Water use on pastoral dairy farms in New Zealand: An analysis of measurements, predictions, and water footprinting

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Abstract

Current water use guidelines for pastoral dairy farms across New Zealand are based on a 1964 study suggesting 70 L per cow per day for stock drinking water (SDW) and 70 L per cow per day for milking parlour water (MPW) use. However, dairy cows and milking parlours have changed significantly over the last half century. This thesis combined detailed monitoring of water use on more than 100 farms in the Waikato, Manawatu, and Canterbury regions with predictive modelling to; set benchmarks for SDW and MPW, analyse temporal and spatial variations of water use for irrigated and non-irrigated dairy farms, and assess the likely impact of climate change on future water demand of pastoral dairy farms across New Zealand. Finally, the thesis applied and evaluated different water footprint methods (the Water Footprint Network method, the Stress-Weighted Water Footprint method, and the Availability WAter REmaining (AWARE) method) to assess the impact of dairy water use on local water resources across different regions of New Zealand. In particular, the effects of varying the accuracy of data sources (local verse global) and the scale of the analysis (regional verse catchment) on the water footprints were investigated.

From this study, in the Waikato region, the mean SDW is 60 L/cow per day and the mean MPW is 49 L/cow per day. In the Manawatu region, the mean SDW is 74 L/cow per day and the mean MPW is 50 L/cow per day. In the Canterbury region, the annual mean SDW is 28 L/cow per day and mean MPW is 64 L/cow per day. For the first time, leakage rates in the supply of SDW were estimated for pastoral dairy farm systems. Average leakage rates were estimated to be approximately 26% in the Waikato region, 47% in the Manawatu region, and 13% in the Canterbury region. Through climate change modelling requirements for

irrigation water were estimated to increase by 17-24%, with the largest increase in Canterbury. Approximately 99% of the volumetric (total volume of water used) water footprint (L/kg fat and protein corrected milk) is associated with the green (from rainfall) and blue (from surface water) water consumed in the growth of pasture and feed at the study farms.

The use of global data sources, as compared to the local data, resulted in underestimation of the volumetric green water footprint (L/kg FPCM) by 12 to 30%, and overestimation of the volumetric blue water footprint (L/kg FPCM) by 3 to 141% in the study regions. Likewise, the water footprint of dairy farming was found to vary markedly with the scale at which this analysis is conducted. The use of local data at a catchment scale gave the most reliable water footprints.

Overall, water use on New Zealand dairy farms has been demonstrated to be much more complex than simple, historic guidelines indicate. The water use values produced in this study can serve as updated industry and policy guidelines, as the industry addresses limits to water availability and future increases in water use requirements for stock drinking water on non-irrigated dairy farms associated with predicted climate change.

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List of Abbreviations

ADD	Average daily demand
AMD	Availability minus demand
AWARE	Available WAater REmaining
Brd	Breed
CF	Characterisation factor
CowBail	Cow to bail ratio
cSDW	Corrected stock drinking water
DM	Dry matter
DM%	Dry matter %
DMI	Dry matter intake
EFR	Environmental flow requirements
ET	Evapotranspiration
ET_{blue}	Blue evapotranspiration/irrigation water
ET_c	Crop specific evapotranspiration
ET_{green}	Green evapotranspiration
ET_o	Reference evapotranspiration
Evap	Potential evapotranspiration
FPCM	Fat and protein corrected milk
IW	Irrigation water
JD	Julian day
K_c	Crop coefficient
LCA	Life cycle assessment
MAR	Mean annual runoff
MeanT	Average daily temperature
Milking	The number of milkings in a day
MilkSol	Milksolids
MilkVol	Milk volume
MinT	Minimum daily temperature
MPW	Milking parlour water
MY	Milk yield
Na	Sodium
NPS-FM	National Policy Statement for Freshwater Management
NSE	Nash-Sutcliffe efficiency
PBIAS	Percentage bias
PDD	Peak daily demand
P_{eff}	Effective precipitation
PKE	Palm kernel expeller
PLS	Partial Least Squares
Rad	Solar radiation
RCPs	Representative concentration pathways

RF	Rainfall
RMA	Resource Management Act
RMSE	Root mean square error
R_{nat}	Natural runoff
RSR	RMSE-observations standard deviation ratio
SDW	Stock drinking water
SRF	Strongly regulated flows
STe_i	Surface time equivalent
SU	Stock unit
TMax	Maximum daily temperature
TMin	Minimum daily temperature
TW	Total water/bore water
VF	Variation factor
VWI	Voluntary water intake
WA	Water availability
WA_{blue}	Blue water availability
WF_{blue}	Blue water footprint
$WFII_{blue}$	Water footprint impact index
WFN	Water Footprint Network
WS_{blue}	Blue water scarcity
WSI	Water stress index
WU	Water withdrawal
WULCA	Water use in Life Cycle Assessment

CHAPTER 1.

General Introduction

1.1 Background and Justification

Agriculture uses more water than any other industry in New Zealand and worldwide. Irrigation water use in New Zealand makes up approximately 46% of total allocated water (Aqualinc, 2010), of which approximately 70% is used for pasture irrigation on dairy farms (Statistics New Zealand, 2012, Corong et al., 2014). With water resource extraction and use coming close to water availability limits in some regions (Ministry for the Environment, 2010), water use in New Zealand, and agricultural water use in particular, has become a prominent issue.

The Resource Management Act (**RMA**) is the over-arching legislation by which natural resources, including water, are sustainably managed in New Zealand (The New Zealand Government, 2017a). The RMA provides guidance on what is best for New Zealand's environment including air, freshwater, and costal marine areas (Ministry for the Environment, 2017) and it allows communities to make decisions on how their own environment is managed through regional and district plans (Ministry for the Environment, 2017). Resource use decisions and consents reflect the regional and district plans, national directions (e.g. National Policy Statements), and objectives in the RMA (The New Zealand Government, 2017b). There is also an increasing level of iwi co-governance in resource management, usually in partnership with the Crown and local government (e.g. Waikato River Authority, 2017). Many of these co-governance agreements between iwi and local government have come about after negotiations, including Treaty of Waitangi settlements (Provost, 2016). Examples of

co-governance are the Waikato river with the Waikato River Vision and Strategy coordinated by the Waikato River Authority and Waikato Regional Council (Waikato River Authority, 2017), and the Te Waihora Co-Governance Agreement between Te Waihora Management Board and Te Rūnanga o Ngāi Tahu and Environment Canterbury (Te Waihora Management Board et al., 2012). Water management is invariably a key consideration in these agreements.

The National Policy Statement for Freshwater Management (**NPS-FM**) was developed in response to increasing water resource use and its associated pressure on the aquatic environment, and is driving policy changes on water allocation of all freshwater bodies in New Zealand (The New Zealand Government, 2014, 2017b). This legislation requires all Regional Councils to set water quantity limits for all water bodies by 2025 to safeguard the life-supporting capacity of New Zealand's fresh water systems. Any over-allocation of the quantity of water in the regions must be phased out within a defined timeframe (The New Zealand Government, 2014).

Dairy farming covers around 9% of New Zealand's land area (Statistics New Zealand, 2012). Dairying is a major water user, and so trends in water use policies such as those described above have significant implications for the dairy industry. The NPS-FM requires Regional Councils to allocate water efficiently and to increase water use efficiency. They are also required to account for the reasonably foreseeable effects of climate change. Some Regional Councils have formulated rules for water use (Waikato Regional Council, 2012a, Horizons Regional Council, 2014) and some Regional Councils are in the process of setting them.

1.1.1 Regional Council policy related to water allocation

Regional Councils manage the water, land, and air resources in each region of New Zealand. They do this through Regional Policy Statements and Regional Plans. Regional Councils have tended to focus on water quality and the allocation of water for irrigation in the immediate past but they are beginning to develop policy related to the allocation of the quantity of water to farms for purposes such as stock drinking and milking parlour (dairy shed) water use. Many councils have either set allocation limits for water quantity, have begun the process, or have put in place interim measures until more data is available. For example, the Waikato Regional Council identified water allocation as a regionally significant issue and followed a statutory process to vary their Regional Plan, termed 'Variation 6', which was eventually contested in the Environmental Court. One part of the contest was disagreement between the Council and the dairy industry over the volume of water required by dairy farms to operate (Waikato Regional Council, 2012b). The court ruled that 70 L per cow per day should be allocated for milking parlour water use as this is the supply of water required by other legislation (Ministry for Primary Industries, 2017). The court said to have a lower value would be contradictory to those regulations (Environment Court New Zealand, 2011).

The 'NZCP1: Code of practice for the design and operation of farm dairies' is the legislation that governs how milking parlours should be operated for milk harvesting and storage in relation to food safety standards (Ministry for Primary Industries, 2017b). The NZCP1 requires that 70 L per cow per day of cold water be available at all milking parlours for the purposes of milk cooling, plant wash, and

cleaning of the dairy, and another 70 L of water per cow per day be available for stock drinking water (Ministry for Primary Industries, 2017b).

The NPS-FM requires accurate accounting systems for water use as they are critically important for water resource management. As major water users, accurate water use data for dairy farms is needed to ensure water allocation is correct. Currently, the volumes of water allocated for use on dairy farms are based on outdated industry guidelines (Tauranga County Council, 1964, Ministry for Primary Industries, 2013). However, the modern dairy cow and today's milking parlours are very different to their counterparts of 1964. We can also expect significant regional and farm system differences not captured by historical guidelines.

There is a pressing need for the dairy industry and policy makers to access robust information on patterns of water use on modern pastoral dairy farms. Furthermore, in order to identify opportunities to increase water use efficiency or reduce total water use, it is important to understand the drivers of water use, and how these vary between regions. This is especially the case for the difference between irrigated and non-irrigated dairy farms.

International literature addressing water use on dairy farms has limited relevance to New Zealand pasture-based systems. For example, stock drinking water has been widely investigated in confinement dairy systems (Murphy et al., 1983, Dahlborn et al., 1998, Cardot et al., 2008), but these systems differ substantially from pasture-based farms (Roche et al., 2013). The feed type in confinement systems is typically high in dry matter % and consistent in quality throughout the year, whereas pasture has low dry matter % in the winter and spring, but often has high dry matter % and lower quality in summer and autumn depending on rainfall.

Predictive models of water use have been produced for confinement systems (Castle and Thomas, 1975, Meyer et al., 2004). Although key drivers are thought to be similar for stock drinking water on pasture-based systems, the predictive models based on confinement systems have not been designed to cover the range of feeds available on pasture-based farms. As dry matter percentage (DM%) is not routinely measured, there is limited data to incorporate DM % into models of water use in pasture-based systems. Water consumption in feed on pasture based farms may be better predicted from other available variables linked to pasture growth and DM%, such as climate and milk production.

There is very little published information of milking parlour water use and a literature search failed to find any models for predicting milking parlour water use on pastoral dairy farms. Available literature was largely from different milking parlour types, such as pipeline and flat parlours (Janni et al., 2009), whereas herringbone and rotary parlours are predominantly used in New Zealand. Also, the milking practices were different in some milking parlour literature, with udder washing and group washing of cows giving much higher water use (Gamroth and Moore, 1995) than is expected in New Zealand where these practices are not the norm (Livestock Improvement Corporation, 2013).

Improved accounting of water use on dairy farms will enable improvements in water resource decision making. These decisions often need to be made at a range of farm, regional and national scales, and having accurate accounts of water use may benefit New Zealand both environmentally and economically. Quantification of water use on dairy farms will also help inform other metrics related to water use such as water footprinting which has been developed to evaluate how water use affects the

environment and the ability of others to use the water resource. Water footprinting (a metric indicating the magnitude of water use and the impacts of water use in the production of a good or service) has become a common way to; evaluate water use; compare a product produced in two different regions; and evaluate ways to reduce the water footprint of a product. Currently there are many different methods for water footprinting (Canals et al., 2009, Ridoutt and Pfister, 2010, Hoekstra et al., 2011), but there is no consensus on which method to use. International databases of water uses and flows have been developed (Alcamo et al., 2003, Water Footprint Network, 2016) to allow the water footprints of products or processes to be calculated. The water footprints calculated using these databases can have uncertainties of ± 30% (at a 95% confidence interval; Zhuo et al., 2014). This lack of accuracy reflects the trade-off between the level of detail used in the analysis, and the ease at which the analysis can be conducted. In other words, the scale at which a water footprinting exercise is carried out can affect the resulting water footprint value. For example, if water footprinting analysis is carried out at a regional scale compared to a catchment scale, there may be considerable difference in quantification of the available water, water consumed in different processes, and assessment of water stress levels and water footprint impacts associated with a production process. There has been little analysis of the effects of using detailed local or global data, or the effect of spatial scale on water footprints of the dairy industry.

1.2 Research Objectives

The first objective of this study was to provide a robust accounting methodology for water use on pastoral dairy farms through quantification of water use on a range of irrigated and non-irrigated dairy farms across New Zealand. The second objective was the development of models to predict water use, from the identification of empirical relationships between measured water use and farm system and climatic drivers. The ability to generate detailed water use data provides an opportunity for the first in-depth analysis of regional and national water use patterns on pastoral dairy farms, and will further the discussion of water footprint methodologies. The on-farm water use data will provide a good benchmark to compare water use efficiency on dairy farms and, in turn, help to reduce and conserve water where over-allocation of resources occurs.

The specific objectives of this study were to;

1. *Measure the volume of water used on irrigated and non-irrigated pastoral dairy farms in contrasting regions of New Zealand;*
2. *Develop predictive models for water use on irrigated and non-irrigated pastoral dairy farms;*
3. *Carry out water use accounting and assess potential impacts of climatic change projections on water demands for dairy farming in all dairying regions of New Zealand; and*
4. *Assess water use on dairy farms using water footprint methods, focussed on a comparison and evaluation of the different methods, input data sources, and spatial scale of the analysis.*

1.3 Thesis Structure

This thesis consists of 6 other chapters which are outlined below.

Chapter 2 provides a review of the relevant literature which focuses on the water use of pasture-based dairy farms for which there is very little research information. Recent water footprint methods are discussed, explaining differences in their methodological approach. This chapter provides an overview of the literature, whereas individual chapters, which have been prepared for publication in Journals, provide reviews of the literature specific to the research presented in that particular chapter.

Chapter 3 seeks to address the lack of information available on water use on pasture-based farms, particularly in New Zealand. This chapter provides detailed water use data collected from non-irrigated dairy farms in the Waikato region. The patterns of milking parlour water use and stock drinking water are analysed and discussed. Leakage of water from the stock drinking water infrastructure is described, and a method for estimating the magnitude of this leakage is developed. This procedure facilitated the calculation of the corrected stock drinking water. A range of predictive models for milking parlour water use and corrected stock drinking water are developed and analysed. The content of Chapter 3 has been published in a peer-reviewed international journal (Higham et al., 2017a).

Chapter 4 provides an assessment of water use on irrigated farms in the Canterbury region, and non-irrigated farms in the Manawatu region, of New Zealand. The water use patterns for each region are analysed, including leakage from the stock

drinking water distribution systems. Water use between the regions is compared. The measured water uses are compared with the predictions using models produced in Chapter 3 for milking parlour water and corrected stock drinking water. The models preformed adequately for the non-irrigated dairy farms, but were not appropriate for use on the irrigated dairy farms in the Canterbury region. Therefore, the models were modified to predict water use on irrigated dairy farms. This paper has been published in a peer-reviewed international journal (Higham et al., 2017b).

Chapter 5 quantifies the total direct water use of dairy farms in New Zealand. Milking parlour water use and corrected stock drinking water are estimated for all dairy cows in all regions of New Zealand. Detailed data was collated from different sources to allow the prediction of water use at a monthly scale for five dairy seasons, from 2010-2011 until the 2014-2015 season. The volume of irrigation used for dairy farms was requested from 15 Regional Councils and unitary authorities. Water use consents were evaluated for water use and the actual use volumes were estimated, along with the consumed volume of water. The likely impact of climate change (Ministry for the Environment, 2016) on future water use in milking parlours and for stock drinking was also estimated for different regions and farm types. This paper has been submitted for publication in an international peer-reviewed journal.

Chapter 6 calculates the water footprint of dairy farming in the three regions considered in Chapters 3 and 4. The volumetric water footprint was calculated and three impact assessment water footprint methods were used. The three methods were the blue scarcity method of the Water Footprint Network (Hoekstra et al., 2011), the stress-weighted water footprint proposed by Ridoutt and Pfister (2010), and the newly developed Available WAter REmaining method of the Water Use in Life Cycle

Assessment (WULCA) group (Boulay et al., 2017). The water footprints calculated using the detailed local data - as presented in chapters 3 and 4 - is compared with the results calculated using global data. The water footprints were also compared at a regional and catchment scale to analyse the effect of scale on the footprints. A sensitivity analysis of the effect of using different environmental flow requirements, as used in the blue scarcity and availability minus demand methods (AWARE method), was also carried out.

Finally, **Chapter 7** provides a review of the major findings from Chapters 3 to 6, and links these together with conclusions of the outcomes of the research presented here, and outlines the areas where further research is needed in water use on pasture-based dairy farms and water footprinting.

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CHAPTER 2.

Literature Review

2.1 Literature Review Summary

This chapter reviews the literature relevant to the following topics:

- Stock drinking water
- Milking parlour water use
- Irrigation water
- Water budget of New Zealand dairy farming
- Water footprinting

In this Chapter the literature on water use on dairy farms is reviewed. This includes water for stock drinking and milking parlour use to establish the current body of knowledge. Irrigation water use is the largest water use in New Zealand, and must be considered to accurately account for water use on dairy farms in New Zealand; however, the focus of this research is not on irrigation so this section will not be expansive. Water use is being examined in increasing detail internationally for its impact on the environment and resources. The water footprints calculated to assess the water used to produce products are being compared to assess which products are more environmentally friendly. Water footprinting is an area of rapid development and increasing focus so will be reviewed here.

2.2 Water Use on New Zealand Pasture-Based Dairy Farms

Over the past 40 years, dairy farms in New Zealand have changed substantially (DairyNZ and Livestock Improvement Corporation, 2015). The most significant

change has been increasing cow numbers, which increased from 2,091,950 in 1975/76 to 5,018,333 in 2014/15 (DairyNZ and Livestock Improvement Corporation, 2015). Increasing cow numbers, especially in regions requiring irrigation, increased water use by dairy farms. There have also been significant improvements in a cows' genetic ability to produce milk and milk production per hectare has increased steadily over the last 20 years (DairyNZ and Livestock Improvement Corporation, 2015). Farms have also changed from all grass low input systems to a range of systems types as described in Table 2-1 (DairyNZ and Livestock Improvement Corporation, 2013). In the 2000-01 milking season, 70% of farms in New Zealand were low input (system 1 or 2), 17% were medium input (system 3) and 13% were high input (system 4 or 5). The percentage of low input farms decreased to 32% by 2012-13, with medium input increasing to 40%, and high to 28% of farms in New Zealand (DairyNZ Economics Group, 2014). The growth and increasing productivity of dairy farming has increased the amount of water required through increased use for stock drinking water, milking parlour water use, and irrigation.

Table 2-1 New Zealand Dairy Production System Types (Ramsbottom et al., 2015).

Production System	Description
System 1	All grass self-contained, no supplement is imported, only supplement harvested off the effective milking platform are fed, and cows are not grazed off during winter.
System 2	Feed imported, either supplement or grazing off, fed to dry cows. Approximately 4-14% of feed in imported.
System 3	Feed is imported to extend lactation (typically autumn feed) and for dry cows. Approximately 10-20% of total feed is imported.
System 4	Feed imported and used at both ends of lactation and for dry cows. Approximately 20-30% of total feed is imported onto the farm.
System 5	Imported feed used all year, throughout lactation and for dry cows. Approximately 25-40 % (but can be up to 55%) of total feed is imported.

Dairy is important for New Zealand's economy; in 2012 dairy exports were worth $11.4 billion and made up 26% of total exports (Statistics New Zealand, 2013). Government and industry expectation is that dairy production will continue to grow in export value. The Dairy Industry Strategy includes a goal that by 2020, New Zealand dairy export earnings will increase by 55% (DairyNZ et al., 2013). Inevitably increased use of water resources is required if this goal is to be achieved. The economic benefits of irrigation are substantial (Flemmer and Flemmer, 2007, Corong et al., 2014), and increased government funding for irrigation through the Irrigation Acceleration Fund may assist with this goal alongside funding to improve freshwater management (Ministry for Primary Industries, 2017a).

There are three main direct water uses on dairy farms; drinking water for dairy cows, milking parlour water use, and irrigation water use. Water is also required for multiple indirect uses such as brought in feed, fertiliser production, electricity generation, in the production of animal health products (Zonderland-Thomassen and Ledgard, 2012), but the focus of this study is on the direct water use only, so these indirect uses are excluded. On an irrigated farm, the amount required for stock drinking water and milking parlour water use is less than 3% of the volume of water required for irrigation (Zonderland-Thomassen and Ledgard, 2012). But for regions and farms where irrigation is not used or is not common, stock drinking water and water for use in the milking parlour are a significant proportion of water taken from the aquatic environment (Environment Waikato, 2007).

2.3 Cow Welfare and Wellbeing

Water has been described as the most important nutrient for dairy cows (Beede, 1994, National Research Council, 2001, Beede, 2005). In general more than half a cow's body weight is water i.e. total body water in dairy cattle typically ranges from 56 – 81% of body weight. The lower value is for fat dry cows, and the higher value is for lactating cows, as fat content has approximately 10% or less water in it. (Houpt, 1970, Murphy, 1992, National Research Council, 2001). In general, 50% of the water in a cow is intracellular fluid, 15% is interstitial fluid and 5% is held in blood plasma (Houpt, 1970). The rest of the water, which can vary widely in volume, is held in the digestive tract.

As water makes up a significant proportion of a dairy cow's body weight, it is critical cows achieve sufficient water intake to maintain their body's water balance. Studies have reported that milk production temporarily decreases if cows have restricted access to water (Cowan et al., 1978, King and Stockdale, 1981). Milk production decreased by 20% when water intake by cows was restricted to half of the average water intake, caused by a decrease in dry matter intake (Burgos et al., 2001). Anything that impacts on water supply to dairy cows, could have significant impact on milk production.

2.4 Dairy Cow Drinking Water

There are three common sources of water for dairy cows; voluntary water intake (VWI), water from feed, and metabolic water derived from feed and body reserves through metabolic processes (Beede, 2005). Total Water Intake (TWI) is used to

describe the combined volume of VWI, water content of feed ingested and metabolic water. The oxidation of feed during metabolism produces water, with different volumes produced for different types of nutrients (Table 2-2) (Houpt, 1970). As volumes of metabolic water are small compared to VWI and water in feed, metabolic water is often ignored in the calculation of TWI. TWI then becomes the combination of VWI and the water content of ingested feed.

Table 2-2 metabolic water volumes (Houpt, 1970)

Compound	Water produced from oxidation (ml/g)
Carbohydrate	0.6
Fat	1.1
Protein	0.4

2.4.1 Dairy cow water intake – pasture systems

There is a paucity of information about water intake of cows on pastoral farms. Where information is available it is typically only for short trial periods, and not measured for a full year. In New Zealand our dairy systems are pasture-based (Hedley et al., 2006), hence the need to study water use in pastoral systems.

2.4.1.1 Stock drinking water – New Zealand

In New Zealand a figure of 70 L/cow per day has been the generally accepted volume of water required for drinking (Waikato Regional Council, 2012a, Ministry for Primary Industries, 2017b). The volume of 70 L/cow per day is based on old data that was first presented by Tauranga County Council in a report on Water Supply and Water Resources. They stated that stock water consumption was highly dependent on weather, and that 15 gallons (56.8 L) should be allowed for average water requirements (Tauranga County Council, 1964). However, it was suggested that water systems on farms should be designed to deliver 70 L/cow per day, the peak requirement for dairy cows (Tauranga County Council, 1964). This 70 L figure was also recommended by Harrington in the 1980's who referenced the Tauranga County Council report and other unpublished data, in a widely published report on the Water Consumption of Sheep and Cattle in New Zealand (Harrington, 1980). This value continues to be used as a guideline in many current publications including DairyNZ farm facts and reports by Regional Councils (Stewart and Rout, 2007, DairyNZ, 2012a, Waikato Regional Council, 2012a, 2014).

Water intake by cows has been measured as part of more recent studies, however, it is often not the focus of the research but instead measured to see if any of the experimental treatments have an effect on the water intake (Jago et al., 2005, Thom et al., 2013).

Stock Units (**SU**) have been used to describe water requirements of different stock classes (Aqualinc, 2004, Stewart and Rout, 2007), and are based on relativity to sheep equivalents; a medium weight ewe rearing one lamb is equal to 1 SU (Aqualinc, 2004). The SU equivalence for a dairy cow is 8-9, depending on her breed and size, and the SU of a beef animal is 6-7. (Stewart and Rout, 2007). Most sources present water requirements on a per head basis (Tauranga County Council, 1964, Harrington, 1980, Stewart and Rout, 2007), but SU are useful for comparisons with other farming types. The water requirements of dairy cows have been summarised by some as average day demand (**ADD**) values, or peak day demand values (**PDD**) (Aqualinc, 2004, Stewart and Rout, 2007). A summary of the published water requirements for dairy cows and other cattle classes in New Zealand are presented in Table 2-3.

Table 2-3. Published Dairy Cow Water Consumption Volumes (L/cow per d) in New Zealand

Source	Animal Description	ADD[1] (L/cow per d)	PDD[2] (L/cow per d)
Campbell (1958)	Milking Jersey cows (11.35 L/day milk)	22.3	50
(Thom et al., 2013)	Predominantly Holstein Friesian cows		77
(Morris et al., 2010)	3 trials 2 indoor 1 outdoor	41	
(Tauranga County Council, 1964)	Milking cows	56.4	70
Aqualinc (2004)	Milking cows (450kg)	36.0	72.0
DairyNZ (2006)	Cows in heat stress		100+
DairyNZ (2012a)	Cow water access	70	
Jago et al. (2005)	Milking Friesian cows (grass fed)	53.7	
	Milking Friesian cows (fed Total Mixed Rations)	73.0	
Harrington (1980)	Milking Friesians		
	Milking Jerseys (Massey, 1952)	22	60
	Milking Friesians (Ruakura, 1977)	27	52
		26	58
	Dry Friesian & yearlings (Ruakura)	15	40
	Friesian calves (Ruakura)	8	30
Australian and New Zealand Environment and Conservation Council [ANZECC] (2000)	Dairy cows in milk	70	85
	Dairy cows, dry	45	60
	Beef cattle	45	60
	Calves	22	30
Lincoln University (2003)	Milking cows	70	
	Dry cows	45	
Quoting 70 L/cow (Stewart and Rout, 2007, Waikato Regional Council, 2012a, Ministry for Primary Industries, 2017b)	Milking cows – 70L/cow not defined as a peak or average value.		

[1]Average daily demand

[2]Peak daily demand

The ADD values have limitations for use as recommendations or guidelines because they are generally measured over hours to months and therefore are only applicable to the specifc time of measurement. Also, the ADD may not include the non-lacating period which for the majority of farmers is during the winter months when cows will drink less water due to cooler temperatures and higher rainfall. Likewise, the ADD may not include the warm summer period when cows are likely to drink more water if the trials were conducted in spring. A more accurate metric could be average milking day demand (**AMDD**), calculated over the period of the milking season where the majority of cows are milked twice a day, because for the majority of farm systems which have a typical 'spring' calving pattern (roughly between July and October) it would include the water consumption associated with peak lactation in spring and lactation in the warmer summer months. Lactation in general places a large water demand on cows, so the period of peak lacation and then the combination of lactation and warmer temperatures in the summer mean these two periods are expected to be the periods when cows have the greatest demand for water. Therefore, AMDD would be a more reasonable figure to base any guidelines or regulations such as consenting limits to ensure cow water demands are adequately met throughout an entire season. The AMDD will be used in this research to see whether this gives reasonable estimates of the drinking water requirements of dairy cows.

2.4.2 Overseas dairy cow water intake

A range of experiments measuring the intake of water have been carried out overseas in confinement systems. Voluntary water intake values from these studies are

presented in Table 2-4. Average water intakes varied from as low as 16 L/cow per day to 90 L/cow per day. At peak intakes, individual days were measured from near 0 to as high as 171 L/cow per day. Like the New Zealand studies most of these studies did not measure water use for an entire year. The average water intakes of the overseas studies were both above and below the 70 L/cow per day used in New Zealand.

2.4.3 Drivers of water intake

The amount of VWI required by dairy cows is affected by a number of factors. Observations of factors affecting water intake have been noted in New Zealand trials, but no trial has been conducted in New Zealand to create a model to predict water intake of dairy cows. Drivers of water intake reported in literature include:

- Body weight (**BW**); water intake increases with increasing size of the cows (Khelil-Arfa et al., 2012).
- Milk yield (**MY**); water intake increases with increasing milk yield (Murphy et al., 1983, Holter and Urban, 1992, Dahlborn et al., 1998, Meyer et al., 2004, Cardot et al., 2008, Khelil-Arfa et al., 2012).
- Stage of lactation; water intake decreases in the later stages of lactation (Holter and Urban, 1992).
- Dry matter intake (**DMI**); water intake increases with increasing dry matter intake (Murphy et al., 1983, Stockdale and King, 1983, Holter and Urban, 1992, Cardot et al., 2008, Khelil-Arfa et al., 2012).
- Dry matter % (**DM%**) of feed; water intake increases as the percentage of water in the feed decreases (Castle and Thomas, 1975, Stockdale and King,

1983, Holter and Urban, 1992, Dahlborn et al., 1998, Cardot et al., 2008, Kume et al., 2010, Khelil-Arfa et al., 2012).

- Concentrates (**Conc**); the increasing proportion of concentrates decreases the water intake, but at the same time increasing DM% increases water intake (Khelil-Arfa et al., 2012).
- Sodium; increasing dietary sodium increases water intake (Murphy et al., 1983, Meyer et al., 2004).
- Temperature; with increasing temperature water intake increases (Murphy et al., 1983, Stockdale and King, 1983, Meyer et al., 2004, Cardot et al., 2008).
- Sunshine hours; exposure to higher sunshine hours increases water intake (Cowan et al., 1978).
- Daily rainfall; cow water intake decreases with increasing rainfall (Cardot et al., 2008).
- Availability of shade; when shade is available water intake decreases (King and Stockdale, 1981).
- Timing and accessibility of water; water intake decreased when access was only provided to at the milking parlour before milking (Cowan et al., 1978, King and Stockdale, 1981).
- The presence of flies changes the pattern of drinking by cows with more frequent smaller drinks (Campbell, 1958).
- Ryegrass staggers; cows affected by ryegrass staggers have decreased water intake (Thom et al., 2013).

2.4.4 Dairy cow water intake predictions for confinement systems

The confinement dairy systems differ substantially from pasture-based dairy farms, as they can maintain more consistent feed composition and quality, and data can be collected from these systems more easily. The easy collection of data has helped to model water intakes in these systems. Table 2-4 presents the variables used to model water intakes in these studies. The dominant relationship in most models is DMI, DM% or MY to water intake. There are known relationships between dry matter intake and MY (Moate et al., 2000), and DM% will directly affect the amount of water ingested in feed. It is foreseeable that increased MY directly requires increased water due to the volume in milk. Dry matter percentage directly affects the total amount of water ingested in feed. Increasing DMI is often linked with increased MY, but there may also be the requirement for water to allow the biological functions to occur normally during digestion.

The models produced had a range of R^2 values from 0.45 to 0.92, showing that they can predict water intakes in those systems reasonably well. The model of Khelil-Arfa et al. (2012) which had the highest R^2, used DM%, MY, Conc, and BW to calculate water intake. This may be sufficient to predict water intakes in confinement systems, but leads to issues for prediction in pasture-based systems when no data is readily available for DM%, DMI, or MY.

Table 2-4. Review of models for variables[1] voluntary water intake (VWI) prediction in dairy farms.

Variables used	R^2 of model	DM % range in feed	Mean VWI (L/cow per day)	Range VWI (L/cow per day)	Description	Source
MY, DM%	0.73	25-88	49.9	20-87	Housed animals Winter in the UK British Friesian cows	Castle and Thomas (1975)
DMI, MY, Na, MinT	0.59	62-63	89.2	17-154	Large Holstein cows Housed, February - July in the USA	Murphy et al. (1983)
MY, DM%	0.67	46-89	63.6 71.6	-	Sweden Swedish red and white cows Housed in individual pens	Dahlborn et al. (1998)
DMI, MY, DM%, JD, JD²	0.64	28-90	36.6	16-61	Forage and concentrates Holstein cows USA, Housed Air-conditioned (18 °C)	Holter and Urban (1992)
MeanT, MY, Na	0.60	21-88	82	14-171	Fed a silage and concentrates Large German Holstein cows Germany Housed	Meyer et al. (2004)
DMI, MY, DM%, MinT, RF	0.45	48	84	24-143	Silage and concentrates Holstein cows Housed animals Involved in a feeding trial run at the same time, feeding TMR France	Cardot et al. (2008)

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Table 2-5 continued.

DM%, DMI, MY, Conc, BW	0.92	12-91	90 63	22-147 23-128	Compiled from 17 French studies, published and unpublished work.	Khelil-Arfa et al. (2012)
DM%, MY, Conc, BW	0.86					
DM%	0.66	38-64	16	0.3-40	Hokkaido Region of Japan A range of silages were fed.	Kume et al. (2010)
DMI, MY, Ash, DM%					Calculated based on fractions of drinking water bypassing the rumen estimated from Cafe and Poppi (1994) (steers) and Woodford et al. (1984) (dairy cows).	Appuhamy et al. (2014)
DMI, MY	-	88	57	26-75	British Friesian x Ayrshire Cows Fed hay and concentrates England	Little and Shaw (1978)
DMI, DM%, MeanT	0.58	20-55	30	15-51	August –October in Kyabram Victoria Australia Fed pasture and hay	Stockdale and King (1983)
Sunshine hours	0.74	38-45	78 60	-	Tropical Queensland – Australia Fed tropical pasture	Cowan et al. (1978)

[1] DMI = Dry Matter Intake, Conc = concentrates, BW = body weight, Ash = ash content, MY = Milk Yield (kg/day), MinT = Minimum daily temperature (°C), Na = Sodium content (g/day), JD = Julian day, MeanT = Average daily temperature (°C), Sunshine Hours = total per day, Conc = % concentrates in the diet, and RF = rainfall (mm).

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Some other factors that have been reported to affect VWI are access to shade, rainfall, flies and health conditions such as ryegrass staggers. (Campbell, 1958, King and Stockdale, 1981, Cardot et al., 2008, Thom et al., 2013). These factors largely relate to the changes in the wellbeing of the animals, and if their wellbeing changes, so too can their water intakes. The presences of flies led to more frequent but smaller drinks, although the effect on the volume of water intake was not reported (Campbell, 1958). Access to shade reduces the influence of climatic variables, including temperature, humidity, sunshine hours, wind and evaporation (not including rainfall), on water intake (King and Stockdale, 1981). Cows affected by ryegrass staggers have been reported to have decreased water intakes (Thom et al., 2013). Rainfall has been reported to decrease water intake of dairy cows (Cardot et al., 2008).

2.4.5 Dairy cow water intake predictions for pasture systems

Two overseas pasture-based studies reported predictive models of water intake (Cowan et al., 1978, Stockdale and King, 1983). One of these was based in Queensland, Australia where cows were grazing tropical pasture of high dry matter (DM) percentages ranging from 38 to 44% (Cowan et al., 1978). The other study fed cows ryegrass pasture and hay, and had DM% ranging from 20 to 55% in the different treatment groups (Stockdale and King, 1983). This study was conducted over a two month period in spring (Stockdale and King, 1983). These studies did not cover a full season and did not have very low DM% pasture (< 20%) therefore they are not expected to be adequate to model water requirements over a full season in New Zealand.

Feed can contain a range of different dry matter (DM) contents depending on the feed type. Dry matter of pasture is typically between 12 and 30% (DairyNZ, 2012b), and total mixed rations can have 49 - 90% DM (Houpt, 1970, Murphy et al., 1983, Jago et al., 2005). The high water content of some pastures results in minimal drinking water requirement for non-lactating ruminants, as they receive enough water in the feed (Houpt, 1970). During summer the DM content can increase substantially. On DairyNZ's Scott farm in the Waikato region, the DM% can reach 35-41 % in very dry summers as presented in Figure 2-1. In wet summers it is between 15-24 % DM. This suggests large differences between years in the amount of water consumed in the pasture by cows and hence related differences in drinking water requirements (DairyNZ, 2014).

Pasture dry matter in the Manawatu also had higher DM % in summer (I. Tait, Massey University, Palmerston North, New Zealand, personal communication), but this was not the case for the DM % of irrigated pasture in Canterbury presented in Figure 2-2 (A. Clement, DairyNZ, Lincoln, New Zealand, personal communication). The DM % did not go above 23% for the two years of measurement.

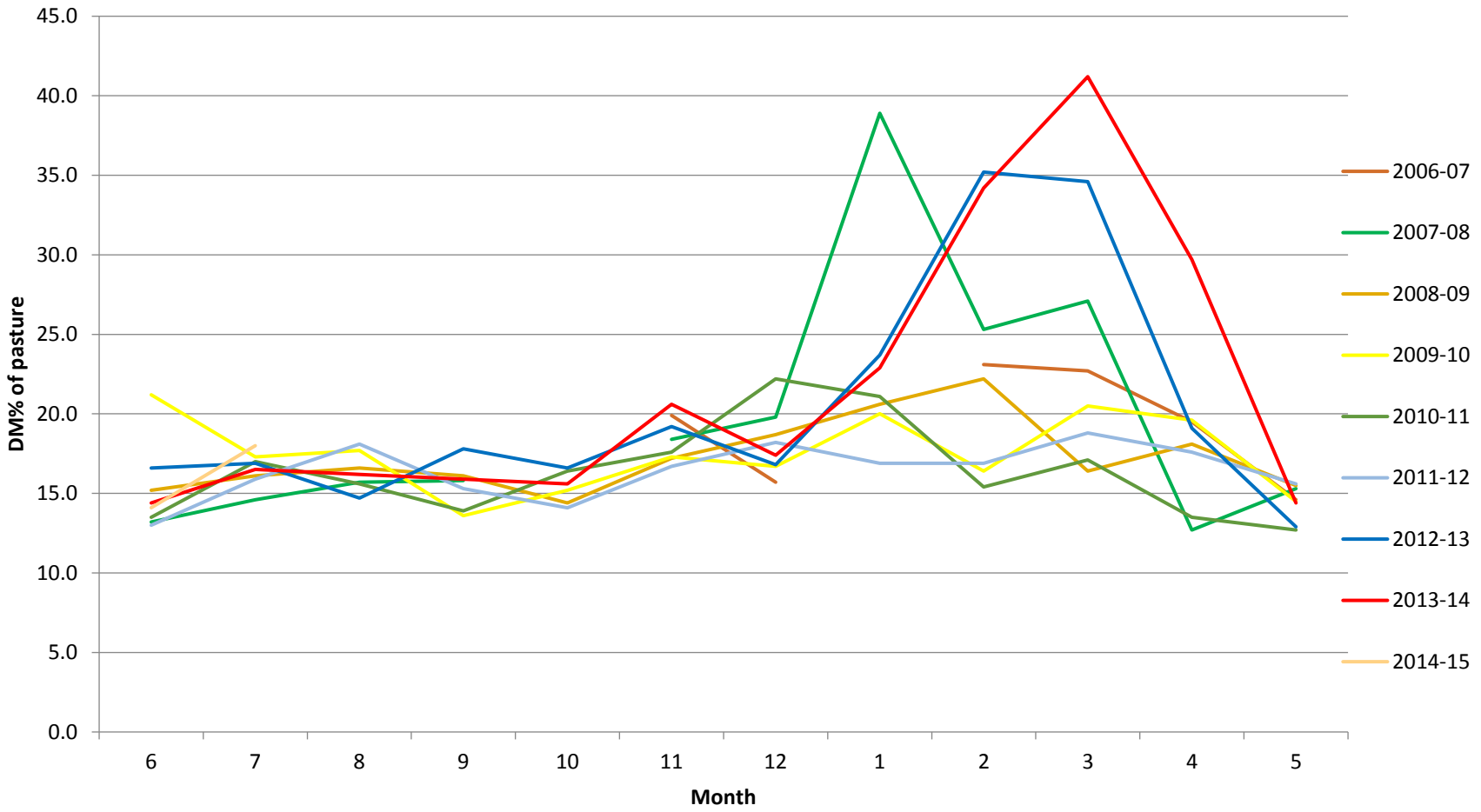

Figure 2-1. Monthly dry matter % of pasture at Scott Farm, a research farm in the Waikato region of New Zealand from 2006-2015 (C. Roach, DairyNZ, Hamilton, New Zealand, personal communication).

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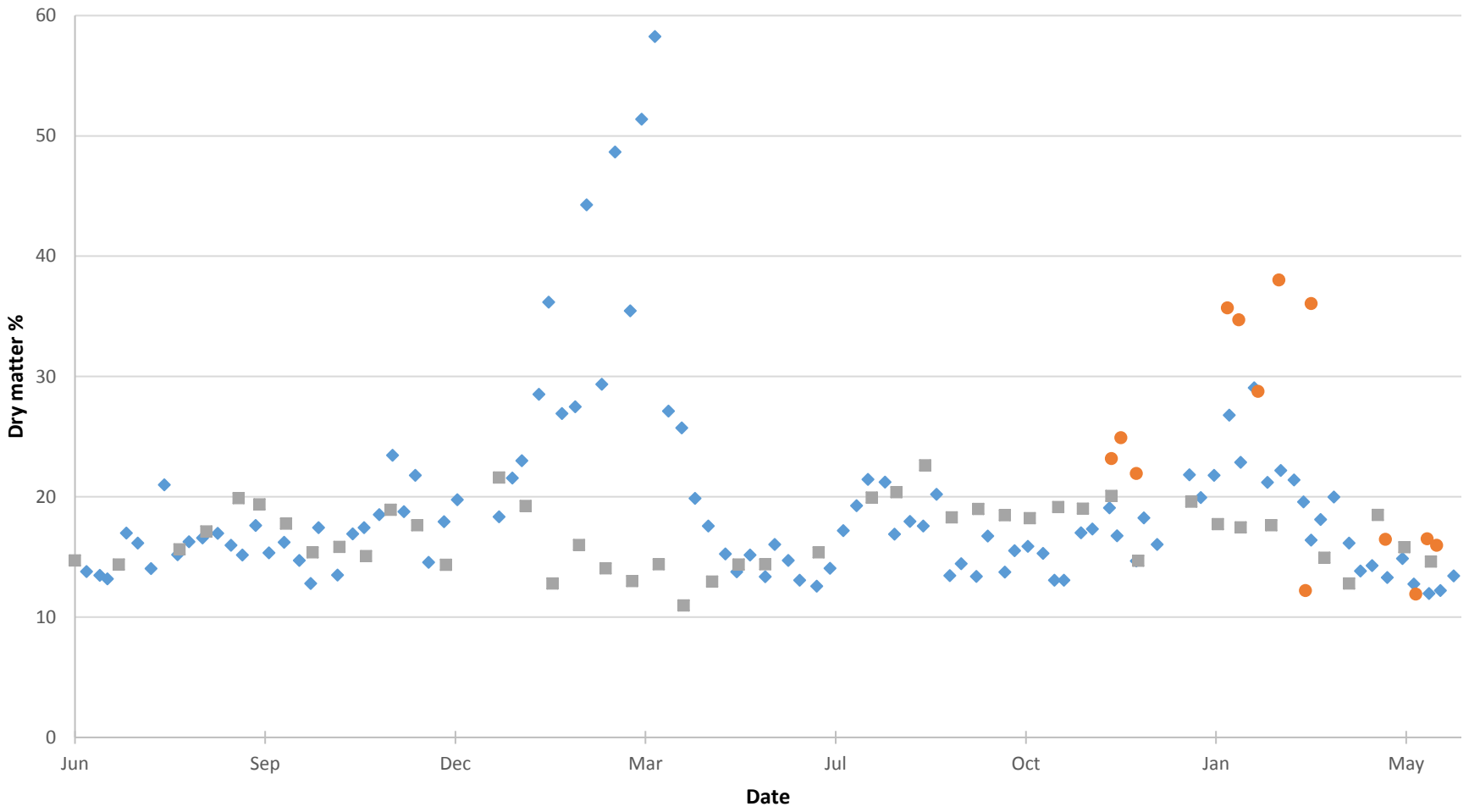

Figure 2-2. Dry matter % of pasture at research farms in the Waikato (weekly measurements, diamonds), Manawatu (a range of intervals, circles), and Canterbury (fortnightly measurements; squares) regions of New Zealand from 1/06/2013 to 31/5/2015 (C. Roach, DairyNZ, Hamilton, New Zealand, personal communication; A. Clement, DairyNZ, Lincoln, New Zealand, personal communication; I. Tait, Massey University, Palmerston North, New Zealand, personal communication).

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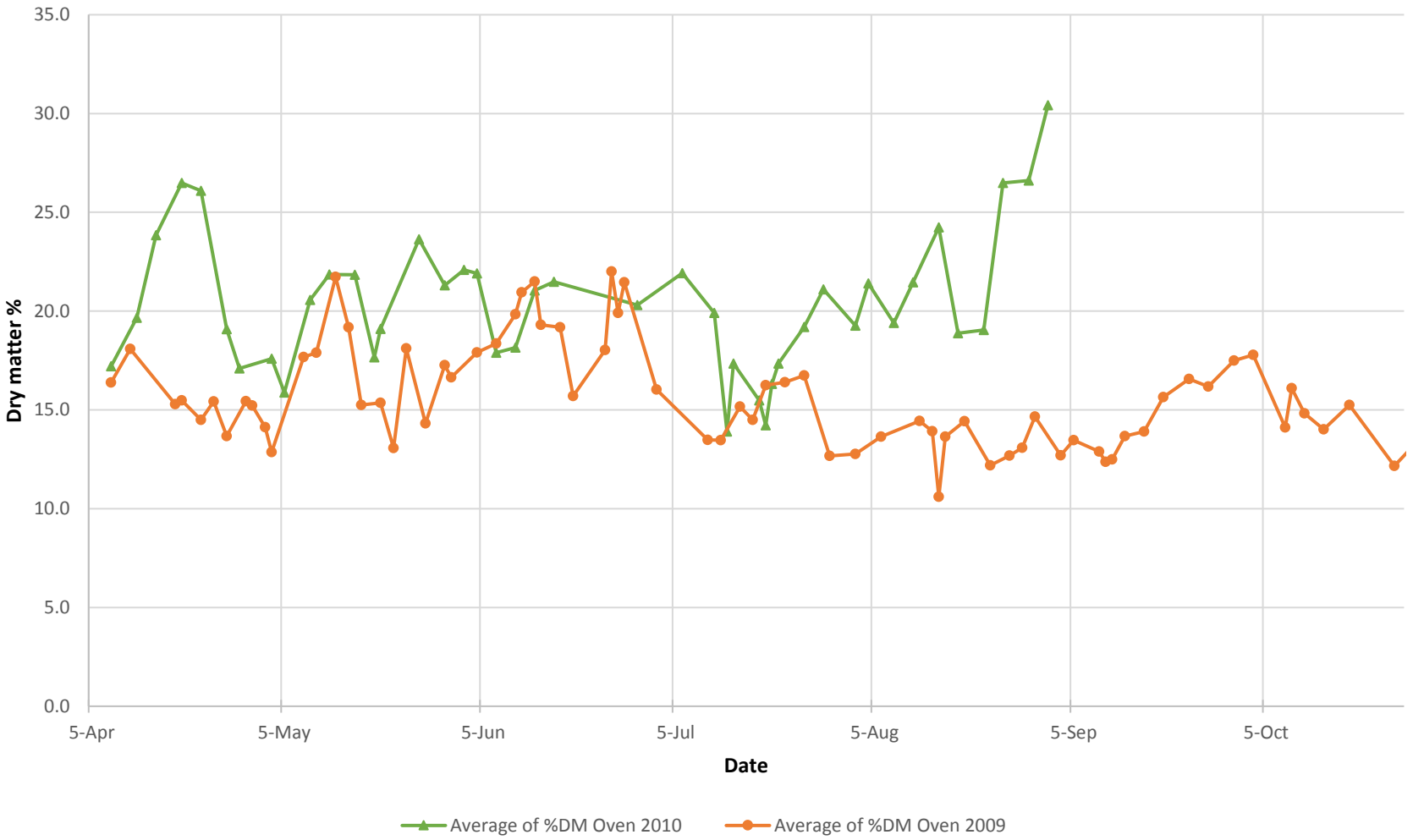

Figure 2-3. Pasture dry matter % in Moorepark, Ireland over two trial periods in the spring and summer of 2009 and 2010 (C. Wims, DairyNZ, Hamilton, New Zealand, personal communication).

Pasture DM % over two years of trial periods in Ireland are presented in Figure 2-3. Dry matter % was lower than the non-irrigated regions in New Zealand in summer, but was greater than values measured on the Canterbury irrigated farms. The estimated water ingested in pasture is presented in Figure 2-4. The simplistic model assumes constant feed eaten throughout the year, where in reality it would vary. Even so, the model indicates that there is significant variation in the amount of water ingested in pasture throughout the year, and also differences between years. The amount of water consumed in feed were above 100 L a day, and below 20 L a day at different times of the monitoring period.

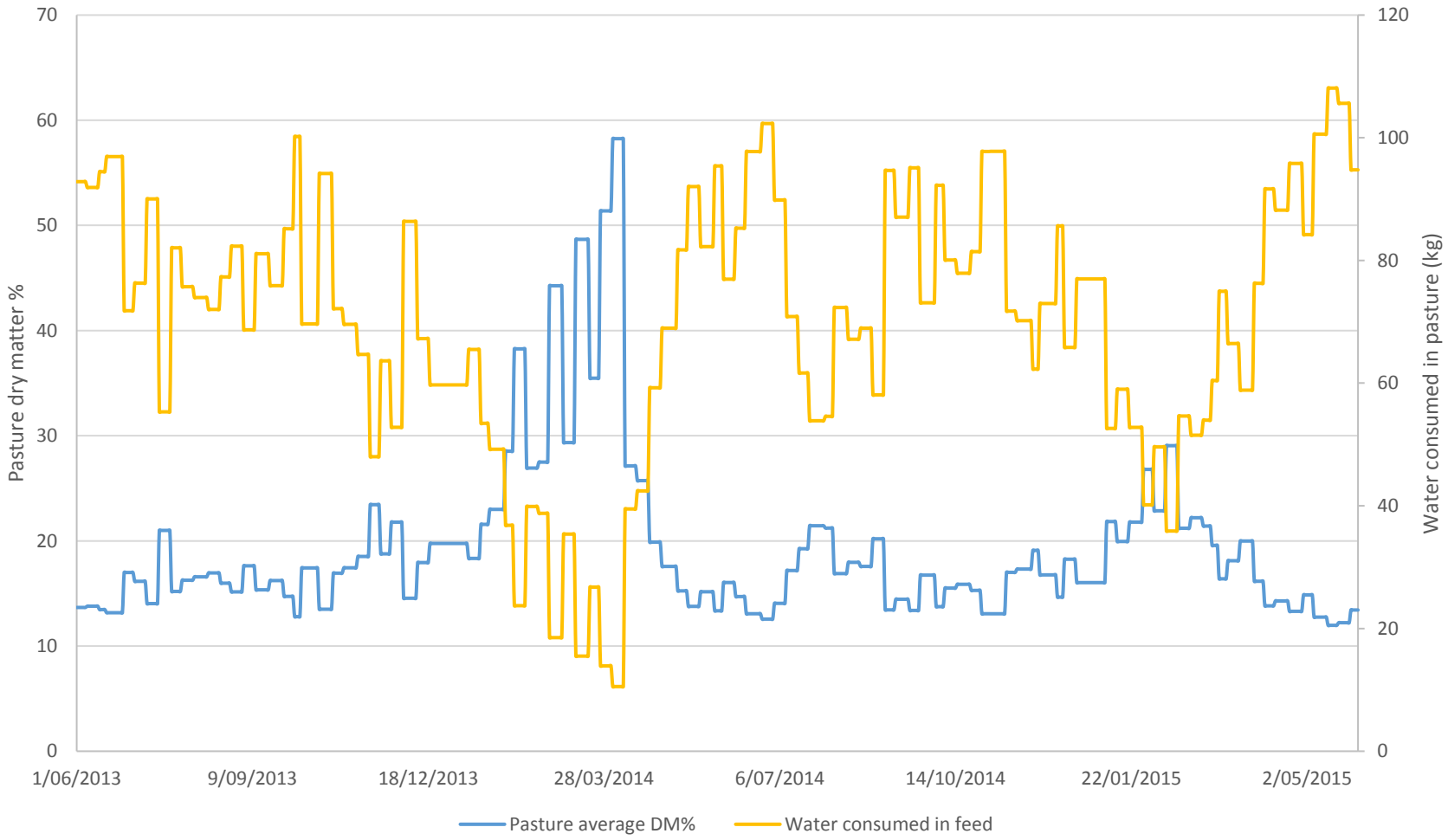

Figure 2-4. Expected water intake through pasture eaten in a simplistic model of 14.7 kg of dry matter eaten per day.

As the variation in water consumed in pasture is expected to be highly variable depending on the time of year, it is not expected that VWI equations developed for confinement systems, where the range in DM % is relatively narrow, will be able to predict dairy cow water intake for pasture-based farms.

2.4.6 Summary

Very few of the published articles on the drinking habits of dairy cows are New Zealand based and unfortunately the different; climatic conditions, cow breed, and high input housed systems often mean that overseas studies are not comparable to the New Zealand system of pastoral farming. The bulk of the New Zealand based articles are more than thirty years old and the only two recent articles are by Jago et al. (2005) and Thom et al. (2013). They studied the behaviour of water intake and measured water intake alongside a ryegrass endophyte trial respectively, but over relatively short periods.

The paucity of relevant information, the importance of dairy as a water user, and the growing importance of water resource management in New Zealand indicate that research is required into the volume of water required per cow on current farm systems 1-5 under New Zealand conditions over a full season.

2.5 Milking Parlour Water Use

Farm milking parlour and feed pads use water for a number of purposes, including: milk cooling; plant wash; pit and yard washing; udder washing; and feed pad sluicing. Water use volumes are increasingly being regulated by Regional Councils (Waikato Regional Council, 2012a, Horizons Regional Council, 2014). Feed pads, although not part of the milking parlour, are included by Regional Councils as an industrial use, so will be discussed here. The volume of water required for washing and cleaning in place (CIP), depends on a number of factors including plant age, milking time, plant type, number of clusters, extensions, amount of concrete area, backing gate with yard wash, flood washing, milking practices, storage volume, feed pads and cow numbers (L. Bowler, DairyNZ, Palmerston North, New Zealand, personal communication).

2.5.1 Milking parlour types

New Zealand values for water use in the milking parlour (MPW) are limited with an allowance of 70 L/cow per day for MPW (Tauranga County Council, 1964, Harrington, 1980) being the most commonly used figure. Where values are given, it is not clear if they are for average or maximum water use, and these values have not been distinguished on parlour type.

Relevant international MPW literature is limited (Meyer et al., 2006), and there is a large variation in water use from 27 to 734 L/cow per day, with some values well above the 70 L/cow per day used in New Zealand. The larger values may be partly due to the volume of water used for udder washing, which is not a routine practice in New

Zealand. Callinan (2009) investigated milking parlours in Northern Victoria, Gippsland and South Victoria in Australia, and estimated MPW of 39.5, 53.0 and 36.2 L/cow per day, respectively in the three regions and an overall average MPW of 42.4 L/cow per day. Murphy et al. (2014) reported annual MPW on 25 Irish dairy farms at 9,908 L/cow per year, which is 27 L/cow per day. Average herd size was 104 cows per farm, and the parlour type was not described, the low herd size may mean stock handling is much easier, and different milking parlour types may have been used, explaining why this value is much lower than 70 L/cow per day. In other literature, milking parlour types are significantly different to those used in New Zealand or were not defined making comparisons of water use difficult (Gamroth and Moore, 1995, Brugger and Dorsey, 2008, Janni et al., 2009).

2.5.2 Primary milk cooling

There are regulations around the cooling of milk in the NZCP1: Code of Practice for the Design and Operation of Farm Dairies, published by the Ministry for Primary Industries (2017b). These regulations specify how a farm dairy should be built and operated, including the temperature milk should be cooled to (primary cooling) and stored at. Although there are many variations, water is generally used in the primary cooling of milk. After the milk has been cooled by the primary cooler, refrigeration units chill the milk in the vat. Present regulations state that the primary cooler must be capable of cooling milk to 18 °C or lower. Changes to milk chilling requirements in the NZCP1 are coming (Ministry for Primary Industries, 2017b). These requirements mean that from June 2018 milk must be cooled more quickly than before,

and these changes are likely to push farms towards the use of rapid cooling technology thereby possibly decreasing water use.

Water cooling guidelines state that water coolers must have a flow rate at least 2.5 times the maximum pumping rate of the milk pump to ensure milk reaches the correct temperature before it enters the vat. Immediate cooling is recommended as best practice, to cool milk to 7°C before it enters the vat. There are different options for immediate cooling, including snap chillers, chilled water and ice banks. Having a primary water cooler before the immediate cooling system will reduce the temperature of the milk entering the immediate cooler, decreasing the electricity requirement and reducing costs.

Although the use of immediate cooling systems remove the need for water cooling, the requirements in the NZCP1 that the plant be cleaned and the parlour washed down for the safe production of milk will mean that a significant amount of water will always be used in milk parlours (Ministry for Primary Industries, 2017b).

Water used in the primary cooler is normally captured, and stored in tanks for use in wash down of the parlour and the washing of the milking plant. Where possible, farms try to match these two volumes, to reduce wastage, and minimise pumping costs. Sometimes this is not possible due to low storage capacity, or the temperature of the cooling water is higher, so flow rates through the primary cooler are increased to ensure that the milk reaches 18°C or less before entering the vat. Where systems do not have enough storage, extra water will overflow the tanks and be lost. Some farms also use stored excess cooler water for stock. There are many different configurations of water systems in parlours, often making direct measurement (e.g. via water metering) difficult.

2.5.3 Plant washing

The NZCP1 states that 70 L/cow per day of cold water should be available for the parlour and plant sanitation, including milk cooling (Ministry for Primary Industries, 2017b). The volume of water used for plant washing will vary, depending on the plant type and number of milking cup clusters. There are two main cleaning procedures; reverse flow washing and recycled washing. Generally older plants have reverse flow washing, where water is passed through the plant and out of the individual cups to clean them (DairyNZ, 2015). This water is deposited in the pit area, and is not recycled through the plant. This is not recommended in any new plant. Recycled washing systems involve recycling wash water through the plant a number of times during the cleaning process, which allows a smaller volume of water to be used with better cleaning. The volumes of water and the number of hot and cold washes are set by the detergent company provider to ensure thorough cleaning. Reverse flow cleaning requires greater volumes of hot and cold water for acceptable cleaning (DairyNZ, 2015).

A recent change to the requirements in the NZCP1 states that after washing with detergents, the plant must be rinsed, with a minimum of 5 L per cluster (Ministry for Primary Industries, 2017b). This is to remove detergent residues but will increase the volume of water used in the cleaning process, especially in plants using reverse flow cleaning. This water can be captured for the initial rinse of the following milking's cleaning programme. This requires a particular set up, and cannot be done in plants using reverse flow cleaning.

2.5.4 Pit and yard washing

Under the NZCP1, the dairy yard must be cleaned after every milking (Ministry for Primary Industries, 2017b). The volume of water required for yard cleaning has not previously been studied. This is probably because of the large variability in yard sizes, shapes, wash systems and people carrying out the cleaning. There are also many different yard wash systems including manual high pressure hose washing, washing backing gate systems, scraping (chain or sand filled pipe), other water jet systems, tipping drums, and flood wash systems. Clean water is used in most of these systems, but green water (recycled effluent water) can be used. The use of green water (recycled effluent) recovered from effluent is allowed for cleaning the yard area only, and is goverened by strict regulations (Ministry for Primary Industries, 2017b). Lincoln University (2003) state in the Farm Technical Manual that high pressure hose wash down generally uses 90 to 100 litres of water per minute.

2.5.5 Udder washing

Udder washing is undertaken for animal health and milk quality reasons. In the 1980-90's the Ministry of Agriculture and Fisheries (MAF) promoted udder washing using high volumes of water (Ministry of Agriculture and Fisheries, 1986). The volume of water required for udder washing was estimated to be between 1,000 to 2,000 litres per milking for a 200 cow farm, so the average volume is 10-20 L/cow per day (Rout, 2003). In a questionnaire carried out by DairyNZ in April 2013, 21% of farmers said they routinely wash teats. Of these farmers, 10% washed all teats, and 88% only the dirty teats (Livestock Improvement Corporation, 2013). If farmers routinely wash the

udders of their cows, then it is likely their milking parlour water use will be higher than those who do not wash their cows' udders.

2.5.6 Feed pads

Feed pads are relatively new to the New Zealand dairy industry. They are not technically part of the milking parlour, but when it comes to water use, it is classed as an industrial activity, requiring resource consent (unless otherwise permitted), the same as milking parlours. Therefore, water use for their cleaning is generally grouped together with milking parlours in resource consents.

As feed pads are not part of the milking parlour they do not have the same regulations under the NZCP1, which means they don't require daily cleaning. Therefore, the farmer is allowed to clean at a frequency they determine. This makes it very difficult to determine the amount of water required for the farm as there will be significant water use peaks when the feed pads are cleaned. Generally feed pads are similar to yards when it comes to cleaning and similar cleaning techniques can be used to clean them. One of the main differences in feed pads is that they are often scraped. The dung can be left to dry to a semi-dried state and then scraped off the feed pad into a holding area. Some feed pads are also covered, making scraping easier as there will be no rain diluting effluent on the feed pad.

2.5.7 Total milking parlour water use

The total water requirements for milking parlour use as reported in New Zealand and a further breakdown of some uses within the milking parlour are presented in Table 2-6.

Table 2-6 Water Use in the Milking Parlour

Source	Milking parlour water requirements
Aqualinc (2004)	70 L/cow per day
DairyNZ (2012a)	70 L/cow per day
Rout (2003)	70 L/cow per day Milk cooling:70 L/cow per day at 3:1 water to milk cooling ratio at peak milk of 20-30 L/cow per day. Average requirements of 40-50 L/cow per day. Plant wash: 3.5 to 5.5 L/cow per day Yard wash: 50 L/cow per day
Rout (2004)	70 L/cow per day
Lincoln University (2003)	10 litres/minute for cup washing. 90-100 litres/minute for high pressure washing down. This was published to be equivalent to 70 L/cow per day by Stewart and Rout (2007).
Tauranga County Council (1964)	75.5 L/cow per day on average. 34-125 L/cow per day range on different farms.
Auckland Council (2012)	From report No. 57, ARWB, 1990 a survey was carried out on 20 farms in the Franklin District. From 6 of these farms the average dairy wash water volume was estimated and then averaged over the 6 farms giving an average of 50 L/cow per day.

The total volume of water required for milking parlour running and cleaning is most often reported as 70 L/cow per day. None of the reports listed in Table 2-6 relate the water use to parlour type. Rotary parlours have been said to be higher users of water, depending on how they are operated (L. Bowler, DairyNZ, Palmerston North, New Zealand, personal communication). The management of parlours can change the volume of water per cow, as does the size of the herd. There is anecdotal evidence of a trend of more efficient water use in parlours with larger herds. This was also noted by the Tauranga County Council (1964) who also noted that herringbone parlours were more efficient than conventional walk through parlours (Tauranga County Council, 1964). This indicates the age of the study, as both herringbone and rotary parlours would now be considered conventional systems.

2.5.8 Summary – milking parlour water use

Milking parlour water use is considered an industrial activity by councils, that typically, when above certain thresholds of water use, require water use consents. There is little known about milking parlour water use in New Zealand. The different types of sheds, and the many different configurations gives large complexity to the water requirements of the different systems. The guideline value of 70 L/cow per day is an outdated value from shed types not commonly used in New Zealand anymore. Therefore research is needed to collect detailed data for use in water allocation and infrastructure planning.

2.6 Irrigation Water Use

Irrigation is vital to the productivity of pastoral dairy farming in several locations in New Zealand. Without it, intensive farming, especially dairying, would likely be uneconomic in these areas. There have been a large number of irrigation schemes established in a number of regions (Irrigation New Zealand, 2014). Early schemes were often initiated with government help and over time have transferred into private management. The largest area irrigated is the Canterbury Plains, which in 2012 had 444,777 ha of land under irrigation (Corong et al., 2014). Over half of the irrigated land in New Zealand is in Canterbury. The type of irrigation has changed over time from being predominately border dyke irrigation, to over 80% spray irrigation systems (Dynes et al., 2010).

Forty nine percent of the 721,394 hectares of land under irrigation in New Zealand is for dairy farming (Statistics New Zealand, 2012, Corong et al., 2014). Dairying had the largest amount of land under irrigation in 10 of the 16 regions in New Zealand (Corong et al., 2014). However, the actual area under irrigation is likely to be lower than the consented area, as regional authorities have reported the actual area of irrigation can be significantly lower than consented area for some consents (Aqualinc, 2010). Of the total area of land consented for irrigation, 76% is for pasture irrigation (Aqualinc, 2010).

Irrigation makes up 46% of the weekly consumptive use allocation in New Zealand, with water for hydroelectricity generation using 41%. However, when looked at on an annual scale, irrigation makes up 21%. The annual allocated consumptive water

volumes presented in Table 2-7 show that the largest user of consumptive water use was for hydroelectricity in Southland, for water used by the Manapouri power station. The amount of water allocated for irrigation in Canterbury dwarfs all other regions making up 62% of the annual consumptive irrigation allocation. The next highest region is Otago, which is 21% of the annual consumptive irrigation allocation. All other regions contribute less than 4% to the annual allocation. Although these regions do not contribute a lot to irrigation use in regard to a national volume, when viewed as a proportion of their regional water use they are significant. In Marlborough 82% of the annual consumptive water allocation is for irrigation. Tasman, Gisborne, and Hawkes Bay range from 68 to 46% of their annual consumptive water allocation for these regions (Aqualinc, 2010). This shows that although the total contribution of irrigation water use may not be great for different regions, but they contribute a large proportion of the water use in those regions.

2.6.1 Summary - irrigation

Irrigation water consents have the most allocation for water use in New Zealand. There is a lot known about irrigation water use because of the benefits to production and economic significance it has in agriculture. Irrigation on dairy farms in New Zealand is dominated by the Canterbury and Otago regions. There is a lot of information available on irrigation, and irrigation is not the main focus of this study. Therefore, irrigation requirements will be discussed, but the research focus will not be on irrigation here.

Table 2-7 Annual water allocation by region and primary use (Aqualinc, 2010).

2.7 Water Footprint Methods

The development of water sustainability measures has been ongoing for some time (Falkenmark, 1989, Gleick, 1996, Ohlsson, 2000), but there has been increased attention recently on water availability and methods to assess it (Ridoutt and Pfister, 2010, Berger et al., 2014, Boulay et al., 2017). This section will focus on recent water footprint methods.

There are two main schools of thought about water footprints; proponents of the Water Footprint Network and those of life cycle assessment (LCA). The Water Footprint Network (WFN) developed the volumetric water footprint based on the actual volumes of water used to produce a product (Hoekstra et al., 2011). There is the direct water use, e.g. irrigation water for a crop, and indirect water use e.g. the water used in the production of the fuel to power the vehicles harvesting the crop. Water use can also be defined as blue, green and grey water footprints. Blue water describes the water taken from surface or groundwater, where green water is the amount of water used that comes from rainfall held in the soil (Hoekstra et al., 2011). The grey water footprint is the amount of water required to dilute contaminants to natural background concentrations and existing ambient water quality standards (Hoekstra et al., 2011). As the grey water footprint has been adequately covered previously (Zonderland-Thomassen and Ledgard, 2012), it will not be analysed in this study but will only be discussed briefly.

In an LCA assessment, the impacts of product water use throughout the production chain on the environment, the water resource, and the ability of others to use water are analysed. There assessments are divided onto two different classes,

midpoint and endpoint assessments. Midpoints are considered to be links in the cause and effect chain such as water scarcity (Bare et al., 2000), whereas the endpoint is an over view of the entire chain such as biodiversity loss. Depending on the methodology and application, they can be either midpoint, endpoint or both (Bare et al., 2000).

2.7.1 Water Footprint Network (WFN) method

Traditionally water use accounting has focused on the direct removal of water from surface or ground water stores, for use in a process, e.g. farming. This is the water required to run that production/process, but it does not show the indirect water use requirements. Through trying to account more fully for water use in the system, the concept of 'virtual water' has been developed. It is the amount of water consumed in the production process of a product. This includes water consumed (lost from the system through evapotranspiration, transfer to another system, or incorporation into the product) in the process and water present in the product (Hoekstra et al., 2011, Herath, 2013). These are referred to as direct (water directly used in process) and indirect (water used in the production of products used in the current system i.e. electricity, brought in feed, etc.) water use (Figure 2-5). The water footprint network has developed a very similar method of water footprinting that categorises water using different colour indicators to be discussed in this section.

Figure 2-5. Schematic showing direct and indirect water use (Hoekstra et al., 2011)

2.7.1.1 Blue water

Blue water is water from surface or ground water resources. The blue water consumed as a result of the process, is considered the blue (consumptive) water footprint. Blue water has a high number of uses, so is considered to have high opportunity costs. But blue water also has a supply cost, as it has to be piped and pumped to the location that it is used (Hoekstra et al., 2011, Herath, 2013).

2.7.1.2 Green water

Green water is water from rainfall held in the soil as soil moisture. Water that is consumed through evaporation and transpiration during production or integrated in the harvested product, e.g. timber, is considered the green (consumptive) water footprint.

Green water use can only occur through occupation of land. The difference of green water to blue water is important, as green water is only available to plants at the precise location where it occurs. Because green water can only be used in one specific location it has a lower number of uses, therefore is seen as having a lower opportunity cost than blue water (Hoekstra et al., 2011, Herath, 2013).

2.7.1.3 Grey water

Grey water is the term used to indicate water pollution. The grey water footprint is an indicator of the pollution that can be associated with a product over its life cycle. It is calculated as the volume of water required to dilute all the pollutants produced to

a safe level, based on existing water quality standards (Hoekstra et al., 2011, Herath, 2013).

The combination of the blue, the green and the grey water is the water footprint of a product under the method of the WFN.

2.7.1.4 Blue water footprint impact index

To assess the local impacts of volumetric blue water footprint, the WFN method suggests calculating the blue water footprint impact index (**$WFII_{blue}$**) (Hoekstra et al., 2011) calculated as the blue water footprint multiplied by the blue water scarcity factor (**WS_{blue}**). Where, **WS_{blue}** is the blue water scarcity defined as the ratio of total blue water consumed (**ΣWF_{blue}**) to total blue water available (**WA_{blue}**) in the geographical region under analysis (Hoekstra et al., 2012). The WS_{blue} has a value of 1 at the point when all the available blue water has been used in a region; blue water use above this (WS_{blue} >1) is taking water from the environmental flow requirements (EFR). The $WFII_{blue}$ is used to contextualise the effects of blue water consumption and to carry out comparisons. For example, a product from two different regions may have very similar blue water footprints but the blue water resource in one region may be fully allocated and therefore under pressure although blue water extracted in the other region may be only a small fraction of total reserves (Hoekstra et al., 2011).

2.7.2 Life Cycle Assessment (LCA) methodologies

Life Cycle Assessment has been widely used for the assessment of various environmental impacts of the production process of products. Notable examples are

greenhouse gas emissions and energy use. Recently water use has also been analysed by LCA (Canals et al., 2009, Pfister et al., 2009, Ridoutt and Pfister, 2010). However, there are challenges in accounting for the environmental impacts of water use. Different LCA methodologies have been developed to quantify these impacts (Canals et al., 2009, Boulay et al., 2017, Pfister et al., 2009, Ridoutt and Pfister, 2010).

2.7.2.1 LCA method proposed by Canals et al. (2009)

The method of Canals et al. (2009) suggests that there are two main ways that water use can impact on freshwater resources, namely freshwater ecosystem impact and freshwater depletion. Freshwater ecosystem impact is described in examples where ecosystems may be damaged due to excessive water abstraction for human purposes (Canals et al., 2009). For example, if water use causes a drop in the ground water levels, which can cause changes in wetlands, or in another example where the environmental flow requirements of waterways are compromised (Canals et al., 2009). Freshwater depletion is an indicator of the impact of the extraction of groundwater on the availability of freshwater for future generations. Green water impact has been excluded, as it is available in natural systems regardless of the process being considered (Canals et al., 2009, Herath, 2013).

2.7.2.2 Water Stress Index (WSI) method of Ridoutt and Pfister (2010).

The method of Ridoutt and Pfister (2010) analyses water use in relation to water scarcity in the area that the water is used. It gives a stress weighted water footprint, which is expressed as an indicator of the impact of blue water consumptive use. The

impact of blue water consumptive use is calculated by multiplying the blue water use by the regional water stress index (Ridoutt and Pfister, 2010, Herath, 2013). As with the method of Canals et al. (2009), green water use is not included, as it is used regardless of the process being evaluated. The WSI is calculated as the withdrawal to availability ratio, and has a range from 0.01 to 1 (Ridoutt and Pfister, 2010). The freshwater withdrawals to hydrological availability (WTA) ratio is calculated for the region under investigation. A variation factor (VF) is applied to the WTA to give WTA*. The VF takes into account the variation in rainfall between months and years, recognising that this temporal variation affects river flows. There are two different variation factors, depending on the waterway in question will determine which is used. Strongly regulated flows (SRF), such as rivers with dams on them, use the square root of the VF. This is because stored water regulates the flow of the river reducing the stress on the river. In other words, the square root of the VF is used for strongly regulated flows (SRF), where stored water reduces the impact variations in rainfall have on the low flows of waterways. The WSI is normalised by dividing by the world WSI. The water withdrawal to water availability ratio can be misleading in the case of water extractions where a proportion of the withdrawn water is returned to the local water resource (Herath, 2013).

2.7.3 Hydrological water footprinting method

A hydrological approach to water footprinting has been taken by Deurer et al. (2011), rather than consumptive use water footprinting. This was done to more accurately reflect the total impact to blue water in the region where the water was taken.

Whereas the consumptive water footprint includes the total blue water lost from the system, the hydrological method accounts for both the blue water extracted as well as the blue water returned to the system. In their study, Deurer et al. (2011) compared water footprinting using the hydrological method to the WFN method for kiwifruit production in New Zealand. This gave quite different results. The WFN method calculated that on average 100 L of water was required to produce one tray equivalent of kiwifruit (i.e. 3.6 kg of kiwifruit). When the hydrological method was used to calculate the water footprint of one tray equivalent of kiwifruit they found that the average of -500 L of water was used. The number is negative, because over a year more water is returned to ground water than is consumptively lost from the system through evapotranspiration (Deurer et al., 2011). Using the hydrological method of water footprinting, the overall level of water consumption can be seen. So it is clear that the land use for kiwifruit production does not have a negative effect on the scarcity of blue water, and it may even have a positive one in most regions of kiwifruit production in New Zealand (Deurer et al., 2011).

2.7.4 The AWARE method water footprint

The Water Use Life Cycle Assessment (**WULCA**) group (Boulay et al., 2017) considered different characterisation factors before deciding on Available WAter REmaining (AWARE) method. The AWARE method calculates the availability minus demand (**AMD_i**). AMD_i is calculated as the amount of water available minus the requirement for human water consumption and the environmental water requirement; the remaining water is then divided by the area. Water availability here is defined as

natural runoff (rainfall minus actual evapotranspiration). The surface-time equivalent (**STe_i**), is calculated as 1/AMD, the inverse of the difference between availability and demand. It can be understood as the surface-time equivalent of unused water up to the point where demand equals availability. The STe_i is normalised by dividing by the $STe_{world\ av}$, and a maximum of 100 is set, as above this value demand is greater than availability, AMD_i becomes negative and the equation loses its meaning. A minimum of 0.1 is also set to create a range from 0.1 to 100 for the Characterisation Factor (CF; a value calculated and used to characterise water use in different areas).

2.7.5 Spatial scale

There are different ideas on what spatial scale to use in water footprinting analyses. The Water Footprint Network (WFN) suggests that whole river basins are analysed as some issues, such as the accumulation of pollutants downstream are only seen through a larger spatial scale (Hoekstra et al., 2011). The WFN also suggest that the disadvantage of fine resolution is that much more data is needed (Hoekstra et al., 2011). However, the accumulation of pollutants refers to the grey water footprints which is not considered here, and in New Zealand there are many catchments within each region, with some catchments differing substantially in water availability within a region (Taylor et al., 2001). To see differences between regions increased spatial resolution may be needed. In water footprinting methods that provide global CF layers (ETH Zurich, 2016, Water Footprint Network, 2016, Boulay et al., 2017), however there is not enough spatial resolution or alignment with New Zealand catchments, and differences in water availability can be lost.

2.7.6 Water footprinting of dairy farming in New Zealand

Zonderland-Thomassen and Ledgard (2012) published the only water footprinting article on New Zealand dairy farming, based on farms in Waikato and Canterbury. Zonderland-Thomassen and Ledgard (2012) calculated the blue, green, and grey water footprints, and also characterised water footprints using the $WFII_{blue}$, WSI, and the freshwater use impacts method (Canals et al., 2009). The water footprint was a cradle to farm gate analysis, considering indirect water uses such as artificial fertiliser production, electricity generation, imported feed, seed production, and replacement stock water use off farm. The total combined blue, green, and grey water footprint for the Waikato region was 945 L/kg fat and protein corrected milk (FPCM), and for the Canterbury region was 1,084 L/kg FPCM. In the Waikato region 72% of the water use was from green water derived from rainfall. In contrast, in the Canterbury region only 46% green water from rainfall with 23% blue water, mainly from irrigation. The WFII was 0.011 L/kg FPCM for the Waikato dairy farms, and was 14.6 L/kg FPCM for the Canterbury dairy farms. The results of the WSI water footprints were 0.011 L H_2O-equivalents/kg FPCM for the Waikato region and were 7.1 L H_2O-equivalents/kg FPCM for the Canterbury region. The freshwater use impacts water footprint for the Waikato dairy farms was 0.0061 L ecosystem-equivalent H_2O/kg FPCM, and for the Canterbury dairy farms was 14.6 L ecosystem-equivalent H_2O/kg FPCM. As the methods calculate the water footprints in very different ways, they are not directly comparable which can make comparing results from different studies difficult. However, the order in which water footprints fall can be compared when the

same regions are analysed through different methods. As the different methods are calculated based on different data this can give different perspectives on the effects of water use between the regions.

2.7.7 Summary – water footprinting

The area of water footprinting has been progressed significantly in the last decade. There have been numerous new methods developed, but there is little consensus as to which method to use. Water footprinting has been carried out on New Zealand, but this was carried out before recent methods were available. The direct water use data was also based on the outdated water use figures, that may not reflect the correct water use on dairy farms.

2.8 Literature Review Summary

Developments around water management policy in New Zealand is driving change in how water resources are managed by councils and dairy farmers. Currently there is a paucity of information on stock drinking water and milking parlour water use to allow councils to allocate water effectively, and for farmers to use in planning. Accounting for water use on dairy farms also requires more data, which is currently available. Water footprinting has been developed as a means to calculate impacts on water, compare water use of products and process between different areas of production, and give information to allow better management of water resources. Recent water footprinting methods have not been used on New Zealand dairy farms, and the water footprints that have been calculated used outdated industry figures for stock drinking

water and milking parlour water use. Therefore, there is an urgent need for information on current water use in pasture-based systems and drivers of water use to see how these influence New Zealand dairy farming.

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CHAPTER 3.

Water Use on Nonirrigated Pasture-Based Dairy Farms

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3.1 Abstract

Water use in intensively managed, confinement dairy systems has been widely studied, but few reports exist regarding water use on pasture-based dairy farms. The objective of this study was to quantify the seasonal pattern of water use to develop a prediction model of water use for pasture-based dairy farms. Stock drinking, milking parlour, and total water use was measured on 35 pasture-based, seasonal calving dairy farms in New Zealand over 2 yr. Average stock drinking water was 60 L/cow per day, with peak use in summer. We estimated that, on average, 26% of stock drinking water was lost through leakage from water-distribution systems. Average corrected stock drinking water (equivalent to voluntary water intake) was 36 L/cow per day, and peak water consumption was 72 L/cow per day in summer. Milking parlour water use increased sharply at the start of lactation (July) and plateaued (August) until summer (February), after which it decreased with decreasing milk production. Average milking parlour water use was 58 L/cow per day (between September and February). Water requirements were affected by parlour type, with rotary milking parlour water use greater than herringbone parlour water use. Regression models were developed to

predict stock drinking and milking parlour water use. The models included a range of climate, farm, and milk production variables. The main drivers of stock drinking water use were maximum daily temperature, potential evapotranspiration, radiation, and yield of milk and milk components. The main drivers for milking parlour water use were average per cow milk production and milking frequency. These models of water use are similar to those used in confinement dairy systems, where milk yield is commonly used as a variable. The models presented fit the measured data more accurately than other published models and are easier to use on pasture-based dairy farms, as they do not include feed and variables that are difficult to measure on pasture-based farms.

3.2 Introduction

Agriculture is the most significant water user in the world, accounting for an estimated 70% of global water withdrawals (World Water Assessment Programme, 2009); most of this water is used for irrigation. Agricultural demand for water is expected to grow to meet the 70% increase in global food production required to feed 9.7 billion people by 2050 (Food and Agriculture Organization, 2009; United Nations, 2015). As a consequence, where freshwater is scarce there will be an increased focus on improving the efficiency of water use (International Water Management Institute, 2007; Wani et al., 2009) and greater regulation of water use on environmental flows and water quality (Scarsbrook and Melland, 2015). Water footprinting methodologies are already being developed to enable water use comparisons between regions to

increase the efficiency of water use (Ridoutt and Pfister, 2010; Zonderland-Thomassen and Ledgard, 2012).

Total water (TW) use on dairy farms is typically divided into 3 key areas: stock drinking water use (SDW), milking parlour water use (MPW), and irrigation water use. Cow water requirements [voluntary water intake (VWI)] have been benchmarked for confinement systems (Murphy et al., 1983; Meyer et al., 2004; Cardot et al., 2008), but limited information exists on SDW (Jago et al., 2005), MPW (Callinan, 2009; Murphy et al., 2014) and TW in pasture-based systems. Although many models can predict VWI (Castle and Thomas, 1975; Dahlborn et al., 1998; Appuhamy et al., 2014), most have been developed in confinement systems, which are markedly different to seasonal pasture-based systems (Roche et al., 2013). For example, confinement dairy systems have a more consistent quality of feed and DMI, which is easier to monitor and use in the predictive models. In comparison, DM of fresh pasture can vary from <12 to >30% (DairyNZ, 2012) and DMI of pasture is difficult to measure accurately. Consequently, many of these models are not practical for use on pasture-based dairy farms. Furthermore, we could not find any published prediction models for MPW or TW from pasture-based dairy farms, or estimation of water loss from SDW distribution systems on pasture-based farms.

Voluntary water intake models are available and include a range of variables. Commonly used variables used to predict VWI are DMI, DM, milk yield, and temperature (Little and Shaw, 1978; Stockdale and King; 1983, Kume et al., 2010). Other variables used include sodium content (Meyer et al., 2004), BW (Khelil-Arfa et al., 2012), sunshine hours (Cowan et al., 1978), rainfall (Cardot et al., 2008), and Julian day (Holter and Urban, 1992). Some of these variables are available on pasture-based

farms or approximated with other measures, whereas others, such as sodium content and DMI, are difficult to measure. The objective of the current study was to quantify the seasonal pattern of water use to set benchmarks and develop prediction models of water use that are applicable to pasture-based dairy farms.

3.3 Materials and Methodology

Water use was measured on 35 dairy farms in the Waikato region of New Zealand (38°S, 175°E) between June 2013 and May 2015. Five farms were excluded from the data set due to insufficient or poor-quality data. Of the farm measurements, MPW, SDW, and TW were all recorded on 21 farms, and the individual water uses MPW, SDW, or TW were recorded on 10, 2, and 2 farms, respectively. The study sample size increased as water meters and telemetry were being installed and more farms began monitoring; the sample size grew until all 35 farms were supplying data, in total, 44.7 farm-years worth of data were collected. No specific average water-use values for any one day were calculated using data with a sample size less than 5 farms.

All SDW, MPW, TW, and farm total milk production data were converted to units per cow per day to allow comparisons across farms on a per-cow basis (L/cow per day, kg of milk fat plus protein, or milk yield/cow per day). Water use, milk fat plus protein yield, and milk volume were calculated from peak yearly cow numbers for the relevant season.

3.3.1 Farm description

All farms were seasonal (spring)-calving dairy farms, and the main characteristics of the case study farms are summarized in Table 3-1. Farm herd size

ranged from 160 to 1,150 cows per farm; 19 farms had herringbone milking parlours and 16 had rotary parlours, with the number of bails (stalls) ranging from 16 to 52 and 30 to 60 bails, respectively. Average rainfall for the farms was 1,053 mm per year. Average yearly maximum and minimum temperatures were 18.8 and 8.6°C, respectively. Average Priestly-Taylor potential evapotranspiration and solar radiation were 2.49 mm/d and 14.6 MJ/m^2 per d, respectively. Average milk volume was 4,536 kg/cow per annum, and average milk fat plus protein yield was 394 kg/cow per annum.

Table 3-1. Characteristics of dairy farms used for water-use analysis.

Variable[1]	Farm count[2]	System type,[3] no. (%)			Cow breed,[4] no., (SD)	Average cow number, no. (SD)	Average daily milk yield, kg/d (SD)	Average daily milk fat + milk protein yield, kg/d, (SD)	Average effective Ha (SD)	Herringbone parlours,[5] No. (%)	Average bail number, no. (SD)	Cow to bail ratio no. (SD)	Average number of houses taking water from stock line, no. (SD)
		1-2	3	4-5									
SDW	23	7 (30)	6 (26)	10 (43)	0.56 (0.267)	492 (204.2)	12.7 (7.88)	1.11 (0.647)	166 (84.9)	11 (52)	39.2 (11.51)	12.4 (2.55)	0.52 (1.123)
cSDW	20	6 (30)	6 (25)	9 (45)	0.56 (0.272)	511 (208.2)	12.8 (7.86)	1.11 (0.639)	172 (87.1)	9 (45)	39.9 (11.49)	12.6 (2.56)	0.47 (1.124)
MPW	31	6 (19)	15 (48)	10 (32)	0.60 (0.241)	534 (225.2)	12.5 (7.94)	1.09 (0.648)	187 (98.7)	17 (55)	40.5 (11.47)	12.8 (2.68)	N/A[6]
TW	23	8 (35)	6 (26)	9 (39)	0.56 (0.291)	490 (200.1)	12.5 (7.81)	1.10 (0.647)	166 (82.8)	14 (61)	38.7 (11.02)	12.5 (2.49)	N/A

[1]SDW = stock drinking water; cSDW = corrected stock drinking water = SDW – Leakage; MPW = milking parlour water use; TW = total water use.

[2]Farm count after the exclusion of data.

[3]System type based of the DairyNZ 1-5 system classification (Ramsbottom et al., 2015).

[4]Cow breed: 1 = Friesian, 0.5 = Friesian-Jersey Cross, 0 = Jersey.

[5]Swing-over herringbone milking parlours (single herringbone); all parlours not herringbone parlours were rotary parlours.

[6]N/A = no measured data.

3.3.2 Data collection

Water use was collected continuously using water meters with a telemetry system. All water-use data were recorded at 15-min intervals, except 3 farms that supplied water-use data with hourly or daily volumes (2 farms measuring MPW; 1 farm measuring TW). The selected farms were categorized by production system type according to the amount of nonpasture feed purchased per cow per annum (Ramsbottom et al., 2015). A system 1 farm is the lowest input production system (pasture-based with no imported feed) and system 5 is the highest input system (25–40% imported feed).

Daily climate data were sourced for the entire study period. A total of 730 daily records on 24-h maximum temperature (°C), 24-h minimum temperature (°C), 24-h rainfall (mm), 24-h solar radiation (MJ/m2), 24-h wind run (km), and 24-h potential evapotranspiration (mm) were obtained from the NIWA Virtual Climate Station Network (Cichota et al., 2008). The Virtual Climate Station Network uses data from weather stations and interpolates it over a 5 by 5 km grid across New Zealand.

3.3.3 Data management and calculations

Total water use is defined as MPW plus SDW and was measured at the source (abstraction point). Stock drinking water is defined here as the VWI of cows (water drank from a trough as opposed to water ingested in feed or metabolic water) and any water loss that occurs in water-distribution systems on farms (leakage incurred distributing water via pipes and troughs to cows in the paddock).

Water-use data were processed using Hilltop Software (Kmoch et al., 2015), a Microsoft (Redmond, WA) Windows-based database and reporting application

suite for hydrology-related time series data. Visual quality checks were performed using the graphing functions of Hilltop Software. Invalid days (i.e., days that had missing data in the 15-min scale caused by recording errors) were removed. Data were excluded from analyses for the following reasons: the water meter for SDW only covered part of the farm (n = 2); a housing development took unknown amounts of water from the SDW line (n = 1); and water uses could not be distinguished from each other (n = 1). Where TW was measured in conjunction with MPW or SDW, using 2 separate water meters, the unknown MPW (n = 11) or SDW (n = 1) value was calculated using equations [1] or [2], via coding in Hilltop Software:

$$MPW = TW - SDW, \quad [1]$$

and

$$SDW = TW - MPW. \quad [2]$$

All SDW data were exported from Hilltop Software at 15-min intervals to ensure all time stamps were identical for the data set. Milking parlour water use and TW were exported from Hilltop Software at daily intervals. Further data management was carried out in MS Excel (Microsoft Corp.). During the initial analysis, water leakage from the distribution system was suspected because of large differences in water usage on individual farms in the 15-min water data sets. Therefore, SDW data were analysed and adjusted (corrected) for loss (i.e., leakage) from the water-distribution system at this time scale using a modification of the minimum night flow leakage estimation method (Tabesh et al., 2009; Cheung et al., 2010). According to this methodology, the average water-use rate between 0000 and 0300 h, defined as average night flow, was subtracted from that day's SDW rate. This method assumes that stock drink negligible quantities during this period

(Jago et al., 2005). Average night flow was used over the minimum flow, as water meters pulse at set volumes, typically between 1 to 100 L. Therefore, low leakage rates can have zero pulses in a 15-min period and small leakages would be missed using the minimum night flow.

Program code was written in R (R Core Team, 2015) to automatically identify when leakage events occurred (Supplemental File S1; https://doi.org/10.3168/jds.2016-11822). The code was written to include the average 15-min flow rate (i.e., leakage) calculated from the 0000 to 0300 h period, which was subtracted from that day's 15-min stock drinking water data. Leakage was deemed to have ended when 4 out of 5 consecutive values were below 0.75 of the calculated leakage rate or when the end of the day was reached. When leakage was identified, then the previous day's data were checked (working backward through the data). If no correction was found in the previous day (as would be the case if a leak began during the day), then the data were corrected. The correction stopped when 4 out of 5 consecutive values were below 0.75 of the calculated leakage rate until the start of the leak was reached. If the day was already found to be corrected, then the script moved onto the next day. Variations in SDW volumes at the 15-min time scale, which did not trigger the end of the correction, can give rise to small negative values once corrected; the script set these to zero. The adjusted SDW was thereafter termed the corrected stock drinking water (cSDW). Three farms were excluded from having their SDW corrected, as the pump and tank infrastructure prevented the pumping pattern being able to be related to water usage due to water filling storage tanks at night. The data from these farms were used for the SDW calculations, but not the cSDW and were not included in the derivations of water-use models. Leakage rates in parlours were 0.7% of MPW. As the leakage

rate was so low, MPW was used without correction in all analyses. Water for domestic use was sourced from the stock water distribution line on 11 farms (Table 3-1). The number of houses on these farms ranged between 1 and 4. A total water use of 1,500 L/d per house was assumed, based on average water use of 300 L/d per person, for a 5-person household (Ministry of Health, 2006); this domestic water use was subtracted from SDW and cSDW. Total water use on 10 farms did not include domestic water use; however, on 13 farms domestic water use was unable to be separated out from TW. As it was estimated to be less than 5% of the TW, this was considered a minor issue and the data were used without correction. On 2 farms houses collected rain water for domestic use; they used SDW to fill their tanks for short periods during summer if rainfall was not sufficient for requirements. This was not accounted for, as we were not able to determine accurately whether SDW water was used in this manner.

3.3.4 Statistical analyses

We calculated the effects of milking parlour type and season on average water use, and the effect of season on the estimated leakage from SDW. For this purpose, the year was split into 5 seasons, aligning the nonmilking period with the winter season (June and July), early spring (August and September), late spring (October and November), summer (December to February), and autumn (March to May). Analysis was based on a split-plot model, with milking parlour type included in the main plot and season and season-by-parlour type in the subplot. Milking frequency was included as a covariate.

Table 3-2. List of farm variables used for water use modelling.

Variable abbreviation	Variable description
TMax	Maximum daily temperature (°C)
TMin	Minimum daily temperature (°C)
Rain	Rainfall (mm)
Evap	Priestly Taylor potential evapotranspiration (mm)
Wind	Wind run (km)
Rad	Solar radiation (MJ/m²)
Milk Sol	Milk solids (milk fat + milk protein, kg)
Milk Vol	Milk volume (L)
Milking	Number of milkings in a day
System	Production system type (1 to 5)
FeedPad_Yes	Feed pad present
YrRound_Yes	Year-round milking
Brd	Cow breed (1 = Friesian, 0.5 = Friesian-Jersey cross, 0 = Jersey)
Cow	Number of cows
EffArea	Farm effective area
Rotary	Milking parlour type (rotary = 1, herringbone = 0)
Bails	Number of bails in the milking parlour
CowBail	Number of cows to number of bails ratio
Cows/ha	Stocking rate (cows/ha)
Houses_Yes	If domestic houses are taking from the stock water line (Yes = 1, No = 0)
HouseNo	Number of domestic houses taking water from the stock water line
Weekend	Weekend days (Yes = 1, No = 0)
ESp	Early spring (Yes = 1, No = 0)
LSp	Late spring (Yes = 1, No = 0)
Sum	Summer (Yes = 1, No = 0)
Aut	Autumn (Yes = 1, No = 0)
Recycle_Yes	Recycling cooler water to stock drinking water (Yes = 1, No = 0)
Recirculate_Yes	Recirculates cooling water into the same tank (Yes = 1, No = 0)
SnapCh_Yes	The parlour has a snap chiller (Yes = 1, No = 0)
RRSC_Yes	One of Recycle_Yes, Recirculate_Yes or SnapCh_Yes is true (Yes = 1, No = 0)
FY_201314	1 June 2013 to 31 May 2014 (Yes = 1, No = 0)
Sq	Squared

Partial least squares regression modelling was used to evaluate the ability of a combination of different colinear variables to predict SDW, cSDW, MPW, and TW (Wold et al., 2001; Sobek et al., 2005). Potential predictor variables were included as linear and quadratic terms. Initial analyses resulted in greater predictive coefficient of determination values for cSDW when compared with SDW, and, therefore, further modelling was confined to cSDW. The initial partial least squares model included all variables relevant to the water use (Table 3-2). This was followed by repeated procedures, in which factors of lowest influence (lowest standardized coefficient) were removed one at a time until a model was produced with a combination of good predictive power (i.e., predictive R2 close to that of the initial model) and parsimony; up to 5 models were presented for each water use. Cross-validation was undertaken using a leave-group-out technique with 50 randomly chosen subsets of the data. The predictive ability of the model is calculated leaving all observations in the same subset out at a time and recalculating the model, resulting in 50 recalculated models. Response variables were log10-transformed to achieve homogeneity of variance. Analyses were carried out using SAS 9.3 (SAS Institute Inc., Cary, NC) and Minitab 16.2 (Minitab Inc., State College, PA).

3.3.5 Water use models comparison and evaluation

We compared the VWI models of Castle and Thomas (1975) and Dahlborn et al. (1998; equations [3] and [4], respectively) with cSDW model 3. These models were chosen because they used DM of pasture in the models, for which we had data, and did not include a DMI variable, for which we did not have data. The DM content of pasture was not measured on individual farms, but weekly DM values, ranging

from 15% in spring to 41% (monthly average) in summer, were used from a local research farm for the period June 2013 to May 2015 (measured on a Waikato research farm; C. Roach, DairyNZ, Hamilton, New Zealand, personal communication). The resulting models were

$$\text{VWI model} = -15.3 + 2.53 \times \text{milk yield} + 0.45 \times \text{DM\%} \quad [3]$$

$$\text{VWI model} = 14.3 + 12.4 \times \text{milk yield} + 0.32 \times \text{DM\%} \quad [4]$$

Models were compared using plots of the predicted versus collected data, the coefficient of determination of the line of best fit, Pearson correlation coefficients, root mean square error, Nash-Sutcliffe efficiency, percentage bias, and root mean square error-to-observations standard deviation ratio (Moriasi et al., 2007).

3.4 Results

Temporal patterns for average TW, MPW, SDW, and cSDW are presented in Figure 3-1 a, b, c, and d, respectively, and monthly and seasonal averages are presented in Table 3-3. All 4 measures of water use show a strong cyclical, seasonal pattern, with relatively high water use in spring and summer. Milking parlour water use increased sharply at the beginning of lactation (winter and early spring) and plateaued until mid lactation (summer). In comparison, SDW requirements were more variable during the same period and peaked in summer.

Table 3-3. Average monthly stock drinking water (SDW), corrected stock drinking water (cSDW[1]), leakage, milking parlour water use (MPW), and total water use (TW) on pasture-based dairy farms (n).

Water use (L/cow per d)	SDW (n = 23)		cSDW (n = 20)		Leakage (n = 20)		MPW (n = 31)		TW (n = 23)	
Month	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Jan	83.9	52.24	59.1	25.70	16.8	29.32	66.9	32.04	157.7	67.12
Feb	82.1	46.51	56.1	21.82	19.9	32.58	59.2	32.11	145.6	58.39
Mar	74.9	50.24	49.4	23.33	19.0	34.04	54.2	33.20	131.6	59.57
Apr	52.9	38.75	32.4	20.74	12.9	20.41	47.2	41.10	108.0	62.90
May	36.0	31.44	19.4	16.37	10.0	16.45	24.5	33.32	64.8	46.51
Jun	25.9	30.79	10.6	12.91	13.0	29.58	11.4	22.25	38.4	37.28
Jul	41.9	45.58	16.6	13.44	15.2	33.56	25.3	25.56	66.5	59.79
Aug	57.0	45.47	32.4	18.42	15.7	31.73	54.6	25.35	115.5	56.37
Sep	59.6	45.81	36.5	19.65	15.3	30.22	62.5	25.44	125.2	57.48
Oct	61.6	54.12	37.2	24.52	14.7	25.31	68.5	36.13	137.5	66.08
Nov	67.2	52.06	43.6	22.91	15.2	24.39	66.0	27.75	136.9	59.46
Dec	71.0	61.01	47.5	23.85	12.0	21.52	65.2	28.57	139.4	72.98
Annual mean	59.5	18.90	34.9	15.7	17.0	7.40	48.7	16.36	113.1	33.87
Maximum daily use	105.0		71.7		55.3		82.0		187.1	
Minimum daily use	15.1		3.8		3.3		9.1		23.9	
Average milking period	69.5	14.86	44.4	12.04	18.7	7.64	62.7	4.68	135.4	19.22
Early spring	30.6	16.12	19.2	15.22	8.4	9.02	21.3	16.80	53.8	31.50
Late spring	54.1	12.78	36.1	12.03	13.6	9.63	61.0	7.34	114.5	18.34
Summer	64.0	12.19	38.5	10.42	18.9	8.06	64.5	3.17	133.1	12.11
Autumn	77.8	12.42	51.4	9.96	19.1	6.18	61.5	4.94	144.7	16.11
Winter	56.4	18.57	32.8	14.49	17.6	8.29	41.4	13.36	103.5	31.26

[1]cSDW = SDW – Leakage

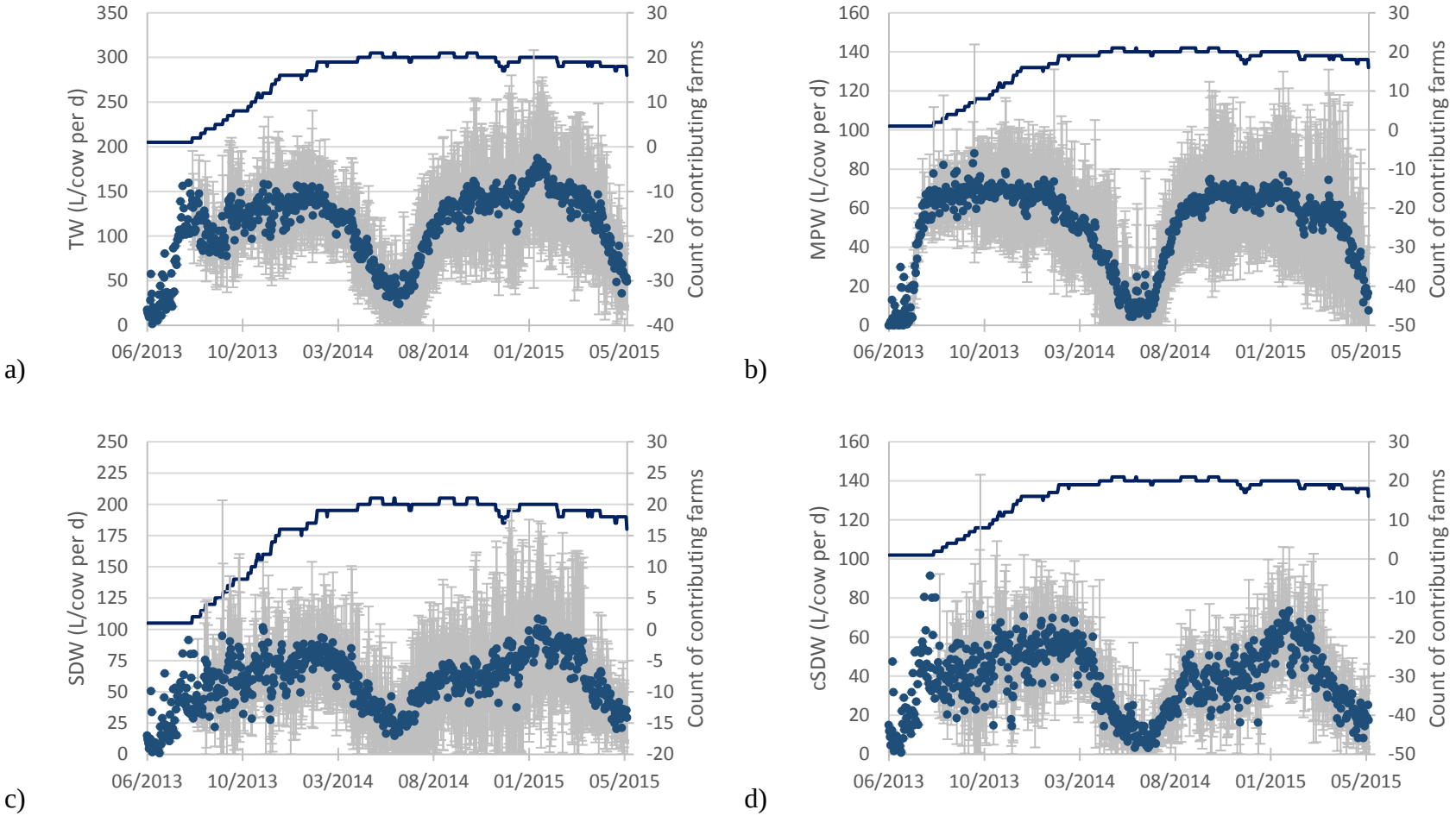

Figure 3-1. Mean daily water use (●, circles) ± 1 SD (error bars) and count of farms contributing to the data (solid line, secondary axis) for (a) total water use (TW), (b) milking parlour water use (MPW), (c) stock drinking water (SDW), and (d) corrected stock drinking water (cSDW).

Total water use, which is a combination of MPW and SDW, increased at the beginning of lactation and was greatest in summer. Annual average SDW (Table 3-3) was 60 L/cow per day; it was highest in summer (78 L/cow per day) and lowest in winter (31 L/cow per day), with the month of January recording the highest SDW (105 L/cow per day) and June the lowest (15 L/cow per day). We found substantial leakage (>21%) from the reticulation systems providing stock drinking water on half the farms (n = 20). Average leakage ranged from 2 to 61% of SDW on individual farms and was 26% of SDW (16 L/cow per day; 5,837 L/cow per year); leakage did not vary with season. Annual average cSDW was 35 L/cow per day; it was highest in summer (51 L/cow per day) and lowest in winter (19 L/cow per day), with the month of January recording the highest cSDW (72 L/cow per day) and June the lowest (4 L/cow per day). Annual average MPW was 50 L/cow per day; it was highest in late spring (64 L/cow per day) and lowest in winter (21 L/cow per day), with the month of August recording the highest MPW (82 L/cow per day) and June the lowest (9 L/cow per day). Although average MPW use was not significantly affected by milking parlour type (average herringbone and rotary MPW use was 50.7 ± 5.7 and 51.9 ± 6.3 L/cow per day, respectively; mean ± SE), we noted an interaction between milking parlour type and season. Herringbone MPW requirements were 5.2 L/cow per day greater ($P < 0.001$) in winter and 2.9 L/cow per day greater ($P < 0.05$) during early spring, whereas rotary MPW use was greater ($P < 0.001$) in late spring, summer, and autumn (3.7, 2.6, and 8.0 L/cow per day more, respectively). Annual average TW was 113 L/cow per day; it was highest in summer (147 L/cow per day) and lowest in winter (53 L/cow per day), with the month of January recording the highest TW (187 L/cow per day) and June the lowest (24 L/cow per day).

Table 3-4. Partial least squared regression model[1] equations (raw coefficients) for predicting corrected stock drinking water use (log_{10} cSDW) on pasture-based dairy farms (n = 22).

Variable	Model 1	Model 2	Model 3	Model 4	Model 5
R^2	0.51	0.47	0.46	0.45	0.45
P	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Constant	0.6516	0.3744	0.3686	0.3596	0.4251
TMax	0.0149	0.0253	0.0296	0.0276	0.0246
TMaxSq	0.0003				
TMin	-0.0125				
TMinSq	0.0006				
Rain	-0.0098	-0.0091	-0.0094		
RainSq	0.0002	0.0001	0.0001		
Evap	0.0402	0.0343	-0.1165	-0.0710	
EvapSq	-0.0088	-0.0139	-0.0081	-0.0146	-0.0168
Wind	-0.0169				
WindSq	-0.0004				
Rad	0.0143	0.0175	0.0405	0.0431	0.0318
RadSq	-0.0001				
Milk Sol	0.1410	0.2831	0.2609	0.3728	0.3722
Milk SolSq	-0.0167				
Milk Vol	0.0042				
Milk VolSq	-0.0004	-0.0006	-0.0005	-0.0008	-0.0008
Milking	0.0955	0.1341	0.3223		
MilkingSq	-0.0048	-0.0380	-0.1237		
System	0.0441	0.0350			
FeedPad_Yes	-0.1033	-0.0503			
Brd	0.0816	0.0657			
Cow	0.0001				
EffArea	0.0009				
Rotary	-0.1988				
Bails	0.0006				
CowBail	-0.0320				
Cows/ha	0.0553				
FY_2013/14	0.0193				
Weekend	-0.0146				
ESp	0.1969				
LSp	0.1410				
Sum	0.1004				
Aut	0.0783				
Houses_Yes	-0.1418	-0.0123			

[1]Variable description in Table 3-2.

Table 3-5. Partial least squared regression models[1] and polynomial regression model equations (raw coefficients) for predicting milking parlour water use (log_{10} MPW) on pasture-based dairy farms.

Variable	Model 1	Model 2	Model 3	Model 4	Model 5
R^2	0.61	0.57	0.55	0.51	0.48
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Constant	1.8750	1.4659	1.1684	0.6290	0.6290
TMax	0.0003				
TMaxSq	0.0002				
TMin	-0.0057				
TMinSq	0.0003				
Rain	-0.0022	-0.0028			
RainSq	0.0001	0.0001			
Evap	0.0084				
EvapSq	-0.0015				
Wind	0.0182				
WindSq	-0.0003				
Rad	0.0030				
RadSq	-0.0001				
Milk Sol	0.2639	0.4674	0.4174	0.5318	
Milk SolSq	-0.0236	-0.1841	-0.2082		
Milk Vol	0.0179	0.0187	0.0259	-0.0246	
Milk VolSq	-0.0003				
Milking	0.2269	0.3180	0.3152	0.4636	0.7043
MilkingSq	0.0294	-0.0259	-0.0214	-0.0561	-0.0868
System	0.0286	-0.0704			
FeedPad_Yes	-0.1119				
Brd	-0.4443	-0.2648	-0.3012		
Cow	0.0000				
EffArea	-0.0001				
Rotary	0.3388	0.0914			
Bails	-0.0062				
CowBail	-0.0253	-0.0387	-0.0285		
Cows/ha	-0.1650				
FY_2013/14	-0.0231				
Weekend	-0.0393				
ESp	-0.0507				
LSp	-0.1091				
Sum	-0.0443				
Aut	0.0597				
Houses_Yes	0.2197				
Recycle_Yes	-0.0011				
Recirculate_Yes	-0.2821				
SnapCh_Yes	-0.0742				
RecyRecirSnapC		0.0155			

[1]Variable description in Table 3-2.

Table 3-6. Partial least squared regression models[1] and polynomial regression model equations (raw coefficients) for predicting total water use (log_{10} TW) on pasture-based dairy farms.

Variable	Model 1	Model 2	Model 3	Model 4
R^2	0.49	0.46	0.43	0.41
P-value	< 0.001	< 0.001	< 0.001	< 0.001
Constant	1.4673	1.4995	1.1042	1.4399
TMax	0.0104	0.0124	0.0154	
TMaxSq	0.0001			
TMin	-0.0060			
TMinSq	0.0001			
Rain	-0.0020			
RainSq	0.0001			
Evap	0.0172			
EvapSq	-0.0046	-0.0109	-0.0113	
Wind	0.0073			
WindSq	-0.0011			
Rad	0.0069	0.0208	0.0156	
RadSq	-0.0001	-0.0001		
Milk Sol	0.1859	0.5446	0.4870	0.9076
Milk SolSq	-0.0330	-0.2542	-0.2653	-0.3021
Milk Vol	0.0105	0.0175	0.0249	
Milk VolSq	-0.0005			
Milking	0.0946			
MilkingSq	0.0014			
System	-0.0219	-0.0321		
FeedPad_Yes	0.0323	0.0717		
Brd	0.0356	0.0115		
Cow	-0.0002			
EffArea	-0.0006			
Rotary	0.1571	0.1578	0.0505	
Bails	0.0041			
CowBail	-0.0153	-0.0233		
Cows/ha	-0.0302			
FY_2013/14	-0.0282			
Weekend	-0.0173			
ESp	0.2338			
LSp	0.2418			
Sum	0.2141			
Aut	0.2190			
Houses_Yes	0.0392	0.0175		
Recycle_Yes	-0.0765			
Recirculate_Yes	-0.0256			
SnapCh_Yes	0.0377			
RecyRecirSnapC		-0.0851		

[1]Variable description in Table 3-2.

Partial least squares regression produced predictive models for cSDW (Table 3-4), MPW (Table 3-5), and TW (Table 3-6). The raw coefficients used to predict $\log_{10}$ water use are presented in these tables, rather than the standardized coefficients on which importance was assessed. We produced 4, 5, and 4 models for cSDW, MPW, and TW, respectively, with their predictive powers varying between 0.41 and 0.61. Whereas the models with a lower number of variables had a lower coefficient of determination, they provide a useful option when data were limited. The water use for cSDW model 3, MPW model 3, and TW model 3 can be calculated using equations [5], [6], and [7], respectively, followed by back transformation (abbreviations are defined in Table 3-2):

$$\text{LogcSDW (Model 3)} = 0.369 + 0.030 \times \text{TMax} - 0.009 \times \text{Rain} + 0.0001 \times \text{Rain}^2 - 0.117 \times \text{Evap} - 0.008 \times \text{Evap}^2 + 0.041 \times \text{Rad} + 0.261 \times \text{Milk Sol} - 0.001 \times \text{Milk Vol}^2 - 0.322 \times \text{Milking} - 0.124 \times \text{Milking}^2 \quad [5]$$

$$\text{LogMPW (Model 3)} = 1.168 + 0.417 \times \text{Milk Sol} - 0.208 \times \text{Milk Sol}^2 + 0.026 \times \text{Milk Vol} + 0.315 \times \text{Milking} - 0.021 \times \text{Milking}^2 - 0.301 \times \text{Brd} - 0.029 \times \text{CowBail} \quad [6]$$

$$\text{LogTW (Model 3)} = 1.104 + 0.015 \times \text{TMax} - 0.011 \times \text{Evap}^2 + 0.016 \times \text{Rad} + 0.487 \times \text{Milk Sol} - 0.265 \times \text{Milk Sol}^2 + 0.025 \times \text{Milk Vol} + 0.051 \times \text{Rotary} \quad [7]$$

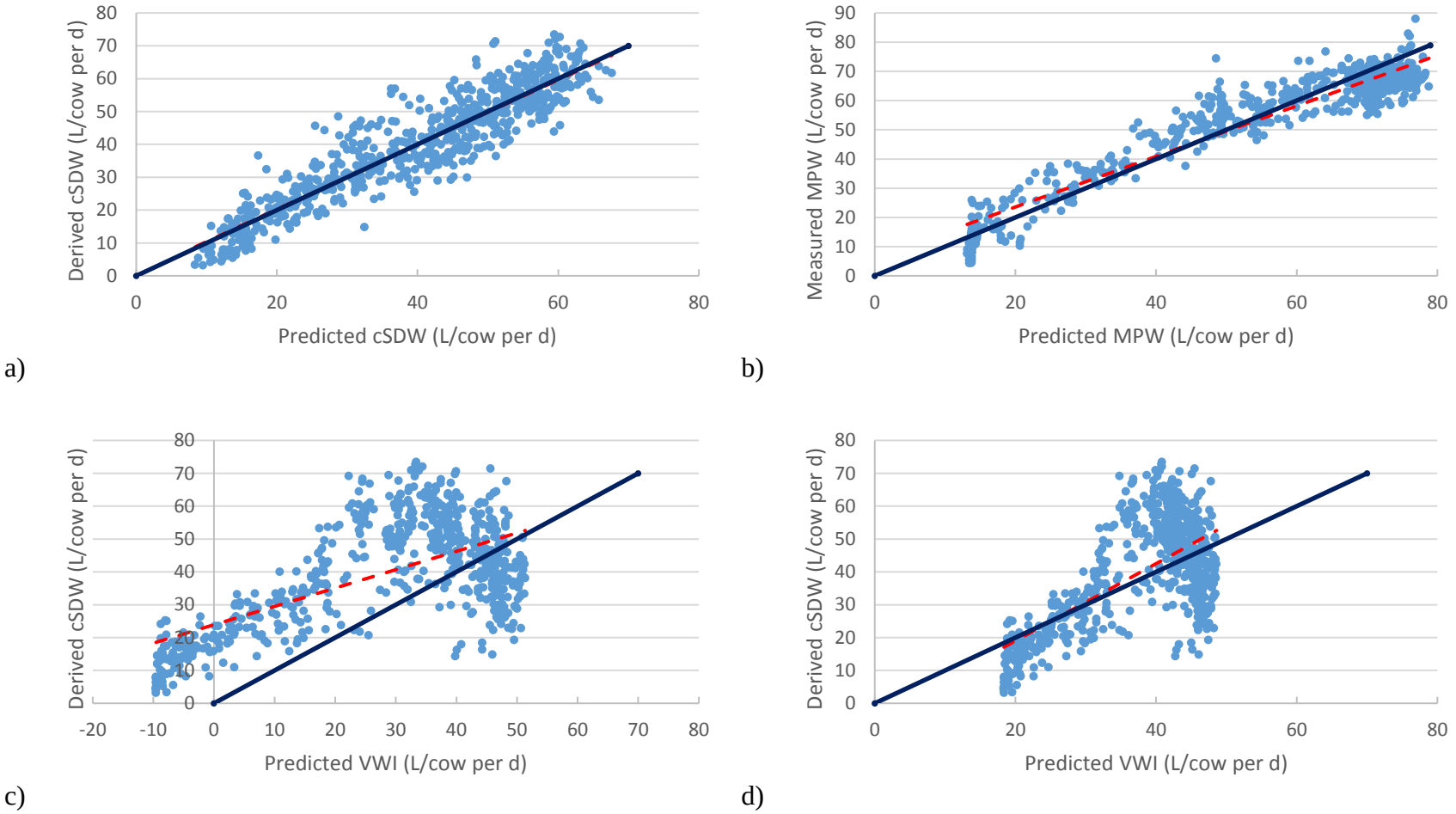

Figure 3-2. Measured or derived mean water use (number of farms ≥5) versus predicted water use (dashed line of best fit) and solid 1:1 line for (a) corrected stock drinking water (cSDW) model 3 (R^2 = 0.84), (b) milking parlour water use (MPW) model 3 (R^2 = 0.90) (c) the model of Castle and Thomas (1975; R^2 = 0.41), and (d) the model of Dahlborn et al. (1998; R^2 = 0.46). WVI = voluntary water intake.

These 3 models were chosen for evaluation because they had a balance between predictive power and number of variables. The variables that were best at predicting cSDW, shown in cSDW model 5 (Table 3-4), were maximum temperature, potential evapotranspiration, solar radiation, and milk production. The variables that were best at predicting MPW, shown in MPW models 4 and 5 (Table 3-5), were milk production variables, cow breed, and the cow-to-bail ratio. The variables that were best at predicting TW, shown in TW model 4 (Table 3-6), were milk production variables.

The cSDW model 3, MPW model 3, and TW model 3 predicted versus observed plot line of best fit gave coefficients of determination of 0.85 (Figure 3-2a), 0.90 (Figure 3-2b), and of 0.81 (plot not presented), respectively. Voluntary water intake predictions calculated using the models of Castle and Thomas (1975) and Dahlborn et al. (1998) versus measured cSDW are presented in Figure 3-2c and Figure 3-2d, with line of best fit coefficients of determination of 0.40 and 0.44, respectively. Prediction versus observed evaluation of cSDW model 3, MPW model 3, TW model 3, and the predictions of Castle and Thomas (1975) and Dahlborn et al. (1998) are presented in Table 3-7. Compared with the VWI models of Castle and Thomas (1975) and Dahlborn et al. (1998), the cSDW model 3 resulted in the best fit for the data.

Table 3-7. Evaluation of models to predict corrected stock drinking water [cSDW[1]; cSDW Model 3, Castle and Thomas (1975), Dahlborn et al. (1998)], milking parlour water (MPW; MPW Model 3), and total water (TW; TW Model 3).

Prediction model comparison to observed data	Line of best fit slope[2]	Line of best fit Y intercept[3]	Line of best fit R^2 [4]	r[5]	RMSE[6]	NSE[7]	PBIAS[8]	RSR[9]
cSDW Model 3	0.98	0.56	0.85	0.92	5.15	0.85	-0.14	0.39
The model of Castle and Thomas (1975)	0.56	23.91	0.40	0.64	16.97	-0.35	9.95	1.16
The model of Dahlborn et al. (1998)	1.17	-4.45	0.44	0.66	10.31	0.42	5.15	0.76
MPW Model 3	0.87	6.26	0.90	0.95	5.36	0.88	-2.15	0.35
TW Model 3	0.87	16.04	0.81	0.90	12.93	0.79	0.38	0.46

[1]cSDW = stock drinking water – leakage

[2]Line of best fit slope (L/cow per d), optimum = 1

[3]Line of best fit Y intercept (L/cow per d), optimum = 0

[4]Line of best fit R^2, optimum = 1

[5]Pearson correlation coefficient, optimum = 1 or -1

[6]RMSE = root mean square error (L/cow per d), optimum = 1

[7]NSE = Nash-Sutcliffe efficiency, optimum = 1, > 0 is acceptable, if < 0 then the mean is a better predictor than the model

[8]PBIAS = percentage bias, optimum = 0, positive values mean underestimation, and negative means overestimation

[9]RSR = RMSE-observations standard deviation ratio, optimum = 0

3.5 Discussion

All measured water uses (SDW, cSDW, MPW, and TW) exhibited a clear seasonal pattern that was aligned with the seasonal calving nature of New Zealand pasture-based dairy systems. Water use in the milking parlour was greatest when milk production was highest, and SDW and TW were greatest during high temperatures in summer. Water use was lowest in winter, when cows were not lactating and temperatures were low. Our study is the first to report this clear cyclical pattern of SDW on pasture-based dairy farms.

The average SDW was 60 L/cow per day (21,734 L/cow per year), and reached a maximum in summer and a minimum in winter. This variability in SDW was associated with both milk production and climate, principally temperature. Substantial leakage (>21% of SDW) was identified on over half of the farms. Leakage rates were highly variable between farms, but we found no difference in leakage between seasons. Although it was impossible to physically check the volume of leakage and, therefore, determine how accurate the correction to SDW was, the stronger correlation between cSDW and climate and milk production variables compared with SDW gives confidence in the validity of the correction.

The 5 smallest leakage rates averaged 6% of SDW, suggesting this may be the best achievable rate (i.e., best management practice). However, no other studies have reported water leakage rates on dairy farms to compare with these results. Municipal water systems have been measured to have between 5 to 58% water leakage and unreported water intakes (Lambert et al., 2002). As well as being an inefficient use of a resource, leakage may temporarily decrease milk production (Cowan et al., 1978;

King and Stockdale, 1981) if water intake of cows is restricted. This reduction in milk production may be as great as 20% if water intake is halved (Burgos et al., 2001).

Corrected stock drinking water is a more accurate reflection of actual water consumed (i.e., cSDW = VWI) than SDW. As SDW is estimated to contain 26% leakage, and as leakage did not vary with season, cSDW followed the same seasonal pattern as SDW but with lower volumes. The average volume of cSDW reported here (35 L/cow per day) is less than that estimated in Ireland (55 L/cow per day), the only other long-term study reported (Murphy et al., 2014). However, the volume is similar to the annual SDW volume recorded in the present study, which may suggest that leakage on Irish dairy farms is similar to New Zealand dairy farms. Other shorter, pasture-based studies measured VWI of cows in Australia (15 to 67 L/cow per day; King and Stockdale, 1981; Stockdale and King, 1983) and SDW (22, 54, and 41 L/cow per day; Campbell, 1958; Jago et al., 2005; Morris et al., 2010) in New Zealand. Average VWI in confinement systems from shorter studies were similar or greater than those reported here, with typical values ranging from 50 to 90 L/cow per day (Murphy et al., 1983; Cardot et al., 2008), and a maximum of 171 L/cow per day (Meyer et al., 2004). Greater water intakes may be expected in confinement systems as cows receive high-DM feed. In pastoral dairying, cows may ingest 30 to 120 L/d of water in feed, which would reduce requirements for drinking water. The day-to-day variability in cSDW may be related to the fluctuating DM% of pasture, caused by changing soil moisture levels, which results in varied amounts of water ingested through feed.

Repairing leaks may be the single most effective step many pasture-based farmers could take to reduce water use. If the average farm size is 335 cows and a 6% leakage rate is achievable, the average farm could reduce water use by 1,687,395

L/farm per year. At a regional level, dairy farm water use could be reduced by 6 billion L. This significant reduction in farm water use would also reduce farm working expenses thorough less electricity use and less maintenance.

Average MPW was 63 L/cow per day during the main milking period of the year. As might be expected, MPW exhibited a clear seasonal pattern that closely matched milk production; this is likely to also be related to cow numbers, which decrease during the season due to culling and staged dry off. Although MPW was similar between rotary and herringbone parlours, rotary parlours used 8 L/cow per day more than herringbone parlours in autumn; this difference is consistent with the report of Callinan (2009). The MPW presented in the current study is consistent with MPW of similar milking parlours that have the same cleaning methods (high-pressure hose wash down; Callinan, 2009). In contrast, MPW reported in our study is higher than smaller parlours of different types that do not use high-pressure hose wash down (Gamroth and Moore, 1995; Janni et al., 2009), and is substantially less than MPW in parlours that group wash cows before milking (Meyer et al., 2006).

The model prediction of cSDW that resulted from our study is easier to use on pasture-based dairy farms than other available models. Our models included climate variables to approximate the soil moisture and, therefore, variation in DM of pasture. Water consumed in feed eaten per day could vary by over 90 L/cow per day between seasons. Existing models, such as those of Cardot et al. (2008), Murphy et al. (1983), and Holter and Urban (1992), have not been created with such a wide range of feed conditions. It is expected that DM and DMI significantly influence cSDW, but these parameters are not easily nor routinely measured on pasture-based farms. Models from intensively managed indoor systems have reported similar or higher coefficient of

determination values compared with our cSDW models, and this reflects the level of monitoring of feed that is possible in these systems. The coefficient of determination values of our models are considered to be reasonable given the lack of feed and intake data and the wide range of environmental and feed conditions. Other variables used in the housed system models (Cowan et al., 1978; Khelil-Arfa et al., 2012) were approximated in our models (BW and sunshine hours, with average breed and solar radiation) and included milk yield and maximum temperature, but not such variables as sodium content due to insufficient data. The models we produced were able to predict cSDW more accurately compared with the existing models of VWI.

We also produced accurate models to predict MPW and TW that are easy to use on pasture-based dairy farms. The initial models that included the most variables had the greatest explanatory power, but the models do not lend themselves to practical use. The models with fewer variables may be more useful for predicting water use, particularly where limited data are available. We were unable to find any other models predicting MPW and TW to compare with our results.

The models produced here will allow increased accuracy of water use to be predicted for farms within a climate region, allowing water to be efficiently allocated. This will aid development of farm infrastructure and water reticulation, and provide benchmark water-use efficiency values to compare individual farms. The water-use values predicted by the models help identify opportunities to improve water-use efficiency (e.g., reduce leakage) and help track progress on farms that are aiming to improve water-use efficiency. The models may also be useful to predict farm water requirements in response to short- and long-term climate change. The detailed benchmark water-use data will be useful in calculating water footprints, removing the

need to rely on lower-accuracy estimates to compare water use between dairy production in different areas. As the models were developed on nonirrigated pasture-based dairy farms, further research is required to evaluate the performance of the models on irrigated pasture-based dairy farms.

3.6 Conclusions

Annual water use on pasture-based, seasonally calving dairy farms was cyclical in response to climate and milk production variables. Significant opportunities to improve water-use efficiency were identified by reducing the 26% of reticulated water that was lost as leakage from the system. Models were developed to predict water use using variables accessible to pasture-based farms. Results from these models for cSDW were more accurate than using VWI models developed for confined feeding systems. The models we presented were the first models we could find predicting MPW and TW, and can be used to benchmark progress for improved water-use efficiency.

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CHAPTER 4.

Water Use on Irrigated Pasture-Based Dairy Farms

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4.1 Abstract

Robust information for water use on pasture-based dairy farms is critical to farmers' attempts to use water more efficiently and the improved allocation of freshwater resources to dairy farmers. To quantify the water requirements of dairy farms across regions in a practicable manner, it will be necessary to develop predictive models. The objectives of this study were to compare water use on a group of irrigated and nonirrigated farms, validate existing water use models using the data measured on the group of nonirrigated farms, and modify the model so that it can be used to predict water use on irrigated dairy farms. Water use data were collected on a group of irrigated dairy farms located in the Canterbury, New Zealand, region with the largest area under irrigation. The nonirrigated farms were located in the Manawatu region. The amount of water used for irrigation was almost 52-fold greater than the amount of all other forms of water use combined. There were large differences in measured milking parlour water use, stock drinking water, and leakage rates between the irrigated and nonirrigated farms. As expected, stock drinking water was lower on irrigated dairy farms. Irrigation lowers the dry matter percentage of pasture, ensuring that the amount

of water ingested from pasture remains high throughout the year, thereby reducing the demand for drinking water. Leakage rates were different between the 2 groups of farms; 47% of stock drinking water was lost as leakage on nonirrigated farms, whereas leakage on the irrigated farms equated to only 13% of stock drinking water. These differences in leakage were thought to be related to regional differences rather than differences in irrigated versus nonirrigated farms. Existing models developed to predict milking parlour, corrected stock drinking water, and total water use on nonirrigated pasture-based dairy farms in a previous related study were tested on the data measured in the present research. As expected, these models performed well for nonirrigated dairy farms but provided poor predictive power for irrigated farms. Partial least squares regression models were developed specifically to simulate corrected stock drinking water, milking parlour water, and total water use on irrigated dairy farms.

4.2 Introduction

The global area of land under irrigation doubled from 1950 to 2000 (Molle et al., 2010), and global water use for irrigated agriculture now accounts for approximately 70% of total freshwater withdrawals (United Nations Educational, Scientific and Cultural Organization, 2015). Water scarcity is an issue in many water basins (Smakhtin et al., 2004; Molle et al., 2010), and 20% of the world's aquifers are being overused (Gleeson et al., 2012). Therefore, the focus on optimizing and managing agricultural water usage is increasing (Scarsbrook and Melland, 2015; Dillon et al., 2016). This focus is needed because the world population is estimated to reach 9.7 billion people by 2050. The amount of food produced will need to increase by 70%

to feed this population (FAO, 2009; United Nations Department of Economic and Social Affairs, 2015); therefore, the pressure on water resources will increase further.

Dairy cow water intake studies have concentrated on confinement systems (Murphy et al., 1983; Meyer et al., 2004; Cardot et al., 2008), and only recent articles are available on pasture-based dairy farms (Chapter 3; Murphy et al., 2017). Significant data are available on the amount of water used for irrigation (Armstrong et al., 2000; Doll and Siebert, 2002), and water use on nonirrigated pasture-based dairy farms in New Zealand has been quantified (Chapter 3). However, data for other water uses on irrigated dairy farms, including stock drinking water (SDW), and milking parlour water use (MPW) remain limited.

Chapter 3 showed the seasonal nature of water use on Waikato non-irrigated pasture-based farms (milking from spring to autumn) and the importance of milk production and climatic variables as drivers of water use. However, further research is needed on the water requirements of dairy farms that use irrigation. As the models developed in Chapter 3 do not include or account for DM percentage in the feed (and therefore ingested water), we do not expect them to reliably predict water use on irrigated farms.

As the allocation of water resources gets close to available limits in waterways in dairying regions, accurate water use figures for SDW and MPW are required. This information is needed to minimize the risks of underestimating water used (where not enough water is left to maintain environmental water flows) or overestimating water used (where the water resource is underused). Water use data are also required for water footprinting studies (Ridoutt and Pfister, 2010; Zonderland-Thomassen and Ledgard, 2012), which can be used to calculate abstractive and consumptive water use for

analysis of the water "embedded" in milk products. This also allows the effect of current and future water extraction patterns to be assessed.

The objectives of the current study were to evaluate the accuracy of previously described water requirement models and to develop new models for predicting water requirements on irrigated dairy farms.

4.3 Materials and Methodology

Water use was measured on 20 irrigated dairy farms in the Canterbury region (−43°S, 172°E) and 22 nonirrigated dairy farms in the Manawatu region (−40°S, 176°E) of New Zealand. Dairy farms with water meters, telemetry, and data loggers already installed (as required by Regional Council rules) were selected, and, where appropriate, additional water meters and data loggers were installed as piping infrastructure allowed. In this manner, as many different water uses as possible were monitored. A complete set of total water [TW, calculated as MPW + SDW; irrigation water (IW) is excluded from TW] use, MPW, and SDW data were recorded on 3 farms in the Canterbury region and 10 farms in the Manawatu region. In addition, individual MPW, SDW, and TW values were measured on 11, 1, and 7 farms in the Canterbury region and 5, 1, and 3 farms in the Manawatu region, respectively. The IW use data were available on 10 of the Canterbury farms as the rest were not telemetered. A total of 29 and 23 years of data (not including submetering) was collected from the irrigated and nonirrigated farms, respectively.

4.3.1 Data collection

Water use data were collected continuously at 15-min intervals using water meters with either telemetry or data loggers. Data loggers were manually downloaded every 4 to 6 mo. Relevant farm data, such as the milking platform area, herd size, parlour type (i.e., herringbone or rotary), and cow breed, were collected (Table 4-1). Farms were categorized according to the type of production system based on the amount of supplementary feed imported onto the farm (Ramsbottom et al., 2015). The number of houses taking water from the stock drinking water line was collected through a questionnaire.

4.3.2 Farm descriptions

Descriptions of the study farms are presented in Table 4-1. Herd size (peak numbers milked) ranged from 480 to 1,420 cows on the irrigated farms and 200 to 1,050 cows on the nonirrigated farms. Daily (24-h) climate data, such as maximum and minimum temperature (°C), rainfall (mm), solar radiation (MJ/m2), wind run (km), and Priestley-Taylor potential evapotranspiration (mm), were obtained from the virtual climate station network (VCSN) site (Cichota et al., 2008) closest to each farm. The VCSN used data from weather stations and extrapolated it over a 5 km × 5 km grid across New Zealand. From the VCSN, the average yearly rainfall, daily maximum temperature, minimum temperature, potential evapotranspiration, and solar radiation for the Canterbury farms were 637 mm, 16.8°C, 6.2°C, 2.1 mm, and 13.1 MJ/m^2, respectively. For the Manawatu region, the corresponding values were 1,017 mm, 17.8°C, 8.3°C, 2.3 mm, and 13.8 MJ/m^2, respectively. Average yearly milk volume and milk fat plus milk protein yield were 4,576 L and 416 kg, respectively, on the irrigated

farms and 4,501 L and 401 kg, respectively, on the nonirrigated farms. Over the 2 yr of measurement, average milk fat and milk protein content was 4.92 and 3.90%, respectively, across all of the irrigated farms and 4.88 and 3.78%, respectively, on the nonirrigated farms (DairyNZ and Livestock Improvement Corporation, 2014, 2015). All monitored farms in Canterbury grazed cows off the farm during winter; in comparison, 79% of farms (n = 15) in the Manawatu region winter grazed off farm for an average of 7.6 wk (range = 6–9.5 wk).

Table 4-1. Characteristics (SD in parentheses) of the dairy farms used for water use analysis.

Region and variable[1]	No. of farms	System type[2], no.			Cow breed[3]	Average no. of cows	Average daily milk yield, kg/d	Average daily milk fat + milk protein, kg/d	Average effective area, Ha	No. of Rotary Parlours[4]	Average no. of bales	Cowbale ratio	Average no. of houses on SDW line
		1-2	3	4-5									
Nonirrigated													
SDW	11	3	7	1	0.65 (0.261)	454 (160.4)	12.8 (7.71)	1.14 (0.649)	182 (80.3)	2	37.4 (11.25)	12.2 (2.01)	0.6 (0.97)
CSDW	8	3	4	1	0.58 (0.258)	499.3 (140.3)	13.0 (8.01)	1.16 (0.678)	201 (83.6)	2	40.8 (10.08)	12.5 (2.07)	0.3 (0.49)
MPW	15	4	8	3	0.66 (0.198)	419 (172.1)	12.6 (7.65)	1.11 (0.639)	170 (83.9)	2	34.1 (12.40)	12.4 (1.90)	N/A
TW	14	5	8	1	0.68 (0.201)	448 (152.7)	12.1 (7.44)	1.07 (0.624)	179 (72.9)	3	35.9 (11.04)	12.6 (1.91)	N/A
IW	4	0	4	0	0.94 (0.125)	854 (151)	13.7 (7.48)	1.19 (0.611)	366 (103.6)	3	54.0 (12.00)	15.8 (1.97)	N/A
Irrigated													
SDW	4	0	2	2	0.41 (0.188)	733 (112.4)	13.1 (7.99)	1.21 (0.702)	196 (30.7)	4	54.5 (4.12)	13.4 (1.22)	0 (0.0)
CSDW	4	0	2	2	0.41 (0.188)	733 (112.4)	13.1 (7.99)	1.21 (0.702)	196 (30.7)	4	54.5 (4.12)	13.4 (1.22)	0 (0.0)
MPW	14	0	10	4)	0.46 (0.116)	772 (163.8)	11.8 (7.44)	1.07 (0.462)	216 (50.3)	12	48.4 (7.07)	15.9 (2.28)	N/A
TW	9	0	5	4	0.50 (0.000)	776 (102.8)	13.9 (8.10)	1.26 (0.698)	210 (23.0)	7	51.1 (6.33)	15.2 (1.73)	N/A
IW	9	2	6	1	0.50 (0.000)	763 (175)	12.8 (7.70)	1.18 (0.672)	201 (42.4)	6	48.7 (5.74)	15.6 (3.13)	N/A

[1] SDW = stock drinking water; cSDW = corrected stock drinking water; MPW = milking parlour water use; TW = total water use; IW = irrigation water.
[2]System type based of the DairyNZ 1-5 system classification, where 1 = all pasture, 2 = 4-14% feed imported, 3 = 10-20% feed imported, 4 = 20-30% feed imported, 5 = 25-40 % feed imported (Ramsbottom et al., 2015).
[3]Cow breed (1 = Friesian, 0.5 = Friesian-Jersey cross, 0 = Jersey).
[4]Rotary parlours (Reinmann, 2003); all other parlours were herringbone swing over milking parlours.
[5]N/A = data not collected.

4.3.3 Data management and calculations

Water use data were imported into Hilltop software (Kmoch et al., 2015). The water use data from data loggers were compared with the manual readings of the water meters. Where a difference existed between the data logger and the water meter (>2%), the data logger water use data were adjusted to match the manual reading of the water meter; this occurred once on 5 farms. The data were checked for gaps and consistency. When gaps were found, the data were truncated, removing any partial days of data.

On 16 farms TW was measured along with either SDW or MPW. The SDW or MPW was subtracted from TW to calculate the unknown MPW (on 13 farms) or SDW (on 3 farms) via coding in Hilltop software in the same way as reported previously (Chapter 3). The SDW data were exported from Hilltop software for formatting and analysis in Microsoft Excel (Microsoft Inc., Redmond, WA). Stock drinking water was exported in 15-min intervals, and MPW, TW, and IW were exported as daily volumes. The volume of water taken from the stock drinking water line by houses was corrected for as previously reported (Chapter 3).

4.3.4 Leakage adjustment

Individual farm SDW data were run through an R Software script (R Core Team, 2015) to adjust for water lost from the distribution system (i.e., water leakage). The script was based on a modification of the "night-time flow, leakage estimation" method (Tabesh et al., 2009; Cheung et al., 2010) as explained and developed in Chapter 3. The output of the script included the SDW value and the corrected SDW (cSDW).

4.3.5 Statistical analyses

The ability of the models developed in Chapter 3 to predict SDW, MPW, and TW on nonirrigated farms was evaluated using the data collected from the current irrigated and nonirrigated farms. Evaluation methods included plots of the predicted versus measured data, the coefficient of determination of the line of best fit, Pearson correlation coefficients, root mean squared error (RMSE), Nash–Sutcliffe efficiency (NSE), percentage bias, and RMSE observations standard deviation ratio (Moriasi et al., 2007).

Because 2 full years of data were not available for some water use categories, a 365-d moving average was calculated when data from 5 or more farms were available. The average of the individual 365-d moving averages was calculated as the overall average of the water use. Standard deviations were calculated for the whole period of the 365-d averages.

4.3.6 Partial least squares modelling

Univariate polynomial partial least squares (PLS) regression modeling was used to evaluate the ability of a combination of different collinear variables to predict SDW, cSDW, MPW, and TW use (Wold et al., 2001; Sobek et al., 2005; Abudu et al., 2011) on irrigated farms. The starting PLS models included all relevant variables (Table 4-2). This was followed by an analysis in which factors of lowest influence (lowest standardized coefficient) were removed one at a time to give models with a range of predictive powers (i.e., predicted coefficient of determination compared with that of the starting model). To allow for greater flexibility of use depending on data availability, 3 or 4 models are reported here: the initial model with all variables and highest coefficient of determination (model 1), the “best” model that maintained a good coefficient of determination and had a lower number of variables (model 2), and 1 or 2 simple models with the minimum number of variables (models 3 and 4). Cross-validation was carried out using a “leave group out” approach with 50 randomly selected

groups, each consisting of 2% of the data. Response variables were log10 transformed to achieve homogeneity of variance. All PLS analyses were carried out using Minitab 16.2 (Minitab Inc., State College, PA).

Table 4-2. List of different farm variables used in the water use analysis.

Variable Abbreviation	Variable Description
TMax	Maximum daily temperature (°C)
TMin	Minimum daily temperature (°C)
Rain	Rainfall (mm)
Evap	Priestly-Taylor potential evapotranspiration (mm)
Wind	Wind run (km)
Rad	Solar radiation (MJ/m²)
MilkSol	Milk solids (milk fat + milk protein, kg)
MilkVol	Milk volume (L)
Milking	Number of milkings in a day
System	Production system type
YrRound_Yes	Year-round milking
Brd	Cow breed (1 = Friesian, 0.5 = Friesian-Jersey cross, 0 = Jersey)
Cow	Number of cows
EffArea	Farm effective area
Rotary	Milking parlour type: rotary = 1, herringbone = 0
Bales	Number of bales (stalls) in the milking parlour
CowBale	Number of cows to number of bales (stalls) ratio
Cows/ha	Stocking rate (cows/ha)
Houses_Yes	If domestic houses are taking from the stock water line
HouseNo	Number of domestic houses taking water from the stock water line
Weekend	Weekend days
ESp	Early spring
LSp	Late spring
Sum	Summer
Aut	Autumn
Recycle_Yes	Recycling cooler water to stock drinking water
Recirculate_Yes	Recirculates cooling water into the same tank
SnapCh_Yes	The parlour has a snap chiller
RRSC_Yes	The parlour either; recycles cooling water to stock drinking water; recirculates cooling water into the same tank; or the parlour has a snap chiller
Irr_Yes	Has irrigation
IrrArea	Irrigation area
Irrmm	Irrigation yearly application (mm)
Irr/EffArea	The % of the milking platform that has irrigation on it
FY_201314	1 June 2013 to 31 May 2014

2.1 Results

Average and peak water use values for the irrigated and nonirrigated farms are presented in Table 4-3. The IW use was approximately 51-fold greater than all other forms of water use combined (TW). The average milking day demand for SDW (from September to February) was 90 L/cow per day for the nonirrigated farms and 39 L/cow per day for the irrigated farms. The average amount of leakage from SDW was 47% on the nonirrigated farms and 13% on the irrigated farms. There was a seasonal pattern for SDW and cSDW for both irrigated and nonirrigated farms (Figure 4-1). The average milking day demand for MPW was 66 L/cow per day for the nonirrigated farms and 90 L/cow per day for the irrigated farms. The pattern of MPW and TW on irrigated and nonirrigated farms is presented in Figure 4-2.

Table 4-3. Average 365-d and peak water use measurements (L/cow per day) for stock drinking water (SDW), corrected stock drinking water (cSDW), leakage, milking parlour water (MPW), total water (TW), and irrigation water (IW).

Water use	Nonirrigated			Irrigated		
	Farms (n)	Average (SD)	Peak	Farms (n)	Average (SD)	Peak
SDW	11	74 (28.1)	162	4	28 (17.1)	68
cSDW[1]	8	33 (15.8))	88	4	25 (15.3)	61
Leakage[2]	8	38 (45.2)	106	4	4 (5.5)	41
Leakage %[3]	8	46.7		4	13.0	
MPW	15	50 (20.4)	85	13	64 (33.8)	118
TW[4]	12	120 (38.0)	197	7	94 (29.4)	220
IW				9	4538	
AMD[5] SDW	11	90 (26.8)			39 (13.6)	
AMD cSDW	8	41 (14.0)			35 (11.9)	
AMD MPW	15	66 (7.5)			90 (9.3)	
AMD TW	12	149 (19.1)			107 (25.7)	

[1] cSDW = SDW – leakage.

[2] Leakage rate (L/cow per d) calculated where n > 5, except Canterbury farms (n = 4).

[3] Leakage percentage rates were calculated on individual farms, and then averaged across farms.

[4] TW = SDW + MPW.

[5] AMD = average milking day, from September (spring) to February (summer).

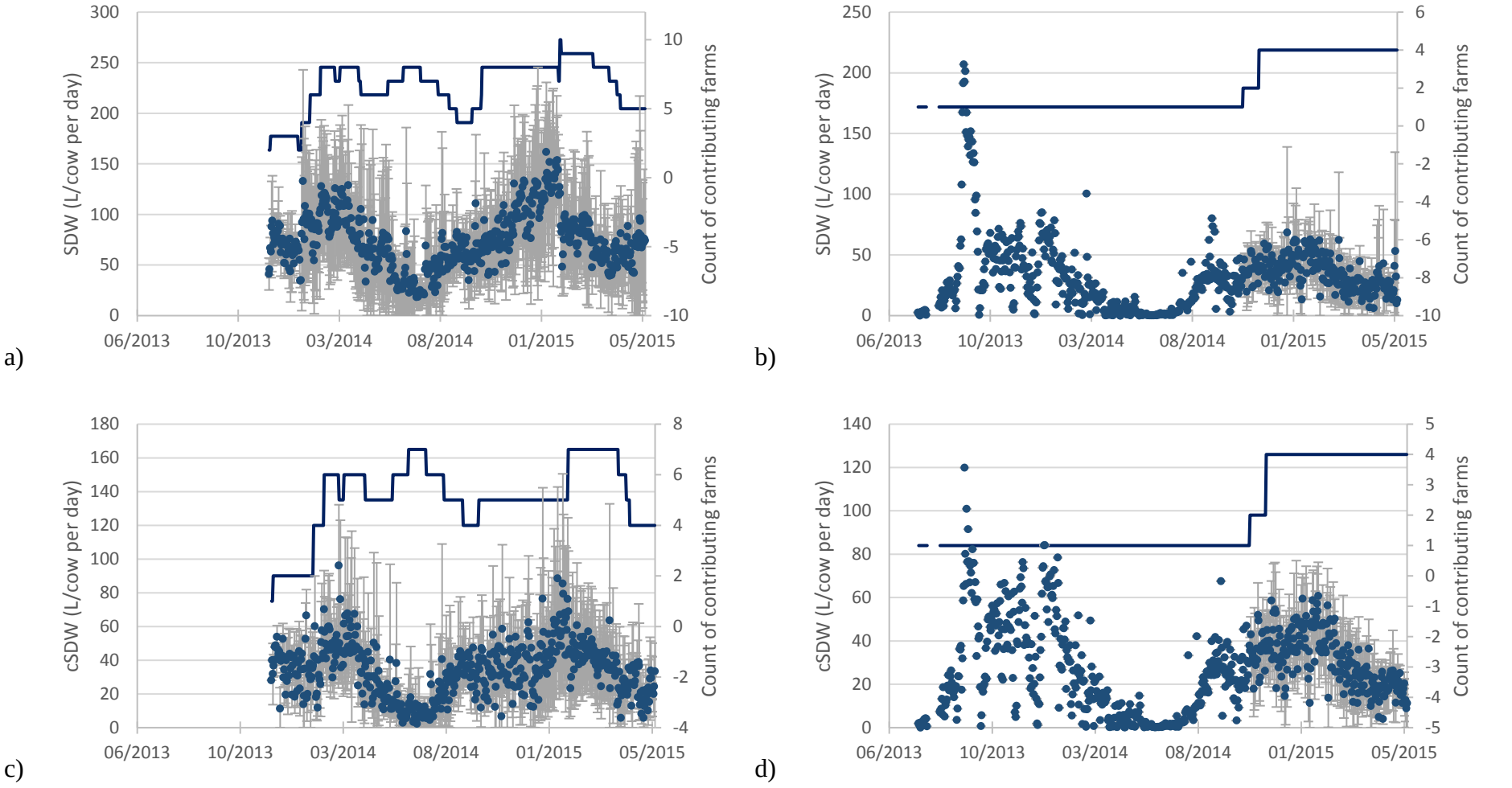


Figure 4-1. Average daily water use (L/cow per d; ± SD), and the count of farms contributing to the data (solid line) for (a) stock drinking water (SDW) on nonirrigated farms, (b) SDW on irrigated farms, (c) corrected stock drinking water (cSDW) on nonirrigated farms and d) cSDW on irrigated farms.

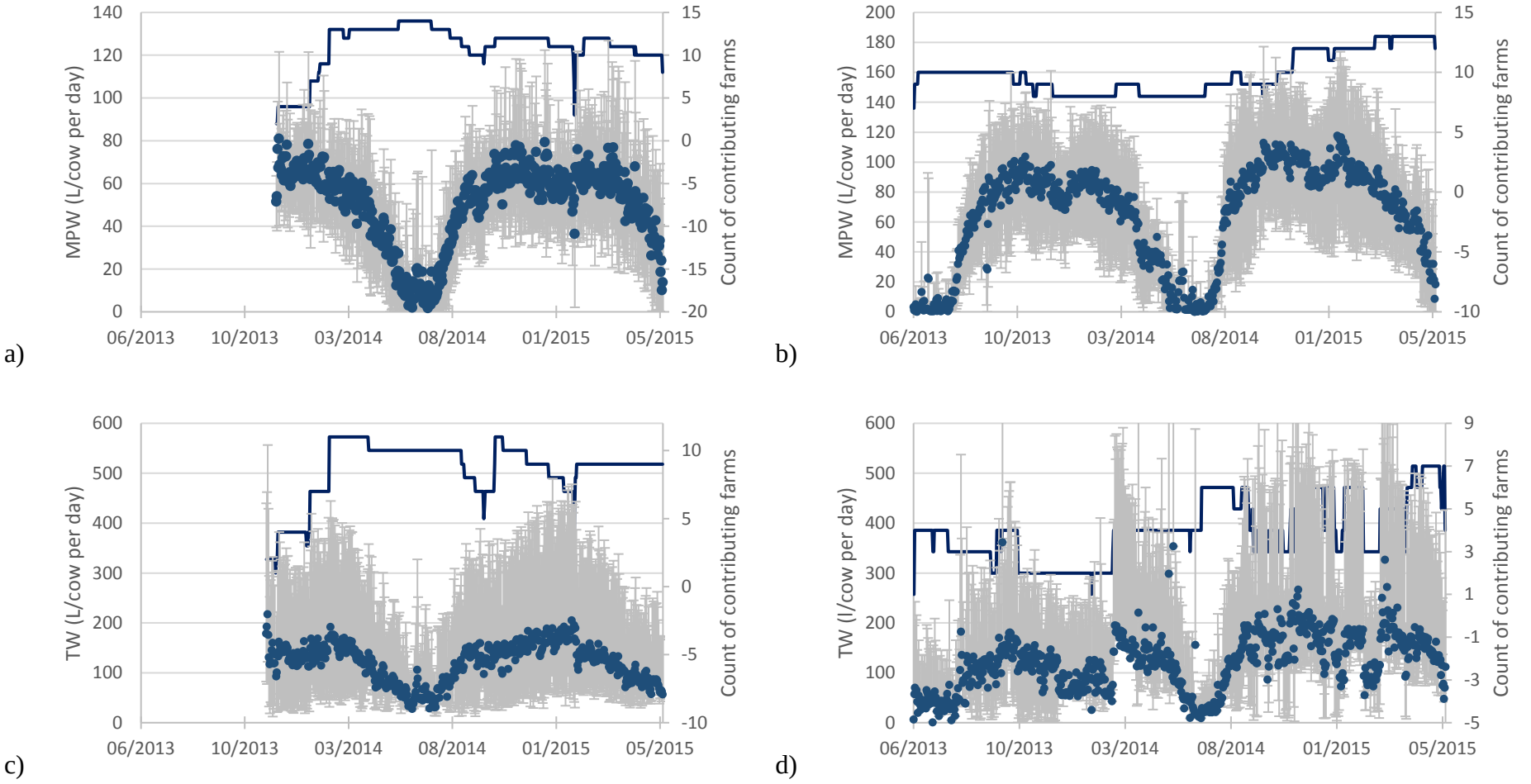


Figure 4-2. Average daily water (L/cow per day; ± SD), and the count of farms contributing to the data (solid line) for (a) milking parlour water use (MPW) on nonirrigated farms, (b) MPW on irrigated farms, (c) total water use (TW) on nonirrigated farms and (d) TW use on irrigated farms (error bars up to 1285 L/cow per d due to leaks truncated at 600 L/cow per day).

4.3.7 Evaluation of water use model predictions

Table 4-4 shows the ability of the cSDW model 3, MPW model 3, and TW model 3 produced in Chapter 3 for a different region (Waikato, New Zealand) to predict cSDW, MPW, and TW for the nonirrigated and irrigated farms in the Manawatu and Canterbury regions. As expected, the existing models predicted all water uses much better for nonirrigated farms than for irrigated farms; all irrigated models had worse lines of best-fit slopes as indicated by the greater percentage bias (i.e., the models both under- and overestimated water use on irrigated farms to a greater extent than on nonirrigated farms; Table 4-4). For irrigated farms the NSE values were low (<0.5) and for cSDW the NSE value was below 0, indicating that the mean is a better predictor than the model. This showed that the model is poor at predicting cSDW on irrigated dairy farms. Evaluation measures (i.e., NSE, percentage bias, RMSE observations standard deviation ratio) for the nonirrigated farms in the Manawatu region were consistent with evaluation measures of nonirrigated Waikato farms on which the model was based (Chapter 3).

Table 4-4. Corrected stock drinking water[1] (cSDW), milking parlour water (MPW), and total water[2] (TW) model predictions compared with the measured or derived water use volumes on the irrigated and nonirrigated pasture-based dairy farms.

Model prediction	Prediction Model comparison to measured data	n	Line of best fit Slope[3]	Line of best fit Y intercept[4]	Line of best fit R-squared[5]	Pearson's correlation coefficient[6]	RMSE[7]	NSE[8]	Percentage bias[9]	RSR[10]
cSDW model 3	Nonirrigated	7	0.79	7.97	0.58	0.80	8.00	0.60	1.67	0.63
	Irrigated	7	0.39	3.06	0.68	0.81	56.67	-5.91	-158.47	2.63
MPW model 3	Nonirrigated	15	0.82	8.31	0.85	0.92	6.62	0.81	-0.79	0.44
	Irrigated	14	1.69	-18.66	0.93	0.96	20.83	0.46	26.27	0.72
TW model 3	Nonirrigated	14	0.84	17.91	0.75	0.90	14.85	0.79	0.62	0.45
	Irrigated	9	0.64	56.82	0.28	0.53	37.54	0.09	11.57	0.95

[1]cSDW = SDW – leakage.
[2]TW = SDW + MPW.
[3]L/cow per day; optimum = 1.
[4]L/cow per d; optimum = 0.
[5]Optimum = 1.
[6]Optimum = 1 or -1.
[7]Root mean square error (L/cow per d); optimum = 1.
[8]Nash-Sutcliffe efficiency; optimum = 1, > 0 is acceptable, if < 0 then the mean is a better predictor than the model.
[9]Optimum = 0, positive values mean underestimation, and negative means overestimation.
[10]RSME-observations SD ratio; optimum = 0.

4.3.8 PLS regression models

The PLS regression models were developed for cSDW, MPW, and TW on irrigated farms, and the results are presented in Table 4-5, Table 4-6, and Table 4-7, respectively. A total of 3, 4, and 4 models were produced for cSDW, MPW, and TW, respectively, with coefficient of determination values ranging between 0.62 and 0.74. The cSDW model 2 (best model) had a coefficient of determination of 0.69, and the predictive equation (equation 1) is presented later. The PLS loading plot of cSDW model 2 is presented in Figure 4-3a, where the first component is dominated by milk production variables and potential evapotranspiration. Increases in this component increase cSDW the most. The second component is dominated by irrigation and rainfall; increases in this component increase cSDW, but to a lesser extent than component 1. The MPW model 3 (best model) had a coefficient of determination of 0.65. The PLS loading plot of MPW model 3 is presented in Figure 4-3b, where milk production variables and the number of milkings in a day drive MPW. The TW model 2 had a coefficient of determination of 0.66. The PLS loading plot for TW model 2 is presented in Figure 4-3c, where the main drivers of component 1 are milk production variables and potential evapotranspiration. The equations for the best models—cSDW model 2 (equation 1), MPW model 3 (equation 2), and TW model 2 (equation 3)—are as follows. The model prediction results were corrected for a constant bias by the addition of 1.25, 15, and −6 to the transformed water uses, respectively. The results of the bias correction are evident in the results of the model evaluation in Table 4-8. The high values (all >0.96, with a maximum value of 1) for the NSE indicates that the plot of observed versus simulated data fits the 1:1 line (NSE <0 indicates that the mean is a better predictor than the model).

$$\text{LogcSDW (model 2 + 1.25)} = 0.0324 + 0.2008 \times \text{MilkSol} - 0.0211 \times \text{Rain} + 0.0768 \times \text{Evap} + 0.1913 \times \text{Milking} + 0.0011 \times \text{Irrmm} \quad [1]$$

$$\text{LogMPW (model 3 + 15)} = 0.2538 + 0.4266 \times \text{MilkSol} - 0.0325 \times \text{MilkSol}^2 + 0.0230 \times \text{Rad} - 0.0008 \times \text{Rad}^2 - 0.0419 \times \text{Evap} + 0.0115 \times \text{Evap}^2 + 1.4137 \times \text{Milking} - 0.4786 \times \text{Milking}^2 \quad [2]$$

$$\text{LogTW (model 2 - 6)} = 5.0573 - 0.1531 \times \text{CowBale} + 0.0487 \times \text{MilkVol} + 0.0881 \times \text{MilkSol} - 0.2149 \times \text{MilkSol}^2 + 0.0878 \times \text{Evap} - 0.0110 \times \text{Evap}^2 + 0.3372 \times \text{Milking} - 0.0400 \times \text{Milking}^2 + 0.7393 \times \text{Rotary} - 0.0276 \times \text{Irr/EffArea} + 0.6851 \times \text{Houses\_Yes} - 0.0674 \times \text{Recycle\_Yes} \quad [3]$$

Abbreviations used in the models are presented in Table 4-2. The results of the model evaluation for irrigated farms for cSDW model 2, MPW model 3, and TW model 2 are presented in Table 4-8. The predicted versus measured or derived plots for cSDW, MPW, and TW are presented in Figure 4-4a, b, and c, respectively.

Table 4-5. Partial least squared regression model equations (raw coefficients) for predicting corrected stock drinking water use (log_{10} cSDW) on irrigated pasture-based dairy farms (n = 4)[1].

Variables	Model 1	Model 2	Model 3
R^2	0.74	0.69	0.62
P	< 0.001	< 0.001	< 0.001
Constant	-0.9847	0.0324	0.0929
TMax	0.0103		
TMaxSq	0.0001		
TMin	-0.0086		
TMinSq	0.0005		
Rain	-0.0312	-0.0211	
RainSq	0.0004		
Evap	0.0324	0.0768	
EvapSq	-0.0017		0.0849
Wind	0.0103		
WindSq	-0.0018		
Rad	0.0077		
RadSq	0.0000		
MilkSol	0.0860	0.2008	0.3206
MilkSolSq	0.0048		
MilkVol	0.0057		
MilkVolSq	0.0000		
Milking	0.1740	0.1913	
System	0.1505		
Brd	-0.0970		
Cow	0.0000		
EffArea	0.0001		
Bales	-0.0004		
CowBale	0.0115		
Cows/ha	0.0582		
FY_201314	-0.0138		
Weekend	-0.0020		
ESp	0.3045		
LSp	0.0575		
Sum	0.0507		
Aut	-0.0109		
IrrArea	0.0005		
Irrmm	0.0005	0.0011	0.0012
Irr/EffArea	0.0015		

[1] A list of variables is presented in Table 4-2.

Table 4-6. Partial least squared regression model equations (raw coefficients) for predicting milking parlour water use (log_{10} MPW) on irrigated pasture-based dairy farms (n = 12).

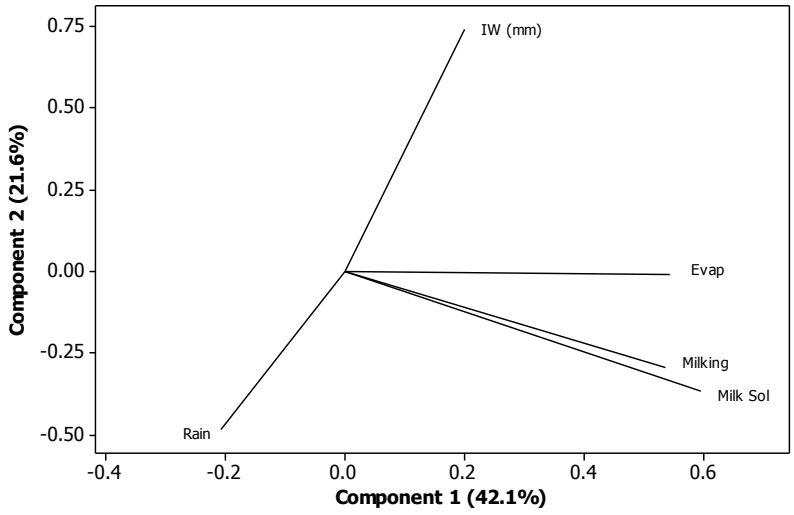
Variables	Model 1	Model 2	Model 3	Model 4
R^2	0.71	0.70	0.65	0.65
P	< 0.001	< 0.001	< 0.001	< 0.001
Constant	-4.4764	-2.2834	0.3040	0.3389
TMax	0.0139			
TMaxSq	-0.0002			
TMin	0.0258			
TminSq	-0.0016			
Rain	0.0025			
RainSq	-0.0001			
Evap	0.0135		0.0424	
EvapSq	-0.0087		-0.0002	
Wind	-0.0172			
WindSq	0.0005			
Rad	0.0084		0.0040	
RadSq	0.0000		-0.0003	
MilkSol	0.4398	0.6033	0.4452	0.4981
MilkSolSq	-0.1462	-0.1344	-0.0492	-0.0635
MilkVol	0.0306			
MilkVolsq	-0.0011			
Milking	0.3759	1.3298	1.4020	1.3925
Milking_Sq	-0.0979	-0.4401	-0.4711	-0.4679
System	-0.4015			
Brd	1.9438	0.6197		
Cow	0.0001			
EffArea	-0.0007			
Rotary	-0.1794			
Bales	-0.0102	-0.0413		
CowBale	0.0461			
Cow/ha	0.5388	0.8966		
Houses_Yes	-0.4452	-0.3110		
Irr/EffArea	0.0250			
IrrArea	0.0021	0.0062		
Irrmm	0.0006			
FY_201314	-0.0966			
ESp	0.5712			
LSp	0.6351			
Sum	0.5206			
Aut	0.4263			
Weekend	-0.0238			
recyORrecircORsnap	0.0770			

[1] A list of variables is presented in Table 4-2.

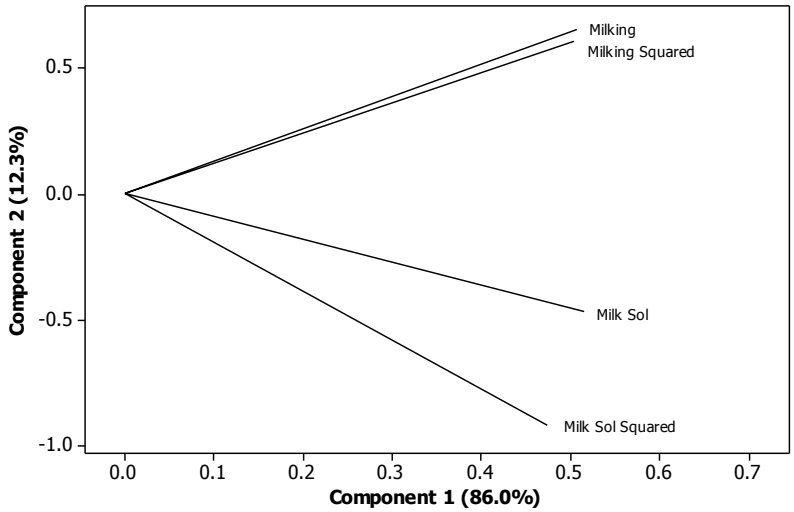
Table 4-7. Partial least squared regression model equations (raw coefficients) for predicting total water use (log_{10} TW) on irrigated pasture-based dairy farms (n = 6).

Variables	Model 1	Model 2	Model 3	Model 4
R^2	0.66	0.66	0.63	0.62
P	< 0.001	< 0.001	< 0.001	< 0.001
Constant	6.2192	7.2839	2.1533	0.9936
TMax	0.0008			
TMaxSq	0.0000			
TMin	0.0243			
TminSq	-0.0015			
Rain	-0.0015			
RainSq	0.0000			
Evap	0.0313			
EvapSq	-0.0062	0.0575		
Wind	-0.0184	-0.0056		
WindSq	0.0031			
Rad	0.0077			
RadSq	-0.0001			
MilkSol	0.1936		0.1979	
MilkSolSq	-0.0813	-0.2341	-0.2512	-0.2876
MilkVol	0.0155	0.0620	0.0533	0.0699
MilkVolsq	-0.0004			
Milking	0.1008	0.5792	0.5564	0.6146
Milking_Sq	0.0368	-0.1646	-0.1667	-0.1784
System	-0.0609			
Brd				
Cow	-0.0008			
EffArea	-0.0023			
Rotary				
Bales	-0.0195			
CowBale	-0.0018	-0.1475		
Cow/ha	-0.0156			
Houses_Yes	0.2324	0.6486	0.3614	0.2646
Irr/EffArea	-0.0156	-0.0432		
IrrArea	-0.0045		-0.0061	
Irrmm	-0.0007			
FY_201314	0.0197			
ESp	0.3747			
LSp	0.3742			
Sum	0.3918			
Aut	0.2289			
Weekend	-0.0367			
recyORrecircORsnap		-0.2270		

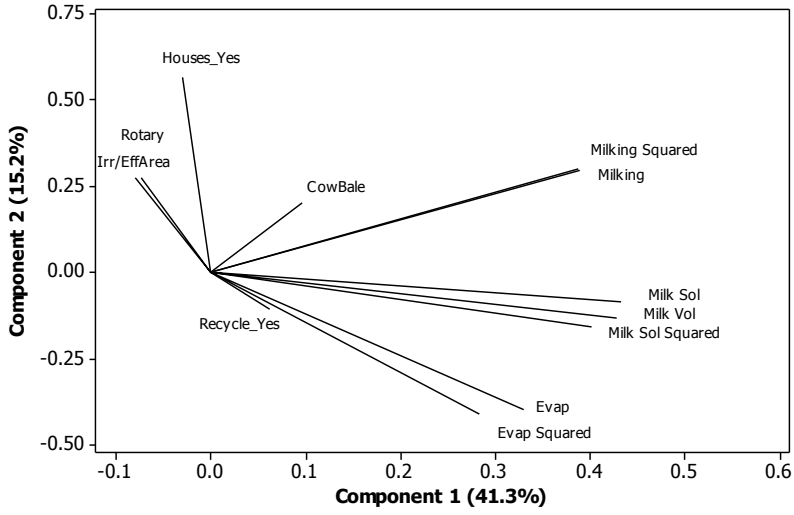
[1] A list of variables is presented in Table 4-2.



a)



b)



c)

Figure 4-3. Partial Least Square regression loading plots (variables defined in Table 4-2) for (a) corrected stock drinking water (cSDW) model 2, (b) milking parlour water use (MPW) model 3 and (c) total water use (TW) model 3.

Table 4-8. Partial least square regression model evaluation for irrigated farms

Prediction Model comparison to measured data	n	Line of best fit Slope[2]	Line of best fit Y intercept[3]	Line of best fit R-squared[4]	Pearson's correlation coefficient (r)[5]	RMSE[6]	NSE[7]	Percentage bias[8]	RSR[9]
Irrigated cSDW model 2 +1.25	4	0.80	5.89	0.77	0.88	5.26	0.96	-0.38	0.20
Irrigated MPW model 3 +15	13	1.17	-10.58	0.92	0.96	8.74	0.98	0.13	0.15
Irrigated TW model 2-6	5	0.80	15.21	0.66	0.81	15.51	0.96	-2.05	0.19

[1]Corrected stock drinking water (cSDW) = SDW – leakage.

[2]L/cow per day; optimum = 1.

[3]L/cow per day; optimum = 0.

[4]Optimum = 1.

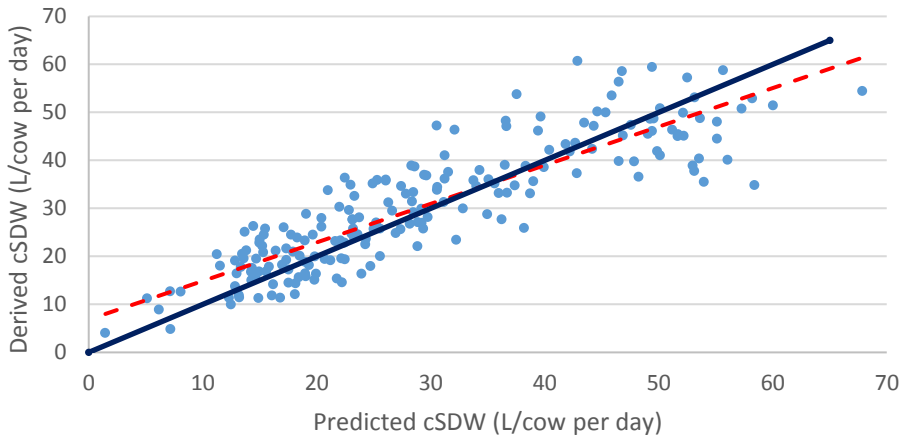
[5]Optimum = 1 or -1.

[6]Root Mean Square Error (L/cow per d); optimum = 1.

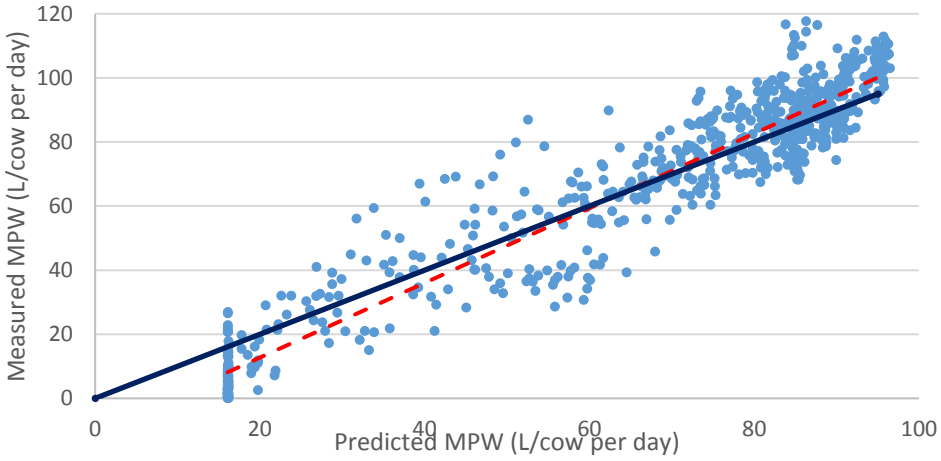
[7]Nash-Sutcliffe efficiency; optimum = 1, > 0 is acceptable, if < 0 then the mean is a better predictor than the model.

[8]Optimum = 0, positive values mean underestimation, and negative means overestimation.

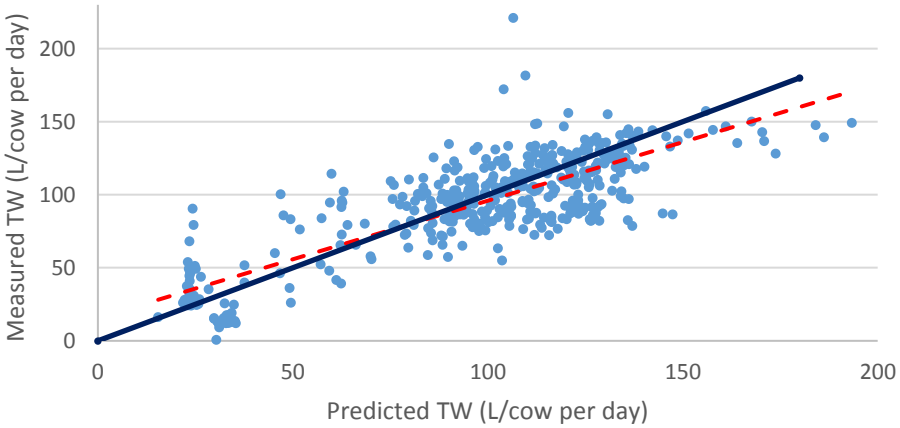
[9]RSR = RSME-observations standard deviation ratio, optimum = 0.



a)



b)



c)

Figure 4-4. Measured or derived water use (number of farms ≥ 5) versus predicted water use (dashed line of best fit) and solid 1:1 line for (a) corrected stock drinking water (cSDW) model 3 ($R^2 = 0.77$), (b) milking parlour water use (MPW) model 3 ($R^2 = 0.90$), and (c) total water use (TW) model 3 ($R^2 = 0.72$).

4.4 Discussion

A seasonal pattern was clear for SDW, cSDW, MPW, and TW in both the irrigated and nonirrigated farms. Although differences are evident, it should be noted that the data are confounded by differing region, farm and herd size, type of milking parlour, and age of infrastructure. The data should be interpreted as a range of values for different water uses across divergent regions and production systems. The data presented here for nonirrigated dairy farms in the Manawatu region are consistent with previous data published on nonirrigated dairy farms (Chapter 3).

There were differences in water use on irrigated and nonirrigated pasture-based dairy farms, including the magnitude of the seasonal patterns between the 2 groups. This is reflective of the seasonal calving operation of New Zealand dairy systems and changing climatic conditions between regions. Average SDW was 23% higher on nonirrigated farms than on irrigated farms despite the irrigated farms being in the Canterbury region and having some of New Zealand's warmest summer temperatures. Lower SDW on the irrigated farms was likely due to a combination of factors but largely attributable to irrigation and leakage rates. Leakage rates (47%) on the nonirrigated farms (n = 8) were much higher than on the irrigated farms (n = 4; 13%). Possible explanations for this include soil type, geological activity, and age of infrastructure. The Manawatu (nonirrigated) region also has frequent earthquakes—7,179 earthquakes in a 9,300-km2 area over the trial period compared with 1,790 earthquakes in a 66,500-km3 area in the Canterbury (irrigated) region (Earthquake Commission and GNS Science, 2016). Many dairy farms in the Canterbury region were established in recent times, whereas dairying is a much older use of land in the

Manawatu region, leading to differences in the age of infrastructure. We do not have information on the age of the infrastructure on farms to analyse the effect it had on leakage rates. Further work is needed to confirm the cause of the higher leakage rates and to understand whether water leakage can be reduced on all farms or whether farms with certain characteristics can be targeted. Although the leakage component explained the majority of the difference in SDW between the 2 regions, irrigated pasture also influenced SDW. This influence was evident in the cSDW values being 8 L/cow per day (24%) higher on average and 27 L/cow per day (31%) higher at peak on the nonirrigated farms compared with the irrigated farms. The main reason for this is the moisture status of the irrigated pasture; the DM content of pasture on an irrigated research farm in Canterbury is typically between 15 and 25% for the whole season (A. Clement, DairyNZ, Lincoln, New Zealand; personal communication, 2016). In contrast, the DM content of nonirrigated pasture on a research farm in the Waikato region, which can experience dry summers similar to the Manawatu region, can average 40% in dry summers (C. Roach, DairyNZ, Hamilton, New Zealand; personal communication, 2016). The reduced DM content of pasture on irrigated farms results in more water being ingested via grass than on nonirrigated farms (e.g., 120 vs. 30 L/cow per day), which reduces cow requirements for cSDW.

Average MPW over the milking period was 24 L/cow per day higher on irrigated farms than on nonirrigated farms. Possible explanations for the higher MPW on irrigated farms include the higher proportion of rotary milking parlours (86%) in the irrigated region than rotary milking parlours (26%) in the nonirrigated region (Chapter 3). Higher numbers of staff employed may be another influence on MPW. Further

consideration should be given to evaluating why MPW is higher on the irrigated farms, as this may allow water reductions to be made in the future.

On the irrigated farms, IW use was much greater than either SDW or MPW. Therefore, when all forms of water use are combined (i.e., TW + IW), water use on the irrigated dairy farms was approximately 39-fold greater than it was on nonirrigated farms. To put this in context, forgoing 1 d of irrigation would save as much water on some farms as that used in MPW over approximately 78 d. Therefore, to reduce overall water use on irrigated dairy farms, focusing on increasing irrigation efficiency rather than reducing MPW may be more productive.

The cSDW model 3, MPW model 3, and TW model 3 developed in Chapter 3 predicted water use on the nonirrigated dairy farms in this study with good accuracy and precision. Given the similarity in observed water use between both sets of nonirrigated farms, the success of the Chapter 3 models is not surprising. It would suggest that we now have a good understanding of water use data on nonirrigated farms and have the ability to predict this water use. As expected, the models of Chapter 3 were not able to predict cSDW, MPW, and TW, respectively, on irrigated pasture-based dairy farms. All models had poor line of best fit slopes, percentage bias, and NSE, and the cSDW model 3 predictions were less accurate than the mean water use on irrigated farms (NSE <0). As the models described in Chapter 3 were not able to predict water use on irrigated dairy farms, new PLS regression models were developed to predict cSDW, MPW, and TW on irrigated dairy farms. These new models performed well for the irrigated farms studied here. The models were very close to the observed water use and overestimated water use only from 0.1 to 2.8%.

The water use figures and predictive models produced in this study will have implications for the management of water use on dairy farms. Farms in geologically active areas or on coarse-textured soils, older farms, or farms in areas with certain topography may require more leakage management than other farms, but further research is needed to investigate this. Water use prediction models will allow more realistic estimation of water use and water use patterns in both nonirrigated and irrigated regions to aid in the allocation of water and the management of water resources. The models will also allow water footprints to be calculated and regional footprints to be compared.

In this study, water meters already available on farms were used for monitoring to keep the cost down, and both telemetry and data loggers were used to collect data. Water meters were also installed on farms in the Manawatu region where it was feasible in the water system. It was very difficult to ensure metering of all water sources on many farms because of complex water reticulation systems. Many older farms in the Manawatu region had been merged to form one larger farm, a consequence having fragmented water systems. This reduced the feasibility of collecting data because the cost of multiple water meters, data loggers, and installation was prohibitive. Data loggers were used as a less expensive data collection option than telemetry. However, this came with a greater workload in data collection and issues with battery life and suitable weatherproof housing to prevent moisture from damaging the data loggers. In future research, we recommend that thorough scoping of data collection options should be evaluated to ensure the data collection method chosen meets requirements and that telemetry be used where budget allows. The remote data access of telemetry systems

allows for easy data monitoring, thus reducing workload significantly and increasing reliability.

4.5 Conclusions and Recommendations

On irrigated dairy farms, the water used for irrigation far exceeded all other forms of water use combined. Corrected SDW on the irrigated dairy farms was lower than that on nonirrigated dairy farms. This can be explained by the larger quantities of water ingested by the cows as they graze the irrigated pasture, which has lower DM. The models developed in Chapter 3 were able to predict water use on the nonirrigated dairy farms of a different region. However, these models were not able to predict water use on irrigated farms. New PLS regression models were developed to predict cSDW, MPW, and TW on irrigated farms. Further research is needed to evaluate the applicability of these models to other irrigated regions. The current study along with the preceding work described in Chapter 3 suggest that we now have a reasonably comprehensive understanding of water use on New Zealand dairy farms and the ability to model this water use.

4.6 Acknowledgements

The authors acknowledge the farmers involved and the effort they put into supplying data for this study. This work was supported by funding from New Zealand dairy farmers through DairyNZ Inc. and the Sustainable Dairying Water Accord (DairyNZ Inc.), and by Horizons Regional Council through assistance with water monitoring and technical guidance.

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CHAPTER 5.

Water use accounting for New Zealand dairy farms

This chapter has been submitted to an international journal as C. Higham, D. Horne, R. Singh, and M. R. Scarsbrook. 2017. Water use accounting for New Zealand dairy farms: Current use and predicted effects of future climate change.

5.1 Abstract

Dairy farm water use was modelled for the period 2010-2015, on 1,150 individual dairy farms in different regions across New Zealand. These data were used to estimate total dairy farm water use for all dairying regions in New Zealand. Irrigation water use on dairy farms was taken directly from the withdrawal consent conditions issued by Regional Councils. Current total water use on New Zealand dairy farms is estimated at 4.8 billion m^3 per year. Of this, approximately 97% is for irrigation, with 70% used for irrigation in Canterbury. The likely impact of climate change on water use on dairy farms was also investigated with an estimate 80% and 0.03% increase in stock drinking water and milking parlour water use respectively, under climate change scenario RCP 4.5 (a stabilization pathways where the increasing CO_2 levels begin to stabilize and do not increase) by the period 2101-2120. Under climate change scenario RCP 4.5 irrigation water is expected to increase between 17-27%, with the largest increase in Canterbury. This is expected to increase irrigation water use on dairy farms already using irrigation, and is also likely to increase the number of farms that irrigate subject to regional rules. Future water use associated with stock drinking and the

milking parlour were predicted under four different climate change projections with three future time periods, and compared with water use calculated for 2010-2015. Stock drinking water on non-irrigated dairy farms was estimated to increase dramatically due to the changes in maximum temperature in the model, by up to 136% by 2101-2120 under the climate change projection RCP 4.5, doubling on dairy farms in some regions as soon as the 2031-2050 period. However, stock drinking water on irrigated dairy farms was not predicted to increase markedly due to the amount of water in irrigated pasture consumed by cows. Milking parlour water use on irrigated and non-irrigated dairy farms is not expected to change substantially as a direct result of the climate change scenarios; any expected change will come through changing milk volumes and milking patterns.

5.2 Introduction

Water use has reached, or is approaching, the sustainable limits in many of the world's water basins. Yet demand for water is expected to increase in all sectors of global primary production (WWAP United Nations World Water Assessment Programme, 2012), and it is estimated that there will be a 40% global water deficit by 2030 under the 'business-as-usual' climate scenario (WWAP United Nations World Water Assessment Programme, 2015). Agricultural production is responsible for most water use and water stress (Hoekstra and Hung, 2002, Ridoutt and Pfister, 2010, Lovarelli et al., 2016). From 1996 to 2005, agriculture used 92% of the total water footprint of the world (Hoekstra and Mekonnen, 2012). The water resource is said to be stressed when, amongst other impacts, ecological form and function is

compromised; there is inadequate water available for current users, and limitations on the ability of others to use the resource. Because water is becoming scarce in many catchments, mitigation strategies that focus on reducing water use are needed (Lovarelli et al., 2016).

New Zealand is considered a water plentiful country, however water allocation has reached the sustainable limit in some waterways at certain times of the year, particularly in Otago and Canterbury (Ministry for the Environment, 2010). In response to this shortage, the New Zealand government developed the National Policy Statement for Freshwater Management (**NPS-FM**; Ministry for the Environment, 2014). The NPS-FM prevents Regional Councils from over-allocating freshwater, and where over-allocation already exists, it is to be stopped. The NPS-FM also requires more efficient use of water and that Regional Councils make regulations to meet the reasonably foreseeable impacts of climate change.

The dairy industry in New Zealand is estimated to be the largest user of water in the agricultural sector (Aqualinc, 2010, Statistics New Zealand, 2011, Corong et al., 2014). But, data used to estimate water use on pasture-based dairy farm water use are limited, and only 'rule of thumb' industry figures were used in regional and national water accounting estimates of stock drinking water and milking parlour water use (Flemmer and Flemmer, 2007, Statistics New Zealand, 2012, Chapter 3). Recently, detailed monitoring has been carried out and empirical water use models have been developed based on water use data from irrigated and non-irrigated, pasture-based dairy farms in three New Zealand regions (Chapter 3, Chapter 4). These studies provided estimates of leakage rates from water distribution systems for stock drinking water. These leakage rates (ranging from 13 to 47% of stock drinking water) are an

important and hitherto unquantified component for water use accounting (Chapter 3, Chapter 4).

Water use differs fundamentally between irrigated and non-irrigated farms. Irrigation water volumes far exceed stock drinking and milking parlour use (Aqualinc, 2010, Statistics New Zealand, 2011, Chapter 4). In New Zealand, the amount of water that farmers can use for irrigation (water take) is tightly regulated and, therefore, water take consents provide a valuable source of data on the amount of 'allowable' water use by irrigators. However, a gap often exists between total 'allowable' and actual farm irrigation water use as measured through metering (Aqualinc, 2010). Irrigation water consents for dairy farming make up approximately 70% of allocated water (excluding hydropower) in New Zealand (Aqualinc, 2010, Statistics New Zealand, 2012, Corong et al., 2014).

Downscaling of global climate change models to regional and national scales has provided a number of predictions for future water availability in New Zealand and potential effects on agriculture (Collins et al., 2012, Lee et al., 2012, Ministry for the Environment, 2016). However, little information is available on the expected water requirements for dairy farms under different climate change scenarios. Irrigation water use under these climate change scenarios is difficult to predict, because of decreased water availability and increased competition with other water users (Collins et al., 2012).

The objective of the study was to create a national water account for New Zealand dairy farms and identify the likely future water needs of the industry under predicted climate change scenarios, while assuming no change in farm practices, cow numbers, or milk production. Accordingly, the study has, for New Zealand, 1)

calculated the total volume of water used for irrigation in all dairying regions from consented volumes; 2) estimated the water use of dairy farms over five farming seasons (2010 to 2015) in all dairying regions, 3) predicted stock drinking water and milking parlour water use of dairy farms under different climate change scenarios over three time periods, and 4) for comparative purposes, likely increases in irrigation water use for the period 2031-2050.

5.3 Materials and Methodology

5.3.1 Farm systems, data sources, and data management

Physical and production data for 1,150 seasonal calving farms for five milking seasons (2010-2011, to 2014-2015) were collected from DairyBase, a database which benchmarks the productivity, profitability and physical aspects of dairy farm businesses (DairyNZ, 2016). The data derive from 926 non-irrigated, and 224 irrigated (> 50% area irrigated) pasture-based dairy farms (Table 5-1 and Table 5-2). The data include: peak number of cows, breed of cows, system type, calving pattern, farm size, irrigation area, planned start of calving, the number of days that cows produced milk per year, the date when half the herd had calved, and milking parlour type and size. Few irrigated dairy farms exist in Northland, Auckland, Taranaki, Gisborne, and Southland, and few non-irrigated farms exist in Hawkes Bay, Tasman, and Canterbury. When data from fewer than five farms of each type were available for a region, that region was modelled by combining the data from that region with the data from the nearest region geographically.

Table 5-1. Average farm and climate variables[1] by region for non-irrigating dairy farms.

Region	Farms (n)[2]	Mean max temp (°C)	Mean min temp (°C)	Mean rad (MJ/m²)	Mean evap (mm)	Mean kg MS/cow per day[3]	Cow breed[4]	Peak cow numbers	Rainfall (mm/yr)
Auckland	16	19.5	11.5	14.8	2.6	1.43	0.60	380	1252
Bay of Plenty	103	18.6	8.9	15.1	2.6	1.37	0.61	396	1375
Canterbury	4	14.9	4.3	14.0	2.2	1.33	0.53	657	687
Hawke's Bay	1	18.5	8.4	14.5	2.5	1.05	0.00	330	1053
Manawatu	97	17.6	8.0	14.0	2.3	1.31	0.61	423	1074
Marlborough	5	17.1	7.5	15.6	2.6	1.11	0.69	344	1110
Northland	64	19.5	11.7	14.8	2.6	1.13	0.45	412	1422
Otago	23	15.3	5.4	12.8	2.0	1.48	0.66	518	646
Southland	56	15.1	5.5	12.5	1.9	1.55	0.70	586	922
Taranaki	104	17.1	9.1	15.1	2.5	1.51	0.54	333	1593
Tasman	4	18.0	7.8	15.7	2.7	0.99	0.88	292	2063
Waikato	395	18.9	8.9	14.8	2.5	1.37	0.60	403	1210
Wellington	8	17.5	8.3	14.3	2.4	1.42	0.76	448	1097
West Coast	46	16.9	8.3	13.0	2.1	1.25	0.46	483	1252

[1]Mean max temp = mean maximum temperature; mean min temp = mean minimum temperature; mean rad = mean solar radiation; mean evap = mean Priestly-Taylor potential evapotranspiration.
[2]Regions with n = < 5 were modelled using the data from the region added to the data of the closest region to give n = > 5.
[3]Mean kg milksolids (milk fat + milk protein) per cow.
[4]Cow breed fraction (0 = Jersey, 0.5 = Friesian-Jersey cross, 1 = Friesian).

Table 5-2. Average farm and average climate variables[1] for irrigating dairy farms.

Region	Farms (n)[2]	Mean max temp (°C)	Mean min temp (°C)	Mean rad (MJ/m²)	Mean evap (mm)	Mean kg MS/cow[3]	Cow breed[4]	Peak cow numbers	Rainfall (mm/yr)
Bay of Plenty	22	19.1	9.1	15.1	2.6	1.48	0.63	427	1269
Canterbury	140	16.6	6.1	13.2	2.1	1.56	0.63	805	650
Hawke's Bay	1	17.5	7.9	14.2	2.4	0.96	0.50	373	877
Manawatu	10	18.0	8.6	14.3	2.4	1.23	0.75	543	958
Marlborough	7	17.2	7.5	15.6	2.6	1.37	0.64	378	1140
Northland	2	19.7	12.0	14.6	2.6	1.51	0.50	415	1371
Otago	15	15.9	5.8	12.9	2.0	1.81	0.64	620	530
Southland	3	15.2	4.8	12.9	2.0	1.86	0.67	801	828
Taranaki	3	17.2	9.3	15.1	2.5	1.34	0.33	283	1302
Tasman	3	17.1	6.2	15.1	2.5	1.10	0.17	337	1151
Waikato	5	18.6	8.5	14.5	2.5	1.55	0.40	436	1148
Wellington	7	18.1	8.1	14.4	2.4	1.37	0.64	411	881
West Coast	5	17.0	8.1	12.8	2.1	1.41	0.39	528	1876

[1]Mean max temp = mean maximum temperature; mean min temp = mean minimum temperature; mean rad = mean solar radiation; mean evap = mean Priestly-Taylor potential evapotranspiration.
[2]Regions with n = < 5 were modelled using the data from the region, added to the data of the closest region to give n = > 5.
[3]Mean kg milksolids (milk fat + milk protein) per cow.
[4]Cow breed fraction (0 = Jersey, 0.5 = Friesian-Jersey cross, 1 = Friesian).

Monthly totals of milksolids (milk fat + milk protein) production for each DairyBase farm were taken from the milksolids levy database (DairyNZ and Livestock Improvement Corporation, 2015) which is administered by DairyNZ. Not all farms were in DairyBase for the full five seasons, and some farms did not supply milk in all seasons. Where there were milksolids production data, but no DairyBase data for some of the years, average values for all the variables were assumed.

Five years of daily records for each farm for maximum temperature (°C), minimum temperature (°C), rainfall (mm), solar radiation (MJ/m^2), wind run (km), and potential evapotranspiration (mm) were obtained from the National Institute of Water and Atmosphere (NIWA) Virtual Climate Station Network (VCSN) (Cichota et al., 2008). The VCSN uses data from individual weather stations and interpolates over a 5 km x 5 km grid across New Zealand. The daily data were averaged for each month.

5.3.2 Irrigation water use

The irrigation water volumes allocated to dairy farms were requested from 15 different Regional Councils issuing water consents. Annual volumes were used where available but when not, the water use was calculated over the irrigation period from October to March (Aqualinc, 2010). When consents included water for uses other than irrigation, then irrigation was assumed to be the main use and the volume was used without modification, i.e. no attempt was made to account for other uses. Other uses included stock drinking water, milking parlour water, and domestic water. Actual use values were supplied by two councils only, Environment Canterbury and the Tasman District Council. The proportion of actual use to consented volume was calculated

using these data. Where Regional Councils did not provide water data, actual water use was calculated using previously reported ratios of actual use to allocated water (Aqualinc, 2010).

The area of land under irrigation in each region was taken from the consent data provided by councils. When this was not available, the area of irrigation in each region was taken from other sources (Statistics New Zealand, 2012, Corong et al., 2014). As the area of dairy farm irrigation taken from these sources was for 2012, it was scaled to match the changes in dairying area in each of the regions since then (DairyNZ and Livestock Improvement Corporation, 2013, 2015).

5.3.3 Water use modelling

Milking parlour water use (**MPW;** L/cow per day) and corrected stock drinking water (corrected means estimated leakage is removed; **cSDW;** L/cow per day) were estimated using empirical models for non-irrigating dairy farms (Chapter 3) and for irrigating dairy farms (Chapter 4). The models used for corrected stock drinking water were the non-irrigated cSDW model 3 (Chapter 3) and the irrigated cSDW model 2 (Chapter 4). The MPW models used were modified to incorporate temperature and rainfall to allow modelling of effects of different climate change scenarios. The non-irrigated MPW model 3 equation was modified to include rainfall and maximum temperature to give equation [1], the R^2 of the new model did not change from the original (0.55). The cow breed is the breed fraction divided into 16 from all Friesian (F16) through to all Jersey (F0). The cow to bale ratio is the total number of cows divided by the number of bales in the milking parlour.

$$log_{10}Non-Irrigated\ MPW\ (Model\ 3_{modified}) = 1.34209 + 0.42072 \times milksolids - 0.19921 \times milksolids^2 + 0.02430 \times milk\ volume + 0.35342 \times milking\ frequency - 0.03828 \times milking\ frequency^2 - 0.30107 \times cow\ breed - 0.02866 \times cow\ to\ bale\ ratio - 0.01890 \times maximum\ temperature + 0.00048 \times maximum\ temperature^2 - 0.00253 \times rainfall + 0.00008 \times rainfall^2 \quad [1]$$

The irrigated MPW model 3 was modified to replace collinear variables with those with data available in climate change predictions to allow climate change modelling. In the modified version of the irrigated MPW model 3, Priestly-Taylor evapotranspiration and solar radiation were replaced with maximum temperature and rainfall, giving equation [2]. The R^2 of the model increased slightly from 0.62 to 0.64.

$$log_{10}Irrigated\ MPW\ \left(Model\ 3_{modified}\right) = 0.019950 + 0.49304 \times milksolids - 0.06235 \times milksolids^2 + 1.34883 \times milking\ frequency - 0.44949 \times milking\ frequency^2 + 0.01614 \times maximum\ temperature - 0.00034 \times maximum\ temperature^2 - 0.00154 \times rainfall + 0.00004 \times rainfall^2 \quad [2]$$

The average per cow MPW and cSDW was calculated for non-irrigated and irrigated farms in each region. The water use per cow was then multiplied by the number of dairy cows in each region on irrigating and non-irrigating farms (Statistics New Zealand, 2012, Corong et al., 2014, DairyNZ and Livestock Improvement Corporation, 2015). Estimated leakage rates (Chapter 3, Chapter 4) were added to the cSDW values to give total stock drinking water (**SDW**) supply. The consumed (evapotranspired) volume of water was estimated by applying the consumptive fraction for agriculture (Shiklomanov and Rodda, 2004).

5.3.4 Climate change scenarios

Possible future changes in rainfall and temperature were taken from modelled climate change scenarios under four representative concentration pathways (RCPs); RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 (Ministry for the Environment, 2016). The RCP 2.6 scenario assumes that some CO_2 removal from the atmosphere will occur from current levels. The RCP 4.5 and RCP 6.0 scenarios are two stabilization pathways where the increasing CO_2 levels begin to stabilize and do not increase. The RCP 8.5 scenario is the pathway where there are increasing and very high levels of greenhouse gas concentrations in the atmosphere. The rainfall and temperature changes are predicted from an average base data set from 1986 to 2005. Base climate data for the period 1986 to 2005 for each farm were downloaded from the virtual climate station network (VCSN) (Cichota et al., 2008). The percentage increase or decreases per season in rainfall (Table 5-3) and temperature (Table 5-4) were applied to the base climate data for the different scenarios and the volume of water required for MPW and cSDW on the irrigated and non-irrigated farms was calculated using equations [1] and [2] for MPW, and those presented in Chapter 3 and Chapter 4 for cSDW. The water use per region was then calculated and compared with the water use calculated for the 2010-2015 milking seasons.

Irrigation water use requirements for the past 30 years in Morrinsville (in the Waikato region), Santoft (in the Manawatu region), and Pendarves (in the Canterbury region) were modelled using a soil water balance with rainfall and FAO56 estimates of evaporation. For any one year, the irrigation requirement is given by the difference

between the reference crop evapotranspiration and the actual evapotranspiration. The climate data necessary for this exercise were collected from the Virtual Climate Station Network (Cichota et al., 2008). Typical available water holding capacities for soils in each region were assumed (See Table 5-9). The impacts of climate change on irrigation requirements were simulated by the water balance following modification of climate data according to the projections presented in the Climate Change report for the RCP 4.5 scenario (Ministry for the Environment, 2016). The modelling of future irrigation requirements under climate change is not as comprehensive as the treatment of potential future changes to MPW or cSDW, neither is it claimed to be a rigorous analysis of the likely impacts of climate change on evaporation rates and rainfall patterns. Rather, predictions of the likely magnitude of increases in irrigation water requirements are included here for comparative purposes, that is to allow increases in irrigation to be compared to increases in SDW and MPW.

Table 5-3. Average annual temperature change (°C) above the base average temperature for 1986-2005 under four different RCP[1] climate change pathways (Ministry for the Environment, 2016).

	RCP 2.6			RCP 4.5			RCP 6.0		RCP 8.5		
Region	2031-2050	2081-2100	2101-2120	2031-2050	2081-2100	2101-2120	2031-2050	2081-2100	2031-2050	2081-2100	2101-2120
Auckland	0.75	0.68	0.73	0.90	1.45	1.67	0.85	1.88	1.03	3.08	3.77
Bay of Plenty	0.75	0.67	0.73	0.87	1.45	1.68	0.83	1.88	1.05	3.10	3.78
Canterbury	0.70	0.65	0.75	0.83	1.38	1.65	0.80	1.75	1.03	2.98	3.65
Hawke's Bay	0.73	0.70	0.73	0.87	1.43	1.68	0.80	1.85	1.08	3.03	3.78
Manawatu	0.70	0.67	0.72	0.88	1.45	1.70	0.83	1.82	1.05	3.10	3.77
Marlborough	0.70	0.65	0.72	0.88	1.43	1.68	0.80	1.80	1.03	3.03	3.68
Northland	0.75	0.70	0.75	0.90	1.43	1.68	0.85	1.85	1.07	3.07	3.78
Otago	0.63	0.60	0.70	0.80	1.27	1.60	0.75	1.63	0.95	2.85	3.55
Southland	0.63	0.60	0.70	0.75	1.25	1.55	0.70	1.53	0.92	2.75	3.48
Taranaki	0.73	0.65	0.72	0.87	1.45	1.70	0.82	1.82	1.05	3.08	3.80
Tasman	0.70	0.65	0.72	0.85	1.43	1.63	0.83	1.75	1.03	3.03	3.70
Waikato	0.75	0.68	0.73	0.88	1.45	1.68	0.83	1.90	1.05	3.08	3.80
Wellington	0.72	0.67	0.72	0.90	1.43	1.68	0.80	1.82	1.08	3.03	3.73
West Coast	0.68	0.65	0.73	0.85	1.40	1.63	0.82	1.75	1.00	2.97	3.67

[1]RCP = representative concentration pathways. There are no predictions available for RCP 6.0 for 2101-2120.

Table 5-4. Average annual rainfall change (%) from the base average rainfall for 1986-2005 under four different RCP[1] climate change pathways (Ministry for the Environment, 2016).

	RCP 2.6			RCP 4.5			RCP 6.0		RCP 8.5		
Region	2031-2050	2081-2100	2101-2120	2031-2050	2081-2100	2101-2120	2031-2050	2081-2100	2031-2050	2081-2100	2101-2120
Auckland	0%	2%	2%	0%	0%	0%	0%	1%	0%	-2%	-5%
Bay of Plenty	1%	1%	1%	1%	0%	0%	2%	1%	1%	0%	-3%
Canterbury	2%	4%	3%	3%	5%	5%	3%	5%	4%	9%	8%
Hawke's Bay	0%	-2%	-1%	-1%	-2%	-1%	1%	-4%	-2%	-2%	-3%
Manawatu	1%	4%	2%	1%	2%	2%	1%	4%	1%	1%	0%
Marlborough	1%	2%	2%	1%	2%	3%	2%	2%	1%	4%	3%
Northland	0%	1%	2%	0%	-1%	-1%	0%	1%	-1%	-4%	-6%
Otago	2%	4%	3%	2%	4%	5%	2%	4%	2%	6%	7%
Southland	3%	6%	3%	4%	7%	7%	2%	8%	4%	9%	9%
Taranaki	1%	3%	2%	2%	2%	2%	1%	4%	1%	2%	-1%
Tasman	2%	2%	2%	2%	4%	3%	2%	3%	2%	7%	5%
Waikato	1%	2%	2%	1%	1%	1%	1%	3%	1%	0%	-2%
Wellington	1%	1%	1%	1%	1%	1%	1%	0%	0%	1%	0%
West Coast	4%	5%	4%	4%	7%	6%	3%	9%	5%	11%	8%

[1]RCP = representative concentration pathways. There are no predictions available for RCP 6.0 for 2101-2120.

5.4 Results

Estimates of the average daily volume of water used for SDW and MPW on irrigating and non-irrigating dairy farms are presented in Table 5-5, along with the total number of cows on irrigating and non-irrigating dairy farms in each region. Only 300 cows in total were farmed on irrigating farms in Gisborne, and up to 975,554 cows in total on irrigating farms in Canterbury. Total cow numbers on non-irrigating farms ranged from 1,048 in the Marlborough region to 1,381,032 in the Waikato region. The collected data totalled to 53,328 farm-years on non-irrigated farms, and 12,432 farm-years on irrigated farms, where one farm-year is one year's worth of data collected on one farm.

The modelled estimates of cSDW, SDW, MPW, and abstracted volumes of irrigation water from consents are presented in Table 5-6. A total of 4.8 billion m^3 of water is abstracted every year for dairy farming in New Zealand, 97% of which is for irrigation. The region with the largest volume of water withdrawal is Canterbury where approximately 3.4 billion m^3 of water is abstracted every year. The total volume of water consumed (through evapotranspiration) in New Zealand is estimated as 3.8 billion m^3 is consumed, and an estimated 1 billion m^3 of water is not evapotranspired, returning through drainage or other means to freshwater systems when calculated using consumptive use fractions.

Table 5-5. The estimated total number of cows on irrigating and non-irrigating farms, estimated average water uses[1] (L/cow per d) for irrigating and non-irrigating farms from 2010-2015, and the amount of data collected in farm-years[2].

	Irrigating farms				Non-irrigating farms			
Region[3]	cSDW	MPW	Cow numbers	Farm-years of data	cSDW	MPW	Cow numbers	Farm-years of data
Auckland	10.1	80.6	1,810	0	32.1	35.1	112,268	960
Bay of Plenty	19.6	77.3	21,048	1,272	31.3	35.4	214,627	6,120
Canterbury	26.6	79.2	975,554	7,848	27.3	39.0	33,620	240
Gisborne	11.7	63.1	300	0	30.1	38.9	4,390	0
Hawke's Bay	11.7	63.1	25,648	24	30.1	38.9	27,591	60
Manawatu	11.9	63.7	47,061	528	30.1	38.7	281,332	5,736
Marlborough	13.4	69.8	15,613	420	29.9	29.2	1,048	288
Northland	10.1	80.6	8,407	120	32.0	38.7	276,988	3,828
Otago	22.4	91.8	104,987	852	27.4	40.1	77,397	1,344
Southland	21.4	92.0	39,077	180	26.1	33.8	534,043	3,312
Taranaki	11.3	65.0	11,559	180	28.1	42.0	484,905	6,204
Tasman	14.3	65.7	17,552	180	29.8	34.7	42,819	240
Waikato	9.8	81.0	48,796	300	32.2	37.5	1,381,032	23,424
Wellington	23.1	70.9	42,482	420	29.6	28.4	30,845	480
West Coast	7.1	71.9	3,681	108	25.8	43.8	151,854	1,092
Total			1,363,573	12,432			3,654,760	53,328

[1]cSDW = corrected stock drinking water; MPW = milking parlour water use.

[2]Farm-years = the total number of years' worth of data collected across all farms.

[3]Regions with farm numbers < 5, were estimated using data available combined with the next closest region. Auckland irrigated farms approximated by Northland and Waikato farms; Gisborne farms and Hawke's Bay farms approximated by Hawke's Bay and Manawatu farms combined.

Table 5-6. Water use estimates (1000 × m³/yr) for regions in New Zealand on dairy farms for milking parlour water use (MPW), corrected stock drinking water (cSDW), stock drinking water (SDW), irrigation water, total abstracted water, and the total consumed (evapotranspired) fraction of water.

Region	MPW	cSDW	SDW	Irrigation	Total abstracted	Total consumed
Auckland	1,493	1,322	1,666	855	4,014	3,131
Bay of Plenty	3,370	2,604	3,281	7,554	14,205	11,080
Canterbury	28,694	9,803	11,078	3,320,234	3,360,006	2,620,804
Gisborne	69	49	73	31	173	135
Hawke's Bay	983	413	607	9,914	11,504	8,973
Manawatu	5,072	3,294	4,843	86,755	96,669	75,402
Marlborough	409	88	99	24,894	25,402	19,814
Northland	4,160	3,265	4,212	5,618	13,990	10,912
Otago	4,649	1,633	1,845	847,172	853,666	665,860
Southland	7,909	5,385	6,085	55,360	69,355	54,097
Taranaki	7,709	5,014	6,468	49,346	63,524	49,549
Tasman	964	557	719	30,484	32,167	25,090
Waikato	20,361	16,387	24,090	124,119	168,570	131,485
Wellington	1,420	692	892	17,850	20,162	15,726
West Coast	2,522	1,439	1,626	94,117	98,265	76,646
New Zealand	89,782	51,948	67,585	4,674,303	4,831,670	3,768,703

Total volumes of cSDW per region for the period 2010-2015 and for the different climate change scenarios are presented in Table 5-7. The largest increase in cSDW is predicted to occur under climate change scenario RCP 8.5 for the 2101-2120 period when the increase in cSDW is predicted to range from 9% to 173% more than the current levels. The total increase for RCP 4.5 at three time periods compared with the 2010-2015 period for all regions studied is presented in Figure 5-1 where the different cSDW figures are plotted with cow numbers in each region, showing the scale of the increase in water use. The predicted increase in cSDW in regions with high levels of irrigating farms is small, with the Canterbury and Marlborough regions increasing by only 8% and 11%, respectively. The greatest increases are predicted for regions dominated by non-irrigating dairy farms, including the Auckland, Bay of Plenty, Southland, Taranaki, Waikato, and West Coast regions; the increase in cSDW in these regions under climate change scenario RCP 4.5 (2101-2120) ranged from 104% to 136% more than the 2010-2015 period. The biggest increase in the volume of water for cSDW is expected to be in the Waikato, Southland, and Taranaki regions, where the high levels of increase along with the greater number of cows will likely give higher total volumes of water required for cSDW.

Table 5-7. Current (2010-2015) corrected stock drinking water volumes (1000 × m³/year) and under different climate change scenarios (RCP 2.6, 4.5, 6.0, and 8.5[1]) at three time periods (2031-2050, 2081-2100, and 2101-2120).

Region	Current	RCP 2.6			RCP 4.5			RCP 6.0		RCP 8.5		
	2010-2015	2031-2050	2081-2100	2101-2120	2031-2050	2081-2100	2101-2120	2031-2050	2081-2100	2031-2050	2081-2100	2101-2120
Auckland	1,322	2,635	2,617	2,627	2,662	2,759	2,805	2,654	2,840	2,679	3,090	3,248
Bay of Plenty	2,604	5,000	4,971	4,987	5,036	5,223	5,318	5,017	5,379	5,088	5,841	6,127
Canterbury	9,803	10,532	10,524	10,534	10,538	10,108	10,567	10,535	10,136	10,547	10,617	10,663
Gisborne	49	88	88	89	89	93	94	89	95	90	104	109
Hawke's Bay	413	665	663	666	672	682	704	671	695	679	762	795
Manawatu	3,294	5,803	5,785	5,812	5,872	6,068	6,196	5,858	6,210	5,937	6,790	7,124
Marlborough	88	97	97	97	97	91	98	97	91	98	100	101
Northland	3,265	5,094	5,072	5,088	5,145	5,328	5,423	5,128	5,482	5,208	5,977	6,286
Otago	1,633	2,542	2,535	2,553	2,561	2,561	2,650	2,558	2,603	2,576	2,799	2,895
Southland	5,385	11,877	11,822	11,956	11,954	12,323	12,607	11,960	12,521	12,096	13,603	14,297
Taranaki	5,014	11,066	10,976	11,056	11,172	11,596	11,811	11,149	11,870	11,303	12,962	13,665
Tasman	557	807	804	808	815	833	853	812	852	822	924	965
Waikato	16,387	31,534	31,306	31,433	31,766	32,974	33,546	31,671	33,976	32,128	36,841	38,822
Wellington	692	1,081	1,078	1,081	1,088	1,094	1,126	1,083	1,115	1,097	1,196	1,241
West Coast	1,439	2,655	2,640	2,661	2,684	2,772	2,822	2,689	2,831	2,705	3,081	3,246
New Zealand	51,948	91,476	90,978	91,447	92,152	94,502	96,620	91,969	96,697	93,053	104,687	109,584
% increase	0	76	75	76	77	82	86	77	86	79	102	111

[1]Climate change scenarios – based on modelling of representative concentration pathway of 2.6, 4.5, 6.0, and 8.5. There are no predictions available for RCP 6.0 for 2101-2120.

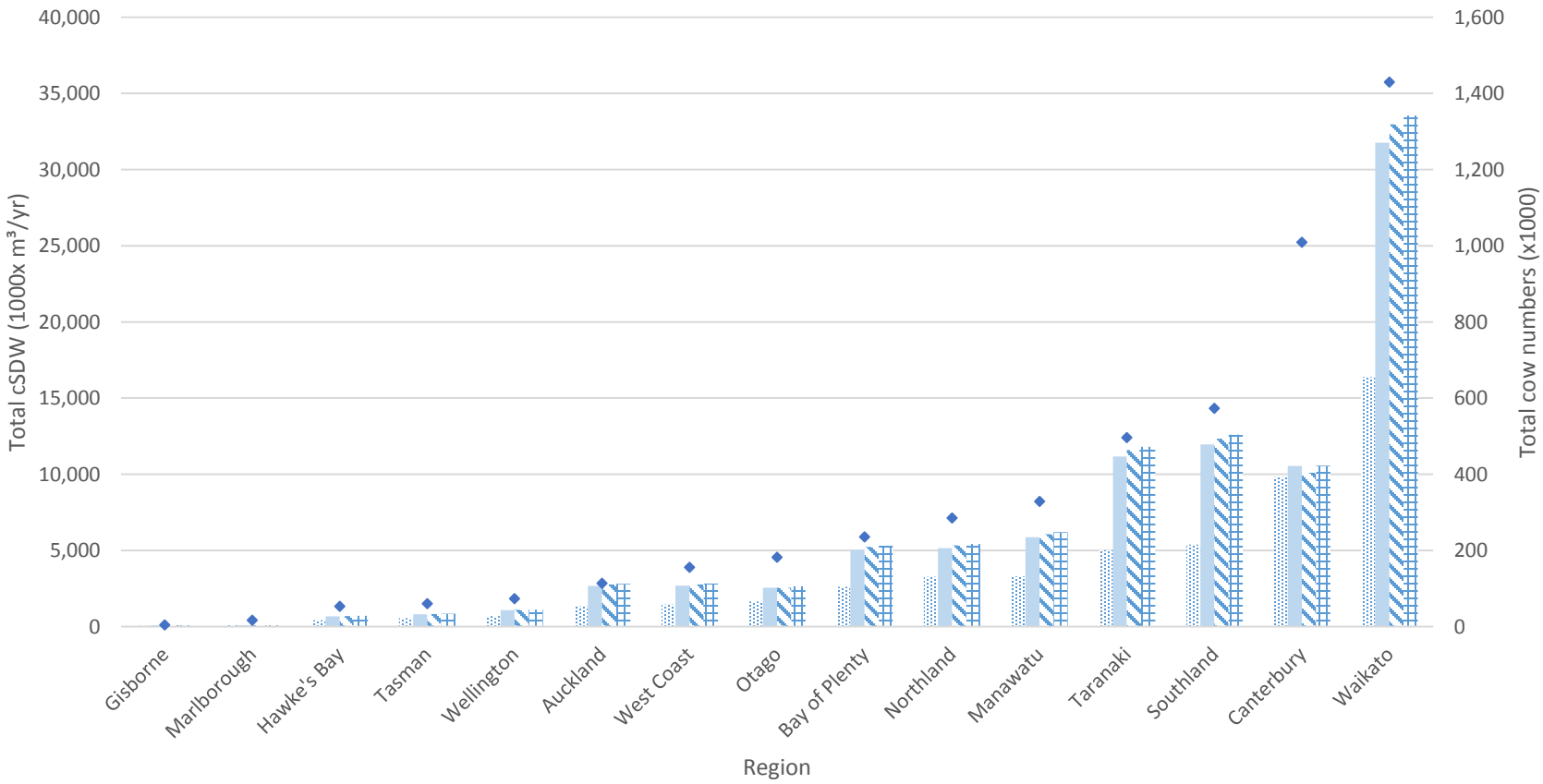

Figure 5-1. Corrected stock drinking water use percent increases compared with current use (2010-2015; dots) for climate change scenario RCP 4.5 with three time periods; 2031-2050 (solid fill); 2081-2100 (diagonal stripes); and 2101-2120 (gridlines), and with total cow numbers (♦) on the second axis.

Total volumes per region of MPW from 2010-2015 and different climate change scenarios are presented in Table 5-8. Under climate change scenario, RCP 8.5, the most extreme scenario, the overall MPW in New Zealand is expected to increase by 1.21%. Modelled MPW both increased and decreased in different regions, and at different time periods. Overall, the differences in predicted increases in MPW under climate change were small and all regions showed less than 3% difference to the 2010-2015 period. The highest increase for MPW under RCP 8.5 was 2.1% in the Canterbury region.

Estimated, current and future, irrigation water requirements, under RCP 4.5 in the 2031-2050 period are presented in Table 5-9. Current irrigation requirements are the least in the Waikato, which has low levels or irrigation. The Manawatu has a moderate irrigation requirement, and Canterbury has the highest requirements for irrigation. Irrigation water use is expected to increase between 17 and 24 percent across all sites.

Table 5-8. Current (2010-2015) milking parlour water use volumes (1000 × m³/year) and under different climate change scenarios (RCP 2.6, 4.5, 6.0, and 8.5[1]) at three time periods (2031-2050, 2081-2100, and 2101-2120).

Region	Current	RCP 2.6			RCP 4.5			RCP 6.0		RCP 8.5		
	2010-2015	2031-2050	2081-2100	2101-2120	2031-2050	2081-2100	2101-2120	2031-2050	2081-2100	2031-2050	2081-2100	2101-2120
Auckland	1,493	1,490	1,489	1,489	1,490	1,492	1,495	1,490	1,495	1,491	1,507	1,517
Bay of Plenty	3,370	3,356	3,355	3,355	3,356	3,362	3,366	3,356	3,368	3,358	3,388	3,406
Canterbury	28,694	28,908	28,902	28,923	28,930	29,028	29,073	28,927	29,088	28,969	29,233	29,288
Gisborne	69	69	69	69	69	69	69	69	69	69	69	69
Hawke's Bay	983	980	980	980	981	983	984	981	984	981	989	992
Manawatu	5,072	5,045	5,043	5,044	5,045	5,047	5,051	5,046	5,050	5,046	5,072	5,091
Marlborough	409	408	408	408	408	410	410	408	411	409	413	413
Northland	4,160	4,151	4,149	4,150	4,153	4,161	4,166	4,152	4,168	4,155	4,203	4,231
Otago	4,649	4,659	4,658	4,661	4,663	4,674	4,682	4,662	4,682	4,667	4,707	4,720
Southland	7,909	7,881	7,878	7,878	7,877	7,861	7,857	7,880	7,856	7,872	7,842	7,847
Taranaki	7,709	7,693	7,689	7,690	7,689	7,681	7,682	7,692	7,678	7,687	7,696	7,724
Tasman	964	959	959	959	960	961	962	959	962	960	967	970
Waikato	20,361	20,282	20,271	20,273	20,283	20,315	20,341	20,287	20,350	20,294	20,495	20,632
Wellington	1,420	1,424	1,424	1,424	1,425	1,428	1,429	1,424	1,430	1,426	1,435	1,438
West Coast	2,522	2,509	2,508	2,508	2,508	2,505	2,505	2,509	2,504	2,507	2,508	2,517
New Zealand	89,782	89,815	89,781	89,813	89,839	89,977	90,071	89,844	90,096	89,892	90,525	90,855
% increase	0.00	0.04	0.00	0.03	0.06	0.22	0.32	0.07	0.35	0.12	0.83	1.19

[1]Climate change scenarios – based on modelling of representative concentration pathway of 2.6, 4.5, 6.0, and 8.5. There are no predictions available for RCP 6.0 for 2101-2120.

Table 5-9. Estimated current irrigation water requirements and future requirements under climate change scenario RCP 4.5 at for the period 2031-2050.

Region	Available water (mm)	Current Irrigation requirement (mm)	Possible Irrigation requirement in 2031 - 2050[1] (mm)	Increase (mm, %)
Waikato	100	220	261	42 (18%)
	150	171	209	38 (22%)
Manawatu	80	257	312	55 (21%)
	120	214	267	53 (24%)
Canterbury	80	402	472	70 (17%)
	120	374	447	73 (19%)

[1]For scenario RCP 4.5.

5.5 Discussion

5.5.1 Current-day water use by the NZ dairy industry

A large data set based on 1,150 dairy farms was used to model water use for the five milking seasons from the 2010-2011 season, to the 2014-2015 season. Detailed data from DairyBase, milksolids production data, and local climate data accessed from the VCSN were used to calculate cSDW and MPW using the empirical models developed in Chapter 3 and Chapter 4. Milking parlour water use was highest in Canterbury, followed by the Waikato. These two regions combined made up approximately 49% of cow numbers (DairyNZ and Livestock Improvement Corporation, 2015) and 55% of the total MPW used in New Zealand. Corrected stock drinking water was highest in the Waikato followed by Canterbury. Once again, cSDW in these two regions made up over half of the cSDW of New Zealand. Overall MPW was estimated to be larger than cSDW.

Irrigation water use dwarfs other water uses (Chapter 3, Chapter 4), and makes up 97% of the total water abstracted on dairy farms in New Zealand. The amount of irrigation in Canterbury was the largest by far, making up approximately 71% of total irrigation water use. Otago uses the second largest amount of irrigation water, at approximately 18% of all irrigation water. The Waikato had the next largest irrigation water use, yet made up only 2.7% of the total irrigation volume in New Zealand.

5.5.2 Estimating irrigation water use

Irrigation water use for the 2014-15 season was estimated by collating the water volumes in allocation consents from councils. Water allocated by the consent is often much more than is actually used for irrigation. To calculate the actual amount of irrigation, actual water use records were requested from councils. Only two councils provided actual water take volumes for the year under analysis, for the rest previously reported actual use rates were used. The actual irrigation water use information supplied by Environment Canterbury suggests that the actual water use for irrigation in Canterbury was 55% of the allocated water in 2014-2015 which was an average year in terms of irrigation water demand. This actual irrigation water use is close to the 60% actual use rate reported by Aqualinc (2010), but the rate for the Tasman region was lower at 30%, down from the rate of 56% previously reported (Aqualinc 2010). The allocated water use rates do not account for any water restrictions put in place when there are low water flows in the waterways from which irrigation water is sourced. This is a further complication when attempting to reconcile the discrepancies between modelled irrigation water demands and actual irrigation water use.

Annual irrigation allocation as calculated can lead to misinterpretation. Since allocated water is not always used, it may over predict actual irrigation water use. Unfortunately values for actual irrigation water use are not always available. This lack of data may be overcome in time with the increased requirements on water metering, telemetry, and reporting. Good information on actual irrigation water use may help Regional Councils and farmers to manage the use of the water resources more efficiently. As water allocation cannot exceed the sustainable limits for waterways,

unused allocation prevents others from using that water. However, the development of more sophisticated technology which allows the real time monitoring of water resources may facilitate the sharing of allocated water amongst users.

5.5.3 Water use by the dairy industry under climate change

Compared with present day irrigation water use, irrigation requirements under climate change scenario RCP 4.5 are estimated to increase by 17-24% of water (38 to 73 mm applied water). Given current climatic conditions, it is clear why there is currently little irrigation in the Waikato, some in the Manawatu and a lot in Canterbury, as the need is low in the Waikato, and some need in the Manawatu, and is greatest need for irrigation in Canterbury. The increased irrigation water requirements will increase the amount of water required by current irrigators. But, subject to regional rules, there may also be an increase in the number of dairy farms that start irrigating under a changing climate, particularly on soils with lower water holding capacities. This could increase the total amount of water withdrawn for irrigation.

Future water estimates were calculated using models that predict cSDW and MPW, based on current milk production and cow numbers. The increase in cSDW on non-irrigating farms was large. Water use as cSDW is predicted to double in Southland and Taranaki by 2031 on non-irrigating dairy farms under the lowest climate change scenario RCP 2.6. An explanation of the model drivers is presented in Appendix B. It is expected that where there are decreases in rainfall, this will reduce the water content of pasture and, therefore, the amount of water ingested in feed by cows (Chapter 3,

Chapter 4). Cows on non-irrigating farms will have to drink more water to compensate for this decreased intake via pasture and other feeds at times of lower rainfall. Pasture growth patterns may change, with pasture growth in some regions occurring earlier in the season (Lee et al., 2012). The estimated cSDW on irrigating dairy farms is not expected to change in any of the climate change scenarios; this was particularly clear for Canterbury (Figure 5-1). This is because the irrigation of pasture with water produces pasture that is low in dry matter throughout the milking season, unlike pasture grown under water stress (DairyNZ, 2012). Accordingly, in the Waikato, Southland, and Taranaki, where most farms are not irrigated, cSDW is predicted to increase dramatically under climate change and should be considered in future water allocation plans. No leakage water was added onto the cSDW to estimate SDW for the climate change projections, as leakage has been found to be variable between regions, and only estimates were available for three regions. In addition, as more pressure is placed on scarce water resources under climate change, farmers should be encouraged to repair all leaks in their water supply and reticulation systems.

Milking parlour water use on irrigating and non-irrigating dairy farms is not expected to change under a warmer climate, and may decrease slightly in some regions. This is because MPW is much more strongly linked to milksolids production, and the number of milkings in a day, than temperature and rainfall. As the climate change projections kept milk production constant from the 2010-2015 levels, any change in MPW will be more likely to come from changing milk production, or changing milking frequency. Milking parlour water use on irrigating dairy farms was larger than on non-irrigating dairy farms with the most difference for Canterbury. This pattern was also

observed for Otago, which has a high proportion of irrigating farms. Milking parlour water use on irrigating dairy farms has been demonstrated to be higher than that on non-irrigating dairy farms, possibly due to the higher proportion of rotary parlours on irrigated farms (Chapter 4). The largest three regions dominated by non-irrigating dairy farms, the Waikato, Southland, and Taranaki regions, had very small changes in MPW.

Overall, the amount of water used for irrigating dairy farms dwarfs the water requirements of dairy farms for SDW and MPW. Through modelling, an increase of 17-24% was estimated under climate change scenario RCP 4.5. At the average estimated increase in irrigation requirements (20%), the increased volume of irrigation water would be greater than the volumes of water currently used for SDW or MPW in New Zealand.

5.6 Conclusions

Water use on both irrigated and non-irrigated dairy farms is predicted to increase under four different climate change projections. Irrigation water is expected to increase by 17-24%, with the largest increase in Canterbury. This is expected to increase water requirements of dairy farms already using irrigation, and is also likely to increase the number of farms that irrigate. Corrected stock drinking water use on non-irrigating dairy farms was estimated to increase dramatically under the climate change projections, with the largest volume of increase in the Waikato. However, cSDW on irrigating dairy farms will not increase under climate change, due to the amount of water consumed by cows through irrigated pasture. Milking parlour water

use on irrigating and non-irrigating dairy farms is not expected to change substantially as a direct result of climate change; any expected change will come through changes to milk volumes and milking patterns. The impact of increasing cow numbers in New Zealand, and the effect of increasing milk production per cow on the future water requirements of pasture-based dairy farms, have still to be determined.

5.7 Acknowledgements

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CHAPTER 6.

Quantification of the Water Footprint of Dairy Farming: the Effect of Water Footprint Methods, Data Sources, and Spatial Scale.

This chapter will be submitted to an international journal as C. D. Higham, R. Singh, D. Horne, M. R. Scarsbrook, and B. E. Clothier. Quantification of the water footprint of dairy farming: the effect of water footprint methods, data sources, and spatial scale.

6.1 Abstract

Water footprinting is increasingly being applied to investigations of water use efficiency and the environmental impacts of water use to help achieve sustainable water resources management. However, the number of water footprint methods, the differences between data sources, and the differing scales of analysis lead to a lack of consistency in these exercises and pose a degree of uncertainty in the comparative analysis of regional water footprints of products and processes. We evaluated three water footprint methods (i.e. Available WAter REmaining (AWARE; WULCA), stress-weighted water footprint (WSI) and blue water scarcity (WFN)) to quantify the water footprint of pastoral dairy farming in three regions of New Zealand. We further assessed the effects of using global or local data, environmental flow requirements, and a regional or catchment scale for the analysis. We found that 99% of the volumetric water footprint (L/kg fat and protein corrected milk) is associated with the green and blue water components of the pasture and other feeds produced on the study farms. The

volumetric green and blue water footprints for pasture and other feeds varies considerably depending on their location and whether they are rain-fed or irrigated. The volumetric blue water footprint (L/kg FPCM) of irrigated farms in the Canterbury region was estimated to be about 2 to 5 times higher than those of the Manawatu and Waikato regions, respectively, due to the greater use of irrigation water in the dry Canterbury region. Interestingly, we found that the different footprint methods had less effect on the magnitude of the water footprint of the case study farms than either the choice of the data sources or the scale of the analysis. The use of global data sources, as compared to the local data, resulted in an underestimation of the volumetric green water footprint (L/kg FPCM) by -12 to -30%, and overestimation of the volumetric blue water footprint (L/kg FPCM) by 3 to 141% in the study regions. The use of local data as compared to the global data also had a large effect on the quantification and ranking of the water footprint characterisation factors and the characterized blue water footprints of milk production across the study regions and catchments of New Zealand. Our results also suggests that the catchment scale assessment of water footprints is needed to detect differences in water use and its associated impact that could otherwise go unnoticed in a national and regional scale analysis. We found that local data at the catchment scale should be collected and used, as using the global data resulted in considerable uncertainty in the characterization factors and characterized water footprints of dairy farming across different regions of New Zealand.

6.2 Introduction

Water is a resource under stress (Smakhtin, 2008, Molden et al., 2010). Globally, a large portion of available water resources is used for agriculture. There is an increasing focus on improving the efficiency of agricultural water use to cope with future water demands (Molden, 2007). Water footprinting has been developed and is increasingly applied to assess the level and impact of water use across the various sectors of agriculture (Canals et al., 2009, Ridoutt and Pfister, 2010, Hoekstra et al., 2011). Water footprints allow the comparison of water use by different products and processes across different regions, and help to both quantify water use efficiency and achieve sustainable water resources management (Zonderland-Thomassen and Ledgard, 2012, Boulay et al., 2015a). However, the science and methodology for water footprinting is being developed, rather than matured and settled. There are a number of water footprint methods being proposed and developed which assess water use differently, including the volumetric water footprints by the Water Footprint Network (**WFN**) method (Hoekstra et al., 2011), and the impact-oriented water footprint indicator based on a water stress or scarcity characterization factor (**CF**) to differentiate the impacts of water use in areas of different water availability (Berger et al., 2014, Pfister and Bayer, 2014, Boulay et al., 2017).

The proposed water footprinting methods differ in their consideration, or not, of different water flows and uses in their accounting of water consumption, and in application of different water stress or scarcity indices for characterisation of the water footprints (Ridoutt and Pfister, 2010; Hoekstra et al., 2011; Boulay et al., 2017). The WFN method accounts for both the ‘green’ and ‘blue’ water consumptions to quantify

volumetric water footprints, and then use the green and blue water scarcity (including environmental flows) to assess water footprint impact indices (Hoekstra et al., 2011). On the other hand, the life cycle assessment (**LCA**) based 'stress-weighted' water footprint method (Ridoutt and Pfister, 2010) accounts for only blue water consumption, and then characterises the volumetric water footprint using a water stress index defined as a ratio of water withdrawals to water availability in a region. Recently, the Water Use in Life Cycle Assessment (**WULCA**) group was formed to build a consensus, with representatives from academia, government, and industry brought together, to collectively develop a method for consistency in quantification and application of water footprinting in order to identify and develop efficient and sustainable production processes (Boulay et al., 2015b). The group reviewed and evaluated different existing water footprint methods and proposed a method based on the Available WAter REmaining (**AWARE**) model with the indicator 1/availability minus demand (**AMD**) to characterise the water footprint within a catchment (Boulay et al., 2017).

A number of water footprints studies have been conducted on milk production in different countries (Ridoutt et al., 2010, Manazza and Iglesias, 2012, Zonderland-Thomassen and Ledgard, 2012, De Boer et al., 2013, Cosentino et al., 2015, Palhares and Pezzopane, 2015, Scheepers and Jordaan, 2016). These studies have used different water footprint methods, data sources and analysis scales, making it difficult to compare these water footprint assessments. Moreover, there have been limited studies applying and evaluating effects of different methods to assess the water footprints of pastoral dairy farming across semi-humid environments such as New Zealand. Zonderland-Thomassen and Ledgard (2012) assessed the water footprint of pastoral dairy farming in New Zealand, quantifying the volumetric water footprint and the blue

scarcity water footprint using the WFN method (Hoekstra et al., 2011), and the stress-weighted water footprint using the water stress index (**WSI**) to characterise the water footprint as suggested by Ridoutt and Pfister, (2010). This study, however, did not include the recently developed AWARE method (Boulay et al., 2017). Also, Zonderland-Thomassen and Ledgard (2012) used global data sets where no local data was available. This occurs in many water footprint studies where life cycle inventory databases (such as Ecoinvent, Agrifootprint, Quantis, WaterStat, SimaPro, etc.) are used to calculate the water footprint of agricultural products in different countries or regions (Kim et al., 2013, Dalla Riva et al., 2017). These databases require less data input as it is often provided or modelled within the database. The models in these databases may use theoretical crop water consumption or use data with limitations in calculating the water consumed in different production processes and they often fail to consider local conditions (Payen et al., 2017). One such case is in calculating a crop's water use, where standard conditions are assumed to quantify irrigation (blue) water consumed by a crop (Perry, 2014, Zhuo et al., 2014). This may be adequate for fully irrigated crops, but the standard models with global data sets may not predict crop evapotranspiration (**ET**) correctly during times of deficit irrigation, or for non-irrigated crops when there is insufficient local rainfall. Zhuo et al. (2014) carried out a sensitivity analysis for maize, soybean, rice and wheat in the Yellow River Basin and found that the crop water footprints were most sensitive to reference evapotranspiration (ET_o) and specific crop coefficients (K_c) values. They estimated that the total water footprints (blue + green) of maize, soybean, rice and wheat had on average uncertainties of ± 30% (at a 95% confidence interval), of which ± 20% came from climatic factors.

Most of the existing water footprint methods have also developed and propose to use global layers of water footprint characterization factors (CFs) such as the WFN, WSI, and AWARE methods (ETH Zurich, 2016, Water Footprint Network, 2016, WULCA, 2016). These CFs layers are calculated using global data or models, e.g. WATERGAP (Alcamo et al., 2003) model used to develop WSI (Pfister et al., 2009) and AMD (Boulay et al., 2017). This is done as local data is often lacking and hard to obtain, and because of this, most authors use global data or models for calculations of water footprints of food production (Zygmunt, 2007, Palhares and Pezzopane, 2015). So far, there has been no evaluation of the effects of calculating CFs using global and local data on water footprints of products from the primary sector, in particular pastoral dairy farming in semi-humid climatic conditions such as New Zealand.

Chapter 3 and Chapter 4 recently measured and quantified local data for dairy farm water use across three different regions of New Zealand. They highlighted significant spatial and temporal variations in water use on dairy farms across the different regions. This poses the question of a possible effect of spatial scale on the quantification and assessment of the water footprint of dairy products. In this study, we aimed to (1) quantify the water footprints of selected dairy farms in three different regions of New Zealand using three water footprint characterisation methods; and (2) assess the effects of using local and global data or models, different spatial scales of analysis, and environmental flow requirements on the resulting characterised water footprints of dairy farming in New Zealand. A final aim is to inform further development and consistency of the water footprinting methodology, procedures and protocols and data bases to help develop cleaner pastoral dairy production in New Zealand and across other, similar parts of the world.

6.3 Materials and Methodology

6.3.1 System analysed – location and details of study farms

We studied a total of 28 irrigated and 60 non-irrigated 'rain-fed' pastoral dairy farms spread across different regions of New Zealand. Table 6-1 summarizes average descriptions of the farms involved in the study. The farms were located in three regions with different climatic conditions across New Zealand (Figure 6-1). The Waikato region is the furthest north receiving adequate rainfall (> 1000 mm yr^{-1}), so dairying in the region is dominated by non-irrigated dairy farms (Table 6-1). There are some irrigated dairy farms in the region. These farms do not require irrigation to exist as dairy farms, but apply some irrigation to fill soil moisture deficits and increase pasture production over the summer period (from December to March). We selected 3 irrigated (totalling ~396 ha) and 42 non-irrigated (totalling ~ 7224 ha) dairy farms representing 1.6% of total dairy ha in the Waikato region. The Manawatu region is located further south of the Waikato region (Figure 6-1) and most of the region receives adequate rainfall (> 1000 mm yr^{-1}) and dairy farms are mainly rain-fed. The south-west area of Manawatu region receive relatively low rainfall (< 1000 mm yr^{-1}) and has an extensive area of coastal sandy soils. This is where the irrigated dairy farms are mainly located. We selected 5 irrigated (~1815 ha) and 18 non-irrigated (~3096 ha) dairy farms representing 4.1% of the total dairy ha in the Manawatu region. The irrigated farms in Manawatu region operate with lower stocking rates than farms in the rest of the region (Table 6-1). The Canterbury region is the furthest south of the farms investigated. They lie to the east of the Southern Alps mountain range, in an area of low rainfall (< 700 mm yr^{-1}). Nearly all dairy farms in this region are irrigated as the rainfall is not

sufficient to sustain adequate grass growth year round. We selected 20 irrigated (~4240 ha) dairy farms representing 1.5% of total dairy area in the Canterbury region.

Farm data was collected from individual farms through a questionnaire. This includes grassland area, stocking rates, the quantity of brought in feed, and milk production data on the farms for two years from 2013 to 2015.

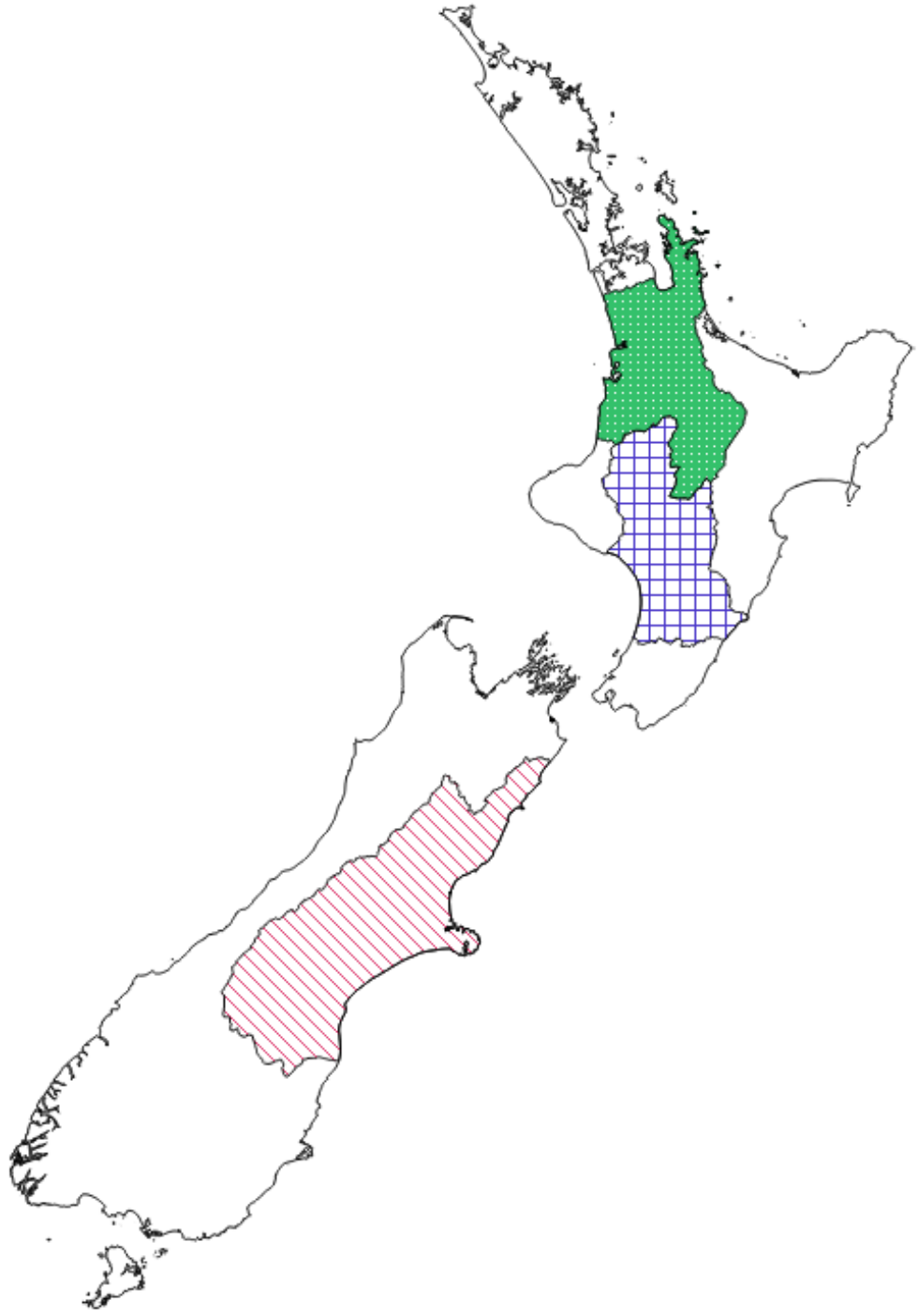

Figure 6-1. Map of New Zealand, showing location of the study regions as the Canterbury region (diagonal lines), Manawatu region (squares), and Waikato region (solid fill).

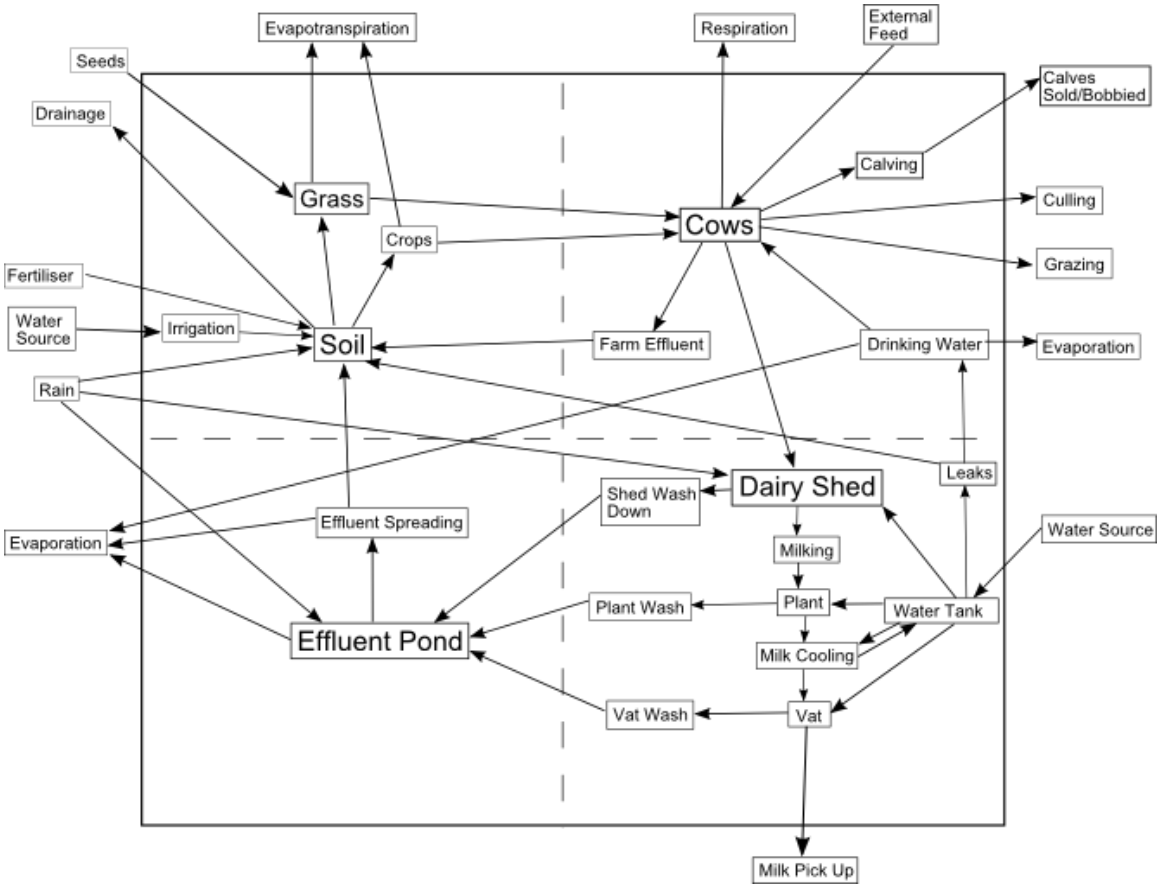

Figure 6-2. Schematic of blue and green water flows on a pastoral dairy farm system.

Table 6-1. Characteristics of selected dairy farms across different regions of New Zealand.

Farm Parameters	Unit	Waikato non-irrigated	Waikato irrigated	Manawatu non-irrigated	Manawatu irrigated	Canterbury irrigated
Farm count	-	42	3	18	5	20
Average grassland area	ha/farm	172	132	172	363	212
Average stocking rate	Cows/ha	3.16	3.23	2.53	2.35	3.87
Milk production (FPCM)	L/cow per yr	5224	5796	5052	5339	5263
Electricity use on-farm	kW h/ha per yr	483	560	483	565	608
Brought-in maize silage	kg DM/ha per yr	1120	1200	1130	1030	1530
Brought-in pasture silage	kg DM/ha per yr	0	0	0	0	1530
Brought-in palm kernel expeller	kg DM/ha per yr	2800	2100	2000	1800	0
Barley grain	kg DM/ha per yr	0	0	0	0	1190
Wheat grain	kg DM/ha per yr	0	0	0	0	1200
Annual rainfall	mm/ha	1053	1074	1030	857	637
Applied irrigation	mm/ha per yr	0	250	0	417	658
Irrigated Area	ha/farm	0	81	0	238	212
% irrigated	%	0	61	0	66	100

Figure 6-2 presents a schematic of system boundaries for production of raw milk and water use on a dairy farm. In this study, we assessed water footprints of selected dairy farms (Table 6-1) with the scope limited to the direct use of water at the farm and in-direct use of water for imported feed. Water use outside the farm gate including transport, processing, fertiliser production, and electricity use were not considered. Water use for the processes excluded here was estimated to be much smaller than the direct water use (Zonderland-Thomassen and Ledgard, 2012). For irrigated farms the contribution of the indirect water use to the total volumetric water footprint was estimated to be small (i.e., <7% of the total including imported feed). For non-irrigated farms the contribution of the indirect water use to the volumetric water footprint was also estimated low (<3% of the total volumetric water footprint) (Zonderland-Thomassen and Ledgard, 2012).

In this study, the functional unit was specified as one kilogram of energy corrected milk, i.e. milk corrected for fat and protein milk (**FPCM**), calculated using the recorded milk production per day into equation [1] (Tyrrell and Reid, 1965, Phyn et al., 2014). The average FPCM was calculated for both the irrigated and non-irrigated farms in each region. The estimated water use was divided between milk and meat production using economic allocation based on the price of milk and meat, with 92% allocated to milk production and the remainder to meat production (Zonderland-Thomassen and Ledgard, 2012).

$$Fat\ and\ Protein\ Corrected\ Milk = milk\ per\ day\ (kg)\ \times [(383 \times fat\ \%) + (242 \times protein\ \%) + 783.2]/3{,}140 \quad [1]$$

6.3.2 Water footprint methods

Water footprinting methods have been developed to account for green, blue, or grey water (Ridoutt and Pfister, 2010, Hoekstra et al., 2011), where the green water is defined as the rainfall that is held within the soil profile and used by the plants, and the blue water is defined as water used from groundwater and surface water resources. Blue water is made available to the plant via irrigation. The grey water is defined as the volume of water required to assimilate contaminants loads to the accepted (standard) levels in receiving water bodies (Hoekstra et al., 2011). Within the water footprint methods, both direct and in-direct water uses for a product or process are accounted for. The direct water use is defined as the water used directly in the production of a product, such as the green water from rainfall and the blue water from irrigation that is used to grow grass. Whereas in-direct water use is defined as the water used indirectly, such as in the manufacturing of fertiliser and production of the electricity that is used on the farm. Here, the direct water footprint has been calculated as the volumes of both green and blue water (m^3) required, on average, to produce 1 kg FPCM at selected irrigated or non-irrigated dairy farms across the study regions. This also included the water used in the production of imported feed that was produced locally. Further, the quantified blue water volumes per farm type (non-irrigated or irrigated) per region were only characterized with different water stress or scarcity indices to assess impacts of the blue water footprints on local water resources. The three main water footprint methods selected for this study are described below.

6.3.2.1 Volumetric water footprint and blue water footprint impact index ($WFII_{blue}$)

The WFN method considers and quantifies the volumes of both the green and blue waters used to produce a product (Chapagain and Hoekstra, 2008, Hoekstra et al., 2011). In this study, the volumetric green water footprint (m^3/kg FPCM) of the selected dairy farms was calculated using equation [2] (Hoekstra et al., 2011) as follows:

$$WF_{Green} = \frac{ET_{green}}{Yield_{FPCM}} \quad [2]$$

where, the ET_{green} is the green water consumption (m^3/ha) quantified as evapotranspiration by the pasture produced on the farm and feed imported, and $Yield_{FPCM}$ is the total kilograms of fat and protein corrected milk (kg/ha).

The volumetric blue water footprint (m^3/kg FPCM) for the selected dairy farms was calculated as the consumptive volume of surface and groundwater required to produce 1 kg FPCM as indicated in equation [3]. The quantification of blue water footprint considered here included the estimates of the blue water that was evapotranspired (**ET_{blue}**) (m^3/ha) by pasture following irrigation, and feed imported (estimated from typical farm use), along with the water used (m^3/ha) for stock drinking (**SDW**) and milking parlour use (**MPW**). In pastoral based dairy farms across New Zealand, some of the *SDW* and *MPW* ends up being applied to pasture as effluent and evapotranspired. The blue water footprint is quantified as follows:

$$WF_{blue} = \frac{\sum ET_{blue} + SDW + MPW}{Yield_{FPCM}} \quad [3]$$

As per the WFN method (Hoekstra et al., 2011), the blue water footprint (**WF_{blue}**) (Eq. 3) was further characterised by the blue water scarcity (**WS_{blue}**) which calculates the blue water footprint impact index (**$WFII_{blue}$**) as follows:

$$WFII_{Blue} = WF_{blue} \times WS_{blue} \quad [4]$$

Where, **WS_{blue}** is the blue water scarcity defined as the ratio of total blue water consumed (**ΣWF_{blue}**) to total blue water available (**WA_{blue}**) in the geographical region (Hoekstra et al., 2012) as follows:

$$WS_{blue} = \frac{\sum WF_{blue}}{WA_{blue}} \quad [5]$$

The WA_{blue} is defined as the natural runoff (**R_{nat}**) minus the environmental flow requirements (**EFR**) as presented in equation [6] (Hoekstra et al., 2012) as follows:

$$WA_{blue} = R_{nat} - EFR \quad [6]$$

The WS_{blue} equals 1 when all of the available blue water has been used an any further withdrawal of blue water will affect the EFR in the region. The blue water footprint impact indices (**$WFII_{blue}$**) (Eq. 4) quantified as the characterized blue water footprint is used to differentiate blue water consumption in the production of a product in areas of contrasting water resources (Hoekstra et al., 2011; Hoekstra et al., 2012).

6.3.2.2 Stress-weighted water footprint ($WF_{Ridoutt}$)

Ridoutt and Pfister (2010) proposed and developed a water footprint method which considers only the blue water consumption, suggesting that green water consumption should be viewed as a product of land occupation, and that this use would occur, more or less, regardless of land use. They also proposed that quantified blue water consumption volumes must be characterised by local water stress conditions to differentiate blue water consumption in the production of a product in areas of differing water resources. The water stress index (**WSI**), as a modified version of WTA, factors in local water stress conditions. The WTA is defined as a ratio of water withdrawal

(**WU**) to water availability (actual runoff; **WA**) (equation [7]) for all users *j*, in each watershed *i* (Pfister et al., 2009).

$$WTA_i = \frac{\sum_j WU_{ij}}{WA_i} \quad [7]$$

This method considers the reduction in the water stress of strongly regulated flows (**SRF**), as water storage can supplement low flows, and is calculated using equation [8] (Pfister et al., 2009, Ridoutt and Pfister, 2010). It also accounts for the variability in monthly and annual rainwater availability, by using the variation factor (**VF)** (Pfister et al., 2009) as follows:

$$WTA^* = \begin{cases} \sqrt{VF} \times WTA \text{ for SRF} \\ VF \times WTA \text{ for non} - \text{SRF} \end{cases} \quad [8]$$

The WSI is then calculated as per equation [9] from WTA* and has a continuous range from 0.01 to 1. The WSI calculated for a given area is finally normalised by dividing it by the world average WSI of 0.602 (Ridoutt and Pfister, 2010).

$$WSI = \frac{1}{1+e^{-6.4\times WTA^*\left(\frac{1}{0.01}-1\right)}} \quad [9]$$

The WF_{blue} is then multiplied by the corresponding WSI quantified for each region where the water use occurred (Eq. 10). This results in a characterised 'stress-weighted' water footprint (**$WF_{Ridoutt}$**) with the units of H_2O-equivalents, where the local water resource availability is built into water footprint assessment of a product or process as follows:

$$WF_{Ridoutt} = WF_{blue} \times WSI \quad [10]$$

6.3.2.3 The AWARE method water footprint (WF_{AWARE})

The AWARE method developed by the WULCA group also accounts for blue water use only, and does not assess green water use (Boulay et al., 2017). This method calculates water availability minus demand (**AMD**$_i$) as a factor to characterise volumetric blue water consumptions by a product or process in a region. The **AMD**$_i$ is calculated by subtracting the water requirements for human water consumption (HWC) and the environmental flow requirements (EFR) from the available water (natural runoff including flow regulation), as follows:

$$AMD_i = \frac{(Availability - HWC - EWR)}{Area} \quad [11]$$

The surface-time equivalent (**STe**$_i$) is further calculated as 1/AMD$_i$ (Eq. 12), i.e. the inverse of the difference between the water availability and demand in the region. It can be understood as the surface-time equivalent of unused water up to the point where water demand equals availability (Boulay et al., 2017).

$$STe_i = \frac{1}{AMD_i} \quad [12]$$

The characterisation factors (CF_{AWARE}) for a region is then calculated from the STe$_i$ for the given region normalised by dividing by the STe$_{worldaverage}$, which is equivalent to the inverse of AMD$_i$ normalised by the dividing the inverse of the AMD$_{worldaverage}$, as follows:

$$CF_{AWARE} = \frac{STei}{STe_{worldaverage}} \quad [13]$$

A maximum value of CF_{AWARE} is set at 100, where either water demand is greater than availability resulting in AMD$_i$ having negative values and equation [12] loses its meaning, or AMD$_i$ < 0.01*AMD$_{worldaverage}$. A minimum value of CF_{AWARE} is also set at 0.1, where the AMD$_i$ > 10*AMD$_{worldaverage}$. This results in a range for

CF_{AWARE} from 0.1 to 100 to characterise the blue water consumption volumes by local water stress conditions to differentiate water footprints in areas of differing water resources.

Boulay et al., (2017) calculated the AMD_i and $AMD_{worldaverage}$ values, using the monthly water data from the WATERGAP model (Alcamo et al., 2003). Boulay et al. (2017) further calculated and produced average STe factors on a 0.5 by 0.5 degree grid at the global scale. In this study, we multiplied the $AMD_{worldaverage}$ (at 0.0136 m^3/m^2-month) by 12 to calculate and apply the average STe *or* CF_{AWARE} factors using the only available annual water flows for local catchments and regions.

The characterized water footprint (WF_{AWARE}) ($m^3_{world\ eq.}/m^3_i$) is calculated by multiplying the blue water consumption by the corresponding STe *or* CF_{AWARE} factors for each region, as follows:

$$WF_{AWARE} = WF_{Blue} \times \frac{STe_i}{STe_{World}} \quad [14]$$

6.3.3 Data sources and spatial scale

The data required for applying the water footprint methods described above was collected from different databases, models and measurements sources, categorised as a global or local data source (Table 6-2). The analysis was further carried out considering two different spatial scales; the regional and catchment scales. The regional scale considers the entire region with many different catchments and water management zones within a similar climatic condition; although the catchment or water management zone scale is the area that captures all water flows to one major waterway or water body in the region. The data collection and analysis was conducted for two (2) years from

01/06/2013 to 31/05/2015. The green water consumption (WF_{green}) was quantified for both the on-farm pasture production over the entire year, and for the imported feed over the growing period for the individual crops (Table 6-1).

Table 6-2. Summary of global and local data sources used in quantification of water footprints of study dairy farms across different regions of New Zealand.

Parameter	Global data source	Local data source
Rainfall (P) and reference evapotranspiration (ET_o)	CLIMWAT 2.0 for CROPWAT.	The National Institute of Weather and Atmosphere Virtual Climate Station Network (Cichota et al., 2008).
Effective rainfall (P_{eff})	USDA Soil Conservation Service method (Smith, 1992).	
Crop coefficients (K_c)	Crop coefficients (Chapagain and Hoekstra, 2004).	Crop coefficients (Chapagain and Hoekstra, 2004).
Green water consumption (ET_{green})	A minimum of ET_c and P_{eff} (Allen et al, 1998; Hoekstra et al., 2011)	A locally developed and calibrated soil water balance model (Scotter et al., 1979), using local climatic and soil conditions.
Irrigation water consumption (ET_{blue})	Difference between ET_c and ET_{green} (Allen et al, 1998; Hoekstra et al., 2011)	The minimum of the difference between the modelled $ET_c - ET_{green}$ (Scotter et al., 1979) for pasture growth and maize silage, and the difference between ET_c and ET_{green} (Allen et al, 1998; Hoekstra et al., 2011) for pasture silage, barley grain, and wheat grain.
WF Palm Kernel Expeller (cake)	Based on globally average green water volume used to produce palm kernel expeller (Chapagain and Hoekstra, 2004).	Based on globally average green water volume used to produce palm kernel expeller (Chapagain and Hoekstra, 2004).
Imported crops	Imported crops based on the Waikato and Canterbury regions from 2004/2005 (Zonderland-Thomassen and Ledgard, 2012).	Average farm imports estimated by the modelling team at Dairy NZ (T. Chikazhe; DairyNZ, Hamilton, New Zealand, Pers. Comm. 2016).

Stock drinking water use (SDW)	Estimated stock drinking water (Zonderland-Thomassen and Ledgard, 2012).	Measured stock drinking water (Chapter 3 and Chapter 4).
Milking parlour water use (MPW)	Estimated milking parlour water use (Zonderland-Thomassen and Ledgard, 2012).	Measured milking parlour water (Chapter 3 and Chapter 4).
Available water (WA)		A locally calibrated and validated rainfall-runoff model (Woods et al. (2006)
Rainfall variation factor (VF)		Calculated by Mellor et al. (2016) from Woods et al. (2006) GIS layer.
Environmental requirements (EWR)		Based on local water allocation limits in the Waikato region. Environmental requirements of 37% were used as is suggested for New Zealand (Smakhtin et al., 2004, Zonderland-Thomassen and Ledgard, 2012).
Water abstractions (WU)		Recorded water allocations and actual water abstraction estimates (Aqualinc, 2010).
Water consumption (HWC)		Actual water abstractions from Aqualinc (2010) and consumptive water fraction from Shiklomanov and Rodda (2004).
WULCA – CF_{AWARE}	Global layer (WULCA, 2016).	Calculated from locally sourced data listed in this table.
Ridoutt – WSI CF	Global layer (ETH Zurich, 2016).	Calculated from locally sourced data listed in this table.
WFN – WS_{blue} CF	Global layer (Mekonnen and Hoekstra, 2016).	Calculated from locally sourced data listed in this table.

6.3.4 Global data sources

In the case of global data sources (Table 6-2), the green water consumed in pasture production was quantified as ET_{green} using the average monthly effective precipitation (**P_{eff}**) and reference evapotranspiration (**ET_o**) based on climatic data taken from CLIMWAT 2.0 for CROPWAT (Food and Agriculture Organization, 2015). This global climatic database provided the required climatic data from the Hamilton Aerodrome site for the Waikato region, the Palmerston North Aerodrome site for the Manawatu region, and the Christchurch Gardens site for the Canterbury region. The reference evapotranspiration (**ET_o**) was multiplied by the crop coefficient (**K_c**) of 1.05 (Allen et al., 1998) to calculate potential evapotranspiration (**ET_C**) for pasture production in different regions. Effective precipitation was calculated using monthly precipitation (**P**) collected from CLIMWAT 2.0 for CROPWAT, using the USDA Soil Conservation Service Method (Smith, 1992, Hess, 2010) over 10 day time steps (Hoekstra et al., 2011, Babu et al., 2015) presented in equations [15a] and [15b] as follows:

$$P_{eff} = P\frac{(\frac{125}{3})-0.2\times P}{(\frac{125}{3})} \text{ for P} \leq 83.3 \text{ mm/10 day period} \quad [15a]$$

$$P_{eff} = (\frac{125}{3}) + 0.1P \text{ for P} > 83.3 \text{ mm/10 day period} \quad [15b]$$

The ET_{green} for pasture production was then calculated as the minimum of the P_{eff} and the crop specific evapotranspiration (**ET_c**) presented in equation [16] (Hoekstra et al., 2011).

$$ET_{Green} = \min\ [ET_c, P_{eff}] \quad [16]$$

The WF_{green} for imported feed was calculated over the growing period for the individual crops detailed in Table 6-1. The WF_{green} of palm kernel expeller (palm kernel cake, **PKE**) was taken from Chapagain and Hoekstra (2004). The WF_{green} was calculated for imported pasture silage, maize silage, barley, and wheat, assuming growth under local climatic conditions. The feed imported in the Canterbury region was assumed to be grown under irrigation, although the feed imported in the Waikato and Manawatu regions were assumed to be rain-fed. The average monthly ET_0 and effective precipitation were taken from CLIMWAT for the Hamilton aerodrome station for the Waikato region, Palmerston North aerodrome station for the Manawatu region, and Christchurch Gardens for the Canterbury region. The ET_{green} was calculated using equation [16] for each crop. Crop coefficients K_c values for imported crops (ryegrass pasture silage, maize silage, wheat, and barley) were taken from Allen et al. (1998) and Chapagain and Hoekstra (2004). The total WF_{green} of feed at the selected dairy farms was calculated by summing the total of all the individual green water footprints of imported and farm grown feed inputs (Table 6-1).

The WF_{blue} was estimated as the total of the consumed irrigation water use (**ET_{blue}**), MPW, and SDW on the farms. The irrigation water consumption (**ET_{blue}**) was calculated as the deficit between ET_c and ET_{green} (Hoekstra et al, 2011), as follows:

$$ET_{blue} = \left(ET_c - ET_{green}\right) \quad [17]$$

The MPW and SDW were calculated from generic industry volumes (70 L/cow per day MPW; 70 L/cow per day SDW) for the lactating and non-lactating periods of the year (Zonderland-Thomassen and Ledgard, 2012). To calculate the consumptive

fraction of SDW and MPW, the agriculture water use consumptive fraction (78%) of Shiklomanov and Rodda (2004) was applied.

Global data sets of the WSI, CF_{AWARE}, and WS_{blue} characterization factors were downloaded as geographic information systems or Google Earth layers, provided by the authors (ETH Zurich, 2016, Mekonnen and Hoekstra, 2016, WULCA, 2016), respectively. These layers were overlaid onto the study regional and catchment boundaries to calculate and use the average values of the characterization factors for characterisation of quantified blue water consumption volumes at different spatial scales.

6.3.5 Local data sources

In case of local data sources (Table 6-2), the green water consumption (ET_{green}) and blue (irrigation) water consumption (ET_{blue}) were calculated for representative irrigated and non-irrigated conditions selected for the irrigated and non-irrigated groups of farms in each region. A locally calibrated and validated soil water balance (Scotter et al., 1979) was applied [Equation 18] to quantify ET_{green} and ET_{blue} for each site, using the local climatic, soils and irrigation data. Where the change in the soil moisture (ΔS) is calculated by subtracting the evapotranspiration (E_t) and runoff plus drainage (R_o) from the volume of rainfall and irrigation (P) inputs as follows:

$$\Delta S = P - E_t - R_o \qquad [18]$$

The soil profile available water values for each site were taken from S-Maps (Lilburne et al., 2012), a locally developed soil database (https://smap.landcareresearch.co.nz/). Thirty years of local climate data was collected

from the Virtual Climate Station Network (VCSN) (Cichota et al., 2008) to establish the soil water balance. The VCSN takes data from locally observed meteorological stations throughout New Zealand and interpolates the data over a 5 x 5 km grid giving climate data for all of New Zealand (https://data.niwa.co.nz/#/home). The potential evapotranspiration was calculated using the FAO-56 method (Allen et al., 1998). The ET_{green} was calculated as per equation [16] using the potential evapotranspiration calculated using the FAO-56 method. The ET_{blue} was calculated as per equation [17]. The ET_{green} and ET_{blue} were also calculated for imported maize silage (Table 6-1) under local conditions, excluding PKE. Crop coefficients K_c values for imported crops (ryegrass pasture silage, maize silage, wheat, and barley) were taken from Allen et al. (1998) and Chapagain and Hoekstra (2004). In the Canterbury region it was assumed that all feed grown was irrigated and that the climate was the same as for the dairy farms. For all imported feed in the Manawatu and Waikato regions it was assumed that they were not irrigated, and were grown in a climate equivalent to the local farms.

The SDW and MPW were calculated from detailed on-farm water meter recordings (Chapter 3 ad Chapter 4). To calculate the consumptive fraction of SDW and MPW, the agriculture water use consumptive fraction (78%) of Shiklomanov and Rodda (2004) was applied again. The MPW and SDW on the Waikato irrigated dairy farms were not directly measured, but were calculated from locally developed models (Chapter 3 and Chapter 4).

The quantification of WS_{blue} (Eq. 5), WSI (Eq. 9) and AMD_i (Eq. 11) for different water footprint methods require the total blue consumed water (WF_{blue} or HWC), available water (WA), rainfall variation factor (VF) and environmental flow requirement (EFR) in a region. In this study, the locally available data and models were

used to calculate these water footprint characterisation factors for the study regions and catchments. The available water (WA) was quantified as the natural runoff (R_{nat}) using the average rainfall (P) minus actual evapotranspiration (ET) estimated by a locally calibrated and validated model from 1960-2006 (Woods et al., 2006). The total blue consumed water (WF_{blue} or HWC) was calculated from recorded average annual water allocations, and estimates of actual water abstraction. In New Zealand, the Regional Councils issue consents for water abstraction for public water supply, industrial and agricultural water use (Land Air Water Aotearoa, 2017). The total consented water allocations for the entire study regions and catchments were collected directly from the Regional Councils responsible for the study regions and catchments. The actual abstraction rates of the allocated water were collected from the Regional Council for the Canterbury region (55%) (A. Paris, Environment Canterbury, Christchurch, New Zealand, Personal Communication, 2016), but were not available for the Manawatu and Waikato regions. The percentage of consented water that was assumed to be abstracted in for the Manawatu and Waikato regions, 28% and 36% respectively, was taken from published data (Aqualinc, 2010). The allocated water was broken down into agriculture, industry, domestic, and non-consumptive allocation. Estimates of water use efficiencies for agriculture (0.78), industrial use (0.10), and public supply (0.13) were used to calculate the total consumed fraction of water from the actual abstraction amounts (Shiklomanov and Rodda, 2004). Local records of water transfers for hydroelectricity generation to and from regions were collected directly from the power companies. These water transfers were considered as a net gain of available water for the receiving region, and as a consumptive take in the region losing the water. The rainfall variation factor (VF) was calculated on a 500 m by 500 m grid across New

Zealand, using the rainfall records at monthly and annual intervals over a period of 41 years from 1972 to 2013 (Mellor, 2016).

The WS_{blue} and AMD_i methods also require estimates of environmental flow requirements (EFR) in a region. However, there are different methods and considerable ranges in EFR estimations (Hoekstra et al., 2011, Zonderland-Thomassen and Ledgard, 2012, Pastor et al., 2014). Therefore, we used a range of EFR's for both WS_{blue} and AMD_i methods to identify the effect they have on the resulting characterised water footprints in the study regions and catchments. The ERF's were set at: 37% of mean annual runoff (MAR) following Zonderland-Thomassen and Ledgard (2012); 30% and 60% of MAR as the minimum and maximum range as suggested by (Pastor et al., 2014); the 80% of MAR as the conservative ERF estimates (Hoekstra et al., 2011); and a locally estimated EFR for water flows regulations in the Waikato region, where 10% of the Q_5 (5 year, 7 day, low flow rate) can be allocated for EFR, equating to 64% of the MAR in the Karapiro catchment in the Waikato region.

6.4 Results

6.4.1 Volumetric WF and its variation on farms

Table 6-3 summarizes the volumetric green and blue water footprints of the study farms calculated with the global and local data sources (Table 6-2). It clearly highlights that 99% of the volumetric water footprint (L/kg FPCM) of the study dairy farms is associated with the green and blue water consumption for pasture and feed production. However, the volumetric green and blue water footprints for pasture and feed production varied considerably depending on the location of the farms and

whether they are rain-fed or irrigated. Use of the local data set suggest that the volumetric green water footprint (L/kg FPCM) in the Manawatu region was about 39 to 116% higher as compared to the Waikato and Canterbury regions (Table 6-3). This is partly explained by the extra feed inputs in the Waikato region, but also the difference in evapotranspiration rates and lower stocking rates, leading to lower production per hectare, and higher water use per kg of product in the Manawatu region.

Using the local data set the irrigated dairy farms in the Manawatu and Waikato regions had no significant differences in their total volumetric water footprint (L/kg FPCM) as compared to the non-irrigated dairy farms in the regions (Table 6-3; local data). This is due to the small irrigation requirements in the Manawatu and Waikato regions which receive relatively higher rainfall (> 850 mm per year). The blue water consumption for pasture and feed production (ET_{blue}) on irrigated dairy farms in the Waikato and Manawatu regions was estimated to be only 9 and 17%, respectively, of the total water (green and blue) consumption for pasture and feed production. However, using the local data set, the blue water consumption for pasture and feed production (ET_{blue}) at irrigated dairy farms in the Canterbury region was estimated to be as high as 45% of total green and blue water consumption for pasture and feed production. The volumetric blue water footprint (L/kg FPCM) of irrigated farms in the Canterbury region was estimated to be about 2 to 5 times higher than the blue water footprint in the Manawatu and Waikato regions, respectively (Table 6-3; local data). This is due to the relatively low rainfall (<650 mm per year) and hence higher irrigation water use on dairy farms in the Canterbury region (Table 6-1).

Table 6-3. Estimates of green and blue consumptive water footprints (L/kg FPCM[1]) on the study dairy farms across different regions of New Zealand.

Water Consumed (L/kg FPCM[1])	Global data						Local data					
	Irrigated farms			Non-irrigated farms		Weighted average[3]	Irrigated farms			Non-irrigated farms		Weighted average[4]
	Canterbury	Manawatu	Waikato	Manawatu	Waikato		Canterbury	Manawatu	Waikato	Manawatu	Waikato	
SDW[2]	2.7	2.1	1.2	2.7	2.7	2.6	1.2	1.9	2.0	2.1	2.2	1.9
MPW[3]	2.4	3.8	2.9	2.4	2.4	2.5	3.2	2.5	2.2	2.6	2.4	2.6
ET_{green}	253.2	546.2	370.8	534.8	370.8	387.6	286.8	620.6	445.7	676.8	526.6	505.4
ET_{blue}	240.3	180.7	107.3	0	0	68.6	234.1	122.0	42.0	0.0	0.0	61.6
Total Blue	245.5	186.6	111.4	5.2	5.2	73.7	238.5	126.3	46.2	4.7	4.7	66.1
Total Green	253.2	546.2	370.8	534.8	370.8	387.6	286.8	620.6	445.7	676.8	526.6	505.4
Total	498.7	732.8	482.2	540.0	375.9	461.3	525.3	747.0	491.9	681.5	531.3	571.5

[1]L/kg FPCM = litres of water used to produce 1 kg of fat and protein corrected milk.
[2]SDW = stock drinking water.
[3]MPW = milking parlour water use.
[4]Weighted average of all irrigated and non-irrigated farms combined.

Table 6-4. Estimates of water footprint characterization factors (CFs) for the blue water scarcity index WS_{blue} (Hoekstra et al., 2011), the water stress index WSI (Ridoutt et al., 2010), and available minus water demand CF_{AWARE} (Boulay et al., 2017) for the study regions in New Zealand. Note relative ranks indicated in parentheses (1 representing the lowest).

Region	Global data			Local data		
	WS_{blue}	WSI	CF_{AWARE}	WS_{blue}	WSI	CF_{AWARE}
Waikato	0.002 (1)	0.010 (1)	0.765 (1)	0.014 (1)	0.011 (1)	0.300 (1)
Manawatu	0.010 (2)	0.010 (1)	0.895 (2)	0.098 (2)	0.015 (2)	0.403 (2)
Canterbury	0.371 (3)	0.012 (3)	7.355 (3)	0.190 (3)	0.040 (3)	0.473 (3)
Coefficient of variation	1.656	0.1035	1.254	0.879	0.698	0.222
Range (min-max)	0.002-0.371	0.010-0.1012	0.765-7.355	0.014-0.190	0.011-0.040	0.300-0.473

Table 6-5. Estimates of water footprint characterization factors (CFs) for the blue water scarcity index WS_{blue} (Hoekstra et al., 2011), water stress index WSI (Ridoutt et al., 2010), and available minus water demand CF_{AWARE} (Boulay et al., 2017) for study catchment or water management zones in New Zealand. Note relative ranks indicated in parentheses (1 representing the lowest).

Region: catchment/zone	Global data			Local data		
	WS_{blue}	WSI	CF_{AWARE}	WS_{blue}	WSI	CF_{AWARE}
Waikato region						
Waikato River catchment	0.002 (1)	0.010 (1)	0.612 (2)	0.031 (2)	0.012 (2)	0.314 (3)
Waihou catchment	0.006 (2)	0.010 (1)	0.600 (1)	0.032 (3)	0.012 (2)	0.307 (2)
Manawatu region						
Rangitikei River Catchment	0.008 (3)	0.010 (1)	1.074 (4)	0.257 (5)	0.028 (5)	0.564 (6)
Upper Ohau Management Zone	0.016 (4)	0.010 (1)	1.000 (3)	0.003 (1)	0.010 (1)	0.216 (1)
Canterbury region						
Orari-Opihi-Pareora Management Zone	0.673 (7)	0.016 (7)	40.840 (7)	0.129 (4)	0.022 (4)	0.874 (7)
Selwyn-Waihora Management Zone	0.353 (6)	0.012 (5)	2.371 (5)	0.361 (6)	0.882 (7)	0.484 (4)
Ashburton	0.234 (5)	0.015 (6)	3.025 (6)	0.375 (7)	0.068 (6)	0.502 (5)
Coefficient of variation	1.580	0.212	2.323	1.048	2.439	0.424
Range (min-max)	0.002-0.673	0.010-0.016	0.600-40.840	0.003-0.375	0.010-0.882	0.0.314-0.874

6.4.2 Effect of different water footprint methods

The volumetric water footprints are routinely characterised using local water stress or scarcity indices to assess their environment impacts in the study regions (Ridoutt and Pfister, 2010; Hoekstra et al., 2011; Boulay et al., 2017). Table 6-4 presents the characterization factors calculated with three different water footprint methods for the study regions, using the global and local data sources (Table 6-2). In general, the CF_{AWARE} had the highest values, followed by the WS_{blue}, with the WSI having the lowest values (Table 6-4). The low values of WSI could be attributed to its lack of considering environmental flow requirements in assessment of water stress levels (Ridoutt and Pfister, 2010).

We used simply the ranking and coefficient of variation to assess how water footprint methods and data sources differentiate water stress levels and water footprints of different farm systems (irrigated or non-irrigated) in the study regions, with a higher coefficient of variations suggesting better differentiation. At the regional scale the characterisation factor WS_{blue} (Hoekstra et al., 2011) had the highest coefficient of variation, followed by the WSI (Ridoutt and Pfister, 2010) and the CF_{AWARE} (Boulay et al., 2017) (Table 6-4; local data). Interestingly, all three water footprint methods ranked the study regions in the same order of water stress or scarcity, except the WSI using the global data sources (Table 6-4). In the case of WSI using the global data sources the ranks of the Waikato and Manawatu regions were in the same order assessing similar water stress level (i.e., the minimum water stress) in the regions (Table 6-4). At the catchment scale for the global data set there was much less agreement in the rankings by different methods (Table 6-5). For example, the rankings

of the WS_{blue} and the CF_{AWARE} values were in the reverse order for the Waikato and Waihou catchments, and for the Rangitikei and Upper Ohau catchments (Table 6-5). The WSI method had the same bottom four ranked catchments as the WS_{blue} and the CF_{AWARE} methods, but these were all ranked the minimum WSI value possible (0.1). The Selwyn-Waihora Management Zone and the Ashburton zone switched order between the WS_{blue} CF and both the WSI and CF_{AWARE}. The WSI and CF_{AWARE} methods had the top three ranked catchments ranked in the same order, and all three methods had the Orari-Opihi-Pareora Management Zone ranked the highest. At the catchment scale in the local data set all three methods ranked the Upper Ohau zone the lowest. The order of the Waikato and Waihou catchments was reversed between the WS_{blue} and CF_{AWARE} methods, and the WSI CF ranked them equivalent. The WS_{blue} and the WSI methods both ranked the Orari-Opihi-Pareora Management Zone and the Rangitikei catchment ranked in the same order, but the Selwyn-Waihora Management Zone and the Ashburton zone were reversed. The CF_{AWARE} ranked the highest four catchments in a different order to both the WS_{blue} and the WSI methods.

Table 6-6 and Table 6-7 present the characterised blue water footprints of milk production at the regional and catchment scales, respectively. In the regional analysis the WF_{AWARE} had the highest water footprint values, followed by the $WFII_{blue}$, with the $WF_{Ridoutt}$ having the lowest values (Table 6-6). The high WF_{AWARE} values are attributed to its associated high CF_{AWARE} values (Table 6-3). However, the $WF_{Ridoutt}$ and $WFII_{blue}$ had higher coefficients of variation than the WF_{AWARE} (Table 6-6; local data). Interestingly, all the water footprint methods ranked the characterised blue water footprints in the same order at the regional scale (Table 6-6).

At the catchment scale some of the characterised blue water footprint values were also higher for the WF_{AWARE}, followed by the $WFII_{blue}$ and $WF_{Ridoutt}$ values (Table 6-7). The highest value was for the WF_{AWARE} for the Orari-Opihi-Pareora catchment which was large due to the CF_{AWARE} global layer pixel having a high CF. At the catchment scale for the global data set there were changes in the order in which the WF's fell. The catchments ranked 1 and 2 were reversed in order, and those ranked 4 and 5 were also reversed in order between the $WFII_{blue}$ and both the WF_{AWARE} and $WF_{Ridoutt}$ methods (Table 6-7). However, there was no difference in the order of catchments between the $WF_{Ridoutt}$ and the WF_{AWARE} methods.

Table 6-6 and Table 6-7 clearly show that the AWARE method (Boulay et al., 2017) produced higher characterised water footprint values in absolute terms than either the Stress-Weighted Water Footprint (Ridoutt and Pfister, 2010) or the WFN (Hoekstra et al., 2011) methods. Overall, however, all three water footprint methods ranked the characterised water footprints of the regions or catchments in a similar order (Table 6-6 and Table 6-7).

Table 6-6. Estimates of characterized blue water footprint of irrigated dairy farms across different regions of New Zealand. Note relative ranks indicated in parentheses (1 representing the lowest).

Region	Global data			Local data		
	$WFII_{blue}$ (WS_{blue})	$WF_{Ridoutt}$ (WSI)	WF_{AWARE} (CF_{AWARE})	$WFII_{blue}$ (WS_{blue})	$WF_{Ridoutt}$ (WSI)	WF_{AWARE} (CF_{AWARE})
Canterbury	99.09 (3)	3.20 (3)	1962.67 (3)	45.41 (3)	9.45 (3)	112.80 (3)
Manawatu	1.95 (2)	2.03 (2)	181.57 (2)	12.39 (2)	1.91 (2)	50.88 (2)
Waikato	0.20 (1)	1.23 (1)	92.65 (1)	0.63 (1)	0.52 (1)	13.86 (1)
Coefficient of variation	1.68	0.46	1.41	1.19	1.21	0.84
Range (min-max)	0.20-99.09	1.23-3.20	92.65-1962.67	0.63-45.41	0.52-9.45	13.86-112.80

Table 6-7. Characterized blue water footprints on catchments of irrigated dairy farms. Note relative ranks indicated in parentheses (1 representing the lowest).

	Global data			Local data		
Catchment/water management zone	$WFII_{blue}$ (WS_{blue})	$WF_{Ridoutt}$ (WSI)	WF_{WULCA} (CF_{AWARE})	$WFII_{blue}$ (WS_{blue})	$WF_{Ridoutt}$ (WSI)	WF_{WULCA} (CF_{AWARE})
Waikato River	0.21 (1)	1.11 (1)	68.16 (2)	1.44 (1)	0.54 (1)	14.48 (2)
Waihou	0.66 (2)	1.11 (1)	66.84 (1)	1.46 (2)	0.55 (2)	14.16 (1)
Rangitikei River	1.48 (3)	1.87 (3)	200.45 (3)	32.49 (4)	3.50 (3)	71.31 (3)
Orari-Opihi-Pareora	165.31 (6)	3.95 (6)	10,026.24 (6)	30.84 (3)	5.17 (4)	208.39 (6)
Selwyn - Waihora	86.63 (5)	2.82 (4)	581.97 (4)	86.03 (5)	210.36 (6)	115.39 (4)
Ashburton	57.46 (4)	3.68 (5)	742.75 (5)	89.52 (6)	16.32 (5)	119.69 (5)
Coefficient of variation	1.27	0.52	2.04	0.97	2.13	0.82
Range (min-max)	0.21-165.31	1.11-3.95	68.16-10,026.24	1.44-89.52	0.54-210.35	14.48-208.39

6.4.3 Effect of local and global data sources

Table 6-3 presents the effects of using global or local data sources on quantification of the volumetric water footprints of the study farms. The use of global data sources resulted in both over- and under-estimation of volumetric water footprints. There was an overestimation of stock drinking water (SDW) by 125% for irrigated farms in the Canterbury region, and from 23 and 29% for non-irrigated farms in the Waikato and Manawatu Regions. Overall, the weighted average SDW (of all irrigated and non-irrigated farms combined) was overestimated by 37% by the global data sources (Table 6-3). The use of global data sources resulted in an underestimation of the milking parlour water use (MPW) by 25% for irrigated farms in the Canterbury region, and 8% for non-irrigated farms in the Manawatu Region. However, the MPW using the global data sources was overestimated by 52 and 32% for irrigated farms in the Manawatu and Waikato regions, respectively.

More importantly, the green water consumption for pasture and feed production (ET_{green}), which was based on the globally available CLIMWAT database, was underestimated by 13 to 42% on all study farms when compared with the estimates based on the locally available climatic database VCSN (Table 6-2). In contrast, the blue water consumption for pasture and feed production (ET_{blue}) based on the global data sources was overestimated, particularly for irrigated farms in the Manawatu and Waikato regions. The ET_{blue} based on the global data sources was estimated to be 3% higher for irrigated farms in the Canterbury region, and about 48 and 141% higher for irrigated farms in in the Manawatu and Waikato regions, respectively. This difference in the ET_{blue} was mainly attributed to lower estimates of effective rainfall, and therefore

larger predictions of irrigation requirements, in the global datasets as compared to the use of local data sets. Perry (2014) also found similar effects where use of local data and models resulted in a reduction in irrigation requirement for sugar cane production in the Inkomati river basin, South Africa. An underestimation of annual ET_{green} has also been reported when the CROPWAT model is used in combination with the USDA's effective rainfall estimates. In comparison, the simulated water balance using long term daily or average monthly weather data gives more reliable quantification of water footprint of pasture production (Hess, 2010).

Overall, the use of global data sources resulted in the total (green plus blue water) volumetric water footprint underestimated by 2 to 5% for the irrigated farms, and by 26 and 41% underestimation for the non-irrigated farms in the study regions (Table 6-3).

The effects of different global and local data sources on the resulting water footprint characterisation factors WS_{blue} (Eq. 5), WSI (Eq. 9) and CF_{AWARE} (Eq. 11) at the regional and catchment scale boundaries are clear in Table 6-4 and Table 6-5. Overall, most of the CFs at the regional scale (Table 6-4) were very small, except for the CF_{AWARE} values for the Canterbury region based on the global data set. However, the use of global data sources resulted in significant over- and under-estimation of the CFs values for different water footprint methods. The CF_{AWARE} based on the global layer was estimated at 7.36 for the Canterbury region, which was about 16 times higher than the CF_{AWARE} value of 0.47 estimated by using the local data (Table 6-4). The global CF_{AWARE} layer as compared to the CF_{AWARE} values calculated using the local data also resulted in CF_{AWARE} values that were more than twice as large for the Manawatu and Waikato regions.

The global WSI layer (Ridoutt et al., 2010) resulted in 9% (Waikato) to 70% (Canterbury) lower WSI values as compared to the local data estimates (Table 6-4). However, the global WS_{blue} layer (Mekonnen and Hoekstra, 2016), as compared to the local data estimates, resulted in 95% higher WS_{blue} values for the Canterbury region, but 86 and 90% lower WS_{blue} for the Waikato and Manawatu regions, respectively. Interestingly, the use of either global layers or local data estimates of characterisation factors WS_{blue}, WSI and CF_{AWARE} ranked the study regions in a similar order (Table 6-4), showing lowest water stress in the Waikato region and highest in the Canterbury region. The use of global layers, however, resulted in a slightly higher variation in the WS_{blue} and CF_{AWARE} values, but lower variation in the WSI values for the study regions (Table 6-4).

The catchment level CF's in Table 6-5, taken from the WSI global layer were all lower than the estimates of WSI based on the local data, except the Upper Ohau zone which was the same for both. However, the WS_{blue} and CF_{AWARE} values were both under- and over-predicted by the global layers at the catchment scale. The global layer CF_{AWARE} was estimated as 47 times higher than the local data estimates for the Orari-Opihi-Pareora zone. This zone has a high CF_{AWARE} value because the pixel on which it is calculated resides over the area of greatest water use in the zone, not the area in the zone where most of the available water is generated. The global layer CF_{AWARE} had the highest coefficient of variation between the study catchments, but when calculated using the local data it had the lowest. In contrast, the global layer WSI had the lowest coefficient of variation between the study catchments, but when calculated using the local data it had the highest. The WS_{blue} layer values were all lower in the global data set, except for the Orari-Opihi-Pareora management zone in the Canterbury region and

the Upper Ohau Management Zone in the Manawatu Region. In these water management zones the global WS_{blue} layer values were about 5 times higher as compared to the local data estimates (Table 6-5).

Table 6-6 and Table 6-7 present the effects of global and local data sources on the characterized blue water footprints of irrigated dairy farms at the regional and catchment scales, respectively. When the use of global data is compared with local data at the regional scale (Table 6-6), there is both over- and under-estimation of the characterised blue water footprints of irrigated farms. The $WFII_{blue}$ for the Manawatu and Waikato regions were underestimated, with the global data resulting in approximately one third and one sixth of the local data values, respectively. The $WF_{Ridoutt}$ for the Canterbury region was also underestimated when the global data set was used as the value was only one third of the local data value. In contrast, the other regions were all overestimated by the global data set, ranging from 1.1 to 2.4 times higher for the $WFII_{blue}$ and $WF_{Ridoutt}$ methods. The WF_{AWARE} was overestimated by use of the global data by 3.6 to 17.4 times relative to the local data set. The $WFII_{blue}$ had the highest coefficient of variation in the global data set, although the $WF_{Ridoutt}$ had the highest coefficient of variation in the local data set. In the global data set, the WF_{AWARE} had a slightly lower coefficient of variation than the $WFII_{blue}$. In the local data set, the WF_{AWARE} had the lowest coefficient of variation. In the global data set, the WF_{AWARE} had the lowest coefficient of variation at the regional scale (Table 6-6).

As for the regional scale, at the catchment scale (Table 6-7) there was both over- and under-estimation of the characterized blue water footprints of irrigated farms using the global data as compared with the local data. For the $WFII_{blue}$ there was underestimation in the global data set for the Waikato, Waihou, Rangitikei, and

Ashburton catchments by 36 to 95% as compared to the local data values. There was also underestimation of the $WF_{Ridoutt}$ using the global data for the Rangitikei, Orari-Opihi-Pareora, Selwyn-Waihora, and Ashburton catchments by 24 to 99% as compared of the local data set value. The characterized blue water footprints of irrigated farms in the Selwyn-Waihora catchment were almost equivalent for both data sets for the $WFII_{blue,}$ but underestimated by 99% for $WF_{Ridoutt}$ and overestimated by 404% for WF_{AWARE} using the global data (Table 6-7). The rest of the catchments were overestimated by the global data set by 3 to 48 times when compared with the local data set; this was the case for all of the catchments for WF_{AWARE}.

When the global data sets were used, there was general agreement of the ranking of the characterized blue water footprints of irrigated farms by the three water footprint methods, with slight changes in order for the Waikato and Waihou catchments for the WF_{AWARE} method, and the Ashburton and Selwyn catchments for the $WFII_{blue}$ method. With use of the local data set, there was significant reordering of the ranking of the characterized blue water footprints of irrigated farms with no catchment having the same position for all three methods (Table 6-7). Use of the global data set in all three methods ranked the Orari-Opihi-Pareora as highest, but for the local data set the three methods all ranked different catchments as the highest characterized blue water footprints of irrigated farms. This is due to the differences in the data the methods use and how they are calculated giving differences in the resulting WF's. The global data set resulted in relatively higher variation in the WF_{AWARE} and $WFII_{blue}$, but lower in the $WF_{Ridoutt}$. The lower variation in the $WF_{Ridoutt}$ method is possibly due to the global CF layer having many areas of New Zealand at or close to the minimum $WF_{Ridoutt}$ value thereby limiting variation. The WF_{AWARE} and the $WFII_{blue}$ have similar variation

because both use available water, taking account of EFR in their calculation. When the local data set were used, $WF_{Ridoutt}$ had the highest range and variation, as compared to the $WFII_{blue}$ and WF_{AWARE}. The high variation in the $WF_{Ridoutt}$ may be due to high levels of water abstraction in the Selwyn-Waihora zone for irrigation.

Table 6-8 presents further evaluation of the effects of local data in terms of the effects that different EFR values had on quantification of the characterization factors and characterised blue water footprints of irrigated farms in the study regions. When the WS_{blue} (WFN) was calculated under different EFRs the values ranged from 0.9 times lower to 4.0 times higher than the WS_{blue} calculated with the base ERF (37% of MAR). When the CF_{AWARE} (WULCA) was calculated under different EFRs the resulting CF_{AWARE} values ranged between 0.9 times less to 6.4 times higher than the base calculation of ERF (37% of MAR). As the available water is defined and calculated differently between methods, the resulting CFs values increased at different rates with increasing EFR levels. Using the highest EFR rate (i.e. 80% of MAR; based on the global data) the CF_{AWARE} was calculated to be 2.8 to 6.4 times higher than that calculated at the base EFR (37% MAR; based in the local data) for the study regions. Using the highest EFR rate (i.e. 80% of MAR; based on the global data) the WS_{blue} was calculated to be 3.1 to 4.0 times higher than that calculated at the base EFR (37% MAR; based in the local data) for the study regions.

Table 6-8. Sensitivity of WS_{blue} (Hoekstra et al., 2011) and CF_{AWARE} (Boulay et al., 2017) and characterised blue water footprints of irrigated dairy farms to different environmental flow requirements (EFR) in different regions of New Zealand.

Method	EFR[1]	Characterization factor			Characterized water footprint		
		Waikato	Manawatu	Canterbury	Waikato	Manawatu	Canterbury
WS_{blue} (WFN)	30%	0.01	0.09	0.17	0.57	11.15	40.87
	37%	0.01	0.10	0.19	0.63	12.39	45.41
	60%	0.02	0.15	0.30	0.95	19.51	71.51
	64%	0.02	0.17	0.34	1.05	21.89	80.26
	80%	0.04	0.31	0.60	1.72	39.01	143.03
CF_{AWARE} (WULCA)	30%	0.27	0.36	0.42	12.54	45.30	99.19
	37%	0.30	0.40	0.47	13.86	50.88	112.80
	60%	0.46	0.82	0.86	21.14	103.23	205.44
	64%	0.51	0.97	1.02	23.48	122.27	243.33
	80%	0.84	1.68	3.01	38.95	212.20	718.84

[1]Percentage of mean annual runoff required for the environmental flow requirements.

6.4.4 Effect of spatial scale

The effect of different spatial scales can be seen in Figure 6-3 (a visual representation of data from Table 6-3) where the regional volumetric blue water footprints for irrigated and non-irrigated dairy farms are compared with the estimated New Zealand weighted average volumetric blue water footprints of dairy farming including both irrigated and non-irrigated dairy farms. It is clear that the New Zealand weighted average does not accurately reflect the water footprints of dairy farms in different regions of New Zealand; in most cases it is markedly different.

In order to further assess the effects of spatial scale, Figure 6-4 (a visual representation of data from Table 6-4) presents characterised blue water footprints for the Canterbury region and the water management zones in the Canterbury region. The $WFII_{blue}$ for different water management zones was approximately 0.6 to 2 times the $WFII_{blue}$ value obtained for the regional scale analysis. Similarly, the $WF_{Ridoutt}$ for different water management zones was approximately 0.5 to 22 times the $WF_{Ridoutt}$ value obtained for the regional scale analysis. The WF_{AWARE} for different water management zones was 1.02 to 1.85 times higher than the WF_{AWARE} values obtained for the regional scale analysis.

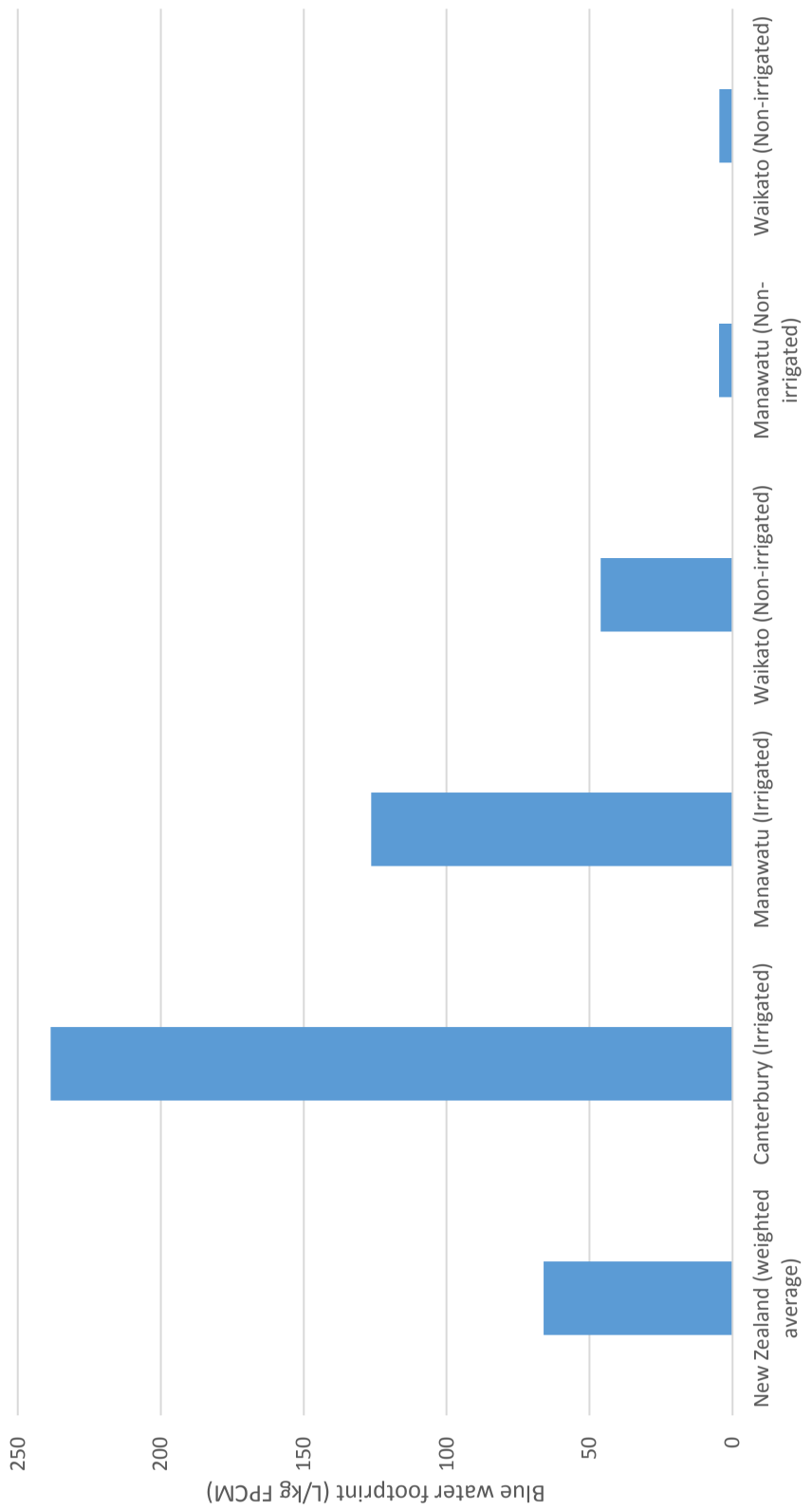

Figure 6-3. Local data volumetric blue water footprints (L/kg fat and protein corrected milk (FPCM)) for New Zealand (weighted average), Canterbury (irrigated), Manawatu (irrigated), Waikato (non-irrigated), and Waikato (non-irrigated).

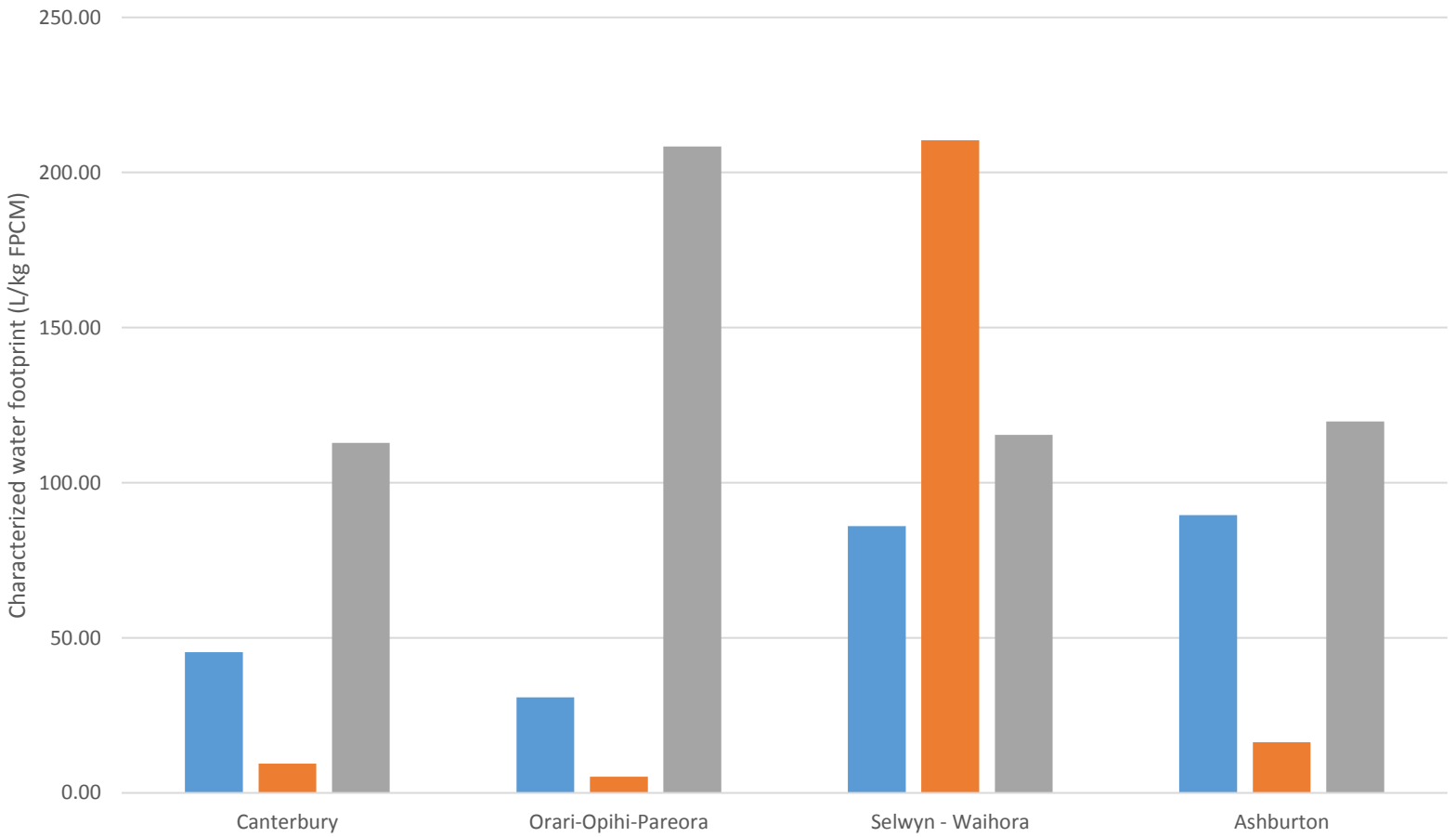

Figure 6-4. Local data characterised water footprints (L/kg fat and protein correct milk (FPCM)) for the Canterbury region and Canterbury management zones for the $WFII_{blue}$ (blue), $WF_{Ridoutt}$ (orange), and WF_{AWARE} (grey) methods.

6.5 Discussion

6.5.1 Evaluation of water footprint method

We applied and evaluated three selected water footprint methods, WFN method, the $WF_{Ridoutt}$ method, and the AWARE method of WULCA, to quantify and differentiate water stress levels and the water footprints of a unit of milk production (L/kg FPCM) of both rain-fed and irrigated dairy farms in different regions/catchments across New Zealand. We used the ranking order and coefficient of variation to assess the ability of different water footprint methods to differentiate the water footprint characterisation factors (CFs, i.e. water stress indicators) (Table 6-4 and Table 6-5) and the characterised blue water footprint of irrigated dairy farms using different data sources and at two spatial scales (Table 6-6 and Table 6-7).

Interestingly, all three water footprint methods ranked the regional level CFs and characterised water footprints in the same order of water stress or scarcity level (Table 6-4and Table 6-6). The global data CFs and the characterised blue water footprints for the study catchments were similar between the water footprint methods with some reversal of order (Table 6-5 and Table 6-7). At the catchment scale, there was some re-ranking in both CFs values and characterised water footprints as determined by the WS_{blue} and WSI methods, with the top two CF values being reversed. However, the ranking order of CF_{AWARE} was substantially different from the WS_{blue} and WSI methods, especially at the higher values, with the top 4 values in a different order (Table 6-5). This may be because the CF_{AWARE} method divides the available water remaining by the area of the catchment (equation [11]). The Canterbury management zones are quite large and generate high volumes

of water mainly in the mountains through snow melt. The inclusion of area may be the difference that causes the re-ranking of CFs, due to the available water remaining per unit area being closer or lower than that of other study regions.

In our evaluation of the different water footprint methods we found that the WSI method is the most flawed. In this method, the use of abstracted water does not account for the return flow of water to same sources. Furthermore, unlike the CF_{AWARE} and WS_{blue} methods, it does not incorporate the EFR. The WFN method takes into account the EFR at a conservative rate of 80% MAR, which can be adopted using local data. The AWARE method accounts for the EFR using the monthly water flows given in the WaterGAP database using the method of Pastor et al. (2014). The EFR rate influences the available water and possibly whether there is over allocation or not. However, the WFN and AWARE methods both provide adequate means to assess the water scarcity in a region, but also have pros and cons. The AWARE method gives a dimensionless value that is normalised by the global average. This is useful when comparing water usage for a product from two different regions. The products can be compared meaningfully if the water footprinting method was applied consistently to both products. The WFN method gives a water footprint that more closely reflects the quantitative volumes of water used and the calculation of the CF is simpler and easier to understand. The WFN method also generates more quantitative information for management purposes. In summary, both the AWARE and the WFN methods appear useful if they are applied consistently and either water footprint value helps to analyse water use of a product and/or process and its associated environmental impacts.

6.5.2 Appropriate data sources and spatial scales

As compared to different water footprint methods, the use of local and global data appeared to have larger impacts on volumetric water footprints, CFs, and characterized blue water footprints of irrigated farms across the study regions and catchments. The use of global data sources, as compared to the local data, resulted in underestimation of the volumetric green water footprint (L/kg FPCM) by -12 to -30%, and overestimation of the volumetric blue water footprint (L/kg FPCM) by 3 to 141% in the study regions. The use of local data as compared to the global data also had a large effect on quantification and ranking of the water footprint characterisation factors and the characterized blue water footprints of milk production across the study. This suggests there are benefits of collecting detailed local data to carry out water footprint analyses at the appropriate scale.

Catchment scale is the more appropriate level to carry out water footprinting exercises. This is because water footprint hotspots can be hidden at the regional scale, but they are likely to be identified at the catchment scale. The CFs and water footprints calculated at regional and catchment scale differed from each other, quite substantially at times. This is true for the Selwyn-Waihora and Ashburton zones in the $WFII_{blue}$ analysis (Figure 6-4), and also the for the Orari-Opihi-Pareora zone for the WF_{AWARE} analysis. If a water footprint is calculated using the regional level analysis there is likely to be significant uncertainty associated with it. As there is often large differences in water availability and use between different catchments within a region, analysis at the catchment or water management zone scale provides the appropriate level of quantification of water footprints for meaningful management purposes. As an example, use of a CF developed for the Canterbury region in the AWARE method would result in a water footprint for the Orari-Opihi-

Pareora zone that is almost 2 times smaller than the value derived using a catchment scale analysis. This clearly illustrates that quantification of water footprints at larger spatial scales can mask or fail to identify hot-spots of water footprints within the region.

The most important data to collect at the catchment scale is the climate data and irrigation water use in pasture and feed production for dairy farms. The rainfall and ET can be highly variable within a region, therefore using a global data source that uses monthly average data from one location within a region can lead to inaccurate water footprints. In this study, as a result of differences in the weather data records, the ET_{green} was significantly underestimated for all farm types using the global data. As ET_{green} was used in the estimation of ET_{blue}, it caused ET_{blue} to be overestimated on all the irrigated farms for the global data set. This can then, incorrectly, suggest that these farms use more water and create more water stress when compared to the same product produced elsewhere. In a world where the consumer is becoming more environmentally conscious and attuned to selecting 'environmentally-friendly' products, it is critical to have accurate data to assess and represent a product's water use and the environmental impacts of this use.

The direct water use on farm is the next most important data to collect after climate data. As irrigation water use is easily the largest volume, this is the most important to collect. It is crucial to identify actual irrigation water used, as opposed to water allocated, as if the water is not used, then there is no impact from it being allocated. The global data also over-estimated SDW on Canterbury farms, and under-estimated MPW on Canterbury farms. Although SDW and MPW make up small proportions of water use in the Canterbury region, in other regions, for example the Waikato, SDW and MPW make up a greater proportion of water use.

Compared with the use of local data sets, global data layers resulted in both over- or underestimation of the CFs of different water footprint methods for the study regions and catchments. The global CFs are mainly based upon estimates of coarse resolution global hydrological models and databases, therefore they are very likely to be less accurate at the regional and catchment scale analysis. The different water availability layers in the global databases affects the CFs. The water use values also affect the CF calculations, especially if they are based on the allocated water, not water actually abstracted and consumed. The global data layers are divided up into pixels (30' by 30' for WS_{blue}, 0.5 by 0.5 degrees for WSI and CF_{AWARE}), which did not align with the study regional or catchments areas. In the CF_{AWARE} global layer for the Orari-Opihi-Pareora zone, the pixel covered the lower plains area of the zone, where most irrigation occurs, but did not include the mountain ranges at the top of the catchment, where most available water is generated. The global CF_{AWARE} layer, therefore, had a CF value 47 times greater than the CF value estimated using the local data. The WS_{blue} global CF layer did not fit the shape of New Zealand very well, and portions of the regions were not covered by it.

One of the main difference when comparing the global and local characterized factors of the Rangitikei catchment (Table 6-6) is the change in ranking between two data sets. The Rangitikei catchment was ranked 1-4 in the global data, but in the local data set it was ranked either 5^{th} or 6^{th} highest across the study catchments. This is likely due to water transfers between the regions through hydroelectricity schemes from the Rangitikei river into the Waikato river (G. Finlay, Genesis Energy, personal communication). This data is commercially sensitive and therefore not readily available, so may not be included in the global

data sets. This data is very important to calculate water footprints with, as it can have a large effect on water footprints at the local scale.

The literature reports different EFRs for waterways to maintain the freshwater ecosystems health (Smakhtin, 2008, Pastor et al., 2014). They include ranges from 30 to 60% of mean annual runoff (MAR). The Water Footprint Network uses a more conservative value of 80% MAR although a value 37% MAR has been used in other analyses across New Zealand (Zonderland-Thomassen and Ledgard, 2012). There are also regional allocation limits which can go beyond what is presented in literature, or calculated EFR's with global models. For example, regional rules in the Waikato region are based on 64% MAR. We assessed the effects of using different EFR values in two of the water footprint methods, WFN and AWARE. As presented in Table 6-8, the use of different EFRs gave very different CFs and characterised blue water footprint of irrigated dairy farms across the study regions.

6.6 Conclusion

We applied and evaluated three selected water footprint methods, WFN method, the Stress-Weighted water footprint method, and the AWARE method of WULCA, to quantify and differentiate water stress levels and the water footprint of a unit of milk production (L/kg FPCM) at different farm types located in different regions/catchments across New Zealand. The water footprint of dairy farms was calculated and it clearly highlights that 99% of the volumetric water footprint (L/kg FPCM) is associated with the green and blue water consumption for pasture and feed. The volumetric green and blue water footprints for pasture and feed varied considerably depending on their location and whether they are non-irrigated (rain-

fed) or irrigated. The volumetric blue water footprint (L/kg FPCM) of irrigated farms in the Canterbury region was estimated to be about 2 to 5 times higher as compared to the Manawatu and Waikato regions, respectively, due to relatively low rainfall (<650 mm per year), hence greater irrigation water use.

The AWARE and the WFN methods are both useful and serve the purpose of a water footprint and, if they are applied consistently, either water footprint is appropriate to use as a tool to analyse the impacts of water use on water scarcity. The AWARE method is good for comparisons of products or processes in different regions, whereas the WFN method is good for making management decisions.

The use of local verse global data sets appeared to have a larger impact on volumetric water footprints, CF's, and characterized blue water footprints of irrigated farms across the study regions and catchments than did the water footprint method. The use of global data led to increased uncertainty in the water footprints calculated. The catchment spatial scale should be used, as catchments within regions can have varying levels of water availability and water use, which are masked when using a regional characterization factor.

6.7 References

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CHAPTER 7.

Conclusions and Recommendations

The National Policy Statement for Freshwater Management requires Regional Councils to put water accounting frameworks in place in all regions of New Zealand. Accurate and up-to-date information will ensure these accounting systems are robust and can enable sustainable use of water resources. As a major user of water the dairy sector will be a core component of water resource accounting systems. A paucity of published water use information in the past has led to simplistic and outdated water use estimates being applied to dairy systems in guidelines and policy. This thesis provides an up-to-date and detailed assessment of water use patterns, their drivers and implications for future including changing climates.

In this thesis, water use data was collected on over 100 dairy farms in the Waikato, Manawatu, and Canterbury regions over two years. Both stock drinking water and milking parlour water use followed a seasonal pattern, being low in winter (June to July) and increasing in spring (August to November) to summer (December to February). Existing water allocations for stock drinking often use an outdated value of 70 L/cow per day. However, the results of this study suggest that water allocation is more useful to farm management if it is over a year or for the milking period, whether average or peak water use values are prescribed (Table 7-1).

Table 7-1. Annual mean, peak, and the average milking day demand (AMDD[2]) water use values for the Waikato, Manawatu, and Canterbury regions.

Water use[1]	Waikato			Manawatu			Canterbury		
	Annual mean	Peak	AMDD	Annual mean	Peak	AMDD	Annual mean	Peak	AMDD
SDW	60	105	70	74	162	90	28	68	39
cSDW	35	72	44	33	88	41	25	61	35
MPW	49	82	49	50	85	66	64	118	90
TW	113	187	135	120	197	149	94	220	107

[1]SDW = stock drinking water, cSDW = corrected stock drinking water (cSDW = SDW – leakage), MPW = milking parlour water, TW = total water (bore).

[2]AMDD calculated from 1st September to 28th February.

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Water use varied considerably depending on farm types and their management. The milking parlour water use only differed between the Waikato and Manawatu regions by 1 L per cow per day. All other water uses were similar in the Waikato and Manawatu regions except for stock drinking water which was 14 L per cow per day higher in the Manawatu due to the greater levels of leakage in this region. There were significant amounts of leakage from stock drinking water reticulation systems. A method was developed to estimate this leakage which in turn allowed for the calculation of corrected stock drinking water. To the best of my knowledge this is the first time leakage rates have been estimated for pastoral dairy farm systems. The average leakage rate was estimated to be approximately 26% on the study dairy farms in the Waikato region; 47% in the Manawatu region; and 13% in the Canterbury region. Once leakage was removed, corrected stock drinking water only differed by 2 L per cow per day between the Waikato and Manawatu regions.

Improved management of water leakage, including detection methods and rapid response has the potential to significantly reduce overall water use (non-consumptive) on pastoral farms. If leakage improved to best practice (6%), then 8.2 billion litres of water could be saved annually in the 3 regions studied. Decreased leakage rates could help reduce the problems typically associated with over allocation of water in the regions and should be a focus for farmer education and support.

Predictive models for milking parlour water use and corrected stock drinking water were developed using data from the Waikato region. The main drivers of stock drinking water were climate and milk production variables. These variables are available through the virtual climate station network and from farm

milk volumes. The models performed adequately for the Manawatu region, but did not perform well for the Canterbury region. The stock drinking water was lower on irrigated dairy farms which probably reflects the greater supply of water in the lower dry matter, irrigated pasture. With greater water intake in irrigated pasture, cows require less stock drinking water. The main driver for milking parlour water use was the number of milkings in a day, followed by milk production variables. As for stock drinking water simulations, these variables are readily available with milk production data available from milk companies (with farmer agreement), and the number of milkings per day is easy to collect from farmers. In New Zealand, 94% of cows are milked twice daily (Livestock Improvement Corporation, 2013). Farmers sometimes change to once a day milking later in the season when available feed is low, and milk production decreases. This causes a drop in both stock drinking water and milking parlour water use.

Measured milking parlour water use was significantly higher on irrigated dairy farms. The higher milking parlour water use on the irrigated farms in Canterbury is partly explained by milking parlour type, as there was a higher proportion of rotary parlours in use in this sample. Herd size and maximum temperature were not significant explanatory variables for water use in the milking parlour.

The development of empirical models for milking parlour water and stock drinking water use provide Regional Councils and the dairy industry with the ability to conduct water use accounting based on a relatively simple and obtainable set of variables (i.e., climate and basic farm data). The empirical models presented here provide a means for rapid water allocation modelling, but do not remove the need for water meters on farms. Water meters should still be used to; assess compliance

against water take consents, to improve water use efficiency, and for leak detection. It would be prudent for Regional Councils outside of the regions investigated here to test the water use models on a small number of farms to ensure the models perform adequately in all regions. This would not necessarily allow for estimation of leakage rates, but, leakage rates could possibly be dealt with through educational programs.

The data and empirical models that have been produced in this thesis have provided the means to significantly increase the accuracy of water resource management in the dairying areas of New Zealand and internationally where there is pasture-based dairy farming. There were regional differences in the water accounts of the dairy farms. The Waikato region had the highest level of stock drinking water, and the Canterbury region had the highest level of milking parlour and irrigation water use. Irrigation water use in the Canterbury region made up 71% of all dairy farm irrigation in New Zealand. The Otago region had the second highest level of irrigation comprising 19% of the total dairy farm irrigation water use in New Zealand.

Climate change scenarios were modelled for irrigated and non-irrigated dairy farms. Four different scenarios were modelled over three time periods. Milking parlour water use on irrigated and non-irrigated dairy farms is not expected to directly increase much as a result of climate change. This is because milking parlour water use is strongly linked to milk production and the number of milkings in a day. Therefore, it would be differences in milk volumes as a consequence of climate change, rather than the changes in temperature and rainfall, that would be likely to drive differences in milking parlour water use. But, as it was assumed that

milk production would remain at the current level in this analysis of the effects of climate change, there were no alterations in milking parlour water use.

Corrected stock drinking water on irrigated dairy farms is not expected to vary with the shifting temperature and rainfall associated with the climate change scenarios. It is not expected to change significantly as irrigation maintains the relatively high moisture content of pasture. However, this will only be the case if water availability does not change, and irrigation continues on these farms. If irrigation reliability decreases, then there will likely be impacts on DM content of pasture, and SDW may increase as a result. In contrast to the irrigated farms, corrected stock drinking water is expected to increase significantly on non-irrigated dairy farms, with the greatest increase in required volume being in the Waikato region. With water allocation approaching the volume limits set by the Regional Council, this may become an issue in the future if SDW demand exceeds these limits. Impacts of climate change on irrigation water use were briefly modelled under climate change scenario RCP 4.5. Through this modelling, an increase of 17-24% was estimated in irrigation water requirements. As this was carried out under a simplistic modelling framework, further, more in-depth research should be carried out.

The water footprints of farms in the Waikato, Manawatu, and Canterbury regions were calculated with three different water footprinting methods. The methods investigated were; the Water Footprint Network (WFN) method, the Water Stress Index (WSI) method; and the Available WAter REmaining (AWARE) method. The WFN and the AWARE methods were both assessed to be adequate in assessing water scarcity and the impacts of dairy farming on the water resources of the study regions. They have different strengths and weaknesses, with the AWARE

method better at comparing water use of products produced at a global scale, whereas the WFN method is better at giving quantitative information for management purposes at catchment or water management zone scale. This being said, the methods can both be used to determine water scarcity and for comparisons if the methods are applied consistently. The WSI method was found to be the least adequate at assessing water scarcity. The method uses abstracted water, and does not consider the water that returns to the system, and there is no consideration of the environmental flow requirements in its calculation. However, the method does account for modified flows that reduce the stress on the environment in summer low flows.

For each of these methods, the effects of a local verse global data set, and catchment verse regional scales were investigated. The results highlights that 99% of the volumetric water footprint (L/kg FPCM) of the study dairy farms is associated with the green and blue water consumed in the production of pasture and feed. The effect of data choice was greater than the effect of different methods on the resulting water footprints. The volumetric blue water footprint (L/kg FPCM) of irrigated farms in the Canterbury region was estimated to be about 2 to 5 times higher as compared to the Manawatu and Waikato regions, respectively, due to relatively low rainfall (<650 mm per year) and therefore greater irrigation water use in the Canterbury region. The use of global data sources, as compared to the local data, resulted in underestimation of the volumetric green water footprint (L/kg FPCM) by -12 to -30%, and overestimation of the volumetric blue water footprint (L/kg FPCM) by 3 to 141% in the study regions. This showed that the use of global data can lead to less reliable water footprints for dairy farms. It is also more appropriate to calculate the water footprint using a catchment spatial scale rather

than a regional scale. This is because a regional scale analysis may mask the patterns of water use that consume less or more water, and different climatic conditions that occur at the catchment scale. The results of this analysis indicate that there would be benefit to the dairy industry collecting the local data required to carry out more detailed calculations of the water footprints. This data can then be made available for use by the international water footprinting community.

7.1 Implications and Future Research

There are a number of implications of this research including suggestions for further research. These include:

- The empirical water use models developed here provide the opportunity to complete water use accounting at catchment, regional and national scales using data that is relatively easy to access. These models provide a significant improvement over outdated default values currently applied by industry and Regional Councils.
- The predictive water use models may be a more accurate reflection of actual water use, and therefore could be used by Regional Councils to allocate water for use on dairy farms, and to check these allocations over time. However, on a cautionary note, it should be noted that the models presented in this thesis are developed to simulate water use on pastoral based dairy farming systems. Therefore, the dairy farming systems with extremely high input and high producing farms may have water use values more similar to the confinement systems found overseas, reflecting the high dry matter content of feed. Hence, high input farms should not be included in this water allocation method until further research has been completed to determine

their water use, and if their water use fits with the models presented here. It is also recommended that the effects of heat stress on water intake should be investigated to ensure the predictions of the models account for heat stress. An adequate supply of water to heat-stressed cows is important to their welfare.

- Water use on partially irrigated dairy farms was not assessed in the development of the models. The level of irrigation water going onto farms is likely to vary the amount of stock drinking water and possibly milking parlour water use. Future research should be completed to identify whether the irrigated models can predict water use adequately of these partially irrigated farms. A conservative alternative in the meantime would be to use the non-irrigated models for stock drinking water, and the irrigated model for milking parlour water use.
- Leakage rates were found to be highly variable between regions, and the development of a methodology to estimate leaks enables future work to determine what the leakage rates are in other regions, and to clarify the main causes. The effects of improving water leakage detection and early intervention may be significant for some regions and may have significant benefits for overall levels of water resource allocation. Further work should identify what education and/or support programmes may be most effective in reducing water leakage rates.
- Water footprinting using detailed local data at the catchment scale is recommended over using generic global data. The use of catchment or water management scale resolution is recommended over regional scale analysis. This is because there can be large climatic differences within a region and

the regional average data may not provide a representative result of the effect of dairying in the catchment.

- Water footprinting of dairy farming in New Zealand should be carried to give a comparison of water use between all regions, and to highlight regions of highest water use and stress.

7.2 References

Livestock Improvement Corporation. 2013. DairyNZ Milking Practices and Technology Monitor. in Report prepared for DairyNZ.

APPENDICIES

Appendix A

Bullet points of publications, presentations, conferences (attendance and presentations), and interactions with Regional Councils and farmers.

- Variation 6 water consent meetings – farmer filling in consents. 2013-2014
- Variation 6 water consents – assisting farmers one on one. 2013-2014
- Waikato Regional Council variation 6 meetings 2013-2015.
- Horizons Regional Council – co-funded data loggers for water meters - 2013
- Scientific writing course – 2014
- Attendance at the Water footprinting: principles, methods and guidelines for: A new tool to better manage scarce and finite water resources in an increasingly competitive and uncertain environment. 2014.
- Attendance at a water meter Master class 2014.
- Higham, C. 2014. Water use research to provide clarity. Inside Dairy.
- Northland Regional Council – meetings to discuss water use and water metering rules - 2015
- Assistance running Smart water use events – 2015
- Presentation at the Water Footprinting: adding sustainable value to New Zealand's primary sector products workshop. New Zealand Life Cycle Management Centre. 2016.
- Attended the Fertiliser Lime Research Centre conference 2016
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- Bay of Plenty Regional Council – pre hearing meetings on water use, water metering and possible rules – 2017

APPENDICIES

Appendix B

Relative importance of factors determining cSDW using the irrigated model

- cSDW prediction on irrigated dairy farms – Waikato was 9.8 L/cow and Canterbury was 26.6 L/cow.
- The main driver of the irrigated cSDW model 2 is irrigation.
- The large decrease in irrigation volume (i.e. going from Canterbury to Waikato) when switching to a region of lower irrigation usage decrease the contribution to cSDW.
- This limits the applicability of the cSDW model to regions similar to that of Canterbury. Rainfall is the largest negative contributor to the model.
- Therefore irrigation affects the model predictions in a significant way and when you move to a region that has a warmer wetter climate, that requires less irrigation it will have a lower prediction for cSDW.

Based on overseas models the main drivers of water intakes in dairy cows are milk yield, dry matter intake, and dry matter %. As DMI and DM% are not readily available on pasture based dairy farms alternative

Table B1. Contribution to cSDW from variables in irrigated cSDW model 2

		Canterbury		Waikato	
Model		Average irrigated farm values	Contribution to total	Average irrigated farms values	Contribution to total
Constant	0.0324	1	0.0324	1	0.0324
Rainfall	-0.0211	1.78	-0.04	3.15	-0.07
EVAP	0.0768	2.1	0.16128	2.5	0.192
MS	0.2008	1.56	0.313248	1.55	0.31124
Milkings	0.1913	2	0.3826	2	0.3826
Irrigation	0.0011	500	0.55	192	0.2112
		$\log_{10}$cSDW	1.402	$\log_{10}$cSDW	1.063
		cSDW	25.2	cSDW	11.6

Reasoning why Southland was not all that different to Waikato

- The Tmax, rad, and evap are all higher in Waikato – this would point to higher water intakes.
- However, for the southland farms the milksoilds production is higher 1.55 compared to 1.37.
- Milk solids provides a fair contribution to the cSDW model.
- While the model has other higher contributing variables such as TMax and the number of milking in a day, these had co-correlated variables that were negative such as Evap, $Evap^2$, and $Milkings^2$.
- So the two sets of factors are somewhat offset, climatewise the Waikato is higher, but milk production it is lower so the two are closer than may have been expected.
- It may be more to do with the farms selected from DairyBase that lead to higher producing farms in the Southland region.

Reasoning for high predictions with climate change.

- Tmax has a strong contribution to cSDW – more than MS production.
- The model has highly collinear variables (0.72) TMax and evap.
- Evap and Evap^2 are both negative.
- The changes in Tmax are not receiving the balance in negative Evap values to properly predict. So it would have been better if Evap were also modelled for climate change or if they were not in the model.
- Also the increases in temperature that occur in early lactation will have an increased effect due to the higher milk production.
- The climate change modelling would be much more thorough if aligned with other models that predicted pasture growth, coupled with milk production, and also predicted changes in dairy cow numbers in the regions.

Table B2. Contribution to cSDW from variables in non-irrigated cSDW model 3

		Waikato		Southland	
Model		Average non-irrigated values	Contribution to total	Average non-irrigated values	Contribution to total
Constant	0.3686	1	0.3686	1	0.3686
Tmax	0.0296	18.9	0.55944	15.1	0.44696
Rainfall	-0.0094	3.315068	-0.03116	2.526027	-0.02374
Rainfall^2	0.0001	10.98968	0.001099	6.380814	0.000638
EVAP	-0.1165	2.5	-0.29125	1.9	-0.22135
EVAP^2	-0.0081	6.25	-0.05063	3.61	-0.02924
Rad	0.0405	14.8	0.5994	12.5	0.50625
MS	0.2609	1.37	0.357433	1.55	0.404395
MilkVol^2	-0.0005	231.716	-0.11586	296.6049	-0.1483
Milking	0.3223	2	0.6446	2	0.6446
Milking^2	-0.1237	2	-0.2474	2	-0.2474
		$\log_{10}$cSDW	1.794277	$\log_{10}$cSDW	1.701405
		cSDW	62.3	cSDW	50.3

APPENDICIES

Appendix C

DRC 16 forms

Included in this appendix are the statements of contributions to Doctoral thesis containing publications. Forms are included for Chapters 3 and 4.