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The Water Footprint of Pastoral Dairy Farming: The Effect of Water Footprint Methods, Data Sources and Spatial Scale †

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Abstract: The water footprint of pastoral dairy milk production was assessed by analysing water use at 28 irrigated and 60 non-irrigated 'rain-fed' pastoral dairy farms in three regions of New Zealand. Two water footprint methods, the WFN-based blue water footprint impact index ($WFII_{blue}$) and the Available WAter REmaining (AWARE) water scarcity footprint (WF_{AWARE}), were evaluated using different sets of global or local data sources, different rates of environmental flow requirements, and the regional or catchment scale of the analysis. A majority (~99%) of the consumptive water footprint of a unit of pastoral dairy milk production (L/kg of *fat- and protein-corrected milk*) was quantified as being associated with green and blue water consumption via evapotranspiration for pasture and feed used at the studied dairy farms. The quantified $WFII_{blue}$ (-) and WF_{AWARE} (m^3 world eq./kg of *FPCM*) indices ranked in a similar order (from lowest to highest) regarding the water scarcity footprint impact associated with pastoral dairy milk production across the study regions and catchments. However, use of the global or local data sets significantly affected the quantification and comparative rankings of the $WFII_{blue}$ and WF_{AWARE} values. Compared to the local data sets, using the global data sets resulted in significant under- or overestimation of the $WFII_{blue}$ and WF_{AWARE} values across the study regions and catchments. A catchment-scale analysis using locally available data sets and calibrated models is recommended to robustly assess water consumption and its associated water scarcity impact due to pastoral dairy milk production in local catchments.

Keywords: agriculture; livestock farming; dairy milk production; dairy water use; sustainable development; water footprint; water scarcity

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1. Introduction

Globally, a large portion of available land and water resources are used for agriculture, including the production of livestock products. There is an increasing focus on improving agricultural water use to help achieve productive food production systems with reduced impacts on freshwater environments. This requires a robust quantification and assessment of water use in different agricultural production systems to help identify potential mitigation measures. Water footprinting has been developed and increasingly applied to quantify and compare the water use of different agricultural products and processes across different regions for promoting water use efficiency and to help achieve productivity and sustainable water resource management in agricultural production systems, including dairy milk production [1–7]. However, several water footprint methods have been developed, including the Water Footprint Network (WFN)-based consumptive water footprint method [8] and the life cycle analysis (LCA)-based environmental impact-oriented water footprint indicators based on water stress or scarcity characterisation factors to differentiate water use in areas of different water availability [9–12]. The proposed water footprinting methods differ in their consideration or not of different water flows and use in their accounting of water consumption and in the application of water stress or scarcity indices for the characterisation of consumptive water footprints as water scarcity impact footprints [8–13].

The WFN method accounts for 'green' rainfall and 'blue' (surface and groundwater) water consumption to quantify consumptive water footprints [8]. Then, it uses green and blue water scarcity (including environmental flows) to assess the water scarcity footprint impact associated with a product or process [8]. On the other hand, the Water Use in Life Cycle Assessment (WULCA) group proposed a method based on the Available WAter REmaining (AWARE) model to quantify and assess the blue water scarcity footprint associated with a product or processes within a catchment [14]. Recently, the FAO Livestock Environmental Assessment and Performance (LEAP) Partnership suggested a consistent application of water productivity and water scarcity impact metrics for assessing water use in livestock production systems and supply chains [15,16].

Researchers have conducted several water footprint studies on dairy milk production in different countries [1–7]. However, these studies have used different water footprint methods, data sources, and analysis scales, making most water footprint assessments incomparable. Moreover, there have been limited studies applying and evaluating the effects of different water footprint methods on the quantification of water footprints of pastoral dairy farming across semi-humid environments such as New Zealand.

Zonderland-Thomassen and Ledgard [7] assessed the water footprint of pastoral dairy farming in New Zealand, quantifying the consumptive water footprint using the WFN method [8] and the stress-weighted blue water footprint using the water stress index (WSI) to characterise consumptive blue water footprints, as suggested by Ridoutt and Pfister [13]. This study, however, did not include the AWARE method [14], recently recommended by the FAO LEAP for assessments of water use in livestock production systems and supply chains [15,16]. Also, Zonderland-Thomassen and Ledgard [7] used global data sets, where no local data were available. A lack of locally measured data occurs in many water footprint studies, in which case, the life cycle inventory databases (such as Ecoinvent, Agrifootprint, Quantis, WaterStat, SimaPro, etc.) are generally used to calculate the water footprint of agricultural products in different countries or regions [17]. 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, lacking consideration of local conditions [17]. Using existing databases requires fewer resources, as they are often provided or modelled within the database. However, existing water footprint methods have developed global layers of water scarcity characterisation factors (*CF*s), such as the WFN [18] and AWARE methods [19]. The global *CF* layers have been calculated using existing global data or models, e.g., the WATERGAP model [20] used to develop the global layer of the AWARE factors [14,19], and other databases used to develop the global layers of water scarcity levels [18,21,22]. There is, so far, limited research available on the evaluation of the potential effects of using locally measured or globally existing data sets, the sensitivity of environmental flow requirements, and regional- or catchment-scale analysis on the quantification of the water scarcity footprints of livestock production systems in semi-humid climatic conditions such as New Zealand.

Higham et al. [23,24] measured and quantified water use on irrigated and non-irrigated 'rainfed' pastoral dairy farms across different regions of New Zealand. They highlighted a significant spatial and temporal variation in water use across dairy farms in different regions in New Zealand. Water availability and environmental flow requirements also vary across different catchments and regions [18,22]. This poses another question of the possible effects of different spatial scales considered for the quantification and assessment of the water scarcity impacts of pastoral dairy farming in agricultural landscapes. Therefore, this study aimed to (a) quantify the water scarcity footprints of different types (irrigated and non-irrigated) of pastoral dairy farms in three different regions of New Zealand, and (b) assess the effects of using local and global data sets or models, different spatial scales of analysis, and environmental flow requirements on the resulting consumptive and water scarcity impact footprints of pastoral dairy milk production in New Zealand. As per the recent recommendations in the FAO LEAP guidelines [15,16], two water footprint methods, the WFN-based blue water footprint impact index ($WFII_{blue}$) [8] and the available water remaining-characterised water scarcity footprint (WF_{AWARE}) [14], were applied and evaluated to quantify and assess the water scarcity impact footprints of pastoral dairy farming in the study catchments and regions. This study aims to inform the further development and consistency of water footprinting methodology, procedures, protocols, and databases to develop a robust quantification and assessment of the water footprints of livestock production systems, especially pastoral dairy milk production in New Zealand and similar climatic conditions in other parts of the world.

2. Methods and Material

2.1. Location and Farming Details of the Studied Farms

A total of 28 irrigated and 60 non-irrigated 'rain-fed' pastoral dairy farms were analysed in different regions of New Zealand. Table 1 summarises average descriptions of the farms involved in this study. The farms were located in three regions with different climatic conditions across New Zealand (Figure 1). The Waikato region is the furthest north, receiving adequate rainfall (>1000 mm yr^{-1}), so pastoral dairy farming in this region is dominated by non-irrigated dairy farms (Table 1). There are some irrigated dairy farms in the region. They 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 three irrigated (~396 ha) and 42 non-irrigated (~7224 ha) dairy farms, representing 1.6% of the total dairy ha in the Waikato region.

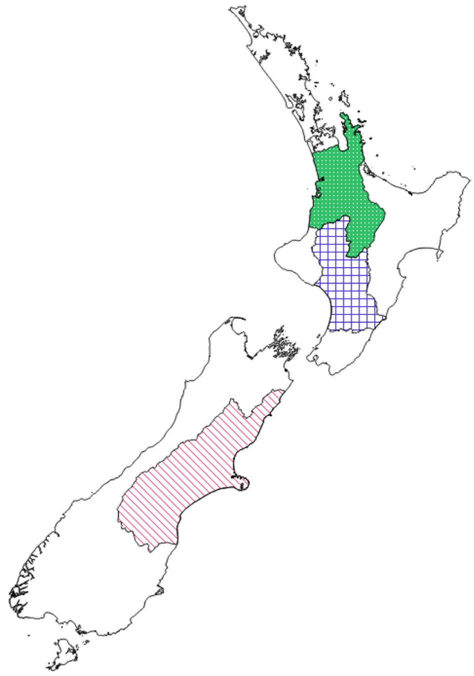

Figure 1. Map of New Zealand, showing locations of the study regions: the Canterbury region (diagonal lines), the Manawatu region (squares), and the Waikato region (solid fill).

The Manawatu region is located further south of the Waikato region (Figure 1) and is divided by a mountain range in between. The south-east areas of the Manawatu region receive adequate rainfall (>1000 mm yr^{-1}), where pastoral dairy farms are mainly non-irrigated 'rain-fed'. The south-west area of the Manawatu region receives relatively low rainfall (<1000 mm yr^{-1}), where the irrigated pastoral dairy farms are mainly located. We selected five 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 the Manawatu region are mainly located on sandy coastal soils and operate with lower stocking rates than farms in the rest of the region (Table 1). The Canterbury region is the furthest south of the farms investigated. They lie east of the Southern Alps mountain range in an area of low rainfall (<700 mm yr^{-1}). Pastoral dairy farms in the Canterbury region are mostly irrigated, as the rainfall is insufficient to sustain adequate grass growth year-round. We selected 20 irrigated (~4240 ha) pastoral dairy farms, representing 1.5% of the total dairy ha in the Canterbury region.

The farms' data were collected from individual farms through a questionnaire. The collated data included records of the grassland area, stocking rates, brought-in feed, and farm milk production for two years from 2013 to 2015 (Table 1).

Table 1. Average characteristics of the pastoral dairy farms (during two years from 2013 to 2015) studied 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/yr	5224	5796	5052	5339	5263
Electricity use on-farm	kW h/ha/yr	482.5	559.70	482.5	564.98	608.3
Brought-in maize silage	kg DM/ha/yr	1120	1200	1130	1030	1530
Brought-in pasture silage	kg DM/ha/yr	0	0	0	0	1530
Brought-in palm kernel expeller	kg DM/ha/yr	2800	2100	2000	1800	0
Barley grain	kg DM/ha/yr	0	0	0	0	1190
Wheat grain	kg DM/ha/yr	0	0	0	0	1200
Annual rainfall	mm/ha	1053	1074	1030	857	637
Applied irrigation	mm/ha/yr	0	250	0	417	658
Irrigated Area	ha/farm	0	81	0	238	212
% irrigated	%	0	61	0	66	100

Note: * *fat- and protein-corrected milk.*

Figure 2 presents a schematic of the water flows within the farm system boundaries for raw milk production and water use on a pastoral dairy farm platform. In this study, we analysed the water footprints of the studied dairy farms (Table 1), with the scope limited to the direct use of water at the farm and the indirect use of water for imported feed. Water use outside the farm gate, including transport, processing, fertiliser production, and electricity use, was not considered. Water use for the processes excluded here was estimated to be much smaller than direct water use [7]. However, the indirect blue water evaporative losses associated with electricity and fertilisers could be relatively higher than the blue water used directly on non-irrigated dairy farms in the Waikato region [7].

This study specified the function unit as one kilogram of energy-corrected milk, i.e., milk corrected for fat and protein (*FPCM*). The *FPCM* (Equation (1)) was calculated using the recorded milk production per day [25,26], as follows:

$$Fat\ and\ Protein\ Corrected\ Milk\ (FPCM) = milk\ per\ day\ (kg) \times \frac{[(383 \times fat\ \%) + (242 \times protein\ \%) + 783.2]}{3.14} \quad (1)$$

The average *FPCM* was calculated for both the irrigated and non-irrigated farms in each region in further analyses. The estimated water use was divided between milk and meat production using economic allocation criteria [8], with 92% of the water use allocated to milk production and the remainder to meat production [7].

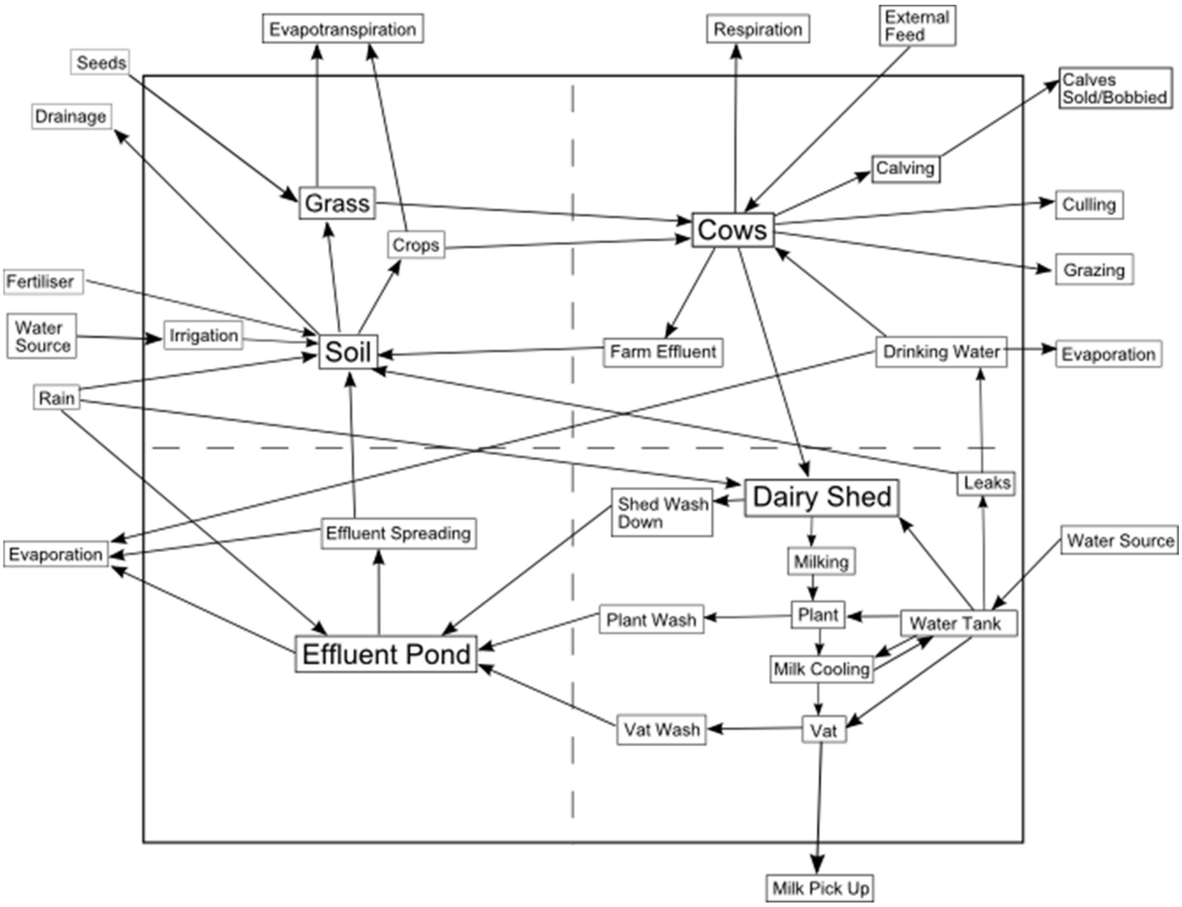

Figure 2. Schematic of water flows on a pastoral dairy farm system in New Zealand.

2.2. Water Footprint Methods

Water footprinting methods have been developed to account for green, blue, or grey water types [8,10], where green water is defined as the rainfall water use that is held within the soil profile and used by the plants. Blue water is stored and used from groundwater and surface water resources. Grey water is defined as the volume of water required to assimilate a contaminant load to the accepted (standard) level in receiving water bodies [8]. Water footprint methods also account for direct and indirect water uses for a product or process. Direct water use is the water used directly in producing a product, such as green water from rainfall and blue water from irrigation used to grow pasture or feed crops on pastoral dairy farms. Indirect water use is defined as water used indirectly, like in manufacturing fertiliser and producing the electricity used on the farm.

In this study, the direct water footprint is calculated as the green and blue water (m^3) consumed to produce 1 kg of *FPCM* at the studied irrigated or non-irrigated dairy farms across the study regions (Table 1). The indirect water footprint included the green and blue water consumed in imported feed considered to be produced locally. Further, the consumptive blue water footprint volumes (m^3/kg of *FPCM*) were multiplied with the quantified water scarcity characterisation factors at the regional or catchment level to quantify blue water scarcity footprint indices to produce 1 kg of *FPCM* at the studied farm types (Table 1).

This study applied two water footprint methods, the WFN-based blue water footprint impact index ($WFII_{blue}$) [8] and the available water remaining (AWARE)-characterised water scarcity footprint (WF_{AWARE}) [14], described as follows.

2.2.1. Quantification of Consumptive Green and Blue Water Footprints

The WFN method accounts for the consumption of green and blue water used to produce a product [8]. The consumptive green water footprint, WF_{green} (m^3/kg of *FPCM*), of the studied dairy farms was calculated using Equation (2) as follows:

$$WF_{Green} = \frac{ET_{green}}{Yield_{FPCM}} \tag{2}$$

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

The quantification of the blue water footprint included the estimates of the evapotranspiration (ET_{blue}) (m^3/ha) from irrigation water of the pasture and feed produced on the farm and feed imported. It also included the water used (m^3/ha) for stock drinking (*SDW*) and milking parlour washing (*MPW*) at the farm. In pastoral-based dairy farms across New Zealand, the *SDW* and *MPW* are applied to pastural land as effluent applications, which is 'consumed' by pasture at the farm through evapotranspiration (Figure 2). Therefore, the consumptive blue water footprint, WF_{blue} (m^3/kg of *FPCM*), [8] for the studied dairy farms was calculated using Equation (3) as follows:

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

2.2.2. Blue Water Footprint Impact Index ($WFII_{blue}$)

As per the WFN method [8], the consumptive WF_{blue} (m^3/kg of *FPCM*) (Equation (3)) was further multiplied by the blue water scarcity (WS_{blue}) (-), calculating the blue water footprint impact index ($WFII_{blue}$) (-), as follows:

$$WFII_{Blue} = WF_{blue} \times WS_{blue} \tag{4}$$

where WS_{blue} is the blue water scarcity, defined as the ratio of the total blue water consumed ($\sum WF_{blue}$) to the total blue water available (WA_{blue}) in the geographical region [8], as follows:

$$WS_{blue} = \frac{\sum WF_{blue}}{WA_{blue}} \tag{5}$$

where the WA_{blue} is defined as the natural runoff (R_{nat}) minus the environmental water requirements (*EWRs*) [8], as follows:

$$WA_{blue} = R_{nat} - EWR \tag{6}$$

WS_{blue} becomes 1 when all available blue water has been used, significantly affecting the *EWRs* in the region [8]. The calculated $WFII_{blue}$ (Equation (4)) is suggested to differentiate the water scarcity impacts of blue water consumption in the production of a product in areas of differing water resources [8,16,18].

2.2.3. The AWARE Method Water Scarcity Footprint (WF_{AWARE})

The AWARE method only accounts for the consumption of blue water and does not assess green water use [14]. This method calculates blue water availability minus demand (AMD_i) as a factor to characterise the blue water consumption of 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 water requirement (*EWR*) from the available water (natural runoff including flow regulation) [14], as follows:

$$AMD_i = \frac{(Availability - HWC - EWR)}{Area} \tag{7}$$

The characterisation factor (CF_{AWARE}) for a region is then calculated as the inverse of AMD_i normalised by dividing the $AMD_{worldaverage}$, as follows:

$$CF_{AWARE} = \frac{AMDworldaverage}{AMD_i} \quad (8)$$

The CF_{AWARE} factor is dimensionless, expressed in m^3 world eq./m^3i, representing a relative value of the environmental impact scope of water consumption in a region [14]. The maximum value of CF_{AWARE} is suggested to be set at 100, where either water demand is greater than water availability, resulting in AMD_i being a negative value and Equation (8) losing its meaning, or $AMD_i < 0.01 \times AMD_{worldaverage}$. The minimum value of CF_{AWARE} is also suggested to be set at 0.1, where $AMD_i > 10 \times AMD_{worldaverage}$. These constraints result in CF_{AWARE} ranging from 0.1 to 100 to characterise the blue water consumption volumes based on local water stress conditions [8].

Boulay et al. [14] calculated AMD_i and $AMD_{worldaverage}$ values using the monthly water data from the WATERGAP model [20] on a 0.5 by 0.5 degree grid at a global scale. However, there was lack of relevant data sets to robustly quantify AMD_i on a monthly basis at the local scale (Table 2). Therefore, in this study, we multiplied the $AMD_{worldaverage}$ (at 0.0136 m^3/m^2-month) by 12 to calculate and apply the average annual CF_{AWARE} factor (Equation (8)) using the available annual water flows in the study regions and catchments.

Table 2. Summary of global and local data sources used in quantification of water footprints of the studied pastoral dairy farms (Table 1) 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 [27].	The National Institute of Weather and Atmosphere Virtual Climate Station Network [28].
Effective rainfall (P_{eff})	USDA Soil Conservation Service method [29].	
Crop coefficients (K_c)	Crop coefficients [30,31].	Crop coefficients [30,31].
Green water consumption (ET_{green})	A minimum of ET_c and P_{eff} [8].	A locally developed soil water balance model [32], using local climatic and soil conditions.
Irrigation water consumption (ET_{blue})	Difference between crop water requirements ET_c and ET_{green} [8,30].	The minimum of the difference between the locally modelled ET_c and ET_{green} [32] for pasture growth and maize silage, and the difference between crop water requirements ET_c and ET_{green} [8,30] 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 [31].	Based on globally average green water volume used to produce palm kernel expeller [31].
Imported crops	Imported crops based on the Waikato and Canterbury regions from 2004 to 2005 [7].	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 [7].	Locally measured stock drinking water [23,24].
Milking parlour water use (*MPW*)	Estimated milking parlour water use [7].	Locally measured milking parlour water [23,24].
Available water (*WA*)		A locally calibrated and validated rainfall–runoff model [33].
Environmental Water Requirements (*EWRs*)		Based on local water allocation limits in the Waikato region. Environmental requirements of 37% were used as suggested for New Zealand [7,34].
Water abstractions (*WU*)		Locally recorded water allocations and actual water abstraction estimates from Aqualinc [35].

Table 2. *Cont.*

Parameter	Global Data Source	Local Data Source
Water consumption (*HWC*)		Locally estimated actual water abstractions from Aqualinc [35] and consumptive water fraction from Shiklomanov and Rodda [36].
$WULCA—CF_{AWARE}$	Global layer [19].	Calculated from the locally sourced data listed in this table.
$WFN—WS_{blue}$	Global layer [18,37].	Calculated from the locally sourced data listed in this table.

The water scarcity footprint metric (WF_{AWARE}), expressed in m^3 world eq., was then calculated by multiplying the consumptive WF_{blue} (m^3/kg of *FPCM*) (Equation (3)) with the corresponding CF_{AWARE} factor (Equation (8)) for each region, as follows:

$$WF_{AWARE} = WF_{Blue} \times CF_{AWARE} \tag{9}$$

The calculated WF_{AWARE} (Equation (9)) is suggested to differentiate the water scarcity impact of blue water consumption in producing a product in areas of differing water resources [14,16].

2.2.4. Data Sources and Spatial Scale

The data required for applying the above-described two water footprint methods, $WFII_{blue}$ (Equation (4)) and WF_{AWARE} (Equation (9)), were collected from different databases, models, and measurement sources, categorised as global or local data sources (Table 2).

The analysis was further carried out considering two different spatial scales, the regional and catchment scales. The regional scale considers the entire region (Figure 1), with many different catchments and water management zones within a similar climatic condition. The catchment or water management zone scale is the hydrological area where all water flows to one major waterway or water body in the area.

The study data collection and analysis were conducted for two (2) years from 1 June 2013 to 31 May 2015 (Table 1). The green and blue water evapotranspiration (ET_{green} and ET_{blue}) were quantified for the on-farm pasture production over the entire year and the imported feed over the growing period for the individual crops (Table 1).

Global Data Sources

In the case of global data sources (Table 2), the green water consumption in pasture and feed 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 [27]. The global CLIMWAT 2.0 database [27] 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 with a crop coefficient (K_c) of 1.05 [29] to calculate the potential evapotranspiration (ET_C) for pasture production in different regions. Effective precipitation was calculated using monthly precipitation (P) collected from CLIMWAT 2.0 [27]. The USDA Soil Conservation Service method [29] was applied over a ten-day time step to quantify precipitation (P_{eff}), as follows:

$$P_{eff} = P\frac{\left(\frac{125}{3}\right) - 0.2 \times P}{\left(\frac{125}{3}\right)} for\ P \leq 83.3\ \text{mm}/10\ \text{days}\ period \tag{10a}$$

$$P_{eff} = \left(\frac{125}{3}\right) + 0.1\ for\ P > 83.3\ \text{mm}/10\ \text{days}\ period \tag{10b}$$

The ET_{green} for pasture production was then calculated as the minimum of the P_{eff} and the crop-specific evapotranspiration (ET_c) [8,30], as follows:

$$ET_{green} = \min\left[ET_c, P_{eff}\right] \tag{11}$$

The ET_{green} for imported feed was also calculated over the growing period for the individual crops detailed in Table 1. The ET_{green} of locally imported pasture silage, maize silage, barley, and wheat was quantified (Equation (11)), assuming their growth under local climatic conditions. The feed crops imported into the Canterbury region were assumed to be grown under irrigation. In contrast, the feed crops imported in the Waikato and Manawatu regions were assumed to be rain-fed grown. The ET_{green} for each locally produced crop (ryegrass pasture silage, maize silage, wheat, and barley) was calculated (Equation (11)) using the estimates of the average monthly ET_0 and effective precipitation (P_{eff}) from CLIMWAT 2.0 [27,29]. The crop coefficient (Kc) values for the imported crops (ryegrass pasture silage, maize silage, wheat, and barley) were taken from [30,31]. The irrigation water consumption (ET_{blue}) was calculated as the deficit between ET_c and ET_{green} [8,30], as follows:

$$ET_{blue} = \left(ET_c - ET_{green}\right) \tag{12}$$

The quantified ET_{green} and ET_{blue} for pasture and locally produced feed crops (mm/ha) (Equations (11) and (12)) were then converted to WF_{green} and WF_{blue} (L/kg of *FPCM*) by using the average stocking rate and milk production on the studied farms (Table 1). The total WF_{green} of feed at the study dairy farms was calculated by summing all the individual green water footprints of imported and farm-grown feed inputs (Table 1). The WF_{green} of palm kernel expellers (palm kernel cake, *PKE*) was taken from Chapagain and Hoekstra [31].

The WF_{blue} was estimated as the total of the irrigation water evapotranspired (ET_{blue}) and the consumptive fractions of the *MPW* and *SDW* used on the farms. The *MPW* and *SDW* were calculated from generic industry volumes (70 L/cow per day for MPW; 70 L/cow per day for *SDW*) for the lactating and non-lactating periods of the year [7]. The *SDW* and *MPW* were further corrected as a 78% consumptive 'evapotranspired' fraction of the total *SDW* and *MPW* used on the farm [36].

Global data sets of the WS_{blue} and CF_{AWARE} characterisation factors (Equation (5) and Equation (8), respectively) were downloaded as geographic data layers developed by Mekonnen and Hoekstra [37] and WULCA [19], respectively. The global WS_{blue} and CF_{AWARE} data layers were overlaid onto the studied regional and catchment boundaries (Figure 1) to calculate and use the average values of WS_{blue} and CF_{AWARE} factors for the characterisation of the quantified WF_{blue} into $WFII_{blue}$ (Equation (4)) and WF_{AWARE} (Equation (9)) indices, respectively, for a kg of *FPCM* produced at the studied irrigated farms across the study regions and catchments.

Local Data Sources

In the case of local data sources (Table 2), the ET_{green} and ET_{blue} were calculated for representative irrigated and non-irrigated conditions at the studied farms (Table 1). A locally developed soil water balance model [32] was applied to quantify ET_{green} and ET_{blue} for pasture production at each site. In this model, evapotranspiration (E_t) is quantified as a function of local climatic conditions (potential evapotranspiration, $E_{t,w}$) and soil water storage (S), where a and b are locally calibrated constants for a soil type, as follows:

$$E_{t,s} = (a + bS)\ and\ E_t = E_{t,w}\ \ if\ \ E_{t,w} < E_{t,s} \tag{13}$$

The soil profile available water values were taken from S-Maps [38], a locally developed soil database (https://smap.landcareresearch.co.nz/; accessed on 1 June 2017). The local climate data were collected from the Virtual Climate Station Network (VCSN) (https://data.niwa.co.nz/#/home; accessed on 1 June 2017). The VCSN takes data from locally observed meteorological stations throughout New Zealand and interpolates the data over a 5 × 5 km grid for all of New Zealand [28].

However, the ET_{green} and ET_{blue} for locally produced feed crops (pasture silage, barley grain, and wheat grain), excluding PKE, were calculated as per Equation (11) and Equation (12), respectively, using the local climate data from the VCSN database [28]. In this case, the reference evapotranspiration, ET_o, was calculated using the FAO-56 method [30] and crop coefficient (*Kc*) values for feed crops (ryegrass pasture silage, maize silage, wheat, and barley) taken from Allen et al. [30] and Chapagain and Hoekstra [31]. In the Canterbury region, it was assumed that all feed grown was irrigated and that the climate was the same as the studied farms. In the Manawatu and Waikato regions, it was assumed that all feed crops were rain-fed and grown in a climate equivalent to the local farms.

The *SDW* and *MPW* were calculated from detailed on-farm water meter recordings at the studied farms, except the irrigated dairy farms in the Waikato region [23,24]. The *MPW* and *SDW* on the Waikato irrigated dairy farms were not directly measured but calculated from locally developed models by Higham et al. [23,24]. As in the case of the global data, a fraction of 78% (based on Shiklomanov and Rodda [36]) was applied to calculate the consumptive fraction of the *SDW* and *MPW*, considering its discharge as an effluent applied to pasture land at NZ pastoral dairy farms.

The locally available hydrological data and models were used to quantify WS_{blue} (Equation (5)) and CF_{AWARE} (Equation (8)) 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 using a locally calibrated and validated model from 1960 to 2006 [33]. The total water consumption (*HWC*) was calculated from the recorded average annual water allocations and estimates of actual water abstraction and fractions consumed in the study regions and catchments. In New Zealand, the Regional Councils require consent for water abstraction for public water supply and industrial and agricultural water use in their regions [39]. Regional Councils supplied the total consented water for different purposes (drinking, industrial, and agricultural) in the study regions and catchments during the study years (2013–15). Based on the locally published data and information available [35,39], the water abstraction (withdrawal) rates of the allocated water locally were estimated at 55% for the Canterbury region, 28% for the Manawatu region, and 38% for the Waikato region. Estimates of actual water consumption fractions for agriculture (0.78), industrial use (0.10), and public supply (0.13) were used to calculate the amounts of water consumed from the estimated water abstraction [36]. Any local records of water transfers for hydroelectricity generation to and from the study regions were collected directly from the power companies. These water transfers were considered a net gain of available water for the receiving region and a consumptive take in the region losing the water.

The quantification of WS_{blue} (Equation (5)) and AMD_i (Equation (7)) also requires estimates of environmental water requirements (*EWRs*) in a region. However, there are different methods and considerable ranges in *EWR* estimation [7,8,14,40]. Therefore, we used a range of *EWR*s for the WS_{blue} and AMD_i methods to analyse their effect on the resulting blue water footprint impact indices, $WFII_{blue}$ and WF_{AWARE}, for pastoral dairy milk production in the study regions and catchments. The *EWR* rates were set at 37% of the mean annual runoff (*MAR*) following Zonderland-Thomassen and Ledgard [7]; 30% and 60% of the *MAR* as the minimum and maximum range, as suggested by Pastor et al. [40]; 80% of the *MAR*, as suggested by [8]; and a locally estimated *EWR* for water flow regulations in the Waikato region, where 10% of the *Q5* (5-year, 7-day, low flow rate) can be allocated for *EWRs*, equating to 64% of the *MAR* in the Karapiro catchment in the Waikato region.

3. Results

3.1. Consumptive Water Footprint and Its Variation on the Studied Pastoral Dairy Farms

Table 3 summarizes the consumptive green and blue water footprints (expressed in *litres* of water per kg of *FPCM*) of the studied farms, calculated using global and local data sources (Table 2). About 99% of the total consumptive *WF* was quantified as being associated with water consumption via evapotranspiration (*ET*) for pasture and feed production at the studied farms. However, the consumptive ET_{green} and ET_{blue} for pasture and feed production at the studied farms varied considerably depending on their location and whether they were non-irrigated (rain-fed) or irrigated (Table 3).

Table 3. Consumptive water footprints (L/kg of *FPCM* [1]) of the studied pastoral dairy farms across different regions of New Zealand.

Water Consumed (L/kg of FPCM [1])	Global Data					Local Data				
	Irrigated Farms			Non-Irrigated Farms		Irrigated Farms			Non-Irrigated Farms	
	Canterbury	Manawatu	Waikato	Manawatu	Waikato	Canterbury	Manawatu	Waikato	Manawatu	Waikato
SDW [2]	2.7	2.1	1.2	2.7	2.7	1.2	1.9	2	2.1	2.2
MPW [2]	2.4	3.8	2.9	2.4	2.4	3.2	2.5	2.2	2.6	2.4
ET_{green}	253	546	371	535	371	287	621	446	677	527
ET_{blue}	240	181	107	0	0	234	122	42	0	0
WF_{blue}	246	187	111	5	5	239	126	46	5	5
WF_{green}	253	546	371	535	371	287	621	446	677	527
Total *WF*	499	733	482	540	376	525	747	492	682	531

Notes: [1] L/kg of *FPCM* = litres of water used to produce 1 kg of fat- and protein-corrected milk. [2] *SDW* = stock drinking water, *MPW* = milking parlour water use.

The studied dairy farms in the Manawatu region were assessed to have a higher consumptive *WF* than the studied farms in both the Waikato and Canterbury regions. The consumptive WF_{green} (L/kg of *FPCM*) in the Manawatu region was estimated to be about 22 to 54% higher than in the Waikato and Canterbury regions (Table 3; local data). A relatively higher WF_{green} in the Manawatu region is partly explained by the differences in the potential evapotranspiration rates and stocking rates, leading to lower production per hectare and higher rainfall water consumed per kg of *FPCM* in the Manawatu region.

The irrigated dairy farms in the Manawatu and Waikato regions resulted in no significant differences in their total consumptive *WF* (L/kg of *FPCM*) compared to the non-irrigated dairy farms in the regions (Table 3; local data). Less irrigation is required in the Manawatu and Waikato regions, which receive relatively higher rainfall (>850 mm per year), especially in the Waikato region (Table 3; local data). The ET_{blue} was estimated, on average, to be only 9 to 16% of the total *ET* (i.e., ET_{green} plus ET_{blue}) at the studied farms in the Waikato and Manawatu regions (Table 3; local data). However, the ET_{blue} was estimated to be as high as 45% of the total *ET* at the studied farms in the Canterbury region. As a result, the consumptive WF_{blue} (L/kg of *FPCM*) of the studied irrigated dairy farms in the Canterbury region was estimated to be about two to five times higher compared to the studied irrigated dairy farms in the Manawatu and Waikato regions, respectively (Table 3; local data). This is because of relatively low rainfall (<650 mm per year), hence the higher irrigation water use on pastoral dairy farms in the Canterbury region (Table 1).

3.2. Effect of Water Footprint Methods

The consumptive water footprints are suggested to be characterised using local water stress or scarcity indices to assess their environmental water scarcity impacts in the study regions [8,14–16]. Tables 4 and 5 present values of the characterisation factors, the WS_{blue} (Equation (5)) [8] and the CF_{AWARE} (Equation (8)) [14], calculated using global and local data sources (Table 2) at the regional scale (Table 4) and catchment/water management zone scale (Table 5).

The CF_{AWARE} yielded relatively higher absolute values than the WS_{blue} (Tables 4 and 5). This was expected due to accounting for different water variables and formulations used in the quantification of WS_{blue} (Equation (5)) and CF_{AWARE} (Equation (8)). The WS_{blue} quantifies the ratio of the cumulative consumptive water footprint ($\sum WF_{blue}$) to the total blue water availability (*WA*) minus environmental flow requirements (*EWRs*) in a geographical area (Equation (5)). The CF_{AWARE} also accounts for total human water consumption (*HWC*) (equivalent to the $\sum WF_{blue}$), *WA*, and *EWRs* in a geographical area. However, the CF_{AWARE} quantifies the available water remaining (AMD_i) per unit area (Equation (7)) and further normalises the CF_{AWARE} by dividing the $AMD_{worldaverage}$ by the calculated AMD_i for the study area (Equation (8)) [14].

Despite the differences in their formulations, both water footprint methods, interestingly, ranked different study regions in the same order (from lowest to highest) in terms of blue water scarcity (WS_{blue}) or the blue water availability minus demand (CF_{AWARE}) (Table 4). However, this consistency in the relative ranking order of the WS_{blue} and CF_{AWARE} factors was somewhat limited at the catchment or water management zone scale (Table 5). This slight inconsistency in the relative ranking order of the WS_{blue} and CF_{AWARE} factors at the catchment or water management zone scale (Table 5) was also reflected in the quantification and relative rankings of the blue water scarcity impact index ($WFII_{blue}$) (Equation (4)) and the water scarcity footprint metric (WF_{AWARE}) (Equation (9)) for a kg of *FPCM* produced at the studied irrigated farms located in different catchment or water management zones (Table 6). Also, in absolute value terms, the AWARE-based WF_{AWARE} values were quantified higher than the WFN-based $WFII_{blue}$ values, especially using global data sources (Table 6).

Table 4. Water scarcity footprint characterization factors (*CFs*), the blue water scarcity index (W_{Sblue}) and the blue water availability minus demand (CF_{AWARE}), calculated for the study regions in New Zealand. Note relative ranks shown in parentheses (1 representing the lowest value).

Region	**Global Data**		**Local Data**	
	WS_{blue} **(-)**	CF_{AWARE} **(m^3 World eq./m^3)**	WS_{blue} **(-)**	CF_{AWARE} **(m^3 World eq./m^3)**
Waikato	0.002 (1)	0.765 (1)	0.014 (1)	0.300 (1)
Manawatu	0.010 (2)	0.895 (2)	0.098 (2)	0.403 (2)
Canterbury	0.371 (3)	7.355 (3)	0.190 (3)	0.473 (3)
Range (min.–max.)	*0.002–0.371*	*0.765–7.355*	*0.014–0.190*	*0.300–0.473*

Table 5. Characterization factors (*CFs*), the blue water scarcity index (W_{Sblue}) and the blue water availability minus demand (CF_{AWARE}), calculated for the study catchment or water management zones in New Zealand. Note relative ranks shown in parentheses (1 representing the lowest value).

Region: Catchment/ Water Management Zone	**Global Data**		**Local Data**	
	WS_{blue} **(-)**	CF_{AWARE} **(m^3 World eq./m^3)**	WS_{blue} **(-)**	CF_{AWARE} **(m^3 World eq./m^3)**
Waikato region				
Waikato River	0.002 (1)	0.612 (2)	0.031 (1)	0.314 (2)
Waihou	0.006 (2)	0.600 (1)	0.032 (2)	0.307 (1)
Manawatu region				
Rangitikei River	0.008 (3)	1.074 (3)	0.257 (4)	0.564 (5)
Canterbury region				
Orari-Opihi-Pareora	0.673 (6)	40.840 (6)	0.129 (3)	0.874 (6)
Selwyn-Waihora	0.353 (5)	2.371 (4)	0.361 (5)	0.484 (3)
Ashburton	0.234 (4)	3.025 (5)	0.375 (6)	0.502 (4)
Range (min.–max.)	*0.002–0.673*	*0.600–40.840*	*0.031–0.375*	*0.0.314–0.874*

Table 6. Quantified water scarcity footprint metrics, the blue water footprint impact index ($WFII_{blue}$) and the Available WAter REmaining-characterised water scarcity footprint (WF_{AWARE}), for pastoral dairy milk production (per kg of *FPCM*) at the studied irrigated dairy farms in the study catchment and water management zones in New Zealand. Note relative ranks shown in parentheses (1 representing the lowest value).

Region: Catchment/ Water Management Zone	**Global Data**		**Local Data**	
	$WFII_{blue}$ **(-)**	WF_{AWARE} **(m^3 World eq./kg of *FPCM*)**	$WFII_{blue}$ **(-)**	WF_{AWARE} **(m^3 World eq./kg of *FPCM*)**
Waikato region [1]	**0.20**	**92.65**	**0.63**	**13.86**
Waikato River	0.21 (1)	68.16 (2)	1.44 (1)	14.48 (2)
Waihou	0.66 (2)	66.84 (1)	1.46 (2)	14.16 (1)
Manawatu region [1]	**1.95**	**181.57**	**12.39**	**50.88**
Rangitikei River	1.48 (3)	200.45 (3)	32.49 (4)	71.31 (3)
Canterbury region [1]	**99.09**	**1962.67**	**45.41**	**112.80**
Orari-Opihi-Pareora	165.31 (6)	10,026.24 (6)	30.84 (3)	208.39 (6)
Selwyn—Waihora	86.63 (5)	581.97 (4)	86.03 (5)	115.39 (4)
Ashburton	57.46 (4)	742.75 (5)	89.52 (6)	119.69 (5)
Range (min.–max.)	*0.21–165.31*	*68.16–10,026.24*	*1.44–89.52*	*14.48–208.39*

Notes: [1] The average values for all the study farms in the region.

Overall, however, both water scarcity footprint indices, $WFII_{blue}$ and WF_{AWARE}, ranked the study regions or catchments/water management zones in a similar order (lowest to highest) based on the quantified water scarcity footprint for a kg of *FPCM* produced at the studied irrigated dairy farms across the study regions and catchments (Table 6).

3.3. Effect of Local and Global Data Sources

Compared to the local data sources, using global data sources (Table 2) resulted in over- and underestimation of the consumptive *WF* of dairy milk production at different farm types (irrigated or non-irrigated) in the study regions (Table 3). The use of global data sets resulted in an overestimation of the *SDW* (in terms of L per kg of *FCPM*) by 125% for the studied irrigated farms in the Canterbury region and by 23 to 29% for the studied non-irrigated farms in the Waikato and Manawatu Regions. However, using global data sets resulted in an underestimation of 40% in the *SDW* for the studied irrigated farms in the Waikato region. The use of global data sets also underestimated the *MPW* by 25% for the studied irrigated farms in the Canterbury region and 8% for the studied non-irrigated farms in the Manawatu Region. In contrast, the global data sets overestimated the *MPW* by 52 and 32% for the studied irrigated farms in the Manawatu and Waikato regions, respectively (Table 3).

The ET_{green} for pasture and feed production based on the globally available CLIMWAT database (Table 2) was underestimated by 12 to 30% on all studied farms compared to the estimates based on the locally available climatic database, the VCSN [28]. In contrast, the global CLIMWAT data-based ET_{blue} was overestimated, particularly in the Manawatu and Waikato regions. The global CLIMWAT data-based ET_{blue} was estimated about 48 and 155% higher for the studied irrigated farms in the Manawatu and Waikato regions, respectively. These differences in the estimation of the ET_{green} and ET_{blue} for pasture and feed production could be mainly attributed to the estimates of less effective rainfall in the global data sets compared to the local data set. Therefore, the irrigation requirements were estimated to be relatively higher using the global CLIMWAT data set [27] than the local climatic data set [28]. Overall, the use of global data sets in this study resulted in the total consumptive *WF* (green plus blue water) being underestimated by 2 to 5% for the irrigated farms and 21 to 29% for the non-irrigated farms (Table 3).

Compared to the local data sources, using global data sources (Table 2) also affected the quantification of the water scarcity characterisation factors, WS_{blue} (Equation (5)) and

CF_{AWARE} (Equation (8)), at the regional and catchment scales (Tables 4 and 5). The CF_{AWARE} based on the global WULCA data layer [19] was estimated at 7.355 for the Canterbury region, which was about 16 times higher compared to the CF_{AWARE} value of 0.473 estimated by using local data (Table 4). The global CF_{AWARE} layer, as compared to the locally calculated CF_{AWARE} values, also resulted in CF_{AWARE} values that were >two times higher for the Manawatu and Waikato regions (Table 4). The global WS_{blue} layer [37], as compared to the locally calculated WS_{blue} values, resulted in 95% higher WS_{blue} values for the Canterbury region but 86 and 90% lower WS_{blue} values for the Waikato and Manawatu regions, respectively (Table 4). The global data layers resulted in a slightly higher range in the WS_{blue} and CF_{AWARE} values for the study regions (Table 4). However, interestingly, using either global or local data, the study regions were ranked in a similar order (from lowest to highest) in terms of the WS_{blue} and CF_{AWARE} values (Table 4), showing the lowest water stress in the Waikato region and the highest in the Canterbury region.

The WS_{blue} and CF_{AWARE} values were also under- or overestimated when using the global data layers at the catchment scale (Table 5). Compared to the local data estimates, the global WULCA data layer [16] reported the CF_{AWARE} as being 47 times higher for the Orari-Opihi-Pareora water management zone (Table 5). This zone had a higher global CF_{AWARE} value assigned because the pixel on which it was calculated resided over the area of greater water use in the zone, not the area in the zone where most of the available water is generated in the headwaters. However, the WS_{blue} values were estimated relatively lower in the global data set [37], except for the Orari-Opihi-Pareora water management zone (Table 5).

The use of different data sources had a significant effect on the overall quantification of the water scarcity footprint indices, the WFN-based $WFII_{blue}$ (-) (Equation (4)) and the AWARE-based WF_{AWARE} (m^3 world eq./kg of *FPCM*) (Equation (9)), for the pastoral dairy milk production across the study catchments (Table 6). As compared to the local data estimates, the global data sets (Table 2) resulted in the quantification of the $WFII_{blue}$ (-) being 36 to 95% lower for most of the study catchments, except Orari-Opihi-Pareora and Ashburton in the Canterbury region (Table 6). In contrast, the global data sets (Table 2) resulted in the quantification of the WF_{AWARE} (m^3 world eq./kg of *FPCM*) being 3 to 47 times higher for the study catchments, notably 47 times higher for Orari-Opihi-Pareora in the Canterbury region (Table 6). The higher WF_{AWARE} values based on the global data (Table 6) could be attributed to the relatively higher CF_{AWARE} values quantified by the global WULCA data layer [16] for the study catchments (Table 5).

Table 7 presents a further evaluation of the effects of local data in terms of different *EWRs* on the quantification of the $WFII_{blue}$ (-) (Equation (4)) and the WF_{AWARE} (m^3 world eq./kg of *FPCM*) (Equation (9)) values for the studied irrigated farms in the study regions. Depending on the *EWR* rates used (30 to 80% of the mean annual runoff (*MAR*)), the quantified $WFII_{blue}$ (-) varied by a factor of 3 to 3.5 times in the study regions (Table 7). Similarly, the quantified WF_{AWARE} (m^3 world eq./kg of *FPCM*) varied by a factor of 3 to 7.2 times in the study region (Table 7). Table 7 highlights a very high sensitivity of the quantification of the $WFII_{blue}$ and WF_{AWARE} values based on the set *EWR* rates used in the study regions.

Table 7. Sensitivity of the water scarcity footprint characterization factors (*CFs*) and characterised water scarcity footprint indices for pastoral milk production on the studied irrigated dairy farms to different environmental water requirements (*EWRs*) in different regions of New Zealand.

Water Footprint Method	*EWR* [1]	Water Scarcity Characterization Factors			Water Scarcity Footprint Indices		
		Waikato	Manawatu	Canterbury	Waikato	Manawatu	Canterbury
			WS_{blue} (-)			$WFII_{blue}$ (-)	
WFN-based method [8]	0.30	0.01	0.09	0.17	0.57	11.15	40.87
	0.37	0.01	0.10	0.19	0.63	12.39	45.41
	0.60	0.02	0.15	0.30	0.95	19.51	71.51
	0.64	0.02	0.17	0.34	1.05	21.89	80.26
	0.80	0.04	0.31	0.60	1.72	39.01	143.03

Table 7. *Cont.*

Water Footprint Method	EWR [1]	Water Scarcity Characterization Factors			Water Scarcity Footprint Indices		
		Waikato	Manawatu	Canterbury	Waikato	Manawatu	Canterbury
		CF_{AWARE} (m^3 world eq./m^3)			WF_{AWARE} (m^3 world eq./kg of $FPCM$)		
AWARE method [12,14]	0.30	0.27	0.36	0.42	12.54	45.30	99.19
	0.37	0.30	0.40	0.47	13.86	50.88	112.80
	0.60	0.46	0.82	0.86	21.14	103.23	205.44
	0.64	0.51	0.97	1.02	23.48	122.27	243.33
	0.80	0.84	1.68	3.01	38.95	212.20	718.84

Note: [1] Percentage of mean annual runoff required for the environmental water requirements.

3.4. Effect of Spatial Scale

The effect of different spatial scales of analysis can be seen in Figure 3, which presents the consumptive WF (L/kg of $FCPM$) quantified using the local data sets (Table 2) for the studied irrigated and non-irrigated dairy farms in the study regions (Table 1). The consumptive WF_{green} varied from 287 L per kg of $FCPM$ for the studied irrigated farms in the Canterbury region to 677 L per kg of $FCPM$ for the studied non-irrigated farms in the Manawatu region, with a weighted average of 505 L per kg of $FCPM$ for all studied irrigated and non-irrigated farms across all study regions (Figure 3).

Compared to the weighted average, the WF_{green} was quantified as being 43% lower for the studied irrigated farms in the Canterbury region but 34% higher for the studied non-irrigated farms in the Manawatu region. In contrast, as compared to the weighted average, the consumptive WF_{blue} was quantified >260% more for the studied irrigated farms in the Canterbury region but about 90% less for the studied non-irrigated farms in the Manawatu and Waikato regions (Figure 3 and Table 3).

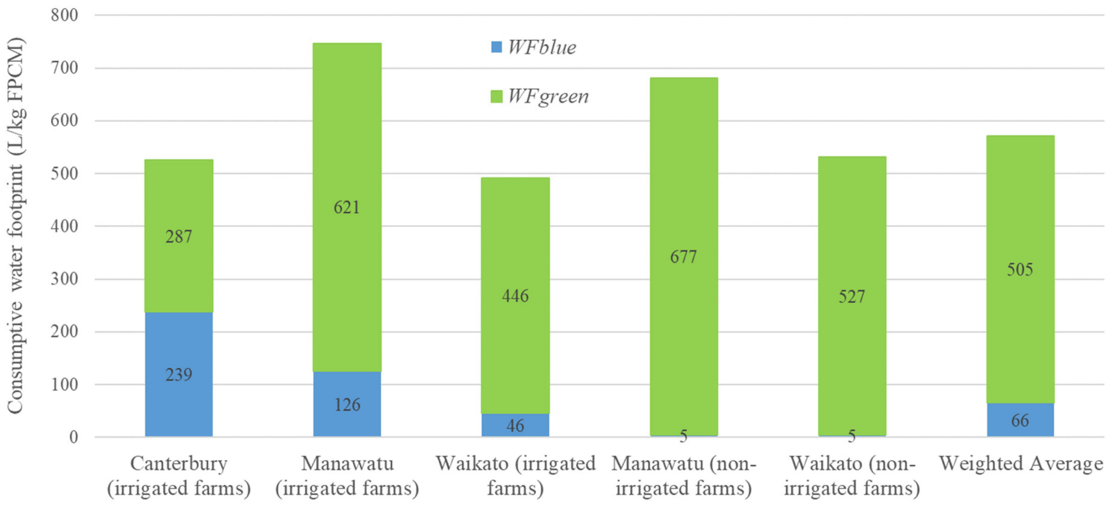

Figure 3. Variability in the consumptive water footprints (green and blue waters) (L per kg of $FPCM$) for the studied irrigated and non-irrigated pastoral dairy farms in New Zealand. The weighted average is for all combined irrigated and non-irrigated farms in the study regions.

Table 6 also further demonstrates the effect of different spatial scales of analysis on the characterised blue water scarcity footprint indices, the $WFII_{blue}$ (-) and the WF_{AWARE} (m^3 world eq./kg of $FPCM$), for the studied irrigated farms in different regions and catchments/water management zones. Using the local data sets, the quantified $WFII_{blue}$ varied from 1.44 (-) per kg of $FPCM$ in the Waikato River catchment to 89.52 (-) per kg of $FPCM$ for the studied irrigated dairy farms in the Ashburton water management zone (Table 6). The $WFII_{blue}$ values were quantified 89 to 97% higher for Selwyn-Waihora and Ashburton but −32% lower for Orari-Opihi-Pareora than the rationalised $WFII_{blue}$ value of 45.41 (-)

for the Canterbury region. Similarly, the quantified WF_{AWARE} varied from 14.16 m^3 world eq./kg of *FPCM* for the study irrigated dairy farms in the Waihou catchment to 208.39 m^3 world eq./kg of *FPCM* for the study irrigated dairy farms in the Orari-Opihi-Pareora water management zone. The WF_{AWARE} values were quantified only 2 to 6% higher for Selwyn-Waihora and Ashburton than the rationalised WF_{AWARE} value of 112.80 m^3 world eq./kg of *FPCM* for the Canterbury region (Table 6). In contrast, the WF_{AWARE} value for the Orari-Opihi-Pareora water management zone was quantified 85% higher than the rationalised WF_{AWARE} value of 112.80 m^3 world eq./kg of *FPCM* for the Canterbury region. Also, the WF_{AWARE} value for the studied irrigated farms in the Rangitikei River catchment was quantified about 40% higher than the rationalised WF_{AWARE} value of 50.88 m^3 world eq./kg of *FPCM* for all studied irrigated farms in the Manawatu region (Table 6).

4. Discussion

4.1. Evaluation of Water Footprint Methods

Water footprinting methods are under development for their potential applications for a robust assessment of water scarcity impacts associated with agricultural production, including pastoral dairy farming. In this study, the two water scarcity footprint indices, the WFN-based $WFII_{blue}$ [8] and the AWARE-based WF_{AWARE} [14], resulted in different absolute values of the water scarcity footprint associated with a kg of *FPCM* (Table 6) produced at the studied irrigated and non-irrigated pastoral dairy farms in different regions of New Zealand (Table 1). This is expected due to the different formulations used for the quantification of the $WFII_{blue}$ (Equation (5)) and WF_{AWARE} (Equation (9)). However, interestingly, the quantified $WFII_{blue}$ and WF_{AWARE} values ranked the study regions and catchments in a similar order of lowest to the highest magnitude in terms of the water scarcity footprint associated with a kg of *FPCM* produced (Table 6).

As an exception, the quantified $WFII_{blue}$ and WF_{AWARE} values ranked the Orari-Opihi-Pareora water management zone as third and sixth (from lowest (first) to highest (sixth)), respectively (Table 6). This was attributed mainly to differences in the quantification of the relatively higher CF_{AWARE} for the Orari-Opihi-Pareora water management zone (Table 5). The calculation of the CF_{AWARE} (Equation (7)) divides the remaining available water (i.e., available water minus human water consumption minus environmental flow requirement) by the geographical area. The Canterbury management zones are quite large in their area and generate their main volumes of water supply mainly in the mountains through snow melt. Including the catchment area in Equation (7) could result in a relatively lower AMD_{i} value, translating into a relatively higher CF_{AWARE} (Equation (8)) value for a larger catchment than a smaller one with similar water availability and demands. In contrast, the WSI_{blue} (Equation (5)) is calculated as a ratio of the cumulative blue water consumption to the total water availability, accounting for environmental water requirements in the geographical area. Using the local data, the WSI_{blue} was quantified relatively less for the Orari-Opihi-Pareora water management zone (Table 5).

The WFN-based $WFII_{blue}$ [8] and the AWARE-based WF_{AWARE} [14] are also highly sensitive to the values of the environmental water requirements used in their calculations (Equations (6) and (7), and Table 7). The WFN-based $WFII_{blue}$ [8] considers *EWRs* at a conservative rate of 80% of the mean annual runoff (*MAR*) [8,37]. The AWARE-based WF_{AWARE} [14] considers the *EWRs* calculated using the method of Pastor et al. [40], using the monthly water flows given in the WaterGAP database [20]. The differences in the *EWR* rates affect the available water and the quantification of water scarcity levels in the study area. Both the WFN-based $WFII_{blue}$ [8] and the AWARE-based WF_{AWARE} [14] methods provide adequate means to assess water scarcity using the locally determined *EWRs* in the study area. However, the AWARE-based WF_{AWARE} [14] normalises the locally determined water availability minus demand (AMD_i) with the global average ($AMD_{worldaverage}$) (Equation (7)) in the calculation of water scarcity levels (CF_{AWARE}) for a study area (Equation (8)). The normalisation of the locally determined AMD_i with the global average $AMD_{worldaverage}$ may be helpful when comparing water usage for a product from two different regions.

However, it is potentially subjected to uncertainty in terms of the data used to quantify the global average $AMD_{worldaverage}$, using global data sources and models [20]. The WFN-based $WFII_{blue}$ [8] quantifies a water scarcity footprint index that more closely reflects the quantitative volumes of water available and consumed locally in a study area.

However, both water footprint methods, the WFN-based $WFII_{blue}$ [8] and the AWARE-based WF_{AWARE} [14], appear to be capable of capturing relative differences in the quantification of the water scarcity footprint indices of a product, e.g., the water scarcity footprint indices for a kg of *FPCM* analysed in this study.

4.2. Appropriate Data Sources and Spatial Scales

The *FAO LEAP* guidelines recommend using primary data to assess water use in livestock production systems and supply chains [15,16]. However, considering the challenges and resources required for primary data collection, the modelled data with inputs from secondary data sources are often used to assess water use in livestock production systems [17]. In this study, the use of local and global data sources (Table 2) had a significant impact on the quantification of the consumptive water footprints (Table 3); the water scarcity characterisation factors, the WS_{blue} (-) and the CF_{AWARE} (m^3 world eq./m^3) (Tables 4 and 5); and the water scarcity footprint indices, the $WFII_{blue}$ (-) and the WF_{AWARE} (m^3 world eq./kg of *FPCM*) values for the studied irrigated farms across the study regions and catchments.

Compared to the local data, the use of global data sources resulted in an underestimation of the consumptive WF_{green} (L/kg of *FPCM*) by −12 to −30% and an overestimation of the consumptive WF_{blue} (L/kg of *FPCM*) by 3 to 141% in the study regions. Hess [41] also found similar effects of an underestimation of annual ET_{green} calculated using the FAO CROPWAT model with the USDA effective rainfall estimation, as compared to the ET_{green} simulated with a water balance model using long-term daily or average monthly weather data for the quantification of the water footprint of pasture production in England. Zhuo et al. [42] also reported a higher sensitivity of crop water footprints to climactic inputs of reference evapotranspiration (ET_0) and precipitation (P) in the Yellow River Basin, China. The use of global or local data sets also affected the relative rankings (from lowest to highest) of the water scarcity characterisation factors (WS_{blue} and CF_{AWARE}) (Table 5) and the characterised water scarcity footprint indices ($WFII_{blue}$ and the WF_{AWARE}) (Table 6) quantified for a kg of *FPCM* produced on the studied irrigated and non-irrigated pastoral dairy farms. The quantified differences in CF_{AWARE} and WS_{blue} values for the study regions and catchments (Tables 4 and 5) could be attributed to different sources of hydrological and water use data and models used at the global and local levels (Table 2).

The catchment scale is a more appropriate level to quantify water footprints for the assessment of the appropriation of water resources and the environmental impacts of water consumption on local freshwater environments. Water footprint hotspots can be hidden at the regional scale, but they can be seen when analysed at the catchment scale (Tables 4 and 5). For example, the Selwyn-Waihora and Ashburton water management zones had similar water scarcity values (CF_{AWARE} and WS_{blue}) (Table 5). However, Orari-Opihi-Pareora had about 1.85 times higher CF_{AWARE} and WS_{blue} values than the regionalised CF_{AWARE} and WS_{blue} values for the Canterbury region (Tables 4 and 5). This example highlights the influences of differences in water availability and use between different catchments on quantifying the water scarcity footprint associated with pastoral milk production across New Zealand.

A majority (~99%) of the consumptive water footprints of a unit of pastoral dairy milk production (L/kg of *FPCM*) was quantified as being associated with the green and blue water consumption via evapotranspiration for pasture and feed used at the studied dairy farms. The most critical data to collect at the catchment scale are the local climate data and irrigation water use in pasture and feed production for dairy farms. Effective rainfall and evapotranspiration (ET) can be highly variable within a region. The use of global data sources with monthly average climatic data from one location within a region can lead to inaccurate estimates of green and blue consumptive water footprints in a catchment (Table 3) [41,42].

The direct water use on a dairy farm is also important data to quantify accurate water footprints of dairy milk production. The actual irrigation water used, as opposed to water allocated, is also crucial to collect, as if the water is not used, then there is no impact from it being allocated. Compared to the actual measurements (Table 2), the use of globally estimated rates (Table 2) resulted in an over- or underestimation of *SDW* and *MPW* on the studied farms (Table 3). While *SDW* and *MPW* made up small proportions of the blue water use at the studied irrigated farms, they primarily used blue water at non-irrigated farms for pastoral dairy production (Table 3).

Compared to the local data, the use of global data sources (Table 2) also affected the over- or underestimation of the water scarcity characterisation factors (WS_{blue} and CF_{AWARE}) (Table 5) for the study regions and catchments. The global WS_{blue} and CF_{AWARE} data layers are mainly based on estimates of coarse-resolution global hydrological models and databases [16,37]. They could be less accurate for regional- and catchment-scale analysis than those calculated using local data (Table 5). The global data layers are divided into pixels (30′ by 30′ for WS_{blue}, 0.5 by 0.5 degrees for CF_{AWARE}), which did not align with the studied regional or catchment areas. In the global CF_{AWARE} layer [16], the pixel covered the lower plains of the Orari-Opihi-Pareora water management zone, where most irrigation occurs. However, it did not include the mountain ranges at the top of the catchment, where most available water is generated. The global WS_{blue} layer [37] also did not fit very well with the shape of the regions across New Zealand.

One of the main differences in the quantification of the WS_{blue} and CF_{AWARE} for the Rangitikei River catchment was the change in their comparative ranking between the use of global and local data sets (Table 5). The WS_{blue} and CF_{AWARE} values for the Rangitikei River catchment were ranked third (from lowest (first) to highest (sixth)) in the global data, but ranked fourth or fifth highest, respectively, in the local data set (Table 5). This could partly be due to water transfers between the regions through hydroelectricity schemes from the Rangitikei River into the Waikato River. Therefore, these data are commercially sensitive and not readily available, so they may not be included in the global data sets. However, these data are critical locally to calculate water footprints with, as they can significantly affect the quantification of water scarcity footprints at the local scale.

As presented in Table 7, the use of different environmental water requirements resulted in a high variation in the $WFII_{blue}$ and WF_{AWARE} values associated per kg of *FPCM* produced on the studied irrigated farms across the study regions. Different *EWR* rates are suggested in the literature for waterways to maintain freshwater ecosystems' health. They include ranges from 30% and 60% of the mean annual runoff (*MAR*) as the minimum and maximum range as suggested by Pastor et al. [40]; the conservative value of 80% *MAR* proposed by the Water Footprint Network [8]; and the 37% *MAR* already used in other analyses across New Zealand [7]. Suppose that *EWRs* are calculated using global databases and models compared to the locally determined *EWRs*. In that case, this may result in a different *EWR* rate and, therefore, different values of the WFN-based WS_{blue} and $WFII_{blue}$ [8] and the AWARE-based CF_{AWARE} and WF_{AWARE} [14] indices for a product produced in a catchment. Therefore, the water footprinting methods would benefit from further research and discussion on the appropriate setting of *EWR* rates, mainly if the quantified water scarcity footprint indices are used for a comparative analysis of different products produced in different catchments.

Also, due to a lack of relevant data availability in this study, it was impossible to quantify the water scarcity characterisation factors (WS_{blue} and CF_{AWARE}) on a seasonal or monthly basis to capture better effects of temporal variability in water availability, water consumed, and environmental flow requirements. Therefore, it is critical to develop robust monitoring and modelling tools to quantify water flows, allocations, and uses for different activities in local catchments. This information is critical to robustly quantify and assess water productivity and water scarcity impact footprints to help develop productive and environmentally sustainable food production systems, including pastoral dairy milk production.

5. Conclusions

The consumptive water footprint of a unit of pastoral dairy milk production (L/kg of *FPCM*) was quantified as being mainly associated (~99%) with green and blue water consumption via evapotranspiration for the pasture and feed used at the studied dairy farms. However, the consumptive green and blue water footprints for pasture and feed varied considerably depending on the farm type (non-irrigated (rain-fed) or irrigated) and their location in different climatic conditions. The consumptive blue water footprint (L/kg *of FPCM*) of the studied irrigated farms in the Canterbury region was estimated to be about two to five times higher compared to the Manawatu and Waikato regions, respectively, due to relatively low rainfall (<650 mm per year), hence the higher irrigation water use.

The WFN-based blue water footprint impact index ($WFII_{blue}$) and the Available WAter REmaining-characterised water scarcity footprint (WF_{AWARE}) indices are capable of capturing relative differences in quantifying the water scarcity footprint for a kg of *FPCM* produced on the irrigated farms in the studied regions and catchments. Interestingly, the quantified $WFII_{blue}$ and WF_{AWARE} values ranked the study regions and catchments in a similar order of lowest to highest magnitude in terms of the water scarcity levels and the water scarcity footprint values for a kg of *FPCM* produced.

However, using local or global data sources greatly affected the quantification of the consumptive 'volumetric' and the water scarcity footprint indices ($WFII_{blue}$ and WF_{AWARE}) associated with a unit of milk production (kg of *FPCM*) produced. Compared to the local data, the use of global data sources resulted in an underestimation of the consumptive green water footprint (L/kg of *FPCM*) by −12 to −30% and an overestimation of the consumptive blue water footprint (L/kg of *FPCM*) by 3 to 141% in the studied regions. The global data sources also resulted in an under- or overestimation of the $WFII_{blue}$ and the WF_{AWARE} *values*, especially the WF_{AWARE} (m^3 world eq./kg of *FPCM*), which was quantified as being 47 times higher for Orari-Opihi-Pareora in the Canterbury region.

Observations of local climatic data, actual irrigation water use, locally calibrated hydrological models, and environmental flow requirements are critical for accurately quantifying and assessing the water scarcity footprints associated with pastoral dairy milk production in local catchments. The catchment or water management spatial scale should be used for the analysis. Catchments within regions can have varying levels of water availability and water use, which are masked when using a regional or national level of water scarcity characterisation factors in the quantification of water scarcity footprint indices associated with a unit of milk production (kg of *FPCM*) produced in local catchments. The lack of relevant data availability locally needs to be addressed to robustly quantify the water scarcity characterisation factors (WS_{blue} and CF_{AWARE}) on a seasonal or monthly basis to capture better effects of temporal variability in water availability, water consumed, and environmental flow requirements for the quantification of the water scarcity footprint indices ($WFII_{blue}$ and WF_{AWARE}) associated with primary production systems, including pastoral dairy milk production in local catchments.

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