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): Activity Report 2019–2020

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Introduction

Northeastern British Columbia (BC) hosts some of the world's largest unconventional gas reservoirs and while the natural gas in these reservoirs has and continues to be developed, some of the effects of this development on the environment are not well understood. Of the possible effects on the environment, a 2014 report by the Council of Canadian Academies (2014) identified the effects of fugitive natural gas as the most uncertain among energy development activities. Fugitive natural gas poses three principal risks: degradation of near-surface water quality, potential for explosions, and greenhouse gas emissions, if the fugitive gas reaches the atmosphere (Cahill et al., 2017).

The overarching objective of The University of British Columbia's Energy and Environment Research Initiative (EERI) is to provide a knowledge base to support decision making around unconventional gas resources in northeastern BC. A key component of the research initiative is the Monitoring Well Installation Project (MWIP), which included the installation of and subsequent sampling of groundwater and sediments from 29 bespoke monitoring wells in northeastern BC. The principal objectives of the MWIP are to better understand near-surface (approximately less than 100 m deep) background groundwater conditions in northeastern BC, to determine the distribution of natural gas in near-surface groundwater, and to determine if natural gas in the near surface is related to energy-development activities. By using bespoke wells in specifically chosen locations, there is a reduction in biases and sampling artifacts that can be introduced when only existing domestic wells are used to characterize groundwater conditions. After the MWIP is complete, the monitoring wells will remain and can be used to provide long-term datasets to systematically characterize groundwater conditions through time.

The MWIP project is a collaboration among The University of British Columbia (UBC), Simon Fraser University (SFU), Heriot-Watt University, the University of Calgary, and colleagues at the BC Oil and Gas Commission (BCOGC) and the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (MFLNRORD). This project builds upon other efforts, including a program led by MFLNRORD and SFU to sample

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and characterize groundwater chemistry from domestic water wells.

The MWIP commenced in spring 2018 and is still being implemented principally by M.Sc. students A. Allen (SFU) and M. Goetz (UBC). The drilling program, site selection criteria, monitoring well locations and an introduction to fugitive-gas concepts can be found in Ladd et al. (2020). Installation of the well network is complete and locations of the monitoring wells are shown in Figure 1. This paper provides an update on the status of the well network and sampling campaigns. In addition, there is a description of four affiliated substudies by A. Allen, M. Goetz and P. Gonzalez who are using samples and data collected in the context of the MWIP.

Status of Monitoring Well Network and Sampling Campaigns

Table 1 shows the sampling dates across four separate sampling campaigns for each of the 29 EERI well locations drilled between 2018 and 2019. A total of 73 sample sets have been obtained over the past two years, the most recent of which were collected between July 16 and 28, 2020. All wells have now been sampled two or more times, except for EERI-27, which has a static water level beyond the reach of the Grundfos MP1 submersible pump used for most wells. In addition to the submersible pump, other equipment used during the most recent sampling campaign included Waterra Pumps Limited D-25 inertial foot valves for EERI-4 and -8; a Westbay® Instruments (Westbay) MOSDAX sampler probe for the Westbay installations in EERI-11 and -18B; and a Geotech Environmental Equipment, Inc. geopump peristaltic pump in combination with a specialized sampling rod for the Sub-Frost Artesian packer from RST Instruments Ltd. installed in EERI-1.

The most recent sampling campaign in July 2020 also afforded the opportunity to collect accurate GPS data for each EERI well location using a Leica Geosystems Viva CS10 field controller in the UTM10 co-ordinate system (Zone 10N). Postprocessing of GPS data was completed by

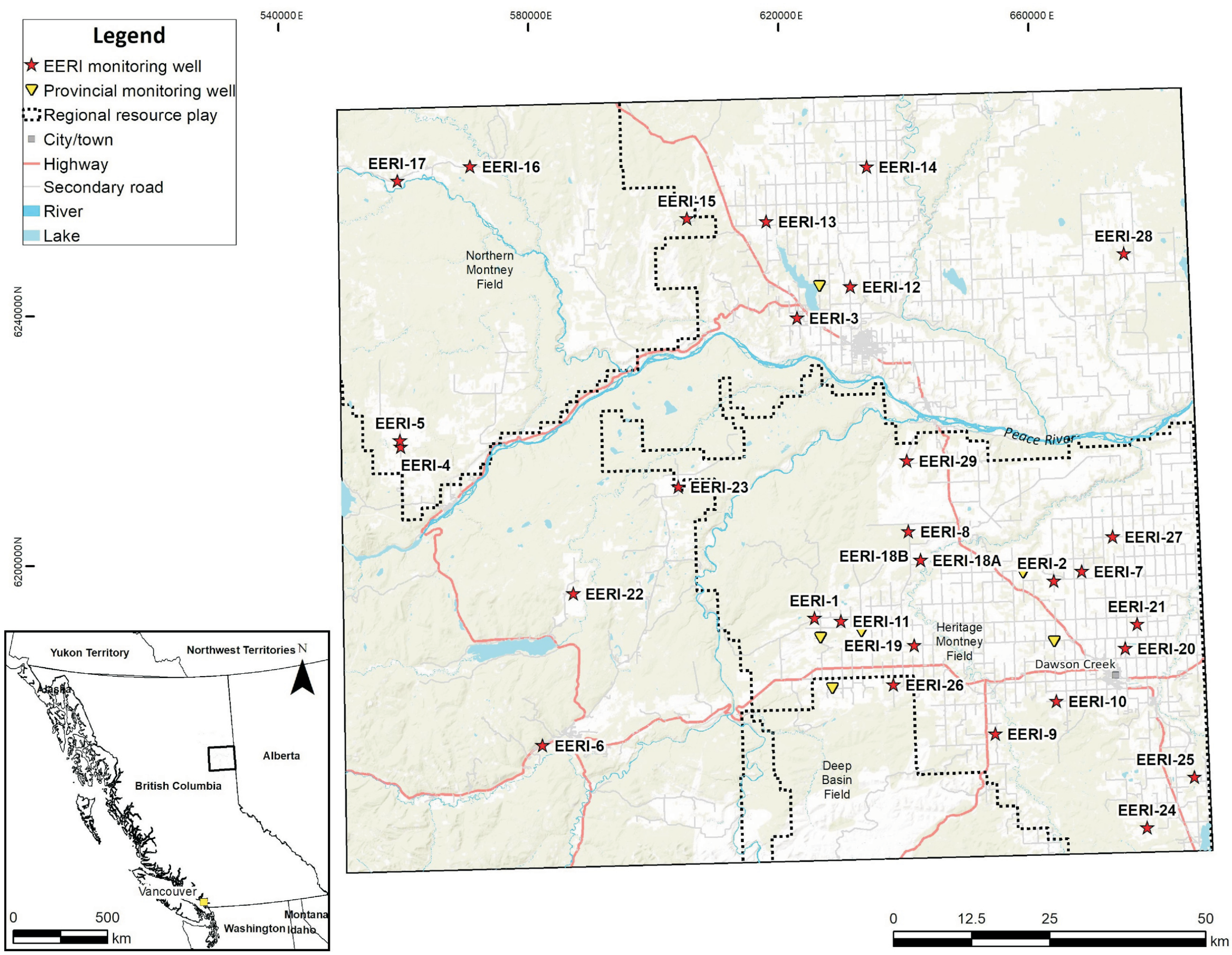

Figure 1. The Monitoring Well Installation Project area with Energy and Environment Research Initiative (EERI) monitoring well locations and regional oil and gas field boundaries, northeastern British Columbia. Background digital elevation model (DEM) from Esri Canada (2019). UTM Zone 10N, NAD 83.

Table 1. Summary of samples and dates of collection from the 29 Energy and Environment Research Initiative (EERI) Monitoring Well Installation Project (MWIP) well locations. Four separate sampling campaigns were undertaken between December 2018 and July 2020 throughout the Peace Region of northeastern British Columbia. Sample collection IDs are based on the well number and order of sampling date (e.g., first sampling date of EERI-1 is denoted as 1-1, second sampling date is 1-2, and so on). No samples were collected from EERI-27 because the depth of the water table was greater than the reach of the pump.

Well name	Winter 2018		Summer 2019		Fall 2019		Summer 2020	
	Date	Sample ID	Date	Sample ID	Date	Sample ID	Date	Sample ID
EERI-1	Dec. 4	1-1	Jun. 28	1-2	Sep. 27	1-3	Jul. 20	1-4
EERI-2	Dec. 4	2-1	Jun. 26	2-2	Oct. 1	2-3	Jul. 17	2-4
EERI-3			Jun. 28	3-1	Oct. 7	3-2	Jul. 24	3-3
EERI-4	Dec. 5	4-1			Oct. 5	4-2	Jul. 26	4-3
EERI-5			Jul. 7	5-1	Oct. 5	5-2	Jul. 26	5-3
EERI-6			Jun. 27	6-1	Oct. 4	6-2	Jul. 25	6-3
EERI-7			Jun. 26	7-1	Oct. 1	7-2	Jul. 17	7-3
EERI-8			Jul. 8	8-1	Sep. 30	8-2	Jul. 19	8-3
EERI-9			Jul. 10	9-1	Oct. 3	9-2	Jul. 18	9-3
EERI-10			Jul. 8	10-1	Oct. 3	10-2	Jul. 18	10-3
EERI-11					Sep. 26	11-1	Jul. 22	11-2
EERI-12			Jul. 8	12-1	Sep. 29	12-2	Jul. 19	12-3
EERI-13			Jul. 8	13-1	Oct. 6	13-2	Jul. 23	13-3
EERI-14			Jul. 12	14-1	Oct. 6	14-2	Jul. 23	14-3
EERI-15					Oct. 6	15-1	Jul. 24	15-2
EERI-16					Oct. 7	16-1	Jul. 28	16-2
EERI-17					Oct. 7	17-1	Jul. 28	17-2
EERI-18A					Sep. 30	18A-1	Jul. 19	18A-2
EERI-18B					Sep. 25	18B-1	Jul. 21	18B-2
EERI-19					Oct. 3	19-1	Jul. 18	19-2
EERI-20					Oct. 2	20-1	Jul. 16	20-2
EERI-21					Oct. 1	21-1	Jul. 17	21-2
EERI-22					Oct. 5	22-1	Jul. 26	22-2
EERI-23					Oct. 5	23-1	Jul. 25	23-2
EERI-24					Oct. 2	24-1	Jul. 16	24-2
EERI-25					Oct. 2	25-1	Jul. 16	25-2
EERI-26					Oct. 3	26-1	Jul. 18	26-2
EERI-27								
EERI-28					Sep. 29	28-1	Jul. 23	28-2
EERI-29					Sep. 30	29-1	Jul. 19	29-2

MFLNRORD staff using Leica Geo Office 8.4. In addition to GPS data, static water level data were downloaded from each Van Essen Instruments Micro-Diver data logger installed in 24 of the 29 well locations (EERI-1, -8, -11, -16 and -27 do not have data loggers installed). Each pressure transducer collects data at four-hour intervals; the datasets covering the longest time period are from EERI-4, -5 and -6, which were installed in February of 2019. Data loggers were installed in the other wells in July and October 2019. The combination of the GPS referenced elevations and pressure transducer datasets will provide static water levels relative to sea level, with data from some wells covering a time period of more than one year.

Descriptions of planned analyses for water samples collected from EERI wells were outlined in detail by Ladd et al. (2020). One alteration to that analysis method is the location and equipment intended to be used for inductively coupled plasma–mass spectrometry (ICP-MS) measurements. These analyses have since been completed using an Agilent Technologies 8800 triple quadrupole ICP-MS at the Water Quality Centre (WQC) at Trent University (Peterborough, Ontario). Table 2 shows the recent status of the separate analysis categories: metals, cations and rare-earth elements by ICP-MS, anion concentrations (includes oxygen-deuterium stable isotopes), inorganic carbon and carbon isotopes, tritium enrichment, and dissolved gas concentrations. To date, all anion measurements and metal, cation and rare-earth-element measurements (ICP-MS) are complete for all 73 sample sets, and 33 inorganic carbon and carbon isotopes samples have been analyzed. No tritium enrichment results have been obtained yet. All of the sample sets submitted for dissolved gas compositions have been analyzed.

Table 2. Summary table showing the status of the analyses for each of the 73 sample sets collected from Energy and Environment Research Initiative (EERI) Monitoring Well Installation Project wells. To date, all anion, inductively coupled plasma–mass spectrometry (ICP-MS) and dissolved gas analyses are complete, and inorganic carbon (and carbon isotopes) analyses are partially complete; tritium analyses have not been completed. Some analyses do not include all 73 sample sets due to incompatible pumping methods (e.g., pumping using Waterra tubing does not allow for carbon isotope sample collection) and preservation issues after sample collection. Sample collection IDs are based on the well number and order of sampling date (e.g., first sampling date of EERI-1 is denoted as 1-1, second sampling date is 1-2, and so on). Table 1 indicates the month and year of sample collection.

Well name	ICP-MS	Anions	Inorganic carbon		Tritium	Dissolved gas
	Complete	Complete	Complete	In progress	In progress	Complete
EERI-1	1-1, 1-2, 1-3, 1-4	1-1, 1-2, 1-3, 1-4	1-1, 1-2, 1-3	1-4	1-2, 1-3, 1-4	1-2, 1-3, 1-4
EERI-2	2-1, 2-2, 2-3, 2-4	2-1, 2-2, 2-3, 2-4	2-1, 2-3	2-4	2-2, 2-3, 2-4	2-2, 2-3, 2-4
EERI-3	3-1, 3-2, 3-3	3-1, 3-2, 3-3	3-1, 3-2	3-3	3-1, 3-2, 3-3	3-1, 3-2, 3-3
EERI-4	4-1, 4-2, 4-3	4-1, 4-2, 4-3	4-1			
EERI-5	5-1, 5-2, 5-3	5-1, 5-2, 5-3	5-1, 5-2	5-3	5-1, 5-2, 5-3	5-1, 5-2, 5-3
EERI-6	6-1, 6-2, 6-3	6-1, 6-2, 6-3	6-1, 6-2	6-3	6-1, 6-2, 6-3	6-1, 6-2, 6-3
EERI-7	7-1, 7-2, 7-3	7-1, 7-2, 7-3	7-1, 7-2	7-3	7-1, 7-2, 7-3	7-1, 7-2, 7-3
EERI-8	8-1, 8-2, 8-3	8-1, 8-2, 8-3				
EERI-9	9-1, 9-2, 9-3	9-1, 9-2, 9-3	9-1, 9-2	9-3	9-1, 9-2, 9-3	9-1, 9-2, 9-3
EERI-10	10-1, 10-2, 10-3	10-1, 10-2, 10-3	10-1, 10-2	10-3	10-1, 10-2, 10-3	10-1, 10-2, 10-3
EERI-11	11-1, 11-2	11-1, 11-2				11-1, 11-2
EERI-12	12-1, 12-2, 12-3	12-1, 12-2, 12-3	12-1, 12-2	12-3	12-1, 12-2, 12-3	12-1, 12-2, 12-3
EERI-13	13-1, 13-2, 13-3	13-1, 3-2, 13-3	13-1, 13-2	13-3	13-1, 13-2, 13-3	13-1, 13-2, 13-3
EERI-14	14-1, 14-2, 14-3	14-1, 14-2, 14-3	14-1, 14-2	14-3	14-1, 14-2, 14-3	14-1, 14-2, 14-3
EERI-15	15-1, 15-2	15-1, 15-2	15-1	15-2	15-1, 15-2	15-1, 15-2
EERI-16	16-1, 16-2	16-1, 16-2		16-2	16-1, 16-2	16-1, 16-2
EERI-17	17-1, 17-2	17-1, 17-2	17-1	17-2	17-1,17-2	17-1, 17-2
EERI-18A	18A-1, 18A-2	18A-1, 18A-2	18A-1	18A-2	18A-1, 18A-2	18A-1, 18A-2
EERI-18B	18B-1, 18B-2	18B-1, 18B-2				18B-1, 18B-2
EERI-19	19-1, 19-2	19-1, 19-2	19-1	19-2	19-1, 19-2	19-1, 19-2
EERI-20	20-1, 20-2	20-1, 20-2		20-2	20-1, 20-2	20-1, 20-2
EERI-21	21-1, 21-2	21-1, 21-2	21-1	21-2	21-1, 21-2	21-1, 21-2
EERI-22	22-1, 22-2	22-1, 22-2	22-1	22-2	22-1, 22-2	22-1, 22-2
EERI-23	23-1, 23-2	23-1, 23-2		23-2	23-2	23-1, 23-2
EERI-24	24-1, 24-2	24-1, 24-2		24-2	24-1, 24-2	24-1, 24-2
EERI-25	25-1, 25-2	25-1, 25-2	25-1	25-2	25-1, 25-2	25-1, 25-2
EERI-26	26-1, 26-2	26-1, 26-2	26-1	26-2	26-2	26-1, 26-2
EERI-27						
EERI-28	28-1, 28-2	28-1, 28-2	28-1	28-2	28-1, 28-2	28-1, 28-2
EERI-29	29-1, 29-2	29-1, 29-2		29-2	29-2	29-1, 29-2

As stated previously, no samples have been obtained from EERI-27. Additionally, some sample sets could not be analyzed for all aspects of the analysis suite planned. Samples from EERI-11 and -18B were not analyzed for carbon isotope or tritium, as the Westbay sampling method does not yield sufficient volumes of water for these analyses. Samples from EERI-4 and -8 were not analyzed for carbon, tritium or dissolved gas due to limitations in the sampling methods.

Occurrence and Origin of Groundwater Methane in the District of Hudson's Hope Potential Water Supply

The District of Hudson's Hope is a small town located within the Peace River valley in northeastern BC, near the Rocky Mountain Foothills (Figure 1). The Peace River valley mimics the shape of an ancient buried valley, paleovalley, of the same name (Hickin and Fournier, 2011). The geology of the study area is broadly an alluvial sand/gravel plain underlain by confining clay and/or till, a thick gravel aquifer in a buried valley, and fractured Cretaceous shale bedrock (Hartman and Clague, 2008).

The construction of the Site C dam, located downstream on the Peace River near Fort St. John, required the District of Hudson's Hope to change its water supply from its current Peace River source (currently extracting a maximum of 829 661 m^3 annually), to groundwater from the buried-valley aquifer. This change in town water supply is required due to the anticipated deterioration of the Peace River water quality and because part of the water supply system will be made inoperable by the flooding caused by the dam installation (Gardiner et al., 2020). To facilitate the change, the District hired a hydrogeology consulting firm, Western Water Associates Ltd. (WWAL), to evaluate the feasibility of the transition via a test well drilling program in 2018–2019, culminating in the drilling and installation of two production wells in the fall of 2019.

Dissolved gas samples collected by the consultants during the feasibility study showed high concentrations (tens of mg/L) of dissolved methane, which prompted the District to contact the EERI group for collaboration. This presented an opportunity to gather additional data to further MWIP's objectives, while collaborating with the District and WWAL. In November 2019, the EERI group collected groundwater geochemistry and dissolved gas samples during pumping tests for one of the production wells. Using the same sampling methodology outlined in Ladd et al. (2020), groundwater discharge was sampled during a four-hour step pumping test (ranging from 12.6 to 37.9 L/s [200 to 600 gal/min]) and during a 72-hour 31.5 L/s (500 gal/min) constant-rate pumping test (Figure 2). The dissolved gas sampling methodology used by EERI differed from that used by WWAL: EERI used evacuated 250 mL containers whereas WWAL used an air/gas separator in conjunction with Tedlar® bags. Dissolved gas concentration and isotopic results from these two methods will be compared, as both have their advantages and disadvantages (Hirsche and Mayer, 2009; Evans, 2017). In addition to the sampling of one well during the production well pumping tests in fall 2019, both production wells and a newly installed monitoring well (screened in the same aquifer) were sampled in the summer of 2020. Results from dissolved gas analyses corroborate WWAL's high dissolved methane concentrations; aqueous geochemistry data analysis is in progress.

Using these data, a substudy was undertaken to investigate the occurrence and source of groundwater methane in the buried-valley gravel aquifer beneath Hudson's Hope. There are concerns over both coal-bed methane (CBM) and fugitive gas in the study area, as an abundance of coal-bearing formations outcrop to the west, and there is unconventional natural gas activity to the north (Altares Field in the Montney Formation; Ryan et al., 2005). A coal-bearing formation of interest to this study is the Gething Formation, which commonly outcrops throughout the Rocky Mountain Foothills in northeastern BC (Gentzis et al., 2006). This unit is 400 m thick on average, varying between 100 and 1100 m, thinning toward the Alberta border. The average cumulative coal thickness in the study area is 6 m with a range of 5–20 m (Ryan et al., 2005). The coal ranks between high-volatile A bituminous and semi-anthracite, which are medium and high ranks of coal in terms of maturity, respectively (Ryan et al., 2005; Ryan and Lane, 2006).

The source of the high concentrations of hydrocarbon will be distinguished using carbon/hydrogen isotopic signatures in methane, ethane and carbon dioxide, and wetness parameter (ratio of methane to higher chain alkanes) from dissolved gas sampling. Whether the methane is from naturally occurring biogenic sources, immature thermogenic

Figure 2. Sampling setup at one of the production wells during a constant-rate pumping test in November 2019, near Hudson's Hope, northeastern British Columbia.

coal or deep formations through anthropogenic migration, it is important to characterize the source of these high concentrations (well above hazard level, typically stated as 10 mg/L) to understand potential legacy contamination, and establish baselines prior to potential future CBM or unconventional gas development near the aquifer chosen for the town's water supply.

Groundwater Recharge in a Confined Paleovalley Setting

While the monitoring well network will allow for a broad assessment of groundwater in the Peace Region, a more focused site study is better suited to quantify processes on the individual aquifer or flow system scale. The hydraulic characteristics of major aquifers of the Peace Region have been the subject of increasing interest over the last decade (Brown et al., 2011; Baye et al., 2016; Morgan et al., 2019; Chao et al., 2020). Even though groundwater is not the main source of drinking water for the over 60 000 residents of the Peace Region, as most large communities source their water supply from major rivers, understanding sustainable yield of groundwater is important for domestic, industrial, agricultural and environmental purposes (Bredehoeft, 2002; Baye et al., 2016; Statistics Canada, 2017). Most groundwater wells in northeastern BC are constructed with a well screen installed in weathered/fractured bedrock, with fewer having the screen installed in buried-valley sand/gravel aquifers (Baye et al., 2016). Buried-valley, or paleovalley, aquifers commonly host significant sources of groundwater in those areas where they are thick and laterally continuous (Hickin et al., 2008). In particular, a buried-valley aquifer located in the Peace River paleovalley near Hudson's Hope was shown to yield 31.5 L/s (600 gal/min) during a 72-hour constant-rate pumping test (Gardiner et al., 2020).

The objective of this study is to determine dominant recharge pathways through low-permeability confining layers to both weathered bedrock and buried-valley aquifers (see Goetz and Beckie, 2020, for more details). The spatial distribution of recharge values, residence times of aquifers and the quantification of the steady-state water balance of this archetypical groundwater flow system of the Peace Region will be determined. Over much of the study area, these aquifers are confined by low-permeability tills, which limit recharge rates but also isolate the aquifers from surficial processes such as drought and surficial contamination (Cummings et al., 2012). Since recharge is a major component of the groundwater budget, the interpreted model results will help inform sustainable extraction of this finite groundwater supply and help quantify the groundwater flow velocity and therefore the advective transport of dissolved fugitive gas potentially released from compromised energy wells (Bredehoeft, 2002; Cahill et al., 2019; Chao et al., 2020). As the study area is in an area of unconventional gas development, it is important to understand typical regional-scale groundwater flow patterns that control the movement of dissolved gases.

There are no specific modelling studies with a primary focus on groundwater recharge of buried-valley settings in northeastern BC. This region is distinct from those described in most other Western Canada Sedimentary Basin (WCSB) studies due to the undulating terrain near the Rocky Mountain Foothills and the lack of features common to the Prairie Pothole Region, which are hypothesized to be the dominant recharge mechanism found in many WCSB buried-valley systems (Meyboom, 1966; Berthold et al., 2004; Cummings et al., 2012). In this study, the hydrogeology of the Sunset paleovalley was conceptualized using available hydrogeological data for buried-valley aquifer systems in northeastern BC and the WCSB, and with data from MWIP monitoring wells within the study area (Figure 1). This study focuses on a single, confined buried-valley/fractured-bedrock aquifer system, which is a hydrogeological setting common to northeastern BC (Hickin et al., 2008, 2016).

In most groundwater systems, the distribution and magnitude of recharge is predominantly dependent on climate (precipitation/evapotranspiration rates), geological framework (confining thickness/conductivity) and topography (runoff/infiltration ratio; Winter, 2001; Sanford, 2002). The dominant factor controlling recharge for this study area is assumed to be lithology, with most recharge likely originating where the confining till/clay is thinnest, resulting in a shorter travel time to assimilation and storage in aquifer material (Andriashek, 2003; Nastev et al., 2005; Cummings et al., 2012). Recharge into buried-valley aquifers depends greatly on the bulk permeability of the confining layer (e.g., till) and groundwater residence times in till material have been shown to range from thousands to tens of thousands of years (Keller et al., 1989). Although buried-valley aquifers are typically confined, localized heterogeneities and discontinuities can create 'windows' of unconfined conditions (Nastev et al., 2005). These windows can then provide hydrological pathways for recharge, which is focused toward weathered bedrock and buried-valley aquifers (Korus et al., 2017).

Using the U.S. Geological Survey's MODFLOW 6 software (Hughes et al., 2017), groundwater-flow models for the shallow (<200 m), regional, multilayered aquifer system were constructed and calibrated. Within the study area, the model quantitatively estimated the spatial distribution and magnitude of groundwater recharge and discharge, the water balance between defined hydrostratigraphic units and residence times of groundwater in aquifers.

Figure 3. Examples of geological material encountered during the Monitoring Well Installation Project drilling campaigns: **a)** fine sandstone, rounded and well sorted; quartz and lithic (±10%) grains, with a few shaly patches and laminar stratification; **b)** dark massive mudstone with brown shaly patches and load-cast structures; fractures in horizontal disposition; **c)** very fine sandstone, rounded, well to moderately sorted; quartz, lithic and mica grains with a shaly matrix in a laminar stratification; **d)** very fine muddy sandstone, rounded and well sorted; quartz, lithic and mica grains with shaly horizons; cross-bedding stratification; **e)** massive medium sandstone, rounded and well sorted; quartz, lithic and mica grains well consolidated in a shaly matrix; **f)** massive medium sandstone, rounded to subrounded and well sorted; quartz, lithic and mica grains very well consolidated in matrix; **g)** clast-poor muddy diamict from the upper soil; **h)** clast-intermediate diamict from the upper soil; **I)** clast-poor diamict from the upper soil. Samples recovered from monitoring wells EERI-7, -8, -11 and -18B (see Figure 1 for locations).

Investigating Petrophysical Properties of Bedrock Strata in the Peace Region

During drilling for the MWIP, a series of core samples were recovered in order to characterize the bedrock's key petrophysical properties, which control the flow and migration of fugitive gas in the shallow subsurface within the Peace Region. Key core samples are undergoing porosity and permeability measurements as well as CT scan analyses to characterize the pore structure and inferflow properties. Figure 3 shows the range of geological material encountered during installation of the MWIP wells, including shale, siltstone and sandstone units in addition to the ubiquitous Quaternary diamict that prevails at surface throughout the region.

Initial results of petrophysical characterization suggest a large range in pore structure properties (i.e., pore-size distribution and mean pore diameter) based on sediment type. Consequently, this has resulted in a large range in key fluid flow parameters; meaning fugitive gas flow in the subsurface within the Peace Region is highly complex and dynamic. Figure 4 shows an example of mercury intrusion capillary porosimetry (MICP) data attained for a very tight mudstone (with thin fine sandstone interlayers) encountered in EERI-11 at a depth of 46.3 m (sample EERI-11_152; Figure 3b). Results show that 80% of the measured pore structure is composed of pores with a pore throat diameter of <0.1 µm. This indicates the strata will act as a robust capillary barrier to flow and significant entry pressures will be required for a gas phase to enter or move through it.

Geochemical Classification of Hydrogeochemical Units and Potential Degradation of Groundwater Quality from Interactions between Methane and Subsurface Materials

The occurrence of methane (CH_4) in shallow groundwater has seen increasing degrees of study in the past decades due to the surge of hydraulic fracturing practices, particularly in North America (Mason et al., 2015). Although methane is

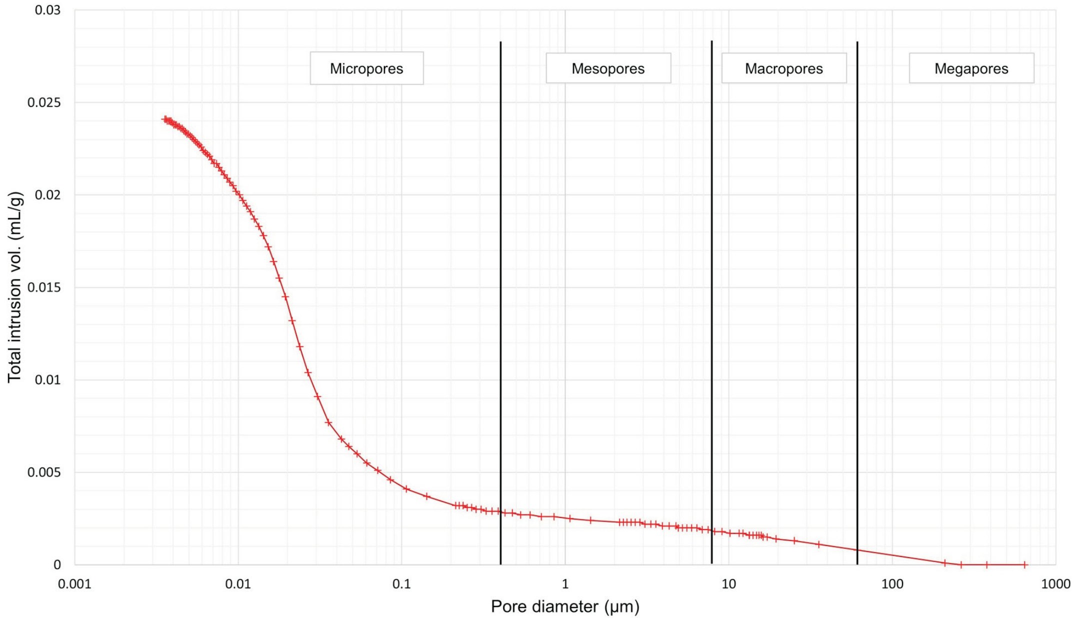

Figure 4. Graph showing percentage of total intrusion volume achieved versus calculated pore throat diameter for a sample of mudstone encountered in monitoring well EERI-11 at 46.3 m depth. Results show a very tight formation with very small pores dominating the pore structure, which infers that this unit would act as a robust capillary barrier to fugitive gas flow in the subsurface.

commonly present in many natural environments, high concentrations in groundwater can lead to detrimental effects on water quality not only as a combustion risk, but also through geochemical alteration of aquifer materials (Van Stempvoort et al., 2005). Characterizing the sediment and bedrock geochemistry of aquifer materials that may be exposed to increased concentrations of methane can provide insight toward assessing risk to the quality of groundwater in those aquifers. Additionally, identifying processes by which production and accumulation of methane occurs is an essential aspect of understanding the potential sources of the methane (Schoell, 1988). Investigating how elevated methane concentrations affect the hydrochemistry of groundwater and the subsequent interactions with geological aquifer materials may indicate specific hazards to groundwater quality.

In most subsurface environments, dissolved methane is relatively stable under anoxic conditions and can easily be advectively transported through groundwater without being involved in any reactions (Appelo and Postma, 2005). However, changes in water chemistry due to methane-related reactions can potentially occur where there are elevated methane concentrations and suitable electron-accepting species over relevant temporal and spatial scales. These can range from methane-oxidation–related processes, such as decreases in pH, increases in alkalinity and increases in trace metal concentrations (Cahill et al., 2017), to methane-driven reduction processes leading to elevated pH and alkalinity and mobilization of trace metals (Van Stempvoort et al., 2005; Schout et al., 2018). Change of pH in groundwater is one of the main driving forces behind mobilization of chemical species. When pH is considered with oxidation reduction potentials (Eh or pe), the stability fields for solids and aqueous phase chemical species can be defined (Faure, 1997; Appelo and Postma, 2005). Reductive dissolution or oxidation of minerals containing heavy and trace metals (such as Cd, Cr, Pb, Ni, Se, Hg, U, As), which can degrade groundwater quality, can occur when the redox conditions are altered. Substitution of heavy metals for primary metals in minerals is common, leading to varying compositions and the potential for release of heavy metals into the environment upon mineral dissolution. Heavy and trace metals may not always be directly incorporated into mineral structures; oxyanions and cations can be sorbed onto surface sites of oxides, clay minerals or organic matter, or within the structure of minerals such as iron and manganese oxides and oxyhydroxides. Changes in pH and Eh induced by methane-related redox reactions can result in mobilization of adsorbed species through ion exchange, desorption processes or dissolution, leading to significant water quality problems (Cullen and Reimer, 1989; Smedley and Kinniburgh, 2002; Appelo and Postma, 2005; Nesse, 2012). Characterizing the mineralogical and chemical composition of aquifer materials and determining the mineral fraction in which toxic metals reside, can aid in the prediction for mobilization of those contaminants into aquifer systems after changes in redox conditions caused by elevated methane concentrations.

The purpose of this study is to understand how dissolved methane in shallow aquifer systems can interact with geological materials leading to changes in groundwater quality. The study focuses on the Peace Region, using data from the recently installed EERI monitoring well network and the sediment and bedrock core and chip samples obtained during drilling.

The first objective is to characterize the geochemical composition of both unconsolidated and bedrock aquifer materials and surrounding subsurface materials. Borehole samples from areas both proximal and distal to oil and gas production will be analyzed. During drilling operations at the 29 EERI well locations, sediment and bedrock samples were obtained approximately every 1.5 m. Of these samples, a subset of 128 samples was chosen for bulk chemical analysis at ALS-Environmental (Vancouver, BC). Whole rock analysis by lithium metaborate fusion, trace element detection by four acid and aqua-regia digestion, and combustion analysis for carbon and sulphur will be completed. Statistical analysis of the bulk chemistry is being used to generalize subsurface materials, based on chemical composition, into hydrogeochemical stratigraphic units, with the aim of providing a predictive means of determining geochemical compositions of sediment and bedrock beyond point data sources, such as boreholes.

The second objective is to determine the potential interactions between methane-containing groundwater and subsurface materials, as well as investigate the subsequent detrimental effects on groundwater quality from water-rock interactions through laboratory experiments and numerical modelling. A smaller subset, 25 of the 128 bulk chemistry samples, have been subjected to a sequential extraction procedure (SEP) in the Aqueous Geochemistry Laboratory at Simon Fraser University (Burnaby, BC). This SEP targets nine separate mineral phases and chemical fractions including

1) water soluble and secondary sulphates,
2) weakly adsorbed fraction,
3) strongly adsorbed fraction, carbonates and monosulphides,
4) easily reducible oxides,
5) reducible oxides and low crystalline oxides,
6) crystalline oxides,
7) acid volatile sulphides,
8) organics and humic substances, and
9) sulphides.

Determining the abundance of potentially harmful chemical species in differently mobilized fractions of subsurface materials will allow for an investigation into the possible interactions between methane-containing groundwater and these materials. The associated risk of groundwater degradation may be approximated depending on the likelihood of species mobilization, which is dependent on the phase or fraction in which it occurs.

Summary

The Energy and Environment Research Initiative groundwater monitoring well network of 29 monitoring stations across the Peace Region has been installed. In 2019–2020, monitoring wells were sampled for inorganic and gas geochemical analysis and isotopic analysis as described in this paper. Hydrochemical analyses of water samples collected in summer 2020 are pending. The data provided by the monitoring well network will be synthesized into a peer-review publication, which is currently underway. Four separate student-led substudies have also been undertaken: i) an examination of the origin of methane in an aquifer located at Hudson's Hope, ii) an investigation of recharge processes and pathways in a typical buried-valley aquifer system in northeastern BC, iii) the petrophysical properties of near-subsurface aquifer materials in northeastern BC, and iv) geochemical classification of hydrogeochemical units and analysis of groundwater quality from interactions between methane and subsurface materials. These studies will first appear in student theses and then in peer-reviewed literature.

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