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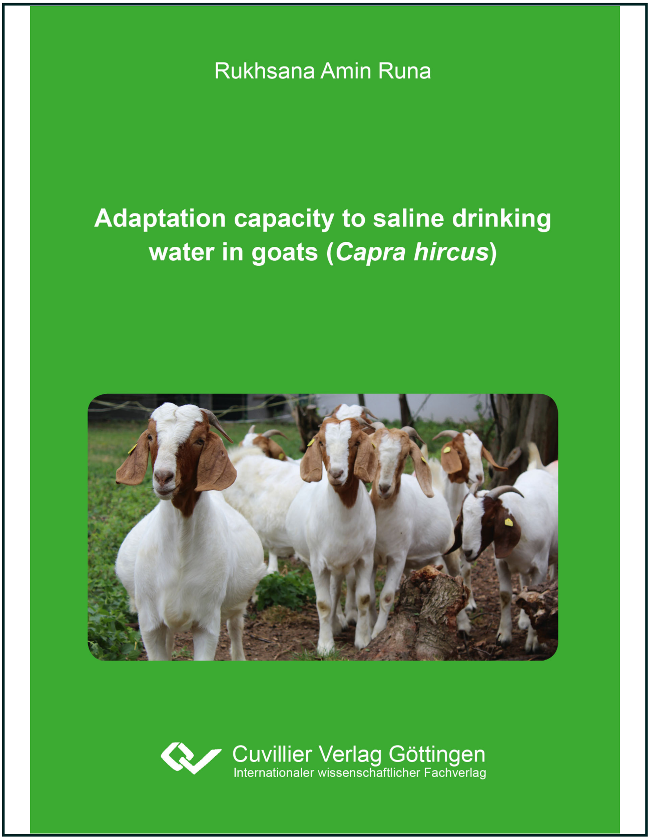
Adaptation capacity to saline drinking water in goats (Capra hircus)



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INTRODUCTION

Water and soil are important natural resources for the survival of living beings. Secured availability of sufficient fresh water is essential for animal production. In many tropical coastal regions, both underground and surface water are being contaminated with increased salinity due to sea level rises resulting from global climate changes (IPCC, 2014; WWAP, 2015). In Europe, nowadays, more moderate coastal habitats are also increasingly confronted with this phenomenon (IPCC, 2014). The problem of increased soil and water salinity is not bounded only within coastal areas as inside water bodies in many arid and pacific areas are also frequently getting contaminated by salinity (Cherfane, 2015; Berthe *et al*., 2015).

The change in climate and its variability may affect natural water balance and fresh water availability by increasing temperature that causes higher water evaporation from soil and open surfaces, and increased transpiration by vegetation (Buytaert *et al*., 2015). Over longer duration, climate induced changes will create huge challenges and threats for local and regional water resources (Buytaert *et al*., 2015). This may also foster greater extremes in weather, including higher temperature, heavy precipitation, droughts, violent storms, sea level rises and ocean acidification (Dessler, 2012; WWAP, 2015). Changes in sea level can affect coastal groundwater, threaten coastal aquifers with potential effects on drinking water quality (Hipsey and Arheimer, 2013) and coastal ecosystems by increasing risk of flood and degradation of essential ecosystem services (World Bank, 2010; Hallegatte *et al.,* 2013). However, it is almost impossible to avoid or abandon these salinity affected areas as they are required for food production. Therefore, it is important to adopt proper adaptation measures or mechanisms for farming practices, such as livestock management in these areas. In doing so, it is a pre-requisite to know the animals' normal physiological capacity of salinity tolerance without impairing their health.

Definition and measurement of salinity

Salinity is the saltiness or quantity of dissolved salt in a water body. Salts are compounds like sodium chloride, magnesium sulfate, potassium nitrate and sodium bicarbonate which dissolve into ions. Saline water (more commonly known as salt water) is defined as water containing a significant concentration of mainly sodium chloride salt. Based upon salinity, water bodies are divided into two classes (Por, 1972), defined as homoiohaline (salinity remains constant over time) and poikilohaline (salinity varies biologically ranging from 0.5 to >300 g/kg). According to the United States Geological Survey, saline water is classified into three categories; in slightly saline water, salt concentration is 1–3 g salt/kg water (0.1–0.3%), in moderately saline water 3–10 g/kg water (0.3–1%), and 10–35 g/kg water (1–3.5%) in highly saline water. Seawater has an average salt content of approximately 35 g/kg water (3.5%) and the saturation level depends on temperature and solubility of salt. However, seawater is not uniformly saline throughout the world. Lower values are found near coasts where rivers enter the ocean compared to salinity in the deep sea. The salinity level of different water sources and areas is presented in Table 1.1.

In the 1980s, a 'Practical Salinity' scale was developed to estimate the salinity of sea water where salinity was measured in 'Practical Salinity Units' (PSU) (Millero, 1993). The current standard for salinity is the 'Reference Salinity' scale (Millero et al., 2008) with the salinity expressed in units of g/kg. It is also expressed in parts per thousand (ppt, ‰) or parts per million (ppm). There are two main methods of determining the salt content of water; Total Dissolved Salts or Solids (TDS) and Electrical Conductivity (EC). EC measurement is much quicker, simpler and is very useful for field measurement compared to TDS (Agriculturevictoria, 2017). Total Dissolved Salts (TDS) is measured by evaporating a known volume of water to dryness, then weighing the solid residue remaining. TDS is recorded in milligrams of dissolved salt or solid in one liter of water (mg/L). Parts per million (ppm) is equivalent to mg/L but it is not a favored unit. Electrical conductivity (EC) is measured by passing an electric current between two metal plates (electrodes) in the water sample and measuring how readily current flows (i.e. is conducted) between the plates. The more dissolved salt is in the water, the stronger the current flow and the higher the EC. The standard EC unit is microSiemens per centimeter (µS/cm). EC measurement can also be used to estimate the TDS by converting with the relationship: TDS (mg/L) = EC (µS/cm at 25^{o}C) x 0.6 (Agriculturevictoria, 2017). Other units are used by some scientist to express the salinity of sea water. However the relationships between them need to be taken into account and µS/cm relates to other units as follows:

1000 µS/cm = 1 milliSiemens/centimeter (mS/cm)

10 µS/cm = 1 milliSiemens/metre (mS/m)

Table 1.1 Water salinity of different water sources and areas (Eilers *et al*., 1990; Anati, 1999)

Water sources	Salinity	
	(TDS, mg/kg)	(%)
Fresh water	< 500	< 0.05
Brackish water	500 – 30,000	0.05 – 3
Saline water	30,000 – 35,000	3 – 3.5
Brine	> 50,000	> 5
Rivers and lakes	< 10 – 500	< 0.001 – 0.05
Average sea water	35,000	3.5
Dead sea	200,000	20

Physiology

Biological role of Na+ (sodium)

Salt (NaCl) is an essential element in animal diets (Suttle, 2010). Animals are often fed sodium (Na^+) and chloride (Cl^-) in the form of salt (NaCl), either salt granule mixed with feed and water or in saltlicks. Salt consists of 39% sodium and 61% chlorine (Hollum, 1998; National Research Council (NRC), 2007). Because of their close ionic interactions, related functions, metabolism and requirements in the animal body, sodium and chlorine are considered as compound salt with Na^+ being the major cation in the interstitial fluids (Suttle, 2010). Sodium plays a dominant role in regulating body fluid homeostasis, control of water metabolism, nerve function and the absorption of chlorine and water (Agricultural Research Council (ARC), 1980; NRC, 2007; Suttle, 2010). It is also involved in transport systems for maintaining body temperature, glucose and amino acids absorption and neuromuscular activities (NRC, 2007). Together with potassium (K^+), sodium is one of the most important ions to regulate osmotic pressure and pH of the body by providing an 'osmotic skeleton' that is 'clothed' with an appropriate volume of water (Michell, 1995; Suttle, 2010).

In cattle and sheep, sodium is mostly absorbed in rumen, omasum and particularly the large intestines (ARC, 1980; Khorasani *et al*., 1997). Sodium uptake from the intestinal lumen is achieved by adhering to glucose and amino acid uptake via co-transporters (Harper *et al*., 1997). Sodium is transported across the cell membrane by ATP-dependent Na^{+}-K^{+} pumps, electroneutral Na-K-Cl co-transporters, Na-HCO_3-Cl co-transporters and Na^{+} Channels (NRC, 2007; Suttle, 2010). Metabolism of sodium is regulated hormonally by activating renin-angiotensin mechanisms. Aldosterone is the responsible hormone, which is excreted from the adrenal cortex when sodium levels decrease in the blood (Hollum, 1998), changing blood pressure and extra cellular fluids through adjusting thirst and water balance (Michell, 1995; Burnier, 2007). Sodium is excreted from the body via urine, skin secretions, and milk (Suttle, 2010).

Sensory thresholds

Saltiness is a unique taste among the five basic taste qualities (sweet, sour, bitter, salty and umami) perceived and detected by human and animals (Sugita, 2006). Sweet, salt and umami flavors are innately appetizing, whereas sour and bitter ones are instinctively unappetizing (Yoshida *et al*., 2006). However, salt taste can trigger two divergent behavioral responses; low concentrations of salt are attractive to animals, while high concentration of NaCl is rejected, even when salt deprived (Chandrashekar *et al.,* 2010). The anatomical units of this taste detection are taste receptor cells, which are located in taste buds and distributed across the different taste papillae of the tongue as well as the respiratory and upper gastrointestinal tracts (Sugita 2006; Yoshida *et al*., 2006). These taste receptor cells activate different gustatory nerves, which transmit the taste information to the brain (Yoshida *et al*., 2006). Response properties of taste receptor cells for different taste qualities depend on the receptors and transduction mechanisms (Lindemann, 2001). To activate salt receptor cells, sodium (Na^{+}) and chloride (Cl^{-}) ions are required (van der Klaauw and Smith 1995) and these receptor cells function through the Na^{+} ion channels of the tongue (Chandrashekar *et al.,* 2010).

Variation in salt taste sensitivity was found to be related to many factors such as individual differences, exposure to foods and water with high sodium contents, age, sex and species (Goatcher and Church, 1970b; Bertino *et al*., 1986). Recent studies revealed that specific genes have also been associated with salt taste perception in humans (Dias *et al*., 2013). Taste function evaluation can be conducted by the estimation of detection and recognition thresholds using different methods. Studies have been carried out investigating the taste responses and thresholds to saline drinking water in sheep (Goatcher and Church, 1970a, b), goats (Bell, 1959) and cattle (Bell and Williams, 1959) by using an electrophysiological method (Bernard, 1964) and two choice preference test (Bell, 1959; Bell and Williams, 1959; Goatcher and Church, 1970a).

Feeding recommendations

Feeding recommendations refer to the minimum intake of nutrients required for production and good health. The recommended levels vary among different animals. Based on NRC (1981 and 1985), Berger (2006) recommended 5,000 mg/kg salt required to the total diet or 10,000 mg/kg salt to the concentrate portion of the diet in goats and sheep. However, sodium requirements for sheep and goats are estimated using a factorial approach considering maintenance, growth, pregnancy and lactation (NRC 2007). Endogenous sodium losses also need to be considered when estimating total daily sodium requirements for small ruminants. Sodium requirements for maintenance and lactation are added to the true absorption rate of 0.91 (NRC, 2007). The absorption rate of sodium in goats is around 80%, which is slightly lower than in sheep (NRC, 2007). The recommended daily sodium intake for sheep and goats are presented in Table 1.2.

Table 1.2 Recommended sodium intake for feed in sheep and goats (NRC, 2007)

	Sodium (g/day)	
	Sheep	Goats
Maintenance	(0.0108 x BW)/0.91	(0.015 x BW)/0.80
Growing	(1.1 x average DWG)/0.91	(1.6 x average DWG)/0.80
Pregnancy (105–133 days)	(0.021 x LBW)/0.91	(0.034 x LBW)/0.80
Lactating	(0.4 x MY)/0.91	(0.4 x MY)/0.80

BW = Body weight; DWG = Daily weight gain; LBW = Lamb born weight; MY = Milk yield

It is important to know the amount of salts present in the drinking water for the calculation of sodium requirements in a feeding plan. The amount of salt in drinking water is largely determined by the total dissolved salt content of the water. There are no distinct requirements of salt in drinking water. However, the following points need to be considered when using saline water for livestock and poultry (Table 1.3). The upper limits of soluble salts in water for livestock are listed in Table 1.4.

Table 1.3 Guidelines for the use of saline water by livestock and poultry (NRC, 1974; Greg, 2014)

Salinity (TDS in mg/L)	%	Effects for livestock
Less than 1,000	0.1	Relatively low level of salinity. Should not present any serious burden to livestock.
1,000 – 2,999	0.1–0.3	Should be satisfactory but may cause temporary and mild diarrhea in unaccustomed livestock. Should have no other effects on health or performance.
3,000 – 4,999	0.3–0.5	Should be satisfactory for livestock, although might cause temporary diarrhea or be refused at first. Poor waters for poultry, often causing watery feces, increased mortality and decreased growth, especially in turkeys.
5,000 – 6,999	0.5–0.7	Can be used with reasonable safety for dairy and beef cattle, sheep, pigs and horses. For pregnant or lactating animals, or horses in work, avoid using water with salinity at higher levels in this range. Unacceptable for poultry.
7,000 – 10,000	0.7–1.0	Considerable risk in using water for pregnant or lactating stock, young animals or any animals subjected to heavy heat stress or water loss. Unacceptable for poultry. Unsuitable for pigs and horses. In general, should be avoided in livestock, although older livestock may subsist on these waters in conditions of low stress.
10,000 – 15,000	1.0–1.5	Risky. Cannot be used for stock other than adult, dry sheep.
Around 19,000	1.9	Toxic: effects will vary depending on the type of salts present.

Table 1.4 Safe upper limit of total salt in water for livestock (Glauert, 2007)

Livestock	mg/L	mS/m	%
Poultry	3,000	545	0.3
Pigs	3,000	545	0.3
Dairy cattle (lactating)	3,500	600	0.4
Beef cattle	5,000	900	0.5
Lambs, weaners, breeder ewes, dry dairy cattle	5,000	900	0.5
Horses	6,000	1,100	0.6
Adult sheep (dry)	10,000	1,820	1.0

Effect of high salt intake

Feed

Ingestion of high salt in feed has an impact on feed and water intake, salt-water balance and hormonal control of energy (Digby *et al*., 2011). Excess sodium intake is associated with water retention, diarrhea, dehydration, muscle cramps and neurological problems (Peirce, 1957; Marai *et al.*, 1995; Kii and Dryden, 2005). Excessive dietary salt intake depresses feed intake (Masters *et al*., 2005; Blache *et al.*, 2007) and increases water intake which is associated with increased rate of nutrient passage, lowered protein degradation in rumen (Digby *et al*., 2011), damage kidneys (ARC, 1980) and reduced energy allocation for production (Arieli *et al*., 1989). High salt diets also affect meat quality by reducing intramuscular fat content (Pearce *et al*., 2008). Moreover, high dietary salt intake has significant consequences on reproductive capacity of rams (Leung and Sernia, 2003). Meyer and Weir (1954) reported increased weight losses during lactation in ewes receiving 13.5% sodium chloride in the diet compared to sheep consuming 9.1% or less. However, excess salt intake does not create any problem as long as animals have free access to fresh water. When animals ingest excess salt, they increase their water consumption, probably in an attempt to increase the urinary excretion of sodium to inhibit its surplus (Wilson and Dudzinski, 1973; Hamilton and Webster, 1987). If salt intake approaches poisoning levels, it has been associated with rapid breathing, diarrhoea, excessive thirst, head pressing, hydropericardium and death (Hungerford, 1990).

Drinking water

Animals can compensate higher salt intake in feed by increasing fresh water consumption. However, when the drinking water has a high salt content, this mechanism does not work and animals cannot get out of the surplus which leads to increased risk of toxicity. There are specific problems for livestock animals associated with the consumption of excess salt, particularly sodium, potassium and chloride in drinking water. Sea water intake leads to higher salt concentrations on the outside of the cell membrane compared to the inside. This difference in salt concentration impairs osmosis and causes cell shrinkage (Giuggio, 2018). To regain an isotonic state, the body attempts to eliminate the excess Na^+ from extracellular fluids through increased urination resulting in dehydration, muscle cramps, thirst, dry mouth and eyes (Giuggio, 2018). The body further tries to compensate this fluid loss by increasing heart rate and constricting blood vessels, which consequently leads to a reduced blood supply to the brain and other organs causing coma and eventually death (Giuggio, 2018).

It was found that 13,000 to 15,000 mg/kg salt in the drinking water only had small effects on production traits in sheep, while long term intake of water containing 20,000 mg/kg or more salt led to severe reduction in food intake, loss of body weight, emaciation and possibly death in sheep, goats and cattle (Peirce, 1957 and 1959; Weeth and Haverland, 1961; Wilson and Dudzinski, 1973; Hamilton and Webster, 1987; McGregor, 2004). High salt exposure in drinking water also has a dramatic effect on the reproductive capacity of ewes (Digby *et al*., 2011). Ewes exposed to 9,000 mg/kg sodium chloride in water occasionally failed to conceive (Peirce, 1968b) and water containing 13,000 mg/kg salt caused distress at parturition, a decrease in lambing percentage and an increase in lamb mortality (Peirce, 1968a, b; Potter and McIntosh, 1974).

Moreover, increased salinity concentration was found to decrease blood volume, plasma volume, urea concentrations as well as extracellular and interstitial fluids in ewes (Assad and El-Sherif, 2002) and German Merino sheep (Meintjes and Engelbrecht, 2004). Increased sodium intake can also alter ion absorption mechanisms resulting in hypertension (Elliott *et al*., 1996) and increased blood pressure associated with renal and cardiovascular diseases (Tuomilehto *et al*., 2001). Godwin and Williams (1986) reported increased urinary volume, electrolyte excretion and glomerular filtration rate in sheep and goats receiving high concentrations of saline water. On the contrary, drinking saline water had no effect on the urea concentration in urine of goats but caused a decrease in sheep and camels (Abou Hussien *et al*., 1994).

Salt tolerance and adaptation

In the coastal areas and some arid islands where natural freshwater is not available, animals are forced to drink saline water throughout their lives. This has helped them to develop certain physiological and behavioral adaptation mechanisms against increased body salinity which have enabled them to survive (Dunson, 1974; Gould, 1990). It has been observed that goats apparently drink seawater on beaches and islands. An increased renal salt excretion through their urine was measured in these animals probably as an adaptation to their living conditions (Dunson, 1974).

Salt tolerance varies between animal species and relates to available fresh water consumption. The salt tolerance in drinking water for livestock is summarized in Table 1.5.

Compared to other mammals, ruminants are more capable to tolerate higher salt in drinking water (Goatcher and Church, 1970b). Some factors affect salt tolerance in animals such as salt ingestion period (Peirce 1957 and 1959), age (Wilson and Dudzinski, 1973), environmental condition (Weeth and Haverland, 1961), physiological adaptation, and even foetal programming (Digby *et al*., 2011). Animals start to show sensitivity against salinity when they are supplied with saline water over longer durations. Sensitivity responses to salt ingestion differ based on food or drinking water (Masters *et al*., 2005). It was found that sheep can tolerate high sodium chloride (NaCl) concentrations ranging from 5% to 20% in their diet (Digby *et al*., 2011) while deer can tolerate at least 6% (Ru *et al*., 2004) and chickens only around 3% (Kare and Biely, 1948).

Excess sodium intake is primarily regulated by the kidneys through controlling sodium reabsorption, mediating changes in the active transport and membrane permeability (Suttle, 2010), and increasing renal sodium excretion through urine (Suttle 2010). It seems that the kidneys' capacity to concentrate urine and its ability to reduce urinary water loss during dehydration is directly related to the relative medullary thickness (RMT) of the kidneys. The greater the RMT, the longer the loop of Henle and therefore the larger the kidney‘s ability to reabsorb water. Increased sodium and chloride ions in plasma following consumption of high saline water can be excreted by (i) increased glomerular filtration rate and changes in renal plasma flow (Potter, 1968), (ii) reduced sodium chloride reabsorption in individual nephrons and (iii) increased water retention (Digby *et al*., 2011). Another powerful adaptive mechanism is the NaK ATPase enzyme, induced in the ilium, liver and kidney after exposure to saline water (Macfarlane, 1982). In its function, it increases the pumping of sodium out of cells and in return the pumping of potassium into the intracellular space.

The renin- angiotensin system (RAS) is responsible to maintain salt and water balance by the secretion of aldosterone, which controls sodium retention and arginine vasopressin (AVP), thereby stimulating water reabsorption by the kidneys (Digby *et al.*, 2011). Ingestion of high amounts of salt leads to increased plasma volume and osmolality, to which the animals body can adapt by exerting negative feedback on aldosterone, thereby reducing sodium reabsorption and promoting sodium excretion (Digby *et al.*, 2011). However, high salt intake from both feed and water does not induce any changes in plasma AVP when the animal consumes sufficient fresh water (Cowley *et al*., 1986).