Evaluation of Water Quality and Nutrition for Dairy Cattle

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Summary

1. Water is the most important essential nutrient supplied to dairy cattle.
2. However, at times and in some dairy farms, quality and provision of water may not be optimal to maximize animal performance and health.
3. Too often dairy producers and their consultants have insufficient understanding of water nutrition of dairy cattle.
4. Two main questions should be examined:
    a) Is water intake normal, depending on physiological state of the animal and its environment?
    b) Are anti-quality factors present in water that may affect water intake, or normal metabolic or physiological functions of animals?
5. Assessing whether or not water intake is normal must be done by measuring water intake (e.g., with in-line flow meters) of groups of animals with specific definable characteristics (e.g., dry matter intake rate, milk yield, dry matter content of the ration, and sodium intake). Specific approaches for measuring water intake are suggested.
6. If water intake, feed intake, and animal performance are sub-optimal; careful evaluation of the quality of water should be initiated by conducting a laboratory analysis for anti-quality factors.
7. Anti-quality factors (constituents in excess or unwanted compounds) that may affect water intake and animal performance include: total dissolved solids, sulfur, sulfate, iron, manganese, nitrate, toxic compounds (e.g., heavy metals, pesticides), and deleterious microorganisms.
8. The pH of water (6 to 9 range), calcium, magnesium, and hardness of water are not believed to affect the intake of water or animal performance.
9. Various treatment methods to remove unwanted constituents (anti-quality factors) from water are surveyed. No single method will remove the potential broad spectrum of unwanted constituents.
10. Practical guidelines for evaluation of water nutrition, as well as placement and management of water receptacles are discussed.

Introduction

Are feed intake and milk yield less than expected because water intake is low? Or, is water intake below normal because of low feed intake and milk production? These are always difficult questions to answer. Within normal physiological limits there is a direct positive relationship between water intake and feed intake. What factors affect this relationship? If problems are suspected, the quality of drinking water being provided, the placement and management of watering stations in the cows' and calves' environment, and other factors known to affect free drinking water intake should be assessed carefully.

Too often dairy producers and their advisers have insufficient understanding of water nutrition of dairy cattle. Having an excellent working knowledge about provision of this most important essential nutrient is crucial for normal performance of dairy cattle and the financial success of dairy businesses.

This paper emphasizes practical evaluation of drinking water quality and nutritional adequacy to meet the demands of dairy cattle. Typically, two main questions (criteria) are of interests when assessing water quality and nutrition. **1)** Is water intake normal, depending on physiological state of the animals and their environment? **2)** Are anti-quality factors present in water that may affect water intake, or normal metabolic or physiological functions of animals?

Water quality analyses of 42 samples in use or being considered for use in operating dairies in the Mid-South and High Plains regions of the United States were provided by the Texas Animal Nutrition Council (facilitated by Ellen Jordan, Texas A & M University), Bill Wailes of Colorado State University, and Matt VanBaale of the University of Arizona for evaluation and discussion.

Citations listed in this paper, as well as other references about water nutrition of dairy cattle, are available at: http://www.msu.edu/~beede/ by clicking on "Extension", and then "Water Ref". The NRC (2001) also provides a thorough review of the research literature about water nutrition for dairy cattle and current gaps in our knowledge. An earlier version of this paper was published in 2005 in the proceedings (pages 1 -18) of the Mid-South Ruminant Nutrition Conference. A major change in the current paper is the new values of nitrate concentrations in Table 5 which were discovered to be incorrect; an error that has been perpetuated in many publications after the original NRC (1974) publication on water quality for livestock.

Why Is Water Important?

Water as an essential nutrient is second only to oxygen in importance to sustain life and optimize growth, lactation, and reproduction of dairy cattle. However, unlike the careful and continuous attention paid by dairy producers and nutritionists to other nutrients in the ration, oftentimes the quality and provision of free drinking water does not receive the attention necessary to ensure optimal nutrition and cattle performance.

The water requirement per unit of body mass of a high-producing dairy cow is greater than that of any other land-based mammal (Woodford et al., 1985). This is because of the high yield of a secretion that is 87% water. Water also is required for digestion and metabolism of energy and nutrients; transport in circulation of nutrients and metabolites to and from tissues; excretion of waste products (via urine, feces, and respiration); maintenance of proper ion, fluid, and heat balance; and, as a fluid and cushioning environment for the developing fetus (Houpt, 1984; Murphy, 1992).

Total water content of the bodies of adult dairy cattle ranges between 56 and 81% of body weight depending upon stage in the lactation cycle (Murphy, 1992). Loss of only about 20 % of total body water is fatal.

Water Quality Factors Affecting Performance

A key consideration in the nutrition of dairy cattle is evaluation of the quality of drinking water. Tables 1, 2, 3, 4, and 5 provide a cross-section of information among various reports relating guidelines for use of water for livestock and threshold concentrations above which specific constituents may cause nutritional and(or) health problems. Readers should note that there is some disagreement among reported values for some constituents in the five tables; a main reason for listing multiple tables. For information in Table 4, adapted from Adams and Sharpe (www.das.psu.edu/teamdairy/), it should be noted that the values are from about 350 water samples in which problems were suspected; thus, the *average* values in the table may be abnormally high.

Factors typically considered in water quality evaluation include odor and taste (organoleptic properties), physical and chemical properties, presence of toxic compounds, concentrations of macro- and micromineral elements, and microbial contamination. Excess concentrations of some of these factors may have direct effects on the acceptability (palatability) of drinking water; whereas, others may affect the animal's digestive and physiological functions, once consumed and absorbed (Beede, 1992; Patience, 1994).

Table 1. Guide for use of saline waters by dairy cattle; total dissolved solids equal TDS.[a]

TDS (mg/liter or ppm)	Comment
Less than 1,000 [fresh water]	Presents no serious burden to livestock.
1,000 - 2,999 [slightly saline]	Should not affect health or performance, but may cause temporary mild diarrhea.
3,000 - 4,999 [moderately saline]	Generally satisfactory, but may cause diarrhea, especially upon initial consumption.
5,000 – 6,999 [saline]	Can be used with reasonable safety for adult ruminants. Should be avoided for pregnant animals and baby calves.
7,000 – 10,000 [very saline]	Should be avoided if possible. Pregnant, lactating, stressed or young animals can be affected negatively.
>10,000 [approaching brine]	Unsafe, should not be used under any conditions.

[a] Salinity and TDS are commonly synonymous terms (NRC, 1974). Total dissolved solids equal the summation [in mg/liter (equivalent to parts per million = ppm)] of all inorganic solutes (constituents) present in water.

Table 2. Water quality criteria for livestock[a].

Quality criteria	Limiting threshold[b] (mg/liter or ppm)	Upper limit guideline[c] (mg/liter or ppm)
Aluminum	5.0	0.5
Arsenic	0.2	0.05
Boron	5.0	5.0
Cadmium	0.05	0.005
Chromium	1.0	0.1
Cobalt	1.0	1.0
Copper	0.5	1.0
Fluorine	2.0	2.0
Lead	0.1	0.015
Manganese	. . .[d]	0.05
Mercury	0.01	0.01
Nickel	1.0	0.25
NO_3-N + NO_2-N	100	. . .
NO_2-N	10.0	. . .
Radionuclides	meeting drinking water objectives	. . .
Selenium	0.05	0.05
Vanadium	0.1	0.1
Zinc	25.0	5.0
Salinity (total soluble salts)	3000.0	. . .
Toxic algae	No heavy growth	. . .
		. . .
Pesticides:		. . .
Aldrin	0.001	. . .
Chlordane	0.003	. . .
DDT	0.05	. . .
Dieldrin	0.001	. . .
Endrin	0.0005	. . .
Heptachlor	0.0001	. . .
Heptachlor epoxide	0.0001	. . .
Lindane	0.005	. . .
Methoxychlor	1.0	. . .
Toxaphene	0.005	. . .
Carbamate and organophosphorus pesticides	0.1	. . .

[a] Criteria provide a general guide for quality of water acceptable for most livestock; water of different quality may be acceptable because of differences in physiological state, age, or condition of animals, species, or because of special rearing conditions or feed components.
[b] Ontario Ministry of the Environment, 1984, Water Management.
[c] NRC, 1974; NRC, 1980; EPA, 1997.
[d] No value available.

Organoleptic Properties. Dairy cows can detect offensive odor and taste. However, cows' perceptions of what is offensive or not is generally poorly understood. Color and turbidity also may be indicators to help assess the organoleptic properties of water. If the water source smells or is unpalatable, cows may not drink enough to meet production needs or it may be completely refused. Most causes of odor and taste are a result of physiochemical properties, substances present in excess, and presence of bacteria and their metabolic byproducts.

Physiochemical Properties. Physiochemical properties of water can be a useful way of helping to determine water quality. These include pH, total dissolved solids (**TDS**), hardness, other substances in excess, sulfate, chloride, nitrate, toxic compounds, and microorganisms.

Anti-Quality Factors Potentially Causing Problems

Primary anti-quality factors, in excessive concentrations, known to affect water intake and (or) metabolism of dairy cattle include TDS, sulfur, sulfate and chloride (both biologically active anions), nitrate, iron, manganese, and fluoride. Other constituents typically listed in water analyses reports and specified as potential risk factors for humans (e.g., arsenic) have not been well studied or documented under field conditions to affect dairy cattle performance or health. Primary examples of water quality factors not believed to be of concern include pH, total hardness, calcium, and magnesium. It is always possible that isolated cases of higher than normal concentrations of mineral elements, microorganisms, or other toxic compounds may be present and deleterious to cattle (Tables 2, 3, and 4). However, typically these cases are extremely difficult to identify and to prove cause and effect. The anti-quality factors (constituents) in drinking water that are known from research reports or experience to cause problems are addressed below. Those for which no negative effects have been found or reported in research are summarized subsequently.

Total Dissolved Solids. TDS is a general term defining the sum of all inorganic matter dissolved in water (Patience, 1994); TDS also indicates the salinity of water. High amounts of TDS generally are considered an unwanted characteristic. However, TDS *per se* may not provide much information about water quality or the specific individual constituents of concern. For example, the TDS concentration could be quite high, influenced mainly by high concentrations of calcium and magnesium, yet little or no influence on water nutrition or cattle performance would be expected (addressed subsequently).

However, high TDS can be an pre-indicator of poor quality water. This may be of practical concern depending upon what specific individual inorganic cations and anions contribute to high TDS. Table 1 provides guidelines for the use of waters containing varying amounts of overall TDS. If and when water analyses indicate high TDS with excessively high concentrations of sodium, chloride, sulfate, iron, and manganese, more extensive evaluation is recommended.

Just a few controlled studies reported the effects of salinity on milk production, with conflicting conclusions. Jaster et al. (1978) found that milk production decreased when cows consumed water containing 2500 ppm NaCl added to tap water that already contained 196 ppm TDS. Challis et al. (1987) found a trend for decreased milk yield when cows were given water with 4300 ppm TDS during hot weather. However, Bahman et al. (1993) reported that water with 3500 ppm TDS did not affect milk production. Solomon et al. (1995) reported results similar to those of Jaster et al. (1978). It should be noted that all of these studies were carried out in semiarid, hot climates. No studies were found with lactating dairy cattle that tested the effects of TDS in cool weather or temperate climates.

Table 3. Guidelines for evaluating water quality for livestock.

Quality factor	Threshold concentration (mg/liter)[a]	Limiting concentration (mg/liter)[b]
Total dissolved solids (TDS)	2500	5000
Cadmium	5	
Calcium	500	1000
Magnesium	250	500[c]
Sodium	1000	2000[c]
Arsenic	1	
Bicarbonate	500	500
Chloride	1500	3000
Fluorine	1	6
Nitrate	200	400
Sulfate	500	1000[c]
Range of pH[d]	6.0 - 8.5	5.6 - 9.0

[a] Threshold values represent concentrations at which poultry or sensitive animals might show slight effects from prolonged use of such water. Lower concentrations are of little or no concern. Note: mg/liter = parts per million (ppm).
[b] Limiting concentrations based on interim criteria, South Africa. Animals in lactation or production might show definite adverse reactions.
[c] Total magnesium compounds plus sodium sulfate should not exceed 50 percent of the total dissolved solids.
Source: California State Water Quality Control Board, 1963.
[d] Acceptable ranges for pH of drinking water.

One study with feedlot steer calves suggested that body weight gains tended to decline more during periods of heat stress (summer) than in winter when cattle consumed water with 6000 ppm TDS; although, the season by water source interaction was not significant (Ray, 1989). Weeth and Haverland (1961) found that growing heifers tolerated 1.75% NaCl in drinking water during the winter, but tolerated only 1.2% NaCl in the summer before toxicity signs presented. Therefore, it may be beneficial to study more extensively the potential interaction between environmental temperature and drinking water salinity to determine effects on lactational performance.

The experiments mentioned above do not address specific potential substances or elements that are part of TDS and are potentially the more problematic factors than TDS itself. Most studies have evaluated added NaCl to a water source to increase the TDS concentration. However, elevated concentrations of NaCl may not be the most unpalatable compound in some natural water sources. In some studies, it is not clear whether TDS or specific mineral elements, such as magnesium or sulfate, were principally responsible for poor water quality causing reduced water intake and milk production (Challis et al., 1987; Bahman et al., 1993).

Sulfur and Sulfate. Sulfur present as hydrogen sulfide (H_2S), imparting the rotten egg smell, is believed to affect water intake. Water intake increased at least in the short-term when water without the smell was offered (Beede, personal observation). However, it is not known what concentration of hydrogen sulfide or what intensity of smell reduces normal water intake, or if cattle adapt to the smell and have normal water intake rates if no other water is available.

Sulfate. Based on field experience, excessively high concentrations of sulfate (and possibly chloride another biologically active anion) in drinking water can reduce water consumption. However, there is some discrepancy in the literature about the maximum tolerable concentration of sulfate. In early work in Nevada, Weeth and Hunter (1971) found in controlled experiments that 3493 ppm sulfate as sodium sulfate reduced water intake, weight gain, and dry matter intake (**DMI**) of heifers. Weeth and Capps (1972) found that maximum tolerance was reached at about 1450 ppm sulfate. There were three concentrations of sulfate in drinking water given to heifers in this experiment, tap water (110), or 1462 or 2814 ppm with added sulfate. Regardless of treatment, the heifers still gained weight. However, heifers given drinking water with higher sulfate gained less than heifers drinking tap water. Heifers also discriminated against the water containing 1462 ppm sulfate, and rejected water with 2814 ppm. These results suggest that the tolerance threshold for sulfate may be around 1450 ppm, at least for heifers.

Digesti and Weeth (1976) did a third experiment to reevaluate the previous tolerance threshold of 1450 ppm and to determine whether or not heifers could tolerate higher chloride or sulfate concentrations in drinking water. Neither health nor growth of heifers was compromised when drinking water contained 2500 ppm of sulfate. There may be some adaptation (e.g., ruminal adaptation) to high sulfate and thus diminished negative animal responses, at least in growing heifers. Heifers rejected high-sulfate water (3317 ppm) supplied as sodium sulfate before rejecting high-chloride water (5524 ppm) added as sodium chloride. Equal molar sodium was provided from both sulfate and chloride salts.

Recent research from the University of British Columbia showed that drinking water was unpalatable to beef heifers and steers if it contained 3200 or 4700 ppm sulfate from sodium or magnesium sulfates. Animals offered high-sulfate water also changed their pattern of consumption, drinking more frequently at night compared with animals offered low-sulfate tap water that drank more during the day. Also when the poorer quality high-sulfate water was offered, animals showed more aggressive behavior towards each other when trying to drink. However, 1500 ppm sulfate did not reduce water consumption (Zimmerman et al., 2002) Based on available research reports and personal field experience, when or if sulfate concentration in water exceeds 1000 ppm it is recommended that careful evaluation be done. A proposed approach for evaluation is listed subsequently. High-sulfate (e.g., 1200 ppm) drinking water compromised lactational performance of fresh dairy cows by causing reduced feed intake and milk yield, and increased incidences of retained placenta and abomasal displacement (Beede, personal observation). When a low-sulfate water source was provided following treatment by reverse osmosis fresh cow problems declined dramatically. Chloride also is a biologically active anion. Therefore, a useful rule of thumb in assessing water quality is to check whether or not the sulfate plus chloride concentrations exceed 1000 ppm. If so, careful evaluation and testing are recommended highly.

Iron. Besides the anions sulfate and chloride, iron in drinking water is probably the most frequent and important anti-quality consideration for dairy cattle. Whereas, iron deficiency in adult cattle is very rare because of abundant iron (Fe^{+3}, ferric iron) in feedstuffs, excess total iron intake can be

Table 4. Average, expected and possible problem concentrations of analytes in drinking water for dairy cattle (adapted from Adams and Sharpe, www.das.psu.edu/teamdairy/). Please note: these values are derived from analyses in which most of the water samples were from farms with suspected animal health or production problems.

Measurement	Average[a]	Expected[b]	Possible problems[c]
pH for cows	7.0	6.8-7.5	under 5.1 or over 9.0
pH for veal calves		6.0-6.4	
		- - - - - - - parts per million (ppm, or mg/ liter) - - - - - - - -	
Total dissolved solids	368	500 or less	over 3,000
Total alkalinity	141	0-400	over 5,000
Carbon dioxide	46	0-50	
Chloride*	20	0-250	
Sulfate	36	0-250	over 2,000
Fluoride	0.23	0-1.2	over 2.4 (mottling)
Phosphate	1.4	0-1.0	
Total hardness	208	0-180	
Calcium	60	0-43	over 500
Magnesium	14	0-29	over 125
Sodium	22	0-3	over 20 for veal calves
Iron	0.8	0-0.3	over 0.3 (taste, veal)
Manganese	0.3	0-0.05	over 0.05 (taste)
Copper	0.1	0-0.6	over 0.6 to 1.0
Silica	8.7	0-10	
Potassium	9.1	0-20	
Arsenic	---	0.05	over 0.20
Cadmium	---	0-0.01	over 0.05
Chromium	---	0-0.05	
Mercury	---	0-0.005	over 0.01
Lead	---	0-0.05	over 0.10
Nitrate as NO_3[d]	34	0-44	over 100
Nitrite as NO_2	0.28	0-0.33	over 4.0-10.0
Hydrogen sulfide	---	0-2	over 0.1 (smell of rotten eggs, taste)
Barium	---	0-1	over 10 (health)
Zinc	---	0-5	over 25
Molybdenum	---	0-0.068	
Total bacteria/100 ml	336,300	under 200	over 1 million
Total coliform/100 ml	933	Less than 1	over 1 for calves; over 15-50 for cows
Fecal coliform/100 ml[e]	---	Less than 1	over 1 for calves; over 10 for cows
Fecal streptococcus/100 ml	---	Less than 1	over 3 for calves; over 30 for cows

[a] For most measurements, averages are from about 350 samples; most samples are taken from water supplies in farms with suspected animal health or production problems.
[b] Based primarily on criteria for water acceptable for human consumption.
[c] Based primarily on research literature and field experiences.
[d] Should not be consumed by human infants if over 44 ppm NO_3 or 10 ppm NO_3-N.
[e] If pollution is from human wastes, fecal *coliform* should exceed fecal *streptococcus* by several times. If pollution is from an animal source, *streptococcus* should exceed *coliform* in refrigerated samples analyzed soon after sampling.
* Free or residual chlorine concentrations up to 0.5 to 1.0 ppm have not affected ruminants adversely. Municipal water supplies with 0.2 to 0.5 ppm have been used successfully. Swimming pool water with 1.0 ppm, or 3 to 5 ppm chlorine in farm systems with short contact time have caused no apparent problems for cattle.

a problem; especially when drinking water contains high iron concentrations. Iron concentrations in drinking water of greater than 0.3 ppm are considered a risk for human health, and are a concern for dairy cattle health and performance (Table 4).

The first concern is that high iron in drinking water may reduce the palatability (acceptability) and therefore amount and rate of water intake. Also, a dark slime formation in plumbing and waterers formed by iron-loving bacteria may affect water intake and even the rate and volume of water flow through pipes.

The predominant chemical form of iron in drinking water is the ferrous (Fe^{+2}) form. The ferrous form is very soluble in water compared with the highly insoluble ferric (Fe^{+3}) form present in feed sources. Highly soluble iron can interfere with the absorption of copper and zinc. The *Ferritin System* in cells in the intestinal wall normally helps control the risk of iron toxicity in animals by controlling iron absorption. However, highly soluble ferrous iron can be readily absorbed by sneaking between cells; thus escaping the normal cellular regulation. Once in the body, the *Transferrin and Lactoferrin Systems* normally bind iron in blood and tissues to control its reactivity. These systems also help control risk of toxicity under normal conditions. However, when excess, highly water-soluble iron in drinking water is absorbed there is an *overload* systemically within the animal and all can not be bound. Deleterious consequences of excess free iron include abundant and excessive amounts of reactive oxygen species (e.g., peroxides) that cause oxidative stress. Oxidative stress damages cell membrane structure, functions, and perturbs otherwise normal biochemical reactions. Consequences of iron toxicity and heightened oxidative stress that are magnified in transition and fresh cows include: compromised immune function, increased fresh cow mastitis and metritis, greater incidence of retained fetal membranes as well as diarrhea, sub-normal feed intake, decreased growth, and impaired milk yield.

Excess iron (greater than 0.3 ppm) in drinking water is much more absorbable and available than iron from feedstuffs, and thus present a greater risk for causing iron toxicity. If high-iron drinking water is present, an alternative water source should be found, or a method to remove the iron from water before consumption by cattle and humans should be employed. Possible methods are addressed subsequently.

Manganese. This micromineral element is often considered along with iron when addressing water quality. However, specific information of the effects of manganese on dairy cattle is limited. In general, a concentration greater than 0.05 ppm is thought to affect water intake because of the off-taste it imparts (Tables 2 and 4). Characteristic black specs and deposits visible in plumbing, in filters, and watering devices are indicators that high concentrations of manganese may be present in water. Removal is possible, as will be addressed subsequently.

Nitrate. Nitrate (NO_3) is another potential problem when present in excess in drinking water for dairy cattle. Nitrate can pollute a water source via contamination of groundwater or runoff into surface waters. A likely potential source of nitrate is from crop or pasture land that has been fertilized.

Nitrate has been linked to reproductive problems of lactating dairy cows. A 35-month study tested the influence of nitrate on reproductive and productive efficiency in Wisconsin (Kahler et al., 1974). Two groups of cows were given tap water (19 ppm of nitrate) or drinking water containing 374 ppm of nitrate (86 ppm NO_3-N; nitrate is about 23 % nitrogen) added as potassium nitrate. During the first 20 months of the study, there was no difference in reproductive performance. However, in the last 15 months cows drinking the high-nitrate water had more services per conception, lower first service conception rates, and longer calving intervals.

In a more recent survey study of 127 dairy farms in northwestern and northeastern Iowa, nitrate concentrations of drinking water were relatively high (Ensley, 2000). In northwestern Iowa (n = 104 farms) average, minimum, and maximum concentrations of nitrate were 30, 1 and 300 ppm, respectively; comparable values for water samples in northeastern Iowa (n = 23 farms) were 25, 9, and 110 ppm, respectively. In northwest Iowa, shallow wells were most prevalent; whereas in the northeast, the majority of wells were 150 feet or deeper. Dairy herd performance (DHI records) and the relationships with nitrate concentrations were evaluated. Herds drinking water with the highest nitrate concentrations had the longest calving intervals, similar to the earlier findings of Kahler et al. (1974).

Table 5 lists guidelines for nitrate concentrations in drinking water for livestock. Threshold concentrations of over 20 ppm NO_3-N or over about 88 ppm NO_3 should be of concern. Careful evaluation of reproductive performance of the herd is recommended. Also, typically there can be some variation in nitrate concentrations in well water; presumably influenced by time of year, amount of precipitation (short-term and longer term), depth of wells and change in aquifer levels, and fertilization practices. These factors should be taken into consideration when assessing effects of water nitrates.

Toxic Compounds. Toxic compounds are another potential influence on water quality. Toxic compounds are defined to be deleterious to man and animals (Patience, 1994). Toxic compounds normally are found in water sources. However, in trace amounts they do not cause problems for livestock. Lead, arsenic, cyanide, and mercury are all examples of toxic compounds found in water. Very little research has characterized their effects through drinking water on dairy cattle performance and health. However, general information about their influences on animal health and performance is available (NRC, 1980). Tables 2, 3, and 4 provide guidelines and threshold concentrations for many of these compounds.

Microorganisms in Water. Contamination of a livestock water source by microorganisms typically is not of concern. However, under certain conditions, microbial populations can explode creating problems for livestock. For example, under certain ambient conditions in an aquatic environment, algae can undergo exponential growth resulting in a bloom and production of toxic compounds. These ambient conditions include warm, sunny weather, ample nutrients present in the water, slow moving water, and wind to concentrate the bloom on the leeward side of the body of water (Galey et al., 1987; Kerr et al., 1987). Studies done by Kerr et al. (1987) and Galey et al. (1987) reported problems occurring from an algae bloom of the cyanobacterium, *Microcystic aeruginosa*, that resulted from these environmental conditions. Both studies showed that if cattle ingested the water, it had detrimental effects, including anorexia, diarrhea, loss of responsiveness, and weakness. In some instances, if enough algae were consumed along with drinking water, cows suffered severe hepatotoxicosis (liver failure) resulting in death due to a toxin produced by the algae. Algae blooms typically are not of as much concern in cooler climates because warm environmental temperatures needed for algae growth are not as frequent or as long in duration.

Factors Not Known To Cause Problems

pH. Water pH is used to describe the acidity or alkalinity of a source. Patience (1994) reported that within a typical range pH does not have a major influence on water acceptability by animals. Drinking water with a pH between 6 and 9 generally is considered acceptable for livestock (NRC, 1974). Deleterious effects of drinking water pH outside the range of 6 to 9 have not been reported in the scientific literature. Slightly different acceptable pH ranges were suggested by others (Tables 3 and 4). Drinking water with pH between 6 and 9 is assumed acceptable and has very little influence on ruminal pH due to the overpowering highly reductive environment in the rumen. However, research on the influences of drinking water pH on animal behavior and performance is limited and it is difficult to draw conclusions, particularly about acceptability of waters outside the pH ranges listed above and in Tables 3 and 4.

Calcium and Magnesium. High concentrations of calcium and(or) magnesium are sometimes found in drinking water. No studies were found in the literature in which negative animal responses resulted from high concentrations of either of these two macrominerals.

Hardness. Hard water is due mainly to high concentrations of calcium and magnesium; but, iron, manganese, strontium, and aluminum also contribute (Patience, 1994). In the 1950s there was interest in softening hard water because it was theorized that hard water reduced water intake, thus reducing milk production. Water containing 290 ppm total hardness had no effect on milk production, weight gain, or water consumption (Graf and Holdaway, 1952). Blosser and Soni (1957) and Allen et al. (1958) confirmed that hardness had no influence on these same animal responses with hardness concentrations of 116 and 190 ppm, respectively.

Based on these studies, it can be concluded that milk production was not compromised by water sources with up to 290 ppm hardness. It was stated that water with average hardness, need not be softened for livestock (Blosser and Soni, 1957). Research has not tested greater hardness. One of the consequences of chemically softening water by ion exchange treatment is the dramatic increase in sodium content,

Table 5. Guidelines for nitrate concentrations in drinking water for livestock[a].

Nitrate (NO_3), mg/liter or ppm	Nitrate-nitrogen (NO_3-N), mg/liter or ppm	Guidelines
0-44	0-10	Safe for consumption by ruminants.
44-88	10-20	Generally safe in balanced diets with low nitrate feeds.
88-177	20-40	Could be harmful if consumed over long periods of time.
177-443	40-100	Cattle at risk and possible death losses.
Over 443	Over 101	Unsafe: possible death losses and should not be used as a source of water.

[a] Adapted and modified from NRC, 1974. Note that some values in the first column (nitrate concentration) have been changed to correct an error that has been perpetuated in a number of publications since 1974.

which replaces calcium and(or) magnesium. Estimating the total intake of sodium by animals from drinking water and the ration may be useful.

Other Factors Affecting Water Intake

Water quality (presence of unwanted anti-quality factors) generally is considered a major factor in evaluating water nutrition of cattle. Other factors that may affect water intake by dairy cows include: mineral ion and protein content in feeds, pH of silage, environmental temperature, drinking water temperature, dry matter content of diet, and adequacy of water supply. Information about these factors is reviewed elsewhere (Beede, 2005; Beede and Myers, 2003; NRC, 2001).

Evaluation of Water Samples from Commercial Dairies in the Mid-South and High Plains

Table 6 presents results of basic laboratory analyses of 42 samples of drinking water (in use or being considered for use) for commercial dairies in the Mid-South and High Plains regions of the United States. Four different laboratories were employed for analyses. Whether or not a value is listed for some constituents in the table depends upon whether or not that particular analysis was requested and whether or not the laboratory conducted that constituent analysis. The top two rows of information in the table provide guideline caution levels for the various constitutes. Please refer to the footnotes in the table for additional explanation. Results for individual water samples are listed in rows 1 through 42 of the table along with the general geographical location of the dairy farm. The results in general are arranged with analyses indicating no or little concern about water quality in the upper rows of the table; whereas analyses indicating potential concern or risk are listed in lower rows. Sets of two or three analyses of particular interest from the same farm are grouped by a rectangle around them to highlight a particular water quality consideration (e.g., samples 16,17, and 18; 33 and 34; 35 and 36; and 37 and 38; and, 39 and 40).

To assess the results, the most important constituents to evaluate are those that potentially could reduce water intake and (or) have deleterious effects on animal performance or health. In this order, I would review values of total dissolved solids (**TDS**), sulfate (**SO_4**), chlorine (**Cl**), iron (**Fe**), and nitrate-nitrogen (**NO_3-N**); the basic anit-quality constituents most likely to be of concern, as previously described, if in excessively high concentrations. Note that ranges are listed in "Beede's Guidelines" for TDS, sulfate, and chloride. This is to indicate that based on field experience it is believed that concentrations of sulfate plus chloride of greater than 500 to 1000 ppm may be deleterious, particularly to fresh cows. If the sulfate plus chloride are greater than 500 ppm, then careful evaluation is recommended.

For most constituents in samples 1 through 15 (rows numbered 1 through 15 in Table 6) concentrations of primary concern do not exceed caution levels. Samples 4, 11, 13, 14, 15, and 16 have TDS concentrations greater than 500 ppm TDS, which should warrant closer inspection of values for the rest of the constituents. Which individual constituents are responsible for the higher TDS values? These samples are not extraordinarily high in any other individual constituents that were analyzed; except, that sulfate of Sample 15 may be of concern. It may be worth re-sampling and re-analyzing each of these water sources and monitoring them periodically over time (e.g., quarterly).

Note that there is a general direct relationship between TDS and conductivity; conductivity values for Samples 4, 11, 13, 14 and 15 tend to increase suggesting that they do contain higher concentrations of dissolved inorganic matter, in comparison to values of other samples in the table with lower conductivity and TDS values. It is just not very clear from the table for Samples 4, 11, 13, 14, and 15 which constituents contributed to higher TDS; it may be other constituents not analyzed for this report. If sub-normal animal performance is suspected for dairy cattle drinking these waters, more extensive water analysis would be indicated.

Sample 3 from West Texas has abnormally high coliform counts. This water should be re-sampled and re-tested to verify the problem and action taken to eliminate the microorganism. Sample 13 contained 22 ppm NO_3-N; the only sample of the 42 samples analyzed to exceed the caution level. Nitrate-N concentrations in well water can fluctuate through time depending upon the proximity to cropland being fertilized and to the amount of precipitation in the area. For these reasons, in this case, it would be prudent to sample well water periodically (e.g., four times/year) to be sure that high nitrate concentrations are not a potential risk factor to affect reproductive performance. Samples 8 and 16 also approach the caution level for NO_3-N. The dairy producer had concerns about water quality for Sample 16 (a shallow well) which also had higher than normal TDS and sulfate concentrations. Therefore, city water (Sample 17) was purchased and mixed (Sample 18) with well water; cow performance improved markedly (personal communication, W. Wailes, Colorado State University, 2006).

Sample 32 from New Mexico contains 1788 ppm TDS. What constituents that were analyzed contribute to the high TDS value? Sodium (411 ppm), sulfate (268 ppm), chloride (511 ppm), and sulfate + chloride (779 ppm) suggest that this water source may affect drinking water intake and animal performance. First, the water should be re-tested to verify results of the first water analysis. Subsequently, if high TDS and constituents are found again, consideration should be given to devising a way to determine if this water truly is affecting animal performance (an approach is suggested subsequently). It likely will be difficult to determine if animal performance is being affected and how much investment should be made to reduce the possible problem.

For the 13 samples from Arizona (Samples 19 through 31) only TDS, chloride, iron and pH were evaluated. Based on the TDS values it is suspected that all of these samples were of concern in terms of water quality. However, it is very difficult to make a more informed evaluation of the samples because of obviously unanalyzed constitutes. Also, it should be emphasized that one should not concluded from these 13 samples that all (or even many) of the water sources in Arizona are high in TDS. This emphasizes the need for complete analysis and evaluation of individual water sources on individual farms; even in comparable geographical and geological locations.

Sample 33 is untreated water from East Texas. Note the extraordinarily high concentrations of iron (7.79 ppm), which greatly exceeds the caution level (0.3 ppm). First, this water sample should be reanalyzed to verify the accuracy of the first analysis. If proven correct, doubtless this water is harmful to dairy cattle. The dairy producer currently treats water (method unknown) used in parlor and for the fresh

Table 6. Comparison of laboratory analyses of drinking water samples for dairy cattle from the mid-south and High Plains regions of the United States.

Sample No.	Location/ Description	Na, ppm	Ca, ppm	Mg, ppm	pH	NO_3-N, Ppm	SO_4, ppm	Conduct.[a], mmhos/cm	TDS[b], ppm	TC[c], cfu/100ml	Fe, ppm	Cl, ppm	Cu, ppm
Laboratory Guidelines[d]	**Caution Level**	**150**	**150**	**80**	**6.5 to 9.0**	**25**	**300**	**1.5**	**1000**		**0.3**	**500**	**0.3**
Beede's Guidelines[e]	**Caution Level**	**150**	**500**	**125**	**7.0 to 9.0**	**20**	**250 – 500[f]**	**1.5**	**500-1000[f]**	**1; 15- 50[g]**	**0.3**	**250 – 500[f]**	**0.3**
1	New Mexico	27	28	9	7.75	1	31	0.34	220	n.d[h]	n.d.	16	0.01
2	West Texas	28	55	26	7.87	3	40	0.57	369	n.d.	n.d.	13	n.d.
3	West Texas	28	51	35	7.96	4	44	0.64	413	65	n.d.	40	n.d.
4	SW Oklahoma	80	95	23	7.53	17	49	0.93	604	n.d.	n.d.	61	n.d.
5	Colorado-well water	8	11	1	7.55	<0.1	6	n.a.[i]	68	n.a.	0.02	4	<0.01
6	Colorado-well water	8	11	1	7.48	<0.1	7	n.a.	69	n.a.	0.05	4	0.16
7	Colorado-city water	7	11	1	7.51	<0.1	6	n.a.	70	n.a.	0.04	4	.03
8	SW Oklahoma	64	63	26	7.75	18	33	0.72	467	n.d.	n.d.	19	nd.
9	Central Texas	16	91	32	7.59	n.d.	55	0.69	445	n.d.	0.13	14	n.d.
10	New Mexico	76	32	8	7.83	n.d.	56	0.57	368	n.d.	0.05	44	n.d.
11	West Texas	65	76	36	7.75	3	103	0.92	597	n.d.	n.d.	112	n.d.
12	West Texas	21	59	32	7.68	3	24	0.60	387	n.d.	n.d.	33	n.d.
13	New Mexico	241	5	1	7.70	22	44	1.15	744	n.d.	n.d.	86	n.d.
14	Central Texas	20	156	6	7.72	12	43	0.91	588	n.d.	0.04	73	n.d.
15	Central Texas	149	82	25	7.59	n.d.	321	1.18	766	n.d.	0.07	80	n.d.
16	Colorado-shallow well	50	127	31	7.30	16	210	n.a.	657	n.a.	0.03	14	<0.01
17	Colorado-city water	6	13	1	8.35	<0.1	4	n.a.	71	n.a.	0.01	4	0.03
18	Colorado-mixed water	4	14	2	8.13	<0.1	48	n.a.	231	n.a.	0.02	10	<0.01
19	Arizona-well	n.a.	n.a.	n.a.	8.0	n.a.	n.a.	n.a.	640	n.a.	<0.04	149	n.a.
20	Arizona-well	n.a.	n.a.	n.a.	7.7	n.a.	n.a.	n.a.	650	n.a.	<0.04	123	n.a.
21	Arizona	n.a.	n.a.	n.a.	8.7	n.a.	n.a.	n.a.	659	n.a.	<0.01	148	n.a.
22	Arizona	n.a.	n.a.	n.a.	8.0	n.a.	n.a.	n.a.	670	n.a.	0.04	140	n.a.
23	Arizona-	n.a.	n.a.	n.a.	7.9	n.a.	n.a.	n.a.	670	n.a.	<0.04	158	n.a.
24	Arizona-cold water	n.a.	n.a.	n.a.	8.7	n.a.	n.a.	n.a.	797	n.a.	<0.01	161	n.a.
25	Arizona	n.a.	n.a.	n.a.	8.1	n.a.	n.a.	n.a.	825	n.a.	<0.01	175	n.a.
26	Arizona	n.a.	n.a.	n.a.	8.1	n.a.	n.a.	n.a.	825	n.a.	0.46	197	n.a.
27	Arizona- well	n.a.	n.a.	n.a.	7.7	n.a.	n.a.	n.a.	830	n.a.	<0.04	307	n.a.
28	Arizona-house water	n.a.	n.a.	n.a.	7.6	n.a.	n.a.	n.a.	839	n.a.	<0.01	198	n.a.
29	Arizona-well water	n.a.	n.a.	n.a.	7.7	n.a.	n.a.	n.a.	1010	n.a.	<0.01	268	n.a.

Table 6 (continued). Comparison of laboratory analyses of drinking water samples for dairy cattle from the mid-south and High Plains regions of the United States.

Sample No.	Location/ Description	Na, ppm	Ca, ppm	Mg, ppm	pH	NO_3-N, ppm	SO_4, Ppm	Conduct[a], mmhos/cm	TDS[b], ppm	TC[c], cfu/100ml	Fe, ppm	Cl, ppm	Cu, ppm
Laboratory Guidelines[d]	**Caution Level**	**150**	**150**	**80**	**6.5 to 9.0**	**25**	**300**	**1.5**	**1000**		**0.3**	**500**	**0.3**
Beede's Guidelines[e]	**Caution Level**	**150**	**500**	**125**	**7.0 to 9.0**	**20**	**250 – 500[f]**	**1.5**	**500-1000[f]**	**1; 15- 50[g]**	**0.3**	**250 – 500[f]**	**0.3**
30	AZ-unsoftened water	n.a.	n.a.	n.a.	7.9	n.a.	n.a.	n.a.	1030	n.a.	<0.01	292	n.a.
31	Arizona-well water	n.a.	n.a.	n.a.	7.7	n.a.	n.a.	n.a.	1100	n.a.	<0.01	243	n.a.
32	New Mexico	411	164	30	7.18	4	268	2.75	1788	n.d.	n.d.	511	n.d.
33	E Texas 1- Untreated	14	6	4	6.83	n.d.	8	0.16	103	n.d.	7.79	15	n.d.
34	E Texas 1-Treated	41	1	<1	7.00	n.d.	6	0.18	116	n.d.	0.03	15	n.d.
35	SW OK 1-Untreated	195	588	154	7.49	13	1899	3.35	2178	87	n.d.	198	n.d
36	SW OK 1-Treated	149	<1	<1	8.33	11	35	0.62	400	n.d.	n.d.	10	n.d.
37	Colorado 1-before R.O.	69	96	51	7.52	4	325	n.a.	706	n.a.	2.67	18	<0.01
38	Colorado 1-after R.O.	2	1	<0.01	6.22	1	1	n.a.	14	n.a.	<0.01	<1	0.82
39	Colorado 2-Untreated	308	299	152	7.59	1	1622	n.a.	2985	n.a.	0.11	61	0.084
40	Colorado 2-city well	11	312	<0.01	7.63	1	38	n.a.	255	n.a.	0.052	12	0.61
41	East Texas	140	336	37	7.50	n.d.	1159	2.06	1339	n.d.	0.32	15	n.d.
42	New Mexico	479	316	341	7.68	<1	2330	5.28	3432	n.d.	0.94	668	n.d.

[a] Conductivity in mmhos/cm; conductivity is a measure of the amount of electrical current that will pass through a water sample; the amount of conductivity is related directly to the amount of dissolved solutes in the water sample; also it is highly related with the total dissolved solids (TDS, ppm) of a sample.
[b] TDS = total dissolved solids in parts per million.
[c] Total coliforms in colony forming unit (cfu)/100 ml.
[d] Laboratory's Guidelines of Midwest Laboratories, Inc., Omaha, Nebraska (www.midwestlabs.com).
[e] Guidelines are reference values based on field experience in commercial dairies (Beede, personal observations) and the research literature about drinking water quality for livestock and humans.
[f] Limited experience suggests that concentrations of sulfate + chloride of greater than 500 ppm may be deleterious to fresh cows. Providing alternate water (with lower sulfate and chloride) seemed to improve performance.
[g] 1 cfu/100 ml for calves; over 15 – 50 cfu/100 ml for mature animals.
[h] n.d. = non-detectable concentration.
[i] n.a. = constituent not analyzed for the particular sample.

and sick cows in this dairy (Sample 34, Table 6). However, the remaining animals receive untreated water. It would be very interesting to evaluate the health records of cows and young calves in this herd to determine if signs of iron toxicity are present, assuming that the original analysis (Sample 33) reported the correct iron content. It also would be very interesting to know what proportions of the iron in this water sample were in the soluble and insoluble fractions. Potential treatment options to remove soluble iron are presented in the next section of this paper.

Results of analysis of Sample 35 illustrate a water sample with very high TDS (2178 ppm) and very high concentrations of sulfate (1899 ppm). Consumption of this water by dairy cattle should be a major concern. After evaluating various treatment options to remove the high solids from this water the dairy producer found a more economical alternative. He was able to purchase his herd's water needs from a nearby town. The town water (Sample 36) illustrates drastically improved water quality.

Samples 37 and 38 from Colorado illustrate a situation in which generally poor water quality from well water is evident (higher than normal TDS, sulfate and very high iron content – sample 37); when the water is treated by reverse osmosis removing the vast majority of these constituents (sample 38) animal performance responded markedly (personal communication, W. Wailes, Colorado State University, 2006).

In another Colorado situation, cow performance was suspected to be depressed greatly when the drinking water was sample 39 (very high concentrations of TDS and sulfate). When the cows were switched to city well water (sample 40) improvement in lactational performance was marked (personal communication, W. Wailes, Colorado State University, 2006).

Samples 41 and 42, from East Texas and New Mexico, respectively, had very high TDS and sulfate concentrations. Sample 41 also is extraordinarily high in calcium and marginally high in iron. Sample 42 is very high in sodium, magnesium, iron and chloride and tremendously high TDS. Likely neither of these waters is fit for dairy cattle, humans, or for most any other living creature as a free drinking water source!

Appendix 1 provides practical information about obtaining samples for water quality analyses.

Possible Water Treatment Methods

Once it's determined by water analysis that unwanted constituents are present and a concern for dairy animal health and(or) performance, the question becomes, "What can and should be done about it?" In many cases this may involve finding a different water source (e.g., new well or perhaps a municipal water source). The other main consideration is whether or not to treat the water to remove anti-quality factors. This has been accomplished successfully and economically in some dairy farms (Beede, personal observations). However, it may not be cost-effective in every case. Careful evaluation of the magnitude of the problem, how much potential benefit can be derived from removing unwanted constituents, and at what cost for the expected improvement in animal performance and health are key considerations. Most dairy farms use relatively large volumes of water and treatment systems must be sized accordingly.

As a general guide, Table 7 lists the common methods to remove specific unwanted constituents from water (https://www./midwest labs.com). This table is meant to provide just a simple initial background on methods that remove particular constitutes. With this information a user can begin to address specific water quality problems with specific water treatment companies in the local area. It is highly encouraged that dairy farmers and their advisers compare effectiveness, life expectancy, volume capacity, maintenance time, and initial and maintenance costs of each type of method with several commercial companies before making any significant financial investments. Extensive investigation is highly recommended.

Activated Carbon Filters (ACF) are used to filter water through carbon granules. Contaminants (constituents) attach to the granules and are removed. Chlorine, some compounds associated with coloration, odor and off-taste of water; mercury; some pesticides; radon gas; and volatile organic compounds can be removed by ACF. Depending upon the amount of water treated, the filters may have to be replaced frequently and regularly or in time contaminants will not be able to attach to the filter. Infrequent filter maintenance may result in bacterial growth on the filter and ineffectiveness.

Air Stripping (AS) involves passing water down a tube while air is forced up through the tube. Contaminants are transferred from water to air and vented off. Whereas, this method is effective to remove hydrogen sulfide, some odors and tastes, radon gas, and some volatile organic chemicals; it typically is not recommended for household or small commercial use because of high energy costs and high noise generation. Bacterial growth also is a potential problem.

Chlorination (C) is an effective and widely used method to kill many kinds of microorganisms in water. It also will aid in removal of unwanted color, odor, or taste from water. This method also will remove hydrogen sulfide and dissolved iron and manganese, if followed by mechanical filtration or an ACF. Radon gas and volatile organic compounds also can be removed by C. Chlorine is pumped directly into the water in proportion to water flow and it may have some residual effects in the system. If the C system is not properly operated, it can be expensive and potentially hazardous if chlorine byproducts are allowed to escape.

In typical systems the chlorine content of the treated water should not be high enough to cause problems for cattle. However in one case I am aware of, the dairy was near the beginning of a municipal water distribution system. From time to time, high concentrations of chlorine were released to the dairy water system when the city was cleaning its system; in this case (1,000 to 1,500 ppm chlorine in water at the dairy) water intake and performance of cows was reduced when chlorine content was high. Another often asked question is, “Is it okay to add chlorine tablets in the water tanks for dairy cattle”? This is done mainly to control algae growth. This practice may affect water intake because spikes in chlorine content in the water tank may affect consumption; even with the slow-release tablets. Alternative methods (cleansers, brush and thorough rinsing) to keep tanks clean are recommended.

Ultraviolet radiation (UR) in which water is passed by a special light source, is another method to kill bacteria in water. There is no residual effect with UR.

However, it is difficult to know if UR is working and it may not work if the water is too cloudy or water is passing by the light source too fast.

Ozonation (O), in which water is exposed to ozone gas, also destroys microorganisms. The equipment typically is quite expensive, however there are no residual effects on the environment or treated water. This method also can be used to remove color, off-taste, odors, hydrogen sulfide, solubilized iron and manganese; if the water is subsequently passed through a mechanical or ACF system.

Distillation (D) can be used to purify drinking water that contains high TDS. This is a very effective way to obtain water with very low concentrations of inorganic compounds, nitrate, odor, off-taste, some pesticides, radium, salt, and volatile organic chemicals that have high boiling points. The impurities are removed by evaporating the water and then recapturing it by cooling. Overall, the process is slow, expensive (high energy cost), and consumes large amounts of water (water recovery typically is not near 100 %). For a dairy farm, large volume capacity may be needed to provide sufficient distilled water, depending upon herd size.

Cation or Anion Exchange (C-A E) systems are used to replace one or more chemical ions with another. The most commonly used system is to soften hard water by passing it through resin beads. In particular, calcium (Ca^{+2}) and magnesium (Mg^{+2}) ions attach to the resin beads and are removed to soften the water. The sodium (Na^{+1}) ion on the resin exchanges with the Ca^{+2} and Mg^{+2} ions. Softened water will have elevated Na concentrations. This may be a consideration for human health for household water; or, as a consideration in overall sodium nutrition of dairy cattle. It was noted previously that there is no evidence reported in the literature that hard water (containing high concentrations of calcium and magnesium) affected dairy animal health or performance.

Various C-A E systems can be useful to remove certain colors, odors, off-taste, barium, radium, soluble iron, and manganese in relatively low concentrations (less than 1 ppm). Anion exchange systems can be used to remove nitrate; however, cation exchange systems will not remove nitrate (Table 7).

Mechanical filters (MF) can be used to remove insoluble iron and manganese, sand, silt, and clay (turbidity). Whereas, these constituents are unlikely to have much direct impact on animal health or performance, they may plug or wear equipment.

Reverse osmosis (RO) technology has been used successfully to remove unwanted constituents from drinking water for dairy cattle (Beede, personal observation). Basically impurities are filtered out of the water using membranes. RO has high initial costs, high membrane replacement cost, requires high volume through-put in the dairy situation because the process is relatively slow. RO systems take routine and consistent maintenance. The potential of RO to remove unwanted constituents in dairy systems will depend on how poor the quality of the water is and what animal performance response can be expected from the RO-treated water. The systems also are somewhat wasteful of water and the high-solids filtrate must be disposed of in some manner. A wide variety of constituents can be removed by RO including: most inorganic substances, nitrate, some pesticides, odors, off-tastes,

Table 7. General guide for major treatment methods to remove unwanted constituents from drinking water (adapted from www.midwestlabs.com).

	Treatment Methods[a]									
Constituent	**ACF**	**AS**	**C**	**D**	**C-A E**	**MF**	**RO**	**UR**	**O**	**OF**
Chlorine	X[b]									
Coliform bacteria, other microorganisms			X					X	X	
Color	X		X		X				X	
Hydrogen sulfide		X	X[c]						X[c]	X
Inorganics [e.g., some marcromineral elements and heavy metals (e.g., lead, mercury, arsenic, cadmium, barium)]	X[d]			X	X[e]		X			
Iron/ manganese – dissolved			X[c]		X[f]				X[c]	X
Iron/ manganese – insoluble						X				X
Nitrate				X	X[g]		X			
Odor and off-taste	X	X	X	X	X		X		X	
Some pesticides	X[h]						X[h]			
Radium				X	X		X			
Radon gas	X	X								
Salt				X			X			
Sand, silt, clay (turbidity)						X				
Volatile organic chemicals	X	X		X[i]			X			
Water Hardness					X					

[a] ACF = activated carbon filter; AS = air stripping; C = chlorination; D = distillation; C-A E = cation or anion exchange; MF = mechanical filtration; RO = reverse osmosis; UR = ultraviolet radiation; O = ozonation; and, OF = oxidizing filters.
[b] Within the table "X" indicates method that can be used to remove part or all of the constituent present.
[c] When followed by mechanical filtration or an activated carbon filter.
[d] Mercury only.
[e] Barium only.
[f] When present in low concentrations.
[g] Anion exchange units will remove nitrate; but, cation exchange units will not.
[h] For information on ways to treat water for specific pesticides, obtain local pesticide health advisory summaries.
[i] Works for volatile organic chemicals with high boiling points.

radium, salt, and some volatile organic compounds.

Oxidizing filters (OF) can remove contaminants by filtering and chemical (oxidizing) reactions. Contaminants typically removed include hydrogen sulfide, undissolved and dissolved iron, and manganese.

Predicting Intake of and Provision of Drinking Water

Beyond laboratory analysis to identify anti-quality factors in drinking water, evaluation nearly always must include measurement and prediction of water intake, accounting for as many variables as possible that might affect water intake. Measured values of free drinking water intake should be compared with those predicted from equations (discussion following; Table 8). Roberts and coworkers emphasized the importance of this comparison (measured water intake vs. that predicted from equations) when trouble-shooting suspected water intake problems (http://psc.wi.gov/electric/newsinfo/document/cattle.pdf).

Factors influencing daily water requirements and intake include physiological state, amount of milk yield and feed intake, body size, level and kind of activity, environmental factors such as temperature and air movement, diet composition including types of feedstuffs (e.g., concentrate, fresh forages, fermented forages, and hays) as well as nutrient composition (e.g., dietary sodium, potassium, and crude protein contents), and quality (or anti-quality) factors in a particular water source. Other factors affecting consumption may include frequency and periodicity of watering, temperature of the water, and social and behavioral interactions of animals.

Water requirements of dairy cattle are met mainly from that ingested as drinking (free) water, that found in or on feed consumed, and a small amount from metabolic oxidation (metabolic water). For all practical purposes drinking water intake plus that associated with the ration represent total water consumption.

Seventy to 97 % of total water consumption by lactating dairy cows was from drinking water (Castle and Thomas, 1975; Little and Shaw, 1978; Murphy et al., 1983; Nocek and Braun, 1985; Holter and Urban, 1992; Dado and Allen, 1994; Dahlborn et al., 1998). Dry matter content of the diet also is an important factor affecting total water consumption (Castle and Thomas, 1975; Stockdale and King, 1983; Dahlborn et al., 1998). In totally mixed rations with DM contents ranging from 50 to 70 %, Holter and Urban (1992) found

Table 8. Prediction using three equations of drinking water intake by lactating dairy cows when each variable (milk yield (MY), dry matter intake (DMI), or dietary DM content (DM%)) was varied while holding the other two variables constant at the center point of the range.

MY, lb/d	DMI, lb/d	DM, %	Castle and Thomas (1975)	Murphy et al. (1983)[a]	Holter and Urban (1992)[b]
MY varied:	DMI constant:	DM % constant:	- - - Drinking water intake, lb/day (gallons/day)[c] - - -		
55	48	60	165 (19.8)	191 (22.9)	180 (21.6)
66	48	60	194 (23.2)	202 (24.2)	187 (22.4)
77	48	60	220 (26.4)	211 (25.3)	194 (23.2)
MY constant:	DMI varied:	DM % constant:			
66	44	60	194 (23.2)	196 (23.5)	176 (21.1)
66	48	60	194 (23.2)	202 (24.2)	187 (22.4)
66	53	60	194 (23.2)	209 (25.0)	198 (23.7)
MY constant:	DMI constant:	DM (%) varied:			
66	48	50	183 (21.9)	202 (24.2)	174 (20.8)
66	48	60	194 (23.2)	202 (24.2)	187 (22.4)
66	48	70	202 (24.2)	202 (24.2)	200 (24.0)

[a] Sodium intake was set at 44 grams/cow per day; minimum daily environmental temperature was set at 50°F.
[b] Julian day was set at 150.
[c] Water intake in gallons/day equals (lb/day X 0.1198).

relatively small differences in drinking water intake; however, when dietary DM content declined from 50 to 30 % (ration moisture content increased from 50 to 70 %), drinking water intake declined by 42 %. Stockdale and King (1983), estimating drinking water intake of lactating dairy cows on pasture, found that only 38 % of total water consumption was as free drinking water.

Diets with high amounts of sodium-containing salts (e.g., NaCl, $NaHCO_3$) or protein (nitrogen *per se*) stimulate water intake (Holter and Urban, 1992; Murphy, 1992). High forage diets also may increase water requirements because of higher excretion of water in feces compared with lower forage diets (Dahlborn et al., 1998).

As mentioned previously there is a direct relationship between DMI and water intake in cattle. If water intake is sub-normal feed DM intake typically will decrease. However, if water intake is normal and sufficient to meet the physiological needs of the animal for maintenance, growth, lactation, and pregnancy; there is no evidence to suggest that increasing water intake beyond normal (e.g., forced-hydration) will result in greater feed intake or performance.

Water Intake of Lactating Cows. Equations developed to predict normal drinking water intake of lactating dairy cows are based on experimental data of water intake and quantifiable independent variables affecting drinking water intake. Three equations for predicting drinking water intake by lactating dairy cows are listed below. Abbreviations represent: MY = milk yield; DMI = dietary dry matter intake; DM% = dietary dry mater percentage; and, JD = Julian Day. Drinking water intake (kg/day) estimated by each equation equals (metric units are preserved to reduce confusion):

(1) Castle and Thomas (1975),

In metric units:
2.53 x (MY, kg/d) + 0.45 x (DM%) - 15.3;

(2) Murphy et al. (1983),

In metric units:
0.90 x (MY, kg/d) + 1.58 x (DMI, kg/d) + 0.05 x (sodium intake, g/d) + 1.20 x (average minimum daily temperature, ^{o}C) + 15.99; and,

(3) Holter and Urban (1992),

In metric units:
0.6007 x (MY, kg/d) + 2.47 x (DMI, kg/d) + 0.6205 x (DM%) + 0.0911 x (JD) - 0.000257 X $(JD)^2$ - 32.39.

Milk yield, DMI, and (or) dietary DM% were significant factors for predicting drinking water intake in each equation; minimum average environmental temperature or Julian Day (a proxy for environmental factors) are in two equations; and, sodium intake is in one equation. Recently, Roberts and coworkers (http://wi.gov/electric/newsinfo/document/cattle.pdf) reported that they had used the equation of Murphy et al. (1983) as a reference equation to compare with measured consumption of water (in-line flow meters) by groups of cows in Wisconsin dairy farms. They noted good agreement between predicted and measured drinking water intake. However, to my knowledge the other equations have not been evaluated and compared with other independently collected data.

Table 8 illustrates predicted drinking water intake calculated using each of the three equations when each variable (milk yield, DMI, and dietary DM percentage) was varied over typical ranges while holding the other two variables constant at the center point of the range. The equations predict generally similar drinking water intakes over the ranges selected for milk yield, DMI, and DM percentage. Water intake in gallons/day can be calculated by multiplying lb/day x 0.1198.

Practical Evaluation of Water Nutrition

Practical Guidelines of Water Consumption. Readers are encouraged strongly to use the prediction equations presented earlier (e.g., Murphy et al., 1983; Holter and Urban, 1992) and compare with actual, measured water intake (approaches for measuring water intake are described below) to evaluate the sufficiency of water intake by dairy cows in specific groups and farm situations. Common rules of thumb (e.g., 4 to 5 lb of water intake/lb of DMI; 3 lb drinking water/lb of milk yield) are just good enough as a first impression, but not accurate enough to determine if water intake is sufficient and normal to meet a specific group of animals' water requirements.

Water Sources. Location and the best physical specifications to optimize water intake are facility-dependent. One common problem observed in some remodeled free stall barns is the *dead end* alley where the water source is located (Beede, personal observation). *Boss* cows may stake-out territory in front of the water source, keeping other cows from drinking. Listed below are some common guidelines for location and physical specifications of water sources.

1. Provide 1 to 2 ft of linear trough space per cow in return alleys or breezeways from the milking parlor. Given the choice, cows will consume large amounts of their daily water consumption needs immediately after milking. In field measurements we found that cows drank as much as 50 to 60 % of their total daily water intake immediately after milking. A good guideline is to provide enough linear water trough space so that at least half of the cows in the parlor will be provided with 2 ft of linear trough space per cow when exiting the parlor. For example, if the parlor is a double-20 herringbone, there should be at least 40 ft of linear trough space, at a location where cows from both sides of the parlor return to their pens through a common lane. Depending upon physical layout and parlor turnover rate, as much as 80 ft of linear water space may be needed to maximize water intake immediately after milking through a double-20 parlor. Cows will line up side-by-side and drink, just like they do to consume ration at the feed bunk.

Another consideration is to use warmed water from the heat exchange unit (e.g., plate cooler) as the source for a trough in the exit lane from the parlor. This water likely is warmer than the well/reserve tank water source in most dairies. Field observations indicate that cows prefer to drink this warm water, even in environments with warm ambient temperatures. One must be sure that the plate cooler supply is continuously sufficient to keep the water level high enough in the trough so that no cow is ever deprived of the amount of water she wants to consume in a short period of time. If it is possible that this supply will be insufficient at any time, another water source to automatically supplement the plate cooler water must be supplied.

2. Provide a minimum of two water sources per group in the areas where cows are housed. Cows should never have to walk more than 50 ft to get a drink of water. Place water sources in close proximity to the feed bunk. These sources should be protected from sunlight. Adequate open space around water sources is crucial. Cross-over alleys in free stall barns should be at least 13.5 ft wide. This allows 1 ft for the width of the water trough, plus 7.5 ft for a cow standing perpendicular to the long dimension of the trough while drinking, plus 5 ft for other cows to pass behind cows that are drinking. With sufficient linear trough space several cows can line-up parallel to drink and they will have sufficient space to back away from the trough after drinking. Also, boss cows may stand at one end or the other preventing more timid cows from drinking. However, boss cows will not be able to guard the entire water trough if sufficient linear trough length and space are provided for other cows. In existing facilities, this may require some remodeling to provide ample space around water sources. For example, removing a couple of free stall spaces and re-locating the water trough might be necessary.

3. Cleanliness is crucial! A good rule of thumb is, "Based on appearance of water in the trough, would you be willing to cup your hands and take a drink? If not, the water is not clean enough for your cows", Beede (1992). Cleaning water sources routinely (daily or weekly) is very important, so not to limit water intake. Troughs or tanks that can be drained or dumped easily to make the cleaning process quicker and more effective are very useful.

4. Be certain that the water filling capacity of the system and at each watering source is sufficient so that cows never have to wait for water to be available. If cows are locked-up for periods of time for some management procedure and then released they should all be able to drink all the water they want in a short time period. Sufficient filling capacity is crucial in this case. If cows ever have to wait for water, changes are needed immediately!

5. Use water receptacles (troughs or tanks) that provide a filled water depth of only 6 to 12 inches. The advantages to relatively shallow troughs are: a) they prevent stagnant water; b) they are easier to clean; c) they will fill rapidly, assuming proper flow rates, so that cows never have to wait to consume water; and, d) they will necessitate that sufficient linear space be available to accommodate all cows that want to drink at any particular time.

6. Use of water cups or small receptacles (e.g., 12-inch diameter cups or bowls) is discouraged strongly for groups of cows. Rarely are enough cups or space provided around the cups or bowls to meet the needs of all cows in the group (Beede, personal observation). Boss cows can claim a water cup preventing other cows from drinking.

7. Head clearance around water troughs should be at least 2 ft on every side; less than that may reduce optimal water consumption because cows may not be able to see their herdmates and may perceive that they do not have adequate space and opportunity to escape from more dominant animals if necessary.

Trouble-Shooting Water Consumption Questions and Potential Problems. Restricted water consumption may be indicated by abnormally firm manure; reduced urine output; infrequent drinking activity; reduced feed intake and (or) milk production; drinking of urine or other accessible sources of liquids (although this may be indicative of other problems such as a dietary sodium chloride deficiency); dehydration; loss of body weight or condition; and increased blood packed cell volume, hematocrit and osmolality (Chase, 1988). Abnormally high consumption of water may be indicated by excessive urine output and loose manure. This may be caused by abnormally high dietary concentrations of mineral elements in the ration (e.g., sodium or potassium).

To determine if water intake is sufficient several questions and approaches should be asked and employed jointly. Are there adequate numbers of watering sources available for each group of animals? Are the water sources clean, do they work properly? Is there sufficient water pressure to fill waterers when several cows want to drink simultaneously, even during peak water usage (e.g., during milking)?

In order to truly know if water consumption is sufficient it must be measured. In-line water meters to each water source are needed. No other water sources, other than those routinely used by each group of cows should be available to animals during the measurement period. Additionally, water intake should be measured for at least 5 to 10 days consecutively. Keep track of the numbers and types of animals with access to each water source. If focusing on measurement of water intake by lactating cows, it may be useful to know water intake of individual groups of cows. It may be necessary to subtract estimated water intake for other animals (e.g., dry cows and heifers) if they too have access to water sources used by lactating cows. Determine daily feed intake for the same days that water intake is measured, determine the moisture content of the rations, and calculate the water intake from the ration. Determine total water consumption (from the drinking water source plus water from the ration). Calculate the total water consumption on a per head basis and compare with prediction equations to determine if water consumption is normal. If water intake is deemed sub-optimal, any or a combination of the potential problems noted previously should be examined.

Assessing Water Quality. Water quality *per se* could be a cause of low water intake. In such cases, before spending a lot of money trying to solve a drinking water problem two additional evaluations are suggested. 1) Provide a sufficient supply of an alternate source of drinking water to a specific group of animals for at least 5 to 10 days; during this time measure water intake. It is a good idea to measure intake of the water source in question for 5 to 10 days before and after the alternate water source is offered. 2) In conjunction with measuring water intake of the alternate water source or after it is determined that intake is sub-optimal, laboratory analysis of the drinking water source should be performed.

The Future

The availability of abundant, clean drinking water will become a challenge in the future as dairy farms are pushed farther and farther from population centers and relocate. Determining the amount and quality of water (well or municipal) available for nourishment of cattle and milking parlor functions are critical for existing dairies, for dairies considering expansion, or before new dairies are built. Evaluating and determining water supply (amount and maximum flow rate) and quality are paramount to a dairy business's investment. Investors and lenders should require a complete water management plan (e.g., draw, uses/consumption, and recycling) and complete evaluation of the chemicals and biological agents carried in the water before any money is loaned, land is purchased, or before a dairy facility is built.

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References

Citations listed in this paper as well as other references about water nutrition of dairy cattle are provided at: http://www.msu.edu/~beede/ by clicking on "Extension" and then "Water Ref".

Appendix 1. Sampling and Analysis of Drinking Water for Dairy Cattle[a,b]

Contact a reputable, certified laboratory:

1. Ask for "Livestock Suitability" Water Analysis.
2. Ask how to take a representative sample.
3. Ask how much sample is needed.
4. Ask what type of container the sample should be collected in and shipped.
5. Ask about types of analyses (chemical and microbial) that can be performed with the "Livestock" analysis and others that may be applicable in your particular situation.

Suggested standard minimum initial analysis: total dissolved solids, sodium, calcium, magnesium, chloride, sulfate, pH, nitrate, iron, manganese, copper, hardness, conductivity

Additional possible for first analysis: total coliform count

Possible Considerations: Water for laboratory analysis should be sampled into a clean plastic container, after repeatedly rinsing with the water to be tested, at the site of discharge into the water tank, trough or bowl, but not at the origin of the water (e.g., the reserve tank). The sample should not be taken by dipping into the tank, because it will be contaminated by feed and saliva. The sample should be sent to a laboratory certified by the appropriate governmental agency. Chemical and microbial measurements are the two main types of tests for drinking water quality. Standard laboratory tests provide concentrations of common mineral elements and some other constituents of interest. A standard water quality analysis is recommended first. If necessary, more extensive testing can be performed for other compounds such as pesticides and contaminants.

Additional analyses: specific analyses at additional costs can be requested, if of interest, for such chemicals as carbon dioxide, bicarbonate, fluoride, phosphate, silica, potassium, arsenic, cadmium, chromium, mercury, lead, hydrogen sulfide, barium, zinc, molybdenum, and streptococcus

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[a] Possible laboratory: Midwest Laboratories, Inc., 13611 "B" Street, Omaha, Nebraska 68144-3693, Tel: 402-334-7770, Fax: 402-334-9121; www.midwestlabs.com .

[b] This information is supplied as a service to dairy farmers and consultants to aid in improving the water nutrition of their cattle. Many possible laboratories can provide analysis services. The one listed is not recommended over other certified laboratories that provide comparable services at comparable prices…..David K. Beede, Michigan State University, East Lansing