Water Quality Analysis of the Effects of CBM Produced Water on Soils, Crop Yields and Aquatic Life

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Montana's water quality standards protect the beneficial uses of water, such as its use for the support of aquatic life, drinking supplies, and agricultural use. Under Montana's Water Quality Act and the federal Clean Water Act, the State's water quality standards consist of two inter-related components: (1) the designated beneficial uses of the waters; and (2) the water quality criteria necessary to support the uses. Montana's water quality criteria are expressed either in the form of numeric concentration limits or in a narrative form (i.e., no toxics in toxic amounts). In instances where the State has not adopted a numeric criteria for a specific parameter of concern, Montana relies on its narrative standards to protect the beneficial uses of water.[1]

Coal bed methane discharge water contains several substances or "materials" that could, at certain concentrations, be harmful to aquatic life or use for irrigation. These substances include sodium, bicarbonate, the amount of sodium relative to the amounts of calcium and magnesium (SAR), and total dissolved solids (TDS). Since Montana does not have numeric standards for these substances, this paper discusses the potential impacts to beneficial uses at specific concentrations of these substances for purposes of analyzing potential impact in the EIS. Because of the complexity in determining the effects of these substances this paper makes numerous simplifying assumptions.

BACKGROUND

Most substances dissolve to a greater or lesser degree in water. For instance, a large amount of table salt, sodium chloride (NaCl), can completely dissolve in water to form sodium (Na^+) and chloride (Cl^-) ions. These and similar salts are called soluble salts. The soluble salts normally present in water are derived from the disintegration or weathering of rock and minerals.

TDS refers to the total amount of soluble salts in water. In areas where there are relatively large amounts of precipitation, most of these salts are flushed into the ground water or to surface streams and do not build up in the soils nor do they occur in high concentrations in the surface or ground water. On the other hand, in areas where there is relatively little precipitation, salts may be present at high concentrations in the soil, and in the surface and ground water. This occurs because there is not enough water to flush the salts out of the basin.

One example of the difference between low and high precipitation areas occurs in the geologic Powder River Basin. In the Powder River Basin the median concentration of TDS in the Tongue River at the Montana/Wyoming boundary is about 500 parts per million (ppm) whereas in the Powder River at the boundary it is about 1100 ppm[2]. This is due to the fact that most of the water in the Tongue River comes from relatively high precipitation areas in the Big Horn Mountains while much of the water in the Powder River comes from the low precipitation areas in central Wyoming. However, when most of the water in the Powder River is coming from the Big Horn Mountains of Wyoming, it too can have a relatively low TDS (less that 500 ppm). On the other hand, when most of the water is coming from rainstorms in central Wyoming both the flow and the TDS can be relatively high.

Determining the TDS of a given water requires a rather complete chemical analysis in a laboratory. This is time consuming and relatively costly. Because ions dissolved in water conduct electricity, the electrical conductivity of water (EC) is a relatively good measure of the TDS of that water. Determining the EC of water is cheap, quick, and can be done at the site. In addition, the EC at a site can be continuously recorded. Although the relationship between EC and TDS varies somewhat depending on the type of ions present, for the purposes of this paper the average relationship between these measurements for the Powder River water is used. This relationship is that the EC equals 1.4 times the TDS. TDS is measured in parts per million (ppm) and EC in micro-Siemens per centimeter (S/cm). In order to prevent confusion only EC values will be used in the remainder of this paper.

The median is the middle number in a range of numbers. One half of the values in a range of numbers will be larger than the median of that range. The median is generally a better representation of the expected condition than the average, which can be distorted by very

large flood flows.

The median EC value of Powder River water at the boundary between Montana and Wyoming was 1610 mS/cm for the period from 1990 through 1999. The minimum was 243 S/cm and the maximum was 2800 S/cm. The relationship between flow and EC varies as does the time of irrigation. Thus, the quality of the water that is actually used for irrigation in the Powder River Basin is not known. The average or median quality of the water in the Powder River is such that the use of that water would probably cause salinity problems if conventional irrigation practices were used.

EC

Regardless of the EC of the irrigation water, salts can accumulate in the soils of irrigated fields unless excess irrigation water is applied. Excess irrigation water removes most of the salts remaining from previous irrigation. The salts build up because the crops extract large amounts of water but minimal amounts of salts. Evaporation likewise removes water from the soil but not salts. In conventional irrigation from 10 to 20 percent of the applied water is flushed through the soil to remove most of the salts from previous irrigation[3]. This is called the leaching fraction and can be increased, if water is available, in order to use water high in TDS without reducing crop yields. It is important to note that the actual leaching fraction is seldom the same throughout a field. Because the fields are not level, all parts of the field do not receive the same amount of water. In addition there are usually differences in soils throughout a field and these differences affect the soil's ability to accept water.

The EC of irrigation water is important because after a threshold value of EC in the soil water is reached further increases cause declines in crop yield. For alfalfa, which is a major crop in the Powder River Basin, this threshold value is about 2000 µS/cm [4]. If the EC of the irrigation water is about 1000 µS/cm a leaching fraction of twenty percent results in a EC in the soil water that is about 1.5 times the concentration in the irrigation water. At a leaching fraction of 30 percent the EC of the soil water is essentially the same as the EC of the irrigation water[4]. This means that if the leaching fraction is 20 percent, irrigation water with an EC greater than 1300 µS/cm (and thus a soil EC of 2000µS/cm) will likely cause decreases in the yield of alfalfa. If the leaching fraction is 30 percent, yield decreases will begin as the EC of the irrigation water increases above 2000 µS/cm. In both cases as the EC of the irrigation water increases above these thresholds the yield of alfalfa will continue to decrease unless the leaching fraction is increased. Increasing the leaching fraction means that an irrigator must use more water solely for flushing salts out of the soil.

These thresholds use a simplifying assumption that a uniform leaching fraction occurs throughout the irrigated fields.

It is seldom possible to apply the same amount of water throughout a field. . This is due to differences in the ease with which water can pass through a soil and, differences in the amount of water applied throughout a field. In fact, in order to achieve a required minimum leaching fraction in all parts of a field the amount of water applied will probably have to be increased so that the average leaching fraction is double the leaching fraction that is required[3]. Precipitation, which contains essentially no salts, increases the effective leaching fraction. There can be, and probably are, yield decreases in parts of a field even if the average EC of the applied water is less than the thresholds. These parts of fields or "sour spots" result from restricted or minimal leaching due to differences in soil permeability or/and uneven delivery of irrigation water. Significant increases in the EC of the irrigation water will probably further decrease yields in these "sour spots" and increase the number and size of such spots.

Various references recommend ECs that will result in "slight to moderate restrictions on use." These recommendations begin at 700 µS/cm[4,5,6]. This value is significantly lower than the values derived above. This is due to the uncertainties in calculating impact levels discussed above, primarily differences in the assumed leaching fraction. The existing median EC value for the Powder River is about 1600 µS/cm and for the Little Powder it is about 1900 µS/cm. The median EC for the Tongue River is about 600 µS/cm. For the Little Bighorn River it is about 700 µS/cm. Although limited data exists for the tributaries to the Powder and Tongue Rivers their median ECs are apparently about 1600 µS/cm. The median EC of Rosebud Creek is about 1100 µS/cm.

The current median EC values in the Powder and Little Powder Rivers and their tributaries exceed the calculated acceptable value if a 20 per-cent leaching fraction is assumed. This indicates that there may already be decreases in yield, or the irrigators are achieving effective leaching fractions in excess of twenty percent, or that they are using water only when its quality is better than the median value. It is likely that all three things are happening in different combinations throughout the irrigated areas. Because of the uncertainties about the assumptions used in the calculations it is difficult to select a limit for EC increases that would be protective.

Irrigation practices in the Powder River Geologic Basin differ. They are "conventional" in the Tongue and Little Big Horn Rivers where flood and sprinkler irrigation throughout the season is practical and the average leaching fraction is probably about 10-15 percent. In the Powder and Little Powder River drainages, much of the irrigation is done by flooding an entire field and holding the water on the field for a period of time. This results in much higher leaching fractions, possibly as high as 30 to 50 percent. Irrigation on the tributaries is usually done through spreader dike systems where runoff is diverted from the stream channels to the fields. Due to a lack of water in most years irrigation is usually limited to periods of high flow for all of the streams except the Tongue River.

During high flow periods the actual EC values are usually less than the median values. In the Powder and Little Powder drainages, the EC of CBM water may be nearly the same as the EC of the surface water. Because of their similarity, CBM discharges may have little effect on the median values but may increase the EC during the periods when irrigation is taking place. Thus, maximum increases in EC may need to be limited during the periods when irrigation is taking place. This may result in a discharge limit that is set in terms of "when the natural values are less than the threshold levels, increases should not cause the instream EC to exceed the threshold." When the natural levels exceed the threshold levels, discharges could still occur without affecting crop yields provided such discharges do not cause increases in the instream concentrations. For example if the natural EC is 2500 µS/cm, discharges at an EC of 2500 µS/cm or less should have no harmful effect on irrigation. This is due to the fact that the discharges will not increase the instream EC.

Threshold or maximum limits for EC and SAR would probably be necessary only for the irrigation season, which extends from March 1 through September 30.

The threshold EC of irrigation water where decreases in crop yield begin in these basins probably lies between 1000 µS/cm and 2000 µS/cm if the leaching fraction ranges from 15 to 30 per-cent. Limiting EC values to between 1400 and 1800 µS/cm would minimize harmful effects the Powder and the Little Powder Rivers and their tributaries, and the tributaries to the Tongue River based on a leaching fraction of 30 percent.

Based on a leaching fraction of 15 percent threshold EC values for the Tongue River main-stem and Little Big Horn Rivers between 900 and 1100 µS/cm would minimize the potential for crop yield declines. Similarly for Rosebud Creek, EC values between 1000 and 1300 µS/cm would minimize the potential for crop yield declines.

These values are listed in Table 1. They should be used for illustrative purposes in the EIS.

SAR

The clay portion of soils consists of very small plate-like structures stacked like decks of cards. Water in soil moves, and it enters soils, by flowing between the "stacks." The plates are held together primarily by calcium ions and to a lesser degree by magnesium ions. Replacement of the calcium ions between the plates with sodium ions tends to force the plates apart and in effect to breakup the "stacks" or "decks."

As the stacks are broken apart, or dispersed, the rate at which water enters the soil (the infiltration) decreases. In some cases this rate may become very close to zero. This makes production of crops impractical. This effect does not occur in soils that have no clay and the size of the effect depends on the amount (and type) of clay in the soils. However, most of the soils in the Powder and Tongue River Basins contain some clay and most of the soils have quite a bit, or a lot, of clay[7].

The effect of sodium on soils is related to the abundance, or ratio, of sodium to the abundance of calcium and magnesium. This is called the sodium adsorption ratio or SAR. The effects are also directly related to the absolute abundance of all of the ions. As the EC of water increases a given SAR becomes less harmful. The mathematical relationship between EC and the SAR that will result in no reduction in infiltration is: SAR = (EC times 0.0071)-2.4754 where EC is expressed as µS/cm[8].

The existing SARs, and the SARs that will result in no reduction in infiltration at the median EC's are given in Table 1. These are only examples. The SARs that should not be exceeded to minimize harmful effects will depend on the actual EC's. As an example, the table lists the "safe" SAR value for the Tongue River at the state line as 1.7. On August 13, 2001 the SAR below the Fidelity discharges was about 3.2. Because the EC was increased due to low flows and the Fidelity discharges, the "safe" SAR was about 5.5.

References

1. Administrative Rules of Montana [ARM 17.30.637(1)(d)]

2. USGS data
3. Hansen, B.R., S. R. Gratton, and A. Fulton. *AGRICULTURAL SALINITY AND DRAINAGE. University of California Irrigation Program.* University of California, Davis. Revised 1999
4. Ayers, R. S. and D. W. Westcot, 1985. *Water Quality for Agriculture.* FAO Irrigation and Drainage paper 29 (Rev 1), Food and Agriculture Organization of the United Nations.
5. Hoffman, Glenn J., *Water Quality for Irrigation.* http:www.ianr.unl.edu/pubs/irrigation/ec782.htm
6. Follett, R.H., and P.N. Soltanpour. Irrigation Water Quality Criteria. November 12, 1999. www.colostate.edu.Depts/CoopExt/
7. Jim Bauder, Extension Soil Scientist Montana State University, personal communication
8. This formula was derived from figure 3 on page 44 in reference 3 cited above.

Bicarbonate Ion Toxicity

Attached is a paper prepared by Don Skaar, which describes the basis for limiting the concentration of ions. This includes concentrations that have a low, moderate and high probability of causing mortality of Fathead Minnows and presumably other fish. The corresponding concentrations are listed in Table 1.

Table 1. Sodium Absorption Ratio (SAR), specific electrical conductivity (EC), and Bicarbonate levels for the Powder River, the Little Powder River, their tributaries and the tributaries to the Tongue River as well as for the Tongue River and Little Big Horn River main-stems and Rosebud Creek that are likely to result in only slight impacts to uses.

	Agricultural Use (Seasonal March through September)				Aquatic Life Use (Apply yearlong)
Station	**Medians[A] SAR**	**SAR at EC**	**EC (µS/cm) EC[B]**	**Median (permissible)[H]**	**Bicarbonate ion**
Powder River					
MT/WY Stateline	4[4]	1600	9	1400---1800[D]	400---870---340[E]
Mouth	4[C]	1800	10	1400---1800	400---870---1340
Little Powder River	6.7	1900	10	1400---1800	400---870---1340
All Tributaries[F]	7	1900	10	1400---1800	400---870---340[G]
Tongue River					
State Line	0.6	580	1.7	900---1100	530---1000---475
Tongue River Reservior	0.6	550	1.4	900---1100	530---1000--1475
Ashland	1.4	780	3.1	900---1100	530---1000--1475
Miles City	1.4	770	3.0	900---1100	530---1000--1475
Little Big Horn River					

Mouth	1.2	712	2.6	900---1100	530---1000---1475
Rosebud Creek					
Mouth	1.6	1100	5.3	900---1100	530---1000---1475

A. Existing values with flows less than 10 CFS deleted
B. "Safe" values calculated using SAR=(EC times 0.0071)-2.4754 where EC is expressed as µS/cm. For instance, if Wyoming is allocated one half of the assimilative capacity the background values at the boundary would be 6.5 and 7 µS/cm at the median flows for the Powder and Little Powder Rivers respectively.
C. Estimated from data at the Locate and Weston stations for the Powder and Little Powder Rivers respectively.
D. Levels that should not cause impacts during the irrigation season. When the natural values are higher than these levels discharges which do not cause instream concentrations to increase will not cause impacts.
E. Values that result in low, moderate and high impacts to fish. See the text for explanation.
F. Due to a lack of data these values are assumed.
G. These values would apply where fish are present.
H. For the purposed of analyzing impacts in the EIS it is necessary to assume that the upstream parties will use part of the assimilative capacity. One way to do this is to assume the assimilative capacity will be shared equally between the parties. Thus the analysis in the EIS could assume that one half of the difference between the permissible levels and the background values in the Powder, the Little Powder Rivers and the Tongue River at the boundary would be allocated to Wyoming. For Tongue River at Ashland one half of the difference would be allocated to the Northern Cheyenne Tribe. For Rosebud Creek on third would be allocated to the Crow Tribe, one third to Montana, and one third to the Northern Cheyenne Tribe.

USE OF BICARBONATE CONCENTRATIONS AS A MEASURE OF TOXIC EFFECTS TO AQUATIC LIFE IN THE POWDER AND TONGUE RIVERS

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Mount et al. (1997) described the acute toxicity of major ions to fathead minnows. The relative toxicity of the ions was: potassium (1.0), bicarbonate (0.45), magnesium (0.33), chloride (0.12), sulfate (0.08), sodium (0) and calcium (0). In CBM production water in the Powder River in Wyoming and at the CX Ranch in Montana, sodium bicarbonate is the most prevalent salt. There should be no toxicity associated with the presence of sodium, but the bicarbonate ion is quite lethal to fish.

The toxicity of sodium bicarbonate (as predicted by Mount et al.1997) is shown below. To this relationship have been added three lines which describe the relative probability of mortality. The low and high probability lines are positioned at the inflection points on the dose-response curve and correspond to mortality levels of 11 and 89%, respectively. The moderate line corresponds to the level that causes 50% mortality.

These three levels are recommended for use in evaluating the effects of bicarbonate loading from CBM production water on fishes in the Tongue and Powder Rivers. However, there is already a certain amount of toxicity associated with the ions levels currently found in these rivers. Based on DEQs water quality database for the 1990s, the station on the Tongue River at Miles City has an average of 270 mg/L HCO_3+CO_3, 29 mg/L Mg, 3.7 mg/L K, 4 mg/L Cl, and 165 mg/L SO_4. Using the Mount model, these ions should have a combined toxicity of 3.9% to fathead minnows. To estimate the amount of additional HCO_3 that could be released into the Tongue River in order to meet the three probability thresholds, it is necessary to calculate the amount of HCO_3 that will cause 7.1 % (11-3.9), 46.1% (50-3.9) and 85.1% (89-3.9) mortality. The Mount model therefore predicts that on the Tongue River at Miles City, it would

take 530 mg/L HCO_3 to meet the low probability threshold, 1000 mg/L to meet the moderate threshold and 1475 mg/L to meet the high threshold.

On the Powder River at Locate (for 1990s data), the mean concentration of ions was: 197 mg/L alkalinity (HCO_3 + CO_3), 81 mg/L Cl, 48.9 mg/L Mg, 6.8 mg/L K, and 682 mg/L SO_4. These ions should have a combined toxicity of 4.8%. Using the same procedure as done for the Tongue River reveals that the HCO_3 that is allowed to meet the thresholds is 400 mg/L, 870 mg/L, and 1340 mg/L, respectively.

MFWP recommends that these three levels of HCO_3 on each of the two rivers be used as a basis for estimating impacts to fish from HCO_3 loading as a result of CBM activities.

Mount, D.R., D.D. Gulley, J.R. Hockett, T.D. Garrison and J.M. Evans. 1997. Statistical models to predict the toxicity of major ions to *Ceriodaphnia dubia, Daphnia magna* and *Pimephales promelas* (fathead minnows). Environmental Toxicology and Chemistry 16 (10): 2009-2019.

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