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Water Footprint Assessment of Beef and Dairy Cattle Production in the Regional Unit of Karditsa, Greece

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Abstract: One of the most important factors affecting water resources is livestock development. This study focuses on estimating the water demands of beef and dairy cattle breeding, as well as the corresponding products, in the Regional Unit of Karditsa (Greece), while simultaneously assessing the pollution caused by this activity in water bodies. The impacts are measured using the water footprint (WF) approach across its three dimensions (green, blue, and gray), considering the quantity of feed and water utilized by each animal type and the production system applied in the research area. For beef production, the intensive system shows a total WF of 90,535 m^3/ton (gray 88%, green 9%, blue 3%), while the semi-intensive system totals 82,027 m^3/ton (gray 84%, green 12%, blue 4%). For dairy cows, the total WF reaches 2750 m^3/year/ton of milk (gray 81%, green 14%, blue 5%). Gray WF was estimated based on pollutant loads from livestock waste using concentration thresholds for biochemical oxygen demand (BOD_5), nitrogen (N), and phosphorus (P), providing a clearer view of water quality degradation linked to livestock activities. These findings can guide regional directorates in addressing key water-related pressures from livestock production.

Keywords: water footprint; livestock water demands; beef and dairy cattle; case study application

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1. Introduction

Between 2000 and 2024, global water consumption increased due to urbanization, the consistently high water demand of the agricultural sector, and rising meat consumption, all of which play a key role in affecting water availability [1]. In recent decades, the production of livestock products has increased to meet the demands of a growing population. In terms of water conservation, the water use of live animals has become more significant. Moreover, within the framework of agricultural water utilization, water footprints (WFs) have become a significant sustainability metric [2].

In the Regional Unit of Karditsa, one of the central challenges is the competing demand for water from Lake Plastira, a key reservoir in the area. This lake serves multiple uses, including domestic water supply, crop irrigation, livestock production, hydroelectric power generation, and recreational activities. These overlapping demands place pressure on the region's water resources, underscoring the need for integrated and sustainable water management.

In Greece, water resources management is implemented through the Water Directorates of each region, which are responsible for coordinating the relevant services involved in different water uses (e.g., the public electricity company for hydroelectric power, irrigation authorities, and water supply services). While both national and international legislation provide a framework, the management of water resources remains a complex and evolving challenge, particularly in the face of climate change.

Although farm animal breeding requires substantial water resources, not enough attempts have been made to estimate these demands. Therefore, for sustainable water management, an index connecting water use and livestock product consumption is needed, and the water footprint concept could be utilized. To describe and evaluate water use in agricultural production systems, such as dairy and meat production, water footprints have been employed [2]. A number of studies present broad assessments of water consumption in animal husbandry [3–7]. Mekonnen and Hoekstra [8], as well as Chapagain and Hoekstra [9,10] performed a thorough evaluation of all three aspects of the water footprint linked to animal products. However, some factors related to pollution caused by livestock activities, such as farm animal waste, were not taken into consideration.

Regarding the virtual water balance, which is obtained by subtracting the volume of exports from the volume of water imports, Greece appears to be among the top twenty net water-importing countries [10]. This virtual water refers to the volume of water used in the production of imported agricultural goods, such as animal feed and livestock products. Because Greece is not self-sufficient in these sectors and relies on imports for these commodities, this dependency elevates Greece's ranking among the top net virtual water-importing countries. Pfister et al. [11] give a similar interpretation, stating that the concept of the water footprint is designed to evaluate the efficiency of freshwater use on a global scale, recognizing it as a finite and valuable resource. Water stress, defined as the ratio between total freshwater withdrawals from all major sectors and total renewable freshwater sources—after accounting for environmental water demands—reached 20.5% in Greece in 2023, an increase compared to 18.5% in 2000 [12,13].

According to the most recent available data published in the FAO database [12], Greece's annual production in 2021 was 33,000 tons of bovine meat and 71,900 tons of bovine milk. The sustainability of water usage can be assessed by contrasting the water footprint of a region with the maximum sustainable water footprint for that region [14]. Hoekstra [15] suggests that water-demanding livestock products should be produced in water-abundant regions rather than in water-scarce regions.

Additionally, consumers are increasingly demanding that food production be sustainable through the efficient use of available natural resources in the production of ever-growing amounts of livestock products [16]. Liao and Su [17] also state that the implementation of the water footprint can provide a strategy for the sustainable utilization of water resources. As feed production requires the most water in livestock production, feed and pasture management strategies should aim for the efficient and sustainable use of both rainwater and irrigation water to reduce the water footprint of feed production [18].

In order to achieve the sustainability of a food production system, such as beef and dairy farming, it is important to manage water resources properly, as these livestock activities have significant environmental impacts through their use of water resources [19]. Therefore, the water footprint can be considered an indicator of how sustainably livestock activities, such as beef and milk production, utilize freshwater [20].

This study aims to assess the quantity and quality deterioration of water resources due to livestock development in the Karditsa Regional Unit, utilizing the water footprint methodology and taking livestock waste into account. The study examines the effects of cattle breeding on water resources, as well as the implications of beef and cow milk production. While previous studies have explored water use in livestock systems, they have not fully accounted for the pollution dimension linked to livestock activities. This study addresses that gap by integrating key pollution parameters, such as biochemical oxygen demand (BOD_5), nitrogen (N), and phosphorus (P), into the gray water footprint. In this context, water footprint metrics can be a valuable tool to support informed decision-making, helping regional authorities balance competing demands more effectively. They offer insight into both water use and pollution across sectors, enabling more adaptive and sustainable water governance in an increasingly dynamic environment.

2. Materials and Methods

2.1. Study Area

The research area encompasses the Regional Unit of Karditsa, located within the Thessaly Region. Situated in southwestern Thessaly, it is predominantly an agricultural region. The area is rural, and its economic advancement is associated with the primary sector. The western and southern regions of the regional unit are characterized by rugged terrain, with livestock development as the key feature of the area [21]. Data collection for the study was conducted during the year 2022.

2.2. Water Footprint in Livestock

The WF method, first described by Hoekstra [22], offers a novel perspective for the concurrent assessment of water usage and pollution. WF serves as an alternative metric for freshwater utilization, encompassing all intermediary processes within the production chain, rather than being limited to conventional evaluations of water withdrawals.

The dimensions of the WF are the following:

1. The blue WF, which pertains to the utilization of surface and groundwater resources throughout the product's supply chain;
2. The green WF, which relates to the rainwater retained in the soil as moisture;
3. The gray WF, which denotes pollution, defined as the volume of freshwater necessary to assimilate the pollutant load [22].

Consequently, the WF is estimated as follows:

$$WF = WF_{green} + WF_{blue} + WF_{grey} \quad (1)$$

The WF of a live animal consists of different components: the indirect WF of the feed (which includes the water used for the cultivation of feed crops) and the direct WF related to the drinking water and service water consumed [22,23]. The WF of an animal is expressed as

$$WF = WF_{feed} + WF_{drink} + WF_{serv} \quad (2)$$

where WF_{feed}, WF_{drink}, and WF_{serv} denote the WF of an animal, considering the production systems associated with feed, drinking water, and service water consumption, respectively. The WF of an animal and each of its three elements can be presented in m^3/year/animal or, when aggregated over the animal's lifespan, in m^3/animal.

For beef cattle and, generally, for animals that provide their products after slaughter, it is most useful to consider the WF at the end of the animal's lifetime. Throughout the beef production chain—from calving to slaughter—water is used to produce grains for animal feed, grow pasture and forage crops, provide drinking water, and care for the animals (e.g., cleaning the animals and their shelters). Additionally, water is used during the slaughtering process [24].

For dairy cattle, it is most efficient to assess the WF of the animal annually, as this yearly WF may be readily correlated with its average annual milk output [5].

In the present study, beef and dairy cattle and their products are under consideration. In the Regional Unit of Karditsa, beef cattle breeding is conducted under intensive and semi-intensive systems, while dairy cattle are bred exclusively under an intensive system. For beef cattle, the animals are divided into two categories, including calves (<1 year) and adult cattle (1–2 years), while for dairy cattle the corresponding categories are calves (<1 year), heifers (1–2 years), and dairy cows (2–5 years).

2.3. Water Footprint of Feed Ingredients

The amount of water of an animal's feed can be divided into two categories: the actual water necessary for preparing the feed mixture and the water contained within the individual feed ingredients. The WF from feeding an animal at the end of its lifespan is computed as follows:

$$WF_{feed} = (q_{mixing} + C \times WF_{crop})/CY \quad (3)$$

where q_{mixing} denotes the volume of water in m^3 necessary for the preparation of the feed mix, C represents the annual quantity of the feed ingredients in tons of dry mass, WF_{crop} indicates the water footprint associated with cultivating the respective crop in m^3/ton, and CY refers to the carcass yield in tons [23].

The appropriate rations were formulated according to the daily requirements of each animal type and age group. The WF for each crop utilized as animal feed was sourced from our prior publications [25,26] to calculate the total WF in terms of feed at the conclusion of the animal's lifespan (m^3/ton). In this study, it was assumed that the animal feed is derived from crops cultivated in the Regional Unit of Karditsa, with the exception of soybean meal, which is not produced in Greece. The WF of soybean was derived from the findings of Mekonnen and Hoekstra [27].

2.4. Water Footprint of Drinking and Service Water

The drinking water consumption requirements of livestock are influenced by the species, age, and weight of the animal, as well as environmental factors, such as the temperature, humidity, and other factors. Another key parameter affecting water demand is the ration followed.

The service water related to animal breeding corresponds to the total amount of water utilized for cleaning the farmyard, washing the animals, and conducting other essential services required to sustain the environment during the animal's lifecycle [27]. According to Chapagain and Hoekstra [10], the components WF_{drink} and WF_{serv} can be determined by relying on the elements presented in Table 1.

Table 1. Drinking and service water requirements (L/animal/day) for cattle in different farming systems.

Animal	Age Group	Drinking Water Requirement		Service Water Requirement	
		Intensive System	Grazing System	Intensive System	Grazing System
Beef cattle	Young calves	5	5	2	0
	Adult cows	38	22	11	5
Dairy cattle	Calves, 0–1 years	5–23	4–18	0	0
	Heifers, 1–3 years	26–70	18–30	11	4
	Milking cows, 3–10 years	70	40	22	5

2.5. Livestock Waste

Livestock waste constitutes a significant source of pollutants and is, therefore, a concern for public health and the environment. Consequently, it is essential to manage livestock waste effectively to reduce the generation of harmful pollutants and to safeguard the environment and water resources. The impact of waste from farming depends on both its quantity and its pollutant concentration. The generation of manure and livestock waste in general is related to the species of animal and the feed program followed [28]. In general, industrial animal production systems deplete and contaminate ground and surface water resources to a greater extent than grazing or mixed systems [27].

The pollutant load parameters considered are biochemical oxygen demand (BOD_5), total nitrogen (N), and phosphorus (P). The assessment of the pollution load is based on the animal's live weight.

The gray water footprint of a process step refers to the volume of freshwater required to dilute pollutants released during that specific stage of production, ensuring water quality standards are met. It is calculated by dividing the pollutant load (L, in mass/time) generated in the process step by the difference between the maximum acceptable concentration of the pollutant (c_{max}, in mass/volume) and its natural concentration in the receiving water body (c_{nat}, in mass/volume).

$$WF_{proc,grey} = L/(c_{max} - c_{nat}) \tag{4}$$

Due to the lack of available data on the naturally occurring rates of the chemicals (N, P, and BOD_5) in the region's water bodies, the gray water footprint was determined using c_{max}, resulting in a more conservative calculation of the gray water footprint [29–31]. The computations were predicated on the maximum permissible concentration of each pollutant, assuming that the water would be reused for agricultural purposes, in accordance with national policies [32].

3. Results and Discussion

The green, blue, and gray water footprints were assessed using the aforementioned approach. Tables 2 and 3 provide indicative presentations of the water footprint associated with feed for cattle raised in intensive and semi-intensive systems, respectively, in the study area. Table 4 presents the calculation of the water footprint of feed consumed by dairy cows reared under the intensive farming system in the study area.

The findings of the water footprint utilized as drinking water for cattle raised under the intensive and semi-intensive systems, as well as for dairy cows (intensive system), are shown in Tables 5–7, respectively, where the service water footprint for beef cattle and dairy cows is also presented.

Tables 8, 10 and 12 present the calculated pollutant load—namely, nitrogen (N), phosphorus (P), and biochemical oxygen demand (BOD_5)—originating from the excretions of cattle raised under intensive and semi-intensive systems, as well as dairy cows raised under the intensive farming system, respectively, in the study area.

Tables 9, 11 and 13 present the gray water footprint from waste for the three study cases above, respectively. The calculation of the total water footprint, including all of its components (green, blue, and gray), for all three cases is shown in Tables 14–16.

The cumulative results concerning the total water footprint are shown in Table 17, where the units were selected according to the type of product.

Table 2. Water footprint associated with feed for beef cattle under the intensive livestock system.

	Type of System:	**Intensive**															
	Type of Product:	**Beef**															
	Feed Crop	**Feed Quantity (kg Dry Mass/Day)**		**Feed Quantity (Tons/Year)**		**WF$_{ingredient}$ (m^3/ton)**			**Water Consumption Associated with Feed (m^3/Year)**						**Total Water Consumption Associated with Feed at the End of Lifetime (m^3)**		
									Calves (<1 Year)			**Adult Cattle (1–2 Years)**					
		Calves (<1 Year)	**Adult Cattle (1–2 Years)**	**Calves (<1 Year)**	**Adult Cattle (1–2 Years)**	**Green**	**Blue**	**Gray**	**Green**	**Blue**	**Gray**	**Green**	**Blue**	**Gray**	**Green**	**Blue**	**Gray**
Concentrates	**Corn**	0.99	1.80	0.36	0.66	101.78	223.44	410.70	36.78	80.74	148.41	66.87	146.80	269.83	103.65	227.54	418.24
	Wheat	0.63	1.62	0.23	0.59	832.25	289.44	1166.70	191.38	66.56	268.28	492.11	171.15	689.87	683.49	237.70	958.15
	Soybean meal	0.70	1.53	0.26	0.56	2037.00	70.00	37.00	520.45	17.89	9.45	1137.56	39.09	20.66	1658.02	56.98	30.12
Roughages	**Alfalfa**	0.99	2.70	0.36	0.99	68.95	169.14	400.00	24.92	61.12	144.54	67.95	166.69	394.20	92.87	227.81	538.74
	Corn silage	0.80	3.60	0.29	1.31	16.96	37.24	68.45	4.95	10.87	19.99	22.29	48.93	89.94	27.24	59.81	109.93
	Total feed volume (tons/year):			1.50	4.11					**Total (m^3):**					2565.26	809.83	2055.18
										Average live weight at the end of lifetime (tons):					0.60		
										Total green WF of feed (m^3/ton):					**4275.43**		
										Total blue WF of feed (m^3/ton):					**1349.72**		
										Total gray WF of feed (m^3/ton):					**3425.29**		

Table 3. Water footprint associated with feed for beef cattle under the semi-intensive livestock system.

	Type of System:	**Semi-Intensive**															
	Type of Product:	**Beef**															
	Feed Crop	**Feed Quantity (kg Dry Mass/Day)**		**Feed Quantity (Tons/Year)**		**WF$_{ingredient}$ (m^3/ton)**			**Water Consumption Associated with Feed (m^3/Year)**						**Total Water Consumption Associated with Feed at the End of Lifetime (m^3)**		
									Calves (<1 Year)			**Adult Cattle (1–2 Years)**					
		Calves (<1 Year)	**Adult Cattle (1–2 Years)**	**Calves (<1 Year)**	**Adult Cattle (1–2 Years)**	**Green**	**Blue**	**Gray**	**Green**	**Blue**	**Gray**	**Green**	**Blue**	**Gray**	**Green**	**Blue**	**Gray**
Concentrates	**Corn**	0.99	1.80	0.36	0.66	101.78	223.44	410.70	36.78	80.74	148.41	66.87	146.80	269.83	103.65	227.54	418.24
	Wheat	0.63	1.62	0.23	0.59	832.25	289.44	1166.70	191.38	66.56	268.28	492.11	171.15	689.87	683.49	237.70	958.15
	Soybean meal	0.70	1.53	0.26	0.56	2037.00	70.00	37.00	520.45	17.89	9.45	1137.56	39.09	20.66	1658.02	56.98	30.12
Roughages	**Alfalfa**	0.99	2.70	0.36	0.99	68.95	169.14	400.00	24.92	61.12	144.54	67.95	166.69	394.20	92.87	227.81	538.74
	Total feed volume (tons/year):			1.21	2.79					**Total (m^3):**					2538.01	750.03	1954.24
										Average live weight at the end of lifetime (tons):					0.50		
										Total green WF of feed (m^3/ton):					**5076.03**		
										Total blue WF of feed (m^3/ton):					**1500.05**		
										Total gray WF of feed (m^3/ton):					**3890.49**		

Table 4. Water footprint associated with feed for dairy cows under the intensive livestock system.

	Type of System:	**Intensive**																				
	Type of Product:	**Cow Milk**																				
	Feed Crop	**Feed Quantity (kg Dry Mass/Day)**			**Feed Quantity (Tons/Year)**			**WF$_{ingredient}$ (m³/ton)**			**Water Consumption Associated with Feed (m³/Year)**									**Total Water Consumption Associated with Feed at the End of Lifetime (m³/Year)**		
											Calves (<1 Year)			**Heifers (1–2 Years)**			**Dairy Cows (2–5 Years)**					
		Calves (<1 Year)	**Heifers (1–2 Years)**	**Dairy Cows (2–5 Years)**	**Calves (<1 Year)**	**Heifers (1–2 Years)**	**Dairy Cows (2–5 Years)**	**Green**	**Blue**	**Gray**	**Green**	**Blue**	**Gray**	**Green**	**Blue**	**Gray**	**Green**	**Blue**	**Gray**	**Green**	**Blue**	**Gray**
Concentrates	**Corn**	0.59	1.08	1.80	0.22	0.39	0.66	101.78	223.44	410.70	21.92	48.12	88.44	40.12	88.08	161.90	66.87	146.80	269.83	52.53	115.32	211.97
	Wheat	0.38	0.97	1.80	0.14	0.35	0.66	832.25	289.44	1166.70	115.43	40.15	161.82	294.66	102.48	413.07	546.79	190.16	766.52	410.09	142.62	574.89
	Soybean meal	0.42	0.92	1.80	0.15	0.34	0.66	2037.00	70.00	37.00	312.27	10.73	5.67	684.02	23.51	12.42	1338.31	45.99	24.31	1002.24	34.44	18.20
Roughages	**Alfalfa**	0.59	1.62	5.40	0.22	0.59	1.97	68.95	169.14	400.00	14.85	36.42	86.14	40.77	100.01	236.52	135.90	333.37	788.40	92.66	227.31	537.57
	Corn silage	0.48	2.16	7.20	0.18	0.79	2.63	16.96	37.24	68.45	2.97	6.52	11.99	13.37	29.36	53.97	44.58	97.87	179.89	30.02	65.90	121.12
	Total feed volume (tons/year):				0.90	2.46	6.57												**Total (m³):**	**1587.55**	**585.59**	**1463.76**

The green water footprint was solely obtained from the growth of crops utilized as animal feed, whereas the blue component was determined by aggregating the blue water footprint of the crops with the water allocated for drinking and cleaning the farmyards. The gray water footprint of livestock operations in the Regional Unit of Karditsa was determined in accordance with water quality regulations, considering the volume of fertilizers and pesticides used in the region for crops together with the quantity of farm waste generated.

Table 5. Water footprint associated with drinking and service water for beef cattle under the intensive livestock system.

	Drinking Water		Service Water	
	Calves (<1 Year)	**Adult Cattle (1–2 Years)**	**Calves (<1 Year)**	**Adult Cattle (1–2 Years)**
Average daily consumption (L/day/animal):	22.74	58.86	2.00	11.00
Total water required at the end of lifetime (L/animal):	29,784.00		4745.00	
Total water required at the end of lifetime (m^3/animal)—blue component:	29.78		4.75	
Average live weight at the end of lifetime (tons):	0.60			
Total blue WF (m^3/ton):	**49.64**		**7.91**	

Table 6. Water footprint associated with drinking and service water for beef cattle under the semi-intensive livestock system.

	Drinking Water		Service Water	
	Calves (<1 Year)	**Adult Cattle (1–2 Years)**	**Calves (<1 Year)**	**Adult Cattle (1–2 Years)**
Average daily consumption (L/day/animal):	19.86	45.90	2.00	11.00
Total water required at the end of lifetime (L/animal):	24,002.40		4745.00	
Total water required at the end of lifetime (m^3/animal)—blue component:	24.00		4.75	
Average live weight at the end of lifetime (tons):	0.50			
Total blue WF (m^3/ton):	**48.00**		**9.49**	

According to the equation $WF = WF_{feed} + WF_{drink} + WF_{serv}$, it appears from Tables 2 and 5 that the contribution of WF_{feed} to the total water footprint for beef cattle under the intensive livestock system was 99.37%, while the corresponding percentages of WF_{drink} and WF_{serv} were only 0.55% and 0.09%, respectively. These findings are in relative alignment with the conclusions of Mourad et al. [33], where the percentage of water allocation of the water footprint for cattle accounted for approximately 99%, specifically referring to the total green water footprint of feed. According to Mourad et al. [33], the average per day water demand (L/day) for beef cattle was 21.5 L for drinking and 6.5 L for service.

Table 7. Water footprint associated with drinking and service water for dairy cows under the intensive livestock system.

	Drinking Water			Service Water		
	Calves (<1 Year)	Heifers (1–2 Years)	Dairy Cows (2–5 Years)	Calves (<1 Year)	Heifers (1–2 Years)	Dairy Cows (2–5 Years)
Average daily consumption (L/day/animal):	13.61	35.32	90.72	0.00	11.00	22.00
Average drinking water required per year (L/year/animal):	23,439.13			5621.00		
Average drinking water required per year (m^3/year/animal)—blue component:	**23.44**			**5.62**		

Table 8. Pollutant load from beef cattle excretions in the intensive livestock system.

	Production of Pollutant Load per Animal (kg/Day/Animal ∗ 1000 TLW)	Average Live Weight at the End of Lifetime (Tons/Animal)	Excretions (kg/Day/Animal)	Excretions (kg/Year/Animal)
N	0.55	0.60	0.33	120.45
P	0.0352		0.0211	7.71
BOD_5	1.30		0.78	284.70

TLW = total live weight in tons.

Table 9. Gray water footprint from beef cattle waste in the intensive livestock system.

	Excretions (kg/Year/Animal)			$c_{max} - c_{nat}$ (mg/L)			Average Live Weight at the End of Lifetime (Tons/Animal)	Average Lifetime (Years)	Gray WF per Pollutant (m^3/ton)			Total Gray WF in the Form of Animal Waste (m^3/ton)
Animal	**N**	**P**	**BOD_5**	**N**	**P**	**BOD_5**			**N**	**P**	**BOD_5**	
Beef cattle	120.45	7.71	284.70	45	2	25	0.60	2	8922.2	12,848.0	37,960.0	**37,960.0**

$c_{max} - c_{nat}$ = difference between the maximum acceptable concentration of the pollutant and its natural concentration in the receiving water body.

Table 10. Pollutant load from beef cattle excretions in the semi-intensive livestock system.

	Production of Pollutant Load per Animal (kg/Day/Animal ∗ 1000 TLW)	Average Live Weight at the End of Lifetime (Tons/Animal)	Excretions (kg/Day/Animal)	Excretions (kg/Year/Animal)
N	0.50	0.50	0.25	91.25
P	0.0280		0.0140	5.11
BOD_5	1.10		0.55	200.75

TLW = total live weight in tons.

Relatively comparable findings were also observed by Murphy et al. [2], who studied the WF of pasture-based beef farms and found that the average WF was 8391 L per kilogram of carcass weight, comprising 98% green WF and 2% blue WF. They also found that the mean blue WF for beef on farms was determined to be 64 L per kilogram of carcass weight. Comparing the pasture-dependent Irish livestock system with the intensive cattle fattening system in our study area, it appears that the former makes better use of water resources derived from the green component of the water footprint. It is becoming clear that climatic conditions, which largely determine the applied farming system, also affect the water footprint of cattle farming. Therefore, to be environmentally sustainable, an intensive cattle farming system must be combined with the efficient cultivation of harvested fodder in terms of water consumption.

Table 11. Gray water footprint from beef cattle waste in the semi-intensive livestock system.

	Excretions (kg/Year/Animal)			$c_{max} - c_{nat}$ (mg/L)			Average Live Weight at the End of Lifetime (Tons/Animal)	Average Lifetime (Years)	Gray WF per Pollutant (m^3/ton)			Total Gray WF in the Form of Animal Waste (m^3/ton)
Animal	N	P	BOD_5	N	P	BOD_5			N	P	BOD_5	
Beef cattle	91.25	5.11	200.75	45	2	25	0.50	2	8111.1	10,220.0	32,120.0	**32,120.0**

$c_{max} - c_{nat}$ = difference between the maximum acceptable concentration of the pollutant and its natural concentration in the receiving water body.

Table 12. Pollutant load from dairy cows' excretions in the intensive livestock system.

	Production of Pollutant Load per Animal (kg/Day/Animal ∗ 1000 TLW)	Average Live Weight at the End of Lifetime (Tons/Animal)	Excretions (kg/Day/Animal)	Excretions (kg/Year/Animal)
N	0.36	0.30	0.11	39.42
P	0.0440		0.0130	4.82
BOD_5	1.80		0.54	197.10

TLW = total live weight in tons.

Table 13. Gray water footprint from dairy cows' waste in the intensive livestock system.

	Excretions (kg/Year/Animal)			$c_{max} - c_{nat}$ (mg/L)			Average Live Weight at the End of Lifetime (Tons/Animal)	Average Lifetime (Years)	Gray WF per Pollutant (m^3/ton)			Total Gray WF in the Form of Animal Waste (m^3/ton)
Animal	N	P	BOD_5	N	P	BOD_5			N	P	BOD_5	
Dairy cows	39.42	4.82	197.10	45	2	25	0.30	2	876.0	2409.0	7884.0	**7884.0**

$c_{max} - c_{nat}$ = difference between the maximum acceptable concentration of the pollutant and its natural concentration in the receiving water body.

In an innovative study, Palhares et al. [34] examined the individual animal WF of fattening calves fed either a conventional diet or a co-product diet, which was calculated at 18,279 and 16,803 L per kilogram of live weight, respectively. These values are much lower than those reported in our study, primarily because the gray component of the WF was not included. Moreover, both the green and total WF were significantly reduced by the use of co-product diets compared to the conventional diets applied in our case. Similar findings were also reported by González-Martínez et al. [35], where the gray component of the WF from animal waste was not quantified.

To further demonstrate the variability across systems, Sawalhah et al. [36] estimated the water footprint of rangeland beef production in New Mexico at 28,203 L/kg of meat. Green water accounted for 82% of the WF used by rangeland forages, while blue water accounted for only 18%.

Gerbens-Leenes et al. [37], in their study of four countries (the Netherlands, China, USA, Brazil), estimated that the mean total WF per kilogram of beef produced was 6752 L in the intensive farming system and 13,149 L in the semi-intensive one. However, the authors reported that the assessment of the gray component of the WF was underestimated, especially in intensive cattle farming systems, where only the contribution of nitrogen fertilization to feed production was assessed, and also in semi-intensive systems, where manure is used for fertilization and affects both the gray and blue components of WF.

Table 14. Total water footprint associated with meat production in the intensive livestock system.

Water Footprint (m^3/ton)						Extra Water Used for the Product (m^3/ton)	Product Fraction (Carcass Yield per Animal in Tons)	Total Water Footprint Associated with Meat Production (m^3/ton)		
Feed			Drinking Water	Service Water	Livestock Waste					
Green	Blue	Gray	Blue	Blue	Gray	Blue		Green	Blue	Gray
4275.43	1349.72	3425.29	49.64	7.91	37,960.00	10.00	0.52	8221.98	2725.52	79,587.10

Table 15. Total water footprint associated with meat production in the semi-intensive livestock system.

Water Footprint (m^3/ton)						Extra Water Used for the Product (m^3/ton)	Product Fraction (Carcass Yield per Animal in Tons)	Total Water Footprint Associated with Meat Production (m^3/ton)		
Feed			Drinking Water	Service Water	Livestock Waste					
Green	Blue	Gray	Blue	Blue	Gray	Blue		Green	Blue	Gray
5076.03	1500.05	3890.49	48.00	9.49	32,120.00	10.00	0.52	9761.59	3014.51	69,250.94

Table 16. Total water footprint associated with milk production in the intensive livestock system.

Water Footprint (m^3/Year)						Milk Yield per Animal (Tons/Year/Animal)	Total Water Footprint Associated with Milk Production (m^3/Ton/Animal)		
Feed			Drinking Water	Service Water	Livestock Waste				
Green	Blue	Gray	Blue	Blue	Gray		Green	Blue	Gray
1587.55	585.59	1463.76	23.40	5.60	7884.00	4.20	377.99	146.35	2225.66

Table 17. Comparison of total water footprint between beef and dairy cows in the Regional Unit of Karditsa.

			Water Footprint			
Product	**Type of System**	**Units**	**Green**	**Blue**	**Gray**	**Total**
Beef	Intensive	m^3/ton	8221.98 (9.08%)	2725.52 (3.01%)	79,587.10 (87.91%)	90,534.60
	Semi-intensive		9761.59 (11.90%)	3014.51 (3.68%)	69,250.94 (84.42%)	82,027.04
Cow milk	Intensive	m^3/year/ton	377.99 (13.75%)	146.35 (5.32%)	2225.66 (80.93%)	2750.00

Arrien et al. [38], in their work on calculating the water footprint (through all three components) of beef cattle farming under intensive, mixed, and extensive systems, found that the WF for the production of a live calf ranged from 4247 to 5912 m^3/animal. The lowest value corresponded to the intensive system and the highest to the extensive, with the mixed system falling between. In that study, the extensive livestock production system had the highest WF, with the green component contributing 99%, while in the intensive system the gray component accounted for 21% and the green for 78%. The major difference compared to our work regarding the estimation of the gray component lies in the inclusion of only manure in its calculation.

As far as dairy cows are concerned, the combined amount of WF_{drink} and WF_{serv} was almost half of the corresponding sum for beef cattle, based on the data presented in Tables 5–7 of the present study. Specifically, the sum of WF_{drink} and WF_{serv} for beef cattle raised under the intensive farming system (Table 5) was slightly higher than that for beef cattle raised under the semi-intensive system (Table 6), a difference attributed to the nature of intensive systems that require the use of feeds with relatively low moisture content. The WF of concentrates is generally greater than that of roughages. This contributes to an increase in water footprints—particularly in the blue and gray components—when transitioning from grazing-based systems to intensive farming systems [37].

Mekonnen and Hoekstra [27] determined that the green WF constituted 91% of the overall WF in dairy farming, whereas the blue WF represented 4%. Additionally, Mekonnen and Hoekstra [8] found that for dairy cows under the industrial farming system, the global green, blue, and gray WF amounted to 1207 L per kilogram of milk.

Table 16, concerning dairy cows, shows that the predominant component of the WF is the gray component, while the green component is larger than the blue one. These findings differ significantly from both the aggregate and individual results of the extensive study by Sultana et al. [39], where the green component of the WF was found to be substantially higher than the other two components. According to Sultana et al. [39], the global average was 1643 L per kilogram of milk, composed of 87% green WF, 7% gray WF, and 6% blue WF.

In our study, the relatively low green WF is largely due to the intensive system applied, which primarily utilizes harvested feedstuffs and minimal pasture in the cows' nutrition. This fact also affects the blue WF, which is relatively higher than that observed in other European countries included in the study by Sultana et al. [39]. Specifically, the average blue and green WF of milk production in Western Europe was reported to be 721 and 59 L per kilogram, respectively. Additionally, according to Sultana et al. [39], the WF_{drink} component of the blue WF is relatively high (15%), influenced by the productive level of the cows, the consumption of concentrated feed, and the degree of drying of the roughage. A recent study [40] on the water footprint of dairy cattle production in Hungary reported that green water demand, represented by the feed, accounted for 99.1% of the total WF. It should be noted that the gray component was not included in this calculation.

Additional research has examined dairy systems in other European countries. Bronts et al. [41] studied the water footprint of dairy systems in the Netherlands and Spain. Reflecting the high efficiency of Dutch conventional systems, the green, blue, and gray WFs per kilogram of milk were estimated at 0.62, 0.09, and 0.14 m^3, respectively. In the Spanish system, the corresponding values were 0.67, 0.15, and 0.09 m^3 per kilogram of milk.

In the present study, the gray WF for dairy cows appears very high, as its calculation includes not only the classic pollutants originating mainly from fertilizers (N and P) but also the BOD_5, which directly reflect the main polluting impact of organic matter. Because the gray WF represents a virtual volume of water rather than actual consumption, it is often excluded from WF assessments [42]. According to Palhares and Pezzopane [43], reducing wastewater emissions, such as by reusing wastewater or using nutritional strategies to minimize nitrogen and phosphorus excretion, can also lead to a reduction in gray WF production.

Cattle breeding has progressed over time to enhance animal productivity, leading to elevated water requirements, yet there are no regulations to safeguard the water resources utilized for this goal. In the Regional Unit of Karditsa, the recorded number of farm animals is 1,049,592, as per data from the Directorate of Rural Economy and Veterinary of the study area. The total count of beef and dairy cattle in the region is 9925.

The findings of the current study, utilizing the water footprint approach, indicated that the predominant water requirements in livestock activities within the study area pertain to the production of animal feed, rather than to direct water consumption or the operation of the livestock facilities [9,10].

Table 17 indicates that the production of beef and dairy milk exhibits a markedly high WF, particularly in comparison to crop-derived products. This is primarily due to the fact that agricultural products, such as corn and cotton, require substantially shorter periods of time (a few months) to reach the ultimate stage of production, whereas meat and milk necessitate far longer periods (years). Additionally, the WF assessment of animal products includes the WF of the crops utilized as animal feed [44].

Comparing the two systems applied in the area (intensive and semi-intensive) for beef cattle, it can be concluded that the blue and green WFs are higher in the semi-intensive system. The main reason for this is that the live weight of the animal at the end of its lifetime is greater under the intensive system (0.6 tons) than under the semi-intensive system (0.5 tons), resulting in a lower water footprint. More specifically, the fact that in the water footprint approach the total production is taken into account (i.e., water use is divided by the corresponding production) has a significant influence on the final results.

As for the gray WF, it can be observed that the value is higher in the intensive system, which is a result of the increased excretions by the animals due to the different type of rations applied and the greater weight of the animals.

In order to compare the WF of the two types of products (meat and milk), they have to be converted to the same units, which means that the total milk production of an animal over its lifetime must be calculated. Even after doing so, it is evident that meat production has a much higher WF because the corresponding production is much lower than that of dairy products. In general, the type of ration and the farming system employed in each instance greatly influence the WF.

This study's estimated gray WF underscores the significant issue of farm waste, a factor disregarded in other research investigations. This highlights the imperative of integrating livestock waste management systems inside of animal production facilities to provide environmental protection and enhance water resource quality.

While our study provides a comprehensive assessment of the water footprint of beef and dairy cattle production in the Regional Unit of Karditsa, we recognize that certain aspects, such as potential seasonal variability in rations, could offer additional insights. These elements, along with further exploration of regional variations and dynamic system parameters, present valuable directions for future research.

4. Conclusions

The water footprint methodology offers important insights into water resources management, as it accounts for indirect water use and water pollution, thereby distinguishing itself from conventional approaches focused solely on water withdrawals. By encompassing its three dimensions—green, blue, and gray—the water footprint provides a comprehensive framework for evaluating both the quantity of water consumed and the quality impacts associated with livestock production. This integrated approach serves as a valuable tool for supporting more effective water management and environmental protection.

Our findings show that the total water footprint for beef production in the Regional Unit of Karditsa reaches 90,534.60 m^3/ton under the intensive system and 82,027.04 m^3/ton under the semi-intensive system, with gray water making up the largest share in both cases (87.91% and 84.42%, respectively). For cow milk, the water footprint amounts to 2750.00 m^3/ton, with 80.93% attributed to gray water. These values underscore the significant contribution of livestock waste to water quality degradation and highlight the need for its inclusion in regional strategies for sustainable agricultural development.

Such insights can support more informed decision making for regional water directorates by identifying specific pressure points related to livestock production, such as the high gray water footprint from manure management or irrigation demands for feed crops. The approach and findings presented here may also be applicable to other Mediterranean regions with similar climatic and agricultural characteristics, as well as other types of livestock beyond beef and dairy cattle. Future research could further strengthen this framework by incorporating seasonal variability, localized pollutant thresholds, and production system differences to improve its utility in broader agro-environmental contexts.

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