1 Introduction

Water is the single most important nutrient for livestock and big game wildlife species. It is the most abundant ingredient of the animal body in all phases of growth and development. A calf's body contains 75 to 80% water at birth and about 55 to 65% water at maturity. While animals can survive for a week or more without food, death is likely in a matter of days without adequate water intake. Water is involved either directly or indirectly in virtually every physiologic process essential to life. Water is the medium in which all chemical reactions in the body take place. Blood, which contains 80% water, is vital in transporting oxygen to the tissues and carbon dioxide from the tissues as well as being the life support system for the body. It is the medium for transporting nutrients, metabolic wastes, and chemical messengers, such as hormones, throughout the body. It provides the chemical base for nutrient digestion and uptake from the GI tract and for the elimination of waste products via urine and bile. Water's physical properties make it an important factor in the transfer of heat and the regulation of temperature in the body. Due to its high specific heat (the ability to absorb or give off heat with a relatively small change in temperature), water is ideally suited as a temperature buffering system for the body. A restriction of water intake lowers feed intake and N retention (i.e. protein), and it increases N loss in the feces. It also results in increased excretion of urea in the urine. Animals may survive a loss of nearly all the fat and about one-half of bodily protein, but a loss of about one-tenth of water from the body results in death.

Obviously, an adequate supply of clean water is necessary to the health of all animals, including human beings. Under most management systems, water is the cheapest and most readily available nutrient. Unfortunately, and probably because of this fact, it is also the most overlooked nutrient. Sources of water include those obtained from wells or surface runoff, water contained in feedstuffs (lush grass may consist of as much as 75% water) and metabolic water obtained from the oxidation of fat and protein in the body. In the arid western United States, good quality water is a scarce commodity, and livestock and wildlife are often forced to survive on what might be charitably described as "less-than-perfect" water due to competition from urbanization, mineral extraction, etc. In most cases, these animals do surprisingly well, but poor quality water has resulted in acute illness and death. It also robs producers via decreased performance (growth, reproduction). Thus, awareness of water quality issues has increased as the competition for resources intensifies. Ranchers, wildlife managers, conservationists, veterinarians, cooperative extension personnel, animal owners, and others need to know whether a particular source of water is safe. One of the more common questions fielded by our laboratories is "what is X ppm of Y in the water going to do to my cattle (horses, deer, etc.)?"

Water consumption is influenced by many factors, including genetics (species, breed), age, body size, ambient temperature and humidity, water temperature, and level of production. For example, cattle (a species that has been studied extensively) consume *an average* of 2 to 4 kg of water for each kg of dry matter consumed and an additional 3 to 5 kg of water per kg of milk produced; however, this average varies dramatically with temperature, especially when the environmental temperature exceeds the thermo-neutral range (5-20 C in cattle) making animals lose increasing amounts of water via respiration and sweating. For example, a 273-kg (600 lb) feeder steer drinks 22.7 L at 5 C or below; at 21 C (70 F), he needs 33 L but at 30 C (roughly 86 F) he requires 54 L or 20% of his body weight per day.[1] At 39 C (roughly 102 F), he would require 116 L.[2] Rations high in Na, fiber, or protein also increase water requirements.[1,3] For example, horses consume twice as much water while on a hay diet compared to a high concentrate diet at the same temperature.[4] The level of production is a very important factor in water requirements. A lactating beef cow requires nearly twice as much water (64 L or about 16% of her body weight) per day at 21 C as the same cow (32.9 L, 9% body weight) when dry (not lactating) at the same temperature, and a high-producing dairy cow of similar size needs 90 L, or nearly 20% of her body weight under the same conditions.[1,5] At 32 C, she may drink as much as 40% of her body weight.[1,6]

The amount (dose) of any water-borne toxicant ingested by a given animal is determined by the concentration of the substance in water *and* by the amount of water the animal drinks. Water intake is technically defined as free-drinking water plus the amount contained in feedstuffs; however, for purposes of simplicity in this report, we have assumed animals are consuming air-dried hay or senescent forage with a minimal (10%) water content and will use the term "intake" to describe the amount of water consumed voluntarily by animals from streams, ponds, etc. The amount an animal drinks is determined by true thirst and appetite. By definition, true thirst is the physiologic drive to consume sufficient water to meet minimum metabolic needs; however, most animals also exhibit an "appetite" for water and consume more than is strictly necessarily to satisfy thirst.[7] Reasons for the latter are many, varied, and do not lend themselves to quantitative prediction. We therefore disregarded appetite in calculating doses from water intake but instead used fairly conservative estimates of thirst in such calculations by disregarding forage water content. Most calculations of potential toxic doses in this report are thus based upon 273 kg (600 lb) feeder cattle that drink approximately 20% of their body weight, or about 8 L per kg of dietary dry matter, per day, at 32 C (90 F). This *may* not provide adequate protection for high-producing dairy cattle, which drink significantly more under similar environmental conditions, but is reasonably conservative for range livestock (beef and sheep) and weather conditions typical of Wyoming. Higher temperatures would also result in higher consumption than our "standard" steer, but sustained periods of such weather are not that common in Wyoming.[8] Finally, there is virtually no information on water consumption by the major wildlife species covered in this report, but it is reasonable to assume that species that evolved in the northern Great Plains would not have greater requirements than domestic cattle.

This report is targeted at domestic livestock and wildlife (beef cattle, horses, sheep, deer, elk, and pronghorn antelope) that rely upon wells, ponds, streams, and other water sources on Wyoming's ranges. Although we have made note of data related to swine where we found them, virtually all modern swine are raised in intensive operations that draw water from systems (municipal, water district, etc.) that are maintained according to human drinking water standards. Similarly, "alternative agricultural" species such as llamas and bison are not included, in part because of a scarcity of data.

Water quality is commonly evaluated by chemical methods that have been designed to be very reproducible and very specific. As a result, the process of analyzing water is fairly straightforward, and many tests are readily available, commercially. Unfortunately, translating these very precise, formal, data to practical recommendations for livestock and wildlife is less cut and dried. As noted by Dr. Art Case, the dean of veterinary toxicologists, "sometimes the cow just didn't read the book." First, many toxicants in water act additively with the same toxicant in feedstuffs. In most such cases, the bottom line is not necessarily the water concentration but rather the total mg of toxicant ingested per kg of the animal's body weight (commonly expressed as "mg X/kg BW"). Throughout this report, we have tried to use realistic estimates of total dietary concentrations of such toxicants to calculate the water concentration of the toxicant required to potentially cause problems.

Second, chemical water quality tests do not usually measure the specific chemical form of the toxicant present. For example, Se as selenite or selenate behaves quite differently in the mammalian body than does selenomethionine, but the typical laboratory just reports total Se. Where possible, we have based recommendations upon the chemical form most likely to be present in typical surface waters in Wyoming and noted any caveats that should be considered if the water source is not "typical". In the absence of other data, we have assumed the free ion in water is equivalent on a mg/kg BW basis to the same chemical in feedstuffs.

Third, typical chemical tests do not differentiate between animal species. Some substances are more toxic in ruminants than monogastrics (simple-stomached animals) as a result of their unique physiology; some are less. While we have tried to identify significant differences where they exist, our recommendations are based upon the most sensitive of our species of interest.

Fourth, many toxic substances interact with other toxicants and/or nutrients in the diet. We have tried to enumerate such interactions in the narrative if they are well documented and, where possible, account for them in the "bottom line" calculations of acceptable water concentrations.

Finally, the rate of exposure influences the potency of many toxicants. A bolus dose of nitrate (NO_3), given via a stomach tube, is much more toxic than the same amount spread over an entire day's grazing. Under summer range conditions typical of the Great Plains, livestock drink once, or, at most, twice a day. Wildlife typically trek to water and drink their fill during the morning and evening twilight. We have, therefore, assumed all of the water-borne daily dose of a given substance will be consumed during a fairly short period, once or twice a day.

Water quality constituents in this report were drawn from common water quality guidelines, prioritized according to how closely, in our experience, existing Wyoming concentrations approached these guidelines and how often the elements in question caused poisoning in Wyoming animals. For example, Hg is much more toxic than many of the elements we studied, but it is rarely present at detectable concentrations in Wyoming water surveys. Copper is a real problem in aquatic organisms, but Cu deficiency is a much bigger problem in livestock than Cu toxicity. We then worked our way as far down this prioritized list as time permitted. Obviously, there are more constituents on our list than we were able to examine, but we believe we covered those most important to Wyoming.

Data used in compiling this report are drawn primarily from scientific literature, including refereed journals, texts, proceedings, abstracts, and theses, with an emphasis on material published during the last 20 years. The basic strategy consisted of 1) searching biomedical databases (e.g. Medline, CAB Abstracts, etc.) for reports of toxicity in any species, 2) examining bibliographies of relevant papers for new leads, and, finally 3) forward searching (e.g. Science Citation Index) for more recent papers that cite earlier work on a given topic. We also solicited well-documented anecdotal data (i.e. field reports) from colleagues at other research and/or diagnostic institutions. Where possible, we tried to validate secondary sources (e.g. reviews, texts) by examining primary documents from which they were drawn. If sufficient data existed for our principle species of interest (beef cattle, horses, sheep, elk, deer, and antelope) we focused on those reports. If not, we attempted to extrapolate from rodents, humans, etc., being careful to identify the uncertainty factors inherent in such extrapolations. Each source was assigned a rating for reliability, with peer-reviewed, experimental studies usually, but not always, being considered more reliable.

As noted previously, the interaction of water quality and animal health is considerably more complex than just "X" mg of "Y" per L of water. For example, many factors have been suggested to influence the palatability of water for animals. Decreased consumption due to bad taste is potentially just as harmful as water deprivation[3], yet the state of the art regarding palatability is still largely qualitative and anecdotal. Acid pH may mobilize toxic metals from plumbing or soil, but the particular effect of a given pH is obviously very dependent on the local situation. A sudden transition to pure water after several weeks on highly saline water may result in so-called "salt poisoning." Where adequate, quantitative data exists for non-directly toxic adverse effects on health, we have incorporated them into the final recommendations. Where there is substantial evidence suggesting such effects exist, but no reproducible, quantitative data were available, we tried to mention the existence of such effects but have not factored them into the final recommendations.

Safety margins are a matter of judgment rather than an exact science. The purpose of safety margins is to compensate for unknown, or unknowable, variables in toxicology data such as genetic variability, sex, life stage, duration of exposure, unforeseen interactions with other toxicants, etc. The standard practice in setting human drinking water standards for non-carcinogens has been to divide the geometric mean of the NOAEL and minimum toxic dose by 10 to 1,000 depending upon whether the data are derived from human exposure, multiple non-human species, or incomplete data in any species. Another approach used in the past has been to set the safe limit at the upper end of the range commonly reported in natural waters as was done with Se.[2] Both approaches, while unarguably "safe," ignore the realities of livestock production in the western United States. Water that is so "perfect" as to meet these theoretically desirable criteria has already been taken for other uses. In this report we have taken the approach of presenting our best estimate of the NOAEL (i.e. will not produce any measurable decrease in performance in the most sensitive class of animal) under a very conservative set of assumptions appropriate to Wyoming and allowing readers to make their own judgment regarding "safety" margins.

The final report, together with the documents it was drawn from, was forwarded to colleagues at four other universities (Washington State University, University of Nebraska, North Dakota State University, and Texas A&M University) for peer review. Their comments were considered and incorporated into the final document.

Although there are many ways of expressing measurements regarding water quality and toxicology, we have chosen to use the following conventions. The dose of a toxicant that causes some particular effect is expressed in milligrams of substance per kilogram of body weight or "mg X/kg BW". The concentration of a substance in water is expressed as milligrams of substance per liter of water or "mg X/L". If the substance is ionized, and the ion is important in terms of toxic effects, it will be described with the standard scientific abbreviation for the ion, e.g. "NO_3^-". Similarly the concentration of a toxicant occurring in dry feedstuffs will be described in terms of parts per million or ppm. Single elements are abbreviated with the standard chemical symbol (e.g. "Se" for selenium).

This report, and the project that created it, was funded by the Wyoming Department of Environmental Quality. Although the authors anticipate they will find the information useful, our intended audience is much broader and includes ranchers, wildlife managers, conservationists, veterinarians, cooperative extension personnel, animal owners, and others. The last concerted effort in the United States to summarize the literature regarding water quality for animals occurred more than 30 years ago[2], and there have been many additions to the knowledge base since that time. We believe this report represents a reasonable starting point for evaluating the adequacy of water quality for animals.