

Article

The Water Footprint of Primary and Secondary Processing of Beef from Different Cattle Breeds: A Value Fraction Allocation Model

Frikkie Alberts Maré *  and Henry Jordaan 

Department of Agricultural Economics, University of the Free State, Bloemfontein 9301, South Africa; JordaanH@ufs.ac.za

* Correspondence: MareFA@ufs.ac.za; Tel.: +27-51-401-3220

Abstract: The high water intake and wastewater discharge of slaughterhouses have been a concern for many years. One neglected factor in previous research is allocating the water footprint (WF) to beef production's different products and by-products. The objective of this article was to estimate the WF of different cattle breeds at a slaughterhouse and cutting plant and allocate it according to the different cuts (products) and by-products of beef based on the value fraction of each. The results indicated a negative relationship between the carcass weight and the processing WF when the different breeds were compared. Regarding a specific cut of beef, a kilogram of rib eye from the heaviest breed had a processing WF of 614.57 L/kg, compared to the 919.91 L/kg for the rib eye of the lightest breed. A comparison of the different cuts indicated that high-value cuts had higher WFs than low-value cuts. The difference between a kilogram of rib eye and flank was 426.26 L/kg for the heaviest breed and 637.86 L/kg for the lightest breed. An option to reduce the processing WF of beef is to lessen the WF by slaughtering heavier animals. This will require no extra investment from the slaughterhouse. At the same time, the returns should increase as the average production inputs per kilogram of output (carcass) should reduce, as the slaughterhouse will process more kilograms.

Keywords: water footprint; beef processing; slaughterhouse; cattle breeds; bottom-up approach; value fraction allocation



Citation: Maré, F.A.; Jordaan, H. The Water Footprint of Primary and Secondary Processing of Beef from Different Cattle Breeds: A Value Fraction Allocation Model.

Sustainability **2021**, *13*, 6914. <https://doi.org/10.3390/su13126914>

Academic Editor: Michael Blanke

Received: 19 May 2021

Accepted: 15 June 2021

Published: 18 June 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Slaughterhouses require good-quality water for processing material destined for human consumption, while the effluent contributes to the organic load of raw sewage treated at sewage plants. The water intake and wastewater discharge of slaughterhouses have been a concern for many years. In 1989, the Water Research Commission (WRC) of South Africa hosted a project to determine water and wastewater management in the red meat industry and found that slaughterhouses consumed approximately 5.8 million m³ water per year [1]. Steffen, Robertson, and Kirsten Inc. [1] found that slaughterhouses utilised between 1.36 and 2.04 m³ freshwater per water-related cattle unit (wrcu). The wastewater (effluent) from the slaughterhouses was approximately 82% of the water intake and typically contained blood, pieces of meat, fat and gut, constant urine, and manure in suspension. These waste materials contribute to the high organic load of the effluent, and the wastewater quality from red meat slaughterhouses is summarised as chemical oxygen demand (COD) of 2380 to 8942 mg/L, total suspended solids (TSS) of 189 to 3330 mg/L, and pH 5.7 to 8.4 [2].

Direct water use and wastewater discharge have always been the measure of total slaughterhouse water consumption. Hoekstra's [3] water footprint (WF) approach, which developed into the water footprint assessment (WFA) concept [4], however, incorporates the indirect water use of a product, process, or business. Therefore, the total water use in terms of blue, green, and grey WFs is reported. The blue WF denotes water from

surface and groundwater, the green WF represents evapotranspiration (ET) of rainwater, and the grey WF is the volume of fresh water required to assimilate the pollution load to ambient water quality. Since the introduction of the WFA, much research has been conducted on the livestock sector to estimate the total WF of farm animal products. The study showed that meat production has one of the highest WFs. Therefore, consumers have been urged to consume less red meat [5] or maintain the same consumption patterns and select products with a lower WF from other regions or production systems [6]. However, the WF information of different products, or the same type of product from different origins, does not exist in many instances [6].

Except for studies like Maré and Jordaan [7], Maré et al. [8], and Palhares et al. [9], which estimated the WF of industrial finished calves, cow-calf production, and a tropical beef cattle production system, respectively, WFs of beef are mostly calculated from national data or on beef from different production systems (grazing, mixed, or industrial) [5,10–16]. Published WFs were also primarily based on the feed, drinking, and service WFs of beef production, with little attention paid to the processing WF of beef. This means that very little information exists on the contribution of the various links in the value chain to the WF of beef. More recent studies that focused on the WFs of livestock in beef production, beef cattle, and livestock products also did not break the WF down to product level or ignored the contribution of processing to the total WF [17–20]. Palhares et al. [9] did indicate that the grey WF of the beef processing plant was included based on the total phosphorus concentration in the effluent but failed to report the findings of the processing WF separately in the article. Further, no explanation was given for why phosphorus was used as the only pollutant while COD is usually the most significant contributor to the pollutant load of beef processing (slaughterhouse) effluent [21]. The neglect of the grey WF in previous research was also reported by Ibidhi and Salem [22], who reviewed literature published on the WFs of livestock products and production systems between 2000 and 2017. They found that one weakness of the existing research is that the grey WFs are mostly estimated on nitrogen leaching only, without considering other pollutants.

Another neglected factor in previous research is allocating the WF to different products and by-products of beef production. For example, Chapagain and Hoekstra [10] proposed the use of product fractions (PF) and value fractions (VF) to allocate the WF of primary (carcass, offal, semen, and rawhide) and secondary processed products (carcass frozen, bovine cuts, bone-in, and meat cured). The authors applied the PF and VF for primary products, but a PF of 0.98 for meat cured was used for secondary processed products. This is arguable, because one cannot obtain 98% boneless beef for curing of a bovine carcass, as there is only about a 50% yield of boneless, trimmed beef from a cold carcass. Further, a VF of 1 for all secondary products was used, because the secondary products were mutually exclusive with only one product at a time. However, in practice, beef carcasses are broken down into different cuts for the retail sector, with the different cuts of beef being sold at different prices. At the same time, the relative size (weight) of each cut also varies.

This article estimates the WF of different cattle breeds at the slaughterhouse and cutting plant and allocates it to the value fraction of the different cuts (products) and by-products. The breeds included Afrikaner, Brahman, Bonsmara, Angus, Simbra, Simmentaler, and Limousin, which represented the most popular breeds farmed in the proximity of the slaughterhouse. Since most beef carcasses are divided into different cuts with different prices and weights, it was not assumed that the different cuts (or secondary processed products) were mutually exclusive. The WF of the slaughterhouse and processing plant vary between breeds, as the carcass weight, bone–meat ratios, and value of the by-products differ between the breeds. The VF and associated WF for various cuts of beef and the by-products from the different breeds must thus be calculated.

2. Materials and Methods

2.1. Slaughter Data

The data for the study were obtained from the Country Meat slaughterhouse situated in Kroonstad in the Free State province of South Africa. The slaughterhouse has a slaughtering capacity of 230 head of cattle per day and has a deboning and packaging plant. Monthly municipal water meter readings and the monthly slaughter numbers were used to determine the slaughterhouse's direct water use for one year (see Figure 1). The slaughterhouse used 25,030 m³ municipal water (1 July 2015–30 June 2016) to slaughter and process 51,703 CUs. There was a strong correlation between the direct water use and the cattle units slaughtered ($r = 0.82$, $p < 0.001$) for the year, which indicated that the relative weight of the animal being processed did not influence the direct water use. The average direct water use per cattle unit was 484 L.

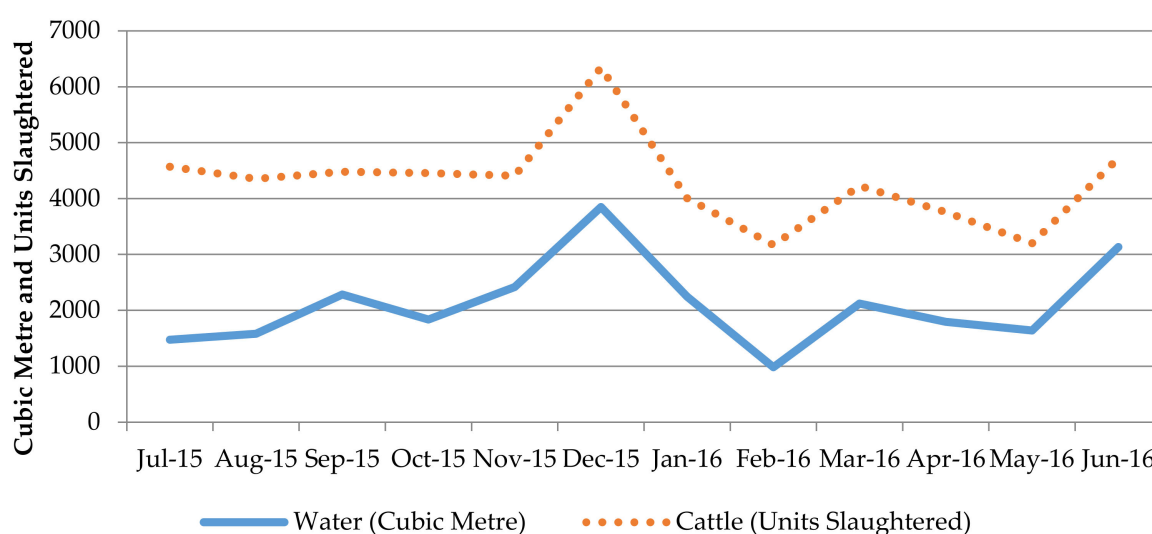


Figure 1. Direct water intake and cattle units slaughtered at the slaughterhouse. Source: The Sernick Group. Unpublished direct water intake and cattle units slaughtered data, 14 July 2016.

The slaughter and deboning data were obtained from 10 animals of each of the seven breeds. Before slaughter, the animals were fed until they reached their optimal economic point of growth (Profit Maximizing Feeding Period). Therefore, the variation in carcass weight between the breeds was considerable [23]. The feeding periods, in weeks, of the different breeds were Afrikaner 15, Brahman 16, Angus 22, Bonsmara 16, Simbra 21, Simmentaler 27, and Limousin 26. The average carcass weight, by-product weight, and the average weight of the different cuts for each breed were used in the analysis. The prices used for the by-products and cuts were the market price at the time of the study. The data for the weights, prices, and values are available in Appendix A, Table A1.

2.2. Water and Effluent Analysis

Water samples of the effluent discharged into the municipal sewage system and input water from the municipality were collected and sent to MLS Laboratory Services (Midrand, South Africa) for quality testing (Tables 1 and 2). Table 1 contains the effluent results that the municipality requires from slaughterhouses, the most important of which is the COD used to determine the discharge tariff. The COD is also the pollutant with the highest concentration and results in the highest grey WF. The slaughterhouse does not treat its effluent before discharging it into the municipal sewage system.

Table 1. Test report of the slaughterhouse effluent water sample.

Analysis	Unit	Result
Faecal coliforms	Cfu/100 mL	55
Biochemical oxygen demand as total O ₂	mg/L	132
Chemical oxygen demand as total O ₂	mg/L	924

Table 2. Test report of municipal supplied water sample.

Test Type	Reporting Units	Results	Specification—Maximum Limit	Uncertainty of Measurement %	Complies to Specification
pH	pH	8.44	5–9.5	4.3	Yes
Electrical conductivity	mS/m	15.4	<170	9.55	Yes
Total dissolved solids	mg/L	122	<1200	9.42	Yes
Chlorine (Cl)	mg/L	3.35	<300	9.89	Yes
Sulphate (SO ₄)	mg/L	5.99	<500	9.41	Yes
Nitrate (NO ₃) as N	mg/L	0.388	<11	10.25	Yes
Nitrite (NO ₂) as N	mg/L	0.021	<0.9	7.06	Yes
Ammonium (NH ₄) as N	mg/L	0.556	<1.5	8.43	Yes
Fluoride (F)	mg/L	<0.213	<1.5	9.86	Yes
Sodium (Na)	mg/L	4.49	<200	12.03	Yes
Aluminium (Al)	mg/L	<0.002	<0.3	6.14	Yes
Iron (Fe)	mg/L	<0.004	<0.3	5.83	Yes
Manganese (Mn)	mg/L	<0.002	<0.1	5.79	Yes
Total chromium (Cr)	mg/L	<0.003	<0.05	5.67	Yes
Copper (Cu)	mg/L	<0.002	<2	2.99	Yes
Nickel (Ni)	mg/L	<0.002	<0.07	5.35	Yes
Zinc (Zn)	mg/L	<0.002	<5	7.48	Yes
Cobalt (Co)	mg/L	<0.002	<0.5	7.9	Yes
Cadmium (Cd)	mg/L	<0.002	<0.003	6.24	Yes
Lead (Pb)	mg/L	<0.003	<0.01	6.74	Yes
Turbidity	NTU	6.39	<1	7.63	No
Free chlorine (Cl ₂)	mg/L	0.2	<5	-	Yes
Colour	Hazen	<5	<15	-	Yes
Free cyanide (CN)	mg/L	<0.01	-	-	-
Phenol	mg/L	0.022	<0.01	-	Yes
Total organic carbon	mg/L	2.21	<10	-	Yes
Taste	FTN	<5	<5	-	Yes
Odour	TON	<5	<5	-	Yes
Arsenic (As)	mg/L	<0.001	<0.01	10.93	Yes
Selenium (Se)	mg/L	<0.005	<0.01	11.42	Yes
Mercury (Hg)	mg/L	<0.007	0.006	-	Yes
Dissolved Uranium (U)	mg/L	<0.001	<0.015	10.98	Yes

Table 2. Cont.

Test Type	Reporting Units	Results	Specification—Maximum Limit	Uncertainty of Measurement %	Complies to Specification
Vanadium (V)	mg/L	<0.001	<0.2	-	Yes
Antimony (Sb)	mg/L	<0.001	0.02	-	Yes
Trihalomethane (THM)	µg/L	13	-	-	-
Dibromochloromethane	µg/L	<2	<100	-	Yes
Bromodichloromethane	µg/L	<2	<60	-	Yes
Monochloramine	mg/L	<0.1	-	-	-
Chloroform	µg/L	12	<300	-	Yes
Bromoform	µg/L	<2	<100	-	Yes

The effluent quality of the slaughterhouse was used to calculate the grey WF, as the quality of the discharge from the Kroonstad municipal sewage treatment plant was not available. The last available discharge quality report from the Department of Water and Sanitation (DWS) [24] is from 2011, and it found that the discharge quality was not up to standard. Furthermore, a private investigation into the discharge quality of sewage treatment plants is done yearly by AfriForum [25]. According to their report, the faecal coliforms form count for the Kroonstad plant was 1 million CfU/100 mL. The faecal coliforms of the sewage treatment plant's discharge were thus approximately 1800 times higher than those of the slaughterhouse's effluent of 55 CfU/100 mL.

Even though De Klerk [25] did not report on the COD level of the sewage plant's discharge, Seo et al. [26] found that the correlation (r) between Faecal Coliforms and COD are significantly ($p < 0.05$) positive at 0.340 on average for the discharge of eight sewage treatment plants. The results of Seo et al. [26] thus suggest that the COD of the sewage treatment plant's discharge will probably be higher than that of the slaughterhouse.

Kroonstad is situated in the Rhenoster/Vals region of the Middle Vaal Water Management Area, which forms part of the greater Vaal River Catchment, part of the greater Orange River Catchment [27]. The Vaal River water quality indicators and availability of water were thus used in this study. According to Rand Water [28], the maximum acceptable concentration ($C_{\max}$) of COD was 20 mg/L, while the natural background concentration (C_{nat}) of the catchment was 15 mg/L for the period 1 July 2015 to 30 June 2016.

Table 2 results showed that the water received from the municipality was of good quality and complied with all the specifications, except turbidity. Furthermore, since the water is purified and treated for human consumption, it does not contain any organic material, and the COD level of the intake water (C_{act}) is equal to zero (0).

2.3. Beef Processing Water Footprint

To estimate the WF for a slaughterhouse and cutting plant, Hoekstra et al.'s [4] calculation framework was followed. The distinction between the blue, green, and grey WF is essential, because the slaughterhouse only has blue and grey WFs. Water in slaughterhouses is used for cleaning, and no water is incorporated into the product. Approximately 82% of the total slaughterhouse's water intake is discharged through the municipal sewer systems, while the rest (18%) is lost due to evaporation [1]. The blue WF in the case of slaughterhouses comprises 18% of the evaporation [4]. The grey WF, as defined by Franke et al. [29], is calculated as (Equation (1)):

$$\text{GWF} = (L/L_{\text{crit}}) \times R, \quad (1)$$

where GWF is the grey WF in volume/time, L is the pollutant load entering a water body in mass/time, L_{crit} is the critical pollutant load in mass/time, and R is the runoff of the water body in volume/time.

The critical pollutant load (L_{crit}) is the load of pollutants that will entirely consume the assimilation capacity of the receiving water body and can be calculated as [29] (Equation (2)):

$$L_{crit} = R \times (C_{max} - C_{nat}), \quad (2)$$

where C_{max} is the maximum acceptable concentration of the pollutant in mass/volume, and C_{nat} is the natural background concentration of the pollutant in mass/volume.

The pollutant load that enters a water body (L) is calculated differently depending on whether it stems from one point or different sources. In the case of a slaughterhouse, it is point source pollution and is therefore calculated as [29] (Equation (3)):

$$L = \text{Effl} \times C_{\text{effl}} - \text{Abstr} \times C_{\text{act}}, \quad (3)$$

where Effl is the effluent volume in volume/time, C_{effl} is the concentration of the pollutant in the effluent in mass/volume, Abstr is the water volume of the abstraction in volume/time, and C_{act} is the concentration of the pollutant in the intake water in mass/volume.

By inserting Equations (2) and (3) into Equation (1), the grey WF (GWF) of a slaughterhouse is calculated as (Equation (4)):

$$\text{GWF} = (\text{Effl} \times C_{\text{effl}} - \text{Abstr} \times C_{\text{act}}) / (C_{max} - C_{nat}), \quad (4)$$

The grey WF for each contaminant must be calculated separately, after which the largest grey WF is taken as the overall grey WF [29].

Although the procedure to calculate the WF can be used as-is for a slaughterhouse (as a business) or per cattle unit (CU) slaughtered (as a product), it is more difficult to calculate the WF of individual cuts or parts of the carcass. As the price in R/kg (R denotes South African Rand (ZAR). The USD/ZAR exchange rate at the time of data collection was \$1.00 = R12.78) of the different cuts and parts differ, while the relative weight of each cut or part also differs between animals, the WF of an individual cut or part of the carcass should be calculated according to its VF. The VF of each of these cuts will vary according to the relative size and build of the animal the carcass stems from.

The slaughter process starts with an animal of a specific live weight (LW), which is then divided into the carcass weight (CW), by-products weight (BPW) (head, skin, and offal), as well as the loss of body fluid weight (BFW), which is the weight of the blood, urine, stomach contents, and other fluids (Equation (5)):

$$\text{LW} = \text{CW} + \text{BPW} + \text{BFW}, \quad (5)$$

The CW and BPW are then multiplied by their respective prices (P) to determine the value (V) of the carcass and by-products (Equation (6)):

$$V_{C \text{ or } BP} = W_{C \text{ or } BP} \times P_{C \text{ or } BP}, \quad (6)$$

The total value (TV) is determined by adding the value of the carcass and by-products and is used to calculate the VF by expressing the value of the carcass or by-products as a factor of the TV (Equation (7)):

$$\text{VF}_{C \text{ or } BP} = V_{C \text{ or } BP} / \text{TV}, \quad (7)$$

The WF for the carcass and by-products are allocated according to the VF of each. However, since the carcass consists of different cuts, each with its own price, the VF of the various cuts in accordance with the value of the carcass should be calculated (Equation (8)):

$$\text{VF}_{\text{Cut1}} = V_{\text{Cut1}} / V_C, \quad (8)$$

where the V for the specific cut (cut1 or cut2) is calculated as (Equation (9)):

$$V_{\text{Cut1}} = W_{\text{Cut1}} \times P_{\text{Cut1}}, \quad (9)$$

The WF per kilogram of the individual cut can then be allocated according to the VF of the cut (Equation (10)):

$$WF_{\text{Cut1}} = (WF_{\text{Carcass}} \times VF_{\text{Cut1}}) / W_{\text{Cut1}}, \quad (10)$$

where the processing WF of the carcass is derived from the processing WF ($WF_{\text{Processing}}$) per animal slaughtered (Equation (11)):

$$WF_{\text{Carcass}} = WF_{\text{Processing}} \times VF_{\text{Carcass}}, \quad (11)$$

One possible solution for a slaughterhouse that wishes to reduce its WF is to determine the effect that the slaughtering of heavier animals will have on its WF. To do this, a simulation with three scenarios was run. The first scenario (No. 1) accounted for the base scenario and assumed that the slaughterhouse slaughters the same total number of animals per year as in the data and that the number of animals from each breed is equal since the specific number of animals per breed that are slaughtered is unknown. The second scenario (No. 2) assumed that only Simmentalers with heavier carcasses are slaughtered, but the total amount of meat produced (total carcass weight) remains the same as in the first scenario, so fewer animals are slaughtered in this case. Finally, the third scenario (No. 3) assumed that the slaughterhouse slaughters only Simmentalers, but with the same number of cattle units as in the past, so the amount of meat produced increases.

3. Results

Since 18% of the direct water used evaporates (blue water), while the remaining 82% ends up as effluent in the sewer system (grey water), the direct water use for processing is divided into a blue WF of 87.12 L/CU slaughtered, while a grey WF is estimated for the remainder of the 396.88 L. The grey WF is calculated by applying Equation (4) and inserting the indicators as obtained from the data. The grey WF was calculated for COD and faecal coliforms, with the COD concentrations resulting in the highest processing grey WF of 73,343 L/CU slaughtered. In comparison, the faecal coliforms grey WF was equal to 185 L/CU.

The total processing WF per slaughtered cattle unit is thus equal to 73,430 L. Since the different breeds result in different dressing percentages, carcass weights, and muscle-to-bone ratios, it is necessary to allocate the processing WF per CU according to the VF of the by-products, carcasses, and cuts of the different breeds to determine whether some breeds utilise less processing water per kilogram of boneless beef than others do. The processing WFs of the seven different cattle breeds are presented in Table 3, with the relationship between their respective processing WFs and their carcass weights shown in Figure 2.

The processing WF per CU (WF_{CU}) is the same for all the breeds. Although the R/kg price of the different breeds' carcasses and by-products is the same, the different relationships between the weight of the carcass (W_C) and by-products' weight caused the carcass VF (VF_C) and by-products VF (VF_{BP}) to differ slightly and thus also the processing WF per carcass (WF_{carcass}). However, the processing WF/kg of the carcass differed notably between the different breeds and ranged from 280.50 L/kg (for the Afrikaner with a carcass weight of 232.97 kg) to 187.45 L/kg (for the Simmentaler with a carcass weight of 349.89 kg). It is also evident from Figure 2 that there is a strong negative relationship between the carcass weight and the total WF per kilogram of the carcass. Lighter carcasses thus have a higher processing WF than heavier carcasses.

Table 3. Processing water footprints of the different cattle breeds.

		Brahman	Afrikaner	Simbra	Bons-Mara	Angus	Simmentaler	Limousin
Processing WF/CU								
BWF	L/CU	87.12	87.12	87.12	87.12	87.12	87.12	87.12
GWF	L/CU	73,343	73,343	73,343	73,343	73,343	73,343	73,343
TWF	L/CU	73,430	73,430	73,430	73,430	73,430	73,430	73,430
Processing WF/by-products								
W _{BP}	kg	97.93	86.66	109.16	117.72	103.76	130.16	118.72
VF _{BP}		0.109	0.110	0.108	0.108	0.108	0.107	0.107
BWF _{BP}	L/BP	9.4	9.5	9.4	9.4	9.5	9.3	9.4
GWF _{BP}	L/BP	7990	8072	7925	7884	7955	7834	7880
TWF _{BP}	L/BP	8000	8083	7935	7894	7965	7843	7889
TWF/KG _{BP}	L/kg	81.7	93.3	72.7	67.1	76.8	60.3	66.5
Processing WF/carcass								
W _C	kg	263.25	232.97	293.45	316.46	278.93	349.89	319.13
VF _C		0.891	0.890	0.892	0.892	0.892	0.893	0.893
BWF _C	L/carcass	77.6	77.6	77.7	77.8	77.7	77.8	77.8
GWF _C	L/carcass	65,352	65,270	65,417	65,459	65,388	65,509	65,463
TWF _C	L/carcass	65,430	65,348	65,495	65,536	65,465	65,587	65,541
TWF/KG _C	L/kg	248.6	280.5	223.2	207.1	234.7	187.5	205.4
Processing WF/kg rib eye								
W _{Rib eye}	kg	2.90	3.03	3.52	4.11	3.91	3.85	4.47
VF _{Rib eye}		0.036	0.042	0.039	0.042	0.045	0.036	0.045
BWF _{Rib eye}	L/kg	0.957	1.080	0.860	0.798	0.904	0.722	0.791
GWF _{Rib eye}	L/kg	806.01	909.63	723.78	671.58	761.11	607.88	666.00
TWF _{Rib eye}	L/kg	806.97	910.71	724.64	672.38	762.02	608.60	666.80
Processing WF/kg topside								
W _{Topside}	kg	15.01	12.58	15.55	16.14	14.23	17.49	18.83
VF _{Topside}		0.073	0.070	0.068	0.066	0.066	0.064	0.076
BWF _{Topside}	L/kg	0.380	0.429	0.341	0.317	0.359	0.287	0.314
GWF _{Topside}	L/kg	319.82	360.94	287.20	266.48	302.01	241.21	264.27
TWF _{Topside}	L/kg	320.20	361.37	287.54	266.80	302.37	241.49	264.58
Processing WF/kg flank								
W _{Flank}	kg	12.11	10.25	11.15	12.97	12.55	12.25	11.81
VF _{Flank}		0.045	0.043	0.037	0.040	0.044	0.034	0.036
BWF _{Flank}	L/kg	0.287	0.324	0.258	0.239	0.271	0.216	0.237
GWF _{Flank}	L/kg	241.48	272.52	216.84	201.20	228.03	182.12	199.53
TWF _{Flank}	L/kg	241.77	272.85	217.10	201.44	228.30	182.34	199.77

WF: water footprint; CU: cattle unit; W: weight; BP: by-product; VF: value fraction; BWF: blue water footprint; GWF: grey water footprint; TWF: total water footprint; TWF/KG: total water footprint per kilogram.

It is clear from Table 3 that the processing WF per kilogram of boneless beef from individual cuts did not only vary between the different breeds but also between cuts due to their different VFs. The three cuts that were used in the analysis can be classified as a high-value cut (rib eye @ R113.64/kg), medium-value cut (topside @ R45.09/kg), and a low-value cut (flank @ R34.05/kg) concerning the carcass price of R35.00/kg. The three cuts were only chosen as an example of the WF for different value cuts, and the methodology can be applied to any cut of the carcass. The relationship between the carcass weight and the processing WF per kilogram of rib eye, a high-value cut, is presented in Figure 3. The relationship for the WF of the rib eye is also negative, as is the WF for the carcass.

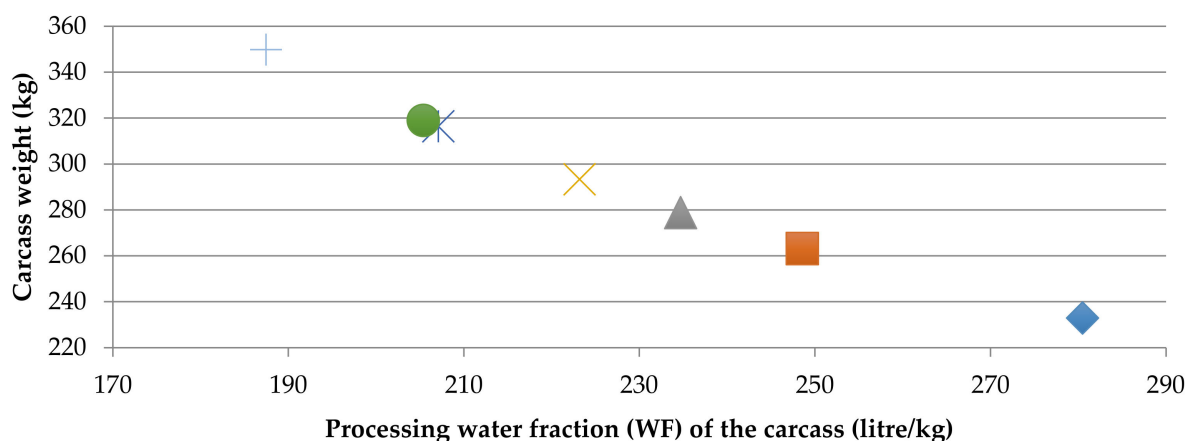


Figure 2. Relationship between the carcass weight and processing water footprint of the different breeds.

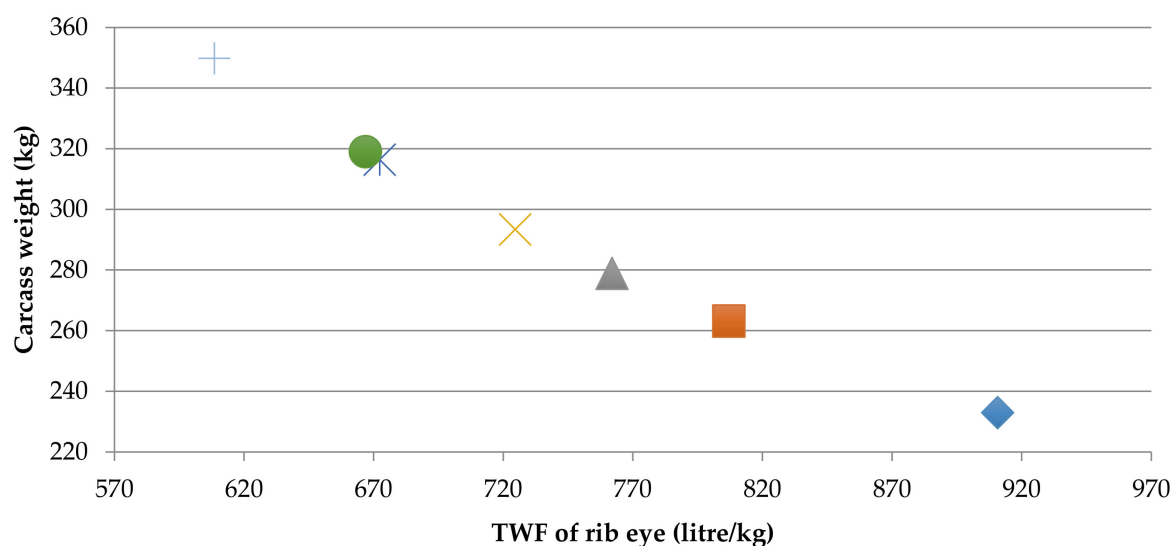


Figure 3. The relationship between the carcass weight and the processing water footprint of the rib eye, as a high-value cut, for the different breeds.

Although the processing WF of a kilogram of rib eye is much higher than that of a kilogram of the carcass for all the breeds, it is interesting that the relationship follows the same slope as the price and VF. The reason is that the R/kg price of the different cuts and carcasses for all the breeds is the same. The percentage difference in the processing WF of a kilogram of a carcass or an individual cut between two breeds will thus remain the same.

Table 4 provides the percentage difference between the processing WF of the Afrikaner, as the breed with the highest processing WF, and the other breeds. These percentages are the same for the differences in the WF per kilogram of the carcasses and the WF per kilogram of the individual cuts. According to Table 4, the Brahman's WF is 11% lower than that of the Afrikaner, while the WF of the Simmentaler is 33% lower than that of the Afrikaner. The correlation between the carcass weight and the WF of the different breeds indicates a strong negative relationship ($r = -0.9916$, $p < 0.001$) between the two factors.

The results show that the relative size of an animal at the slaughter point has a large effect on the processing WF of the slaughtered animal because the processing WF decreases as the carcass weight of the animal increases. The same effect can also be found in terms of the individual cuts of beef, where the WF of cuts from larger carcasses is lower than for smaller carcasses.

Table 4. Differences in the processing water footprints of the breeds in relation to the Afrikaner.

Breed	Carcass Weight (kg)	Differences in the Processing WF in Relation to the Afrikaner
Afrikaner	232.97	-
Brahman	263.25	−11%
Angus	278.93	−16%
Simbra	293.45	−20%
Bonsmara	316.46	−26%
Limousin	319.13	−27%
Simmentaler	349.89	−33%

The outcomes of the simulations with three scenarios are presented in Table 5. When the second scenario is used, the results indicate that the number of animals slaughtered decreases by 16.15%, while the same output in total carcass weight is realised. The important aspect is that the total WF of the slaughterhouse decreases by 16.15% as well, while the WF/kg carcass reduces by 17.29%.

Table 5. Results of the simulation of the three slaughter scenarios.

No.	Description	Cattle Units Slaughtered	Carcass Weight (kg)	Total Weight (tonne)	Total Water Footprint ('000 m ³)	Water Footprint/kg Carcass (L)
1	Different breeds	51,703	293.40	15,170	3797	226.7
2	Simmentaler (same total weight)	43,354	349.90	15 170	3184	187.5
3	Simmentaler (same cattle units)	51,703	349.90	18,091	3797	187.5
(2-1)	Difference	−16.15%	19.26%	0.00%	−16.15%	−17.29%
(3-1)	Difference	0.00%	19.26%	19.26%	0.00%	−17.29%

Comparing the third scenario with the first, the number of cattle units slaughtered remains the same, but the total weight produced increases by 19.26%. Thus, although the total WF remains the same for both scenarios, the WF/kg carcass also decreases by 17.29% as in the second scenario.

4. Discussion

The results indicated that in terms of the whole carcass, the processing WF/kg of the Simmentaler, as the heaviest breed, was at 187.5 L/kg in total 33% lower than that of the Afrikaner, the lightest breed, at 280.5 L/kg. The calculated water footprint may seem very low when compared to other studies like Mekonnen and Hoekstra [5,30], who found the global WF for a kilogram of boneless beef to be 15,415 and 17,387 L/kg for South Africa, or Palhares et al. [9], who estimated the WF of beef from a tropical production system as between 29,828 and 32,470 L/kg carcass weight. However, one must remember that the WF in this study is only for beef processing, not beef as a final product. The authors could not find any literature where the processing WF of beef was reported separately. Although some authors, like Palhares et al. [9], did mention that the processing plant's WF was included in the final WF, it was not reported separately. Noya et al. [31] did report the WF of pork separately as percentages for the different links in the value chain. Their results indicated that the slaughter, cutting, and processing of pork contributes 3% to the total WF of final products, while the grey WF of the slaughterhouse and cutting plant contributes 99% and 97%, respectively, to the total WF of the two plants. Almost all other existing

literature on the WF of beef, or meat, focuses primarily on the contribution of the WF of animal feed, as it makes up the bulk of the total WF for the final product. The problem with not reporting on the WFs of the individual links of the value chain is that it is challenging to make management decisions or policy suggestions to manage or decrease the WF of the final product, as the contributions of the different links are unknown.

Like Junior and Dziedzic [19] and Palhares et al. [9], most of the existing literature reports the WF in terms of beef cattle on either per kilogram of a live animal or per kilogram of a carcass. Only some studies, like Chapagain and Hoekstra [10] and Mekonnen and Hoekstra [11], broke it down into products (carcass, beef bone-in, and boneless beef) and by-products (offal, leather, and semen). However, the studies that did break the WF down into products and by-products using product and value fractions made some questionable assumptions about the product weights and values. There is also no existing literature that breaks down the beef products and by-products to final products purchased by consumers. Consumers, for example, do not purchase “boneless beef” from a retailer, but rather a specific cut like “rib eye steak”. Although not for beef, Noya et al. [31] calculated the WF for the pork supply chain and included cut pork, ham, dry-cured ham, spicy sausage, and fuet as final products and indicated that the WF of these products ranged between 9.60 and 15.60 m³/kg. These reported WFs are substantially larger than those calculated in this study, but they include the WF of the whole supply chain and not only processing. However, Noya et al. [31] did not publish the WF for slaughtering, cutting, and processing of the final products separately, although it was done for the carbon footprint. There was no transparent methodology on how the WF was allocated to the different products, but it seems to be done on weight and not value. In this study, we allocated the WF of processing beef to some final products and by-products with a value fraction allocation model and found that in terms of a specific cut of beef, a kilogram of rib eye from the Simmentaler had a processing WF of 608.60 L/kg, compared to the 910.71 L/kg for the rib eye of the Afrikaner. A comparison of the different cuts indicates that higher value cuts also have considerably higher WFs than lower value cuts, with the difference between a kilogram of rib eye and flank being 426.26 L/kg for the Simmentaler and 637.86 L/kg for the Afrikaner. Although the allocation was only done for the processing WF, the same methodology can be applied to allocate the total WF of beef production to final products. This will enable consumers to make an informed purchasing decision, as the WF of the different meat products can be compared.

Effluent discharge by slaughterhouses remains a primary environmental concern, with researchers publishing a range of titles on this topic. Musa and Idris [21] reviewed the most recent advances in physical and biological treatment technologies of slaughterhouse wastewater (slaughterhouse effluent). The review included four (4) physicochemical and six (6) biological treatment methods but concluded that further research needs to be conducted to harness the most cost-effective wastewater treatment. Most of the existing technologies that improve effluent quality have high investment costs or high energy demand (running costs) or require large surface areas to install [21]. Thus, it will require additional investment costs from the slaughterhouse without any immediate return, basically disincentivising the slaughterhouse to perform the installation.

Another option to reduce the WF, as identified in this study, would be to focus on the slaughtering of heavier animals. In the simulation that was performed, comparing the third scenario with the first shows that the number of cattle units slaughtered remains the same. Still, the total carcass weight produced increases by 19.26% when only the heavier Simmentaler breed is slaughtered. Therefore, although the total WFs for the two scenarios are the same, the WF/kg carcass also decreases by 17.29%, as in the second scenario. The slaughterhouse will, in this case, not reduce its total WF, as it will remain the same, but it will improve its environmental impact per kilogram of output. This will require no extra investment from the slaughterhouse, while the economic returns should increase as the average production inputs per kilogram of production (carcass) reduces, as more kilograms will be processed.

5. Conclusions

The objective of this study was to estimate the WF of different cattle breeds at a slaughterhouse and cutting plant and allocate the WF according to different cuts (products) and by-products, based on the product and value fraction of each. The direct water use of the slaughterhouse per cattle unit slaughter was 484 L, which might not seem high, but the very high organic load of the effluent results in a grey WF of 73,430 L per slaughtered cattle unit. The heavier breeds had lower processing WFs per kilogram carcass than the lighter breeds, while the more expensive meat cuts had higher processing WFs than cheaper cuts.

This study was novel because the beef processing WF was estimated through a bottom-up approach using primary data. The study provided a framework for allocating the WF of beef to individual cuts that stemmed from a carcass on the VF of each. The same VF allocation model can assign the total WF of beef production according to different cuts (products) and by-products destined for the retail sector. In terms of providing information to customers on the environmental footprint of their consumption, the allocation of the WF of beef according to the VF of the products is vital to make informed choices.

It is recommended that the WF of beef production, according to a bottom-up approach for all the links in the value chain, should be estimated. The total WF can then be allocated according to the VF allocation model to provide WF information of individual beef cuts. The specific and accurate information can be expanded to include different production methods and cattle breeds and applied to set benchmarks for the WF of beef production and specific beef products and by-products. The uptake of WF information for government policy formation is currently very low. Although many reasons may be offered on why this is the case, one reason is the accuracy of the existing estimated WFs. Most of the current WFs literature was estimated with a top-down approach using country-level data. If, for example, an environmental tax should be imposed on the WF of products, the WF on which the tax is based must be accurate to avoid public uproar. The bottom-up analysis of the WF of beef (or any other product) will provide data that will be accurate enough for policy formulation.

Author Contributions: Conceptualization, F.A.M. and H.J.; methodology, F.A.M.; formal analysis, F.A.M.; writing—original draft preparation, F.A.M.; writing—review and editing, H.J.; supervision, H.J.; project administration, H.J.; funding acquisition, H.J. Both authors have read and agreed to the published version of the manuscript.

Funding: This research was partly funded by the Water Research Commission of South Africa, project number K5/2397//4.

Institutional Review Board Statement: Ethical review and approval were waived for this study, due to the fact that the data was obtained from normal red meat production processes. The animals were thus not subjected to any experimental practices.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. Some of the data are not publicly available due to the sensitive nature thereof in a competing environment.

Acknowledgments: The authors acknowledge the Sernick Group for their contributions.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

Table A1. Weights, prices, and values for the different products and by-products.

		Brahman	Afrikaner	Simbra	Bonsmara	Angus	Simmentaler	Limousin
Weights								
Live Weight (kg)	kg	429.00	404.40	483.00	521.90	484.11	565.50	498.80
Carcass Weight (kg)	kg	263.25	232.97	293.45	316.46	278.93	349.89	319.13
By-Products Weights								
Head (kg)	kg	12.37	10.95	13.79	14.87	13.11	16.44	15.00
Offal (kg)	kg	48.70	43.10	54.29	58.55	51.60	64.73	59.04
Hide (kg)	kg	36.86	32.62	41.08	44.30	39.05	48.98	44.68
Total By-Products (kg)	kg	97.93	86.66	109.16	117.72	103.76	130.16	118.72
Carcass Cuts Weights								
Rib Eye (kg)	kg	2.90	3.03	3.52	4.11	3.91	3.85	4.47
Top Side (kg)	kg	15.01	12.58	15.55	16.14	14.23	17.49	18.83
Flank (kg)	kg	12.11	10.25	11.15	12.97	12.55	12.25	11.81
Values								
Carcass @ R38.50/kg	R	R 10,135	R 8969	R 11,298	R 12,184	R 10,739	R 13,471	R 12,287
By-Products Values								
Head @ R100/head	R	R 100.00	R 100.00	R 100.00	R 100.00	R 100.00	R 100.00	R 100.00
Offal @ R9.35/kg	R	R 455.36	R 402.98	R 507.60	R 547.40	R 482.48	R 605.22	R 552.02
Hide @ R15.50/kg	R	R 571.25	R 505.54	R 636.79	R 686.72	R 605.28	R 759.26	R 692.51
Total By-Products	R	R 1127	R 1009	R 1244	R 1334	R 1188	R 1464	R 1345
Carcass Cuts								
Rib Eye @ R125/kg	R	R 361.97	R 378.58	R 440.18	R 514.25	R 488.13	R 481.10	R 558.48
Top Side @ R49.60/kg	R	R 744.26	R 623.99	R 771.42	R 800.52	R 705.58	R 867.73	R 933.90
Flank @ R37.45/kg	R	R 453.50	R 383.89	R 417.61	R 485.91	R 470.07	R 458.62	R 442.20

References

1. Steffen, Robertson and Kirsten Inc. Consulting Engineers. Water and Wastewater Management in the Red Meat Industry. WRC Project No 145, TT 41/89. Available online: <http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/TT-41-89.pdf> (accessed on 17 April 2015).
2. Department of Water Affairs and Forestry (DWAF). *Guidelines for the Handling, Treatment and Disposal of Abattoir Waste*; Draft August 2001; DWAF: Pretoria, South Africa, 2001.
3. Hoekstra, A.Y. (Ed.) Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade. In *Value of Water Research Report Series No. 12*; UNESCO-IHE Institute for Water Education: Delft, The Netherlands, 2003.
4. Hoekstra, A.Y.; Chapagain, A.K.; Aldaya, M.M.; Mekonnen, M.M. *The Water Footprint Assessment Manual: Setting the Global Standard*; Earthscan: London, UK, 2011.
5. Mekonnen, M.M.; Hoekstra, A.Y. A global assessment of the water footprint of farm animal products. *Ecosystems* **2012**, *15*, 401–415. [\[CrossRef\]](#)
6. Hoekstra, A.Y. The water footprint of animal products. In *The Meat Crisis: Developing More Sustainable Production and Consumption*; D'Silva, J., Webster, J., Eds.; Earthscan: London, UK, 2010; pp. 22–33.
7. Maré, F.A.; Jordaan, H. Industrially Finished Calves: A Water Footprint-Profitability Paradox. *Water* **2019**, *11*, 2565. [\[CrossRef\]](#)
8. Maré, F.A.; Jordaan, H.; Mekonnen, M.M. The Water Footprint of Primary Cow-Calf Production: A Revised Bottom-Up Approach Applied on Different Breeds of Beef Cattle. *Water* **2020**, *12*, 2325. [\[CrossRef\]](#)
9. Palhares, J.C.P.; Morelli, M.; Novelli, T.I. Water footprint of a tropical beef cattle production system: The impact of individual-animal and feed management. *Adv. Water Resour.* **2021**, *149*, 103853. [\[CrossRef\]](#)
10. Chapagain, A.K.; Hoekstra, A.Y. Virtual water flows between nations in relation to trade in livestock and livestock products. In *Value of Water Research Report Series No. 13*; UNESCO-IHE Institute for Water Education: Delft, The Netherlands, 2003.
11. Mekonnen, M.M.; Hoekstra, A.Y. The green, blue and grey water footprint of farm animals and animal products. Volume 1: Main report. In *Value of Water Research Report Series No. 48*; UNESCO-IHE Institute for Water Education: Delft, The Netherlands, 2010.
12. Ercin, A.E.; Aldaya, M.M.; Hoekstra, A.Y. The water footprint of soy milk and soy burger and equivalent animal products. *Ecol. Indic.* **2012**, *18*, 392–402. [\[CrossRef\]](#)

13. Hoekstra, A.Y. The hidden water resource use behind meat and dairy. *Anim. Front.* **2012**, *2*, 3–8. [[CrossRef](#)]
14. Ridoutt, B.G.; Sanguansri, P.; Freer, M.; Harper, G.S. Water footprint of livestock: Comparison of six geographically defined beef production systems. *Int. J. Life Cycle Assess.* **2012**, *17*, 165–175. [[CrossRef](#)]
15. Gerbens-Leenes, P.W.; Mekonnen, M.M.; Hoekstra, A.Y. The water footprint of poultry, pork and beef: A comparative study in different countries and production systems. *Water Resour. Ind.* **2013**, *1–2*, 25–36. [[CrossRef](#)]
16. Bosire, D.K.; Ogutu, J.O.; Said, M.Y.; Krol, M.S.; De Leeuw, J.; Hoekstra, A.Y. Trends and spatial variation in water and land footprints of meat and milk production systems in Kenya. *Agric. Ecosyst. Environ.* **2015**, *205*, 36–47. [[CrossRef](#)]
17. Bhagat, S.; Santra, A.K.; Mishra, S.; Khune, V.N.; Bobade, M.D.; Dubey, A.; Yadav, A.; Soni, A.; Banjare, S.; Yadav, G. The water footprint of livestock production system and livestock products: A dark area: A review. *Int. J. Fauna Biol. Stud.* **2020**, *7*, 83–88.
18. Cosentino, C.; Adduci, F.; Musto, M.; Paolino, R.; Freschi, P.; Pecora, G.; D'Adamo, C.; Valentini, V. Low vs high “water footprint assessment” diet in milk production: A comparison between triticale and corn silage based diets. *Emir. J. Food Agric.* **2015**, *27*, 312–317. [[CrossRef](#)]
19. Junior, U.J.R.; Dziedzic, M. The water footprint of beef cattle in the amazon region, Brazil. *Ciência Rural* **2021**, *51*, e20190294. [[CrossRef](#)]
20. Ngxumeshe, A.M.; Ratsaka, M.; Mtileni, B.; Nephawe, K. Sustainable Application of Livestock Water Footprints in Different Beef Production Systems of South Africa. *Sustainability* **2020**, *12*, 9921. [[CrossRef](#)]
21. Musa, M.A.; Idris, S. Physical and Biological Treatment Technologies of Slaughterhouse Wastewater: A Review. *Sustainability* **2021**, *13*, 4656. [[CrossRef](#)]
22. Ibidhi, R.; Salem, H.B. Water footprint of livestock products and production systems: A review. *Anim. Prod. Sci.* **2020**, *60*, 1369–1380. [[CrossRef](#)]
23. Oosthuizen, P.L.; Maré, F.A. The profit-maximising feeding period for different breeds of beef cattle. *Agrekon* **2018**, *57*, 108–120. [[CrossRef](#)]
24. Department of Water and Sanitation (DWS). 2011 Green Drop Report. Available online: <https://www.dws.gov.za/Documents/GD/GDFS.pdf> (accessed on 8 June 2021).
25. De Klerk, L. AfriForum’s Blue and Green Drop Project. November 2020. Available online: https://afriforum.co.za/wp-content/uploads/2020/11/Blou-en-groen_2020_Engels.pdf (accessed on 8 June 2021).
26. Seo, M.; Lee, H.; Kim, Y. Relationship between Coliform Bacteria and Water Quality Factors at Weir Stations in the Nakdong River, South Korea. *Water* **2019**, *11*, 1171. [[CrossRef](#)]
27. Department of Water Affairs and Forestry (DWAF). *Middle Vaal Water Management Area: Overview of Water Resources Availability and Utilisation*; Report No. P WMA 09/000/00/0203; DWAF: Pretoria, South Africa, 2003.
28. Rand Water, Quarterly Water Quality Status of the Vaal Dam Reservoir Catchment, 1 July 2015–30 June 2016. Available online: http://www.reservoir.co.za/forums/vaaldam/vaaldam_forum/vaaldam_chemical_2016/RW_VaalDam_Apr-Jun2016.pdf (accessed on 21 October 2016).
29. Franke, N.A.; Boyacioglu, H.; Hoekstra, A.Y. Grey water footprint accounting: Tier 1 supporting guidelines. In *Value of Water Research Report Series No. 65*; UNESCO-IHE Institute for Water Education: Delft, The Netherlands, 2013.
30. Mekonnen, M.M.; Hoekstra, A.Y. The Green, Blue and Grey Water Footprint of Farm Animals and Animal Products. Volume 2: Appendices. In *Value of Water Research Report Series No. 48*; UNESCO-IHE Institute for Water Education: Delft, The Netherlands, 2010.
31. Noya, I.; Aldea, X.; Gasol, C.M.; González-García, S.; Amores, M.J.; Colón, J.; Ponsá, S.; Roman, I.; Rubio, M.A.; Casas, E.; et al. Carbon and water footprint of pork supply chain in Catalonia: From feed to final products. *J. Environ. Manag.* **2016**, *171*, 133–143. [[CrossRef](#)] [[PubMed](#)]