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Water Use and Conservation on a Free-Stall Dairy Farm

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Abstract: Livestock watering can represent as much as 20% of total agricultural water use in areas with intensive dairy farming. Due to an increased emphasis on water conservation for the agricultural sector, it is important to understand the current patterns of on-farm water use. This study utilized in situ water meters to measure the year-round on-farm pumped water (i.e., blue water) on a ~419 lactating cow confined dairy operation in Eastern Ontario, Canada. The average total water use for the farm was 90,253 ± 15,203 L day^{-1} and 33,032 m^3 annually. Water use was divided into nutritional water (68%), parlour cleaning and operation (14%), milk pre-cooling (15%), barn cleaning, misters and other uses (3%). There was a positive correlation between total monthly water consumption (i.e., nutritional water) and average monthly temperature for lactating cows, heifers, and calves (R^2 = 0.69, 0.84, and 0.85, respectively). The blue water footprint scaled by milk production was 6.19 L kg^{-1} milk or 6.41 L kg^{-1} fat-and-protein corrected milk (FPCM) including contributions from all animal groups and 5.34 L kg^{-1} milk (5.54 L kg^{-1} FPCM) when excluding the water consumption of non-lactating animals. By applying theoretical water conservation scenarios we show that a combination of strategies (air temperature reduction, complete recycling of milk-cooling water, and modified cow preparation protocol) could achieve a savings of 6229 m^3 annually, a ~19% reduction in the total annual water use.

Keywords: milk production; water; footprint; water recycling; conservation; partitioning; efficiency

1. Introduction

In the past 100 years, agricultural production has accounted for as much as 80% of global freshwater consumption [1]. While green water can be made scarce and is important for global water resource allocation, blue water is more relevant from the point of view of industrial environmental impact assessments [2]. This is partially because natural vegetation consumes green water in much the same way as rain-fed agricultural land [3], whereas blue water withdrawals are almost entirely anthropogenic, and, in cases of fossil groundwater, non-renewable [4].

Total agricultural blue water (fresh surface/groundwater) use in Canada is estimated to be between 1.7 and 2.3 billion m^3 year^{-1}. While irrigation represents the bulk of this agricultural water use, livestock watering makes up between 5% to 10% of the total, which in turn represents up to 230 million m^3 of blue water annually [5,6]. In Canadian provinces where rain-fed agriculture predominates and there is intensive dairy production, such as Ontario and Quebec, livestock watering approaches 20% of the provincial totals [6].

Non-irrigation blue water use on dairy farms typically includes water consumption, milking equipment, parlour, and pipeline cleaning, washing down of the holding area, milk cooling, and temperature control [7]. In a European study, water meters read monthly by farmers determined a milk production water footprint (WF) of between 1.2 to 9.7 L kg^{-1} of fat-and-protein-corrected milk (FPCM) [8]. Capper et al. [9] found that water consumption on American dairies has decreased from 10.8 L kg^{-1} milk to 3.8 L kg^{-1} milk between 1944 and 2007. Drastig et al. [10] calculated that the mean blue water (fresh surface/ground water) consumption required to produce 1 kg of milk was 3.94 ± 0.29 L. Drastig et al. [10] reported that the majority of water use was for cow consumption (82%), whereas milk processing (cow preparation, bulk tank cleaning and line flushing) contributed 11% of the water use and the remainder (7%) was for barn cleaning and disinfection. However, some these figures were derived from models that may not include the water requirements of on-farm replacement animals. Moreover, a detailed understanding of dairy farm water uses and temporal dynamics is required to understand how farmers can adjust management practices to conserve water.

Water is the most important foodstuff of lactating cows [11,12] and daily water consumption of lactating dairy cows in Ontario can be as much as 155 L day^{-1}, up to triple that of dry cows [13]. In order to achieve optimal milk production in dairy cows, sufficient amounts of water, energy, protein and minerals are necessary [14]. Cardot et al. [15] identified several factors that affect free water intake, namely dry matter intake (DMI), milk yield, and to a lesser extent minimum temperature and rainfall. Links between production and heat stress have been demonstrated previously [16]. Both the consumption of dry matter (DM) and milk production decrease when the temperature humidity index (THI) was >60 [17]. Furthermore, water consumption increases linearly under mild heat stress when THI exceeds 30 [17] and hence daily water use fluctuations are typically greater in summer months [18]. Heat stress mitigation, such as cow showers, can decrease cow body temperature by 0.2 °C and showered cows spend half as much time near water bowls [19]. Lin et al. [20] showed that misters can decrease average daily air temperature by ~2 °C using 16.7 L cow^{-1} day^{-1} and ~4 °C using 44.2 L cow^{-1} day^{-1}.

To improve understanding of the current patterns of on-farm water use and potential avenues for water conservation, this study intended to:

1. Determine the total annual pumped groundwater (on-farm blue water) and blue water footprint of a dairy farm.
2. Partition the groundwater flow by type of use.
3. Identify areas for blue water conservation and provide estimates of potential savings.

2. Materials and Methods

2.1. Dairy Farm Site

The one-year monitoring period was from 1 October 2015 to 30 September 2016 for a total of 366 consecutive days. The trial was conducted on a confined dairy operation located in Eastern Ontario (44.981804°, −75.366390°). Herd information was collected from detailed monthly farm records obtained from the dairy herd management service (CanWest DHI) and the farmers. The operation included ~973 Holstein cows. During the monitoring period, the herd averaged 419 ± 13 lactating cows and 54 ± 6 dry cows (~11% of herd). In addition, it was estimated based on quarterly observations (counts) that there were ~60 transition cows (pre-fresh, fresh). The replacement animal populations fluctuated from month to month but were typically ~240 heifers and ~200 calves.

2.1.1. Animal Housing

The cow, heifer and calf animal groups were each housed in separate barns on the farm. The free-stall main barn housed lactating cows, transition cows (pre-fresh, fresh), and dry cows. A second free-stall barn housed the heifers, and a third barn housed the calves in 21 pens (~10 calves per pen). The main barn was cooled using 16 box fans evenly distributed throughout the building (four per quadrant). The calf barn was cooled using five high-volume low-speed fans and air circulation was aided by two positive pressure ventilation ducts. The heifer barn relied on passive ventilation from the roof, open sides (controlled with curtains), and ends of the building.

2.1.2. Animal Diets

Lactating cows were fed 25.2 kg day^{-1} dry matter (DM) as a total mixed ration (TMR) comprised of corn silage, ensiled field peas, high moisture corn, and supplements. Feed was analysed using the following methods: AOAC 930.15 for DM, Dumas combustion method for crude protein, and ICP-OES for nutrients. A dietary analysis of the feed given to the main animal categories is presented in Table 1. Pre-weaned calves (3–72 day) were fed milk replacer delivered by CF1000+ calf feeders (DeLaval Canada, Peterborough, ON, Canada).

Table 1. Typical feed constitution for each animal type (heifers and cows). Each analyte was measured in duplicate from feed laid out for each animal type. Values are mean ± SD.

Parameter	Heifers	Cows
Dry Matter (%)	45.7 ± 1.00	49.2 ± 3.43
Crude Protein (%DM)	13.3 ± 0.54	14.9 ± 1.29
Ca (%DM)	1.32 ± 0.01	0.96 ± 0.04
P (%DM)	0.34 ± 0.01	0.36 ± 0.03
K (%DM)	1.37 ± 0.06	1.02 ± 0.07
Mg (%DM)	0.33 ± 0.01	0.40 ± 0.01
Na (%DM)	0.44 ± 0.01	0.34 ±0.14
Ca:P ratio	3.91 ± 0.06	2.70 ± 0.57

2.1.3. Milk Production

The milkhouse holding area and milking parlour (12 × 2 parallel) was perpendicularly connected to the main barn. The dairy cows, which were housed in the barn year-round, were milked 3× daily at 0300 h, 1100 h, and 1900 h with each milking event taking ~4–5 h. The bulk tank (31,593 L capacity) was emptied every 1–2 days depending on milk pick-up.

Average daily milk production was extrapolated from test day production data and herd size data corresponding to the monitoring period, which were obtained from CanWest DHI (Guelph, ON). *FPCM* was calculated using the following equation:

$$FPCM = M_{raw} \times \left(0.337 + 0.116 \times M_{fat} + 0.06 \times M_{pr}\right), \quad (1)$$

where *FPCM* is fat-and-protein-corrected milk, in kg, and M_{raw} is the average daily milk production, in kg. M_{fat} and M_{pr} are the respective average fat and protein contents of the milk, expressed as a percentage [21].

The average daily milk production based on monthly farm records for the monitoring period was 34.8 ± 0.8 kg cow^{-1} day^{-1} with a fat content of 3.8% and a protein content of 3.2%. Corrected to 4.0% fat and 3.3% protein, the milk production averaged 33.6 kg cow^{-1} day^{-1} *FPCM*.

2.2. Water Use Overview

Water was used in various aspects of the farm management, specifically, drinking water for each group of cattle (lactating cow, dry cow, heifer, and calf), milk parlour sanitization, milk pre-cooling (i.e., plate cooler), cow misting and general farm cleaning (i.e., barn floor and farm equipment wash-down). All on-farm water was drawn from two wells located on the property (Total Dissolved Solids 1039 mg L^{-1}, pH 7.5, nitrate-N 10.5 mg L^{-1}, $p < 1$ mg L^{-1}, Na 186 mg L^{-1}, sulphate 95.7 mg L^{-1}). These figures are all within the range of the acceptable guidelines, where applicable [22]. Water was analysed using the following methods: electrical conductivity (EC) for total dissolved solids, ion-selective electrode meter (ISE) for NO_3–N, and ICP–OES for nutrients.

Drinking water was stored in a 5678 L plastic reservoir with inlets controlled by float valves (Figure 1, "primary reservoir"). In addition, the milk pre-cooling water was freely discharged into this reservoir (without float valve control). Any overflow from this reservoir was diverted to an overflow reservoir (Figure 1, "overflow"). This reservoir was always full when inspected on site visits. All water that went into overflow was considered wasted, although attempts were made to use some of it for milkhouse floor cleaning. Overflow from this reservoir flowed to the manure pit.

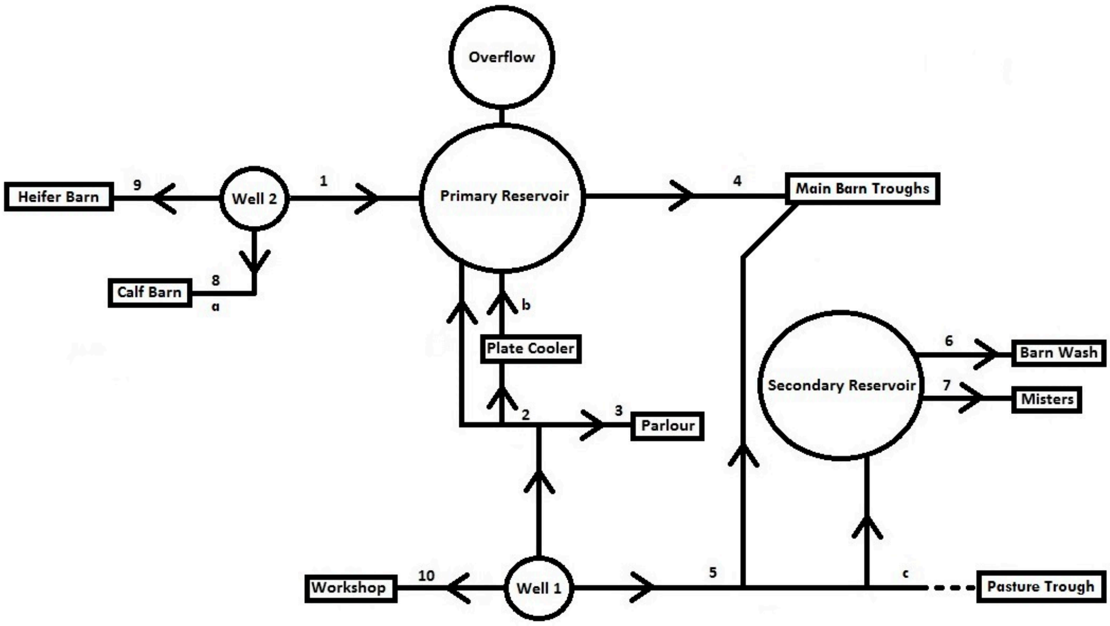

Figure 1. Simplified water flow diagram outlining the location of the 10 in-line flow meters (1–10) and placement of the transit-time flow meters (TTFMs) used to measure water to the calf barn (**a**), from the plate cooler (**b**), and to the pasture trough (**c**). Not to scale.

2.2.1. Nutritional Water

Cows in the main barn had free access to drinking water by means of 11 automatically replenishing 227 L troughs. Furthermore, water was added daily to the Total Mixed Rations (TMR). The heifer barn was equipped with seven automatically replenishing 250 L tip tank troughs. During a construction period from 15 June 2016 to 8 October 2016, the dry cows were moved to a nearby pasture equipped with a single large water trough. Calves received water delivered with the milk replacer described in the previous section and also had access to eight automatically replenishing ~20 L water bowls.

2.2.2. Milk Pre-Cooling

Milk was pre-cooled before entering the bulk tank using an in-line plate cooler system (Fabdec Limited, Ellesmere, UK). Water used by the plate cooler was discharged into the primary reservoir (Figure 1).

2.2.3. Parlour Sanitizing and General Cleaning

Sanitizing, rinsing, detergent washing and acid rinsing of the milk pipelines was conducted after each milking and the milkhouse floor was cleaned daily (parlour sanitizing). According to the sanitization protocol, each pipeline cleaning event used ~720 L of water for a total of 2160 L daily. The bulk tank was cleaned routinely after milk was removed for transport. This used ~400 L of water per wash according to the prescribed protocol, and a portion of this was reused for floor cleaning. After each milking, the standing area in the main barn was hosed down with a high-volume hose pumping from a ~500 L basin that was gradually filled by a low-volume hose with a float valve (general cleaning). General cleaning also included occasional farm equipment cleaning.

2.2.4. Cow Misting

The main barn was equipped with high-pressure misters located above the feed bunks and arranged in four zones for cooling the cows. These misters were automatically activated when the in-barn temperature reached or exceeded 21 and 24 °C, as per the following automated two-step program:

1. 21 °C, 24 s in each zone successively followed by a 10-min rest period.
2. 24 °C, 36 s in each zone successively followed by a 7-min rest period.

2.3. Flow Measurements

The farm owners and the farm's plumber were interviewed to understand the sources and pathways of water throughout the farm. In addition, water pipes were visually inspected and surveyed with a portable transit time flow meter (TTFM) (Greyline Instruments Inc., Long Sault, ON, Canada) to confirm the information. Ten in-line model 1000JLPRS multi-jet propeller flow meters with pulse outputs (Carlon Meter, Grand Haven, MI, USA) were installed between 1 August 2015 and 22 September 2015 in strategic locations to monitor and partition whole-farm water use (Figure 1). Seven were dispersed in the main barn to measure: (1, 2) inflow from the two wells; (3) flow to the parlour; (4) flow to the main barn troughs from the primary reservoir; (5) flow from well 1 to the main barn bowls and secondary reservoir; (6) flow used for washing the main barn floor; and (7) flow to the misters. The other three meters measured flow to: (8) calf barn; (9) heifer barn; and (10) farm workshop (Figure 1). Due to a plumbing change, the flow to the calf barn was measured using a TTFM from 26 October 2015 to 14 June 2016. Data from six meters were stored on data loggers (CR200X, CR800; Campbell Scientific, Logan, UT, USA) and the other four meters were stored on USB storage devices (USB-505, Measurement Computing, Norton, MA, USA) as 10 min, 1 h, and 1 d averages. Due to a partial instrument failure with the meter on the mister line, daily mister water use for the entire period was estimated using an equation generated from periods of successful data acquisition. Plate cooler waste was visually observed overflowing from the primary reservoir. This waste flow was determined by subtracting the difference between measured inflow (Meters 1 and 2) and outflow (Meter 4) from the primary reservoir.

For further partitioning water use, a follow-up measurement campaign was conducted using a TTFM to measure flow of the plate cooler water return from 30 June to 6 July 2016. Another TTFM was installed on the line supplying the dry cow pasture water trough from 15 June to 24 June 2016. Gaps in the dry cow pasture drinking water time series before the TTFM was installed were filled using a water intake vs. temperature response equation developed from lactating cow data. The pasture trough was visually observed to be overflowing due to the trough not being level. This waste flow was determined by measuring flow into the trough when no cows were drinking during site visits, and verified each day by flow measured in the middle of the night when cows were inactive.

2.4. Environmental Measurements

In-barn air temperature was measured using a shielded thermistor every 10 s and recorded as 10 min, 1 h, and 1 d averages on a CR200X datalogger (Campbell Scientific, Logan, UT, USA). In-barn humidity was measured using a CS215 temperature RH probe (Campbell Scientific); however, the sensor failed in the midst of the study, therefore gaps were filled using average daily relative humidity (RH) recorded at the Ottawa Central Experimental Farm Weather Station (45.383262°, −75.714079°). With these data, THI was calculated according the following equation [23]:

$$THI_{avg} = (1.8 \times T_a + 32) - (0.55 - 0.0055 \times RH) \times (1.8 \times T_a - 26), \quad (2)$$

where THI_{avg} is the average daily THI, T_a is the average daily air temperature (°C), and RH is the average daily relative humidity (%).

3. Results

3.1. Environmental Conditions

The average RH and air temperature (T_a) for the monitoring period was 69 ± 15% and 12.5 ± 7.3 °C, respectively. The resulting average THI was 57 ± 11. The average monthly temperatures and THI are presented in Figure 2, illustrating the seasonal changes with high values occurring from May to Aug. The number of days in which daily average T_a exceeded 25 °C was 11, 5, 3, and 4 for May, June, July, and August, respectively. Likewise, the number of days in which THI exceeded 75 was 8, 3, 3, and 1 for May, June, July, and August, respectively.

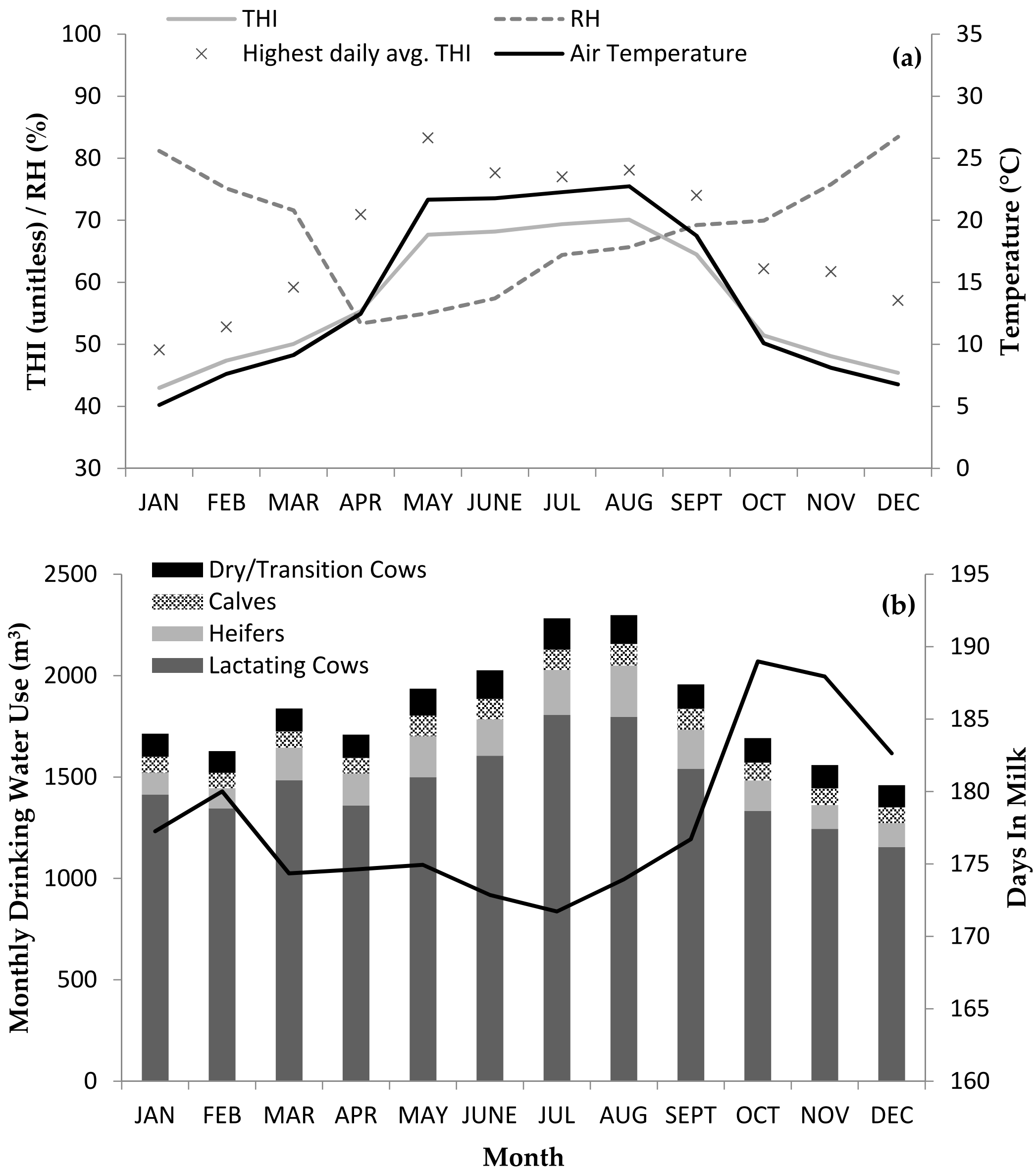

Figure 2. (**a**) Average monthly THI and air temperature (°C). (**b**) Total monthly drinking water consumption (m^3) broken down by animal category (lactating cows, dry/transition cows, calves and heifers). The solid line is the average monthly days in milk (DIM).

3.2. Total Farm Water Use

The average total daily water use (1 October 2015 to 30 September 2016) for the farm was 90,253 L ± 15,203 L and the annual water use was 33,032 m^3 (Table 2). The majority of the on-farm water use was for nutritional water (68%), while milking parlour cleaning and operation contributed 14%, waste represented 15% (including unrecovered plate cooler return water and pasture trough overflow), and barn cleaning, misters and other water use (misters, cleaning) represented 3% (Figure 3).

Misters were operational between May and October and were estimated to have had a cumulative water use of 480.5 m^3 for this period (Table 2). The cumulative value was based on measured and gap-filled data. Gaps were filled using the following equation, which was developed by regression of measured air temperature and water use for misting:

$$MIST_{daily} = 658.79 \times (T_a) - 11,250, \tag{3}$$

where $MIST_{daily}$ is the total daily water demand of the mister system (L day^{-1}), and T_a is the average daily barn air temperature (°C) (RMSE = 712, R^2 = 0.84, $p < 0.001$).

Table 2. Allocation of total on-farm water uses.

Component	Annual Water Use (m^3 $year^{-1}$)	Daily Water Use (m^3 d^{-1})
Drinking Water	22,101	60.4 ± 8.8
Plate Cooler Waste	4649	12.7 ± 7.9
Milk Parlour	4451	12.2 ± 1.7
Barn Cleaning	702	1.9 ± 0.89
Misters	481	1.3 ± 2.1
TMR	474	1.3 ± 0.81
Pasture Waste *	175	0.48 ± 0.82
Total	33,032	90.3 ± 15.2

Note: * Overflow in the pasture water trough occurred during a portion of the summer, but for consistency of calculation was assigned a daily value based on the entire year.

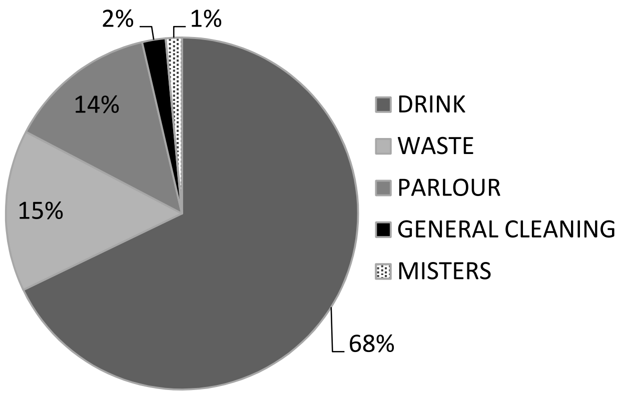

Figure 3. Breakdown of total farm water use (%) including drinking, waste, parlour (foot baths, parlour floor cleaning, cow cleaning, line sanitization), general cleaning (i.e., barn floor and farm equipment), and mister water use. Waste includes water that was not recovered from the plate cooler return and water spilled from the pasture bowl.

3.3. Drinking Water

The majority of the drinking water (80%) was used to service the lactating cows, whereas heifers, dry/transition cows, and calves made up the remaining 9%, 7%, and 4%, respectively (Figure 4). The average daily water consumption per animal for the lactating cows (excluding TMR water addition) was 114 ± 13 L day^{-1}, for dry cows was 36 ± 5.2 L day^{-1}, for heifers was 22 ± 8.2 L day^{-1}, and for calves was 12 ± 2.9 L day^{-1}. These water consumption values are generally in the ranges identified in local government documents [13] (Table 3). Note that dry cow drinking water for the entire monitoring period was estimated using an equation developed from the period where they were pastured separately in combination with the drinking water temperature response of lactating cows:

$$DC_{drink} = 0.636 \times T_a + 27.03, \quad (4)$$

where DC_{drink} is the daily water consumption per dry cow (L cow^{-1} day^{-1}) and T_a is the daily average barn air temperature (°C) (RMSE = 3.0, R^2 = 0.48, p < 0.001).

Table 3. Measured and published water consumption per animal category (L day^{-1}) showing the mean ± SD of measured daily values as well as the published range of water consumption.

	Measured Water Consumption (L day^{-1})	Published Water Consumption † (L day^{-1})
Lactating Cows	114 ± 13	110–132 ‡
Dry Cows	36 ± 4.7	34–49
Heifers	22 ± 8.2	14.4–36.3
Calves	12 ± 2.9	4.9–13.2

Note: † [13]; ‡ Adjusted for Holstein dairy cows producing 34.8 kg day^{-1} of milk.

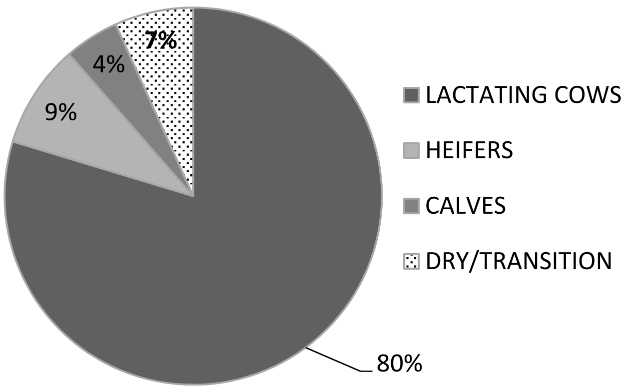

Figure 4. Breakdown of drinking water use (%) by animal category (lactating cows, dry/transition cows, calves and heifers). The dry and transition cow water was modelled based on a period when the dry cows were placed in pasture on a separate water supply.

Water consumption was greater in warm weather months compared to cool months and this was observed for all animal categories (Figure 2). The relationship between each month's average daily water consumption and average monthly temperature had a positive correlation for lactating cows, heifers, and calves (R^2 = 0.69, p < 0.001; R^2 = 0.84, p < 0.001, R^2 = 0.85, p < 0.001; respectively) (Figure 5a). The heifer barn was not equipped with cooling equipment (i.e., fans, misters) and this may explain the steeper slope (~3×) of the water consumption response of this animal group compared to lactating cows and calves. The THI was also positively correlated to water consumption but did not provide better correlation than simply using air temperature as a predictor. For example, using daily data, both THI and T_a had similar fits (R^2 = 0.60, p < 0.001) with the total drinking water use (Figure 5b). The results were no different if only considering the drinking water supplied to lactating cows. In a long trial such as this it appears that temperature was the major driver of THI, as exemplified by the fact that average daily THI and average daily air temperature were very strongly correlated (R^2 = 0.99, data not shown). This is primarily because the annual range of T_a (CV = 0.54) is greater than that of RH (CV = 0.21) (Figure 2). However, it is possible that more complete on-farm RH measurements would have yielded better results for THI [23].

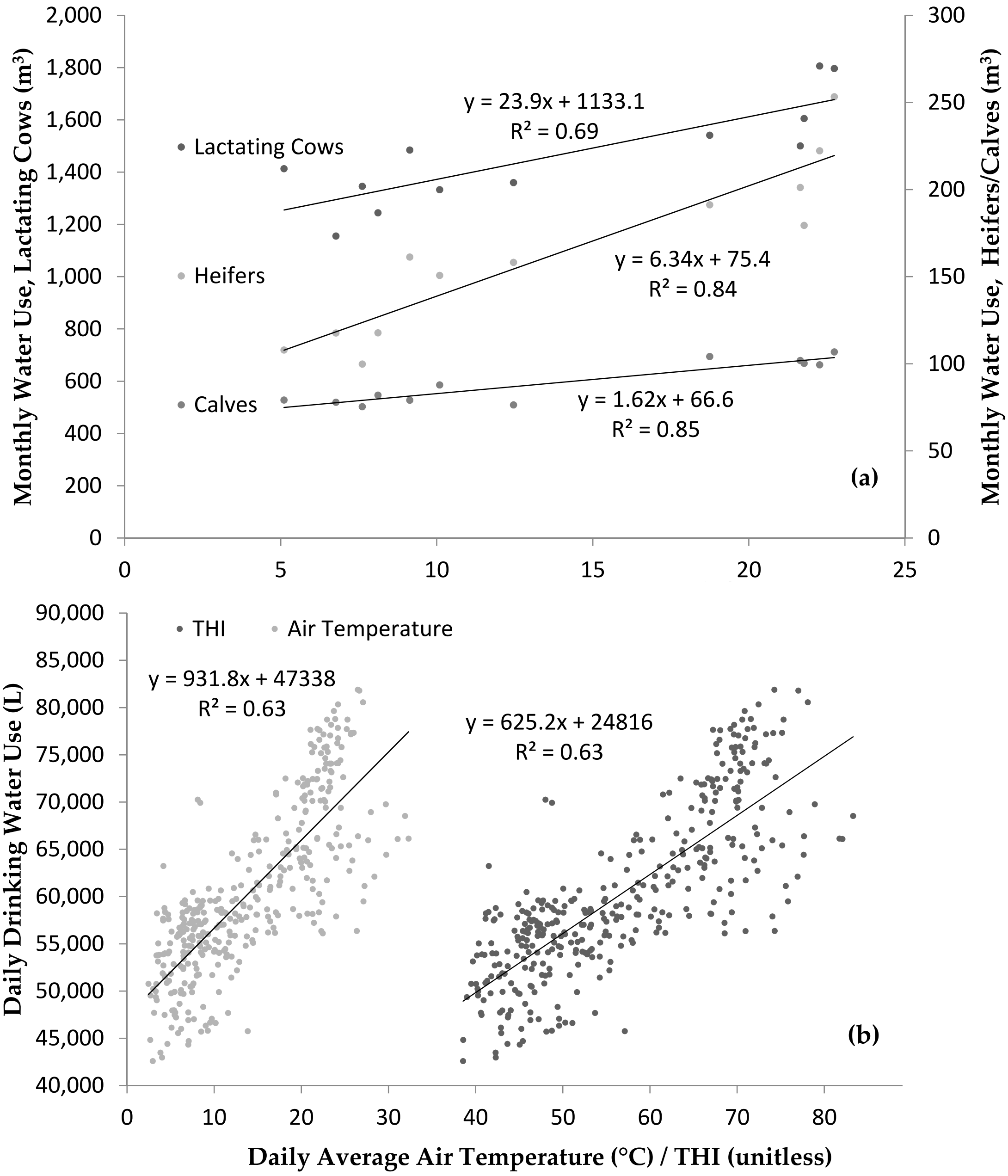

Figure 5. (**a**) Average monthly air temperature (°C) plotted against average monthly water consumption (m^3) for lactating cows, heifers and calves. (**b**) Total daily drinking water use (L) plotted against THI (unitless) and average daily air temperature (°C).

3.4. Parlour Wash

The average daily use of the parlour wash was 12,160 ± 1741 L, of which, according to the sanitization protocol, 2560 L was used in the daily washing procedure of the milk pipeline and bulk tank. Of the remaining 9600 L, ~4300 L was used by a high-volume hose for parlour floor cleaning. We can express the final 5300 ± 759 L as 4.2 ± 1.8 L for each cow cleaning instance.

3.5. Recycling Milk Pre-Cooling Water (Plate Cooler)

The plater cooler flow rate was 0.5 L s^{-1} (during milking periods) and corresponded to a daily water use of ~2× the daily milk production, which is in the range of the recommended water:milk plate cooler ratio [24]. Plate cooler flow discharged into the primary reservoir. However, while in use, the plate cooler flow exceeded drinking water consumption and exceeded the reservoir capacity. As a result, 12,702 ± 7900 L overflowed from the primary reservoir into wastewater daily, on average (i.e., overflowed and entered the manure storage). This study observed the effect that plumbing design can have on water conservation. Due to a plumbing change, the daily plate cooler waste increased from 3801 ± 3403 L to 15,604 ± 6685 L. Prior to the change, most of the water destined to the main barn water troughs was drawn through meter 4, from the primary reservoir (into which the plate cooler water was returned). After the change, most of the water was drawn from another line through meter 5, reducing demand on the primary reservoir. As a result, the capacity to reuse plate cooler return water as drinking water was severely reduced, leading to the observed ~11,800 L increase in daily plate cooler waste. This illustrates that plumbing changes in a dynamic farm environment can have unintended effects on seemingly unrelated water components.

Effective plumbing design for plate cooler water recycling should account for water supply and demand dynamics. The plate cooler operates during periods when drinking water demand was lower due to cow movement from the free stall areas into the milk parlour or adjacent holding area (Figure 6). While in use, hourly flow for the plate-cooler into the primary reservoir was ~1719 L h^{-1}, whereas the draw from this reservoir was <500 L h^{-1} at times. Therefore, plate-cooler reservoirs must be designed to handle the intra-day water supply and demand, which are not apparent from typical "guidelines" for water use like Table 3. In other words, the average daily flow is not equally distributed throughout the day, but rather concentrated in short periods of very high flow.

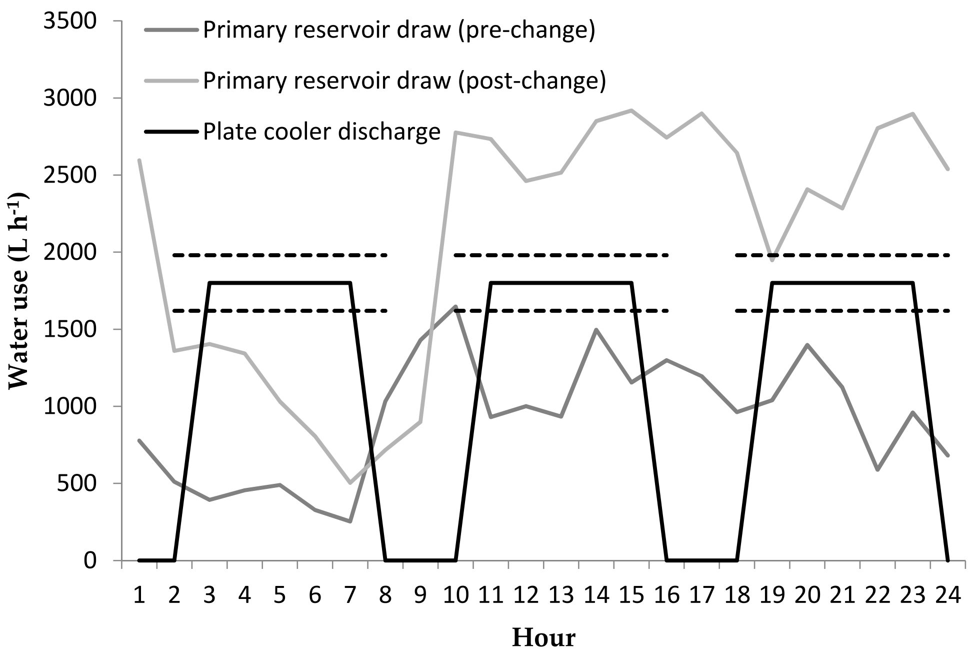

Figure 6. Typical day showing hourly water draw from primary reservoir (L) (*pre-* and *post-* change in plumbing design) and milk pre-cooling water use based on the average flow rate (L) ± 1 SD (dashed lines) at times of operation (0300 h, 1100 h, and 1900 h milking times). Water is wasted as overflow when the plate cooler discharge exceeds the primary reservoir draw.

3.6. Milk Dynamics

The average days in milk (DIM) for the monitoring period was 178 day and the monthly average DIM was slightly greater in the fall and winter months compared to the summer months (Figure 2b). The total milk produced over the year was 5366 t, which converts to 5150 t FPCM. Milk per cow and FPCM per cow were highest in March and April. The lowest per cow production months were October and December for milk and August and September for FPCM (data not shown). Despite these temporal trends, no obvious link between average monthly milk/FPCM production per cow (kg) and average monthly temperature (°C) were observed. However, the total milk fat and protein percentage was negatively correlated with average monthly air temperature (milk fat + protein = $-0.0227 \times T_a + 7.27$, $R^2 = 0.67$, data not shown). This finding is consistent with a previous study of milk fat and protein dynamics in Ontario [25].

The WF scaled by milk production was 6.19 L kg^{-1} milk (6.41 L kg^{-1} FPCM), including contributions from all animal groups and 5.34 L kg^{-1} milk (5.54 L kg^{-1} FPCM) when excluding the water consumption of replacement animals and dry cows. This is higher than the figures determined by Drastig et al. [10] and Capper et al. [9] in their modelling studies.

3.7. Water Conservation Scenarios

In this section a series of water conservation exercises are explored to estimate potential savings. The predicted effect on water consumption of decreased average barn air temperature was modelled based on the relationship between total monthly drinking water use to temperature:

$$W = 33.85 \times T_{a,m} + 1372.1, \tag{5}$$

where W is the predicted total monthly water use (m^3) and $T_{a,m}$ is the average monthly air temperature (°C) (RMSE = 121, $R^2 = 0.77$, $p < 0.001$).

In months where $T_{a,m}$ exceeded 18 °C, the measured total monthly water use was replaced with the predicted total if the average monthly temperature was decreased by 2 °C. This analysis showed that if the average barn air temperature were to be maintained at 2 °C lower without the aid of additional water, 351 m^3 of water could be saved annually. Cows regulate their water consumption along with feed intake [15], which affects milk production [26]. When heat stress is a factor, cows may decrease their feed intake and milk production while at the same time increasing their water intake, amplifying the effect on the milk water footprint (i.e., non-productive increase in water consumption). Maintaining cooler temperature may therefore have beneficial effects on milk production, which we did not account for here. Strategies such as better ventilation [27] or lower stocking density [28] can be used to lower ambient air temperatures without the use of additional water. Both of these strategies may increase the cost of operation, however, increased cow comfort can have a positive effect on milk production, which may balance out these additional costs.

If the plate cooler water and other water losses were fully recycled instead of wasted to manure storage, an additional 4882 m^3 in water savings could be achieved. Some researchers have noted that water reuse is currently the most common water saving strategy employed by the farms they surveyed. As the most impactful strategy, considering 55% of surveyed farms did not employ water reuse strategies, there is still a large capacity for water savings industry-wide [18]. The costs associated with proper recycling may include whole farm plumbing survey and design by qualified professionals with or without additional one-time costs such as increasing the holding capacity of the water delivery systems. It is worth noting that after this study, farmers increased the primary reservoir capacity to increase reuse of plate-cooler water.

As was reported in an earlier section, 5300 L day^{-1} of water was used for cow preparation, which represents 4.2 ± 1.8 L for each cow cleaning instance. According to the literature, moist towel cow preparation can be conducted with only 1.9 L per cow preparation [29], therefore, the water use for cow preparation can theoretically be reduced to ~2400 L day^{-1} if the moist towel cow preparation method was optimized for water efficiency, thereby potentially saving 1061 m^3 annually. Here again, optimizing the cow milking procedure may increase the operational cost by increasing the time requirement per milking event.

Combining all of these strategies could lead to a total potential saving of 6229 m^3 annually, a 19% reduction of the annual water use, and reduce the milk production water footprint to 4.18 L kg^{-1} milk (excluding replacement animals) (Table 4).

Table 4. Theoretical water conservation scenarios and their expected effect on milk production water footprint (WF).

No.	Water Saving Strategy	Annual Farm Water Consumption m^3 $year^{-1}$	Reduction %	WF Including Replacements L kg^{-1} Milk (FPCM †)	WF Excluding Replacements L kg^{-1} Milk (FPCM †)
1	Current water use	33,032	-	6.19 (6.41)	5.34 (5.54)
2	2 °C decrease in air temperature	32,682	1.1	6.12 (6.35)	5.28 (5.47)
3	Reduce cow preparation water requirement	31,971	3.2	5.99 (6.21)	5.14 (5.33)
4	Recovery of water losses	28,208	14.6	5.29 (5.48)	4.44 (4.60)
5	Combination of strategies 2–4	26,796	18.9	5.02 (5.20)	4.17 (4.33)

Note: † L kg^{-1} fat-and-protein corrected milk (FPCM) is given in brackets.

In scenario 5 (Table 4), drinking water represents 82% of the total water use, which closely resembles values reported by Drastig et al. [10]. By accurately measuring and partitioning water use our results help to validate the water modelling methods used by previous studies. However, our results also highlight the reality of on-farm blue water waste, which would not be considered by existing theoretical models.

Feed dense in energy and protein are necessary for high milk yields [14] and DMI intake is positively correlated to drinking [15]. Therefore, there is limited potential to alter feed intake for the sake of water conservation without negatively affecting milk production. Reducing mild heat stress and minimizing the size of the replacement herd offer some limited potential for conserving drinking water to meet water conservation goals on dairy farms. These scenarios demonstrate that the non-drinking components of dairy farm water use can be optimized. This was also demonstrated in a case study by Brugger and Dorsey [30], who audited and optimized the water usage on a ~1000 cow dairy. By correcting several sources of waste (leaks, plate cooler flow rate, and cleaning protocol) they were able to conserve ~30,000 m^3 annually.

4. Conclusions

Dairy farm operations withdraw appreciable quantities of sub-surface blue water. Some water savings can be achieved through reducing cow drinking by optimizing cow comfort (i.e., reducing barn temperature). The largest potential for water savings observed in this study was related to improving plumbing design to collect, store and re-use cooling water. The dairy industry is unique in that a greater portion of processing takes place at the farm level. Process optimization to reduce water use practiced in other industrial settings is not well established within the dairy industry framework and this research illustrates that there is potential benefit from such optimization. A measure of the proportion of total water used as drinking water could be used as an indicator of milk production efficiency. For instance, farms where drinking water contributes <80% of the total water use may be operating at a sub-optimal level, from a water efficiency point of view. We know that many dairy farmers are already taking steps to implement water saving strategies on their farms [18]. An industry or government sponsored water use assessment program could identify potential water savings and help selecting water-saving strategies from a cost–benefit point of view.

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