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Modeling of water consumption in goats and sheep: Review of the main equations used

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A B S T R A C T

Efficient management of water resources is a crucial challenge for the production of small ruminants, especially in tropical and semi-arid regions. This article aims to compile and discuss the main equations and approaches used to estimate water consumption in sheep, highlighting the importance of mathematical modeling in simulating water requirements. The analysis considers variables such as dry matter intake, metabolizable energy, body weight, ambient temperature, as well as estimation techniques like the isotopic dilution of body water. Water losses through different physiological pathways and the effects of temperature and water restriction on animal performance are also addressed. The review demonstrates that there is no universally applicable equation, making it essential to adapt models to specific environmental, physiological, and productive conditions. In this sense, the integrated understanding of the factors that influence water consumption is fundamental for the formulation of more sustainable and efficient diets and management strategies.

R E S U M O

A gestão eficiente dos recursos hídricos é um desafio crucial para a produção de pequenos ruminantes, sobretudo em regiões tropicais e semiáridas. Este artigo tem como objetivo reunir e discutir as principais equações e abordagens utilizadas para estimar o consumo de água em ovinos, destacando a importância da modelagem matemática na simulação das exigências hídricas. A análise contempla variáveis como consumo de matéria seca, energia metabolizável, peso corporal, temperatura ambiente, além de técnicas de estimativa, como a diluição isotópica da água corporal. Também são abordadas as perdas hídricas por diferentes vias fisiológicas e os efeitos da temperatura e da restrição hídrica no desempenho animal. A revisão demonstra que não há uma equação universalmente aplicável, sendo essencial a adaptação dos modelos às condições ambientais, fisiológicas e produtivas específicas. Nesse sentido, a compreensão integrada dos fatores que influenciam o consumo de água é fundamental para a formulação de dietas e estratégias de manejo mais sustentáveis e eficientes.

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Introduction

Programming and mathematical modeling are fundamental tools in the simulation of animal production systems. Modeling allows representing strategies and biological processes, simulating the interactions between physical and physiological factors in breeding systems (Tedeschi *et al.*, 2011). Currently, mathematical models are widely used to increase the feed efficiency of herds, mitigate greenhouse gas (GHG) emissions, and reduce nutrient losses to the environment, promoting the sustainability of livestock systems (Bell *et al.*, 2015).

Modeling in animal science is marked by challenges such as the variability of biological systems, interactions between nutrition, genetics, and environment, as well as the practical constraints of data collection. Therefore, the application of modeling in animal science requires specific considerations and adaptations (Tedeschi *et al.*, 2025). The application of models throughout the production cycle is essential to understand the effects on water consumption and the physiological responses of animals, allowing for the improvement of forage evaluation and the formulation of more efficient diets (Rashamol *et al.*, 2019).

Water resource management is the greatest challenge of today, especially when the scarcity of this resource leads to serious socioeconomic and environmental consequences, caused both by physical scarcity and poor management (Peixoto *et al.*, 2022). Although there are several mathematical equations used to estimate water consumption in animals, many are independent of each other and used within simulation systems. According to Appuhamy *et al.* (2016), most existing models require the dry matter intake of animals, which may not be routinely available on commercial farms. Other existing models allow predicting free water consumption without using dry matter intake, as addressed by Liu *et al.* (2025) when developing a predictive regression equation model of water intake behavior in dairy cows based on variations in rumen temperature, providing a new perspective on water management for dairy animals.

In this way, the objective of this review is to present the main equations used to estimate water consumption and use in goats and sheep.

Literature Review

Water and its use in estimating body composition in live animals

Water intake has been widely studied in recent years, as it reflects the variation in food consumption through the adjustment of weight gain and body composition. The residue of this determination represents the variation in the requirements for basal metabolic processes and not differences in productivity, constituting a relevant characteristic in the search for biological indicators of feed efficiency (Montanholi *et al.,* 2017).

Water consumption (WC) varies according to dry matter intake (DMI), ambient temperature, and water loss from body tissues. Considered factors also include concentrate and forage intake, water consumption in kg or minutes, total consumption time, daily number of visits to the concentrate trough or feeding occasions, and drinking trough (Montelli *et al.*, 2019).

Although body weight (BW) is commonly used as a parameter to determine the energy and nutritional needs of ruminant animals, the assessment of body condition, estimated through the body condition score (BCS), provides greater accuracy and can modify the objectives of the management program (Xiong *et al.*, 2023). However, the quantification of lean mass and fat is more accurate when obtained through the estimation of total body water (TBW), using one or more body water dilution markers, such as antipyrine (Janus and Suszycka, 1996), deuterium oxide (Al-Ramamneh *et al.*, 2010), tritiated water (Silanikove *et al.*, 1987), and urea (Agnew *et al.*, 2005), provided that the appropriate correction factors are applied (Sheng and Huggins, 1979).

The inverse relationship between total body water (TBW) and body weight (BW) with the amount of body fat is used to develop equations that estimate body composition based on slaughter data (NRC, 2007). Normally, the amount of TBW ranges from 51 to 81% of body weight, however, when the water present in the gastrointestinal tract is removed, this concentration is around 55 to 68%. The variation in TBW or in body weight free of intake shows a direct relationship with fat content, since fat contains no water.

In adult animals, the water content of fat-free body mass is relatively constant, ranging from 68% to 76%. Of the fat-free mass, about 80% to 82% is composed of protein and 18 to 20% of minerals (Gerhard *et al.*, 1996). It is possible to estimate the amount of lean mass and body fat based on the lean body weight corrected for intestinal water, considering that lean body mass is composed of 73% water. Body fat can then be estimated by subtracting lean body mass from empty body weight (NRC, 2007).

Metabolic water is a strategic source of hydration for animals, especially in environments with limited water availability, generated according to the type of metabolized energy substrate (100 g of carbohydrates = 60 g of water, 100 g of protein = 42 g of water, 100 g of lipids = 110 g of water). Although lipids are the main potential source of metabolic water, the hydrolysis of fats results in lower effective water retention compared to carbohydrate oxidation (Araújo *et al.*, *2010)*. Thus, with the information that the amount of water formed by oxidation in the organism depends on the type of food metabolized, diets with higher energy density offered to sheep in a semi-arid environment possibly result in greater production of metabolic water, allowing the animals to maintain their productive performance regardless of water restrictions (Moura *et al.*, 2020). Oliveira *et al.* (2024) observed that lambs in a semi-arid region subjected to water restriction and on a high-energy diet naturally expressed thermoregulatory responses, as the energy diet provides the formation of a greater amount of metabolic water with the oxidation of nutrients, due to the higher amount of carbohydrates in the high-energy diet probably increasing the production of metabolic water.

Water catchment

Determining water requirements is a process that requires solving a water balance equation, in which water intake must be sufficient to offset all water losses. However, voluntary water consumption, through the intake of free water, is considered the main variable to be met in order to fulfill the animal's water requirement, being estimated by the equation below (NRC, 2007):

$$\boldsymbol{CA = CAL + AL + AMe + ARe + (AI)}$$

where: CAL - free water consumption, AL - water present in food, AMe - metabolic water produced by the chemical oxidation of the nutrients metabolized from food, ARe - water released from physiological tissue reservoirs, in addition to water from the intracellular compartment (ICF) that is released during the breakdown of proteins (such as muscle), and AI - measurement of inspired water, necessary for estimating water intake to balance the water balance equation.

In free-ranging animals, the direct measurement of free water intake is limited, and water requirement can be estimated through isotopic dilution of water. Isotopes such as tritiated oxide (T2O) and deuterium oxide (D2O) are used to calculate the water turnover rate (WTR) (Preston, 1969). When the animal is in water balance, the rate of water turnover provides an estimate of water intake, provided that the overestimation of reservoir volume is corrected, as reported by Sheng and Huggins (1979).

According to the NRC (2007), during the first weeks of life, the intake of water from breast milk meets the hydration requirements of lactating lambs for two to three weeks of life, decreasing exponentially over time. After weaning, lambs' water consumption depends on dry matter intake and growth rate. The NRC (2007) estimates that the water requirement for growth after weaning in sheep is on average 143 mL/kg metabolic weight ($PC^{0,75}$), with variations between 137 and 164 mL/kg $PC^{0,75}$ depending on the species and environmental conditions. In the field, the TRA can be even higher, exceeding 350 mL/kg $PC^{0,75}$, especially when animals consume forages with high moisture content, which can result in water intake exceeding the physiological requirements (NRC, 2007).

Water loss

Water can be lost to the environment through evaporation during respiration, through (cutaneous) transpiration, via drool or licking (insensible water loss - IWL), urine (U), and feces (F). Sensible water loss is related to ambient temperature and exposure to solar radiation. Some physiological adaptations help minimize these losses, such as nasal heat exchangers that significantly reduce water loss through evaporation in species adapted to both hot and cold environments (Blix *et al.*, 1983).

The proportion of metabolic heat that is dissipated from the animal's body through evaporation increases with rising environmental temperatures and a decreasing temperature gradient between the animal and the air. The differences in the proportion of evaporative cooling to total heat loss (heat produced) vary from species to species, and the evaporative proportion in cattle is between 16,6–18,3 °C (Silanikove, 2000).

When water intake (WI) is reduced, there is a decrease in cutaneous and respiratory evaporation. This reduction is also associated with lower urinary and fecal loss. Urinary loss depends on the animal's ability to concentrate urine (NRC, 2003), while fecal loss is linked to the efficiency of water reabsorption in the intestine, resulting in drier feces. Species well adapted to hot climates can concentrate urine above 2,000 mOsm/L, while most ruminants reach up to 500 mOsm/L (NRC, 2007).

The water loss can be estimated by the following equation (NRC, 2007):

$$PA = EAL + U + F + TAL + MAL$$

where TAL- water loss due to the expansion of physiological reservoirs, plus water gain in the tissues during lean mass accumulation, and MAL- water loss in milk.

Assuming that an animal reaches the steady state through the consumption of free water, then:

$$CAL = PA - (AL + AMe + ARe)$$

The TRA can be estimated from body weight (BW) and the variables AL and AMe can be estimated from dry matter intake (DMI), feed water content, and diet metabolizability. Any change in BW or body condition can provide an estimate of RE. When the BW trend is positive, RE is replaced by AL (NRC, 2007). When water requirements are expressed as total water intake (TWI), we have (NRC, 2007):

$$CTA = CAL + PA$$

However, since the measures of free water consumption (CAL) and total water consumption (CTA) underestimate the actual consumption (CA) and water losses (PA), the water renewal rate has been widely used, especially in situations where free water consumption cannot be measured (NRC, 2007).

Total water consumption in relation to metabolic body weight

When dealing with different species and body weights, an initial way to estimate water consumption is to use the relationship between the water turnover rate (WTR) and body weight (BW), which is given by the equation (NRC, 2007):

$$TRA = aPC^{b}$$

Adult mammals, fed and kept confined and within the thermoneutral zone, the equation that describes this relationship is shown below:

$$TRA = 0,159 * PC^{0,946}$$

where the coefficient "a" is equal to 0.159 and the exponent "b" ranges from 0.79 to 0.99 (NRC, 2007).

Under field conditions the equation changes. The coefficient "a" increases to 0.326 and the exponent "b" decreases to 0.818:

$$\boldsymbol{TRA = 0,326 * PC^{0,818}}$$

These changes suggest a possible underestimation of the equation derived from confined animals, when observing the reduction in the exponent "b". Such a variation factor may be related to: Within the same species, the AMDR can vary up to six times, and the available information was not limited according to seasons of the year, sex, or productivity, which may affect the accuracy of the estimates (NRC, 2007).

For species adapted to dryland regions, the cited equations tend to overestimate the RWI, due to a possible increase in total body water content, extracellular fluid volume, as well as the water turnover rate in these ruminant animals (Macfarlane, 1964). In this context, Ostrowski *et al.*, (2002) developed a specific equation based on data from 10 species from desert regions, providing estimates closer to the physiological reality of these animals.

$$\boldsymbol{TRA = 0,127 * PC^{0,926}}$$

Another way to estimate water consumption can also use the relationship between metabolic weight and total water consumption (TWC/MW). Freitas *et al.*, (2021), observed that the ratio between total water intake/metabolic body weight was 0.25 ± 0.10 L/kg; moreover, the animals more efficient in water use ingested less water per kg of body weight.

Total water consumption in relation to dry matter consumption

The relationship between water intake and food intake can be an important factor for the poor performance of animals, because, in the absence of water points, animals spend more energy trying to quench their thirst (Ben Salem and Smith, 2008). Animals can obtain water through free water, food (mainly moist and succulent foods), or metabolic water (Van Driessche *et al.*, 2025).

Dry matter intake directly influences water consumption, especially in young animals. Giger-Reverdin *et al.* (2011) report that lactating goats have the ability to use water more efficiently than other ruminants, since the total water intake/dry matter intake ratio is lower than in other ruminants and they are able to substitute between the water ingested from the diet and the water ingested from the drinking trough.

Higher water intake via food and total water intake in diets are related to the levels of dry matter in the diet, confirming the importance of providing water through food in arid regions, where drinking water is scarce (Silva *et al.*, 2021). Cordova-Torres *et al.* (2017) confirm that diets containing water-rich foods can reduce water intake and excrete a considerable volume of urine. This occurs due to the regulation of body fluid osmolarity, which is controlled by the renin-angiotensin-aldosterone mechanism that acts harmoniously by adjusting the intake and excretion of free water, with the kidney being the main organ responsible for maintaining homeostasis (Reece, 2017).

The existence of water in an adequate form in body tissues is an essential prerequisite for the normal maintenance of life, performing a fundamental function for all living cells (Aganga *et al.*, 1992). Although the water consumption requirements can be influenced by factors such as temperature, relative humidity, lactation, pregnancy, and diet, it can be determined by the equation predicted by the NRC (2007), according to dry matter intake:

$$\boldsymbol{CTA = 3,86 * CMS - 0,99}$$

Estimated water consumption for growing lambs is 4–6 L of water/kg of DM at 16–25 °C or 2 L of water/kg of OM at 15 °C (Freitas *et al.*, 2021). For 36-month-old ewes, during winter water consumption ranges from 9% to 11%, while in summer it reaches values between 19 to 25% according to total body weight (Khan and Ghosh, 1989). In the table below (Table 1), Ward *et al.* (2023) report an estimate of daily water intake by different categories of sheep.

Table 1.

Water consumption by sheep according to animal category and weight range.

Type of animal	Weight range (kg)	Water requirement range (L/day)*	Typical average water use (L/day)**
Lamb	27–50	3.6–5.2	4.4
Pregnant meat sheep/lamb	80	4.0–6.5	5.25
Ewe in lactation with unweaned lambs	80+	9.0–10.5	10
Pregnant milk ewe/lamb	90	4.4–7.1	5.75
Lamb/ewe in lactation	90	9.4–11.4	10.4

*Result of the environment and animal management.
**Typical consumption over a year, daily, under agricultural conditions.
Source: Ward *et al.* (2023).

Al-Ramamneh (2017), investigating the preference for cold or hot water by Awassi lambs under heat stress, found that the animals consumed more hot water (3.65 L/day) compared to cold water (3.00 L/day) and stated that it is mandatory to provide fresh, clean, sufficient, and accessible water to all animals. However, if the water points are exposed to direct sunlight and placed far from shaded animals, the animals use a large portion of the available body water to dissipate heat through evaporation. The authors conclude that the provision of cold water to Awassi lambs under heat stress, although not preferred by the animals, would dissipate heat better and promote greater animal comfort in hot climates. In confined dairy goats in the Brazilian semi-arid region, Ramos *et al.* (2020) observed an average consumption of 5.77 L/day (sorghum silage and palma-based diet), almost double the value predicted (2.87 L/day) by the NRC equation (2007).

In general, species and breeds that have evolved or been selected for arid and semi-arid conditions show low water use compared to species and breeds adapted to humid regions, as a result of adaptations involving behavioral and physiological responses that maximize water intake and minimize water loss (NRC, 2007).

Maranhão et al. (2022), in a study related to the modeling of the water balance of a ruminant production system (scenario with 300 animals of each species) in the Brazilian semi-arid region, report that the higher water demand of sheep compared to goats increases water consumption from a reservoir with a capacity of 6,481 m³ by about 18% (123 m³), an amount sufficient to supply a family of five people for 223 days (110 L per person/day). The authors further report that in years when the reservoir dries completely, due to natural losses and intense use, it is up to the producer or technician to size the production system for that available volume of water. Once the water demand of the production system is known, it is possible to manage the use of this resource.

Total water consumption in relation to energy consumption

Macfarlane and Howard (1972) infer that water use by ruminants is more related to energy metabolism than to dry matter intake, making it pertinent to relate free water intake (FWI) or water turnover rate (WTR) with digestible energy intake (DEI), metabolizable energy (ME), or daily energy expenditure (DEE) (Haggarty, 1991). Wallace *et al.* (1972) report that for sheep, water requirements are estimated as 0.62 mL/kcal of ME combined with 1.37 mL/kg of DMI. The generalized recommendation is 1 mL/kcal of ME (NRC, 2003). However, it is still unclear whether this ratio equally applies to different physiological stages such as growth, gestation, and lactation.

The evidence that WRA depends on energy metabolism is supported by the hypothesis that the allometric exponent “b” should be equal to 0.75, a value similar to that of the metabolic rate. However, the observed values for “b” in interspecies studies range from 0.79 to 0.90, which may be attributed to the influence of body fat on body weight (BW), affecting the relationship between metabolism and water consumption. Thus, it has been proposed that the best way to express WRA would be as a function of total body water (TBW). Despite these variations, the estimated values of “b” do not differ statistically from 0.75, which is why recommendations are often expressed as a function of metabolic weight (Macfarlane and Howard, 1972).

In studies with different breeds of goats, Silanikove (1989) found a high correlation between energy and water metabolism ($r^2 = 0.99$; $n = 32$). In sheep, the relationship between total water intake (TWI) and digestible energy intake (DEI) was estimated at 0.524 mL/kcal, according to a factorial approach of Wallace *et al.* (1972).

Torres *et al.* (2021), in a study on empirical equations for predicting drinking water intake in growing lambs, present that variables associated with energy requirement improve the accuracy of models for predicting water consumption. The authors state that the efficiency of energy retention in growing lambs ranges from 0.30 to 0.57, with the remainder lost in the form of heat, and that water renewal has a significant interaction with energy renewal and thermoregulatory processes, due to its relation to the efficient use of feed, as well as with changes in body heat production from caloric increment through nutrient metabolism, such as the efficient use of energy for growth.

Although this estimate is useful for maintenance diets, it may not accurately reflect water needs in more demanding productive stages, such as growth and lactation, especially when the diet has a high content of protein, salts, or secondary compounds, which increase urinary and fecal losses. In addition, under grazing conditions, factors such as movement between feeding areas and water points, or seasonal migrations, can increase energy expenditure without adequate compensation through ME intake, thus raising the actual water requirement. Therefore, estimates based solely on energy intake may underestimate the water requirement of sheep in extensive systems or under specific diets (NRC, 2007).

Effects of temperature and water deprivation

Exposure to high temperatures influences water consumption due to the decrease in dry matter intake (DMI), while the requirements for evaporative cooling and cutaneous water loss increase (NRC 2007). In a study conducted by Forbes *et al.* (1968) on confined sheep, they observed that the DMI/Water consumption ratio increased with the rise in average temperature (°C). Khan and Ghosh (1989) reported an increase in water turnover in sheep of 6% in winter and 7% in summer, and that mountain and desert breeds outperform arid breeds in terms of water turnover.

Marai *et al.* (2000) observed higher water intake (frequency/hour) from 11:00 to 19:00 compared to the time from 7:00 to 11:00 in summer compared to winter. The increase in water consumption was determined to be 50%, while water loss decreased by approximately 25% in feces and 40% in urine during heat stress. Maloiy *et al.* (2008), studying thermal stress on dry matter intake in different species, observed that dehydration influenced food consumption in goats by 58.3%, followed by sheep at 48%. Silanikove (1985) mentioned that dehydration is a condition associated with an increase in the mean retention time of food and fluid in the rumen, which is affected by a decrease in salivary flow.

Evaporative cooling through breathing and water loss through the skin via sweat glands, salivation, or licking of body surfaces are fundamental thermoregulation mechanisms when the ambient temperature is higher than the body temperature. Although these mechanisms increase water demand (WD), species adapted to desert environments exhibit various strategies that reduce these losses, both through behavior and through physiological responses related to evaporative, urinary, and fecal water loss (NRC, 2007).

Conclusion

Water is an essential nutrient, whose intake and utilization vary according to multiple physiological, environmental, and nutritional factors. The application of mathematical equations to estimate water consumption in sheep is a strategic tool to optimize livestock management, especially in regions subject to heat stress and water scarcity. Despite the existence of several equations, none of them proves to be fully universal, which reinforces the need for adjustments according to the reality of production systems, breeds, and environments. The use of methods such as isotopic dilution, combined with modeling based on energy consumption, body weight, and dry matter, allows for a more precise understanding of water requirements. Therefore, the adoption of integrated and adaptive approaches contributes not only to the improvement of animal performance but also to the sustainability of production systems.

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