Temporal and spatial water use on irrigated and nonirrigated pasture-based dairy farms

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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 parlor 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

parlor, 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 parlor water, and total water use on irrigated dairy farms.

Key words: water use, water efficiency, irrigation, milking parlor, pasture system

INTRODUCTION

The 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 (Higham et al., 2017; 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 (Higham et al., 2017). However, data for other water uses on irrigated

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dairy farms, including stock drinking water (SDW), and milking parlor water use (MPW) remain limited.

The study of Higham et al. (2017) showed the seasonal nature of water use on 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 by Higham et al. (2017) 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.

MATERIALS AND METHODS

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.

Table 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 parlors ⁴	Average no. of bales	Cow:bale 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 ⁵
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
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

¹SDW = stock drinking water; cSDW = corrected stock drinking water; MPW = milking parlor water use; TW = total water use; IW = irrigation water.

²System type based on the DairyNZ (Hamilton, New Zealand) 1-to-5 classification system: 1 = all pasture; 2 = 4 to 14% of feed imported; 3 = 10 to 20% of feed imported; 4 = 20 to 30% of feed imported; 5 = 25 to 40% of feed imported (Ramsbottom et al., 2015).

³1 = Friesian; 0.5 = Friesian-Jersey cross; 0 = Jersey.

⁴Rotary parlors (Reinmann, 2003); all other parlors were herringbone swing-over milking parlors.

⁵N/A = data not collected.

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, parlor type (i.e., herringbone or rotary), and cow breed, were collected (Table 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.

Farm Descriptions

Descriptions of the study farms are presented in Table 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/m², 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/m², 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

Table 2. Farm variables used in the water use analysis

Abbreviation	Description
TMax	Maximum daily temperature (°C)
TMin	Minimum daily temperature (°C)
Rain	Rainfall (mm)
Evap	Priestley-Taylor potential evapotranspiration (mm)
Wind	Wind run (km)
Rad	Solar radiation (MJ/m ²)
MilkSol	Milk solids (milk fat + milk protein; kg)
MilkVol	Milk volume (L)
Milking	No. of milkings/d
System	Production system type
YrRound_Yes	Year-round milking
Brd	Cow breed (1 = Friesian; 0.5 = Friesian-Jersey cross; 0 = Jersey)
Cow	No. of cows
EffArea	Farm effective area
Rotary	Milking parlor type (1 = rotary; 0 = herringbone)
Bales	No. of bales (stalls) in the milking parlor
CowBale	No. of cows:no. of bales (stalls) ratio
Cows/ha	Stocking rate (cows/ha)
Houses_Yes	Domestic houses taking water from the stock water line
House_No	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	Recycles cooler water to stock drinking water
Recirculate_Yes	Recirculates cooling water into the same tank
SnapCh_Yes	Parlor has a snap chiller
RRSC_Yes	Parlor recycles cooling water to stock drinking water, recirculates cooling water into the same tank, or has a snap chiller
Irr_Yes	Has irrigation
IrrArea	Irrigation area
Irrmm	Irrigation yearly application (mm)
Irr/EffArea	Percentage of the milking platform that has irrigation on it
FY_201314	June 1, 2013, to May 31, 2014

farms ($n = 15$) in the Manawatu region winter grazed off farm for an average of 7.6 wk (range = 6–9.5 wk).

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 (Higham et al., 2017). 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 (Higham et al., 2017).

Leakage Adjustment

Individual farm SDW data were run through an R Software script (R Core Team, 2015) to adjust for wa-

ter 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 by Higham et al. (2017). The output of the script included the SDW value and the corrected SDW (cSDW).

Statistical Analyses

The ability of the models developed by Higham et al. (2017) 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 (Moriassi 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.

Partial Least Squares Modeling

Univariate polynomial partial least squares (PLS) regression modeling was used to evaluate the ability of a combination of different collinear variables to predict

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

Water use	Nonirrigated			Irrigated		
	Farms (no.)	Average (SD)	Peak	Farms (no.)	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 (17.8)	106	4	4 (5.5)	41
Leakage % ³	8	46.7		4	13.0	
MPW	15	50 (20.4)	85	14	64 (33.8)	118
TW ⁴	14	120 (38.0)	197	9	94 (29.4)	220
IW				9	4,880	
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)	

¹cSDW = SDW – leakage.

²Leakage rate (L/cow per day) calculated where $n > 5$ except Canterbury farms ($n = 4$).

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

⁴TW = SDW + MPW.

⁵AMD = average milking day; from September (spring) to February (summer).

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 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 $\log_{10}$ transformed to achieve homogeneity of variance. All PLS analyses were carried out using Minitab 16.2 (Minitab Inc., State College, PA).

RESULTS

Average and peak water use values for the irrigated and nonirrigated farms are presented in Table 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.

Figure 1. Average daily water use (L/cow per day; $\pm$ 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 SDW (cSDW) on nonirrigated farms, and (d) cSDW on irrigated farms. Color version available online.

There was a seasonal pattern for SDW and cSDW for both irrigated and nonirrigated farms (Figure 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 2.

Evaluation of Water Use Model Predictions

Table 4 shows the ability of the cSDW model 3, MPW model 3, and TW model 3 produced by Higham et al. (2017) 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). 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 (Higham et al., 2017).

Figure 2. Average daily water use (L/cow per day; $\pm$ SD) and the count of farms contributing to the data (solid line) for (a) milking parlor water (MPW) use on nonirrigated farms, (b) MPW use on irrigated farms, (c) total water (TW) use on nonirrigated farms, and (d) TW use on irrigated farms (error bars up to 1,285 L/cow per day due to leaks truncated at 600 L/cow per day). Color version available online.

Table 4. Corrected stock drinking water¹ (cSDW), milking parlor water use (MPW), and total water² (TW) model predictions compared with the measured or derived water use volumes on irrigated and nonirrigated pasture-based dairy farms

Model prediction	Prediction model comparison with measured data	n	Line of best fit slope ³	Line of best fit Y intercept ⁴	Line of best fit R-squared ⁵	Pearson correlation coefficient ⁶	RMSE ⁷	NSE ⁸	Percentage bias ⁹	RSR ¹⁰
cSDW model 3	Nonirrigated	8	0.79	7.97	0.58	0.80	8.00	0.60	1.67	0.63
	Irrigated	4	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

¹cSDW = stock drinking water (SDW) − leakage.²TW = SDW + MPW.³L/cow per day; optimum = 1.⁴L/cow per day; optimum = 0.⁵Optimum = 1.⁶Optimum = 1 or −1.⁷Root mean squared error (L/cow per day); optimum = 1.⁸Nash–Sutcliffe efficiency; optimum = 1, >0 is acceptable. If <0, then the mean is a better predictor than the model.⁹Optimum = 0; positive values mean underestimation and negative values mean overestimation.¹⁰RSME observations SD ratio; optimum = 0.**Table 5.** Partial least squares regression model equations (raw coefficients) for predicting corrected stock drinking water use (log₁₀ cSDW) on irrigated pasture-based dairy farms (n = 4)¹

Variable	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		

¹A list of variables is presented in Table 2.

PLS Regression Models

The PLS regression models were developed for cSDW, MPW, and TW on irrigated farms, and the results are presented in Tables 5, 6, and 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 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 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 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 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).

$$\begin{aligned} \text{LogcSDW}(\text{model } 2 + 1.25) = & 0.0324 + 0.2008 \times \text{MilkSol} \\ & - 0.0211 \times \text{Rain} + 0.0768 \times \text{Evap} + 0.1913 \times \text{Milking} \\ & + 0.0011 \times \text{Irrmm} \end{aligned}$$

[1]

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

[2]

$$\begin{aligned} \text{LogTW}(\text{model } 2 - 6) = & 5.0573 - 0.1531 \times \text{CowBale} + 0.0487 \\ & \times \text{MilkVol} + 0.0881 \times \text{MilkSol} - 0.2149 \times \text{MilkSol}^2 + 0.0878 \\ & \times \text{Evap} - 0.0110 \times \text{Evap}^2 + 0.3372 \times \text{Milking} - 0.0400 \\ & \times \text{Milking}^2 + 0.7393 \times \text{Rotary} - 0.0276 \times \text{Irr/EffArea} \\ & + 0.6851 \times \text{Houses_Yes} - 0.0674 \times \text{Recycle_Yes} \end{aligned}$$

[3]

Abbreviations used in the models are presented in Table 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 8. The predicted versus measured or derived plots for cSDW, MPW, and TW are presented in Figures 4a, b, and c, respectively.

Table 6. Partial least squares regression model equations (raw coefficients) for predicting milking parlor water use ($\log_{10}$ MPW) on irrigated pasture-based dairy farms ($n = 12$)¹

Variable	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			

¹A list of variables is presented in Table 2.

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 parlor, 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 (Higham et al., 2017).

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

Table 7. Partial least squares regression model equations (raw coefficients) for predicting total water use ($\log_{10}$ TW) on irrigated pasture-based dairy farms ($n = 6$)¹

Variable	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		

¹A list of variables is presented in Table 2.

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 analyze 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 parlors (86%) in the irrigated region than rotary milking parlors (26%) in the nonirrigated region (Higham et al., 2017). 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 by Higham et al. (2017) 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

Figure 3. Partial least squares regression loading plots (variables defined in Table 4) for (a) corrected stock drinking water model 2, (b) milking parlor water use model 3, and (c) total water use model 3.

farms, the success of the Higham et al. (2017) 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 Higham et al. (2017) 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 by Higham et al. (2017) 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.

CONCLUSIONS

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 by Higham et al. (2017) 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.

Table 8. Partial least squares regression model evaluation for irrigated farms

Prediction model comparison with measured data ¹	n	Line of best fit slope ²	Line of best fit Y intercept ³	Line of best fit R-squared ⁴	Pearson correlation coefficient 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 milking parlor water use model 3 + 15	13	1.17	−10.58	0.92	0.96	8.74	0.98	0.13	0.15
Irrigated total water model 2 − 6	5	0.80	15.21	0.66	0.81	15.51	0.96	−2.05	0.19

¹Corrected stock drinking water (cSDW) = stock drinking water − leakage.

²L/cow per day; optimum = 1.

³L/cow per day; optimum = 0.

⁴Optimum = 1.

⁵Optimum = 1 or −1.

⁶Root mean squared error (L/cow per day); optimum = 1.

⁷Nash–Sutcliffe efficiency; optimum = 1, >0 is acceptable. If <0, then the mean is a better predictor than the model.

⁸Optimum = 0; positive values mean underestimation and negative values mean overestimation.

⁹RSME observations SD ratio; optimum = 0.

Figure 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 parlor water (MPW) use model 3 ($R^2 = 0.90$), and (c) total water (TW) use model 3 ($R^2 = 0.72$). Color version available online.

Further research is needed to evaluate the applicability of these models to other irrigated regions. The current study along with the preceding work described by Higham et al. (2017) 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.

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