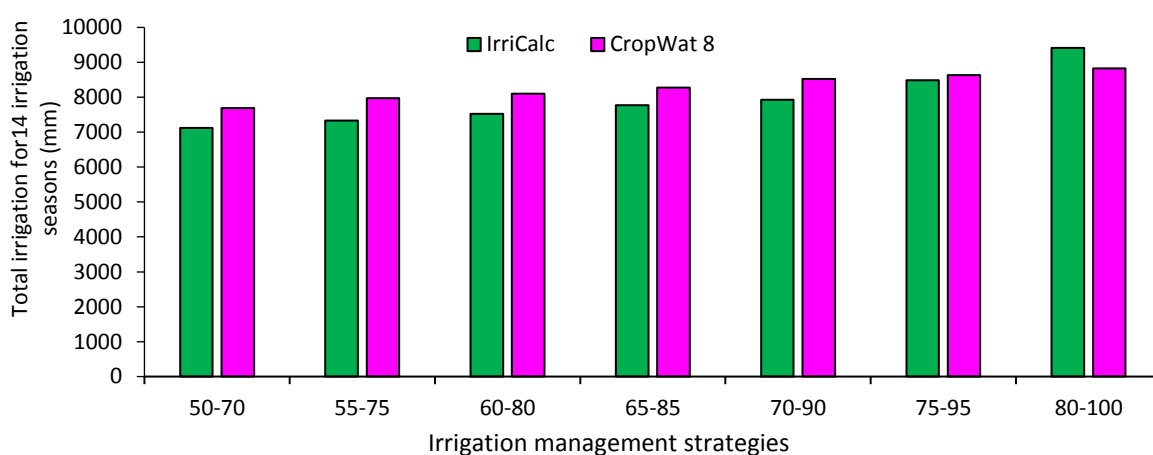


Figure 5-4: Total irrigation estimates from IrriCalc and CropWat 8 for 14 irrigation seasons (2001/02 to 2014/015) under different seven irrigation management strategies (50-70 stands for irrigation starting at 50% of PAW and stopping at 70% of PAW and so on)

Irrigation estimates varied significantly with adopted irrigation management strategies and crop coefficient values but not greatly with models. Both models indicated that irrigation with constant crop coefficient of 1.0 would produce over-irrigation.

5.3.3 Deep percolation estimates

Similar to irrigation estimates, deep percolation was also estimated using IrriCalc, separately for peak and shoulder irrigation seasons based on the variable K_c values comprising 0.6 and 1.0 for post and pre-grazing conditions, respectively, and for the above mentioned 49 irrigation strategies. For the detailed analysis, seven irrigation strategies were considered: irrigation starting at 50, 55, 60, 65, 70, 75 and 80% of PAW and stopping correspondingly at 70, 75, 80, 85, 90, 95 and 100% of PAW. The main objective of this test was to investigate the impact of applying the same depth of water, at different triggers, on deep percolation events.

Like irrigation estimates, deep percolation prediction also varied significantly with the adopted irrigation management strategies. Deep percolation predictions for both peak and shoulder irrigation seasons demonstrated similar trends with the higher the PAW based irrigation trigger points, the higher the deep percolation. Figure 5-5 shows the combined deep percolation estimates for peak and shoulder irrigation period over 14 irrigation seasons.

Compared to the first (irrigation starts at 50% of PAW and stops at 70% of PAW), the last irrigation strategy (irrigation starts at 80% of PAW and stops at 100% of PAW) produced up to 350% more deep percolation which differs from year to year. Yearly differences in deep percolation estimation are attributed to differences in annual rainfall amount and their distribution. For example, during 2014/015 season, total rainfall was 394 mm which produced less deep percolation than during 2013/014 season with rainfall totalling 738 mm. In general, deep percolation estimates increased significantly when irrigation filled more than 80 and 90% of PAW, respectively during shoulder and peak irrigation season.

Deep percolation was also estimated using CropWat 8 model and compared with IrriCalc results. To enable comparison between deep percolation estimates from two models, the same crop coefficient value of 1.0 and seven irrigation strategies were applied: irrigation starting at 50, 55, 60, 65, 70, 75 and 80% of PAW and stopping correspondingly at 70, 75, 80, 85, 90, 95 and 100% of PAW.

Figure 5 6 presents the results of IrriCalc and CropWat 8 predicted deep percolation over 14 irrigation seasons. Both models reflected the impacts of adopted irrigation management scenarios on deep percolation. As can be seen, the higher the PAW based irrigation triggers, the higher is the deep percolation depth. In general, there are no significant differences in deep percolation estimates by the two models.

However, deep percolation estimates from CropWat 8 is slightly higher for the first five irrigation strategies, which is understandable as under those irrigation strategies CropWat 8 predicted higher irrigation than IrriCalc. While for the last irrigation strategies (Irrigation starts at 80% PAW and stops at 100% PAW), deep percolation estimates from IrriCalc is higher as IrriCalc predicted irrigation was also higher under that strategies. For both models over-irrigation resulted in increased deep percolation. In other words, whenever models predicted higher irrigation they also predicted higher deep percolation.

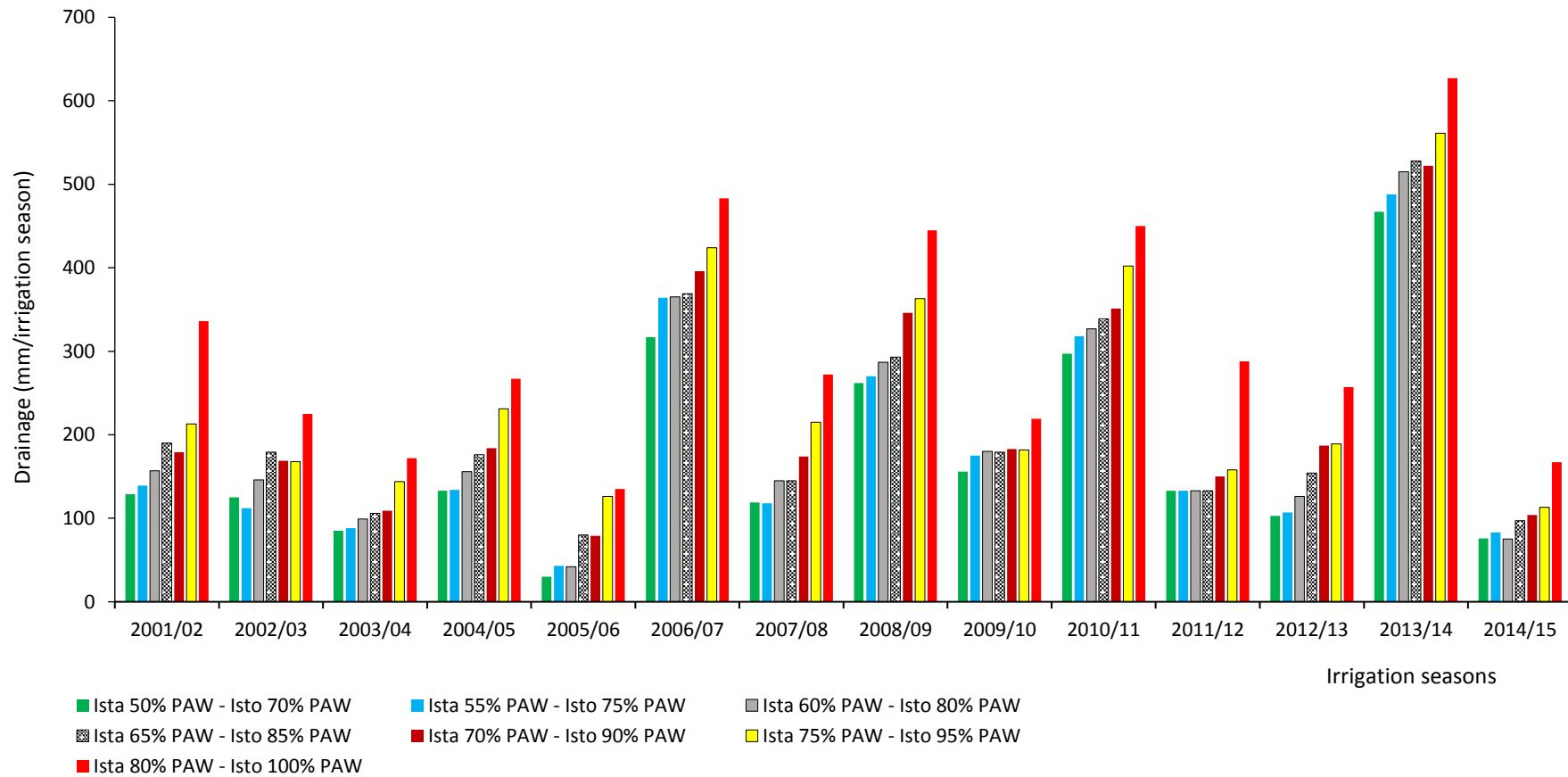


Figure 5-5: Deep percolation estimates from IrriCalc over 14 irrigation seasons (2001/02 to 2014/015) under different seven irrigation management strategies (Ista stands for irrigation starting and Isto stands for irrigation stopping points as percentages of PAW)

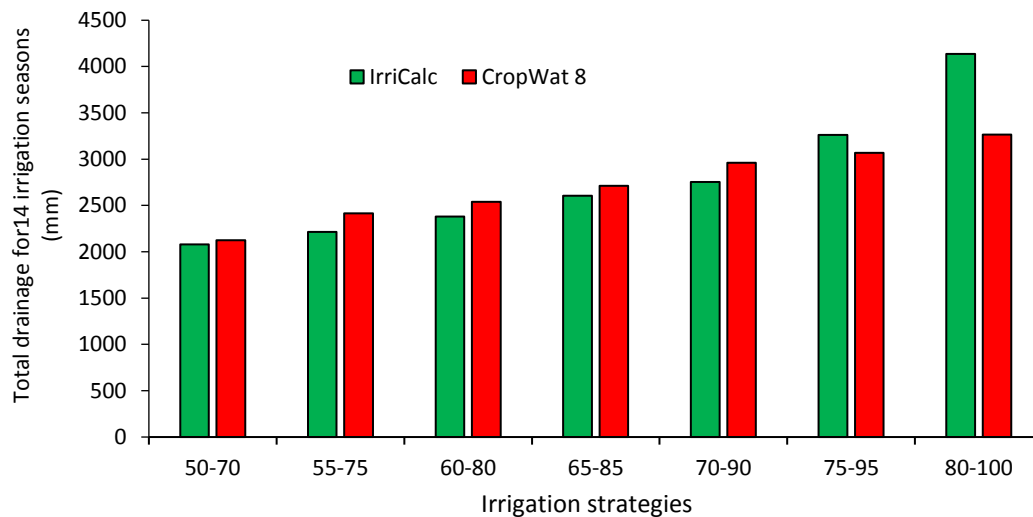


Figure 5-6: Total deep percolation estimates from IrriCalc and CropWat 8 for 14 irrigation seasons (2001/02 to 2014/015) under different seven irrigation management strategies (50-70 stands for irrigation starts at 50% of PAW and stops at 70% of PAW and so on)

5.3.4 Minimizing Irrigation and Deep percolation

Effective rainfall were higher when PAW based irrigation triggers were lower. Rain efficiency implies the percentage of total rainfall that is stored in plant root zone. The higher the rain efficiency, the lesser the net irrigation requirement and consequently deep percolation loss is minimum.

Over the whole 14 irrigation seasons, the first irrigation strategy: irrigation starts at 50% of PAW and refills soil up to 70% of PAW, produced the lowest deep percolation depths of 2432 mm, equivalent to 174 mm per year, see Table 5-1. While, over the same time span, the last irrigation strategy: irrigation starts at 80% of PAW and filling soil up to 100% of PAW, produced 4343 mm of deep percolation resulting in an annual average deep percolation depth of 310 mm. Compared to the former, later irrigation strategy, which does not allow any room for the storage of the potential rainfall, will use 1.4 times more irrigation water and will result in nearly double the deep percolation. This indicates a substantial deep percolation reduction and water saving by regulating irrigation strategies.

For several cases rainfall during the whole season was more than actual crop water needs, which resulted in unavoidable deep percolation. Even in the first irrigation strategy (irrigation starts at 50% of PAW and refills soil up to 70% of PAW), which allows sufficient space for potential rainfall, on average 20% of the total rain was lost through deep percolation. In fact, it is not possible to irrigate farms without some water losses due to deep percolation (Kitani, 1999). However, deep percolation events could be minimized by maximizing effective rainfall by implementing the proper irrigation strategy.

Table 5-1: IrriCalc predicted total irrigation and deep percolation over 14 irrigation seasons (2001/02 to 2014/15) under different irrigation management strategies

Irrigation starting as % PAW	Irrigation stopping as % PAW	Total irrigation (mm)	Total deep percolation (mm)	% more irrigation compared to previous strategy	% more deep percolation compared to previous strategy
50	70	4848	2432		
55	75	5009	2572	3%	6%
60	80	5209	2753	4%	7%
65	85	5445	2968	5%	8%
70	90	5623	3133	3%	6%
75	95	5999	3489	7%	11%
80	100	6899	4343	15%	24%

5.3.5 Optimal irrigation range

Irrigation and deep percolation estimates from IrriCalc and CropWat 8 indicated that irrigation applications that fill soil moisture above 80 and 90% of PAW, respectively during shoulder and peak irrigation season create significantly high deep percolation. Irrigation start at 50% PAW cannot address evapotranspiration uncertainty that may push soil moisture below management allowable deficit and reduce potential yield.

Analysis of the available data over 16 years of record showed the maximum daily potential evapotranspiration (PET) of 7 and 14 mm, respectively during shoulder and peak irrigation seasons. Irrigation applications at 55 and 57% of PAW, during shoulder and peak irrigation season respectively, would provide a buffer for the maximum daily potential evapotranspiration (PET) of 7 and 10 mm. However, from a practical aspect, irrigation start at 60% of PAW during peak irrigation season will be more applicable, as farmers mostly regulate irrigation at 5% increments in PAW. Thus, minimum soil moisture limit to start irrigation at 55 and 60% of PAW, respectively for shoulder and peak irrigation seasons and maximum soil moisture limit to stop irrigation correspondingly at 80 and 90% of PAW can address both precipitation and evapotranspiration uncertainty.

Irrigation that fills soil moisture to 90% of PAW allows for 14 mm rainfall harvesting that is equivalent to almost three days irrigation saving under centre pivot irrigation which applies 5 mm of irrigation in one day. Similarly, irrigation that fills soil moisture to 80% of PAW provides space for 28 mm rainfall which is equivalent to nearly six days irrigation saving under centre pivot irrigation. Maintaining irrigation within the specified range, as shown in Figure 5-7, can allow for the mitigation of both environmental risk, caused by deep percolation, and the production risk caused by soil moisture stress. In addition, specified irrigation range would also address reliability risk associated with the operation of the irrigation system itself.

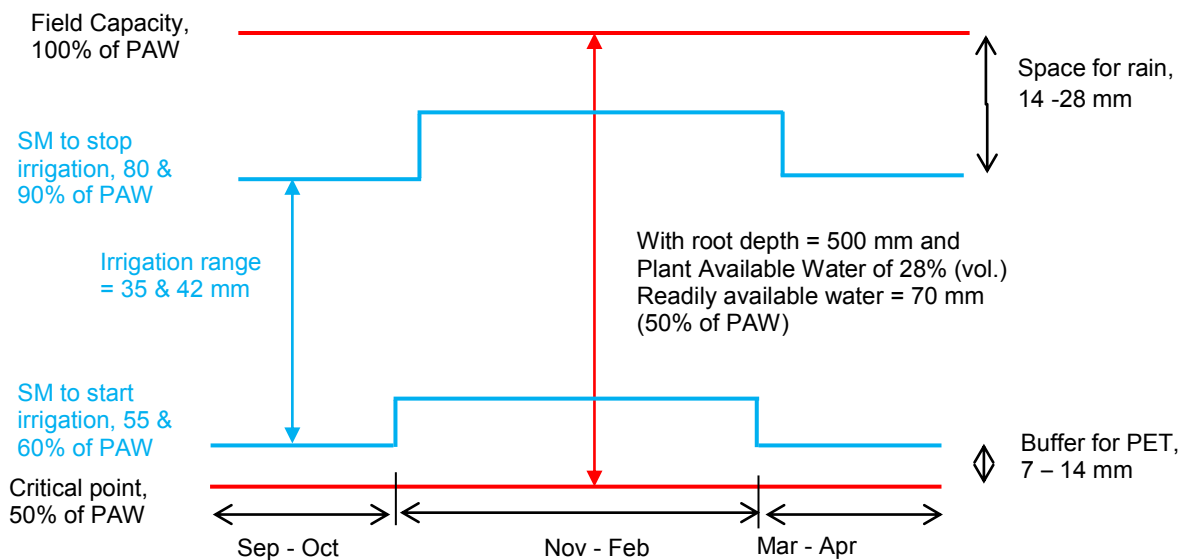


Figure 5-7: Optimal irrigation range for rotational grazing systems based on LUDF field experiments

IrricCalc results showed that over 14 irrigation seasons proposed optimal irrigation range for this case study would reduce 8% deep percolation compared to when irrigation starts at critical point and fills soil up to the field capacity. Likewise, proposed optimal irrigation range would reduce 12% deep percolation compared to the commonly applied irrigation strategy in New Zealand dairy farms (irrigation starts at 50% of PAW and stops at 80% of PAW during shoulder season and irrigation starts at 70% of PAW and stops at 100% of PAW during peak irrigation season).

The research is applicable to other climatic regions and soil types, however further scenario specific modelling would be required to determine the actual trigger points to start and stop irrigation for those. Undertaking this exercise for areas with higher incidence of summer rainfall would likely be extremely beneficial, as this will help better manage deep percolation losses. In comparison, there is little benefit in undertaking this exercise for soils of low PAW as the change in trigger point (in terms of soil moisture content) is relatively small. The irrigation system design parameters also need to be considered, both the return period and the design capacity as these could also affect the trigger points.

5.4 Conclusions

Irrigation estimates for 14 irrigation seasons under a constant K_c of 1.0, the widely applied approach in New Zealand, were 40% more than when adopting variable K_c values comprising 0.6 and 1.0, respectively for post and pre-grazing conditions. Thus, irrigation planning with a standard K_c of 1.0 places more abstractive pressure on the water resource and potentially deteriorates water quality through a greater number of deep percolation events. The results demonstrated that optimal minimum soil moisture levels to start irrigation are 55 and 60% of PAW, respectively for shoulder and peak irrigation season and maximum soil moisture levels to stop irrigation are correspondingly at 80

and 90% of PAW. Using these trigger points would improve performance in terms of maximum rain water use and thus, reduce non-profitable deep percolation losses and net irrigation requirement. Irrigation start at 55 and 60% of PAW, respectively during shoulder and peak irrigation seasons, provides buffer to address evapotranspiration uncertainty, thereby minimising soil moisture stress induced yield reduction. Irrigation application that fill soil moisture to 80 and 90% of PAW, respectively during shoulder and peak irrigation season provides storage for potential rainfall and in turn reduces irrigation requirements and deep percolation events. Application of variable crop coefficient values comprising 0.6 and 1.0, respectively for post and pre-grazing conditions and proposed optimal irrigation ranges can serve as useful guidelines to design irrigation planning for rotational grazing systems. Such irrigation methods can contribute to conserve water and the environment by reducing irrigation requirements and deep percolation events without production losses.

Chapter 6

Overall Conclusions

Expanding dairy farming around the world including New Zealand is creating ever increasing pressure on already stressed water resources, causing adverse impacts on the environment, especially on water quality and demanding further research to improve irrigation efficiency. The whole community, ranging from farmers and concerning agencies to scientific societies are keen to explore the options for improving irrigation efficiency and environmental integrity. Conceptual framework developed for this study that highlights a need to account for crop coefficient, soil moisture and water balance in irrigation planning demonstrated promising outcomes in terms of irrigation water saving. After the analysis of the results the study revealed the following specific conclusions:

1- New derived crop coefficients based on grazing rotation contribute to irrigation efficiency improvement

A new relationship between K_c and h , which is correlated to the grazing rotation, has been developed. This $K_c - h$ relationship can serve as a useful tool to develop a crop coefficient time series for different grazing rotations for estimating actual crop water requirement under grazing conditions. Irrigation scheduling that incorporates proper K_c can potentially conserve water and, therefore, reduce leaching of nutrients without yield loss.

2- Spatial and temporal variability of deep percolation measurement varies significantly across the farm

Deep percolation losses through the studied 20 lysimeters indicated great variations with lysimeters, seasons and years. Compared to first block of 10 lysimeters installed within silty loam soils, second block of 10 lysimeters within sandy loam soils produced significantly higher deep percolation. Variations in deep percolation measurements through the two blocks of lysimeters were attributed to differences in soil types beside the lysimeters that affect water holding capacity of soils. Seasonal and annual variations in deep percolation measurements were linked to the amount of rain plus irrigation received by the lysimeters. The higher the total water received by the lysimeters, the higher was the deep percolation losses through the lysimeters. However, variations in deep percolation measurements from the adjoining lysimeters installed just 1m apart was also quite high, which stresses the conclusion of the high variability of soil response across a farm.

3- Strategic placement of soil moisture monitoring sites is essential to improve irrigation planning

Soil moisture measurements varied significantly with space and time. Highly varied soil moisture measurements across the paddocks meant complexity in irrigation planning based on soil moisture monitoring. Aquaflex and lysimeters, which were utilized to derive a relationship between K_c and h , are located 125 m apart within different soils. Disparity in soil texture beside Aquaflex and lysimeters was clearly reflected in soil moisture measurement. When Aquaflex soil moistures were used in the water budget equations for the lysimeters' data, the coefficient of determination R^2 for the $K_c - h$ relationship was 0.43, which was raised to 0.66 when adjusted Aquaflex soil moisture values, based on TDR measurements, were adopted. Hence, the conclusion is strategic placement of sensor for irrigation planning is essential.

4- Current irrigation strategies adopted by majority of Canterbury dairy farmers are insufficient to address grazing rotation and weather uncertainties

Pastoral survey conducted with Canterbury dairy farmers revealed that the majority of dairy farmers grazed their pasture based on the recommended "3-leaf" theory. The survey also indicated that pasture cover just before and after grazing were comparable to the recommended values in the literatures. Average annual pasture productions, as reported by majority of farmers, were approximately equivalent to the maximum achievable for Canterbury.

However, irrigation strategies adopted for different seasons were insufficient to address the issue of water quantity and quality. Due to rotational grazing system, pasture canopy varies significantly across the paddocks, but farmers apply irrigation uniformly regardless of grazing rotations. During shoulder seasons (September – October and March – May) irrigation replenishes soil leaving sufficient room for potential rain. However, during peak irrigation season (November-February), the majority of farmers fill soil up to or close to its Field Capacity (FC) which is prone to produce significant deep percolation when rainfall follows the irrigation events. As irrigation strategies obtained from the survey were representative of all dairy farms across Canterbury, it is likely that high deep percolation, and therefore low irrigation efficiency is common.

5- The optimum minimum soil moisture level to start irrigation are 55 and 60% of PAW, respectively for shoulder and peak irrigation season and maximum soil moisture levels to stop irrigation are correspondingly at 80 and 90% of PAW.

Two soil-plant-atmosphere models IrriCalc and CropWat 8 were used to estimate irrigation and deep percolation for a range of irrigation management strategies and crop coefficient values. Results indicated that net irrigation requirements and deep percolation events vary greatly with adopted crop coefficient values and irrigation management strategies. Over the 14 irrigation seasons (2001/02 to 2014/015) constant crop coefficient of 1.0 would have required 40% more irrigation than

when adopting variable K_c values comprising 0.6 and 1.0 respectively for post and pre grazing conditions. Conventional irrigation planning with a constant K_c of 1.0 therefore places more abstractive pressure on the water resource, and also produces more deep percolation events which can cause contamination of water bodies.

Despite efficiency benefits, a trigger of irrigation at 50% of PAW comes with risk, as it cannot address evapotranspiration uncertainty. Significantly higher deep percolation losses occurred when irrigation replenished the soil moisture above 80 and 90% of PAW, respectively during shoulder and peak irrigation season. The results demonstrated that when the minimum soil moisture levels to start irrigation are 55 and 60% of PAW, respectively for shoulder and peak irrigation season and maximum soil moisture levels to stop irrigation are correspondingly at 80 and 90% of PAW, water use and deep percolation losses were minimised for rotational grazing pasture, without compromising potential production.

Limitations

- For the lysimeters' experiment, it was assumed that all lysimeters get equal amount of irrigation application because, 10 lysimeters are under one span of a centre pivot irrigator and the remaining 10 lysimeters are under the adjacent span. However, irrigation applications may vary from sprinklers to sprinklers, and due to windy conditions. Therefore, ideally, irrigation application on each lysimeter should have been measured. However, this assumption is not expected to have significant impact on the results.
- Based on soil moisture recorded by 200, 500 and 900 mm TDR probes, it was concluded that soil mass below 500 mm in the lysimeters is at field capacity and has no significant role in the mass balance inside the lysimeter. Therefore, only the top 500 mm soil depth was considered to estimate ET_a based on lysimeter data. Frequent deep percolation, Aquaflex soil moisture readings, dry down experiments and current irrigation strategy on the farm also supports the claim. Therefore, our assumption might have provided sufficiently accurate results.

Future research

Findings of the study highlighted the following further research opportunities for enhancing the experimental outcomes.

- There is a potential to extend this research to explore the impacts of irrigation management practices on freshwater by testing quality of the deep percolation from the lysimeters, and thus estimating the total load of nutrients which leaches to the groundwater system from LUDF. This was beyond the scope of this research.

- The relationship between $K_c - h$ could be extended to other regions under different climatic regime.
- The research was focussed on crop coefficient of ryegrass-based pasture and therefore, it might be beneficial to research other grass species.
- More rigorous soil moisture measurements should have been done at each 100 mm interval of the soil profile to come to the conclusion regarding the depth of soil in the lysimeters to be used in the water budget equation.
- Optimal irrigation strategy was identified based on 16 years of available climatic data. The research could be extended with new climatic scenarios in the face of climate change.

Appendix A

A.1 Copy of the paper accepted for conference proceeding

DETERMINING THE OPTIMAL IRRIGATION STRATEGY FOR ROTATIONAL GRAZING SYSTEMS

DÉTERMINATION DE LA STRATÉGIE D'IRRIGATION OPTIMALE POUR LES SYSTÈMES DE PÂTURAGE EN ROTATION

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ABSTRACT

The soil moisture content start and stop points, more commonly known as irrigation trigger points, for rotationally grazed pasture are often ambiguous and imprecise. A water balance model, IrriCalc, was used to analyse the impacts of different soil moisture triggers upon the irrigation required and subsequent drainage losses over a long-term period to investigate optimal irrigation ranges within the soil water holding capacity taking into consideration rainfall and evapotranspiration uncertainties. For the analysis, available daily climatic data over a 15 year period (2000 to 2015) was used to account for climatic variability. The experiments were conducted at the Lincoln University Dairy Farm (LUDF), Canterbury, New Zealand during the period August 2014 to March 2016. The results showed a trigger point to start irrigation at 55 and 60% of plant available water (PAW), respectively on the shoulder (September to October and March to April) and peak (November to February) irrigation seasons, and stopping irrigation correspondingly at 80 and 90% of PAW were optimal. Adopting this irrigation strategy will help better manage environmental risk, caused by nutrient leaching loss through increased drainage, and production risk resulting from soil moisture stress. Maximising effective rainfall during the irrigation season as well as minimising drainage will help irrigators better balancing the growing tension between water use for agricultural production and the environment.

Keywords: Threshold soil moisture content, Rotationally grazed pasture, IrriCalc, Optimal irrigation range, Irrigation and drainage, New Zealand.

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1. INTRODUCTION

Settled agriculture started about 10,000 years ago and farmers have been practicing controlled irrigation for over 6,000 years (Postel, 1999). However, despite having several ways to measure soil-water-plant-atmosphere parameters, there is still a lack of irrigation scheduling that addresses changing weather and crop water demands. There has been an increasing awareness to vary the amount of water applied based on crop demands and plant available water (PAW) (Hedley & Yule, 2009). However, current irrigation strategies adopted by a majority of Canterbury, New Zealand dairy farmers for pasture production are insufficient to address grazing rotations and weather uncertainty (KC, 2016). Under rotational grazing, pasture canopies (height as well as density) vary greatly across the farm but irrigation requirement is estimated, mostly based on a constant pasture coefficient (K_c) of 1.0 regardless of canopy stage (Van Housen, 2015).

During shoulder seasons (September to October and March to May) irrigation mostly starts when soil moisture drops to 50% of PAW and fills up to 80% of PAW. During peak irrigation seasons (November to February) irrigation starts around 70% of PAW and fills up to 100% of PAW, leaving no space for potential rain (KC, 2016). Due to lack of weather considerations in irrigation planning, irrigation events often coincide with, or are followed by, rainfall creating drainage events. Nutrients leaching through deep percolation and surface runoff is probably the biggest environmental issue for irrigated farming in New Zealand (Cameron et al., 2012; Thomas & Morini, 2005).

Applying the right amount of water at the right time is essential to minimise drainage and nutrient losses that may then create water pollution (Belaqziz et al., 2014). To address the issue of drainage induced nitrate leaching, along with other concerned agencies, farmers, scientists and researchers in New Zealand are keen to explore the options for improving irrigation efficiency through the application and expansion of carefully identified and evaluated irrigation scheduling methodologies (DairyNZ, 2013). Several previous studies such as Gheysari et al. (2009); Rawnsley et al. (2009); Snow et al. (2007); Wheeler and Bright (2015) indicated that irrigation variability impacts greatly on drainage. However, there have been very few studies that estimate irrigation and drainage under a range of irrigation management strategies and crop coefficients using long term climatic data to account for climatic variability. Trigger points to start and stop irrigation for rotational grazing systems are not well addressed.

The objective of this research was to determine the optimal irrigation trigger points for a given soils water holding capacity taking into consideration seasonal variations in rainfall and evapotranspiration, and accounting for actual pasture water requirement under a grazing rotation. The water balance model IrriCalc was used to estimate crop water requirement and drainage losses, to identify threshold soil moisture levels to start and stop irrigation. The adoption of an optimal irrigation strategy will make an important contribution towards improving irrigation scheduling and agricultural water management for rotational grazing systems in New Zealand and around the world. In addition, it would also decrease water pollution by reducing nutrient leaching from pastoral farms to water resources.

2. MATERIAL AND METHODS

Site description

Experiments were conducted on Lincoln University Dairy Farm (LUDF) (40° 38' 40.26" S and 172° 26' 35.86" E), South Island, Canterbury, New Zealand. The LUDF has 160 ha of irrigated land with two blocks: north block (80 ha) totalling 11 paddocks and south block (80 ha) totalling 10 paddocks with each paddock size ranging from 6 to 10 ha. Each paddock is individually managed for grazing but collectively for irrigation. The study site has an average annual rainfall of 666 mm, reference evapotranspiration of 870 mm and mean annual maximum and minimum temperatures of 32°C and 4°C, respectively (South Island Dairying Development Centre (SIDDC), 2014). On average, 450 mm per annum of irrigation is applied by three different irrigation systems including centre-pivot that irrigates 80% of the farm. Soils in the north block range from silty loam to sandy loam with some stones, while soils on the south block range from silty clay loam to clayey (South Island Dairying Development Centre (SIDDC), 2014).

Irrigation and Drainage estimates using IrriCalc

Researchers such as Fessehazion (2011) have advised use of a tool which is locally known by farmers instead of introducing another new tool. The IrriCalc, a daily water balance model, developed

by Aqualinc Research Limited, New Zealand (Bright, 2009), which is well known by New Zealand dairy farmers, was used in this research. The two key parameters used by IrriCalc that vary spatially are the PAW and K_c (Bright, 2009). IrriCalc has been tested and validated using lysimeter data installed in a number of pastoral farms in Canterbury, including Camden Farm (224 ha) Dunsandel, which is representative of irrigated pastoral farms in the region (Bright, 2009). The distance between Camden Farm and LUDF is 25 km and both have similar climates and soils resulting in a similar pasture growth dynamics. Van Housen (2015) tested the accuracy of irrigation demand and drainage depths determined using a soil water balance model (equivalent to IrriCalc) with an averaged K_c determined from nine lysimeter datasets located at three sites across the Canterbury Plains (i.e. very different climates and soils) and found that modelled results were within 10% of measured drainage. In addition, IrriCalc has been set up for Canterbury conditions and therefore the model can be used to predict irrigation demand and drainage depth without further validation.

Net irrigation requirement is estimated as a difference between actual crop water need and effective rainfall. Actual crop water need is equivalent to the multiplication of reference evapotranspiration (ET_r) and K_c . FAO Penman-Monteith equation was used to estimate ET_r using daily climatic data. The difference between total rainfall and the amount of rainfall actually lost through drainage in a daily water balance calculation is referred to as effective rainfall. Total rainfall that exceeds field capacity in a daily soil water balance is accounted as drainage losses. Field observations indicate no surface runoff from the study area, therefore, no overland flow was assumed.

IrriCalc evaluates daily changes in the root zone soil water content, accounting for all incoming and outgoing water in the root zone using the following soil water balance equation:

$$S_{t_2} = S_{t_1} + P_{t_2-t_1} + I_{t_2-t_1} - D_{t_2-t_1} - AET_{t_2-t_1}$$

Where S_{t_2} = soil water content on day t_2 , S_{t_1} = soil water content on day t_1 , $P_{t_2-t_1}$ = rain between t_1 and t_2 , $I_{t_2-t_1}$ = irrigation between t_1 and t_2 , $D_{t_2-t_1}$ = drainage between t_1 and t_2 , $AET_{t_2-t_1}$ = actual evapotranspiration between t_1 and t_2 . Above equation was applied for one-day time intervals and units of all variables of the equation are in mm.

IrriCalc calculates daily soil moisture status over the simulation period and if soil moisture drops to the user defined refill point, a user specified amount of irrigation is applied. Different options are available in the model to regulate irrigation planning. This study adopted the option that regulates irrigation application based on user defined soil moisture limits, i.e. irrigation start and stop points as certain percentages of PAW.

A pasture root depth of 500 mm as per field observation was used. PAW at 28% volume and readily available water (RAW) at 14% volume were used for the calculation as estimated for the experimental plot. To account for climatic variability a daily time series of climatic data available for 15 years during the period 2000 – 2015 was collected from Broadfield weather station (data source, NIWA; 43°35'53", 172°28'12" and altitude of 18 m). Irrigation and drainage were estimated using IrriCalc separately for shoulder and peak irrigation season based on two K_c alternatives: 0.6 and 1.0 correspondingly for post and pre grazing conditions as "newly" derived by KC (2016) and the most commonly used constant value of 1.0. Under each K_c option 49 irrigation strategies were adopted: irrigation starts at 50, 55, 60, 65, 70, 75 and 80% of PAW and stops for each starting trigger, at 70, 75, 80, 85, 90, 95 and 100% of PAW correspondingly.

3. RESULTS AND DISCUSSIONS

Irrigation estimates

Figure 1 compares the average annual irrigation estimates under the two K_c alternatives and 49 irrigation scenarios. Over the 14 irrigation seasons (2001/02 to 2014/015) irrigation requirement for a constant K_c of 1.0 was "on average" 40% higher compared to K_c values of 0.6 and 1.0 respectively for post and pre-grazing conditions. Irrigation requirement was also estimated by using daily time series of K_c values for one year period as suggested by Bright (2009). Cumulative irrigation predicted for 14 irrigation seasons for a constant K_c of 1.0 was found to be 15% higher compared to when applying a daily time series of K_c values.

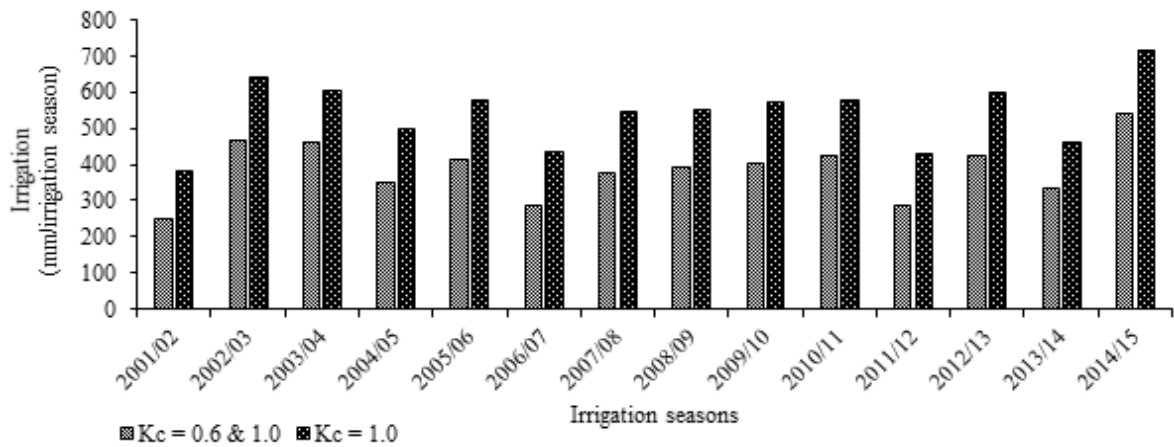


Figure 1. Average irrigation estimates from IrriCalc for 14 irrigation seasons (2001/02 to 2014/015) under 49 irrigation management strategies and two crop coefficient values: $K_c = 0.6$ and 1.0 respectively for post and pre-grazing conditions; and a constant $K_c = 1.0$ (estimations d'irrigation moyen de IrriCalc pour 14 saisons d'irrigation (2001/02 à 2014/015) dans le cadre des stratégies de gestion 49 d'irrigation et deux valeurs de coefficient de récolte : $K_c = 0,6$ et $1,0$ respectivement pour les conditions de post et pré- pâturage ; et un K_c constant = $1,0$).

For the detailed analysis K_c values of 0.6 and 1.0 respectively for post and pre grazing conditions and seven irrigation strategies were considered: irrigation starting at $50, 55, 60, 65, 70, 75$ and 80% of PAW and stopping correspondingly at $70, 75, 80, 85, 90, 95$ and 100% of PAW. Irrigation requirement was estimated separately for shoulder and peak irrigation season. This test was undertaken to investigate net irrigation requirements when irrigation aimed to fill the same soil moisture depth at different triggers.

Annual irrigation estimates varied significantly with adopted irrigation management strategies. In general, irrigation estimates for both peak and shoulder irrigation seasons showed similar trends with the higher the PAW based irrigation trigger points, the higher irrigation requirements. Figure 2 shows the combined irrigation estimates for both peak and shoulder irrigation period over 14 irrigation seasons. Compared to the first (irrigation starts at 50% of PAW and stops at 70% of PAW), the last irrigation strategy (irrigation starts at 80% of PAW and stops at 100% of PAW) consistently produces significantly higher annual irrigation volume (or depth) which differs greatly from year to year. For example, during 2006/07 season, irrigation requirement under the last irrigation strategy was 100% more than the first, during 2014/015 it was higher only by 19% . There was no specific link of wet and dry years with differences in irrigation requirement under a different irrigation strategy. For example, rainfall during two irrigation seasons 2001/02 (650 mm) and 2005/06 (645 mm) were similar. However, during 2001/02 irrigation requirement under last irrigation strategy was 106% more than the first, during 2005/06 it was higher only by 33% .

Rather than total rainfall amount during irrigation season, patterns of individual rain events would have impacted on irrigation estimation. For example, any rainfall event that occurs before soil moisture drops to irrigation trigger levels minimises the irrigation requirement. However, if rainfall follows irrigation events, it will have no impact on irrigation estimation, especially if irrigation fills 100% of PAW. In general, irrigation requirements increases significantly when irrigation replenished the soil moisture above 80 and 90% of PAW, respectively during shoulder and peak irrigation season.

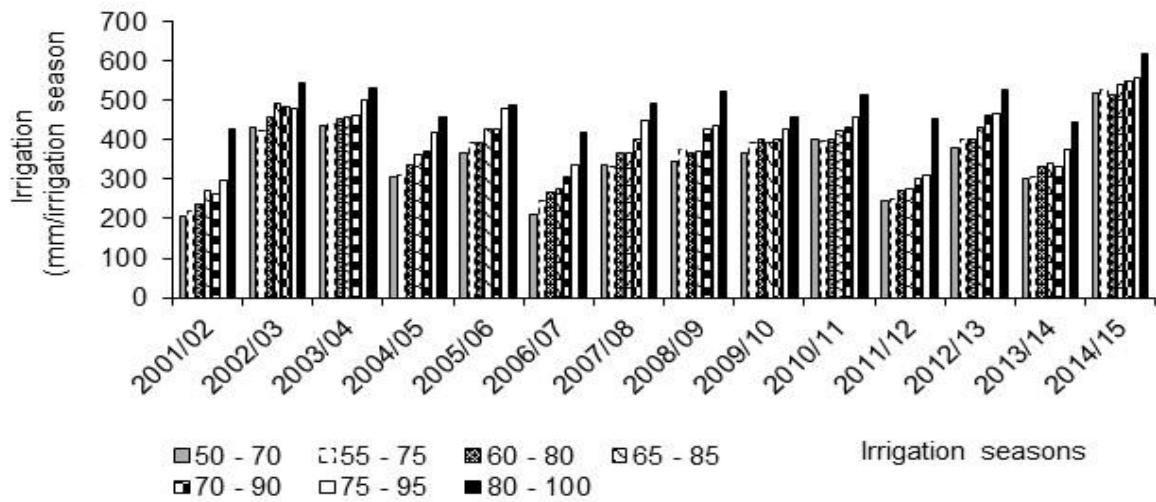


Figure 2. Irrigation estimates from IrriCalc over 14 irrigation seasons (2001/02 to 2014/015) under seven irrigation management strategies. 50 – 70 stands for irrigation starting at 50% of PAW and stopping at 70% of PAW and so on (Les estimations d'irrigation de IrriCalc de plus de 14 saisons d'irrigation (2001/02 à 2014/015) de moins de sept stratégies de gestion de l'irrigation. 50 - 70 stands pour l'irrigation à partir de 50% de PAW et d'arrêt à 70% de PAW et ainsi de suite).

Drainage estimates

Similar to irrigation estimates, drainage was also estimated separately for peak and shoulder irrigation season based on the K_c values of 0.6 and 1.0 for post and pre-grazing conditions, respectively, and for the above mentioned 49 irrigation strategies. For the detailed analysis, seven irrigation strategies were considered: irrigation starting at 50, 55, 60, 65, 70, 75 and 80% of PAW and stopping correspondingly at 70, 75, 80, 85, 90, 95 and 100% of PAW. The main objective of this test was to investigate the impact of applying the same depth of water, at different triggers, on drainage events.

Like irrigation estimates, drainage prediction also varied significantly with the adopted irrigation management strategies. Drainage predictions for both peak and shoulder irrigation seasons demonstrated similar trends with the higher the PAW based irrigation trigger points, the higher the drainage. Figure 3 shows the combined drainage estimates for peak and shoulder irrigation period over 14 irrigation seasons. Compared to the first (irrigation starts at 50% of PAW and stops at 70% of PAW), the last irrigation strategy (irrigation starts at 80% of PAW and stops at 100% of PAW) produced up to 350% more drainage which differs from year to year. Yearly differences in drainage estimation are attributed to differences in annual rainfall amount and their distribution. For example, during 2014/015 season, total rainfall was 394 mm which produced less drainage than during 2013/014 season with rainfall totalling 738 mm. In general, drainage estimates increased significantly when irrigation filled more than 80 and 90% of PAW, respectively during shoulder and peak irrigation season.

Rainfall efficiencies were higher when PAW based irrigation triggers were lower. Over the whole 14 irrigation seasons, the first irrigation strategy: irrigation starts at 50% of PAW and refills soil up to 70% of PAW, produced the lowest drainage depths of 2432 mm, equivalent to 174 mm per year. While, over the same time span, the last irrigation strategy: irrigation starts at 80% of PAW and filling soil up to 100% of PAW, produced 4343 mm of drainage resulting in an annual average drainage depth of 310 mm. Compared to the former, later irrigation strategy, which does not allow any room for the storage of the potential rainfall, will use 1.4 times more irrigation water and will result in nearly double the drainage. This indicates a substantial drainage reduction and water saving by regulating irrigation strategies. When drainage losses were reduced by about four times (from 135 to 34 mm yr⁻¹) the

nutrient leaching reduced nearly by six times (from 55 to 10 kg N ha⁻¹ yr⁻¹) (Moir et al., 2007). This implies nutrient leaching can be reduced significantly by minimizing drainage losses.

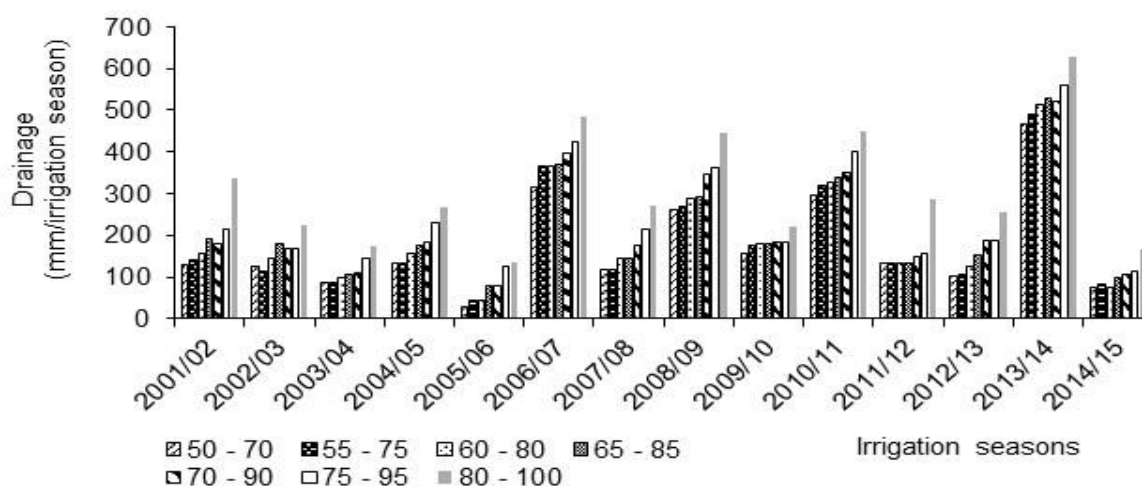


Figure 3. Drainage estimates from IrriCalc over 14 irrigation seasons (2001/02 to 2014/015) under seven irrigation management strategies. 50 – 70 stands for irrigation starting at 50% of PAW and irrigation stopping at 70% of PAW and so on (Les estimations de drainage de IrriCalc de plus de 14 saisons d'irrigation (2001/02 à 2014/015) de moins de sept stratégies de gestion de l'irrigation. 50 - 70 stands pour l'irrigation à partir de 50% de PAW et l'irrigation d'arrêt à 70% de PAW et ainsi de suite).

Optimal irrigation range

Average monthly reference evapotranspiration (ET_r) estimated and precipitation (P) recorded at Broadfield weather station over the 15-year period (2000 to 2015) indicate the need for irrigation as ET_r usually exceeds P during spring, summer and autumn (September to May). Maximum daily ET_r over the 15 years period was 10 mm, while maximum daily rainfall was 74 mm. This indicates that daily rainfall can be several times greater than the ET_r , suggesting a need for flexible irrigation strategies to capture maximum rain water for storage in the root zone and thus reducing drainage losses.

Results demonstrated minimum soil moisture limit to start irrigation at 55 and 57% of PAW, respectively for shoulder and peak irrigation seasons and maximum soil moisture limit to stop irrigation correspondingly at 80 and 90% of PAW can address both precipitation and evapotranspiration uncertainty. Irrigation started at 55 and 57% of PAW, during shoulder and peak irrigation season respectively, would provide a buffer for the maximum daily potential evapotranspiration (PET) of 7 and 10 mm, based on the analysis of the available data over 15 years of record. However, from a practical aspect, irrigation starts at 60% of PAW during peak irrigation season will be more applicable, as farmers mostly regulate irrigation at 5% increments in PAW.

Irrigation that fills soil moisture to 90% of PAW allows for 14 mm rainfall harvesting that is equivalent to almost three days irrigation saving under centre pivot irrigation which applies 5 mm of irrigation in one day. Similarly, irrigation that fills soil moisture to 80% of PAW provides space for 28 mm rainfall which is equivalent to nearly six days irrigation saving under centre pivot irrigation. Maintaining irrigation within the specified range as shown in Figure 4 can allow for the mitigation of both environmental risk, caused by drainage, and the production risk caused by soil moisture stress.

The research is applicable to other climatic regions and soil types, however further scenario specific modelling would be required to determine the actual trigger points to start and stop irrigation for those. Undertaking this exercise for areas with higher incidence of summer rainfall would likely be extremely beneficial, as this will help better manage drainage losses. In comparison there is little likely benefit in undertaking this exercise for soils of low PAW as the change in trigger point (in terms of soil moisture

content) is relatively small. The irrigation system design parameters also need to be considered, both the return period and the design capacity as these could also affect the trigger points.

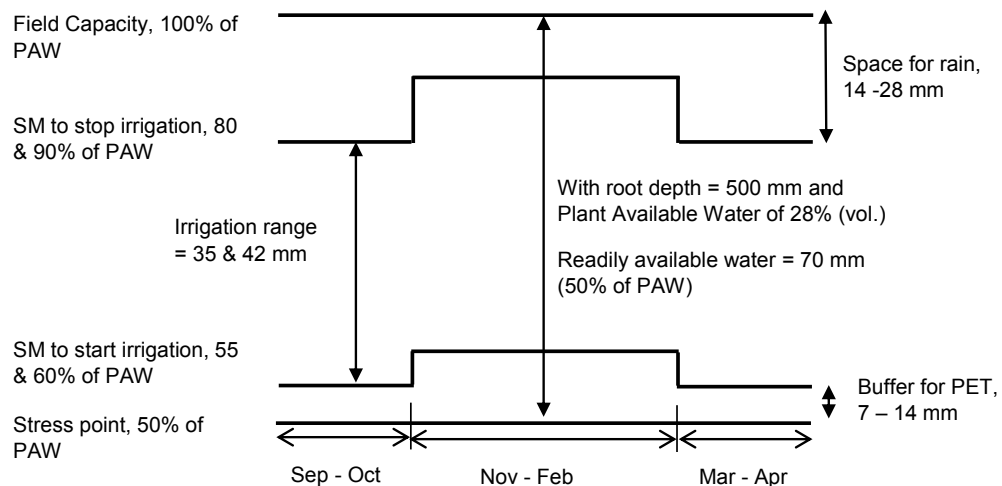


Figure 4. Optimal irrigation range during shoulder (September to October and March to April) and peak (November to February) irrigation seasons for rotational grazing pasture based on LUDF field experiments. PAW = plant available water, SM = soil moisture (gamme d'irrigation optimale lors de l'épaule (Septembre à Octobre et Mars à Avril) et le pic (Novembre à Février) saisons d'irrigation pour le pâturage en rotation des pâturages sur la base des expériences de terrain LUDF. PAW = plante eau disponible , SM = humidité du sol).

4. CONCLUSIONS

Results of LUDF experiments with applications of IrriCalc predicted cumulative irrigation and drainage for 14 irrigation seasons (2001/02 to 2014/15), under two K_c scenarios and 49 irrigation management strategies. Both irrigation and drainage estimates varied significantly with K_c values and irrigation management strategies. Irrigation estimates for 14 irrigation seasons under a constant K_c of 1.0, the widely applied approach in NZ, was 40% more than when adopting K_c values of 0.6 and 1.0 respectively for post and pre-grazing conditions. Thus, irrigation planning with a standard K_c of 1.0 places more abstractive pressure on the water resource and potentially deteriorates water quality through a greater number of drainage events. The results of this irrigation and drainage study demonstrated that optimal minimum soil moisture levels to start irrigation are 55 and 60% of PAW, respectively for shoulder and peak irrigation season and maximum soil moisture levels to stop irrigation are correspondingly at 80 and 90% of PAW. Using these trigger points would improve performance in terms of maximum rain water use and thus, reduce non-profitable drainage losses and net irrigation requirement. Irrigation started at 55 and 60% of PAW, respectively during shoulder and peak irrigation season provides buffer to address evapotranspiration uncertainty, thereby minimising soil moisture stress induced yield reduction. Irrigation application that fill soil moisture to 80 and 90% of PAW, respectively during shoulder and peak irrigation season provides storage for potential rainfall and in turn reduce irrigation requirements and drainage events. Application of "newly" derived crop coefficient values of 0.6 and 1.0, respectively for post and pre-grazing conditions and proposed optimal irrigation ranges can serve as useful guidelines to design irrigation planning for rotational grazing systems. Such irrigation methods can contribute to conserve water and the environment by reducing irrigation requirements and drainage events without production losses.

5. ACKNOWLEDGEMENT

The authors express their appreciation to Professor Bart Schultz from UNESCO-IHE, Delft, the Netherlands for external review input.

Appendix B

B.1 Questionnaire Used for Pastoral Survey

B.2 Approval letter to conduct survey

Research and Commercialisation Office

T 64 3 423 0817
PO Box 85084, Lincoln University
Lincoln 7647, Christchurch
New Zealand

Application No: 2014-14

5 August 2014 www.lincoln.ac.nz

Title: Irrigation scheduling: a soft adaptor to weather uncertainties and irrigation Efficiency Improvement Initiatives

Applicant: Birendra K.C.

The Lincoln University Human Ethics Committee has reviewed the above noted application.

Thank you for your response to the questions which were forwarded to you on the Committee's behalf. I am satisfied on the Committee's behalf that the substantive issues of concern have been satisfactorily addressed.

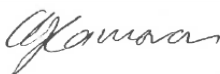
I am pleased to give approval subject to the following:

- Please ensure that the list of participants and codes is kept separate from the data to avoid anyone other than you or your supervisor being able to link participants to their data.
- Please correct the wording in the Research Information Sheet in paragraphs 5 and 6: "you may be assured of your **anonymity**..", "To ensure **anonymity** ..." (Not, "confidentiality")
- Please note that the Research Information Sheet still needs editing for language errors. For example, the word "quarries" should be "queries", "demolished" should be "destroyed". Please note that these are not the only errors to be corrected in order to bring the document up to a professional standard.

Subject to these changes, I am pleased to give final approval to your project. Please advise Alison Hind when you have completed your research and confirming that you have complied with the terms of the ethical approval.

May I, on behalf of the Committee, wish you success in your research?

Yours sincerely



Caitriona Cameron
Acting Chair, Human Ethics Committee

PLEASE NOTE: The Human Ethics Committee has an audit process in place for applications. Please see 7.3 of the Human Ethics Committee Operating Procedures (ACHE) in the Lincoln University Policies and Procedures Manual for more information.

B.3 Research information sheet

Invitation to participate as a subject in a project: You are invited to participate as a subject in a project entitled “Irrigation scheduling: a Soft Adaptor to Weather uncertainties and Irrigation Efficiency Improvement Initiatives”

This project has a focus on, researching methods for the better management of irrigated pasture. As part of my research I would like to understand current irrigation practice upon pastoral farms, particularly in relation to grazing strategies. This will inform my PhD how it can best contribute towards improved irrigation efficiency for pastoral farms.

Your participation in this project involve providing information about your irrigation practices and grazing strategies. This survey is voluntary and will take around 45 minutes to complete.

There will not be follow-up to this activity and there are no risks involved in participating in this project. In addition, there are no risk in the performance of the tasks and application of the procedures.

The results of the project may be published, but you may be assured of your anonymity in this investigation. Your identity will not be made public, or made known to any person other than the researcher and his supervisors.

All information will be used for the research purpose only. To ensure anonymity only the code given to each survey document will be used to summarise the outcome of the survey. All the hard copies of the survey will be locked in my locker on campus. After my course completion all the survey documents will be locked in my main supervisor’s locker for 5 years and then destroyed.

The project is being carried out by Birendra K.C. a PhD student in the Faculty of Environment, Society and Design at Lincoln University. If you have any queries or would like to discuss anything about this surveying we would be please to provide you any information.

Main supervisor of the research and his address is:

Magdy Mohssen
Senior Lecturer
Department of Environmental Management
Faculty of Environment, Society and Design
Room 158, NRE building, P O Box 85084
Lincoln University, Lincoln 7647
Christchurch, New Zealand
p +64 3 4230433 extn: 30433 | m +64 276856604 | f +64 3 3253615
e- Magdy.mohssen@lincoln.ac.nz

The project has been reviewed and approved by the Lincoln University Human Ethics Committee.

B.4 Invitation for participation

Name of Project: *PhD research*

You are invited to participate in a project called "Irrigation scheduling: a Soft Adaptor to Weather uncertainties and Irrigation Efficiency Improvement Initiatives" by completing the following questionnaire.

The aim of the project is to collect information about farmer's irrigation patterns and grazing strategies to see how we can improve the efficient use of our precious water resources by improving irrigation efficiency.

The questionnaire is confidential, and you will not be identified as a respondent. You may at any time withdraw your participation during our telephone conversation. However, once the conversation is complete it will be assumed that you have consented for me to use the information for the study and publication with the understanding that confidentiality will be preserved.

B.5 Consent Form

Name of Project: Irrigation Scheduling: a Soft Adaptor to Weather uncertainties and Irrigation Efficiency Improvement Initiatives

I have read and understood the description of the above-named project. On this basis I agree to participate as a subject in the project, and I consent to publication of the results of the project with the understanding that confidentiality will be preserved. I understand that I may withdraw from the project, including withdrawal of any information I have provided at any time of the telephone conversation. However, once the telephone conversation is completed it is assumed that i have consented to use the answer for the study and publication.

Code: _____

Signed: _____ Date: _____

B.6 Questionnaire used

A. Personal information

1. Code number:.....
2. Address:.....
3. Region:.....
4. Do you wish to get a summary of the result of this study?
(a) Yes (b) No

B. Pasture characteristics and grazing strategies

1. Average pasture cover just before grazing..... kg dry matter per ha (kgDM/ha)
2. Average pasture cover just after grazing.....kg dry matter per ha (kgDM/ha)
3. Grazing return interval
 - (a) During early spring (September).....days
 - (b) During late spring (October, November).....days
 - (c) During summer (December, January).....days
 - (d) During late-summer (February).....days
 - (e) During autumn (March, April, May).....days
4. Estimated average root depth of the pasture.....millimetre (mm)
5. How old is the pasture.....years
6. Annual pasture yield, kg dry matter per ha (kgDM/ha) in following years (whichever is available)
2009.....2010.....2011.....
2012.....2013.....2014.....

C. Farm characteristics

1. Farm size.....ha
2. Numbers of paddocks.....
3. Average annual rainfall.....mm
4. Average annual evapotranspiration if known.....mm
5. Soil types on the farm
 - (a) Soil type 1.....
 - (b) Soil type 2.....
 - (c) Soil type 3.....
6. Depth of top soil
 - (a) Soil type 1.....mm
 - (b) Soil type 2.....mm
 - (c) Soil type 3.....mm
7. Water holding capacity (wilting point - field capacity)
 - (a) Soil type 1.....mm
 - (b) Soil type 2.....mm
 - (c) Soil type 3.....mm

D. Irrigation System

1. Which types of spray system do you have?
 - (a) Centre pivot for.....% of farm
 - (b) Long lateral for.....% of farm
 - (c) K-line for.....% of farm
 - (d) Rotary boom for.....% of farm

- (e) Fixed sprinklers for.....% of farm
- (f)for.....% of farm
- (g) for.....% of farm
- 2. System capacity..... l/s/ha or mm/day (whichever is applicable)
- 3. Peak irrigation duration (how many hours can you irrigate for a day)hours/days
- 4. Maximum irrigation return interval (how long before you can get back).....days
- 5. How much water do you typically use over a season.....m³ or mm (please specify)
- 6. How much power do you typically use over a season.....kwh

E. Irrigation Process

- 1. Do you consider weather forecasts when making irrigation decisions?
 - (a) Yes (b) No
- 2. If yes, how do you use them as part of your irrigation strategy?

.....

.....
- 3. What is your strategy for determining when to start irrigation at the beginning of each season?

.....

.....
- 4. What is your trigger point for irrigation during following zones?
 - Zone - I (Shoulder Season, September and October)
 - (a)mm below field capacity or% of field capacity
 - Zone - II (Peak Irrigation Season, November to February)
 - (b)mm below field capacity or% of field capacity
 - Zone - III (March and April)
 - (c)mm below field capacity or% of field capacity
- 5. What is irrigation stopping point through each zone?
 - Zone - I (Shoulder Season, September and October)
 - (a) After supplying.....mm irrigation or mm below / % of FC
 - Zone - II (Peak Irrigation Season, November to February)
 - (b) After supplying.....mm irrigation or mm below / % of FC
 - Zone - III (March and April)
 - (c) After supplying.....mm irrigation or..... mm below / % of FC
- 6. Different paddocks within a farm can have different soil types. Do you make irrigation decision based on actual soil types in different paddocks?
 - (a) Yes (b) No
- 7. Different paddocks within a farm can have different pasture heights. Do you make irrigation decision based on actual pasture height in different paddocks?
 - (a) Yes (b) No

B.7 E-mail used

Dear all,

I am a PhD student studying at Lincoln University. My PhD's has a focus on, researching methods for the better management of irrigated pasture. As part of my research I would like to understand current irrigation practice upon pastoral farms, particularly in relation to grazing strategies. This will inform my PhD how it can best contribute towards improved irrigation efficiency for pastoral farms.

I would be grateful if you could provide me with 45 minutes of your time for a telephone call. This will allow me to complete the enclosed questionnaire based on our telephone conversation. The survey is mainly focused on your irrigation practices and grazing strategies. Participation is voluntary, however your response would be valuable to me in better targeting my research objectives.

You can withdraw your response at any time during our telephone conversation. However, once the conversation is complete it will be assumed that you have consented for me to use your answer for the study.

The research data will remain confidential. Only a summary of responses will be made public through my research.

Please find attached electronic copies of our survey documents that include project information form, consent form and questionnaire. If you would like to know or discuss anything about this survey please feel free to contact me or Andrew Curtis.

I look forward to talking with you.

Sincerely,
Birendra K.C.
PhD student
Faculty of Environment, Society and Design
Lincoln University
Email: birendra.k.c@lincolnuni.ac.nz
Mobile: 0223593785

Andrew Curtis
Co-supervisor
Chief Executive
Irrigation New Zealand
6 Sonter Road, Wigram
Christchurch 8042
Canterbury, New Zealand
Email: acurtis@irrigationnz.co.nz
Telephone: (64) 3 341 2225
Fax: (64) 3 341 2205

B.8 Telephone script used

Name of Project: PhD research entitled "Irrigation scheduling: a Soft Adaptor to Weather uncertainties and Irrigation Efficiency Improvement Initiatives"

Hello, my name is Birendra K.C. I am a postgraduate student in the Environment, Society and Design Faculty at Lincoln University undertaking study for PhD degree. You might have received electronic copies of our survey documents that include cover letter, consent form, project information form, script of the telephone conversation and questionnaire.

Main aim of the survey is to study irrigation patterns and grazing strategies on New Zealand dairy farms to improve agricultural water management by improving irrigation efficiency. I would like to invite you to participate in a project.

Your telephone number was obtained from Irrigation New Zealand and selected randomly by our research team.

Your participation in this project involve providing information about pasture and soil characteristics on your dairy farm and your irrigation strategies. It will take around 45 minutes to complete.

Participation in the research is voluntary and you may decline to answer questions or withdraw at any time of our telephone conversation. If you do withdraw at any stage, any information you have already provided will be discarded. However, once our conversation is completed it is considered that you consented to use the information for the study.

All the information you provided during the conversation will remain confidential to me as researcher and my supervisors.

Are you prepared to participate in this research project?

Interview schedule

Interview started time:.....

Interview completed time:.....

Thank you for your time. If you have any questions regarding this research, please contact me or my supervisor:

My name is Birendra K.C.
Telephone number: +64 3 3257255

My supervisor's name is Dr Magdy Mohssen
Telephone number: +64 3 4230433 extn: 30433

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