FINAL

SODIUM WATER QUALITY FOR LIVESTOCK AND WILDLIFE A LITERATURE-BASED ANALYSIS

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Executive Summary

The Wyoming Environmental Quality Council (EQC) is considering updating numeric chemical constituent criteria in Chapter 1 of the Wyoming Water Quality Rules and Regulations. The updated criteria are proposed for the protection of livestock (the proposal is referred as the agricultural use rule).

Of the numerical chemical criteria under review, the criterion for sodium is under close scrutiny as conflicting analyses have proposed different water quality thresholds to be protective of livestock and wildlife (Hunter 2007, Raisbeck et al. 2007). In preparation for the EQC review, SRC has prepared an analysis of livestock effects from sodium exposure utilizing all available sources of information on sodium toxicity to livestock and wildlife. SRC compiled peer-reviewed scientific literature on sodium effects on animal species and sought to determine, based on literature findings, a sodium level in water that is protective of animal species of interest in Wyoming, including livestock (cattle, sheep, horses), and wildlife (birds, mammals).

Overall, the sensitivity of various livestock receptors to sodium toxicity appeared to be in the order beef cattle > swine > dairy cows > horses > sheep.

Based on SRC's analysis, a water quality threshold at or below 3,500 mg/L should protect against adverse effects in livestock and wildlife. In Wyoming, produced water surface discharges are likely to be consumed by wildlife, cattle, sheep and horses. A produced water discharge sodium WQT of 3,500 mg/L should be protective of these receptors.

Previous testimony by Raisbeck et al. (2007) identified a sodium water quality criterion of 1,000 mg/L to prevent long-term adverse effects in livestock. The water quality criterion appeared to specifically be based on studies demonstrating a decline of milk production in dairy cows. Upon review of the references provided for this criterion, however, none of these studies support the conclusion that adverse effects occur just above 1,000 ppm sodium; in fact, these studies do not demonstrate adverse effects below 6,000 ppm sodium. The lack of an accounting of all sodium consumption in key studies, as well as normalization of exposure concentrations to intake rates, and consideration of statistical differences may have contributed to this discrepancy. Thus, the conclusion of this review is that the sodium water quality criterion recommended by Raisbeck et al. (2007) is not supported by the literature.

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1 INTRODUCTION

The Wyoming Environmental Quality Council (EQC) is considering updating numeric chemical constituent criteria in Chapter 1 of the Wyoming Water Quality Rules and Regulations. The updated criteria are proposed for the protection of livestock (the proposal is referred as the agricultural use rule).

Of the numerical chemical criteria under review, the criterion for sodium is under close scrutiny because previous testimony of the adequacy of current limits to protect livestock and wildlife appear conflicting. An analysis by Hunter (2007) demonstrated support for sodium limits >3000 mg/L. On the other hand, Raisbeck et al. (2007) recommended a sodium limit of 1000 mg/L. Each effort was based on a different dataset and different methodology to derive a water quality threshold (WQT).

The rule will apply to all surface water bodies in Wyoming, including surface water bodies created or impacted by produced water surface discharges from coal bed natural gas (CBNG) or conventional oil and gas production. Thus the revised criteria could affect CBNG and conventional oil and gas operations depending on whether produced water discharges exceed the new limits. Produced water surface discharges currently meet all applicable regulations.

In preparation for the EQC review, SRC has prepared an analysis of livestock effects from sodium exposure utilizing all available sources of information on sodium toxicity to livestock and wildlife. SRC compiled peer-reviewed scientific literature on sodium effects on animal species and sought to determine, based on literature findings, a sodium level in water that is protective of animal species of interest in Wyoming, including livestock and wildlife.

2 WILDLIFE AND LIVESTOCK USE OF SURFACE WATER BODIES IN WYOMING

In Wyoming, livestock and wildlife (birds, mammals) species utilize both natural and produced surface water bodies for food, shelter, breeding ground and water resources. Discharges from produced water often create important habitat for wildlife species. An abundance of game species have been noted in the Powder River basin and the Bighorn basin in areas that have discharges of produced water (SWWRC et al. 2002, RETEC 2004).

A primary agricultural use of creeks and reservoirs in Wyoming is for livestock ranching. Livestock species reported by Wyoming ranchers and the US Department of Agriculture (USDA) are predominately beef cattle, and some sheep and horses. Most beef cattle in Wyoming are raised on the open range, with typically <1% feedlotted (NASS 2005). Livestock use of surface water bodies tends to be year-round, sometimes with little variation of water bodies for drinking. Wildlife frequently use water sources on more of a seasonal basis.

3 OVERVIEW OF THE METABOLISM AND TOXICITY OF SODIUM

Essentiality

Sodium is an essential nutrient. It is the primary cation of extracellular fluids. Sodium is required for osmotic regulation in the body and nerve, muscle and brain function. Salt deficiency can cause pica behavior (chewing or licking wood, rocks, etc), reduction in appetite, and failure to grow or lactate. Long-term deficiency will cause death from dehydration.

Most livestock species require between 0.1 and 0.4 percent sodium in their diet for basic growth and productivity (NRC 2005). Minimum requirements for several types of livestock are summarized below:

Animal	Minimum daily requirement, NaCl (%)	Equiv. Na requirement (ppm)
Swine	0.08 – 0.25%	315 - 984
Horses	0.1 – 0.18%	393 - 708
Cattle (beef)	0.08 – 0.2%	315 - 393
Cattle (dairy)	0.1 - 0.46%	393 - 1810
Sheep	0.18 - 0.43%	708 - 1692

References: NRC 1985, 1989, 1998, 2000, 2001.

Metabolism

Most terrestrial animals have evolved an efficient process to absorb sodium from the gastrointestinal tract. Once absorbed, sodium is recycled into the intestinal tract via bile and salivary, pancreatic and intestinal epithelial secretions. A high intestinal sodium concentration is required to transport glucose, amino acids, and other nutrients across the mucosa. If adequate water is present, most animals can tolerate relatively large doses by increasing sodium excretion (Mason and Scott 1974, Weeth et al. 1968, Wilson 1966). Excess sodium is excreted readily by the kidneys as long as water is available.

Toxicity

Acute effects of excessive sodium (as sodium chloride) intake in livestock include excess salivation, vomiting, diarrhea, ataxia, disorientation, blindness, seizures and paralysis (NRC 1980, 2005). Subchronic effects in mammals include reduced feed and/or water intake, and subsequent reduction in weight gains. In birds, effects include reduced reproductive rates and weight loss associated with prolonged reductions in food and water intake.

The mechanisms underlying toxicity are related to cellular dehydration. When extracellular sodium concentrations become elevated, water is drawn out of the cell down the concentration gradient, resulting in cellular shrinking (NRC 2005). The cellular shrinking results in damage to the small blood vessels that supply the superficial portions of the brain, causing brain damage.

According to the literature published to date, livestock species that appear most susceptible to elevated sodium are growing cattle. Studies on sheep (Peirce 1957, 1959, 1962, 1963), for example, indicate that sodium chloride levels up to 13,000 mg/L do not adversely affect sheep health, weight gain or wool production. In swine, Anderson and Stothers (1978) showed that 6,000 mg/L sodium chloride did not affect weight gain in pigs. There are few, if any adequate studies on horses to suggest a maximum tolerable limit, however it is generally assumed that tolerance in horses is equivalent to other monogastric species and/or cattle (see Section 4.5 for further detail).

4 METHODS

Methods used to derive a WQT were similar to USEPA methods to derive wildlife soil screening levels (USEPA 2003). Other relevant guidelines included:

- Guidelines for Exposure Assessment (US EPA 1992a),
- Wildlife Exposure Factors Handbook (US EPA 1993),
- Generic Assessment Endpoints for Ecological Risk Assessments (Draft) (US EPA 2002),
- other relevant federal and state regulations and guidance, and
- the general literature.

The steps to derive sodium WQTs for livestock and wildlife are the following:

1. Select relevant endpoints
2. Assemble toxicological database
3. Determine data usability
4. Compute no effect and low effect levels
5. Derive lower bound and upper bound WQTs for each receptor-endpoint pair
6. Derive final WQT that incorporates all receptor-endpoint pairs

Each of these steps is described below.

4.1 Select Relevant Endpoints (Measures of Protection)

Assessment endpoints are explicit statements of an environmental value that is to be protected (US EPA 1998). Consistent with Wyoming Department of Environmental Quality (WDEQ) water quality regulations, the assessment endpoint identified in this risk analysis is the protection of the health and well-being of populations of Wyoming livestock and wildlife species from adverse effects of consuming surface water.

From the broad assessment endpoint, more specific measurement endpoints can be identified. Measurement endpoints are defined as measurable environmental characteristics that are related to the values (i.e., assessment endpoints) that are to be protected (US EPA 1992). Measurement endpoints to protect animal health in this analysis include developmental, reproductive and longevity effects. Growth effects are usually considered less desirable for evaluation of health endpoints, because growth effects can be short-term or reversed, depending on the exposure program, and the relationship between growth and other adverse effects is uncertain. However, for livestock species, measurement endpoints that include growth rate or weight gain were included in this analysis because this parameter is important for livestock management practices. Feed or water intake rates, feed efficiency and other measures of digestion rates were not considered adequate endpoints in themselves to evaluate the well-being of livestock species, because research has shown that there is considerable individual variation in these parameters above and below that expected or predicted on the basis of size and growth (see review in NRC 2000). Individuals of the same body weight often require widely different amounts of feed for the same level of production.

4.2 Assemble Toxicological Database

A thorough review of literature from scientific, peer reviewed sources was undertaken to assemble a database of toxicological literature pertaining to sodium. A number of secondary sources of information were also reviewed for assurance that all relevant studies were assembled into the database. Secondary sources of literature included:

1. NRC 1974
2. NRC 1980
3. NRC 2005
4. Raisbeck et al. 2007
5. Agricultural extension bulletins (web-based)

Primary sources of information ranged from veterinary anecdotes of “salt” poisoning, case histories from livestock owners, and the more standardized toxicity experiments utilizing control groups and measured doses of sodium in food and/or water. All types of studies were initially considered and assembled into the database.

Literature on the effects of sodium on a variety of livestock species was available. For livestock species, attention was focused on cattle because it is the most common type of livestock in Wyoming and the livestock type most expected to consume non-municipal sources of water (thus with a potential for higher sodium content). For other livestock species, literature studies that covered the range of toxicity thresholds found in the literature were assembled into the database. Thus, every relevant study on sodium toxicity in livestock was reviewed but not every study for receptors other than cattle (or horses) was necessarily assembled into the database.

Swine and chickens are generally not raised in areas of open range. These livestock species are raised in intensive operations that draw their water from municipal systems. Municipal systems are maintained according to human drinking water standards and must meet total dissolved solid (TDS) criteria <500 mg/L. Thus, these species of livestock are not primary receptors for natural and produced water surface bodies in Wyoming. Therefore, we did not include an analysis of risk to chickens. Swine studies were reviewed for the primary purpose of a weight of evidence characterization for horses (see data gaps, section 4.6).

Primary endpoints of interest in the review included growth, milk production, wool production, reproductive parameters, and death. Endpoints that included behavioral changes or chemical analyses of blood, serum or milk were not reviewed.

A total of 155 literature records were assembled into the database.

4.3 Determine usability of data records

Not all data records that were compiled were usable for this analysis. Criteria for discarding a particular data record from final analysis included the following:

1. Treatment interactions: Multiple toxicants were evaluated simultaneously* and/or the animal was deprived of water or feed before or during the study.
2. Differences in effects relating to dose were not statistically determined.
3. Critical data required to compute dose (e.g., exposure concentrations) was missing. This information does not include body weights or ingestion rates, which were estimated if information was missing.
4. Data were not peer reviewed.

*Components of TDS were an exception, to a degree, because these constituents occur naturally in Wyoming surface waters and current limits allow up to 3,000 ppm sulfate and 5,000 ppm TDS. Additionally, sodium was typically administered to the test animal in the form sodium chloride, and thus chloride concentrations tended to be very high in some cases. Therefore, a study was not considered to have treatment interactions if other TDS components were less than or equal to the following concentrations:

Constituent	**Upper Limit (ppm)**
Bicarbonate/carbonate	2,000
Calcium	300
Chloride	(no limit)
Magnesium	500
Nitrate	300
Potassium	500
Sulfate	3,000
Total TDS	5,000

Studies considered adequate for this analysis are shown in Table 4-1; studies that did not meet the minimum criteria specified above are shown in Table 4-2.

4.4 Compute Dose-Based Toxicity Thresholds

Toxicity thresholds were reported in several ways, most typically either as a dose-based value (i.e., mg sodium per kg body weight per day) or a concentration value (e.g., ppm). Exposure will vary depending on a test animal’s sodium intake rate, and toxicity thresholds can be affected by differences in body weights. Therefore, we normalized exposure rates across studies by computing dose-based toxicity thresholds from information provided in the study. Details, equations and results of dose-based calculations are presented in Appendix A.

In some cases, body weights and/or ingestion rates were not reported (these parameters are needed to compute dose-based thresholds). In these cases, representative, average body weights and ingestion rates were obtained elsewhere (Table 4-3) and used to compute dose in the study of interest.

We computed dose based toxicity thresholds corresponding to a no-effect adverse level (NOAEL) and a low-effect adverse level (LOAEL). A NOAEL is defined in this document as the highest concentration or dose that *did not* result in a significant effect of interest. A LOAEL is defined as the lowest concentration or dose that *did* result in a significant effect of interest.

Another piece of information frequently missing from studies was a complete analysis of sodium content in all ingested materials (i.e., feed, water and/or salt supplements). Sodium is a ubiquitous element; it is present in both animal feed and water (unless deionized). Additionally, some test animals were frequently allowed access to salt licks or other salt supplements in addition to feed and water. Unfortunately, it was somewhat uncommon for the author to report sodium content in whichever material was not of interest, nor a report of the amount of supplementary salt consumed. For example, if the author was supplementing a lamb’s water source with sodium, the sodium content of the water was reported but not the feed that the lamb also consumed daily. In these cases, unless otherwise noted, it was assumed that livestock were fed or watered at normal nutritional levels, and that supplementary salt intake was negligible. Assumed concentrations in feed and water are shown in Table 4-4.

4.5 Determine Water Quality Thresholds for Receptor-Endpoint Pairs

NOAELs and LOAELs were computed for each receptor-endpoint pair using all studies that met the criteria for an acceptable study (see Section 4.3). Dose-based NOAELs and LOAELs were then converted to concentration-based effect thresholds for a “typical” livestock receptor with characteristics shown in Table 4-3. Equivalent WQTs were then computed by subtracting the estimated sodium content of a typical livestock feed (Table 4-4) from the total NOAEL or LOAEL. Equations and results are presented in Appendix A.

4.6 Derive a Single, Final Water Quality Threshold

Once WQTs were determined for each receptor-endpoint pair, the last step in the process was to derive a single WQT that would be protective of all the receptors considered. Studies on cattle and sheep were abundant, so WQTs derived in each study were plotted by receptor for various endpoints to show the range of WQTs derived (Figures 4-1 and 4-2). Average WQTs for each receptor-endpoint pair were also calculated (Tables 4-5 and 4-6). A final WQT was selected based on evaluation of the range and average of WQTs, and professional judgement. In general, the final WQT was derived that was less than the lowest LOAEL. However, in one case an outlier was apparent or in other cases data gaps precluded a reliable estimate (see Section 5 for discussion).

4.7 Data Gaps

There were virtually no studies on sodium toxicity in horses. In an anecdotal account of salt poisoning in cattle, Ohman (1939) alluded to the fact that horses were reluctant to drink saline water at all (so were the cattle). Ramsay (1924) suggested that horses could be maintained on water with up to 9,500 mg/L TDS, although specific TDS components were not described. Only Schryver et al. (1987) demonstrated that ponies were not adversely affected when fed a diet supplemented with 5% NaCl.

Horses are monogastric, and uptake of soluble ions has been demonstrated to be similar to other types of monogastrics such as rats and swine (Gooneratne et al. 1989, Raisback et al. 2007). Toxicity studies with fluoride (Shupe and Olson 1969), nitrate (Burwash et al. 2005) or molybdenum (Tipton et al. 1969), for example, have demonstrated that the toxicity thresholds of horses tend to be similar to swine, and higher than that of cattle or, at times, sheep. Thus, the assumption for the computation of WQTs was that toxicity thresholds of sodium in swine and cattle are probably comparable to that of horses.

Similarly, there was a general lack of data available for non-livestock species. Embry et al. (1959) and Heller (1933) reported sodium toxicity in rats, although statistical analysis was lacking from both studies and crucial dosing information was missing in Heller (1933). There were a few veterinary accounts of salt poisoning in dogs (Baird 1969, Barr et al. 2004, Hughes and Sokolowski 1978, Khanna et al. 1997), but crucial information was often missing from these accounts such as the dose of sodium ingested. Krista et al. (1961) conducted a series of toxicity studies, one of them on mallard ducks, and reported NOAELs and LOAELs on growth and intake rates. Other than these references, data specifically addressing wildlife toxicity to sodium appear to be absent. To evaluate the potential effect of sodium on other endpoints in birds, we extrapolated results of studies addressing reproductive and mortality parameters in chickens to mallard ducks. Mallards were selected as the representative bird species in this analysis. Average NOAEL and LOAEL values obtained from studies on chickens were used to compute WQTs for mallard ducks. For mammalian wildlife, we assumed that toxicity thresholds for livestock would be comparable to mammalian wildlife species in Wyoming.

5 RESULTS

There was typically a large range in WQTs computed from individual studies, as well as some overlap between NOAEL and LOAEL-based WQTs. Some of this variability is undoubtedly due to the lack of full reporting by various authors on the total sodium intake of the test animals. For example, only Jaster et al. (1978) reported actual sodium intake from a salt supplement given freely to dairy cows during an experiment on milk production. Nominal sodium intake concentrations including the salt supplement were in the range of 12,000 ppm sodium (Na). Other studies on milk production in dairy cows (Nestor et al. 1988, Randall et al. 1974) did not report supplemental salt intake rates, though this is a typical practice, and resulting nominal Na intake rates were often lower than normal nutritional levels for dairy cows (see Tables 4-5 and 4-6).

Studies evaluating growth of beef cattle were the most abundant (Figure 4-1). Most studies only identified a NOAEL from the experiment, and indicated that significant, adverse effects were not found from sodium concentrations as high as 9,000 mg/L. In comparison, only 4 LOAEL values were identified; studies included two experiments by Weeth and Haverland (1961) and one each by Leibholz et al. (1980) and Croom et al. (1982). Three out of 4 LOAEL-based WQTs were >5000 mg/L. Conversely, Weeth and Haverland (1961) reported a WQT of ~500 mg/L during a winter experiment. A second experiment conducted by the same authors over the summer yielded a LOAEL-based WQT >10,000 mg/L and growth rate differences were less than in the winter experiment. The reason for the exceptionally low LOAEL value in Weeth and Haverland’s winter experiment is unclear, and none of the 13 other studies indicate that this result is typical. Thus, the result of Weeth and Haverland’s winter experiment on growing cattle was determined to be an outlier in the context of other growth studies.

Overall, the sensitivity of various livestock receptors to sodium toxicity appeared to be in the order beef cattle > swine > dairy cows > horses > sheep.

Based on the review of the WQTs for each receptor and endpoint, a water quality threshold at or below 3,500 mg/L should protect adverse effects in livestock and wildlife. This is a conservative estimate that is typical of reported NOAEL values for beef cattle and sheep and is well below reported LOAELs. In Wyoming, produced water surface discharges are likely to be consumed by wildlife, cattle, sheep and horses. A produced water discharge sodium water quality threshold of 3,500 mg/L should be protective of these receptors.

This WQT assumes a daily feed intake of ~800 mg/kg sodium for cattle, which is likely to be an overestimate for open range herds given that sodium in grass hay is typically 300 mg/kg or less (Amaral et al. 1985, Harvey et al. 1986). Other livestock and wildlife species are expected to consume less sodium in the diet (see Table 4-4), and this was accounted for in the derivation of WQTs for these species. This recommended WQT is less than estimated concentrations of sodium that could result in a deleterious effect on livestock or wildlife, which are estimated >3800 mg/L for cattle, sheep, swine, wildlife and horses (Appendix A).

Although udder edema was not considered to be an endpoint of interest in this analysis, studies pertaining to udder edema were briefly reviewed. Instances of udder edema in adult dairy cows were reported by Nestor et al. (1988) and Randall et al. (1974) given >7000 ppm sodium. The cows were administered sodium in the diet. Based on a water intake rate of 32 L per day, this equates to a WQT <3000 mg/L. Juvenile cows did not show signs of udder edema until sodium content reached higher levels (Nestor et al. 1988), an equivalent of >7,500 mg/L if supplemented in the water. However, there were some important study limitations in Nestor and Randall, including the fact that supplemental sodium intake was not reported nor was the sodium content in the basal feed. When daily sodium intakes were calculated from dose-based NOAEL values, many of the resulting intake rates were less than daily requirements for dairy cows. Thus, it is uncertain whether sodium intake rates were underestimated or whether the dairy cows were undernourished during the study. Udder edema is not thought to interfere with growth or long-term milk production (Melendez et al. 2006).

Some previous studies have reported varying effect thresholds depending on the type of feed administered. Harvey et al. (1986), for example, suggested that sodium in water affected growing cattle at lower concentrations when fed a concentrate formula than when fed alfalfa hay (differences were not statistically determined). However, the difference may largely be due to the high sodium content in the concentrate relative to the hay, thus exposing growing cattle in the former group to a higher sodium content overall. The study does point out, however, that sodium content in feed is an important consideration in considering total sodium exposure to the animal.

Toxicity from elevated sodium tends to occur at lower concentrations if other TDS components are present in water or feed at elevated concentrations (these conditions were taken into consideration when the WQT was derived). In a series of studies, Peirce (1950, 1966, 1968a, 1968b) showed that toxicity of sodium will occur at lower concentrations (~4,000 ppm Na) to sheep when sulfate, magnesium, potassium or carbonates are also elevated in water. In a subchronic study on rats, Embry et al. (1959) experimented with several different mixtures of TDS – sodium chloride, sodium sulfate, magnesium chloride, magnesium sulfate, or calcium chloride – and found that tolerance to sodium chloride was highest. Other salts affected growth rates at lower doses, with magnesium chloride and magnesium sulfate affecting growth at the lowest dose levels. Similar results were found by Weeth and Hunter (1971) in their study on cattle. The USEPA (1976) advises that “livestock and poultry can survive on saline waters up to 15,000 mg/L salts of sodium and calcium combined with bicarbonates, chlorides and sulfates. But only 10,000 mg/L of corresponding salts of potassium and magnesium could be tolerated. The approximate limit for highly alkaline waters containing sodium and calcium carbonates is 5,000 mg/L.” NRC (1974) suggested that an upper limit of 5,000 mg/L TDS should be used as a benchmark for livestock (dairy and beef cattle, sheep, swine, and horses), based on a similar literature review.

6 COMPARISON TO PREVIOUS ANALYSIS

A report by Raisbeck et al. (2007) identified a sodium water quality criterion of 1,000 mg/L to prevent long-term (chronic) adverse effects in livestock. Specific endpoints identified were growth and “production indices,” although the water quality criterion appears to be specifically based on a decline of milk production in dairy cows. Upon review of the references provided for this criterion (Table 6-1), however, none of these studies support the conclusion that adverse effects occur just above 1,000 mg/L Na. In fact, these studies do not show adverse effects occurring below 6,000 ppm sodium (Table 6-2).

Studies reviewed in Raisbeck et al. do not appear to be normalized to intake rates and body rates. Concentration-based NOAELs and LOAELs are shown in Table 6-2. Some references did not meet minimal criteria for an acceptable study as described previously, including identifying statistical differences. Only one study shows that cattle growth was adversely affected at a sodium water concentration less than 5,000 ppm (Weeth and Hunter 1971) and in this study, the sulfate level in water was 3,300 mg/L. The same experiment with sodium chloride (NaCl) yielded no adverse effect (Weeth and Hunter 1971).

An overall lack of accounting for total sodium consumption in feed, water and supplements may have contributed to the discrepancy between the literature and the recommendation for a sodium water quality limit of 1,000 mg/L. In a study by Jaster et al. (1978), milk production showed marginal declines ($0.05<p<0.08$) when dairy cows were supplemented with 2,500 mg/L NaCl in the drinking water. However, dairy cows were also given access to a free salt supplement. Jaster et al. (1978) reported that an average of 30 g NaCl was consumed daily in the treatment group. Therefore, the total sodium exposure resulting in adverse effects was much higher (>12,000 ppm) than reported for just the water.

Thus, the conclusion of this review is that the sodium water quality criterion recommended by Raisbeck et al. (2007) is not supported by the literature.

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APPENDIX A

Equations and Raw Results of Dose-Based Values and Water Quality Thresholds for Livestock and Wildlife

APPENDIX A

Introduction

This appendix describes the equations used to derive NOAELs, LOAELs and WQTs. Results per receptor and per endpoint are presented in the last section.

Equations

Water quality thresholds were derived for each receptor-endpoint pair from average NOAELs and LOAELs for that receptor-endpoint. The equation for water quality threshold is:

$$WQT = [(EC \bullet BW / IR_w) - (DI_f \bullet cf)] \qquad (1)$$

where:

WQT = water quality threshold (mg Na per L)
EC = effect concentration (ie, NOAEL or LOAEL) (mg Na per kg BW per day)
BW = body weight (kg wet)
IR_w = daily ingestion rate of water (L per day)
DI_f = daily ingestion of Na in food (mg per kg per day)
cf = conversion factor from kg to L, equal to 1.

The NOAEL or LOAEL is calculated from the threshold concentration in water and food. The equations are:

$$NOAEL = C_w \bullet IR_w / BW + C_f \bullet cf \bullet IR_f / BW \qquad (2)$$
$$LOAEL = C_w \bullet IR_w / BW + C_f \bullet cf \bullet IR_f / BW \qquad (3)$$

where:

$NOAEL$ = no adverse effect concentration (mg Na per kg BW per day)
C_w = threshold concentration of Na in water (mg/L)
IR_w = daily ingestion rate in water (L-day)
BW = body weight (kg wet)
C_f = threshold concentration of Na in feed (mg/kg)
IR_f = daily ingestion rate of feed (kg-day)
cf = conversion factor from kg to L, equal to 1.

The nominal sodium concentration is the total sodium concentration that the receptor is exposed to. The calculation is:

$$\text{Nominal Na} = C_w + (C_f \bullet cf) + C_s \qquad (4)$$

where:

C_w = concentration of Na in water (mg/L)
cf = conversion factor from kg to L, equal to 1.
C_f = concentration of Na in feed (mg/kg)
C_s = concentration of Na in salt supplements (mg/kg); assumed to be zero unless otherwise noted.

Results
Dose-based values and nominal concentrations are presented in Table A-1.

Table A-1. Calculated doses and concentrations of sodium reported in each study.

Receptor	Endpoint	Sodium concentration (ppm)	LOAEL (mg/kg-day)	NOAEL (mg/kg-day)	Study
Adult cattle dairy	Growth	24435		1342	Amaral et al. (1985)
Adult cattle dairy	Milk Production	24435		1342	Amaral et al. (1985)
Juvenile swine pig	Growth	3222		671	Anderson and Stothers (1978) (Exp. 1)
Adult chicken laying	Egg Production	14802	1097 [a]		Balnave and Scott (1986) (exp 1)
Adult chicken laying	Egg Production	14597		1080 [a]	Balnave and Scott (1986) (exp 1)
Adult chicken laying	Egg Quality	14802	1097 [a]		Balnave and Scott (1986) (exp 1)
Adult chicken laying	Egg production	2643		245 [a]	Balnave et al. (1989) (Exp. 1)
Adult chicken laying	Egg quality	2643	245 [a]		Balnave et al. (1989) (Exp. 1)
Adult chicken laying	Egg quality	1856		140 [a]	Balnave et al. (1989) (Exp. 1)
Adult chicken laying	Egg production	2643		271 [a]	Balnave et al. (1989) (Exp. 2)
Adult chicken laying	Egg quality	2092	196 [a]		Balnave et al. (1989) (Exp. 2)
Adult chicken laying	Egg quality	1856		162 [a]	Balnave et al. (1989) (Exp. 2)
Adult chicken laying	Egg Production	15501		1101 [a]	Belnave and Scott (1986) (exp 2)
Adult chicken laying	Egg Quality	15501	1101 [a]		Belnave and Scott (1986) (exp 2)
Adult chicken laying	Egg Quality	15621		1080 [a]	Belnave and Scott (1986) (exp 2)
Adult cattle dairy	Milk Production	6992		90	Canal and Stokes (1988)
Juvenile cattle beef	Growth	27327	1017		Croom et al. (1982) (exp 1)
Juvenile cattle beef	Growth	19551		832	Croom et al. (1982) (exp 1)
Adult cattle dairy	Milk production	4756		141	Demott et al (1968)
Juvenile sheep lamb	Growth	115873	780		Hamilton and Webster 1987
Juvenile cattle beef	Growth	21506		406	Harvey et al. 1986 (Trial 1-corn)
Juvenile cattle beef	Growth	18322		381	Harvey et al. 1986 (Trial 1-hay)
Juvenile cattle beef	Growth	18263		403	Harvey et al. 1986 (Trial 2-corn)
Juvenile cattle beef	Growth	23390		399	Harvey et al. 1986 (Trial 2-hay)
Adult cattle dairy	Milk Production	13825	731		Jaster et al. (1978)
Adult cattle dairy	Milk Production	12061		459	Jaster et al. (1978)
Adult chicken laying	Egg Production	3282		455 [a]	Krista et al. (1961) (exp 2)
Adult chicken laying	Egg Production	1709		172 [a]	Krista et al. (1961) (exp 2)
Adult chicken laying	Egg quality	3282		455 [a]	Krista et al. (1961) (exp 2)
Adult chicken laying	Egg quality	1709		172 [a]	Krista et al. (1961) (exp 2)
Adult duck	Growth	5643	593		Krista et al. (1961) (exp 3)
Adult duck	Growth	4462		526	Krista et al. (1961) (exp 3)
Juvenile cattle beef	Growth	19031		520	Leibholz et al. (1980)
Juvenile cattle beef	Growth	28031	624		Leibholz et al. (1980)
Adult cattle beef	Growth	36618		760	Meyer and Weir (1954) (cattle Exp.)
Juvenile sheep lamb	Growth	50387		2986	Meyer and Weir (1954) (Exp. 2)
Adult sheep	Growth	5982	821		Peirce (1957)
Adult sheep	Growth	4015		549	Peirce (1957)
Adult sheep	Wool Production	5982	821		Peirce (1957)
Adult sheep	Wool Production	4015		549	Peirce (1957)
Adult sheep	Growth	5196		261	Peirce (1959)
Adult sheep	Wool Production	5196		261	Peirce (1959)
Adult sheep	Growth	5182		457	Peirce (1960)
Adult sheep	Wool Production	5182		457	Peirce (1960)
Adult sheep	Reproduction	5164	259		Peirce (1968a)
Adult sheep	Reproduction	3984		200	Peirce (1968a)
Adult sheep	Wool Production	5164		259	Peirce (1968a)
Adult sheep	Mortality	5196	261		Peirce (1968b)
Adult sheep	Reproduction	5196	261		Peirce (1968b)
Adult sheep	Reproduction	4015		201	Peirce (1968b)
Adult sheep	Wool Production	4015	201		Peirce (1968b)
Juvenile sheep lamb	Growth	4015	437		Peirce (1968b)
Adult horse	Mortality	5000	880		Schryver et al. (1987)
Juvenile cattle beef	Growth	5736		412	Weeth and Haverland (1961) (exp 1-winter)
Juvenile cattle beef	Growth	7703	326		Weeth and Haverland (1961) (exp 1-winter)

Table A-1. Calculated doses and concentrations of sodium reported in each study.

Receptor	Endpoint	Sodium concentration (ppm)	LOAEL (mg/kg-day)	NOAEL (mg/kg-day)	Study
Juvenile cattle beef	Growth	5539	1186		Weeth and Haverland (1961) (exp 2-summer)
Juvenile cattle beef	Growth	4752		866	Weeth and Haverland (1961) (exp 2-summer)
Juvenile cattle beef	Growth	8686		1075	Weeth et al. (1960)
Juvenile cattle beef	Growth	3375		215	Weeth et al. (1968) (Exp. 2 - 2 days)
Adult chicken laying	Egg Quality	1968		170 [a]	Yolowitz et al. (1990) (exp 1)
Adult chicken laying	Egg Production	2068		163 [a]	Yolowitz et al. (1990) (exp 2)
Adult chicken laying	Egg Quality	2068	163 [a]		Yolowitz et al. (1990) (exp 2)

Notes:

[a] These NOAELs and LOAELs reflect dose to a chicken. In the analysis, nominal Na concentrations were used to compute dose-based thresholds for mallard ducks.

Figure 4-1. NOAEL and LOAEL-based Water Quality Thresholds for Growing Beef Cattle

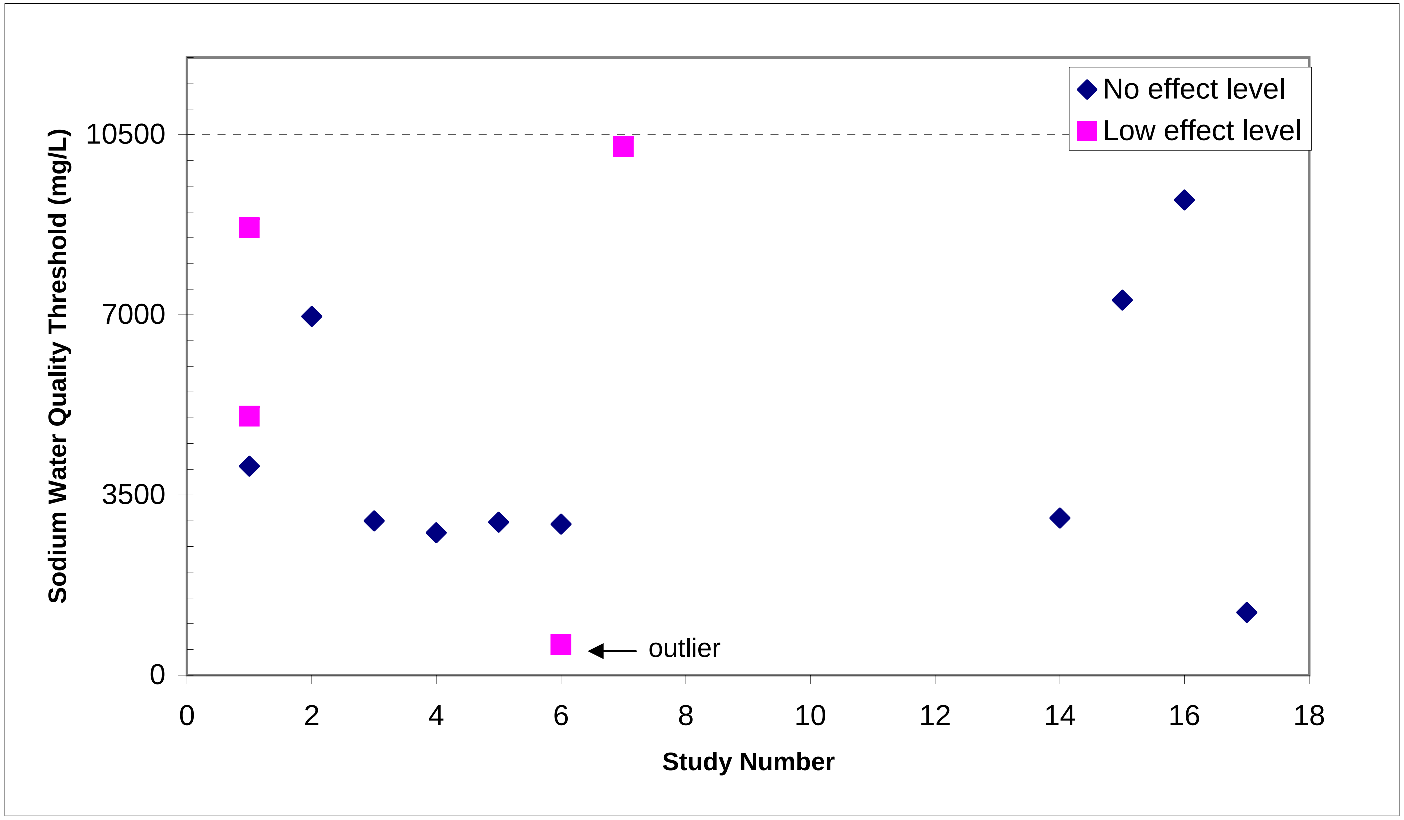

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Figure 4-2. NOAEL and LOAEL-based Water Quality Thresholds for Sheep: Growth and Wool Production

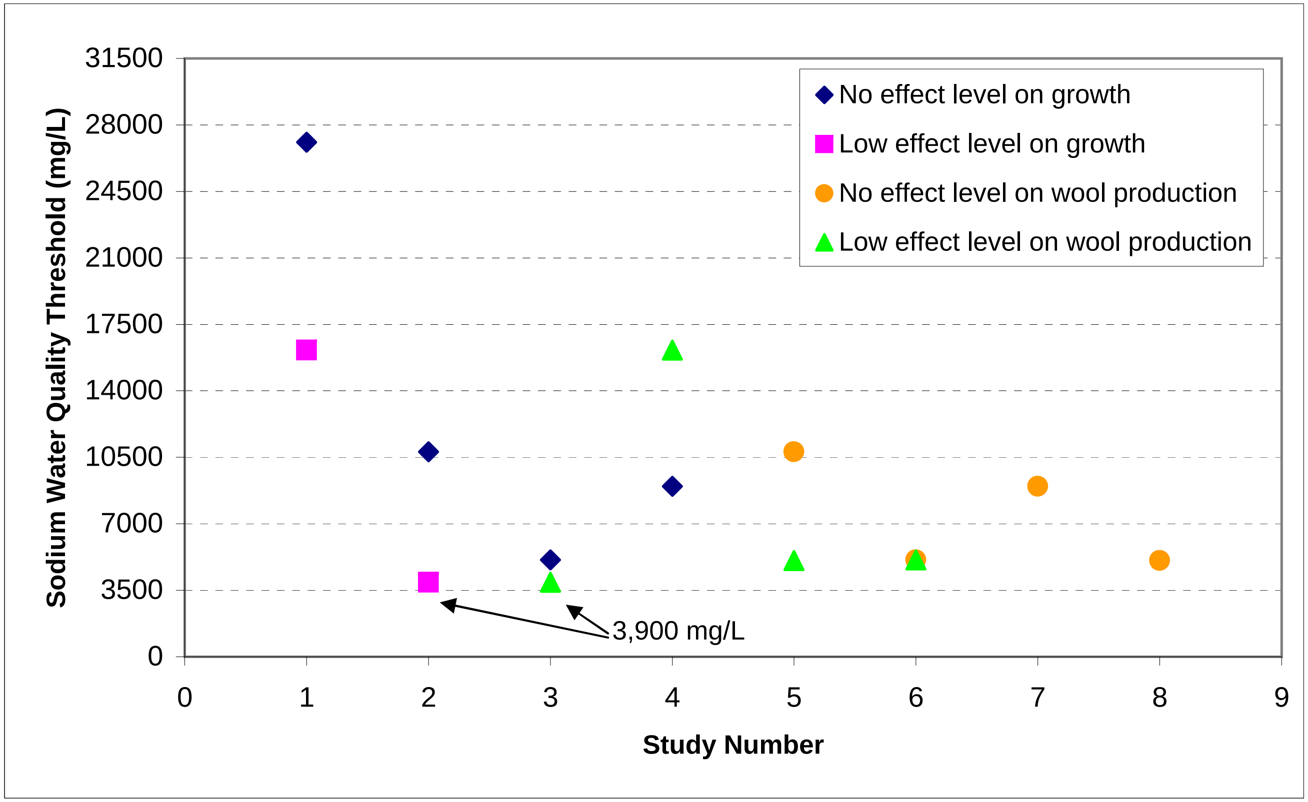

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Table 4-1. Studies that Met the Criteria for an Acceptable Study

Reference	Note
Amaral et al. (1985)	*
Anderson and Stothers (1978) (Exp. 1)	
Balnave and Scott (1986) (exp 1)	
Balnave et al. (1989) (Exp. 1)	
Balnave et al. (1989) (Exp. 2)	
Belnave and Scott (1986) (exp 2)	
Canal and Stokes (1988)	
Croom et al. (1982) (exp 1)	
Demott et al (1968)	
Hamilton and Webster 1987	
Harvey et al. 1986 (Trial 1-corn)	
Harvey et al. 1986 (Trial 1-hay)	
Harvey et al. 1986 (Trial 2-corn)	
Harvey et al. 1986 (Trial 2-hay)	
Jaster et al. (1978)	
Kare and Biely (1948)	
Koletsky (1958)	
Koletsky (1959)	
Krista et al. (1961) (exp 1)	
Krista et al. (1961) (exp 2)	
Krista et al. (1961) (exp 3)	
Leibholz et al. (1980)	
Meyer and Weir (1954) (cattle Exp.)	*
Meyer and Weir (1954) (Exp. 2)	*
Nestor et al. (1988) (NaCl exp.)	
Peirce (1957)	
Peirce (1959)	*
Peirce (1960)	*
Peirce (1962)	*
Peirce (1963)	*
Peirce (1968a)	*
Peirce (1968b)	*
Potter and McIntosh (1974)	
Potter et al. (1972)	
Randall et al (1974) (location A)	
Randall et al (1974) (location A)	*
Randall et al (1974) (location B)	
Rossi et al. (1998)	*
Rossi et al. (1998)	
Sapirstein et al. (1950)	
Schryver et al. (1987)	
Weeth and Haverland (1961) (Exp 1)	
Weeth and Haverland (1961) (Exp 2)	
Weeth and Lesperance (1965) (Exp. 2)	
Weeth and Lesperance (1965) (Exp. 3)	
Weeth et al. (1960)	
Weeth et al. (1968) (Exp. 1-ad libitum)	
Weeth et al. (1968) (Exp. 2 - 2 days)	
Wilson (1966)	
Yolowitz et al. (1990) (exp 1)	
Yolowitz et al. (1990) (exp 2)	

Note

* Some treatment interactions were present in parts of this study. These data were not included in final analysis.

Table 4-2. Studies that Did Not Meet the Criteria for an Acceptable Study

Reference	Rationale
Baird (1969)	[c] [d]
Ballantyne (1957)	[c] [d]
Balnave and Yolowitz (1987) (weeks 1-5)	[a]
Barr et al. (2004)	[c] [d]
Berg and Bowland (1960)	[c] [d]
Boyd et al. (1966)	[c]
Challis et al. (1987)	[b]
Croom et al. (1983)	[e]
Embry et al. (1959) (exp 1-rat)	[c]
Embry et al. (1959) (exp 4-poultry)	[c] [d]
Embry et al. (1959) (trial 2-cattle)	[c]
Fountaine et al. (1975)	[b] [c]
Frens (1946)	[c]
Grout et al. (2006	[b]
Gudmundson and Meagher (1961)	[c] [d]
Heller (1930)	[c] [d]
Heller (1932)	[c] [d]
Heller (1933) (cattle)	[b] [c]
Heller (1933) (chickens)	[c]
Heller (1933) (rats)	[c]
Hibbs and Thilsted (1983) (case 1)	[b] [c]
Hughes and Sokolowski 1978	[c] [d]
Johnson et al. (1959)	[b] [c]
Jones et al. (1984)	[c] [d]
Kare and Biely (1948)	[c]
Khanna et al. (1997)	[c]
Lames (1968)	[c]
Larsen and Bailey (1913)	[c] [d]
Medway and Kare (1959)	[c] [f]
Medway and Kare (1959) (Exp. 1)	[c] [f]
Ohman 1939	[c] [d]
Patterson et al. (2003)	[a]
Pearson and Kallfelz (1981)	[b] [c] [d]
Pretzer (2000)	[c] [d]
Ramsey (1924)	[c]
Sandals (1978)	[c] [d]
Sautter et al. (1957)	[c] [d]
Scrivner (1946)	[c] [g]
Selye (1943)	[c] [d]
Solomen et al. (1995)	[b] [g]
Spafford (1941)	[c] [d]
Tomas et al. (1973)	[c]
Trueman and Clague (1978)	[c] [d]
Weeth and Hunter (1971)	[b] [c]
Wilson (1967) (Exp. 1)	[c]
Yolowitz et al. (1990)	[b]

Notes:

[a] No effect thresholds were identified
[b] Treatment interactions
[c] No statistical analysis used to identify threshold.
[d] Missing critical study components, such as control group or exposure concentrations.
[e] Data not peer-reviewed (abstract only)
[f] Route of administration not oral
[g] Data and conclusions incongruous

Table 4-3. Default Receptor Body Weights and Intake Rates.

Receptor:	BW (kg)	Source	IR-water (L-day)	Source	IR-feed (kg-day)	Source	Notes
Adult cattle dairy	540	[b]	32.9	[b]	7.3	[b]	assumes 70F temperature
Juvenile cattle dairy	275	[b]	29.5	[b]	6.50	[b]	assumes 70F temperature
Adult cattle beef	540	[b]	24.2	[b]	5.4	[b]	assumes 70F temperature
Juvenile cattle beef	275	[b]	29.5	[b]	6.50	[b]	assumes 70F temperature
Rat	0.35	[a]	0.028	[a]	0.028	[a]	adult
Dog	23	[n]	1.12	[n]	0.45	[n]	medium size dog, indoors.
Horse	450	[p]	38	[q]	7.5	[q]	
Adult sheep	150	[e]	7.6	[i]	1.01	[e]	
Juvenile sheep	40	[m]	4.4	[m]	0.27	[e]	
Adult swine	15	[g]	68	[g]	2.50	[g]	
Juvenile swine	7	[m]	1	[m]	1.17	[g]	weaner
Pygmy goat (adult)	65	[j]	2.8	[k]	0.45	[j]	IR rates assume summer conditions.
Juvenile turkey	0.562	[l]	0.07868	[m]	0.031	[c]	1 day old; IR scaled to BW
Mallard duck	1.13	[o]	0.064	[o]	0.27	[o]	

Sources:

[a] USEPA 1988
[b] Winchester and Morris 1956
[c] NAS 1981
[d] NAS 2000
[e] Average of parameters reported by Peirce (1959, 1962, 1963, 1968a, 1968b) (before treatments)
[g] NRC 1998
[h] Kare and Biely (1948)
[i] North Dakota State Univ. extension publication. http://www.ag.ndsu.edu/pubs/ansci/livestoc/as954w.htm
[j] UC Davis extension bulletin http://www.goats4h.com/GoatsHome.html
[k] McGregor 1986
[l] Assumed same params as 2 day old chicks from Kare and Biely (1948)
[m] Ontario Ministry online at http://www.omafra.gov.on.ca/english/engineer/facts/07-023.htm#7
[n] Personal communication with local vet.
[o] US EPA 1993

Table 4-4. Default Sodium Content in Water and Feed.

Receptor:	NaCl (%)	Sodium (%)	Sodium (ppm)	Notes
Adult cattle dairy	0.56	0.22	2200	NRC (2001) recommendation for dairy cow during milk production stage, non-pregnancy.
Juvenile cattle dairy	0.20	0.08	800	NRC (2001) recommendation for dairy cow during non-milk production stage, non-pregnancy.
Adult cattle beef	0.2	0.07868	787	NRC (2000) recommendation for beef cattle is 0.07% Na per day, or 11-15 g salt/day
Juvenile cattle beef	0.2	0.07868	787	NRC (2000) recommendation for beef cattle is 0.07% Na per day, or 11-15 g salt/day
Rat	7.71	3.033114	30331	Assume 2% USP XIV salts containing 7.71% NaCl
Dog	0.013	0.005	50	
Horse	0.150	0.059	585	NRC (1989)
Adult sheep	0.01	0.005	50	NRC (1985) nutrient requirements of sheep, "good forage" category.
Juvenile sheep	0.01	0.005	50	NRC (1985) nutrient requirements of sheep, "good forage" category.
Adult swine	0.20	0.080	800	NRC (1998) - Nutrient requirements of swine, 10th edition
Juvenile swine	0.20	0.080	800	NRC (1998) - Nutrient requirements of swine, 10th edition
Pygmy goat (adult)	---	---	---	Nutritional levels not obtained for this receptor.
Juvenile turkey	0.38	0.15	1500	NRC (1984)
Mallard Duck	0.013	0.005	50	
Water	0.008	0.0031	31.5	Weeth and Hunter (1971), Challis et al. 1987, Jaster et al. 1978

Table 4-5. Concentrations of Sodium that ***Did Not*** Result in Adverse Effects on Livestock and Wildlife

Receptor	Endpoint	Water Quality Threshold	Note	Avg NOAEL (mg/kg BW per day)	Avg NOAEL (ppm)	No. of Studies
Beef Cattle (adult)	Growth	16172		760	36618	1
Beef Cattle (juvenile)	Growth	4349		551	14261	10
Dairy cows (adult)	Growth	21227		1342	24435	1
Dairy cows (adult)	Milk Production	3205		244	6527	4
Horse	Mortality	9836		880	50000	1
Mallard Duck	Egg Production	8745	[b]	498	6063	7
Mallard Duck	Egg quality	6362	[b]	363	4382	6
Mallard Duck	Growth	13598	[b]	773	5052	2
Mallard Duck	Growth	9237		526	4462	1
Sheep (adult)	Growth	8286		422	4798	3
Sheep (adult)	Reproduction	3907		201	4000	2
Sheep (adult)	Wool Production	7480		382	4889	4
Sheep (juvenile)	Growth	27095		2986	50387	1
Swine (juvenile)	Growth	3897		671	3222	1

Notes:

The threshold NOAEL value is shown here. Average Na threshold was taken for categories with >1 study.

Water threshold calculated from the average dose-based NOAEL value unless otherwise noted.

[a] Water threshold could not be calculated from dose-based NOAEL (resulting value was <0, reflecting less sodium intake than assumed for generic receptor).

[b] Extrapolated from studies on adult chickens.

Table 4-6. Concentrations of Sodium that ***Did*** Result in Adverse Effects on Livestock and Wildlife

Receptor	Endpoint	Water Threshold	Note	Avg LOAEL (mg/kg BW per day)	Avg LOAEL (ppm)	No. of Studies
Beef Cattle (adult)	Growth	---	[d]			
Beef Cattle (juvenile)	Growth	6561		788	17150	4
Dairy cows (adult)	Milk Production	11198		731	13824	1
Dairy cows (adult)	Growth	---	[d]			
Mallard Duck	Egg Production	19319	[b]	1097	14802	1
Mallard Duck	Egg Quality	9845	[b]	560	7421	5
Mallard Duck	Growth	---	[d]			
Mallard Duck	Growth	10420		593	5643	1
Sheep (adult)	Growth	16154		821	5982	1
Sheep (adult)	Mortality	5101		261	5196	1
Sheep (adult)	Reproduction	5082		260	5180	2
Sheep (adult)	Wool Production	10036		511	4999	2
Sheep (juvenile)	Growth	3923		437	4015	1
Swine (juvenile)	Mortality	5808	[c]	944	80928	1

Notes:

The threshold LOAEL value is shown here. Average Na threshold was taken for categories with >1 study.

Water threshold calculated from the average dose-based LOAEL value unless otherwise noted.

[b] Extrapolated from studies on adult chickens.

[c] Route of administration was by drenching.

[d] There were no studies that identified a LOAEL for this receptor & endpoint.

Table 6-1. References Provided by Raisbeck et al. (2007) in Support of Sodium Water Quality Limit

Report No	Reference	Receptor	Endpoint	Threshold Class	Avg LOAEL (ppm)	Notes
560	Amaral et al. (1985)	Dairy cows (adult)	Growth, Milk Production	NOAEL	24,435	cows fed a low fiber diet to see Na effect with diet.
559	Croom et al. (1982) (exp 1)	Beef Cattle (juvenile)	Growth	LOAEL	27,327	
559	Croom et al. (1982) (exp 1)	Beef Cattle (juvenile)	Growth	NOAEL	19,551	
531	Croom et al. (1983)	Beef Cattle (juvenile)	Growth	LOAEL	19,701	Data not peer-reviewed; is abstract only.
531	Croom et al. (1983)	Beef Cattle (juvenile)	Growth	NOAEL	818	Data not peer-reviewed; is abstract only.
532	Harvey et al. 1986 (Trial 1-corn)	Beef Cattle (juvenile)	Growth	NOAEL	21,506	
532	Harvey et al. 1986 (Trial 1-hay)	Beef Cattle (juvenile)	Growth	NOAEL	18,322	
532	Harvey et al. 1986 (Trial 2-corn)	Beef Cattle (juvenile)	Growth	NOAEL	18,263	
532	Harvey et al. 1986 (Trial 2-hay)	Beef Cattle (juvenile)	Growth	NOAEL	23,390	
560	Heller (1933) (cattle)	Dairy cows (adult)	Milk Production	LOAEL	7,716	Based on non-quantitative account of production in 1 cow.
558	Heller (1933) (cattle)	Dairy cows (adult)	Growth	NOAEL	6,732	Not statistically determined.
559	Heller (1933) (cattle)	Dairy cows (adult)	Milk Production	NOAEL	6,732	Not statistically determined.
547	Jaster et al. (1978)	Dairy cows (adult)	Milk Production	LOAEL	13,824	Marginal significance (0.05<p<0.08)
547	Jaster et al. (1978)	Dairy cows (adult)	Milk Production	NOAEL	12,061	Marginal significance (0.05<p<0.08)
581	Meyer and Weir (1954) (cattle Exp.)	Beef Cattle (adult)	Growth	NOAEL	36,618	
581	Meyer and Weir (1954) (Exp. 2)	Sheep (juvenile)	Growth	NOAEL	50,387	
546	Peirce (1957)	Sheep (adult)	Growth, wool production	LOAEL	5,982	
546	Peirce (1957)	Sheep (adult)	Growth, wool production	NOAEL	4,015	
578	Peirce (1959)	Sheep (adult)	Growth, wool production	NOAEL	2,796	
578	Peirce (1959)	Sheep (adult)	Growth, wool production	NOAEL	5,196	
575	Peirce (1960)	Sheep (adult)	Growth, wool production	NOAEL	5,182	
576 - 580	Peirce (1962, 1963, 1966, 1972)	Sheep (adult)	Growth, wool production	NOAEL	4,212	
558	Weeth and Haverland (1961) (exp 1-winter)	Beef Cattle (juvenile)	Growth	LOAEL	7,216	
558	Weeth and Haverland (1961) (exp 1-winter)	Beef Cattle (juvenile)	Growth	NOAEL	5,736	
558	Weeth and Haverland (1961) (exp 2-summer)	Beef Cattle (juvenile)	Growth	LOAEL	5,539	
558	Weeth and Haverland (1961) (exp 2-summer)	Beef Cattle (juvenile)	Growth	NOAEL	4,752	
574	Weeth and Hunter (1971)	Beef Cattle (juvenile)	Growth	LOAEL	2,448	Water Sulfate = 3300 mg/L
574	Weeth and Hunter (1971)	Beef Cattle (juvenile)	Growth	NOAEL	2,447	Not statistically determined.
539	Weeth et al. (1968) (Exp. 2 - 2 days)	Beef Cattle (juvenile)	Growth	NOAEL	3,375	Not statistically determined.

Note:

Only those studies reporting effects on growth or production indices were included here, because these were the endpoints Raisbeck et al. 2007 based its sodium recommendation on.