Installation of a Purpose-Built Groundwater Monitoring Well Network to Characterize Groundwater Methane in the Peace Region, Northeastern British Columbia (NTS 093P/09–16, 094A/01–08)

B. Ladd, The University of British Columbia, Vancouver, British Columbia, bladd@eoas.ubc.ca

A.G. Cahill, The Lyell Centre, Heriot-Watt University, Edinburgh, Scotland

M. Goetz, The University of British Columbia, Vancouver, British Columbia

A. Allen, Simon Fraser University, Burnaby, British Columbia

L. Welch, British Columbia Oil and Gas Commission, Kelowna, British Columbia

B. Mayer, University of Calgary, Calgary, Alberta

C. van Geloven, British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development, Prince George, British Columbia

D. Kirste, Simon Fraser University, Burnaby, British Columbia

R.D. Beckie, The University of British Columbia, Vancouver, British Columbia

Ladd, B., Cahill, A.G., Goetz, M., Allen, A., Welch, L., Mayer, B., van Geloven, C., Kirste, D. and Beckie, R.D. (2020): Installation of a purpose-built groundwater monitoring well network to characterize groundwater methane in the Peace Region, northeastern British Columbia (NTS 093P/09–16, 094A/01–08); *in* Geoscience BC Summary of Activities 2019: Energy and Water, Geoscience BC, Report 2020-02, p. 131–144.

Introduction

Western Canada has experienced rapid oil and gas development over recent decades, particularly involving the exploitation of unconventional resources such as shale oil and gas. In British Columbia (BC) alone, approximately 15 000 wells have been drilled since 2000, 64% of which are hydraulically fractured natural gas wells (BC Oil and Gas Commission, 2018; E. Sandl, pers. comm., 2018). Concerns about environmental impacts from such activities have grown alongside this development, with a particular focus on fugitive gas migration (Council of Canadian Academies, 2014). Environmental impacts associated with fugitive gas, composed primarily of methane (Darrah et al., 2014), include degradation of groundwater quality (Kelly et al., 1985; Van Stempvoort et al., 2005; Cahill et al., 2017), explosive risk and greenhouse gas emissions (Vidic et al., 2013; Bachu, 2017; Forde et al., 2019a).

In particular, groundwater methane is a topic of great interest and concern in areas of intensive oil and gas development. Due to methane's ubiquitous natural presence in groundwater, it can be difficult to delineate and distinguish dissolved methane sources and distribution, and assess if elevated levels bear any relation to oil and gas activity (e.g., Osborn et al., 2011a, b; Saba and Orzechowski, 2011). This is particularly true in regions where little or no baseline information is available, which is typically the case. Current limitations in resolving the origins and nature of elevated dissolved methane in regions of petroleum resource development include 1) a lack of baseline data and 2) general reliance on domestic well data, which may introduce data biases and uncertainties (e.g., missing or unreliable well construction information, unregulated sample collection points, maintenance issues, etc.). Overall, great uncertainty persists regarding the true extent of impacts from fugitive gas due to a lack of conclusive data and systematic monitoring.

In this project, the aim is to address such uncertainties in the Peace Region of northeastern BC, an area of intensive historical conventional and ongoing unconventional development. Key aims of the project are to determine current groundwater quality in the Peace Region with a specific focus on the distribution, concentration and origin of dissolved methane. Ultimately, the project aims to characterize groundwater systems across the Peace Region and provide insights to assess potential anthropogenic impacts to groundwater from oil and gas development and related activities. The key aims will be achieved by 1) installing a dedicated, targeted, purpose-built and scientifically designed groundwater monitoring well network proximal to energy wells for collecting samples to be analyzed for all major aqueous chemistry parameters (including dissolved

---

This publication is also available, free of charge, as colour digital files in Adobe Acrobat® PDF format from the Geoscience BC website: http://www.geosciencebc.com/updates/summary-of-activities/.

methane), and 2) installing a portion of these wells in areas distant from oil and gas development to assess baseline groundwater conditions in the region. Through the drilling (including high-resolution geological logging and sampling of sediment core) and installation of a groundwater well network followed by regular, systematic geochemical sampling, data will be collected to determine methane distribution and origin and its potential relationship to oil and gas activity in the Peace Region. Additionally, as a legacy the installed groundwater monitoring infrastructure will be available for ongoing assessment of cumulative effects in the context of continued natural gas development in the region over the coming decades and provide a platform for future research activities.

This paper describes the installation of the network and initial sampling program. Installation began in the summer of 2018 and was completed in the fall of 2019, with a total of 29 monitoring wells in the network. The first round of groundwater samples from the completed network was collected after the final wells were drilled and developed; laboratory analytical results are currently pending. This paper explains the design, planning and logistics for the monitoring network installation, with details on project stages including a) desktop studies, field reconnaissance and permission process; b) drilling logistics and methods, core logging and sampling, and well completions; and c) water sampling conducted to date and plans for the future. The data collected from these wells will complement existing domestic and monitoring well data, and will be used to create a comprehensive, robust and scientifically defensible groundwater dataset from which policy and regulation can be informed.

Background

Fugitive Gas Migration

Fugitive gas migration occurs when natural gas from target or intermediate formations is unintentionally mobilized in the subsurface during oil and gas development activities; usually as a result of wellbore integrity failure or other casing issues (Cahill et al., 2019). Fugitive gas primarily consists of methane (Darrah et al., 2014) and can travel to ground surface where it may manifest as bubbling around the wellhead or stressed vegetation, or often, go undetected (Briskin, 2015; Province of British Columbia, 2018; Forde et al., 2019b). The number of oil and gas wells with gas migration in Canada is not well known, but the current documented percentage of gas migration occurrences is 0.58% (out of more than 25 000 wells) and 0.73% (out of more than 300 000 wells) in BC and Alberta, respectively (Bachu, 2017; E. Sandl, pers. comm., 2018). Current documentation may not reflect the true extent of the problem, as identifying gas migration is often dependent on the effort and resources spent to do so (e.g., Forde et al., 2019b). Fugitive gas migration is an existing and potentially growing problem, which requires somewhat urgent consideration as the population of active and inactive energy wells across Canada and the world continues to grow, and age, with more cases of leakage almost certain to manifest in the future.

Geological Setting

The project area is a subset of the Peace Region, which is located in the northeastern portion of BC, with an average elevation of 610 m. The Peace Region is situated primarily within the Alberta Plateau of the Interior Plains physiographic subdivision of BC (Holland, 1964). In this area, the plateau has been dissected by the Peace River forming the Peace River Lowland (Holland, 1964). It is of low relief with flat to gently undulating terrain. It includes the communities of Fort St. John to the north, Dawson Creek to the east and Chetwynd to the west and Tumbler Ridge to the south of the project area. There are six main rivers flowing within the area. They are the Peace, Pine, Murray, Halfway, Beatton and Kiskatinaw rivers, serving to divide both the overall Peace Region and the project area into five watersheds. The climate is characterized by long cold winters and short warm summers with mean annual temperatures below 0ºC in the northern valleys. The average annual precipitation is estimated between 350 and 500 mm with approximately 200 mm falling as snow (Schaefer, 1978; Environment and Climate Change Canada, 2019). The region soils are dominated by luvisols, and land cover consists of forest, grasslands and cultivated areas. Topography includes mountainous terrain in the south and west, capturing a small portion of the Rocky Mountain Foothills, and a relatively flat area in the northeastern portion (Holland, 1964; Catto, 1991).

Installation of the Energy and Environment Research Initiative Groundwater Monitoring Well Network

Overview

Commencing in August 2018 and ending in September of 2019, a regional groundwater monitoring well network was installed in the Peace Region consisting of 29 monitoring well stations (Figure 1). The project area was chosen as a subset of the Peace Region that encompassed major population centres and areas of both historical and ongoing resource development. Drilling and associated activities were contracted to third parties, and all other work was carried out primarily by The University of British Columbia's Energy and Environment Research Initiative (EERI) Monitoring Well Installation Project (MWIP) team, in particular M.Sc. students M. Goetz and A. Allen. Significant support was provided by BC Oil and Gas Commission, BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development, and Geoscience BC personnel. Local

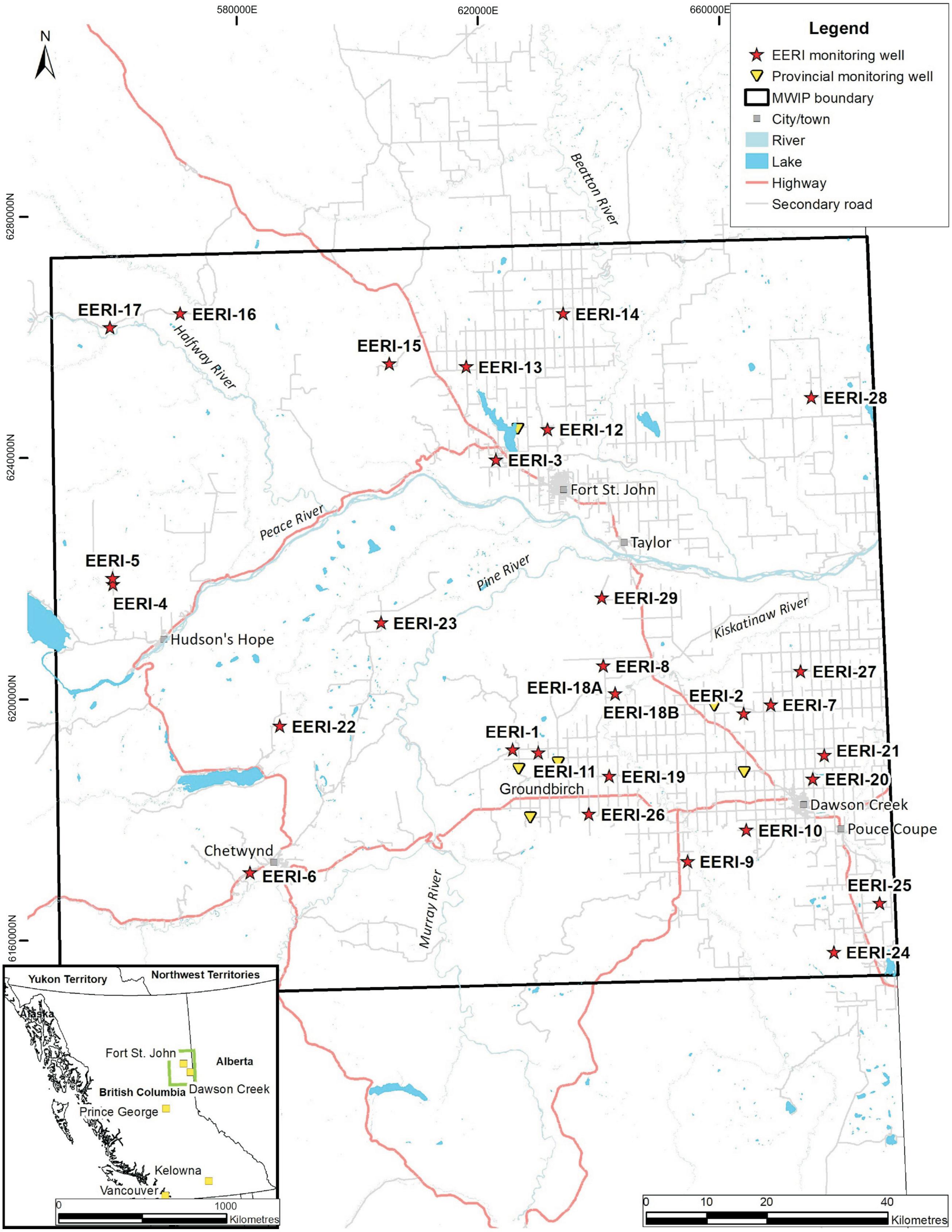

Figure 1. The project area (black outline) and the locations of the 29 Energy and Environment Research Initiative (EERI) monitoring well stations (stars). Abbreviation: MWIP, Monitoring Well Installation Project.

community and government consultation was sought throughout.

Table 1 provides an overview of well details, including location, completion details, and relation to nearby energy and domestic water wells. Nine out of the 29 monitoring well stations are baseline stations, whose purpose are to provide data for understanding the baseline groundwater geochemistry in the region, including determining baseline levels of dissolved methane. The other 20 stations are proximal stations, which were positioned in areas of high energy well density based on a set of criteria. One station, EERI-18, contains two wells, EERI-18A and EERI-18B, which have different well installations, the second to accommodate a Westbay Instruments (Westbay) installation (see 'Westbay Multilevel Installations' section for more detail). Further information on site selection and installation of the well network will be reported in subsequent sections.

Pre-Drilling Planning and Preparation

Well Selection Criteria

At the outset of the project, the MWIP team set a goal of approximately 30 wells for the network in consideration of budgetary and other logistical factors. A general framework was developed as a starting point to locate well sites, with the foremost stipulation being that about one third of the wells would be baseline wells and the rest proximal wells. General criteria that applied to all wells included factors such as

- regional coverage within the project area—spatially and geologically representative;
- hydrogeological considerations such as targeting topographic lows in order to capture representative samples of more evolved groundwater in nonrecharge areas, locating paleovalleys and targeting areas of low drift thickness, and using available domestic and provincial groundwater well resources to increase chances of penetrating groundwater zones;
- reasonable road access and preference for sites on Crown land for ease of permissions and continued long-term access; and
- consideration of provincial observation well locations to avoid duplication.

The main criteria used to classify wells as baseline and proximal were the distance from the nearest energy well and the density of energy wells within a 3 km radius. For baseline wells, the following initial criteria were used as guidelines for siting the wells:

- primarily, preferably no closer than 1.5 km from an energy well, with 1 km as a stricter bound (one groundwater monitoring well became an exception to this criterion);
- secondarily, energy well density should be kept to a minimum in the surrounding 3 km radius; and
- an effort was made to select a portion of baseline sites within 0.5–1 km distance from an existing water well (domestic or provincial), which was assigned a paired status as opposed to an unpaired status.

For proximal wells, the following initial criteria were used as guidelines for siting the wells:

- less than 400 m from the surveyed location of an energy wellhead (as close as logistically possible);
- maximize energy well density in the surrounding 3 km radius; and
- as much as possible, given the small quantity of EERI proximal groundwater monitoring wells compared to the number of energy wells in the project area (approximately 7580 energy wells; BC Oil and Gas Commission, 2019), the closest energy wells to EERI proximal wells should provide a general representation of the overall energy well population in the project area, which includes consideration of well status (active/abandoned/orphaned), orientation (vertical/horizontal/deviated), and fluid type (gas/oil/mix), as well as future development.

Even though great effort was given to adhere to the above guidelines, some exceptions were made due to the need to balance other criteria and field logistics. Site selection quickly became limited due to a preference for installation on Crown land. Installing wells on accessible public land severely restricted the area available to locate wells in the project area. If Ministry of Transportation and Infrastructure (MOTI) Crown land was selected, it was generally just the width of a roadway corridor. The presence of buried and overhead utilities and pipelines also restricted the use of other available locations. An additional key constraint for determining monitoring well location involved ensuring appropriate space and terrain for a drill rig to operate, which further limited options.

Wells were drilled over the course of the project in five campaigns, each following the general work plan of desktop spatial analysis, ground-truthing, acquiring permissions, drilling and installation. Each campaign informed subsequent activities, in an iterative manner such that the project progress became more streamlined. The first two campaigns focused on drilling baseline wells, and the latter three focused on proximal wells.

Spatial Analysis GIS Process

Prior to each of the five MWIP drilling campaigns, preliminary locations that conformed to the criteria above were assessed using a GIS-based spatial analysis. Esri's ArcMap was used to visualize data from various sources. Domestic well data, and surficial attributes (such as hydrology, roads, elevation contours) were retrieved from the BC Data Catalogue (DataBC, 2019a). Groundwater geochemical data, used primarily for baseline well site selection, was taken

Table 1. Overview of well details for the 29 groundwater monitoring well stations in the Energy and Environment Research Initiative (EERI) network. Type refers to whether the well adheres to baseline or proximal criteria.

Well name	Latitude	Longitude	Type	Total depth (mbgl)	Static water level (mbtoc)	Completion type	Screened lithology	Energy wells within 3 km radius	Proximity to nearest energy well (m)	Proximity to nearest domestic water well (m)	Nearest energy well orientation	Nearest energy well fluid type	Nearest energy well status	Nearest energy well: hydraulic fracturing?
EERI-1	55.8543	-120.9896	Baseline	53	Artesian	ML	Sandy gravel/sand	3	1557	60	N/a	N/a	N/a	N/a
EERI-2	55.8962	-120.3754	Baseline	46	28.86	ML w/ SG	Shale	37	1331	609	N/a	N/a	N/a	N/a
EERI-3	56.2864	-121.0119	Baseline	54	46.55	SS	Sandstone/ shale/siltstone	4	883	197	N/a	N/a	N/a	N/a
EERI-4	56.1129	-122.0418	Baseline	49	36.31	ML w/ SG	Siltstone/ sandy gravel and diamict/ silt-sand	1	2378	680	N/a	N/a	N/a	N/a
EERI-5	56.122	-122.0425	Baseline	78	23.8	SS w/ pump[1]	Shale	0	3263	120	N/a	N/a	N/a	N/a
EERI-6	55.6804	-121.6906	Baseline	103	23.64	OH	Shale/ sandstone	1	1666	405	N/a	N/a	N/a	N/a
EERI-7	55.9083	-120.3026	Proximal	39	29.24	SS	Sandstone	48	70	1481	Vertical	Gas	Aban.	No
EERI-8	55.9749	-120.7433	Proximal	30	28.84	SS	Sandstone/ shale	55	438	2631	Vertical and horizontal	Gas	Active	Yes
EERI-9	55.6795	-120.5379	Proximal	70	21.52	SS	Sandy gravel	39	214	2008	Horizontal	Gas	Active	Yes
EERI-10	55.7231	-120.3799	Baseline	32	8.34	SS	Shale	6	1729	723	N/a	N/a	N/a	N/a
EERI-11	55.8486	-120.9226	Proximal	77	Artesian	WB	Sandstone/ siltstone	21	321	960	Vertical	Gas	Active	Yes
EERI-12	56.3294	-120.8716	Proximal	38.5	29.65	SS	Sandstone	42	265	696	Vertical	Mixed oil and gas	Aban.	No
EERI-13	56.4262	-121.0851	Proximal	69	26.17	SS	Sandstone	52	175	719	Vertical	Oil	Susp.	Yes
EERI-14	56.5008	-120.8204	Proximal	65	52.38	SS	Shale	46	541	737	Vertical	Gas	Active	Yes
EERI-15	56.4335	-121.2908	Proximal	87	56.97	SS	Sandstone	20	183	5085	Horizontal	Gas	Cased	No

Table 1 (continued)

Well name	Latitude	Longitude	Type	Total depth (mbgl)	Static water level (mbtoc)	Completion type	Screened lithology	Energy wells within 3 km radius	Proximity to nearest energy well (m)	Proximity to nearest domestic water well (m)	Nearest energy well orientation	Nearest energy well fluid type	Nearest energy well status	Nearest energy well: hydraulic fracturing?
EERI-16	56.5148	-121.8509	Proximal	42	10.95	SS	Mudstone	21	106	647	Horizontal	Gas	Aban.	Yes
EERI-17	56.4956	-122.0409	Proximal	23	9.92	ML w/ SG	Sandy gravel	13	152	853	Deviated	Gas	Active	Yes
EERI18A	55.9329	-120.7145	Proximal	21	3.73	SS	Sandstone/ siltstone	108	140	2396	Horizontal	Gas	Active	Yes
EERI-18B	55.9329	-120.7145	Proximal	47	4.02	WB	Sandstone/ siltstone	108	140	2396	Horizontal	Gas	Active	Yes
EERI-19	55.8105	-120.7375	Proximal	69	38.41	SS	Mudstone	42	345	543	Horizontal	Gas	Active	Yes
EERI-20	55.7952	-120.1988	Proximal	99	9.67	SS	Mudstone	23	97	2250	Horizontal	Gas	Active	Yes
EERI-21	55.8296	-120.1665	Proximal	106	65.91	SS	Conglomerate	49	173	1246	Horizontal	Gas	Active	Yes
EERI-22	55.8979	-121.6046	Baseline	44.5	17.38	SS	Sandy gravel	0	7498	424	N/a	N/a	N/a	N/a
EERI-23	56.0484	-121.3304	Proximal	40	22.65	SS	Shale	15	259	879	Deviated	Gas	Susp.	Yes
EERI-24	55.5362	-120.162	Proximal	87.2	55.96	SS	Siltstone/ mudstone	40	180	1493	Horizontal	Gas	Active	Yes
EERI-25	55.6062	-120.037	Baseline	38.4	9.71	SS	Diamict	50	1132	881	N/a	N/a	N/a	N/a
EERI-26	55.755	-120.794	Proximal	18.3	4.77	SS	Mudstone/fine sandstone	13	180	1260	Horizontal	Gas	Susp.	Yes
EERI-27	55.9562	-120.22	Proximal	123	>93	SS	Sandy silt/ clay	23	306	2812	Horizontal	Gas	Active	Yes
EERI-28	56.3627	-120.162	Proximal	57.9	44.15	SS	Shale	29	301	3588	Vertical	Undefined	Aban.	No
EERI-29	56.0765	-120.741	Proximal	59.4	36.79	SS	Silt/sand, lesser diamict	32	198	2891	Horizontal	Gas	Active	Yes

[1] Permanent pump installed due to agreement with landowner

Abbreviations: Aban., abandoned; mbgl, metres below ground level; mbtoc, metres below top of casing; ML, multilevel well; N/a, not available; OH, open hole in bedrock; SG, soil-gas port; SS, single screen well; Susp., suspended; WB, Westbay Instruments multilevel well from a database of groundwater in northeastern BC, which has been compiled as part of the Northeast BC Aquifer Characterization Project (D. Kirste, work in progress). Energy well data was retrieved from the BC Oil and Gas Commission Open Data Portal (BC Oil and Gas Commission, 2019). Drift thickness and bedrock topography were obtained from Hickin and Fournier's (2011) preliminary maps. Unfortunately, the drift thickness data did not cover the entire MWIP area and the drilling results from this program did not match the small scale preliminary interpretation. Data from drilling programs such as this will be useful for refining the understanding of local bedrock topography and drift thickness.

Buffers for the domestic water wells and energy wells were subsequently created in ArcMap using their corresponding criteria's radii. The energy well density was determined and visualized using the BC Data Catalogue's British Columbia Geographic System (BCGS) 1:5000 scale grid (DataBC, 2019b) to create grid cells of 9 km^2, in combination with the 'Spatial Join' tool to attribute the number of energy wells per grid cell. The grid cell size of 9 km^2 was chosen in order to be large enough to capture multiple energy well pads in a single cell, and to be reproducible using a publicly accessible grid.

Buried Utilities and Ground-Truthing

Two methods were used in concert to determine viability of a site based on the location of underground utilities:

1) AccuMap™ oil and gas mapping software (IHS Markit, 2019) was used to visualize locations of high-pressure oil and gas pipelines. For monitoring well site selection, a minimum distance of 30 m from pipeline right-of-ways would have to be maintained to avoid requiring a Proximity Agreement from the corresponding energy company. This agreement requires some lead time, and was avoided in all site selection cases in order to reduce logistical delay.
2) The online BC 1 Call website (https://www.bc1c.ca/) was used to locate all underground utility types. Tickets were submitted online for each location of interest, BC 1 Call identified any buried lines and the appropriate utility companies were subsequently contacted for permission. Types of utilities included telecommunication lines, underground ducts, low-pressure gas pipelines and high-pressure energy pipelines.

Prospective locations that passed the buried utility investigation graduated to ground-truthing. Team members travelled to these locations for field reconnaissance/verification. Field reconnaissance involved checking to see if 1) the location was viable for drill rig access, 2) overhead utilities would interfere with the drill rig and 3) the surface area was large enough for drill rig set up. During these trips, any landowners located in proximity of potential drill locations were contacted in person to be informed of drilling activities. This process typically took place a couple weeks before the drilling campaign commenced and was combined with prior drilling campaigns when possible.

Permissions Process

The MWIP permission requirements can broadly be divided into four categories according to land ownership type:

- the majority of monitoring wells are located on MOTI land, which are narrow strips (<20 m) of Crown land between public roads and the property lines of private landowners, these monitoring well locations required a permit from MOTI prior to drilling;
- two monitoring wells are located on Crown community pasture land (EERI-8 and EERI-24), these locations did not require any official permission;
- several monitoring wells are located adjacent to energy well pad access roads, which are on private land; these locations required verbal, email and/or contractual permission from both the private landowner and the energy well pad owner; these locations were selected to ensure some monitoring well locations attained the greatest proximity to energy wells;
- two monitoring wells are located on private land (EERI-4 and EERI-5), owned by a ranch owner with long-term involvement in other EERI-related research.

Challenges and Limitations

Key limitations which inhibited installing monitoring wells in ideal locations included

- buried utilities: areas of interest with high density energy wells typically had a high density of buried high-pressure pipelines, many of which run parallel to public roads, under MOTI land;
- incompatible land use/cover: power lines, steep/narrow ditches and marshes prevent drill rig access and set up, which requires a relatively flat, dry working space with a minimum footprint of 25 by 4 m; these hazards were not always evident when siting the wells using Google Earth;
- private land ownership: most private landowners were in support of monitoring well installation on or adjacent to their property; in some instances, landowners did not support monitoring well installation on their property for various personal reasons (e.g., noise while drilling, stigma of potentially contaminating or exhausting their water source);
- energy well pads: energy well pads are typically 100–200 m in length and width, and drilling directly on the well pads was not viable due to additional permissions needed from the well pad owner; finding sites off well pads but within the 400 m criterion was challenging, as the selection area was limited and factors such as roadside ditches, fences, tree cover and other terrain obstacles further restricted options.

Drilling Campaigns

The timeline of the five campaigns conducted for the EERI groundwater monitoring well network is shown in Table 2. Drilling contractors, drilling method and installation types evolved throughout the project as the MWIP team learned from challenges and new information during each campaign. Overall, installations were designed to conform to provincial groundwater monitoring well standards, with two boreholes reserved for Westbay multilevel installations. The latter were chosen during drilling, based on geological, hydrogeological and geographic suitability. In some cases, other multilevel installations and soil gas ports were constructed (Table 1). A summary of each drilling campaign is given below.

Campaign 1: The first four baseline monitoring wells were installed using a truck-mounted Terra Sonic International TSi 150T SONIC rig. A primary reason for choosing a sonic drilling method was that sonic coring results in highly preserved intact samples from unconsolidated sediments, which show the highest level of lithological detail. However, a major limitation was the TSi drill's inability to advance through the top portion of weathered bedrock (e.g., incompetent shale), which is a common lithology in the

Table 2. Timeline of the five drilling campaigns conducted over the course of the project.

Drilling campaign	Dates	EERI wells completed	Drilling methods
1	Aug. 22–Sep. 1, 2018	1 to 4	Sonic
2	Feb. 3–12, 2019	5 to 6	Air rotary
3	Jun. 19–Jul. 7, 2019	7 to 14	Sonic, air rotary, diamond (HQ core)
4	Aug. 1–20, 2019	15 to 23	Sonic, air rotary, diamond (HQ core)
5	Sep. 15–27, 2019	24 to 29	Sonic, air rotary

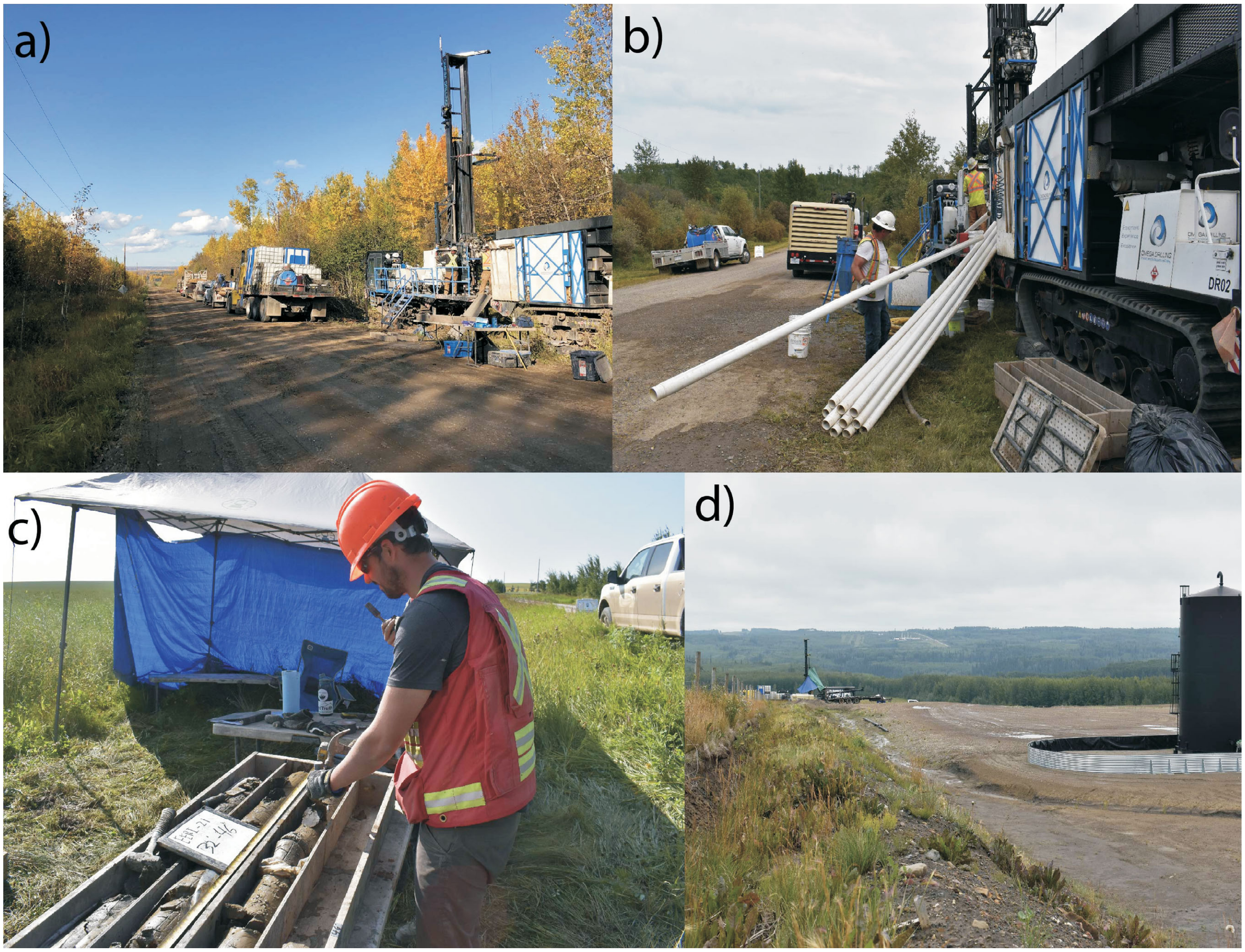

Figure 2. Drilling activity during the summer of 2019 campaigns: **a)** drilling at well EERI-26; **b)** installing polyvinyl chloride (PVC) pipe at well EERI-15; **c)** logging core at well EERI-21; **d)** view of well EERI-18 drill site (left-middle) with well pad in the foreground (right) and a natural gas processing plant in the distant background (on the ridge).

Peace Region. As a result, target depths were not reached in most cases on this campaign.

Campaign 2: This campaign used a truck-mounted Ingersoll Rand TH60 air rotary rig with bedrock coring abilities. Air rotary drilling was chosen in response to the difficulties encountered during the previous campaign with sonic methods in bedrock. This campaign was plagued by unexpected extreme cold conditions (a severe cold weather warning issued the day prior to commencement leading to temperatures lower than –40°C), which resulted in several delays and only two monitoring wells being completed out of a planned four. Monitoring well installations for this campaign were 17.8 cm (7 in.) steel surface casing through overburden, with the bedrock section left open-hole due to cold weather–related complications. Leaving the boreholes open-hole allowed flexibility in constructing other well installations at a later date in better conditions.

Campaign 3: Eight monitoring wells were installed using a Boart Longyear LS™600 track-mounted sonic rig. This drill rig was capable of switching between sonic, air rotary and diamond core drilling methods, which was found to be very advantageous for this project. The track mount was an additional advantage, providing more flexibility to drill in variable terrain. The typical drilling sequence was drilling sonic through the overburden and then through the incompetent bedrock (which the LS 600 was able to do). If no productive formation had been encountered at that point, the driller would switch to air rotary to continue through competent bedrock in search of productive fracture networks. Monitoring well installations for this campaign were single screen 7.6 cm (3 in.) PVC pipe, with 3–6 m of screen. The only exception was EERI-11, which was drilled with HQ diamond coring through bedrock and left open-hole for subsequent Westbay installation.

Campaigns 4 and 5: Due to the success of the third campaign, the same drill rig, method and equipment were used for these remaining campaigns. The majority of completed monitoring wells were single screen 7.6 cm (3 in.) PVC pipe, with 3–9 m of screen. The exceptions were EERI-17, which had an additional shallow gas tubing port; EERI-18B, which was drilled with the same method as EERI-11, HQ diamond coring and left open-hole for subsequent Westbay installation; and EERI-22, which used 10.2 cm (4 in.) PVC pipe instead of 7.6 cm (3 in.) PVC pipe due to material limitations.

Well Development

All wells, except for the two artesian wells and the two wells slated for Westbay installations, were developed during campaigns 3–5 using the airlift method with a trailer-mounted air compressor. Wells were screened with 20-slot PVC screen of varying length depending on the well and geology, generally 3 m, and sand packed with 10/20 filter sand to a minimum of 3 m above the top of the screen. Well development typically took place between two and ten days following the well completion, and wells were airlifted for a minimum of two hours or until the water was clear or clarity was no longer seen to be improving noticeably.

Geology and Core Sampling

The well-documented heterogeneity and unpredictability of the Peace Region Quaternary geology presents a great challenge for shallow monitoring well installation. The main confining units, diamict (Figure 3a) and glaciolacustrine clay (Figure 3b), were the most common sediment types encountered. Drill core was logged throughout drill-

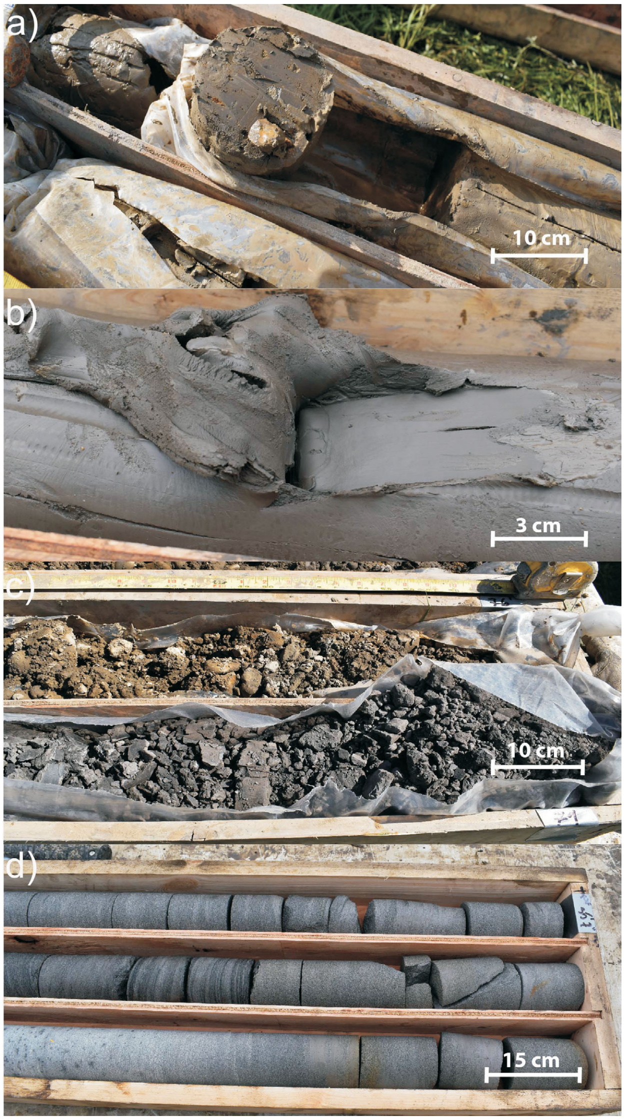

Figure 3. Examples of common lithologies found during drilling in the Peace Region: **a)** core from well EERI-12 showing silty, fine sand diamict (10 metres below ground level [mbgl]); **b)** core from well EERI-9 showing glaciolacustrine clay (15 mbgl); **c)** core from well EERI-17 showing sandy gravel overlying bedrock shale (contact at 23 mbgl); and **d)** HQ core from well EERI-18B showing Dunvegan Formation medium sandstone (11 mbgl).

ing and the EERI monitoring wells were generally screened in four different lithologies:

1) sand/silt: this was the least common screened lithology, as these sediments were encountered at very shallow depths and were not very productive in most cases;
2) gravel: gravel units were typically encountered near the centre of paleovalleys, and sometimes overlaid the top of the bedrock as a basal gravel (Figure 3c);
3) sandstone/conglomerate: the most productive monitoring wells were screened in Dunvegan Formation sandstone (Figure 3d), which is a common aquifer source for domestic wells in the Peace Region; conglomerate was only encountered in EERI-21;
4) shale/siltstone/mudstone: monitoring wells in these bedrock units have moderate to low yield, and they were typically screened because a more permeable unit had not been encountered.

Sediment core samples were taken of every EERI monitoring well during logging and are in the process of being analyzed in the Aqueous Geochemistry Lab in Earth Sciences at Simon Fraser University (Burnaby, BC) and the ALS-Geochemistry laboratory (North Vancouver, BC) in order to determine a depth profile of various physical and chemical properties. During air rotary drilling, grab samples of drill cuttings were collected directly from the cyclone. Samples for targeted sequential extractions and cation exchange capacity analysis were taken every 1.5 m (5 ft.), and samples for permeability and grain size distribution analysis were taken once per hydrostratigraphic unit. Select samples will be used for X-ray diffraction and energy-dispersive X-ray spectrometry analysis.

Figure 4. Installation of Westbay Instruments system in well EERI-11. The foreground shows the layout of the packers (green) and casing with measurement and pumping ports (white casing) during installation.

Westbay Multilevel Installations

Westbay systems provide the advantage of allowing data collection at multiple discrete depths within a single well. These systems consist of a series of alternating packers and casing that contain hydraulic head measurement and pumping ports (Figure 4). The packers hydraulically seal different zones from one another, whereas the measurement and pumping ports allow direct connection with the formation in the designated monitoring zone. Westbay systems therefore allow the attainment of high-resolution vertical profiles of chemistry and hydraulics, which is advantageous in tracking variations and sources of methane concentrations in groundwater and delineating flow systems and vertical hydraulic connectivity. Two proximal wells were completed with Westbay systems in the Groundbirch area west of Dawson Creek, EERI-11 and EERI-18B (Figure 1). Based on lithological logs and wireline geophysics data from EERI-11, the Westbay systems were designed by the MWIP team and Westbay personnel and customized to each borehole (Table 3). The MWIP team assisted with installation and were trained on the Westbay sampling system. The first set of samples from these wells was collected in late September.

Groundwater Sampling

Groundwater samples will be collected from the newly installed EERI monitoring well network three times per year: early spring, summer and late autumn. To date, one full

Table 3. Depth of zones, measurement ports and pumping ports for Westbay Instruments systems in wells EERI-11 and EERI-18B. All depth measurements are metres below ground level.

Zone	Measurement port depth	Pumping port depth	Top of zone	Bottom of zone
		EERI-11		
1	70.9	72.4	70.7	76.6
2	64.8	66.3	64.6	66.7
3	58.7	60.2	58.5	60.6
4	55.7	57.2	55.4	57.6
5	52.6	54.1	52.4	54.5
6	49.6	51.1	49.4	51.5
7	45.0	46.5	44.8	48.5
		EERI-18B		
1	39.7	41.2	39.5	41.6
2	33.6	35.1	33.4	35.5
3	25.4	26.9	25.1	27.3
4	19.6	21.1	19.3	21.5
5	16.5	18.0	16.3	18.4

sampling round has been carried out for the entire network (with the exception of EERI-27), which occurred late September–early October 2019, and wells that were installed at the beginning of the drilling process have had additional samples taken at earlier dates (Table 4). Water samples are obtained using either a Grundfos MP1 groundwater sampling pump or a Waterra Pumps Limited D-25 inertial foot valve when necessary.

Sample types, collection methods and analytical methodology are summarized in Table 5. Groundwater field parameters including temperature, pH, electrical conductivity

Table 4. Record of number and date of sampling rounds taken at each well in the Energy and Environment Research Initiative groundwater monitoring well network. Sampling rounds generally consist of measuring field parameters (temperature, pH, electrical conductivity, dissolved oxygen and oxidation-reduction potential) and collecting water samples for analyses described in Table 5. Where sampling deviated from this collection regime, a note is made.

Well name	Number of sampling rounds	Sample dates	Notes
EERI-1	3	Dec. 4, 2018; Jun. 28, 2019; Sep. 28, 2019	Laboratory analysis of major and minor cations, trace metals, and anions completed for first two sample suites collected. Other analyses and third round sample analyses are in progress.
EERI-2	3	Dec. 4, 2018; Jun. 26, 2019; Oct. 1, 2019	Same as above.
EERI-3	2	Jun. 28, 2019; Oct. 7, 2019	Laboratory analysis of major and minor cations, trace metals, and anions completed for first sample suite collected. Other analyses and second round sample analyses are in progress.
EERI-4	2	Dec. 5, 2018; Oct. 5, 2019	Same as above.
EERI-5	2	Jul. 2, 2019; Oct. 5, 2019	Same as above.
EERI-6	2	Jun. 27, 2019; Oct. 4, 2019	Same as above.
EERI-7	2	Jun. 26, 2019; Oct. 1, 2019	Same as above.
EERI-8	2	Jul. 8, 2019; Sep. 30, 2019	Same as above.
EERI-9	2	Jul. 10, 2019; Oct. 3, 2019	Same as above.
EERI-10	2	Jul. 8, 2019; Oct. 3, 2019	Same as above.
EERI-11	1	Sep. 27, 2019	Westbay multilevel well. Water sample suite taken, but system precludes use of flow-through cell for field parameters to be measured. Laboratory analysis is in progress.
EERI-12	2	Jul. 8, 2019; Sep. 29, 2019	Laboratory analysis of major and minor cations, trace metals, and anions completed for first sample suite collected. Other analyses and second round sample analyses are in progress.
EERI-13	2	Jul. 8, 2019; Oct. 6, 2019	Same as above.
EERI-14	2	Jul. 12, 2019; Oct. 6, 2019	Same as above.
EERI-15	1	Oct. 6, 2019	Laboratory analysis is in progress.
EERI-16	1	Oct. 7, 2019	Laboratory analysis is in progress.
EERI-17	1	Oct. 7, 2019	Laboratory analysis is in progress.
EERI-18A	1	Sep. 30, 2019	Laboratory analysis is in progress.
EERI-18B	1	Sep. 25, 2019	Westbay multilevel well. Water sample suite taken, but system precludes use of flow-through cell for field parameters to be measured. Laboratory analysis is in progress.
EERI-19	1	Oct. 3, 2019	Laboratory analysis is in progress.
EERI-20	1	Oct. 2, 2019	Laboratory analysis is in progress.
EERI-21	1	Oct. 1, 2019	Laboratory analysis is in progress.
EERI-22	1	Oct. 5, 2019	Laboratory analysis is in progress.
EERI-23	1	Oct. 5, 2019	Laboratory analysis is in progress.
EERI-24	1	Oct. 2, 2019	Laboratory analysis is in progress.
EERI-25	1	Oct. 2, 2019	Laboratory analysis is in progress.
EERI-26	1	Oct. 3, 2019	Laboratory analysis is in progress.
EERI-27	0	N/a	Water level was deeper than the length of the pump; field parameters and samples unable to be collected.
EERI-28	1	Sep. 29, 2019	Laboratory analysis is in progress.
EERI-29	1	Sep. 30, 2019	Laboratory analysis is in progress.

Abbreviations: N/a, not available; Westbay, Westbay Instruments.

Table 5. Summary of sample types, collection method and analysis methodology to be performed three times per year for all wells in the Energy and Environment Research Initiative groundwater monitoring well network.

Sample type	Collection/preservation	Analysis method	Analytical results
ICP	125 mL volume, filtered and preserved with ultra-pure nitric acid to 2% by volume	Inductively coupled plasma–emission spectrometry (ICP-ES) and inductively coupled plasma–mass spectrometry (ICP-MS)	Major and minor cations, trace metals, rare-earth elements
Anions	250 mL volume, filtered	Ion chromatography, alkalinity titration, isotope ratio mass spectrometry	Alkalinty (as HCO_3^-), major anions, oxygen-deuterium isotopes
Carbon-14	500 mL volume, filtered, preserved with 2 mL of 5M NaOH and $SrCl_2$	Accelerator mass spectrometry (^{14}C), isotope ratio mass spectrometry ($\delta^{13}C$)	$\delta^{13}C$ and $\delta^{14}C$
^3H	1000 mL volume, filtered, no headspace	Liquid scintillation counting (LSC)	Tritium enrichment
Dissolved gas and soil gas	~250 mL volume, collected in evacuated sample vials containing bactericide	Numerous	He, H_2, O_2, N_2, CH_4, CO_2, H_2S, and higher chain hydrocarbons, as well as $\delta^{13}C$ for CH_4 and CO_2

Abbreviation: M, molar

(EC), dissolved oxygen (DO), and oxidation-reduction potential were measured onsite using Thermo Scientific™ Orion™ 3-Star digital multiparameter meters during sample collection. Alkalinity (as HCO_3^-) was measured by titration using a Mettler Toledo EasyPlus Titrator Easy pH system.

Filtered samples were collected from each well for anion and elemental analysis, as well as determining stable isotopes of water, dissolved gases, tritium and carbon-14 contents. Groundwater samples for major and minor cations, trace metals and rare-earth elements were preserved with ultra-pure nitric acid (HNO_3) to 2% by volume, for analysis by inductively coupled plasma–emission spectrometry (ICP-ES) and inductively coupled plasma–mass spectrometry (ICP-MS) at the Applied Geochemistry group (AGg) Chemistry Lab at the University of Calgary (Calgary, AB). Separate samples remained unacidified for analysis of major and minor anions by ion chromatography (IC), dating analysis of tritium isotope (^3H) by liquid scintillation counting (LSC), and analysis for deuterium and oxygen isotope composition by isotope ratio mass spectrometry (IRMS). Additional samples were preserved by precipitation of dissolved inorganic carbon as $SrCO_3$ through the addition of NaOH and $SrCl_2$ for analysis of $\delta^{13}C$ using IRMS. Groundwater samples will be analyzed for tritium content by enrichment and low level proportional counting at the University of Miami's Tritium Laboratory (Miami, Florida). Samples for carbon-14 will be determined by accelerator mass spectrometry (AMS) and $\delta^{13}C$ by IRMS at the André E. Lalonde Accelerator Mass Spectrometry Laboratory at the University of Ottawa (Ottawa, ON). Dissolved gas and soil-gas samples were analyzed at the AGg Chemistry Lab using gas chromatography (Varian, Inc. CP4800 portable gas chromatograph). Isotopes of carbon and hydrogen of methane were analyzed by isotope ratio mass spectrometer (Thermo Electron Corporation Finnigan™ MAT 253 with Thermo Scientific TRACE™ GC Ultra gas chromatograph and GC IsoLink™ IRMS system), at the University of Calgary's Isotope Science Laboratory.

Conclusions

The EERI groundwater monitoring well network was successfully completed with 29 monitoring stations installed across the Peace Region. These stations were strategically located to monitor both baseline groundwater geochemistry and groundwater geochemistry in proximity to oil and gas activity. Initial groundwater samples of the entire network were collected in September to October 2019, with continued sampling planned to occur three times each year. Furthermore, the EERI groundwater monitoring well network will provide opportunities for collaboration and use by other parties who may benefit from the network. The EERI wells have already been used for downhole seismic studies (Monahan et al., 2020), and there is current interest in future work with other partners. Thus, the EERI groundwater monitoring well network will not only allow ongoing data collection to better understand groundwater methane in the context of oil and gas development, but also offer a resource for additional scientific studies in the Peace Region.

Acknowledgments

The authors gratefully acknowledge:

- L. Smith for peer-reviewing this manuscript;
- C. and E. Weder for granting permission to drill EERI-4 and EERI-5 on their property;
- the combined efforts of BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development and Ministry of Transportation and Infrastructure for granting permissions to drill on roadside Crown land; and

- the many private landowners and energy companies who gave their approvals to drill next to their lands.

This work was funded by Geoscience BC and the BC Oil and Gas Commission.

References

Bachu, S. (2017): Analysis of gas leakage occurrence along wells in Alberta, Canada, from a GHG perspective – gas migration outside well casing; International Journal of Greenhouse Gas Control, v. 61, p. 146–154, URL <https://doi.org/10.1016/j.ijggc.2017.04.003> [November 2019].

BC Oil and Gas Commission (2018): Number of wells drilled in B.C. - annually; BC Oil and Gas Commission, URL <https://iris.bcogc.ca/reports/rwservlet?prd_ogcr9960a> [September 2018].

BC Oil and Gas Commission (2019): Open data portal; BC Oil and Gas Commission, web application, <https://data-bcogc.opendata.arcgis.com/> [April 2019].

Briskin, J. (2015): Potential impacts of hydraulic fracturing for oil and gas on drinking water resources; Groundwater, v. 53, no. 1, p. 19–21.

Cahill, A.G., Beckie, R.D., Goetz, M., Allen, A., Ladd, B., Welch, L., Kirste, D., Mayer, B. and van Geloven, C. (2019): Characterizing dissolved methane in groundwater in the Peace Region, northeastern British Columbia, using a regional, dedicated, groundwater monitoring well network; *in* Geoscience BC Summary of Activities 2018: Energy and Water, Geoscience BC, Report 2019-02, p. 105–122, URL <http://cdn.geosciencebc.com/pdf/SummaryofActivities2018/EW/2017-002_SoA2018_EW_Cahill_DissolvedMethane.pdf> [October 2019].

Cahill, A.G., Steelman, C.M., Forde, O., Kuloyo, O., Emil Ruff, S., Mayer, B., Mayer, K.U., Strous, M., Ryan, M.C., Cherry, J.A. and Parker, B.L. (2017): Mobility and persistence of methane in groundwater in a controlled-release field experiment; Nature Geoscience, v. 10, no. 4, p. 289–294, URL <https://doi.org/10.1038/ngeo2919> [April 2017].

Catto, N.R. (1991): Quaternary geology and landforms of the eastern Peace River region, British Columbia, NTS 94A/1, 2, 7, 8; BC Ministry of Energy, Mines and Petroleum Resources, BC Geological Survey, Open File 1991-11, 19 p.

Council of Canadian Academies (2014): Environmental impacts of shale gas extraction in Canada: the expert panel on harnessing science and technology to understand the environmental impacts of shale gas extraction; Council of Canadian Academies, Ottawa, Ontario, 262 p.

Darrah, T.H., Vengosh, A., Jackson, R.B., Warner, N.R. and Poreda, R.J. (2014): Noble gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett shales; Proceedings of the National Academy of Sciences of the United States of America, v. 111, no. 39, p. 14076–14081, URL <https://doi.org/10.1073/pnas.1322107111> [November 2019].

DataBC (2019a): B.C. Data Catalogue; Government of British Columbia, datasets, URL <https://catalogue.data.gov.bc.ca/dataset?download_audience=Public> [October 2019].

DataBC (2019b): BCGS 1:5,000 grid; BC Ministry of Lands, Forests, Natural Resource Operations and Rural Development and GeoBC, dataset, URL <https://catalogue.data.gov.bc.ca/dataset/bcgs-1-5-000-grid> [November 2019].

Environment and Climate Change Canada (2019): Canadian climate normals 1981-2010 station data: Fort St John A; Government of Canada, URL <https://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?searchType=stnName&txtStationName=fort+st+john&searchMethod=contains&txtCentralLatMin=0&txtCentralLatSec=0&txtCentralLongMin=0&txtCentralLongSec=0&stnID=1413&dispBack=1> [October 2019].

Forde, O.N., Cahill, A.G., Beckie, R.D. and Mayer, K.U. (2019a): Barometric-pumping controls fugitive gas emissions from a vadose zone natural gas release; Scientific Reports, v. 9, article no. 14080, 9 p., URL <https://doi.org/10.1038/s41598-019-50426-3> [October 2019].

Forde, O.N., Mayer, K.U. and Hunkeler, D. (2019b): Identification, spatial extent and distribution of fugitive gas migration on the well pad scale; Science of the Total Environment, v. 652, p. 356–366, URL <https://doi.org/10.1016/j.scitotenv.2018.10.217> [November 2019].

Hickin, A.S. and Fournier, C.M.A. (2011): Preliminary bedrock topography and drift thickness of the Montney Play area; BC Ministry of Energy, Mines and Petroleum Resources, Energy Open File 2011-1 and Geoscience BC, Report 2011-07, 2 maps, scale 1:500 000, URL <http://cdn.geosciencebc.com/project_data/GBC_Report2011-7/GBC_Report2011-07_BCMEM%20OF2011-1.pdf> [November 2019].

Holland, S.S. (1964): Landforms of British Columbia, a physiographic outline; BC Ministry of Energy, Mines and Petroleum Resources, Bulletin No. 48, 138 p.

IHS Markit (2019): AccuMap™; IHS Markit, mapping, data management and analysis software, URL <https://ihsmarkit.com/products/oil-gas-tools-accumap.html> [October 2019].

Kelly, W.R., Matisoff, G. and Fisher, J.B. (1985): The effects of a gas well blow out on groundwater chemistry; Environmental Geology and Water Sciences, v. 7, issue 4, p. 205–213, URL <http://link.springer.com/article/10.1007/BF02509921> [November 2019].

Monahan, P.A., Hayes, B.J., Perra, M., Mykula, Y., Clarke, J., Galambos, B., Griffiths, D., Bayarsaikhan, O. and Oki, U. (2020): Amplification of seismic ground motion in the Fort St. John–Dawson Creek area, northeastern British Columbia (NTS 093P, 094A); *in* Geoscience BC Summary of Activities 2019, Geoscience BC, Report 2020-02, p. 1–12.

Osborn, S.G., Vengosh, A., Warner, N.R. and Jackson, R.B. (2011a): Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing; Proceedings of the National Academy of Sciences of the United States, v. 108, issue 20, p. 8172–8176, URL <https://doi.org/10.1073/pnas.1100682108> [November 2019].

Osborn, S.G., Vengosh, A., Warner, N.R. and Jackson, R.B. (2011b): Reply to Saba and Orzechowski and Schon: methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing; Proceedings of the National Academy of Sciences of the United States of America, v. 108, issue 37, p. E665–E666.

Province of British Columbia (2018): Oil and Gas Activities Act, Drilling and Production Regulation; British Columbia Regulation 282/2010 (Oil and Gas Commission), URL <http://www.bclaws.ca/civix/document/id/complete/statreg/282_2010> [November 2018].

Saba, T. and Orzechowski, M. (2011): Lack of data to support a relationship between methane contamination of drinking water wells and hydraulic fracturing; Proceedings of the National Academy of Sciences, v. 108, issue 37, p. E663–E663, URL <https://doi.org/10.1073/pnas.1108435108> [November 2019].

Schaefer, D.G. (1978): Climate; *in* The Soil Landscapes of British Columbia, K.W.G. Valentine, P.N. Sprout, T.E. Baker and L.M. Lawkulich (ed.), BC Ministry of Environment, p. 3–10, URL <http://www.env.gov.bc.ca/esd/distdata/ecosystems/Soils_Reports/Soil_Landscapes_of_BC_1986.pdf> [November 2019].

Van Stempvoort, D., Maathuis, H., Jaworski, E., Mayer, B. and Rich, K. (2005): Oxidation of fugitive methane in ground water linked to bacterial sulfate reduction; Groundwater, v. 43, issue 2, p. 187–199, URL <https://doi.org/10.1111/j.1745-6584.2005.0005.x> [November 2019].

Vidic, R.D., Brantley, S.L., Vandenbossche, J.M., Yoxtheimer, D. and Abad, J.D. (2013): Impact of shale gas development on regional water quality; Science, v. 340, no. 6134, URL <https://doi.org/10.1126/science.1235009> [November 2019].