DISSOLVED METHANE IN POWDER RIVER BASIN GROUNDWATER

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Cover photo: Flowing stock well in the Powder River Basin, Montana. Photo by Don Sasse, MBMG.

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ABSTRACT

The highest measured concentrations of methane in Montana groundwater are found in the Powder River Basin in Rosebud and Powder River Counties. High levels of methane in groundwater can be a safety concern; accumulated methane at discharge points is an asphyxiation and explosive hazard. High levels of methane can also complicate sample collection when the well produces a mixture of water and methane gas. To reduce degassing of methane prior to sample collection, samplers must ensure a completely filled discharge pipe, thereby preventing the exposure of the groundwater sample to air.

Methane migration away from coalbed-methane production wells can increase free methane in nearby domestic and stock wells. However, a lack of pre-development methane analyses makes it difficult to determine whether the source of methane in a well is local or migrated. The Coalbed Methane Protection Program surveyed dissolved methane concentrations in wells along the Powder River and Otter Creek to establish a dataset of quantified methane concentrations in area groundwater; these data serve as a point of comparison for future sampling. This survey resulted in 106 samples from 59 sites. The dissolved methane concentrations provide a picture of spatial variability within these watersheds and a basis for identifying temporal trends in concentration in future groundwater samples.

INTRODUCTION

Dissolved methane [$CH_{4(aq)}$] is commonly found in eastern Montana groundwater (MBMG, 2021), and at high concentrations it can be an explosive or asphyxiation concern for water well users. The United States Office of Surface Mining recommends mitigation of methane gas at the wellhead when concentrations are between 10 and 28 mg/L; at concentrations of 28 mg/L and above, immediate action is needed to prevent an explosive hazard (Eltschlager and others, 2001).

Methane in Powder River Basin groundwater, including commercially produced coalbed methane (CBM), is generated by respiration of microbes living within coalbeds and referred to as biogenic methane (Schoell, 1983). The methane in coal is not stored as free gas; it is both dissolved in the water and adsorbed onto the coal and held in place through hydrostatic pressure (Puri and Yee, 1990). The biogenic methane in domestic and stock wells is typically locally generated. When those wells are pumped, the reduction in hydrostatic pressure can release adsorbed methane from nearby aquifer sediments, thereby increasing concentrations of dissolved methane in groundwater. CBM production wells intentionally release methane in the same way; however, closely spaced CBM wells create a cone of depression that can extend up to 2 mi from the edge of the field (Meredith and others, 2012). While CBM wells are designed to capture the methane they release, free methane at the edge of the field can migrate away from the capture zone (USGS, 2000). Unintentional migration of methane away from CBM production wells can increase the methane concentration in groundwater at private domestic and stock wells.

Distinguishing the source of the methane, whether local or migrated, may be desirable in situations where migrated methane causes the total methane concentration at a well to increase to a level that requires mitigation, resulting in additional costs to the well owner. However, it is difficult to distinguish locally generated methane from migrated methane because CBM production occurs in areas where aquifers frequently have locally generated methane; in some locations the coal aquifers used for domestic and stock water are also CBM production targets. Additionally, the source of methane cannot be distinguished through isotopic analysis because both locally generated methane and migrated methane are biogenic in origin.

The State of Montana’s Coalbed Methane Protection Act (CBMPA; MT DNRC, 2021) provided funding to eligible Montana water users to offset the costs of impacts from CBM development, including increased methane in their wells. However, aside from anecdotal observations from the well users, there was little historical, quantitative evidence of the concentration of locally generated methane in their groundwater. It was, therefore, difficult for the CBMPA administrators to determine whether an individual well had been adversely impacted from methane migration caused by CBM production and was eligible for funding assistance. For this reason, the Coalbed Methane Protection Program, formed of Montana Conservation Districts tasked with administering the Act, undertook a survey of the occurrence and distribution of methane concentrations in Powder River Basin groundwater. This survey provides a dataset of quantified, dissolved methane concentrations with which to look for spatial and temporal patterns in the watershed and to compare future analyses. Representatives from the Montana Bureau of Mines and Geology (MBMG) served as the technical advisors to the Program. MBMG staff provided Program field staff access to MBMG monitoring wells for repeat sampling, identified locations where elevated methane might be present based on CBM production history, suggested improvements to sampling protocols, and recommended additional sampling for quality assurance/quality control. The MBMG hosts the dissolved methane results in the Groundwater Information Center Database (GWIC; MBMG, 2021). This sampling program resulted in 106 analyses of methane concentrations in groundwater samples from 57 wells and 2 springs (appendix A).

METHODS

Sample Site Selection

Sample locations were chosen first from landowner requests for CBMPA financial support for the replacement of methane-impacted wells. These requests came primarily from along the Powder River near the Montana–Wyoming state line. Additional sites were selected from well owners who expressed concern over the level of methane in their wells but did not seek CBMPA financial assistance, including sites along Otter Creek. Following these sites, permission was sought to sample nearby wells along the Powder River and Otter Creek to ascertain the spatial variability of methane concentrations in groundwater along these streams. When access allowed, wells were sampled multiple times to assess seasonality and sample collection methods. Wells along the Powder River that were included in the MBMG CBM groundwater monitoring network (Kuzara and others, 2016) were also sampled for replicate analyses (e.g., wells 221592 and 223695, table 1).

All sampled wells and springs are in the Fort Union Formation, which is composed of interbedded sandstone, shale, and coal. For most wells, well completion records (i.e., driller's well logs) were not available, so identifying the specific aquifer within the Fort Union that each well draws from is not possible.

Field Sampling Procedures

As much as individual wellhead conditions allowed, samples for methane analysis were collected in accordance with the Montana Bureau of Mines and Geology standard operating procedure for groundwater sample collection (Gotkowitz, 2022), which is consistent with the United States Geological Survey (USGS) sampling protocols (Koterba and others, 1995). The USGS protocols for the National Water Quality Assessment Program do not specifically address methane; however, analysis of volatile organic compounds is included. The USGS National Field manual (USGS, 2006b) stipulates that sample collection of water with dissolved gases, such as methane, should avoid degassing. Specifically, samplers should avoid increasing water temperature or leaks in the sampling and pressure systems; however, the manual does not address sampling for dissolved gasses from *in situ* pumps and plumbing. The USGS specifies low-discharge, submersible pumps are preferred to collect samples for volatile organic compound analysis (Koterba and others, 1995). The survey of groundwater methane concentrations reported here relied on existing stock and domestic wells, or springs developed for stock use, and the in-place plumbing was used.

Methane quickly escapes from the groundwater into the atmosphere when groundwater is brought into contact with air (USGS, 2006a). Therefore, collecting a representative sample for methane analysis can be difficult. Stock and domestic wells often have supply pipes that run some horizontal distance (feet to miles) before a sample can be collected. If the pipe is not completely full, the water is in contact with air throughout its travel time in the pipe. When possible, field sampling methods were modified to ensure a completely filled pipe until the sample point. This was done through elevating the discharge end of the pipe, providing back pressure by constricting the discharge, or adding a new sampling point closer to the wellhead. The new configuration was allowed to stabilize for the amount of time needed to discharge at least one volume of water from the pipe, if that volume could be determined. Field parameters of temperature, pH, and specific conductance were also measured during purging to assess if stable conditions had been reached.

Many of the sampled wells along the Powder River are under artesian conditions, with unrestricted discharge at the surface; the water pressure in the pipe is enhanced when free methane gas is also present. This creates a frothy, sporadic discharge (fig. 1). When collecting samples from wells with high levels of free methane, multiple attempts were made to col-

Table 1. Reproducibility in methane sampling.

GWIC ID	Location (NAD 83) Latitude	Longitude	Depth (ft.)	Sample date	Methane (mg/L)
105735	45.08938	-105.85653	330	4/13/2015	31
				6/3/2015	18
				3/2/2016	21
				6/7/2018	26
105738	45.14007	105.76384	330	7/28/2015	0.012
				4/7/2016	0.015
				5/3/2018	0.011
105741	45.12638	-105.74893	340	7/28/2015	0.0087
				4/7/2016	0.012
				5/3/2018	0.0094
191466	45.16751	-105.76840	710	7/29/2015	6.2
				3/1/2016	5.2
				5/3/2018	7.7
191506	45.06941	-105.85937	450	4/13/2015	21
				5/4/2016	16
				6/7/2018	21
283921	45.03609	-105.87459	575	4/13/2015	15
				6/2/2015	9.6
				5/2/2017	17
				5/3/2018	21
284310	45.13710	-105.79171		7/28/2015	7.1
				3/1/2016	6.9
				5/3/2018	8.7
284576	45.08883	-105.84683		4/14/2015	19
				6/3/2015	12
				7/29/2015	17
284642	45.11560	-105.82237		4/14/2015	0.019
				6/2/2015	0.013
				7/29/2015	0.020
				4/7/2016	0.020
				6/7/2017	0.027
				5/3/2018	0.022
221592	45.17590	-105.90094		5/6/2015	8.9
				6/2/2015	15
				8/31/2015	11
				3/1/2016	11
				5/2/2017	24
				6/7/2018	16
223695	45.05411	-105.87794	1000	5/6/2015	9.4
				6/3/2015	11
				7/29/2015	9.1
				10/8/2015	9.0
				3/1/2016	14
				4/5/2017	14
				5/3/2018	11
				6/7/2018	16
266481	45.01836	-105.86652	300	5/7/2015	0.96
				7/27/2015	7.2
				8/31/2015	4.0/9.4*
				5/3/2018	37

Note. GWIC ID is the site identification number on the Groundwater Information Center Database: http://mbmggwic.mtech.edu/. Well depths are noted if known. ND (non-detect) indicates the methane concentration of the sample is below the laboratory reporting limit of 0.0010 mg/L.
*Two samples were collected on this date: direct discharge (4.0 mg/L) and providing back pressure (9.4 mg/L).

Figure 1. Free methane gas in flowing well 266481 results in frothy discharge into a stock pan. Collecting a representative sample is difficult because the flow is sporadic, and droplets spray across the pan.

lect a representative sample using one or more of the previously mentioned modifications. Of these replicate samples, the highest dissolved methane concentrations resulted from samples collected after developing some backpressure over the discharge pipe. This was accomplished with a splitter and a small hose (fig. 2) or a nitrile glove to slow the water (fig. 3), while allowing water and methane gas to escape. Each wellhead was unique and called for a different approach. Field samplers focused their modifications primarily on preventing exposure of the groundwater to the atmosphere prior to collection.

Samples were submitted to an analytical laboratory in Billings, Montana for dissolved methane analysis. The analytical method (following section) required two 40-ml bottles, filled with no headspace, and preserved with sulfuric acid added to the sample bottle after filling. The laboratory-recommended sample collection includes gently pouring the sample down the side of the vial without agitation and replacing the cap quickly (written commun., Jillian Miller, August 6, 2021).

Analytical Methods

Analytical laboratories use a gas chromatograph with flame ionization detector to analyze for dissolved methane in water (EPA methods 3810/RSK175 and SW8015 Mod.; Energy Laboratories, 2022; U.S. EPA, 2001). Analysis is performed on the gas headspace in the sample bottle or an inert-gas bubble added to the sample that equilibrates with the dissolved gas. The concentration of dissolved methane in the water sample is calculated using Henry's law: the concentration of gas in the liquid (water sample) is proportional to the partial pressure of the gas in headspace above the liquid. The laboratory reporting limit for dissolved methane is 0.0010 mg/L.

Figure 2. The replicate samples collected from well 266481 with the highest dissolved methane concentrations were collected after constricting the discharge. The splitter allowed a high-flow rate pathway while the small hose created a laminar flow conditions for collection.

Figure 3. Existing stock wells, such as well 221592, often lack pipe fittings and threads. Field personnel must be flexible, and creative, in developing appropriate sampling methods. Here, plumbers' tape secures a sampling glove to the end of a threadless pipe. Holes in the glove split the flow to minimize turbulence. Restricting the flow allowed the discharge pipe to fill, reducing groundwater contact with the atmosphere.

Dissolved methane analytical results collected throughout Montana and contained in the online database GWIC (MBMG, 2021) used various laboratories and analytical methods. All samples collected for the Powder River Basin survey presented here were analyzed by a single laboratory and one analytical method, SW8015.

RESULTS AND DISCUSSION

Dissolved Methane Concentrations

With few exceptions, dissolved methane concentrations in Montana groundwater are low. Of the 347 Montana wells with results in MBMG's database (MBMG, 2021), 86 percent had less than 1 mg/L dissolved methane (164 non-detectable and 134 less than 1 mg/L; fig. 4A). A result of "non-detectable" indicates concentrations below the laboratory reporting limit of 0.0010 mg/L. The exceptions include elevated methane concentrations in deep wells in central Montana (well 2743; 26.2 mg/L) and northeastern Montana (wells 430095 and 154904, concentrations 21.0 and 18.0 mg/L, respectively): total depths range from 840 (well 154904) to 1,624 ft (well 2743) below ground surface. These wells also had detectable ethane, which indicates a non-biogenic source of methane (Meredith, 2019). A more detailed discussion about methane in northeast Montana groundwater can be found in Meredith (2019).

The highest levels of dissolved methane in Montana groundwater are found in the Powder River Basin in southeastern Montana (fig. 4B). Of the 59 sites sampled in the Powder River Basin along the Powder River and Otter Creek, 36 percent had less than 1 mg/L of dissolved methane (3 sites non-detectable, 18 sites less than 1 mg/L). The highest methane concentration measured in the state was in the Powder River Basin, 37 mg/L (appendix A). Because degassing during sample collection results in the loss of methane from the water sample, analytical results may skew low. Therefore, for wells sampled multiple times or with multiple methods, the highest results from each site are displayed on figure 4.

Samples from three Powder River Basin wells had dissolved methane concentrations over the 28 mg/L level recommended for immediate action to prevent explosive conditions (Eltschlager and others, 2001). All are stock wells that are not enclosed. Thirty-one sample sites, which were sampled a total of 53 times, had dissolved methane concentrations that fell within the 10–28 mg/L range recommended for mitigation to prevent accumulation of methane (appendix A). Site selection was not randomized, so these results are not a comprehensive evaluation of Powder River Basin groundwater; sampling focused on areas where landowners reported high levels of methane in their groundwater.

Along the Powder River, dissolved methane concentrations decrease northward with increasing distance from CBM production that occurred south of the state line, in Wyoming. This was also the area where landowners identified new problems of excessive methane gas and water-level declines in their wells. This may indicate some component of methane migration away from CBM production. In contrast, landowners along Otter Creek generally reported a history of methane problems that pre-date CBM production. Additionally, there is no spatial trend, similar to that observed along the Powder River, away from CBM production in either the Montana or Wyoming CBM fields (fig. 4B). Otter Creek results may, therefore, represent locally generated methane. However, given the lack of previous methane analyses and the minimal information on well completion, definitive conclusions about methane migration cannot be made at this time.

Variability in Methane Concentrations

Twelve Powder River Basin wells were sampled three or more times (table 1). Analytical results from a single well generally varied 10 to 30 percent (defined as standard deviation/average; table 2) and rarely changed classification for recommended mitigation. The exception was well 266481, which varied from 0.96 mg/L (low risk) to 37 mg/L (immediate action needed). The results from this well, pictured in figure 1, illustrate the challenges of collecting a representative groundwater sample with high dissolved methane concentrations and underscore the importance of considering quality assurance measures in the sampling plan.

Evaluation of sampling reproducibility needs to consider the seasonality associated with agricultural practices. As cattle and sheep are moved into and out of fields, pumping from stock wells creates a temporary cone of depression that can release methane dissolved in the groundwater or adsorbed onto the matrix material of the aquifer. Samplers should note whether

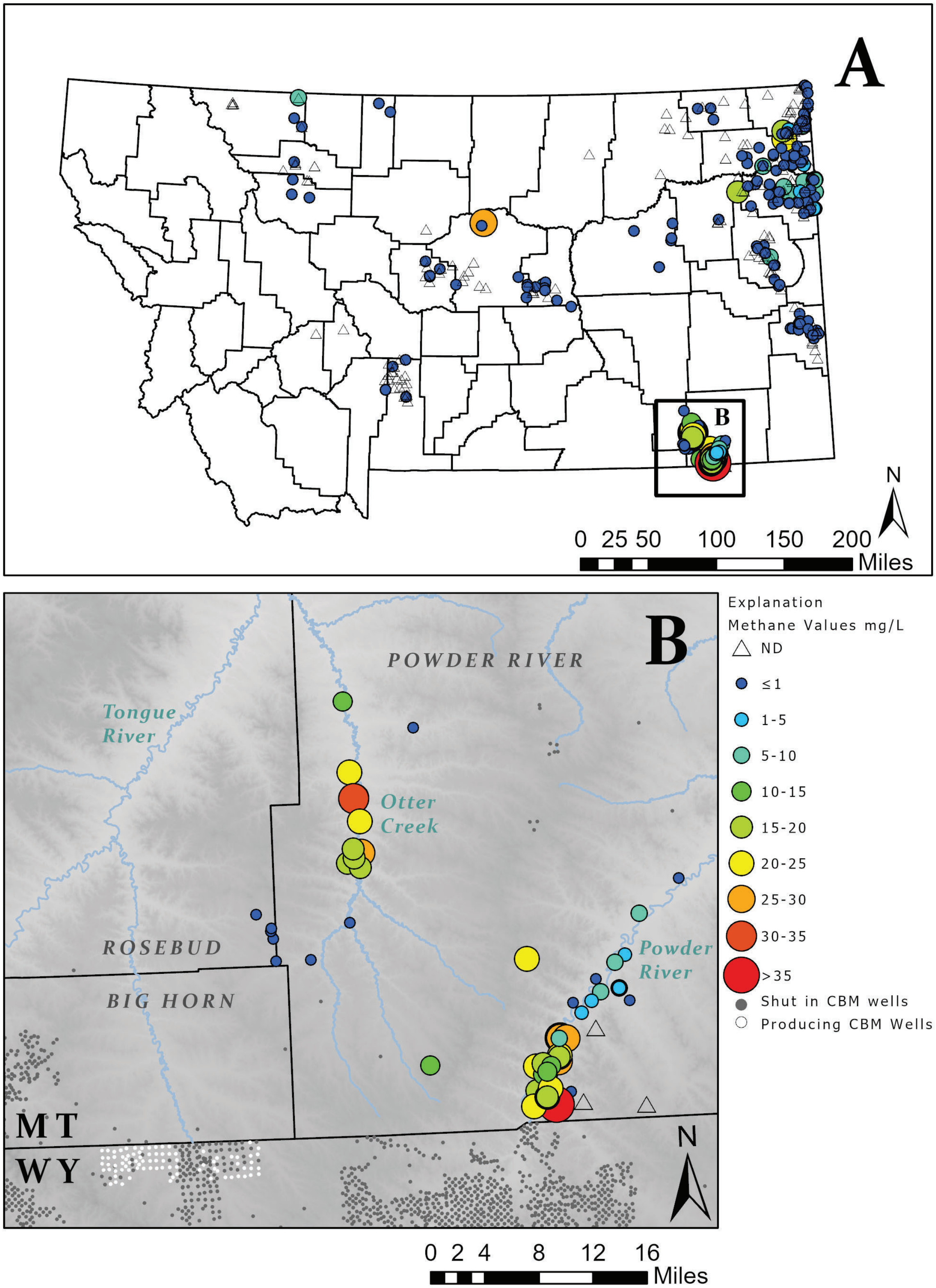

Figure 4. Dissolved methane concentrations have been analyzed in groundwater samples throughout Montana (A) and the Powder River Basin, which includes the Otter Creek and Powder River watersheds (B).

a well is in use or idle and, if known, for how long. Similarly, flowing artesian wells that are intermittently allowed to flow freely (creating a zone of lower pressure/cone of depression) and otherwise shut-in (i.e., well 283921), can create non-uniform sampling conditions.

A direct comparison between sample collection methods was made on August 31, 2015 on well 266481. Samples were collected using a direct catch method, which involved filling the sample bottle directly from the stock tank discharge, and a back-pressure method using a t-splitter and laminar flow hose

Table 2. Variability in methane sampling.

GWIC ID	Samples (*n*)	Average Methane (mg/L)	Max Methane (mg/L)	Standard Deviation	StdDev/ Ave
105735	4	24	31	4.9	0.21
105738	3	0.013	0.015	0.0017	0.13
105741	3	0.010	0.012	0.0014	0.14
191466	3	6.4	7.7	1.0	0.16
191506	3	19	21	2.4	0.12
283921	4	16	21	4.1	0.26
284310	3	7.6	8.7	0.8	0.11
284576	3	16	19	2.9	0.18
284642	6	0.020	0.027	0.0041	0.21
221592	6	14	24	5.0	0.35
223695	8	12	16	2.5	0.21
266481	4	12	37	14	1.17

Note. GWIC ID is the site identification number on the Groundwater Information Center Database: http://mbmggwic.mtech.edu/.

(fig. 2). These samples had dissolved methane concentrations of 4.0 and 9.4 mg/L, respectively. While this is only a single comparison, it demonstrates the influence of sample collection method on the analytical results of dissolved gases.

CONCLUSIONS

The highest levels of dissolved methane measured in Montana groundwater are found in the Powder River Basin. This survey has shown that collecting a groundwater sample representative of dissolved methane concentrations using existing pumps and plumbing can be difficult; therefore, this and previous sampling efforts may have results that are skewed low. However, wells with free gas presented the greatest challenge for collecting representative samples. As most areas in Montana have low levels of methane, the error associated with sampling from wells blowing high levels of gas (which creates sporadic flow from the wellhead) may not be a widespread concern. Sampling methods should focus on maintaining a full pipe of water upstream of the sample collection point, thereby minimizing exposure of the sample to atmosphere. Given the variability of the data, limited access for repeat sampling, and limited information about well/aquifer completion, this dataset does not support definitive conclusions on the source of methane in the sampled wells. This paper provides a baseline for the current conditions and the basis for future evaluations of impact from CBM production on private wells.

RECOMMENDATIONS

Coalbed-methane production in Montana and Wyoming has slowed since 2009 (Meredith and others, 2019). Wyoming coalbed-methane fields near the Powder River, in particular, had a sharp decrease in production in 2015 (Kuzara and others, 2016), and water levels in nearby wells have started to recover (fig. 5). As production slows and water levels recover from the associated drawdown, dissolved methane concentrations should, correspondingly, decrease for two reasons: (1) reduced pumping from CBM production wells will reduce the amount of liberated methane that can migrate; and (2) the increased hydrostatic pressure should reduce local desorption of methane. Future sampling efforts should include revisiting sites in areas where water levels have recovered to determine if concentrations of dissolved methane have declined.

A direct comparison of methods, including open-system collection (the method presented here), semi-closed system (an inverted sample bottle is filled under water), and a closed system (the sample is collected without contact with the atmosphere) was performed by Molofsky and others (2016). They found that sampling method affected results only for water that effervesced (bubbles formed from degassing methane). For groundwater that effervesced, the closed system sample method resulted in significantly higher measured methane concentrations as compared to the open and semi-open sample methods.

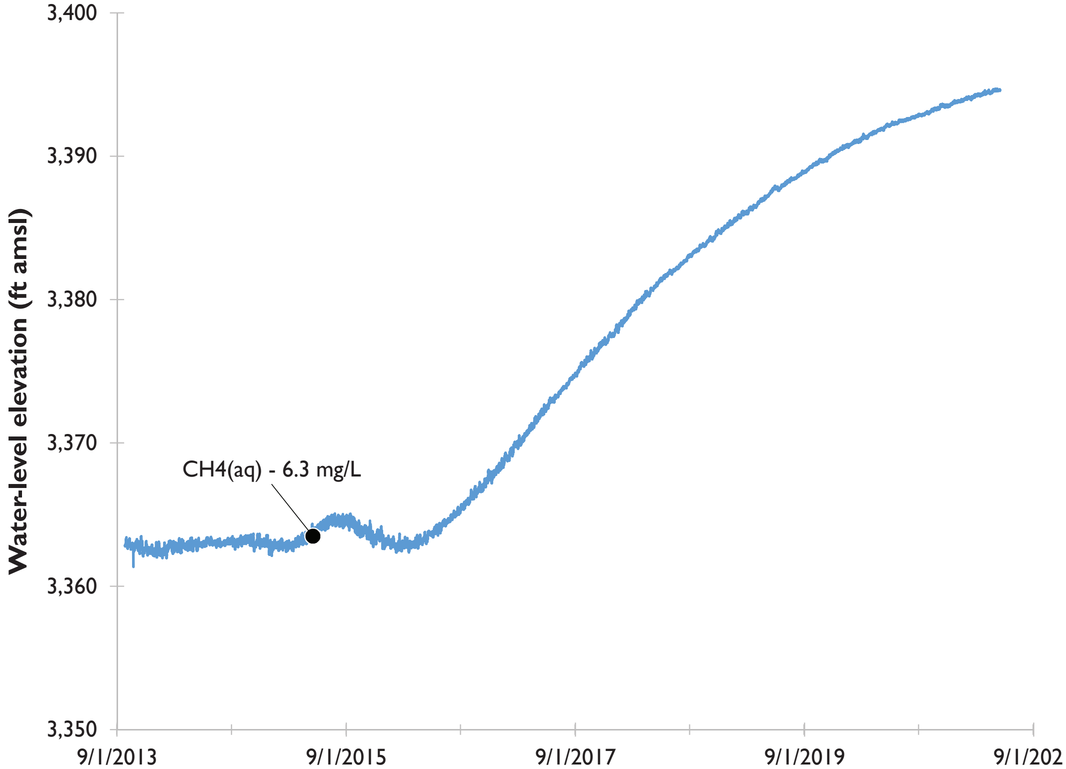

Figure 5. The water level of MBMG monitoring well 277327, near the Montana/Wyoming state line, has been increasing since Wyoming coalbed methane development slowed in 2015. Dissolved methane in groundwater from this well was 6.0 mg/L on May 18, 2015. As water levels recover, the concentration of dissolved methane may decrease.

Effervescence and free methane in wells were commonly seen in this survey of the Powder River Basin; therefore, future sampling efforts should consider a closed system as described in Molofsky and others (2016). Additionally, wells with construction and completion records and a history of water-level measurements should be prioritized for sampling, if the goal is to identify potential for CBM-related water-level drawdown or methane migration. Sampled water should also be analyzed for major ions; this information can help identify the aquifer matrix because coal and sandstone tend to have distinct geochemistry (Meredith and Schwartz, 2016).

Additional recommendations include adding a length of hose to the sample splitter such that the non-sampled discharge does not contact the atmosphere until it is away from the sample point. Given the difficulty in collecting representative samples for dissolved methane, an adequate number of quality assurance/quality control samples should be collected.

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REFERENCES

Eltschlager, K.K., Hawkins, J.W., Ehler, W.C., and Baldassare, F., 2001, Technical measures for the investigation and mitigation of fugitive methane hazards in areas of coal mining: Office of Surface Mining Reclamation and Enforcement, 125 p.

Energy Laboratories, 2022, Specific testing information for water analysis, available at https://www.energylab.com/services/water/ [Accessed April 2022].

Gotkowitz, M. (ed.), 2022, Standard procedures and guidelines for field activities: Montana Bureau of Mines and Geology Open-File Report 746, 96 p.

Koterba, M.T., Wilde, F.D., and Lapham, W.W., 1995, Ground-water data collection protocols and procedures for the national water-quality assessment program: Collection and documentation of water-quality samples and related data: USGS Open-File Report 95-399, 123 p.

Kuzara, S., Meredith, E., Wheaton, J., Bierbach, S., and Sasse, D., 2016, 2015 Annual coalbed-methane regional groundwater monitoring report, Powder River Basin, Montana: Montana Bureau of Mines and Geology Open-File Report 679, 96 p., 3 sheets.

Meredith, E., 2019, A recommended organic analyte sample set for groundwater sampling around oil and gas development: Montana Bureau of Mines and Geology Report of Investigations 26, 28 p.

Meredith, E., and Schwartz, C., 2016, Synoptic groundwater sampling on the Ashland Ranger District: Montana Bureau of Mines and Geology Open-File Report 670, 52 p.

Meredith, E., Wheaton, J., and Kuzara, S., 2012, Coal-bed-methane basics: Ten years of lessons from the Powder River Basin, Montana: Montana Bureau of Mines and Geology Informational Pamphlet 6, 29 p.

Meredith, E., Wheaton, J., Kuzara, S., and Bierbach, S., 2019, 2018 Annual coalbed-methane regional groundwater monitoring report: Powder River Basin, Montana: Multiple uses of groundwater: Montana Bureau of Mines and Geology Open-File Report 719, 1 plate.

Molofsky, L.J., Richardson, S.D., Gorody, A.W., Baldassare, F., Black, J.A., McHugh, T.E., and Connor, J.A., 2016, Effect of different sampling methodologies on measured methane concentrations in groundwater samples: Groundwater v. 54, no. 5, p. 669–680.

Montana Bureau of Mines and Geology (MBMG), 2021, Ground Water Information Center (GWIC) online database, available at https://mbmggwic.mtech.edu/ [Accessed August 11, 2021].

Montana Department of Natural Resources and Conservation (MT DNRC), 2021, Coal bed methane protection act program, available at http://dnrc.mt.gov/divisions/cardd/conservation-districts/coal-bed-methane [Accessed August 11, 2021].

Puri, R., and Yee, D., 1990, Enhanced coalbed methane recovery, paper presented at the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, September 1990, Paper SPE-20732-MS, doi: https://doi.org/10.2118/20732-MS.

Schoell, M., 1983, Genetic characterization of natural gases: AAPG Bulletin, v. 67, no. 12, p. 2225–2238.

U.S. Environmental Protection Agency (EPA), 2001, Technical guidance for the natural attenuation indicators: Methane, ethane, and ethane: U.S. EPA Region 1—New England.

U.S. Geological Survey (USGS), 2000, Coal-bed methane: Potential and concerns: USGS Fact Sheet FS-123-00.

U.S. Geological Survey (USGS), 2006a, Methane in West Virginia ground water: Fact Sheet 2006-3001.

U.S. Geological Survey (USGS), 2006b, National field manual for the collection of water-quality data: Collection of water samples: U.S. Geological Survey Techniques of Water-Resource Investigations, Handbooks for Water-Resource Investigations, book 9, chap. A4, 231 p.

APPENDIX A:
DISSOLVED METHANE RESULTS

Appendix A: Dissolved methane results.

GWIC ID	Location (NAD 83)		Depth (ft.)	Sample Date	Methane (mg/L)
	Latitude	Longitude			
8012	45.22277	-106.16699	225	8/6/2019	0.046
104244	45.28637	-106.16645	455	8/1/2018	18
105048	45.25468	-105.66539	1283	6/4/2015	0.027
105057	45.21901	-105.72803		6/4/2015	6.6
105079	45.17521	-105.75285	921	7/28/2015	3.8
105720	45.15105	-105.79812		6/4/2015	0.0070
105731	45.12639	-105.83476	325	6/4/2015	0.012
105735	45.08938	-105.85653	330	4/13/2015	31
				6/3/2015	18
				3/2/2016	21
				6/7/2018	26
105738	45.14007	-105.76384	330	7/28/2015	0.012
				4/7/2016	0.015
				5/3/2018	0.011
105741	45.12638	-105.74893	340	7/28/2015	0.0087
				4/7/2016	0.012
				5/3/2018	0.0094
144496	45.38379	-106.15779	320	6/11/2019	23
144969	45.23543	-106.30815	225	9/9/2014	0.0030
153457	45.03135	105.84344	140	8/6/2015	0.49
191466	45.16751	-105.76840	710	7/29/2015	6.2
				3/1/2016	5.2
				5/3/2018	7.7
191506	45.06941	-105.85937	450	4/13/2015	21
				5/4/2016	16
				6/7/2018	21
197194	45.06612	-106.05467	1038	8/20/2015	15
198977	45.21741	-106.28723	spring	9/9/2014	0.0014
217431	45.42867	-106.05779	260	9/6/2019	0.21
221592	45.17590	-105.90094		5/6/2015	8.9
				6/2/2015	15
				8/31/2015	11
				3/1/2016	11
				5/2/2017	24
				6/7/2018	16
223695	45.05411	-105.87794	1000	5/6/2015	9.4
				6/3/2015	11
				7/29/2015	9.1
				10/8/2015	9.0
				3/1/2016	14
				4/5/2017	14
				5/3/2018	11
				6/7/2018	16
226673	45.06390	-105.87170	575	4/13/2015	15
				3/1/2016	0.97
255445	45.45995	-106.16312	380	9/6/2019	12
264809	45.05981	-105.87717	680	10/8/2015	12
				3/2/2016	13
265113	45.06026	-105.89523	410	11/4/2015	25
265115	45.06313	-105.88435	300	6/23/2016	16
266481	45.01836	-105.86652	300	5/7/2015	0.96
				7/27/2015	7.2
				8/31/2015	4.0/9.4*
				5/3/2018	37
275410	45.18461	-106.22812		9/9/2014	0.0025
275414	45.20892	-106.28401	Spring	9/9/2014	0.0025
275415	45.22007	-106.28585		9/9/2014	0.0011
277326	45.01637	-105.90370	423	5/18/2015	12
277327	45.01637	-105.90370	115	5/18/2015	6.0
283919	45.59359	-106.27594		11/3/2014	0.023

Appendix A, *continued*.

GWIC ID	Location (NAD 83) Latitude	Location (NAD 83) Longitude	Depth (ft.)	Sample Date	Methane (mg/L)
283921	45.03609	-105.87459	575	4/13/2015	15
				6/2/2015	9.6
				5/2/2017	17
				5/3/2018	21
283928	45.02726	-105.87988		3/5/2015	17
				6/2/2015	12
284284	45.12774	-105.80659	400	7/28/2015	0.012
				5/3/2018	0.011
284310	45.13710	-105.79171		7/28/2015	7.1
				3/1/2016	6.9
				5/3/2018	8.7
284527	45.06623	-105.85991		4/14/2015	22
284549	45.06580	-105.86168	67	4/14/2015	24
284576	45.08883	-105.84683		4/14/2015	19
				6/3/2015	12
				7/29/2015	17
284642	45.11560	-105.82237		4/14/2015	0.019
				6/2/2015	0.013
				7/29/2015	0.020
				4/7/2016	0.020
				6/7/2017	0.027
				5/3/2018	0.022
284643	45.02046	-105.82559		7/27/2015	ND

GWIC ID	Location (NAD 83) Latitude	Location (NAD 83) Longitude	Depth (ft.)	Sample Date	Methane (mg/L)
284650	45.09873	-105.80181		8/6/2015	ND
284675	45.01432	-105.73069		8/6/2015	ND
285346	45.03410	-105.89549	130	10/6/2015	19
285614	45.05098	-105.88451		5/6/2015	7.6
				7/27/2015	14
287233	45.33110	-106.14513	440	8/2/2018	24
287396	45.08917	-105.85776		5/5/2016	9.6
287518	45.29725	-106.14516	480	6/12/2019	27
287678	45.02681	-105.87978	560	6/23/2016	22
				6/6/2018	15
287734	45.0647	-105.86041	420	6/24/2016	26
				6/6/2018	19
287735	45.08894	-105.84696	400	6/23/2016	26
				6/6/2018	20
292673	45.35438	-106.14535	320	9/8/2019	1.1
293470	45.07059	-105.85808	650	5/3/2017	19
				6/7/2018	21
294765	45.30157	-106.15688	525	5/2/2019	16
298220	45.0599	-105.87199	325	9/5/2018	15
298265	45.0691	-105.85911	600	9/5/2018	20
298956	45.28130	-106.14703		8/1/2018	20
301864	45.35653	-106.15046		6/12/2019	26
302681	45.35545	-106.15262		9/8/2019	32

Note. GWIC ID is the site identification number on the Groundwater Information Center Database: http://mbmggwic.mtech.edu/. Well depths are noted if known. ND (non-detect) indicates the methane concentration of the sample is below the laboratory reporting limit of 0.0010 mg/L.
*Two samples were collected on this date: direct discharge (4.0 mg/L) and providing back pressure (9.4 mg/L).