PRE- AND POST-COAL BED NATURAL GAS DEVELOPMENT SURFACE WATER QUALITY CHARACTERISTICS OF AGRICULTURAL CONCERN IN THE UPPER TONGUE RIVER WATERSHED

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ABSTRACT

The Upper Tongue River watershed lies at the northern end of the Powder River geologic structural basin in northeastern Wyoming and southeastern Montana. Development of coal bed natural gas (CBNG) resources in the basin has the potential to affect surface water quality as substantial quantities of water are produced to enhance CBNG extraction. CBNG water production in the Upper Tongue River watershed began in 1999 in some tributary watersheds and by 2004 was substantial throughout the Upper Tongue River watershed. In Wyoming the majority of the produced water is currently released to off-channel impoundments and some on-channel impoundments. In Montana the majority of the produced water is currently directly discharged to the Tongue River.

The purpose of this study is to determine whether there have been any statistically significant increases in specific conductance (SC) and/or sodium adsorption ration (SAR) at selected USGS stream gauging stations in the Upper Tongue River watershed since CBNG development began. A secondary objective is to compare the pre- and post-CBNG development SC and SAR to Montana's surface water quality standards. Data reviewed for this study include discrete sample water quality data published by the USGS for selected stream gauging stations in the Upper Tongue Watershed and CBNG water production data published by the Wyoming Oil and Gas Conservation Commission and the Montana Board of Oil and Gas Conservation. Surface water quality data collected during water years 1967 through 2005 were split into two data sets representing the pre- and post-CBNG development time periods. The pre- and post-CBNG time periods were then analyzed using graphical and statistical methods. The statistical techniques include calculation of basic parametric statistics, regression analysis to facilitate

graphical comparison of pre- and post-CBNG development data, and a non-parametric rank-sum test to determine whether there are statistically significant differences between the pre- and post CBNG development time periods.

Surface water quality data from four key USGS monitoring stations in the Upper Tongue River watershed show that generally there do not appear to be statistically significant increases in SC or SAR coincident with CBNG development through water year 2005. At three of the four stations, SC and SAR are lower in the post-CBNG development time period than in the pre-CBNG development time period. The exception is the Tongue River station downstream of the Wyoming-Montana Stateline, where SAR is higher by a factor of about 2 on average and SC is roughly the same in the post-CBNG development time period relative to the pre-CBNG development time period. Monitoring information in the Upper Tongue River watershed is not sufficient to determine whether the post-CBNG development increase in SAR at the Stateline station is due to direct discharges to the river from CBNG development in Montana, discharge from Prairie Dog Creek (a tributary characterized by higher SAR than in the Tongue River) or a characteristic of the lower flows observed during the post-CBNG development time period.

The evaluated main-stem Tongue River stations met Montana's applicable SC and SAR water quality standards in both the pre- and post-CBNG development time periods. Most of the evaluated tributaries to the Tongue River also met applicable SAR standards during both time periods; the exception is Hanging Woman Creek where SAR has routinely exceeded applicable standards. None of these tributaries met applicable SC standards during either time period. Thus, there appear to be no substantial differences between the pre- and post-CBNG development time periods with respect to meeting Montana's SC and SAR standards.

In summary, CBNG development does not appear to have had a substantial impact on SC and SAR in discrete water samples from the evaluated USGS monitoring stations in the Upper Tongue River watershed through water year 2005. However, it is important to recognize that CBNG development is anticipated to substantially increase in the future and, consequently, may result in measurable impacts to surface water quality as measured by SC and SAR.

INTRODUCTION

The Upper Tongue River watershed lies at the northern end of the Powder River geologic structural basin in northeastern Wyoming and southeastern Montana (Figure 1). Substantial energy resources are present within the basin, including uranium, oil, coal, and conventional natural gas, which have been mined from the basin for decades. More recently, coal bed natural gas (CBNG) has been produced from the basin, due to the development of economical means of extraction. Production of CBNG involves pumping water from target coal seams, which lowers hydrostatic pressure in the coal beds and allows the confined natural gas to flow. Most CBNG produced water in the Upper Tongue River watershed within Wyoming currently is discharged into constructed reservoirs, where it may evaporate or infiltrate into the ground and potentially migrate towards or become part of the stream channel flow (Kathy Shreve, Wyoming DEQ, personal communication, 2006). Most produced water from CBNG development in Montana currently is discharged directly to the Tongue River, though about a third of the discharged water is currently treated (Fidelity Exploration and Production, personal communication, 2006).

The Tongue River watershed is used as a source for irrigation water in Montana. Two water quality parameters of agricultural concern, for which Montana has set surface water quality standards, are specific conductance and sodium adsorption ratio. The impact of these parameters on agricultural resources is discussed in detail by Ayers and Westcot (1985) and Hansen and others (1999). Specific conductance (SC), which is a measure of the ability of a substance to conduct an electric current at a specific temperature (25^{o}C), is used as an indicator of the concentration of dissolved solids in water. Irrigation water with excessive dissolved solids can have a negative impact on plant health. The sensitivity of the plant to dissolved solids depends on the crop. Sodium adsorption ratio (SAR), which is a measure of the relative quantity of sodium ions to calcium and magnesium ions in water, is used to estimate the degree to which the irrigation water will disperse clays in soil and potentially affect soil infiltration rates. The overall effect of irrigation water on soil infiltration depends on the quantity and type of clays present in the soil and on the interaction between the flocculating effects of higher SC and the dispersive effects of higher SAR

Discharge of CBNG produced water in the Upper Tongue River watershed has the potential to affect surface water quality. Substantial quantities of water are produced as a result of CBNG extraction. Cumulative water production from CBNG wells in the Upper Tongue River watershed exceeds 30 trillion barrels and is projected to increase (WYOGCC, 2006). CBNG produced water in the Powder River structural basin is characterized as sodium-bicarbonate type water, in which the dominant cation is sodium and the dominant anion is bicarbonate (Rice and others, 2000). The SC and SAR of the CBNG produced water generally increases from south to north and from east to west (Figure 2). In the Wyoming portion of the Upper Tongue River watershed, the CBNG produced water mean SC is 1950 uS/cm and its mean SAR is 23 (based on review of water quality data through 2005 from the WYPDES Public Access database). In the Montana portion, the produced water mean SC is roughly the same (1990 uS/cm) but its mean SAR is about double (53) (Bobst, 2005). In contrast, the SC and SAR of the Tongue River in the Upper Tongue River watershed are below 1500 uS/cm and 3.0, respectively (based on review of USGS data from water years 1967 through 2005).

The purpose of this study is to determine whether there have been any statistically significant increases in SC and/or SAR at selected USGS stream gauging stations in the Upper Tongue River watershed since CBNG development began. A secondary objective is to compare the pre- and post-CBNG development SC and SAR to Montana's applicable surface water quality standards.

METHODS

Data Considered

The data reviewed for this study include water quality data published by the USGS for selected stream gauging stations in the Upper Tongue Watershed for water years 1967 through

2005 (Figure 3) and CBNG water production data through 2006 available from the Wyoming Oil and Gas Conservation Commission (Figure 4) and the Montana Board of Oil and Gas Conservation.

The USGS stations shown in Figure 3 are those in the Upper Tongue River watershed with sufficient data to statistically evaluate pre- and post-CBNG development time periods. Of these seven stations, four were selected for detailed analysis. These are: “Tongue River at Monarch, Wyoming” (USGS # 6299980), “Tongue River at State Line near Decker, Montana” (USGS # 6306300); “Goose Creek below Sheridan, Wyoming” (USGS # 6305500); and “Hanging Woman Creek near Birney, Montana” (USGS # 6307600). In this paper, these stations will be referred to as the Tongue River at Monarch, Tongue River at Stateline, Goose Creek below Sheridan, and Hanging Woman Creek near Birney stations, respectively. The Tongue River at Monarch station represents stream conditions upstream of the CBNG development areas. The Tongue River near Stateline station represents stream conditions in the Tongue River downstream of CBNG development in Wyoming and Montana. The Goose Creek below Sheridan and Hanging Woman Creek near Birney stations represent stream conditions downstream of CBNG development areas in tributary watersheds.

The data used in this study are the discrete sample water quality data published by the USGS on the National Water Information System Web Interface (USGS NWIS Web Water Data, 2006). Specifically, SC and the constituents from which SAR is calculated (sodium, calcium, and magnesium) were extracted from the database. SAR was calculated using the following equation:

$$SAR = \frac{[Na^{+}]}{\sqrt{\frac{1}{2}\left([Ca^{2+}] + [Mg^{2+}]\right)}}$$

where $[Na^{+}]$, $[Ca^{2+}]$, and $[Mg^{2+}]$ represent concentrations in milliequivalents per liter for each constituent (Hansen and others, 1999).

CBNG water production data obtained from the Wyoming Oil and Gas Conservation Commission and the Montana Board of Oil and Gas Conservation web sites were used to determine when CBNG production started in each sub-watershed of the Upper Tongue River. Monthly CBNG water production rates shown in Figure 4 indicate that CBNG water production in the Tongue River watershed upstream of the Wyoming-Montana Stateline started mid-1999, stopped in 2000, and then substantially increased by mid-2001. In the Hanging Woman Creek watershed, substantial water production started in 2004, though a small amount of water was produced in 2002. In the Prairie Dog Creek watershed, CBNG substantial water production began in 2000. According to the Wyoming Department of Environment Quality, the produced water from CBNG development in the Tongue River watershed within Wyoming is released primarily to off-channel impoundments and some on-channel impoundments (Kathy Shreve, WY DEQ, personal communication, 2006). A minor amount is released directly to Goose Creek and the Tongue River. CBNG water production in Montana started in April 1999 in the Squirrel Creek watershed. The majority of this produced water is discharged untreated to the Tongue River. Since 2006, however, approximately a third of the discharged water has been treated to reduce SAR (Fidelity Exploration and Production, personal communication, 2006).

Since the early 2000’s, a number of the stations considered also have continuous data for stream discharge and specific conductance in addition to discrete sample data. The collection methods used for both types of data are described by Clark and Mason (2006). The continuous data were not used in this study so as not to bias the statistical analysis by the very large data sets resulting from continuous measurement. However, in order to verify that the discrete data provide information representative of the continuous data, the discrete and continuous water quality data at the Tongue River at Stateline station were compared. Figure 5 shows the correspondence between mean monthly statistics calculated and published by the USGS for the continuous data for water years 2000 – 2005) and mean monthly statistics calculated using the discrete sample data for the same time period. The continuous and discrete sample SC and SAR data are closely correlated, with linear regression correlation coefficients of about 0.9 and slopes very close to one.

Data Analysis

The discrete sample, stream water-quality data for each station were split into two data sets representing the pre- and post-CBNG development time periods and analyzed using graphical and statistical methods. Time series data for discharge, SC, and SAR as well as the relationships between discharge and SC or SAR and between SC and SAR, were examined in the two time periods and evaluated to determine if there are any statistically significant differences between the two time periods.

The statistical techniques used in this study include calculation of basic parametric statistics, regression analysis to facilitate graphical comparison of pre- and post-CBNG development data, and a non-parametric rank-sum test (Helsel and Hirsch, 2002) to compare the pre- and post CBNG development data.

RESULTS AND DISCUSSION

Discharge

The instantaneous stream discharge measurements corresponding to the water quality measurements at each of the four stations analyzed in detail are shown in Figure 6. Figure 7 shows the calculated mean stream discharge rates for the pre- and post-CBNG development time periods, including the irrigation season (March – October), non-irrigation season (November – February), and individual months within the pre- and post-CBNG time periods.

At each of the stations analyzed, mean stream discharge rates in the post-CBNG time period are typically lower than in the pre-CBNG time period. The greatest differences occur in the irrigation season months. At the two Tongue River stations and the station on Goose Creek, the mean discharge rates are lower by a factor of 2 or less. At the Hanging Woman Creek station, the mean discharge rates are lower by one to two orders of magnitude.

Discharge versus Concentration Relationships

Many streams exhibit a nonlinear inverse relationship between stream discharge and concentration, in which higher concentrations are typically observed at lower discharge rates. Figure 8 shows plots of discharge versus SC and discharge versus SAR for each of the four stations. Data for the pre- and post-CBNG development time periods are shown with different symbols. A nonlinear power curve is fit to each set of data.

Three of the four stations (Tongue River at Monarch, Goose Creek below Sheridan and Tongue River at Stateline) show a consistent inverse relationship between discharge and SC for both the pre- and post-CBNG time periods. At each of these stations, the SC in the post-CBNG time period is lower than that of the pre-CBNG time period for discharge rates below 100 cubic feet per second. Thus, it does not appear that the generally lower discharge rates of the post-CBNG time period have resulted in higher SC; rather, on average SC is lower.

Three of the four stations (Tongue River at Monarch, Goose Creek below Sheridan and Tongue River at Stateline) also show a consistent inverse relationship between discharge and SAR for both the pre- and post-CBNG time periods. At the first two stations, the SAR in the post-CBNG time period is lower than that of the pre-CBNG time period for discharge rates below 100 cubic feet per second, as was observed for SC. At the Tongue River at Stateline station, however, the SAR values in the post-CBNG time period appear higher than in the pre-CBNG time period for discharge rates less than 100 cubic feet per second.

At the Hanging Woman Creek Birney station, the discharge versus concentration data are very scattered and the regression fit is very poor. SC and SAR tend to be lower in the post-CBNG time period than in the pre-CBNG time period. However, in contrast to the other stations, SC and SAR concentrations in either time period appear to increase with increasing discharge below a discharge rate of about 10 cubic feet per second.

SC versus SAR Relationships

Many streams exhibit a linear relationship between SC and SAR, in which higher SAR values correspond to higher SC values. Figure 9 shows plots of SAR versus SC for each of the four stations. Data for the pre- and post-CBNG development time periods are shown with different symbols. At all four of the stations, there is an approximately linear relationship between SAR and SC and little visual difference between the pre- and post-CBNG development time periods.

Time Series Analysis

Time series plots for SC and SAR at each of the four stations are shown in Figure 10. These plots show that at most stations the SC and SAR in the post-CBNG time period appear similar to or slightly lower than the SC and SAR in the pre-CBNG time period. The exception is SAR at the Tongue River Stateline station, where the post-CBNG SAR appears higher than the pre-CBNG SAR.

Figures 11 and 12 present the calculated mean SC and SAR values for the pre- and post-CBNG development time periods. Statistics also are calculated for the irrigation season (March – October), non-irrigation season (November – February), and individual months. Sufficient data are generally available to test the significance of differences between the pre- and post-CBNG development time periods when the historic data are grouped into irrigation and non-irrigation seasons. There are not, however, sufficient data to test the significance of differences between the two time periods for individual months.

Tongue River at Monarch, Wyoming

There has been no CBNG development upstream of the Tongue River Monarch station. Water quality before and after the time CBNG water production began in downstream areas (substantial production began in approximately July 2001) is compared to determine whether there have been any changes in upstream water quality coincident with the timing of CBNG development.

When all the SC data are considered, the post-July 2001 mean is approximately 10% lower than the pre-July 2001 mean. A similar difference is observed when comparing the pre- and post-July 2001 means for the irrigation season. The rank sum tests indicate these differences are statistically significant. A similar 10% decrease is noted between the pre- and post-July 2001 means for the non-irrigation season, but due to the limited number of samples the difference is not statistically significant. When the individual months are considered separately, the mean SC for the post-July 2001 time period appear lower than the pre-July 2001 time period for most months; the exceptions are May, June, July, and August.

When all the SAR data are considered, the post-July 2001 mean is approximately 25% lower than the pre-July 2001 mean. A similar difference is observed when comparing the pre- and post-July 2001 means for the irrigation and non-irrigation seasons. The rank sum tests indicate these differences are statistically significant. When the individual months are considered separately, the mean SAR for the post-July 2001 time period is lower than the pre-July 2001 time period for most months; the exceptions are June and July.

All SC and SAR measurements in both time periods are less than Montana’s mean monthly and instantaneous maximum water quality criteria.

Goose Creek below Sheridan, Wyoming

When all the SC data are considered, the post-CBNG time period mean is approximately 6% lower than the pre-CBNG time period mean. A similar difference is observed when comparing the pre- and post-CBNG time period means for the non-irrigation season. The rank sum tests indicate these differences are statistically significant. A similar decrease is noted between the pre- and post-CBNG time period means for the irrigation season, but the difference is not statistically significant. When the individual months are considered separately, the mean

SC for the post- CBNG time period is lower than in the pre-CBNG time period for most months; the exceptions are June, July, October, and November.

When all the SAR data are considered, the post-CBNG time period mean is approximately 15% lower than the pre-July 2001 mean. A similar difference is observed when comparing the pre- and post-CBNG time period means for the irrigation and non-irrigation seasons. The rank sum tests indicate these differences are statistically significant. When the individual months are considered separately, the mean SAR for the post-CBNG time period is lower than in the pre-CBNG time period for most months except July.

Mean monthly SC values for this station during both the pre- and post-CBNG time periods exceed Montana's mean monthly SC standard for tributaries in all months except May and June; Montana's mean monthly SAR standard is met in all months.

Hanging Woman Creek near Birney, Montana

When all the SC data are considered, the post-CBNG time period mean is approximately 12% lower than the pre-CBNG time period mean. A similar difference is observed when comparing the pre- and post-CBNG time period means for the irrigation season. The rank sum tests indicate these differences are statistically significant. There is less difference between the pre- and post-CBNG time period means for the non-irrigation season, and that difference is not statistically significant. When the individual months are considered separately, the mean SC for the post- CBNG time period is lower than the pre-CBNG time period for most months except January and February.

When all the SAR data are considered, the post-CBNG time period mean median is approximately 15% lower than the pre-July 2001 mean. A similar difference is observed when comparing the pre- and post-CBNG time period means for the irrigation season. The rank sum tests indicate these differences are statistically significant. There is less difference between the pre- and post-CBNG time period means for the non-irrigation season, and that difference is not statistically significant. When the individual months are considered separately, the mean SAR for the post-CBNG time period is lower than the pre-CBNG time period for most months except January.

SC and SAR measurements exceed Montana's mean monthly and instantaneous maximum water quality criteria for tributaries in all months.

Tongue River at Stateline near Decker, Montana

When all the SC data are considered, there is no statistically significant difference in SC between the pre- and post-CBNG time period.

When all the SAR data are considered, the post-CBNG time period mean is approximately 75% higher than the pre-July 2001 mean. A 95% increase is observed when comparing the pre- and post-CBNG time period means for the irrigation season. The rank sum tests indicate these differences are statistically significant. There is a smaller difference between the pre- and post-CBNG time period means for the non-irrigation season, and the difference is not statistically significant. When the individual months are considered separately, the mean SAR for the post-CBNG time period is higher than the pre-CBNG time period in all months.

There is insufficient monitoring information to determine whether the post-CBNG development increase in SAR at the Tongue River at Stateline station is due to direct discharges to the river from CBNG development in Montana, discharge from Prairie Dog Creek (which has had CBNG development in Wyoming and is characterized by higher SAR than the main stem) or a characteristic of the lower flows observed during the post-CBNG development time period.

All historic SC and SAR measurements are below Montana's applicable mean monthly and instantaneous maximum surface water quality standards.

REFERENCES

Publications

Ayers, R. S., and Westcot, D.W., Water Quality for Agriculture, FAO Irrigation and Drainage Paper 29 (Rev 1), Food and Agriculture Organization of the United Nations, 1985

Bobst, A., "Water Year 2004, Overview of Surface Water Monitoring Data for EC and SAR in the Tongue River Watershed", BLM Miles City Field Office, March 2005

Clark, M.L, and J.P. Mason, "Water-quality monitoring and regression analysis for specific conductance and sodium-adsorption ratios and load estimates for dissolved solids for four sites in the Powder River Basin, Montana and Wyoming 2001-2004," USGS SIR 2006-5113, 2006

Hanson, B., S.R. Gratton and A Fulton. "Agricultural Salinity and Drainage." University of California Irrigation Program. University of California, Davis, 1999

Helsel, D.R and R.M. Hirsch, "Statistical Methods: Techniques of Water-Resources Investigations of the United States Geological Survey, Book 4, Hydrologic Analysis and Interpretation", http://water.usgs.gov/pubs/twri/twri4a3/, 2002

Rice, C.A.1, Ellis, M.S.1, and Bullock, J.H., Jr., "Water co-produced with coalbed methane in the Powder River Basin, Wyoming: preliminary compositional data," USGS Open-File Report 00-372, 2000

On-Line Sources

MBOGC: http://bogc.dnrc.state.mt.us/jdpintro.asp

USGS NWIS Web Water Data: http://waterdata.usgs.gov/nwis

WYOGCC: http://wogcc.state.wy.us/

WYPDES Public Access Database: http://deq.state.wy.us/wqd/npdes/