Measurements of elevated total dissolved gas pressure in an Albertan groundwater monitoring well

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ABSTRACT
Interest in measuring total-dissolved-gas-pressure (TDGP) of groundwater in Alberta is increasing due to concerns about potential effects of coal-bed methane development on shallow aquifers and the use of natural attenuation to treat groundwater affected by petroleum hydrocarbons. There is currently little guidance on the most appropriate procedure for making these measurements. Continuous measurement of TDGP in a monitoring well, with the use of an inflatable packer to seal the well screen from the atmosphere, suggests that groundwater may be degassing via the well and that it may take several weeks or more to achieve a representative value.

RÉSUMÉ
On s'intéresse de plus en plus à la mesure de la pression-du-gaz-total-dissous (PGTD) des eaux souterraines de l'Alberta en raison des préoccupations que suscitent les effets possibles de la mise en valeur du méthane de houille sur les aquifères peu profonds et l'utilisation de l'atténuation naturelle pour traiter les eaux souterraines contaminées par des hydrocarbures pétroliers. Il existe peu de lignes directrices à l'heure actuelle sur la méthode de mesure la plus appropriée. La mesure continue de la PGTD dans un puits de surveillance, au moyen d'une garniture gonflable qui isole le filtre de puits de l'atmosphère, porte à croire que les eaux souterraines peuvent se dégazer par le puits et qu'il faudra peut-être plusieurs semaines ou plus pour obtenir une valeur représentative.

1 INTRODUCTION

The importance of dissolved gases in groundwater has increased over the past decade. For instance, the recent development and rapid growth of the coal bed methane (CBM, or natural gas from coal) industry in Alberta has raised public concerns over natural gas migration into shallow aquifers. Hydraulic fracturing and pumping associated with CBM wells have the potential to initiate or augment methane migration to shallow aquifers. Methane in groundwater can pose an explosion and asphyxiation risk during extraction of well water or by escaping into basements, well pits, etc. However, the determination of whether methane gas has migrated from CBM-targeted formations to shallow aquifers is complicated by the fact that methane can be generated within these shallow aquifers through bacterial reactions (Aravena & Wassenaar, 1993). In addition, there can be leaks from operating or abandoned conventional gas wells to shallower depths (e.g. Coleman et al., 1977; Erno and Schmitz, 1994). Thus, to better understand the background groundwater gas conditions in the province, Alberta Environment (AENV) initiated a program with industry of baseline water well testing for areas targeted for CBM development and a sampling cycle of their existing monitoring well network.

In addition, degassing of groundwater has been reported during the natural remediation of petroleum hydrocarbon groundwater plumes (e.g. Amos et al., 2005). This behaviour may affect microbial degradation rates dependent on the transfer of electron acceptors such as oxygen. In addition, gas bubble formation may occur and reduce the permeability (more than an order of magnitude, based on numerous gas trapping studies) and, thus, water flow through the plume. Degassing may also enhance the transport of volatile contaminants to the vadose zone, potentially affecting vapour transport to soils or buildings. Together, these processes are likely to exert significant control over the extent and persistence of hydrocarbon groundwater plumes. There is also some potential that they are also occurring in groundwater affected by oil sand tailings ponds, which can contain elevated levels of dissolved organic compounds. However, the mechanisms of gas formation and potential movement (ebullition) in aquifers, and contaminant plumes especially, are currently not well understood. A better understanding of these gas processes will provide the opportunity to improve existing remediation strategies or to develop new ones.

The most common methodology for determining dissolved gas conditions of groundwater involves gas and water collection from "open" boreholes or piezometers – one time or periodically. Gas volume and gas composition (molar ratios), from gas samples or gas extracted from water samples, are measured. This method requires proper well purging, alters the water pressure conditions and likely leads to degassing losses (McLeish et al., 2007). Recently, Manning et al. (2003) reported on the use of dissolved gas pressure sensors for providing valuable in situ and real-time information on dissolved gas conditions of groundwater. This method may also minimize analytical costs. However, there is still a lack of information on the proper use of this technology for groundwater monitoring. Two major concerns are i) the potential for continuous degassing losses from groundwater via the well; and ii) the possible transient nature of the dissolved gas pressure. Both have serious implications for how much measurements are representative of the conditions within the aquifer.

The goal of this preliminary study was to assess the legitimacy of these concerns (i.e. determine whether groundwater dissolved gas pressure monitoring of wells requires a more in-depth investigation). The test well for this work was an Alberta Environment (AENV) monitoring well in Rosebud, Alberta, which is known to be 'gassy'. A down-hole probe with total dissolved gas pressure (TDGP) sensor and data-logging capabilities was used to make continuous and long-term measurements. Also, an inflatable borehole packer was installed in the well for part of the monitoring period to isolate the groundwater from the atmosphere, thus preventing any potential degassing losses.

2 TDGP DEFINITION

A gas dissolved in a given liquid will exert a set partial pressure (p_i) to a gas phase with which it is in equilibrium, as described by Henry's Law:

$$H_i(T,S) = \frac{C_i}{p_i} \qquad [1]$$

where H_i is Henry's law constant for gas i and is a function of temperature (T) and salinity (S); and C_i is the concentration of dissolved gas i. H_i is assumed independent of hydrostatic pressure (or depth of water).

Total dissolved gas pressure is the sum of all partial pressures of each individual gas species present, i.e. TDPG = $\Sigma\, p_i$, as stated by Dalton's law of partial pressures. Common units for TDGP and their conversions are: 1 atm = 101.3 kPa = 10.33 m water = 760 mm Hg.

Gas composition (molar ratios) can be determined from lab-estimated groundwater gas concentrations of gas or water samples. However, these need to be multiplied by TDGP in order to estimate an actual 'in-situ' dissolved gas concentration (McLeish et al., 2007). In other words, groundwater dissolved gas concentrations are proportional to TDGP.

Total dissolved gas pressure is also an important parameter in gas bubble formation and growth. Generally, the TDGP must exceed the sum of the hydrostatic pressure and the capillary pressure (which involves interfacial forces and pore properties) for a bubble to form in an aquifer. Additional nucleation thresholds may also come into play (Jones et al., 1999). However, as a first approximation, gas bubbles are unlikely to be present until the TDGP is greater than the hydrostatic pressure. Note also that bubble formation and growth will act to lower the TDGP of the surrounding water.

Thus, measurement of the pressure of the gas in an incompressible TDGP sensor chamber in equilibrium with dissolved gases in the groundwater will provide information on the general state of the groundwater gases and be used to calculate the concentrations of specific dissolved gases.

3 STUDY SITE

The well of interest is located in the town of Rosebud, Alberta, (N 51.181°, W 112.569°) and is part of the AENV Groundwater Observation Well Network (GOWN). According to the well installation report (Blyth, 2007), the well was completed in the Horseshoe Canyon Formation of the Late Cretaceous Edmonton Group. The surface elevation is 793 m.a.s.l. and the total depth is 55.34 m. The well is composed of 12.5-cm (outer diameter) PVC liner with a 2.74-m section of 20 slot machined screen at the end. The screened interval includes a coal seam, likely less than 1 m thick, shale and fine-grained sandstone. The apparent well yield after development was approximately 2.5 litres per minute. Dissolved gas measurements conducted by Alberta Environment (personal communication) indicate that the dissolved gas is predominantly methane, with minor nitrogen gas.

4 METHODOLOGY

A down-well minisonde (Hydrolab), with sensors for total dissolved gas pressure (TDGP), dissolved oxygen (DO, with LDO sensor), pH, electrical conductivity, temperature and water pressure, and a meteorological station (Environment Canada), with sensors for barometric pressure, rainfall, air temperature and humidity, were installed at the site in October, 2007. The minisonde was powered by internal batteries, so no surface connection was required. Data were logged continuously at an interval of 0.25 to 3 hours. The sonde was replaced with a duplicate sonde and data downloaded every 2 to 5 weeks. Sondes were calibrated in the lab before each deployment. The TDGP membranes were also dried periodically as per the manufacturer's recommendations. Well water level, measured manually with a water level tape (Solinst), was usually about 13.2 m below ground surface.

The minisonde was positioned in the well such that the sensors were in the top third portion of the well screen (Fig. 1). It was suspended using stainless steel wire from the bottom of the core of the inflatable packer (Roctest) or from the well cap (when the packer was not installed; this set-up not shown in Fig. 1). When installed, the packer was connected to the well cap by stainless steel wire. The rubber gland of the packer was inflated using compressed air or nitrogen through a polyethylene tube connected to surface. This line was also connected to a pressure transducer on the meteorological station for monitoring inflation pressure. The packer core was capped top and bottom, so when the gland was inflated, the packer sealed the well screen area from the water and air in the well above. Water level measurements above the packer indicated no apparent leakage during the intervals it was inflated. The packer and attached minisonde were raised and lowered in the well, for installation, removal or to allow for downloading data, using a winch-pulley system.

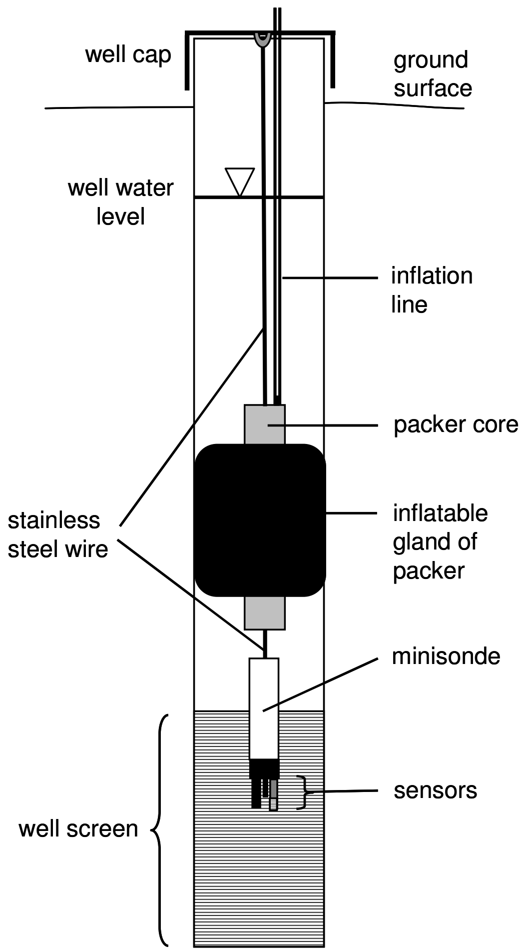

Figure 1. Schematic of the monitoring well set-up with the packer was installed and inflated. When not inflated, the gland of the packer would not touch the well wall around its entire circumference. Not to scale.

5 RESULTS AND DISCUSSION

Significant changes in TDGP and DO were caused by the recovery and redeployment of the minisondes (Figure 2). The sharp changes represent the transition from atmospheric conditions and the initial equilibration period after the probe has been re-immersed in the well water. The TDGP typically increased rapidly from atmospheric pressures (around 680 to 700 mm Hg) over 1 to 3 hours. Probe equilibration times are generally reported as 5 to 20 minutes (Manning et al., 2003), but this applies to water that is circulated or agitated (e.g. moving the probe in the water column). This was not possible for this probe-well set-up, so longer equilibration times are expected. Following the initial equilibration period, the TDGP changed slowly and, generally, smoothly (Fig. 2), showing little response to fluctuations in barometric pressure (not shown). However, the TDGP values did not return to their previous level following the removal and re-deployment of the minisonde, which likely indicates some mixing of water within and degassing from the well due to the retrieval activities.

The temporal pattern for DO following each minisonde deployment was opposite that of the TDGP, with concentrations decreasing over time following an initial spike (Fig. 2). The groundwater DO reached near-zero values (below the detection limit of about 0.13 mg L^{-1}) relatively quickly and remained at those levels until the next deployment, indicating that this part of the aquifer was likely anaerobic. This is in agreement with the dissolved gas composition, of predominantly methane with a small fraction of nitrogen gas, obtained by Alberta Environment. Together with the high TDGP readings, these conditions could represent substantial methanogenesis, although methane gas transport from a different source cannot be ruled out.

The short-lived spikes in DO concentrations (Fig. 2) may indicate mixing occurring within the well, oxygen uptake, potentially by microbes in the region around the well screen, or even gas exchange occurring with the TDGP sensor. Further investigation is required to address this issue.

This monitoring well exhibited substantially higher TDGP values than the maximum values reported for groundwater in the literature, although few studies have employed groundwater TDGP measurements. The pertinent details of these studies are given in Table 1. Calculations of dissolved gas concentrations based on literature values or, more likely, assuming atmospheric pressure, would be low by between 1.5 to 3 times. It is also note-worthy that the TDGP measured in this study (Fig. 2) reached values over the range provided by most commercially-available sensors (about 1500 mm Hg) and has almost reached the limit for this sensor (2400 mm Hg).

Table 1. Measurements of total dissolved gas pressure (TDGP) of groundwater reported in the literature and this study.

Study	*TDGP (atm)*	*TDGP (mm Hg)*	*Well / aquifer conditions*
Manning *et al.*, 2003	1.65	1250	Air-rotary drilling – air entrapment
McLeish *et al.*, 2007	1.3	1000	Wells with CO_2 and CH_4
Visser *et al.*, 2007	> 2*	> 1500*	Denitrification (N_2 produced)

This study	3.1	2360	Well with CH_4; still increasing

* maximum probe limit

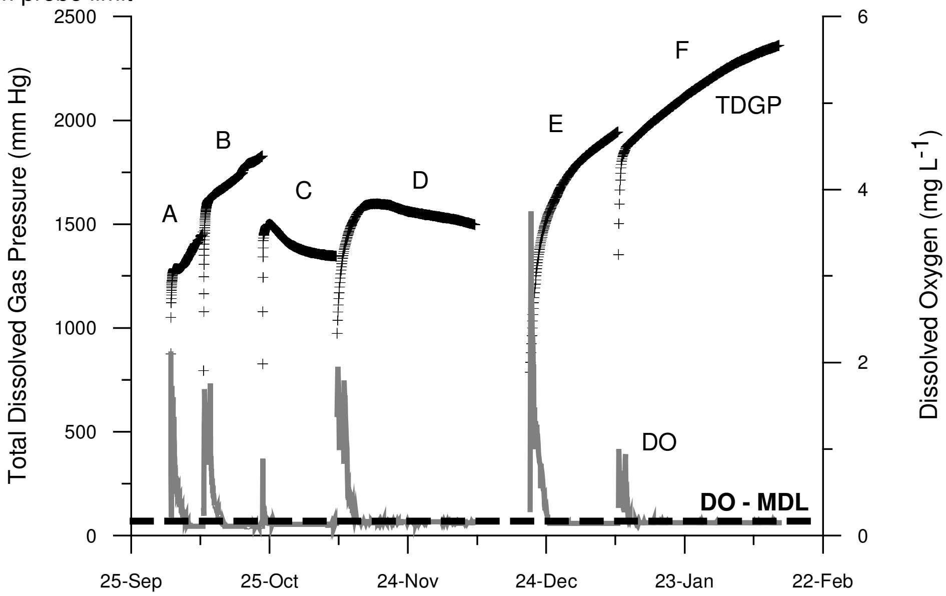

Figure 2. Groundwater properties total dissolved gas pressure (TDGP - symbols) and dissolved oxygen (DO – grey line) as measured by the minisonde in the screened section of the Rosebud monitoring well. Note the minimum detection limit (dotted horizontal line) for the dissolved oxygen sensor (DO - MDL). Deployment periods are indicated by letters corresponding with the conditions outlined in Table 2.

As noted above, for gas bubbles to occur, the gas pressure in the bubbles, and thus the equilibrated TDGP, generally must be greater than the water pressure. The water pressure at the minisonde sensors was approximately 2870 mm Hg (equivalent to 39 m of water). The maximum measured TDGP in the well was less than this water pressure (Fig. 2), so it is unlikely that any bubbles had formed on the probe at this depth to date. Since the measured TDGP may not yet have reached values representative of the aquifer, there could be gas bubbles in the aquifer. In addition, gas bubbles could have been forming higher in the water column within the well (where the water pressure is lower, though TDGP may be lower too), potentially degassing the well water. Of note, degassing / bubbling noises were heard from the well on the date of initial minisonde-packer installation.

To quantitatively investigate the potential for degassing of groundwater through the well itself, TDGP was measured for time intervals when the well was sealed (inflated packer) and unsealed. The TDGP results for each monitoring period are plotted versus deployment time in Figure 3. The conditions for each period are outlined in Table 2. In comparing the monitoring periods when the packer was inflated (first two and last two) versus those it was not inflated (middle two), the data show a difference in the temporal trends. TDGP increased over the period with the packer inflated towards an asymptotic value that was not reached in our monitoring, but decreased with time (after initial probe equilibrium increase), when the packer was not deployed (period C) or when it deflated during deployment (period D). The decline for the period of Nov. 8 to Dec. 8 was not as rapid, likely because the packer, though deflated, was still in the well and was able to reduce the circulation within the well. This suggests that the well water is degassing when the packer is not in place and inflated, and that measurements made in an unsealed well may not be representative of conditions in the aquifer away from the well.

Table 2. Details on each deployment of the minisonde.

	Deployment period	*Conditions*
A	Oct 3 – Oct 10	Packer installed and inflated (first time for this well)
B	Oct 10 – Oct 23	Packer inflated
C	Oct 23 – Nov 8	Packer removed – open well condition
D	Nov 8 – Dec 8 $^{\xi}$	Packer installed, but it deflated on the 2nd day
E	Dec 20 – Jan 8 $^{\xi}$	Packer inflated
F	Jan 8 – Feb 12	Packer inflated

ξ minisonde position was about 25 cm lower in well screen

Considering only the monitoring periods with the packer inflated (periods A, B, E, F; Figs 2 and 3) the the TDGP values tended to increase over subsequent monitoring intervals (i.e. with greater total time that the well was sealed from the atmosphere). This suggests that single-day samples may not be representative of the actual aquifer conditions. Rather, long-term monitoring or measurements following long-term packer deployment may be required. As the TDGP values do not appear to have reached a constant value (Fig. 2), the time required to achieve equilibrium with the aquifer conditions for the Rosebud well cannot currently be determined.

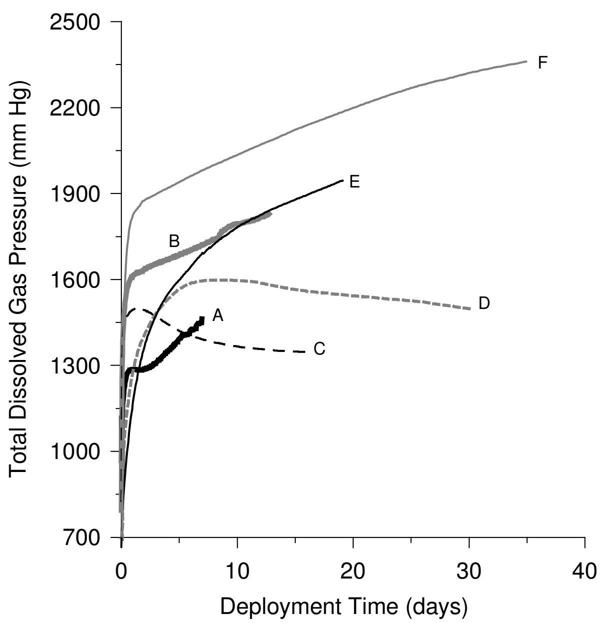

Figure 3. Total dissolved gas pressure of groundwater in the screened section of the Rosebud monitoring well, for each monitoring. See Table 2 for details. Solid lines indicate deployment periods with continuous packer inflation, dashed lines are deployments without packer inflation.

Finally, the minisonde data also show that the rise in TDGP after deployment was not as steep for the intervals Nov.8-Dec.8 and Dec.20-Jan.8 (periods D and E, thin black and dotted grey lines). The packer was installed for both intervals, but was not inflated for period D. However, we do not suspect that this is a degassing issue. One difference for both of these intervals compared to the other four is that the minisonde was positioned at a slightly lower (about 25 cm) depth in the well screen. Thus, the difference in the rate of TDGP increase (equilibration time) may indicate that there are differences in the flushing at different positions along the well screen. This may indicate variation in the groundwater flow through different layers (e.g. coal versus shale). If this is the case, then this finding indicates that the TDGP sensor is sensitive to such differences, and that monitoring position within the well screen may be an important consideration. However, further study is required before a definitive statement can be made on this effect.

6 POTENTIAL IMPLICATIONS

These observations indicate that TDGP of Albertan groundwater can be higher than generally assumed or for the few reported measurements in the literature. This suggests that lab-determined groundwater gas concentrations (those not adjusted for elevated TDGP) may underestimate actual concentrations by more than three times, raising concerns about how the dissolved gas conditions in aquifers are currently measured. Thus, there is a need to develop continuous monitoring technology for long-term deployment in sealed wells (e.g. with inflatable packer), to provide improved information on a key set of groundwater conditions. This may lead to better decision-making or regulations concerning coal-bed methane activities. This may also have implications for managing or enhancing natural attenuation of petroleum-impacted groundwater. Outcomes of this include a more secure environment and cleaner groundwater for both people and local ecosystems.

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