# Peace Region Scientific Groundwater Monitoring Network Installation Study

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**Peace Region Scientific Groundwater Monitoring Network Installation Study**
Project 2017-002 Final Report

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

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

**B. Ladd, The University of British Columbia, Vancouver, British Columbia**

**P.S. Gonzalez The Lyell Centre, Heriot-Watt University, Edinburgh, Scotland**

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

**D. Kirste, 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**

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

## Executive Summary

Rapid expansion of unconventional gas extraction has been accompanied by environmental concerns related to fugitive gas due to wellbore integrity failure of energy wells, principally in the United States (Vidic et al., 2013). The risks associated with fugitive gas migration (GM) include deterioration of groundwater quality, increase in greenhouse gas emissions, and explosive hazards in confined spaces. Northeastern British Columbia (NEBC) hosts some of the world's largest unconventional gas reservoirs, which contribute more than 60% of the province's total gas production as of 2016 (Adams and Balogun, 2016). However, no assessments of baseline groundwater quality were conducted prior to energy resource development, and therefore groundwater dissolved natural gas conditions were poorly understood on a regional scale.

This project, conducted through the Energy and Environment Research Initiative (EERI) at the University of British Columbia and performed in complement to two other projects (see http://www.geosciencebc.com/projects/2016-043/ and http://www.bcogris.ca/sites/default/files/hs-2018-02-gas-migration-final-report-march20.pdf), aspires to address knowledge gaps about environmental impacts and environmental fate of GM in geology typical of NEBC. The principal research objective is to characterize groundwater quality in the Peace Region of NEBC, an area of active oil and gas development, with a specific focus on the distribution, concentration, and origin of dissolved hydrocarbons, principally methane. The project objectives were achieved by the installation of and sampling from a network of 29

monitoring wells (MW) distributed through the Peace Region at locations determined by criteria described in earlier Geoscience BC reports (Allen et al., 2021; B. Ladd et al., 2020). Results from this project will inform appropriate groundwater monitoring strategies in light of continued oil and gas development for the region.

In this activities report, we provide the motivation, background, and information on the project progression as well as summaries of our principal findings, which are fully described in peer-reviewed journal publications and student theses, some under preparation. These knowledge products include:

- An overview of fugitive gas in northeastern BC, and preliminary results from this project in the context of the wider EERI program.
- A study focusing on determining the distribution and sources of dissolved natural gas, principally methane, based on sampling from the newly installed monitoring network of 29 wells, and from domestic wells across the Peace Region.
- A study quantifying recharge mechanisms of a buried-valley groundwater system using a steady-state groundwater flow model.
- A manuscript describing regional-scale and local-scale methane characterization studies, as well as the buried-valley recharge study mentioned above.
- A study of the geochemical composition of subsurface materials in NEBC and how fugitive gas could affect groundwater quality.
- A study investigating the petrophysical properties of sedimentary formations encountered during drilling across the Peace Region to better constrain how mobile any fugitive gas may be in the shallow subsurface.

**Principal findings**

- Productive groundwater zones are typically found at base of quaternary sediments or the fractured top of bedrock (Goetz, 2021).
- Median groundwater total dissolved solids (TDS) content in samples from the monitor-well network was approximately 1800 mg/L, ranging from a minimum of 489 mg/L to a maximum of approximately 5997 mg/L (water TDS is considered excellent if it is less than 300 mg/L; water with TDS > 1200 mg/L is considered unacceptable for human consumption) (Allen, 2021).
- Spatially averaged groundwater recharge rates in the Sunset Paleovalley, a system representative of NEBC, were estimated to be 16 mm per year; groundwater flow was slow - residence times averaged 2900 years (A. M. Goetz et al., 2021).

- Dissolved methane is ubiquitous in groundwater; concentrations in most samples are less than 0.1 mg/L. Concentrations greater than 1 mg/L were found in only 3 of 29 monitoring-well samples (Allen, 2021; Goetz, 2021 and Goetz et al 2021 in preparation).
- Stable carbon isotopes, and the concentrations of methane, ethane and propane, indicate a biogenic origin of natural gas from all but one sample from the monitoring-well network (Allen, 2021; Goetz, 2021 and Goetz et al 2021 in preparation).
- Dissolved natural gas concentrations were not correlated with proximity of monitoring well to energy wells (Allen, 2021; Goetz, 2021 and Goetz et al 2021 in preparation).
- Methane concentrations in groundwater samples collected from the water-supply wells for the town of Hudson's Hope ranged from between 24.7 to 95.9 mg/L. No higher-chain hydrocarbons were detected in the samples. Stable-carbon isotopes suggest that the methane is thermogenic. The methane is not related to energy development; the most likely origin is the Gething Formation coalbeds, which underlie the town's buried-valley water-supply aquifer (Goetz, 2021).
- The highest methane concentration from monitoring-well network samples was 32.0 mg/L in well EERI 16. Isotopes and wetness indicate that the gas is thermogenic. There are two potential explanations for origin of the gas: 1) proximal energy wells, 3 of which are less than 200 m from EERI 16, although there are no reports of surface casing vent flow, gas migration, or abandoned well leaks; 2) natural geologic pathways, associated with faulting, could connect the sampling depth to a deeper gas source. Further investigation is required to distinguish between these explanations (Allen, 2021; Goetz, 2021 and Goetz et al 2021 in preparation).
- Water quality results from samples from domestic water wells were statistically equivalent to those from samples collected from newly installed monitoring wells (Allen, 2021 and Goetz et al in preparation).

Ultimately, the data and knowledge resulting from this project have allowed us to comprehensively assess regional groundwater natural gas conditions in the Peace Region, northeastern BC. Findings from the various research outputs will help support policy making by regulators and provide technical guidance for groundwater protection and GM, including informing groundwater monitoring strategies.

## Introduction

Technological advances in hydraulic fracturing have led to the increase of natural gas exploitation from low-permeability siltstone and shale in Canada since the early 2000's (Kerr, 2010). With this extensive, rapid expansion in unconventional gas extraction comes the increase of the general public's concern about potential effects of natural gas development on shallow groundwater resources (Gordalla et al., 2013; Osborn et al., 2011; Zoback et al., 2010). The main mechanism by which deep thermogenic gas unintentionally enters shallow groundwater systems is hypothesized to be related to wellbore integrity failure of energy wells (Gurevich et al., 1993; Jackson & Dusseault, 2014). This anthropogenic migration of natural gas (primarily methane) is typically coined "fugitive gas" (FG), which is defined by the flow of gas outside of the surface casing of an energy well (BC Oil and Gas Commission, 2020; Hammond et al., 2020; Hildenbrand et al., 2020; Jackson et al., 2013; Matthews et al., 2014; Osborn et al., 2011; Vidic et al., 2013). While methane itself is non-toxic for human consumption, there are several environmental concerns related to FG. Potential negative environmental impacts from this unintentional release of hydrocarbons include deterioration in groundwater quality, greenhouse gas emissions and explosive risk in confined spaces (Caulton et al., 2014; Darling and Gooddy, 2006; Forde et al., 2019; Gorody, 2012; Jackson et al., 2013; Kang et al., 2014; Williams and Aitkenhead, 1991).

Methane is one of the dissolved gases most commonly identified in groundwater systems at low concentrations, and has various origins and generation processes (Darling and Gooddy, 2006). Methane can originate from shallow anoxic groundwater systems, natural migration from deeper formations via structural features, or desorption from coal beds (Schoell, 1988; Whiticar, 1999). Therefore, identifying, and distinguishing FG from naturally occurring methane can be challenging.

Northeastern British Columbia (NEBC) hosts some of the world's largest unconventional gas reservoirs, which contribute over 60% of the province's total gas production as of 2016 (Adams and Balogun, 2016). Despite years of energy development in the Peace Region of NEBC, no assessments of baseline groundwater quality had been conducted prior to this study, and therefore groundwater and natural gas conditions in the top 100 m of the subsurface were poorly understood on a regional scale (Cahill et al., 2019). As of January 2018, the BC Oil and Gas Commission (BCOGC) had 145 reported confirmed gas migration (GM) cases from approximately 25 thousand energy wells (0.6%) within BC, with most cases occurring outside the Peace Region (Sandl et al., 2021a). Within the Peace Region, the Montney Resource play had 26 reported cases of approximately 19 thousand energy wells (~0.13%) (Cahill et al., 2019). As noted by Sandl et al (2021b), this is likely an underestimate as inspections and testing for GM is only required after evidence of possible GM is observed.

While the use of domestic water wells to gather groundwater data is undoubtedly a reasonable approach and has been shown to provide useful data (Darrah et al., 2014; Humez et al., 2020), concerns relating to sampling artifacts, lack of well construction and lithology records, non-discrete sampling intervals and poor well completions (Jackson & Heagle, 2016) limit the confidence in domestic well samples to be used to accurately detect and assess dissolved FG in groundwater. In this study, we assess dissolved hydrocarbons in near-surface groundwater by designing and constructing a network of 29 monitoring wells across the Peace Region of NEBC. To date, no study has designed and installed a purpose-built monitoring well network in a region of extensive historic and ongoing resource development. Furthermore, the design of this well network (described in Ladd et al (2020)) includes strategic placement of wells both distal and proximal to oil and gas wells. The study also compares samples from the monitoring wells with those from nearby domestic water wells to assess effectiveness of domestic well data in FG studies.

Key gaps in our knowledge of GM and FG in NEBC are: (1) FG and GM prevalence and causes are poorly understood; (2) there is a paucity of the baseline subsurface characterization data required to identify FG and GM; (3) there is a paucity of groundwater and solid-phase geochemical data required to assess the effects of GM on groundwater quality.

## Principal research objectives

To address concerns and uncertainties on the potential impact on groundwater quality from energy development, this study aimed to characterize natural gas in shallow (<100m) groundwater systems across the Peace Region of NEBC. The primary objective of this project was to determine current groundwater quality in the Peace Region with a specific focus on the distribution, concentration, and origin of dissolved hydrocarbons. The principal research objective was addressed through the installation of a network of 29 scientifically designed monitoring wells (Figure 1). The network was established in three phases:

1) As described in Ladd et al. (2020), a general framework was developed to strategically locate potential monitoring well locations. The general criteria of the framework included: regional coverage, hydrogeological considerations, and road/land access. Roughly one-third of monitoring wells were located in baseline areas that are distal from existing energy development (>1km from nearest energy well). Concurrently, two-thirds of monitoring wells were installed proximal to energy wells (<500m from nearest energy well) to assess if and where stray gas affects shallow groundwater. Proximal monitoring wells were sited near energy wells with attributes that best

represent the overall energy-well population in the project area. Attributes include well status (active/abandoned/orphaned), orientation (vertical/horizontal/deviated), and fluid type (gas/oil).

2) In 2018-2019, 29 monitoring wells were installed over the course of the project in five campaigns (Figure 2). The well locations, depths, principal selection criteria (attributes) are provided in Table A1. The monitoring wells were designed to conform to provincial groundwater monitoring well standards to ensure that representative samples of groundwater could be collected. Two of the 29 wells were Westbay multilevel sampling systems, intended to assess groundwater quality and flow in the vertical direction, such as described in the study by Meyer et al. (2014). A complete description of the monitoring network, including well logs, is available in Goetz (2021).

3) In 2019-2020, groundwater geochemical and dissolved-gas samples were taken over the course of four sampling campaigns. Sampling methods are outlined in Ladd et al. (2020), and in section 2.2.3 of Goetz (2021), while sample collection dates are provided in Allen et al. (2021).

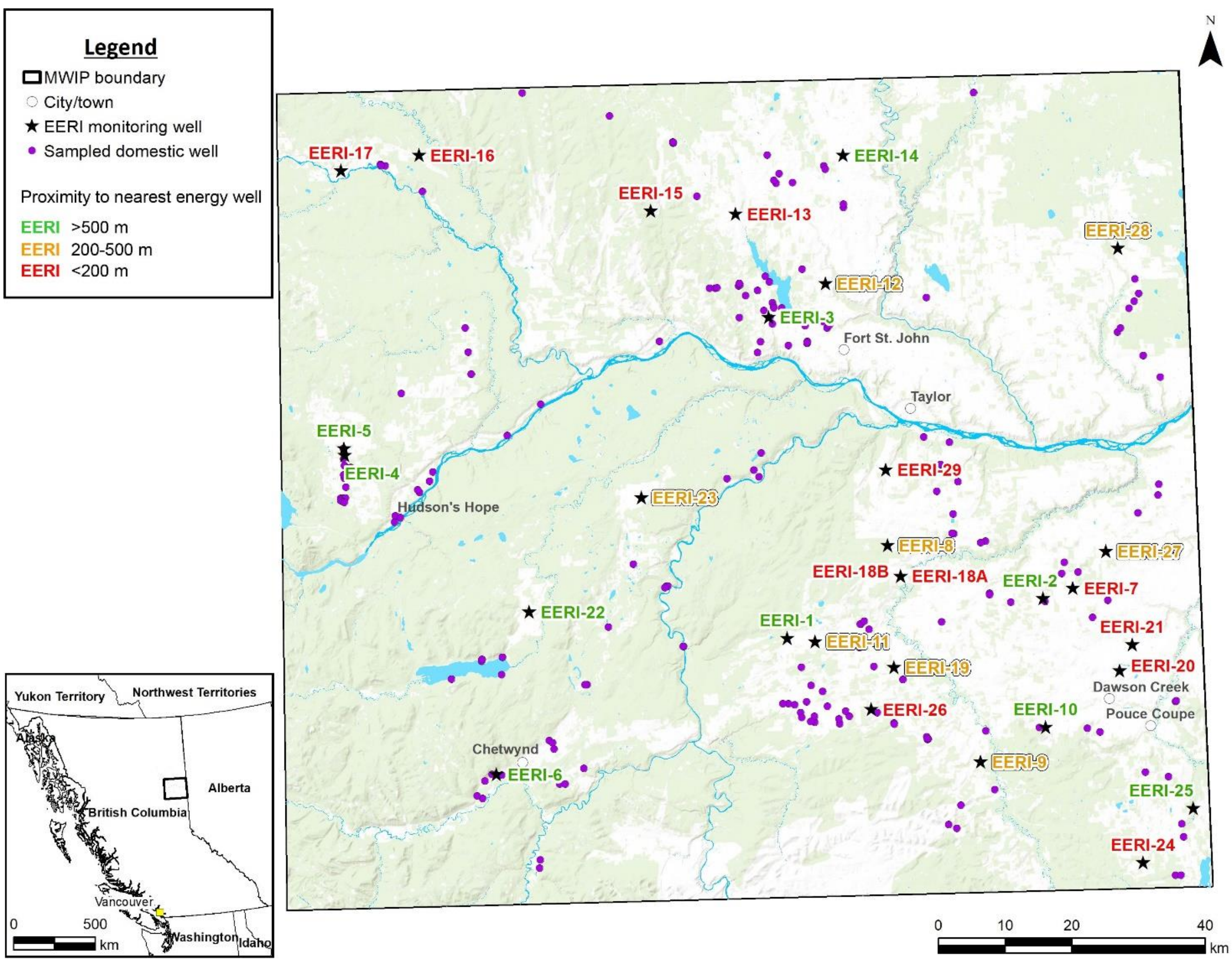


**Figure 1.** EERI monitoring well and domestic well locations in the Peace Region, NEBC. UTM Zone 10N, NAD 83.

**Figure 2.** Drilling equipment (Boart Longyear Sonic Track LS600) used for the majority of the monitoring well installations.

MSc students A. Allen and M. Goetz supervised the drilling and installation of the monitoring-well network, and collected two samples of groundwater from each sampling point, and plotted and analyzed the monitoring data, leading to the signature publication of this work, item 4) below (M. Goetz et al., 2021).

MSc. student M. Goetz used geological data collected in the context of installing the monitoring-well network to develop a model of groundwater flow in the Sunset Paleovalley, a typical buried-valley aquifer system. The objective was to characterize groundwater flow rates and water balances, information which can be used to better understand the longevity of FG and its transport and flushing through a representative groundwater system. M. Goetz also evaluated the source of high concentration dissolved methane in the Hudson’s Hope water supply wells, which are completed in a buried-valley aquifer that is isolated from energy wells and therefore represent natural background conditions at this site.
MSc. student A. Allen characterized the geochemical compositions for unconsolidated sediments and sedimentary rock strata representative of the Peace Region of British Columbia to better understand solid-

phase controls on groundwater geochemistry. He assessed the potential for these geological materials to release trace metals and other species of concern when exposed to methane and other hydrocarbons associated with FG.

A component of PhD. student P. Gonzales's research is to quantify those rock properties that affect the migration of fugitive gas. The laboratory/experimental study is based upon the analysis of core samples collected by A. Allen and M. Goetz during monitoring-well installation.

## Study area

The project took place in NEBC, a region of intensive oil and gas activity. The study area includes the communities of Fort St. John, Dawson Creek, Chetwynd, and Hudson's Hope. The shallow geology of the study area is generally highly heterogeneous overburden composed of complex sequences of till, glaciolacustrine, glaciofluvial, fluvial and lacustrine deposits (Chao et al., 2020), overlying Cretaceous bedrock shale, siltstone and sandstone (Riddell, 2012). Natural gas from unconventional energy resources has been primarily exploited from the lower Triassic aged Montney Formation, with most of the current and future activity located near Dawson Creek, BC. This formation is located approximately 800-4000 m below ground surface, with a thickness varying between 100-300m (Dixon, 2000). Energy wells in BC are required to set their surface casing a minimum of 600 m below ground level (mbgs) or to the base of known groundwater aquifers, whichever is deeper, to protect shallow groundwater resources. Water wells in the region rarely exceed 150 m below ground surface (Riddell, 2012).

## Research products and findings

In addition to addressing the primary research objectives, various complementary studies developed over the course of the main project. Here we compile and present 6 of our findings by providing summaries of, and links to, our published knowledge products.

1. Cahill, Aaron G., Roger D. Beckie, Bethany Ladd, Elyse Sandl, Maximillian Goetz, Jessie Chao, Julia Soares, et al. "Advancing Knowledge of Gas Migration and Fugitive Gas from Energy Wells in Northeast British Columbia, Canada." *Greenhouse Gases: Science and Technology* 9, no. 2 (2019): 134–51. https://doi.org/10.1002/ghg.1856.

This publication presents an overview of the complementary fugitive gas studies at UBC.

Petroleum resource development is creating a global legacy of active and inactive onshore energy wells. Unfortunately, a portion of these wells will exhibit gas migration (GM), releasing fugitive gas (FG) into adjacent geologic formations and overlying soils. Once mobilized, FG may traverse the critical zone (the near-surface environment where processes occur that regulate the natural habitat and determine the availability of life-sustaining resources), impact groundwater, and emit to the atmosphere, contributing to greenhouse-gas emissions. Understanding of GM and FG has increased in recent years, but significant gaps persist in knowledge of (1) the incidence and causes of GM, (2) subsurface baseline conditions in regions of development required to delineate GM and FG, and (3) the migration, impacts, and fate of FG. Here we provide an overview of these knowledge gaps as well as the occurrence of GM and FG as currently understood in British Columbia (BC), Canada, a petroleum and natural gas producing region hosting significant natural gas reserves. To address the identified knowledge gaps within BC, the Energy and Environment Research Initiative (EERI) at the University of British Columbia has implemented several field-focused research projects including: (1) statistical analyses of regulatory data to elucidate the incidence and causes of GM, (2) characterization of regional hydrogeology and shallow subsurface conditions in the Peace Region of the Montney resource play, and (3) investigation of the migration, impacts, and fate of FG in the shallow subsurface through controlled natural gas release. Together, the EERI investigations will advance understanding of GM and FG, provide scientific data that can inform regulations, and aid development of effective monitoring and detection methodologies for BC and beyond.

2. Goetz, Maximillian, and R. D. Beckie. "Groundwater Recharge in a Confined Paleovalley Setting, Northeastern British Columbia." Geoscience BC Summary of Activities 2020: Energy and Water, November 2020. http://www.geosciencebc.com/i/pdf/SummaryofActivities2020/EW/Sch_Goetz_EWSOA2020.pdf.

   Also, published in a revised form as:

   Goetz, A. Maximilian, Roger D. Beckie, and Aaron G. Cahill. "Groundwater Recharge in a Confined Paleovalley Setting, Northeast British Columbia, Canada." *Hydrogeology Journal* 29, no. 5 (August 1, 2021): 1797–1812. https://doi.org/10.1007/s10040-021-02359-3.

   and as chapter in the MSc. thesis of M. Goetz.

   In this study, the hydrogeology of the Sunset Paleovalley in NEBC was conceptualized using data from newly installed, scientifically designed monitoring wells and available hydrogeological data for buried-valley aquifer systems in the Western Canadian Sedimentary Basin. Using this conceptual model, a regional-scale, steady-state, groundwater-flow model was constructed to assess recharge magnitude and mechanisms, fluxes, and residence times to inform aquifer management. The calibrated average aerial recharge rate was 16 mm/yr., within the range of recharge estimates previously reported for NEBC (0.5 - 78 mm/yr.). The average residence times for buried valley sand/gravel and weathered bedrock aquifers was estimated at 3,200 and 2,900 years respectively; indicative of a slowly flushed system, consistent with the 1,300 mg/L average total dissolved solids groundwater chemistry. The current groundwater extraction rates are a small fraction of the simulated groundwater discharge to the Kiskatinaw River. Our findings can support management of groundwater resources in similar hydrogeological settings common to NEBC.

3. Goetz, Andreas Maximilian. "Regional Groundwater Conditions in Northeast BC: Results from a Monitoring Well Network in an Area of Historical and Ongoing Unconventional Natural Gas Development." MSc Thesis, University of British Columbia, 2021. https://open.library.ubc.ca/soa/cIRcle/collections/ubctheses/24/items/1.0396328

In this thesis, natural gas in near-surface (<110 m) groundwater in the Peace Region of NEBC, is assessed based on the sampling of the newly installed network of 29 purpose-built monitoring wells across the region. Analyses of groundwater samples from the monitoring wells (MW) suggest that dissolved methane, microbial in origin, is ubiquitous at low concentration (< 2 mg/L) in the critical zone of the study area. Based on gas composition and isotopic signatures, only one MW showed signs of potential thermogenic gas from a nearby energy well. However, the origin of the thermogenic gas is not certain: potential sources include unintentional leak from an energy well, or natural via a preferential flow path such as faulting, that connects a deeper gas zone to monitoring-well depths. No evidence of pervasive thermogenic natural gas was found in the study monitoring wells. This study explores similar research questions as bullet #2 but does not include results from sampling of domestic water wells in the Peace Region.

Additionally, within the same study area, groundwater collected from the domestic water supply wells in the District of Hudson's Hope buried valley aquifer show very high methane concentrations (>28 mg/L) which were determined to be from a coal bed methane (CBM) source, and not related to natural gas development wells. This finding suggests that high levels of naturally occurring methane may be of concern in the region where highly transmissive aquifers are in hydraulic connection with underlying coal-bearing zones.

Lastly, a sub-study focusing on quantifying recharge mechanisms of one of the paleovalleys of the Peace Region is investigated by constructing a steady-state groundwater flow model (thesis chapter version of bullet #3).

4. Allen (2021) "Geochemical Compositions of Subsurface Materials and the Potential Impacts on Groundwater Quality from Fugitive Methane within the Peace Region, British Columbia." MSc, Earth Sciences, Simon Fraser University, August 19, 2021. https://theses.lib.sfu.ca/6591/show

This research is comprised to two main components, the first endeavors to provide representative geochemical compositions for unconsolidated sediments and sedimentary rock strata found around the Peace Region of British Columbia. Classifying generalized units with related geochemical compositions and associated potentials for interactions with groundwater systems may allow regionally occurring hydrogeochemical units to be identified. Whole rock geochemistry of 128 sediment cores and chip samples obtained from EERI wells during drilling were analyzed for major oxide compositions, trace metal concentrations, and rare-earth element concentrations. Variations in compositions for major oxides are used to infer similarities within and between units. Select trace metals including Cr, Ni, Cu, As, Se, Cd, Sb, Hg, Pb, and U were investigated to present the likelihood of high concentration occurrences in different units, relating to potential for mobilization in groundwater. Rare earth element patterns and compositions are used to infer relationships between units relating to provenance, and to reinforce the compositional similarities and differences observed in major oxide and trace metal compositions.

The second component focuses on the mobilization potential for potentially toxic trace metals due to changes in groundwater chemical conditions initiated by the introduction of increasing methane into hydrogeologic systems from gas migration. A sequential extraction procedure (SEP) was performed on 24 sediment and core samples targeting different mineral phases and species fractions including: water soluble, weakly adsorbed, strongly adsorbed and carbonates, easily reducible oxides, reducible oxides, crystalline oxides, acid volatile sulfides, organics, and sulfides. Analysis of these fractions are compared to whole rock analysis results for trace metal compositions to deduce the proportion which could potentially be mobilized, and therefore identify the relative hazard related to different hydrogeochemical units. Abundance of potentially mobilized fractions are incorporated into numerical models representing various groundwater compositions identified in the Peace Region. Addition of methane into these models at different concentrations and rates simulates the extent of mobilization for different units and water compositions, indicating potential risks for degraded groundwater quality in relation to methane concentration.

**Further research findings: Work in progress**

5. Goetz, M., Allen, A., Cahill, A. G., Kirste, D. M., Welch, L., Ladd, B., et al. (2021). Fugitive gas not pervasive in near-surface groundwater of the Peace Region, British Columbia after 70 years of oil and gas development. *In Preparation for submittal to PNAS or ES&T*.

In this study, we assess methane in near-surface groundwater in the Peace Region of NEBC by installing a network of 29 purpose-built monitoring wells across the region, some as close as 70 m proximal to energy wells. In addition, we collected 252 groundwater samples from domestic water wells in the same region over a five-year period. Results reveal that the Peace Region consists of highly heterogeneous Quaternary geology (Figure 3) that hosts groundwater resources in which dissolved methane is ubiquitous, generally low (< 2 mg/L) in concentration and generally exhibits microbial-origin signatures. No correlation between dissolved hydrocarbon gases and proximity to or density of petroleum resource wells was observed. We measured dissolved methane, propane and butane, stable carbon isotopes, and inorganic species in addition to pH and specific conductance. Based on gas composition and isotopic signatures, only one monitoring well showed signs of potential thermogenic gas, although the origin is uncertain. Possible sources of the thermogenic gas include fugitive gas from a nearby energy well, or gas flux from an intermediate-depth gas zone transported via natural preferential pathways to monitoring-well depths. Our findings show that thermogenic gas can be present in the near-surface potable groundwater zone, but it is not pervasive. Furthermore, water quality observed in samples from newly installed purpose-built monitoring wells were statistically equivalent to those attained from existing domestic water wells, supporting the use of domestic wells as effective tools for monitoring and assessing dissolved gases in critical-zone groundwater.

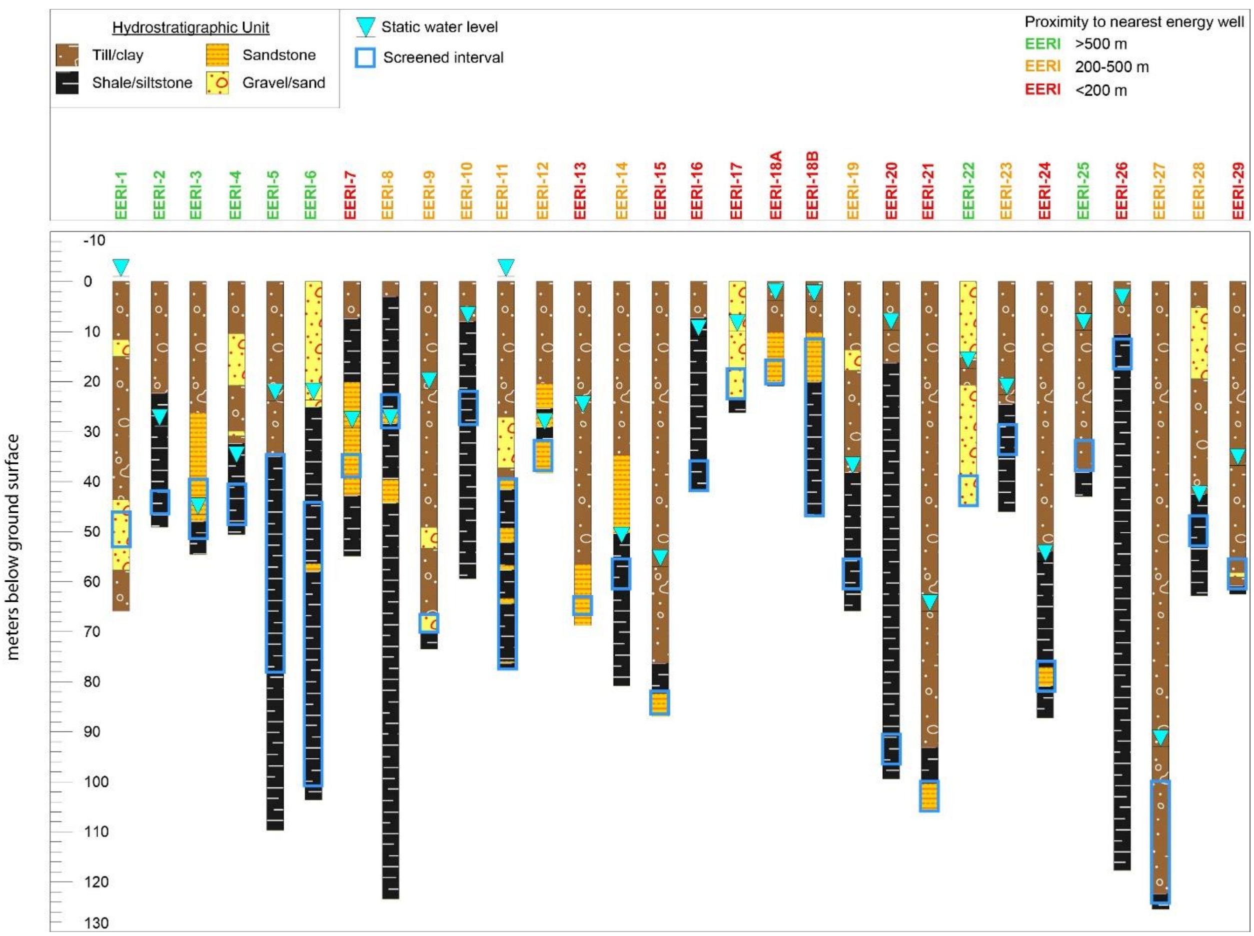

**Figure 3.** Generalized hydrostratigraphy of the 29 monitoring wells, showing the static water levels and screened depths relative to ground surface.

6. Gonzalez *et al.* 2022. Characterizing Petrophysical Properties of Shallow Sedimentary Bedrock in the Peace Region, BC with a view to Constraining Mobility of Fugitive Gas in the Subsurface. (Paper based upon PhD thesis of P. Gonzalez; expected May 2022)

To better constrain the potential for fugitive gas migration in the Peace Region of Northeast British Columbia, rock core samples of regionally important sedimentary formations attained during drilling of the project monitoring wells are being subjected to detailed characterization of petrophysical properties (e.g., Figure 4). The aim is to quantify various intrinsic rock properties that will influence the migration of fugitive gas out of an energy well structure into various lithologies if integrity failure occurs. The most important properties are porosity, pore- and grain-size distributions, permeability, threshold capillary pressures and displacement pressures. To date, we have separated this rock-core investigation into two phases of analyses. In the first phase we selected six representative sedimentary bedrock cores based on their level of preservation, competence, and consolidation and two samples of surficial diamictite, which is the main confining unit across the area of study. Samples were sent for Mercury Intrusion Capillary Analysis (MICP) (MCA Services Laboratories, Cambridge, UK), which provided us with porosity data that enabled the estimation of pore-size distribution from which pressure and conditions needed to initiate the displacement of groundwater by gas to allow migration through rock. In the second phase, we selected seven additional competent rock samples from two specific monitoring wells (EERI-11 and EERI-18B) for a more detailed examination of the effects of permeability and variations of petrophysical properties may have during subsurface fugitive gas migration within the Peace Region. Analyses undertaken in the second phase included thin-section petrographic analyses for insights into the mineralogy and fabric of the units along with helium porosity and gas permeability intrusion and extrusion profiles, measured using a nitrogen gas permeameter, to better understand how mobile fugitive gas may migrate in the subsurface of the Peace Region. Additionally, four samples from EERI-11 have been analysed by MICP, providing a high-resolution porosity dataset for this specific location. These samples will also be examined using a Micro-CT scanner to gain unprecedented insight on the sedimentary rocks’ pore network and its flow properties with respect to fugitive gas. Results from these core investigations will provide new insights into Peace Region sedimentary bedrock properties including; texture, volume factors, permeability, porosity, pore-size parameters, and the geometry of particles; all necessary to assess the risks posed by fugitive gas and predict its migration, impacts and fate in the subsurface of the Peace Region.


**Figure 4:** Core samples attained during drilling of the EERI monitoring well network which have been advanced for detailed petrophysics characterization to better constrain factors controlling migration of fugitive gas out of an energy well structure into various lithologies if integrity failure occurs.

## Conclusion

The data and knowledge from this project have allowed us to comprehensively assess regional groundwater natural gas conditions in the Peace Region, northeastern BC. Our findings can be used to support policy-making by regulators and provide technical guidance for groundwater protection and gas migration groundwater monitoring strategies. As a legacy, the groundwater monitoring network can be used to monitor groundwater quality of the Peace Region and can provide opportunities for collaboration with others. This report only summarizes the principal findings. We note that we have intentionally focused on publishing detailed findings in the international peer-reviewed literature, where they can receive the imprimatur of the broader scientific community and be more widely disseminated.

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Appendix A

Table A-1. Overview of well attributes for the 29 groundwater monitoring wells in the EERI network. Type refers to whether the well adheres to baseline or proximal criteria. Abbreviations: Aban., abandoned; masl, meters above sea level, mbgl, meters below ground level; mbtoc, meters below top of casing; ML, multilevel well; SG, soil gas port; SS, single screen well; OH, open hole in bedrock; WB, Westbay multilevel well.

| Well name | Top of casing elevation (masl) | Latitude | Longitude | Type | Total depth (mbgl) | Static water level 2019 (mbtoc) | Static water level 2020 (mbtoc) | Completion type | Screened lithology | Energy wells per 9km^2 | 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: fracked? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **EERI-1** | 704.1191 | 55.85430784 | -120.98949433 | Baseline | 53 | Artesian | Artesian | ML | sandy gravel/sand | 3 | 1557 | 60 | N/A | N/A | N/A | N/A |
| **EERI-2** | 745.4688 | 55.89597199 | -120.37538301 | Baseline | 46 | 28.86 | 28.78 | ML w/ SG | shale | 2 | 1331 | 609 | N/A | N/A | N/A | N/A |
| **EERI-3** | 720.2876 | 56.28623881 | -121.01181838 | Baseline | 54 | 46.55 | 46.534 | SS | sandstone/shale/siltstone | 2 | 883 | 197 | N/A | N/A | N/A | N/A |
| **EERI-4** | 713.8515 | 56.11255608 | -122.04089832 | Baseline | 49 | 36.31 | 25.79 | ML w/ SG | siltstone/sandy gravel & diamict/silt-sand | 0 | 2378 | 680 | N/A | N/A | N/A | N/A |
| **EERI-5** | 715.2874 | 56.12138897 | -122.04520920 | Baseline | 78 | 23.8 | - | SS w/ pump ^ | shale | 0 | 3263 | 120 | N/A | N/A | N/A | N/A |
| **EERI-6** | 634.3881 | 55.68044194 | -121.69037621 | Baseline | 103 | 23.64 | 23.62 | OH | shale/sandstone | 1 | 1666 | 405 | N/A | N/A | N/A | N/A |
| **EERI-7** | 775.0387 | 55.90835285 | -120.30260664 | Proximal | 39 | 29.24 | 29.26 | SS | sandstone | 39 | 70 | 1481 | vertical | gas | Aban. | no |
| **EERI-8** | 809.0346 | 55.97453571 | -120.74348635 | Proximal | 30 | 28.84 | 28.87 | SS | sandstone/shale | 24 | 438 | 2631 | vert and hor | gas | Active | yes |
| **EERI-9** | 712.5432 | 55.67944275 | -120.53788280 | Proximal | 70 | 21.52 | 21.39 | SS | sandy gravel | 17 | 214 | 2008 | horizontal | gas | Active | yes |
| **EERI-10** | 775.5116 | 55.72312214 | -120.38686272 | Baseline | 32 | 8.34 | 8.135 | SS | shale | 1 | 1729 | 723 | N/A | N/A | N/A | N/A |
| **EERI-11** | 694.6096 | 55.84549326 | -120.92331725 | Proximal | 77 | Artesian | | WB | sandstone/siltstone | 12 | 321 | 960 | vertical | gas | Active | yes |
| **EERI-12** | 674.2585 | 56.33129812 | -120.87364619 | Proximal | 38.5 | 29.65 | 29.4 | SS | sandstone | 17 | 265 | 696 | vertical | mixed o/g | Aban. | no |
| **EERI-13** | 716.7768 | 56.42639017 | -121.08513043 | Proximal | 69 | 26.17 | 26.045 | SS | sandstone | 10 | 175 | 719 | vertical | oil | Susp. | yes |
| **EERI-14** | 695.2302 | 56.49690261 | -120.82005826 | Proximal | 65 | 52.38 | 52.04 | SS | shale | 10 | 541 | 737 | vertical | gas | Active | yes |
| **EERI-15** | 681.7341 | 56.43348239 | -121.29093253 | Proximal | 87 | 56.97 | 56.85 | SS | sandstone | 6 | 183 | 5085 | horizontal | gas | Cased | no |
| **EERI-16** | 711.5707 | 56.51487842 | -121.85103236 | Proximal | 42 | 10.95 | 10.595 | SS | mudstone | 8 | 106 | 647 | horizontal | gas | Aban. | yes |
| **EERI-17** | 616.1124 | 56.49575992 | -122.04097347 | Proximal | 23 | 9.92 | 8.19 | ML w/ SG | sandy gravel | 5 | 152 | 853 | deviated | gas | Active | yes |
| **EERI18A** | 731.4046 | 55.93282743 | -120.71444441 | Proximal | 21 | 3.73 | 3.35 | SS | sandstone/siltstone | 43 | 140 | 2396 | horizontal | gas | Active | yes |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **EERI-18B** | 731.3355 | 55.93284418 | -120.71449426 | Proximal | 47 | 4.02 | - | WB | sandstone/siltstone | 43 | 140 | 2396 | horizontal | gas | Active | yes |
| **EERI-19** | 712.146 | 55.81053134 | -120.73732854 | Proximal | 69 | 38.41 | 38.34 | SS | mudstone | 24 | 345 | 543 | horizontal | gas | Active | yes |
| **EERI-20** | 731.6792 | 55.79523356 | -120.19876950 | Proximal | 99 | 9.67 | 9.8 | SS | mudstone | 13 | 97 | 2250 | horizontal | gas | Active | yes |
| **EERI-21** | 671.7911 | 55.82961920 | -120.16646878 | Proximal | 106 | 65.91 | 65.76 | SS | conglomerate | 16 | 173 | 1246 | horizontal | gas | Active | yes |
| **EERI-22** | 706.1782 | 55.89793737 | -121.60457459 | Baseline | 44.5 | 17.38 | 17.15 | SS | sandy gravel | 0 | 7498 | 424 | N/A | N/A | N/A | N/A |
| **EERI-23** | 686.368 | 56.04858955 | -121.33040150 | Proximal | 40 | 22.65 | 22.415 | SS | shale | 6 | 259 | 879 | deviated | gas | Susp. | yes |
| **EERI-24** | 765.7252 | 55.53622929 | -120.16157164 | Proximal | 87.2 | 55.96 | 17.44 | SS | Siltstone/mudstone | 20 | 180 | 1493 | horizontal | gas | Active | yes |
| **EERI-25** | 671.6269 | 55.60608814 | -120.03725423 | Baseline | 38.4 | 9.71 | 9.616 | SS | diamict | 8 | 1132 | 881 | N/A | N/A | N/A | N/A |
| **EERI-26** | 797.4735 | 55.75500042 | -120.79373652 | Proximal | 18.3 | 4.77 | 4.73 | SS | mudstone/fine sandstone | 6 | 180 | 1260 | horizontal | gas | Susp. | yes |
| **EERI-27** | 659.9092 | 55.95624266 | -120.21942553 | Proximal | 123 | >93 | 98.365 | SS | sandy silt / clay | 9 | 306 | 2812 | horizontal | gas | Active | yes |
| **EERI-28** | 697.8911 | 56.36269113 | -120.16229258 | Proximal | 57.9 | 44.15 | 43.95 | SS | shale | 3 | 301 | 3588 | vertical | undefined | Aban. | no |
| **EERI-29** | 701.3867 | 56.07648041 | -120.74107108 | Proximal | 59.4 | 36.79 | 37.02 | SS | silt/sand, lesser diamict | 23 | 198 | 2891 | horizontal | gas | Active | yes |

^permanent pump installed due to agreement with landowner

Appendix B

## Links to publications derived from this project

Allen (2021) “Geochemical Compositions of Subsurface Materials and the Potential Impacts on Groundwater University Quality from Fugitive Methane within the Peace Region, British Columbia.” MSc, Earth Sciences, Simon Fraser, August 19, 2021. https://theses.lib.sfu.ca/6591/show

Cahill, Aaron G., Roger D. Beckie, Bethany Ladd, Elyse Sandl, Maximillian Goetz, Jessie Chao, Julia Soares, et al. “Advancing Knowledge of Gas Migration and Fugitive Gas from Energy Wells in Northeast British Columbia, Canada.” *Greenhouse Gases: Science and Technology* 9, no. 2 (2019): 134–51. https://doi.org/10.1002/ghg.1856.

Goetz, Andreas Maximilian. “Regional Groundwater Conditions in Northeast BC: Results from a Monitoring Well Network in an Area of Historical and Ongoing Unconventional Natural Gas Development.” MSc Thesis, University of British Columbia, 2021. https://open.library.ubc.ca/soa/cIRcle/collections/ubctheses/24/items/1.0396328

Goetz, Maximillian, and R. D. Beckie. “Groundwater Recharge in a Confined Paleovalley Setting, Northeastern British Columbia.” Geoscience BC Summary of Activities 2020: Energy and Water, November 2020. http://www.geosciencebc.com/i/pdf/SummaryofActivities2020/EW/Sch_Goetz_EWSOA2020.pdf.

Published in a revised form as:

Goetz, A. Maximilian, Roger D. Beckie, and Aaron G. Cahill. “Groundwater Recharge in a Confined Paleovalley Setting, Northeast British Columbia, Canada.” *Hydrogeology Journal* 29, no. 5 (August 1, 2021): 1797–1812. https://doi.org/10.1007/s10040-021-02359-3
The post-print of this article is included in Appendix C of this report.

Appendix C

Post print of Goetz, A. M., Beckie, R. D., & Cahill, A. G. (2021). Groundwater recharge in a confined paleovalley setting, Northeast British Columbia, Canada. *Hydrogeology Journal*, *29*(5), 1797–1812. https://doi.org/10.1007/s10040-021-02359-3

# Groundwater recharge in a confined paleovalley setting, Northeast British Columbia, Canada

Maximilian Goetz[1]*, Roger Beckie[1], Aaron Cahill[2]

1. Energy and Environment Research Initiative, The University of British Columbia, 2207 Main Mall #2020, Vancouver, Canada. Email: mgoetz@eoas.ubc.ca
2. The Lyell Centre, Heriot-Watt University, Edinburgh, Scotland

## Abstract

Ancient river channels or sub-glacial drainage networks infilled with younger sediments can include significant deposits of highly permeable sands and gravels. Despite being hidden at surface, such systems are ubiquitous globally, can form highly productive groundwater reservoirs and have significant influence on regional hydrogeology, contaminant transport and local water resources. Consequently, the hydraulic characteristics of such buried valley or "paleovalley" aquifers have been the subject of increasing study. In this study, the hydrogeology of the Sunset Paleovalley in Northeast British Columbia (NEBC) was conceptualized using data from newly installed, scientifically designed monitoring wells and available hydrogeological data for buried-valley aquifer systems in NEBC and the Western Canadian Sedimentary Basin (WCSB). Using this conceptual model, a regional-scale, steady-state, groundwater-flow model was constructed to assess recharge magnitude and mechanisms, fluxes, and residence times to inform aquifer management. The calibrated average aerial recharge rate was 16 mm/yr., within the range of recharge estimates previously reported for NEBC (0.5 - 78 mm/yr.). The average residence times for buried valley sand/gravel and weathered bedrock aquifers was estimated at 3,200 and 2,900 years respectively; indicative of a slowly flushed system, consistent with the 1,300 mg/L average total dissolved solids groundwater chemistry. The current groundwater extraction rates are a small fraction of the simulated groundwater discharge to the Kiskatinaw River. Our findings can support management of groundwater resources in similar hydrogeological settings common to NEBC.

## Keywords

Recharge · Numerical Modeling · Conceptual Model · Canada

## 1. Introduction

Buried valley or "paleovalley" aquifers are ancient river channels or sub-glacial drainage networks infilled with younger sediments commonly characterized by highly permeable (> 1 m/d) sands and gravels confined by low permeability (< 0.01 m/d) aquitards (Cummings et al., 2012; Gates et al., 2014; Kamp & Maathuis, 2012; Kehew & Boettger, 1986; Ritzi et al., 2000). The architecture of paleovalley sedimentary systems are known to be incredibly complex (Cummings et al., 2012; Korus et al., 2017; Morgan et al., 2019; Pugin et al., 2014) and the location of sand/gravel aquifers within the overburden packages is often unpredictable. Where present, lenses of sand and gravel within these systems can form highly productive groundwater aquifers. Such buried-valley aquifers are found in glaciated terrains worldwide, and in particular throughout the Western Canadian Sedimentary Basin (WCSB).

For groundwater resource management it is important to understand and characterize recharge mechanisms, magnitude, and spatial distribution as part of the water balance (Nastev et al., 2005;

Pétré et al., 2019). Recharge rates depend on climate (precipitation/ evapotranspiration rates), geological framework (confining thickness/conductivity), and topography (runoff/infiltration ratio) (Sanford, 2002; Winter, 2001). Recharge to paleovalley aquifers depends strongly on bulk permeability of the confining layer. In the WCSB, groundwater travel times in confining till have been shown to range from thousands to tens of thousands of years (Cravens & Ruedisili, 1987; Keller et al., 1989). Based on environmental tracers, slug and laboratory test, recharge rates through confining till in WCSB settings have been estimated at 0.5 – 3 mm/yr. (Hayashi et al., 1998; Shaw & Hendry, 1998). These low-permeability deposits both limit recharge and protect groundwater from potentially detrimental surficial processes such as drought and contamination (Cummings et al., 2012). Based on environmental traces such as tritium, the dominant pathway for recharge in paleovalley systems has previously been hypothesized to be “windows” of thin (or even absent) surficial confining material. Such geological windows result in shorter travel times (Andriashek et al., 2003; Cummings et al., 2012; Gates et al., 2014; Nastev et al., 2005; Pétré et al., 2019) and allow focused recharge to underlying weathered bedrock and buried-valley aquifers (Korus et al., 2017).

The Peace Region in Northeast British Columbia (NEBC) is located on the western edge of the WCSB, bordering the Canadian Rocky Mountains (Fig. 1). Spurred by increasing reliance on groundwater in the energy sector, the hydraulic characteristics of major aquifers of the Peace Region in Northeast BC have been the subject of increasing interest over the last decade (Baye et al., 2016; Chao et al., 2020; Foundry Spatial, 2011; Hickin & Best, 2012; Morgan et al., 2019). Although groundwater is not the main source of drinking water for most large communities in the Peace Region, as most towns with populations greater than 500 draw from river water, understanding the groundwater resources is important for current and future domestic, industrial, agricultural and environmental use (Baye et al., 2016; Bredehoeft, 2002). However, buried-valley aquifers can be significant sources of groundwater where they are thick and laterally continuous (Hickin et al., 2008). For example, a buried-valley aquifer located in the Peace River paleovalley near Hudson's Hope, BC was shown to yield 31.5 L/s (600 gpm) during a 72 hour constant rate pumping test (Gardiner et al., 2020). However, recharge regimes for paleovalley aquifer systems are difficult to quantify and many knowledge gaps persist.

The hydrogeology of buried valley systems around the world has been studied using numerical models (Seifert et al., 2008; Seyoum & Eckstein, 2014; Shaver & Pusc, 1992), however, few numerical analyses have sought to characterize paleovalleys in the Peace Region. In one of the few, Morgan et al (2019) simulated regional groundwater flow in a system of paleovalleys in NEBC, located in the Halfway River region, focusing on the continuity of buried-valley aquifers, and their importance on regional groundwater flow. This study found that buried-valley aquifers do not play a significant role for regional (i.e., ~60 km scale) groundwater flow, however this was not surprising as the permeable channels associated with these features were modeled as regionally discontinuous. Comparatively, Morgan's study covered several distinct paleovalleys, had a large unconfined aquifer component, and aquifers were conceptualized to have considerable connection to surface water. To date no modeling studies with a primary focus on groundwater recharge in buried-valley settings in NEBC have been undertaken.

The objective of this study is to determine the spatial distribution of recharge rates, residence-times of aquifers, and the steady-state water balance of the Sunset Paleovalley, an archetypical groundwater system which is located in the southern Peace Region, west of Dawson Creek, BC (Fig. 1). The first step consisted in developing the hydrogeological framework and conceptual model of the system, focusing on the shallow (<200 m), regional (~15 km) groundwater flow of the multilayered aquifer system. Next, a 3-D, steady-state, saturated-flow model was formulated (MODFLOW 6 software developed by Hughes et al., 2017). A steady-state analysis was selected because only two long-term monitoring points were available within the model domain, the aquifer dynamics were expected to be slow, and because the longer-term flow dynamics and water balance of the near-surface potable or near-potable water aquifers were the principal focus.

This modelling study complemented a larger regional characterization of shallow groundwater in the Peace Region described in Allen et al. (2021). In 2018–2019, 29 monitoring-well stations were installed in various aquifer types throughout the Peace Region as part of the Energy and Environment Research Initiative (EERI), a component of the Monitoring Well Installation Project of the University of British Columbia. These stations provided high-quality lithological and hydrogeological data on Quaternary and bedrock material. Monitoring wells EERI-1 and EERI-11 are located within this study's model domain and provided key data to construct the conceptual hydrogeological model (Fig. 2).

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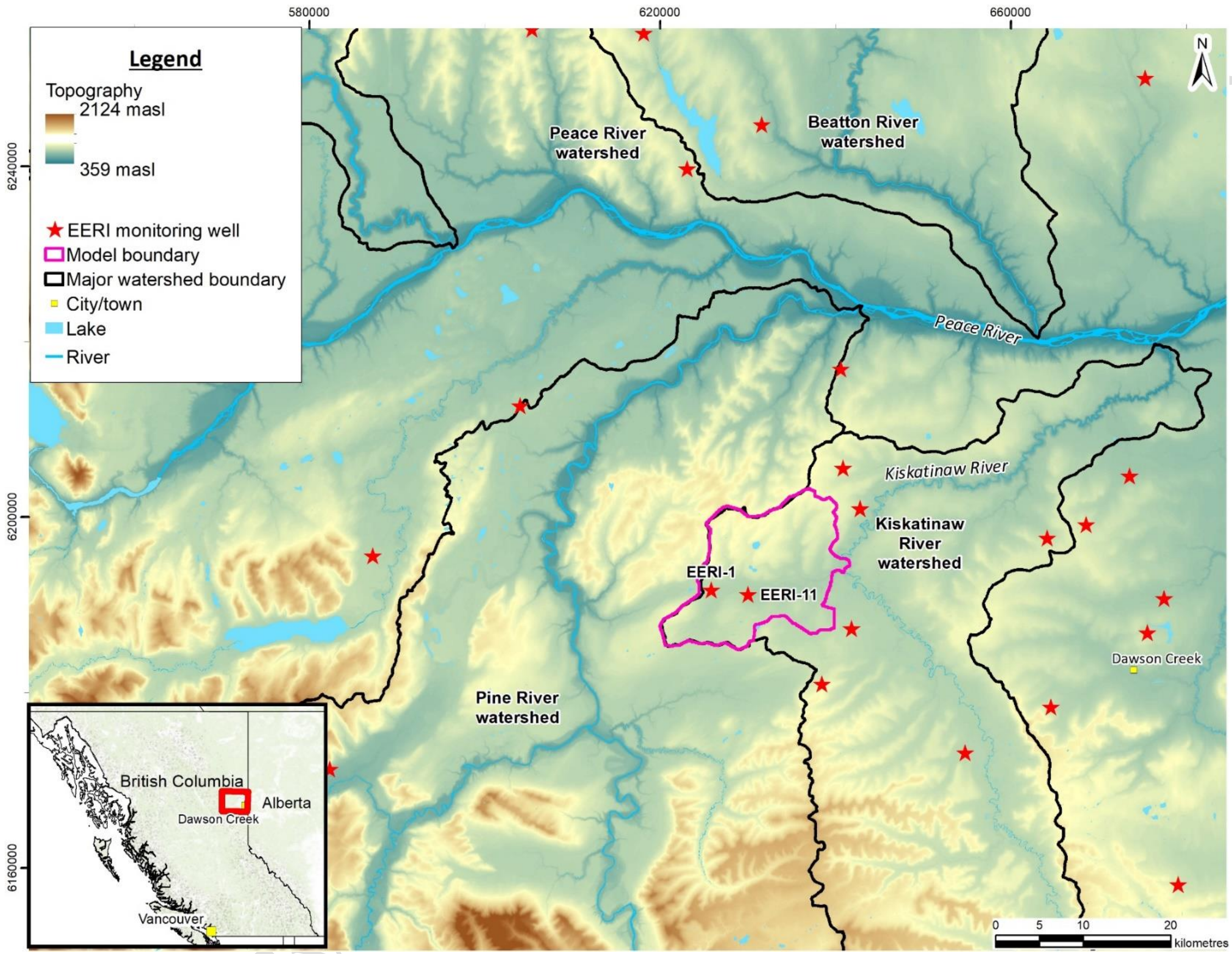


Fig. 1 Regional map showing the study area location, with Digital Elevation Model (DEM) of NEBC and major watershed boundaries. DEM is in units of m.a.s.l. (meters above sea level).

# 2. Study area

## 2.1 Physiography

The Sunset paleovalley is one of the Peace Region’s smaller paleovalleys (Fig. 2) delineated by Hickin et al. (2008), with an elevation ranging from 660 to 900 m above sea level (masl). It is considered part of the Alberta Plateau of the Interior Plains physiographic region of BC (Holland, 1964).

The climate of the study area has mean annual temperatures below 0°C, with daily average temperatures ranging between -17°C and 22°C. Average annual precipitation ranges from 350 to 500 mm, approximately 200 mm of which falls as snow (Environment and Climate Change Canada, 2020). Peak freshet due to snowpack melting occurs in the spring, with most meltwater coming from mountainous regions to the west of the study area. A generally rural region, the dominant land usages within the study area include agriculture, timber harvesting and energy development (Baye et al., 2016).

The study area is located in the Sunset Creek sub-basin of the Kiskatinaw River watershed, with the river forming the eastern drainage for surface water (Fig. 1). Originating in the foothills of the Rocky Mountains, the Kiskatinaw is a groundwater-fed, drought-stressed river with a mean base-flow index ranging between 58 and 75% (2007–2011; Saha et al., 2013). Groundwater contribution to the Kiskatinaw River is highest during drought and snowfall events, and lowest during wet seasons and freshet. Average annual runoff for the Kiskatinaw River Basin (1966–2008) comes from precipitation (14.2%), with the remainder consisting of evapotranspiration and groundwater recharge (Foundry Spatial, 2011). The flow rate of the Kiskatinaw River varies greatly, averaging 10 $m^3$/s and dropping to 0.052 $m^3$/s during the winter months (Saha et al., 2013). It is important to understand groundwater contribution to this river, as it is the principal source of water to the communities of Dawson Creek and Pouce Coupe as well as to thousands of rural residents of the Peace Region. Dawson Creek water demand increases by 3.2% per year on average (Saha et al., 2013).

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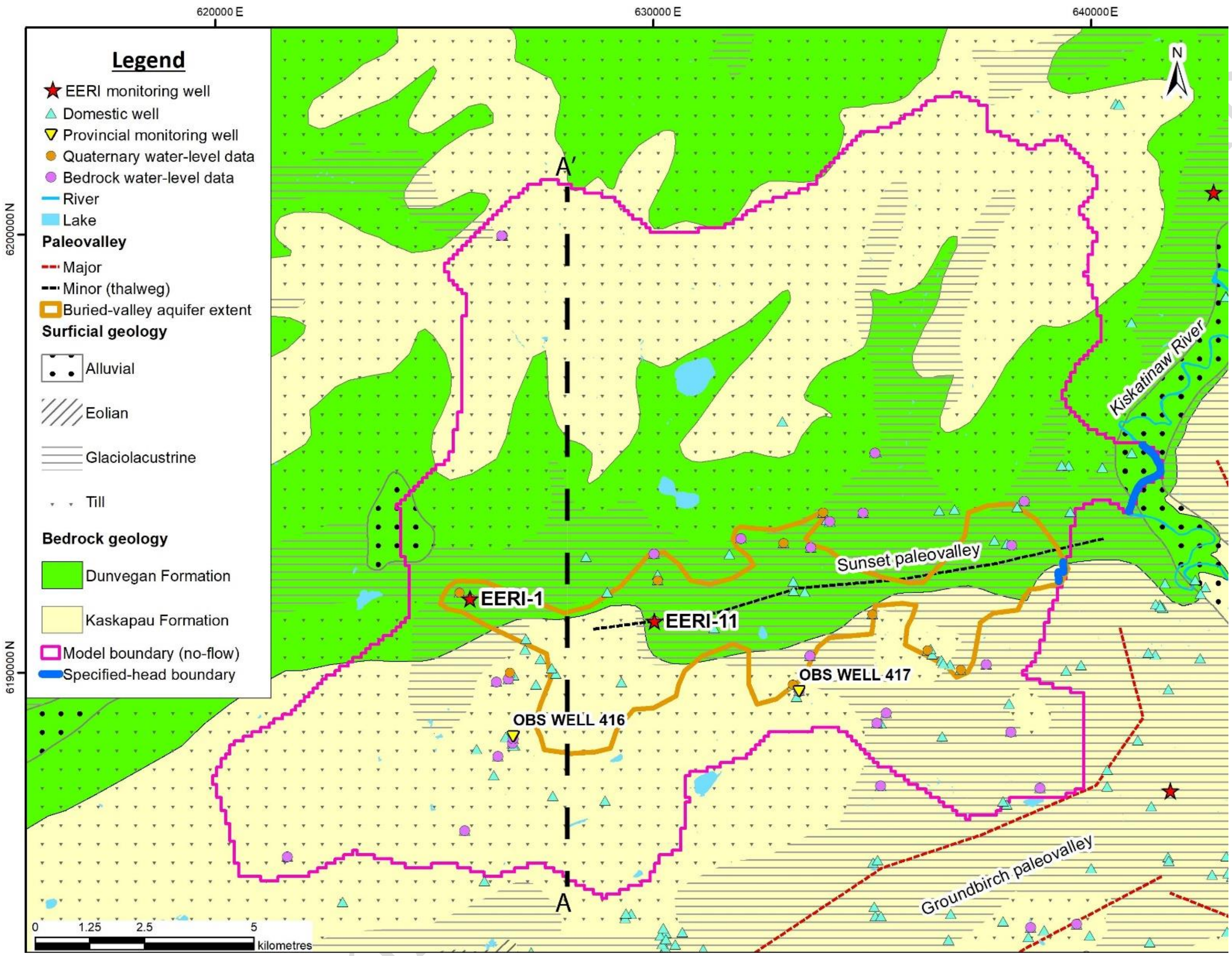


**Fig. 2.** Surficial, bedrock, and water well data of the study area, in the southern Peace Region in NEBC. The model area is shown in pink, and the vertical black dotted line represents a transect indicating the location of the conceptual model cross section in Fig. 5. Spatial locations of no-flow and specified-head boundary conditions for the numerical model are displayed.

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### 2.2. Regional Geology

Located near the western limits of the WCSB, the shallow geology of the Sunset Creek valley generally consists of glaciogenic Quaternary sediments that overlie the topmost, southwest-dipping, Upper Cretaceous sedimentary bedrock strata (Fig. 2; Hickin & Fournier, 2011; Riddell, 2012). The shallow bedrock formations are interpreted to be the result of successive marine transgressive-regressive cycles (Riddell, 2012). There are two bedrock formations of interest mapped within the study area: the Dunvegan and Kaskapau formations (BC Ministry of Energy, Mines and Petroleum Resources and BC Geological Survey, 2020). The Dunvegan Formation is an Upper Cretaceous non-marine to marine deltaic sandstone/siltstone that is primarily mapped in low-elevation parts of the study area. This formation is the most important shallow reservoir for freshwater domestic groundwater in northeastern BC (Riddell, 2012). The overlying Kaskapau Formation shale/siltstone is more regionally extensive, but also hosts aquifer potential to some degree (Lowen Hydrogeology Consulting, 2011; Riddell, 2012). The uppermost bedrock strata are often observed as being weathered/fractured, which is likely the result of long-term mechanical weathering of bedrock surfaces caused by Pleistocene glacial erosion (Gao, 2011; Imrie, 1991). This secondary-fracture enhancement of the permeability has created observed hydraulic conductivities orders of magnitude greater than those observed in underlying competent bedrock counterparts (Riddell, 2012).

The extent, composition, lithology and genesis of major Quaternary paleovalley stratigraphy has been thoroughly studied in the Peace Region (Catto, 1991; Hartman & Clague, 2008; Hickin et al., 2008, 2016; Hickin & Best, 2013; Lowen Hydrogeology Consulting, 2011) where the paleovalleys were carved and filled by various glacially related processes, such as preglacial rivers, and further incised by proglacial or subglacial channels (Cummings et al., 2012). Valley shape, specifically depth-to-width ratio, can vary greatly, with larger paleovalleys being broad and shallow, and smaller paleovalleys being narrow and deep (Andriashek et al., 2003; Pugin et al., 2014). Created glacially or interglacially, these paleovalleys sometimes mimic the shape of modern major river valleys sometimes mimic the shape of these paleovalleys, such as the Peace, Pine and Kiskatinaw paleovalleys. Others, such as the Groundbirch and Sunset paleovalleys, are completely blanketed by till and glaciolacustrine deposits, leaving little surface expression.

Major paleovalleys can contain multiple minor buried valley channels creating a complex architecture of erosional surfaces, crosscutting relations and nested buried-valley aquifers (Pugin et al., 2014). There are two main groupings of unconsolidated paleovalley aquifers, based on the stratigraphic position of the aquifer within the overburden package (Cummings et al., 2012). The first, and typically most transmissive and laterally continuous, is the buried-valley aquifer, which overlays directly or near the top of bedrock surface. These buried-valley aquifers are typically located along the center, deepest position of the paleovalley, where the thalweg of the ancient channel would have been located. The second type is less laterally continuous, called the inter-till aquifer. These were formed as glaciofluvial valleys eroded into proglacial spillways or tunnel-valley settings. Inter-till aquifers are stratigraphically shallower, and more recent than buried-valley aquifers. These smaller, typically isolated aquifers within till/clay aquitard units are known to have lower yields (Nastev et al., 2005). Airborne Electromagnetic Survey (AEM) and seismic profiles have been the ideal method to delineate complex valley fill and most accurately locate buried-valley aquifers (Hickin & Best, 2013; Korus et al., 2017; Morgan et al., 2019; Pugin et al., 2014; Russell et al., 2004). The hydrogeological framework of an inter-till aquifer system was recently characterized at the 100 m x 100 m site scale in an area north of the study area, near Hudson's Hope, BC (Chao et al., 2020).

# 3. Materials and methods

### 3.1. Geological conceptualization

The Quaternary and shallow bedrock geology of the Sunset paleovalley was broadly conceptualized using lithological data from 85 registered domestic well records entered in the WELLS database, two provincial monitoring wells and two monitoring wells newly installed within the study area as part of the current investigation. Unfortunately, the lithological logs of most of the domestic wells are of extremely poor quality, providing little descriptive information and often lumping units together (Baye et al., 2016). Therefore, the only highly detailed logs in the paleovalley were obtained from the newly established monitoring wells EERI-1 and EERI-11. These monitoring wells were installed using the sonic drilling method through Quaternary sediment and diamond coring through bedrock. The sonic drilling method uses high-frequency vibrations to drive the drill bit downward, retrieving high-quality unconsolidated sediment core in the process. Combining these two drilling methods made it possible to retrieve much more detailed and higher quality logs than would have been possible relying solely on air rotary drilling. Both EERI wells are located in topographic lows, near the Sunset paleovalley thalweg (Fig. 2). The inferred depositional history of the sequence stratigraphy of encountered in EERI-1 and EERI-11 were determined with the aid of detailed descriptions from a study on the Quaternary stratigraphy of the adjacent Groundbirch paleovalley (Hickin et al., 2016), which shares a similar elevation and paleovalley depositional setting. The generalized sequence stratigraphy depositional history of the Late Wisconsinan Sunset paleovalley is interpreted as glaciolacustrine sediments deposited by glacial advance, which were overlain by ice-contact sediments, in turn overlain by retreat-phase glaciolacustrine sediments. The geology at monitoring well EERI-1 consists of ~66 m of mainly till and sand/gravel intervals; the well does not reach bedrock (Fig. 3). Monitoring well EERI-11

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extends through 40 m of clay, diamict and sand overlying 37 m of medium sandstone interlayered with siltstone. Overall, fine detail of the high-resolution lithology logs (e.g., small sand lenses in EERI-1, and sandstone/siltstone interlayers in EERI-11) did not contribute to the conceptual model of this study. These details are shown in Figure 3, to primarily illustrate the well-documented heterogeneity of the overburden in the Peace Region, and the give a sense of the degree of interbedding in the Dunvegan Formation).

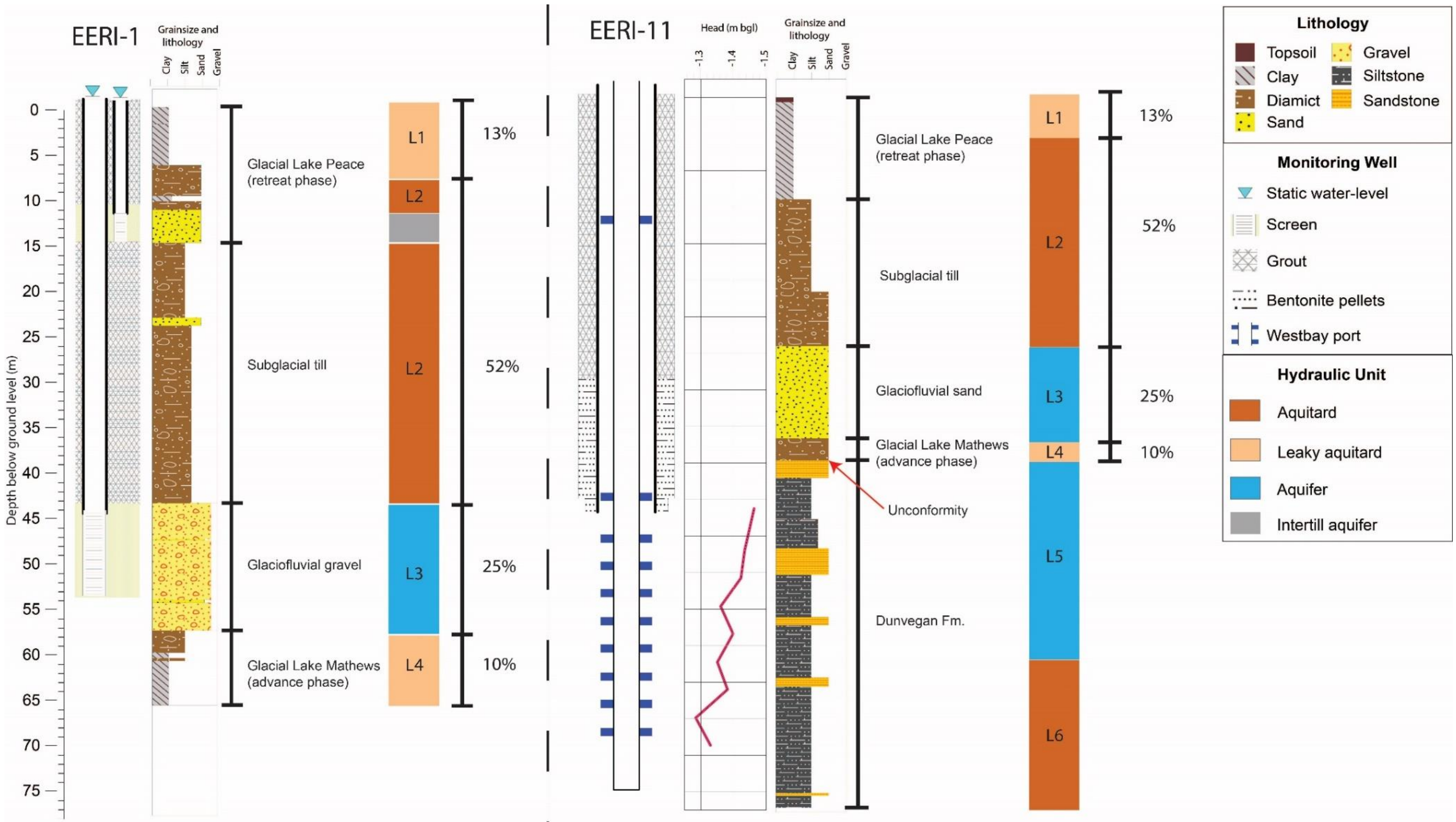


**Fig. 3** Well completion, hydraulic head, high-detail lithological logs, depositional interpretation, and hydraulic hydrostratigraphic units of EERI-1 and EERI-11. The "fraction of drift thickness" Quaternary layer structure is shown, which was used for layer definition of the conceptual model.

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**3.2. Groundwater flow**

Hydraulic-head fluctuations in long-term monitoring data provide insights into groundwater recharge dynamics. Hydraulic-head data was available from 35 groundwater wells, made up of domestic, provincial observation and EERI wells (Fig. 2). Although 85 domestic well records entered in the WELLS database are located within the model domain, only head data from 31 wells that provided both reliable lithological and static-water records (22 in bedrock and 9 in Quaternary units) were used to calibrate the numerical model. Domestic wells chosen for study must have all of the following three attributes: a static-water record, depth details showing which material the well was screened in and did not lump multiple lithological units together into single intervals (e.g., silt/clay/gravel 0-50 m).

The newly installed EERI monitoring wells provided more recent (2019–2020) and reliable hydraulic-head measurements than domestic wells. Monitoring well EERI 1 is a nested multilevel well, with screens installed in the deeper glaciofluvial gravel and shallower sand units; both these screened units are artesian. Monitoring well EERI 11 is a multilevel well developed by Westbay® Instruments and equipped with nine pressure measurement ports, all located in the weathered bedrock Dunvegan Formation; all nine showed artesian pressure when measured during two sampling events in 2019 and 2020. The nine ports were designed based primarily on structural logging, placing ports in locations with higher observed fracture frequency. The results from downhole petrophysical logs also aided in the design of the Westbay, with gamma, induction, density, and neutron log data taken into account. In terms of vertical flow definition, the depth-discrete hydraulic-head data from the EERI-11 Westbay® and the EERI-1 nested multilevel well were not used to contribute to the conceptual model. Depth discrete data is shown in Figure 3 primarily as supplemental information.

Two provincial groundwater monitoring wells (OBS Well 416 and 417) exist in the southern upland region of the model with long-term transient data (Fig. SI-1). Both wells are screened within the weathered bedrock; OBS 416 is primarily weathered sandstone with intercalations of shale and siltstone, and OBS 417 is shale/siltstone (Baye et al., 2016). Although more pronounced in OBS 416, the yearly trend in both of these wells shows a rise in hydraulic head roughly 2 months lagging peak freshet, followed by a steady decline for the rest of the year. OBS 416 has only 3 m of till cover, compared to 12 m in OBS 417. The yearly fluctuations of OBS 416 are roughly 1 meter, compared to 0.1 meters for 417. As these two wells are located in hypothesized recharge areas, this could indicate that roughly 9 m of extra till cover causes roughly an order of magnitude less seasonal fluctuation in groundwater level. Spikes in water level during or lagging after spring freshet can suggest the screened weathered bedrock aquifer is well connected to inputs from surficial recharge. However, fluctuations in head could also be due to surface-moisture loading, not recharge response (van der Kamp & Maathuis, 1991).

### 3.3. Hydrogeological Conceptual Model

A schematic hydrostratigraphic section for the Sunset paleovalley model is shown in Fig. 4. The Sunset paleovalley has similar morphology and geology and, therefore, expected flow patterns to those identified in the study by Nastev et al. (2005) and Pétré (2019). Precipitation is expected to infiltrate to groundwater mostly in topographic highs, where impermeable till/clay is thin or absent. Infiltrated water then flows into the regional weathered-bedrock aquifer, with the flow direction mimicking bedrock topography toward the valley centre. From this point, the groundwater will either continue to flow in the weathered bedrock toward groundwater discharge points, flow

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upward into more permeable buried-valley sand/gravel aquifers due to strong hydraulic-conductivity contrasts, or travel downward to recharge deep groundwater. Groundwater in both gravel and bedrock aquifers is expected to ultimately flow roughly parallel to the long axis of the bedrock valley (Shaver & Pusc, 1992) toward their outflow points, such as springs, or into regional drains, such as the Kiskatinaw River.

#### ***3.3.1. Hydrostratigraphic Unit Definition***

Eight hydrostratigraphic units (HSU) have been identified for the conceptual model of the Sunset paleovalley: five Quaternary hydrofacies HSU (weathered till/clay, alluvium, unweathered till, buried-valley sand/gravel, and basal till) and three bedrock hydrofacies HSU (weathered-bedrock Dunvegan Formation sandstone, weathered Kaskapau Formation shale and competent shale). All HSU’s are shown in Fig. 4, except the alluvial HSU, as the transect does not intersect an alluvial region. The contact between weathered bedrock HSU’s Dunvegan and Kaskapau Fm.’s are estimated based on bedrock mapping (BC Ministry of Energy, Mines and Petroleum Resources and BC Geological Survey, 2020) and represented by the black dotted lines in Fig 4.

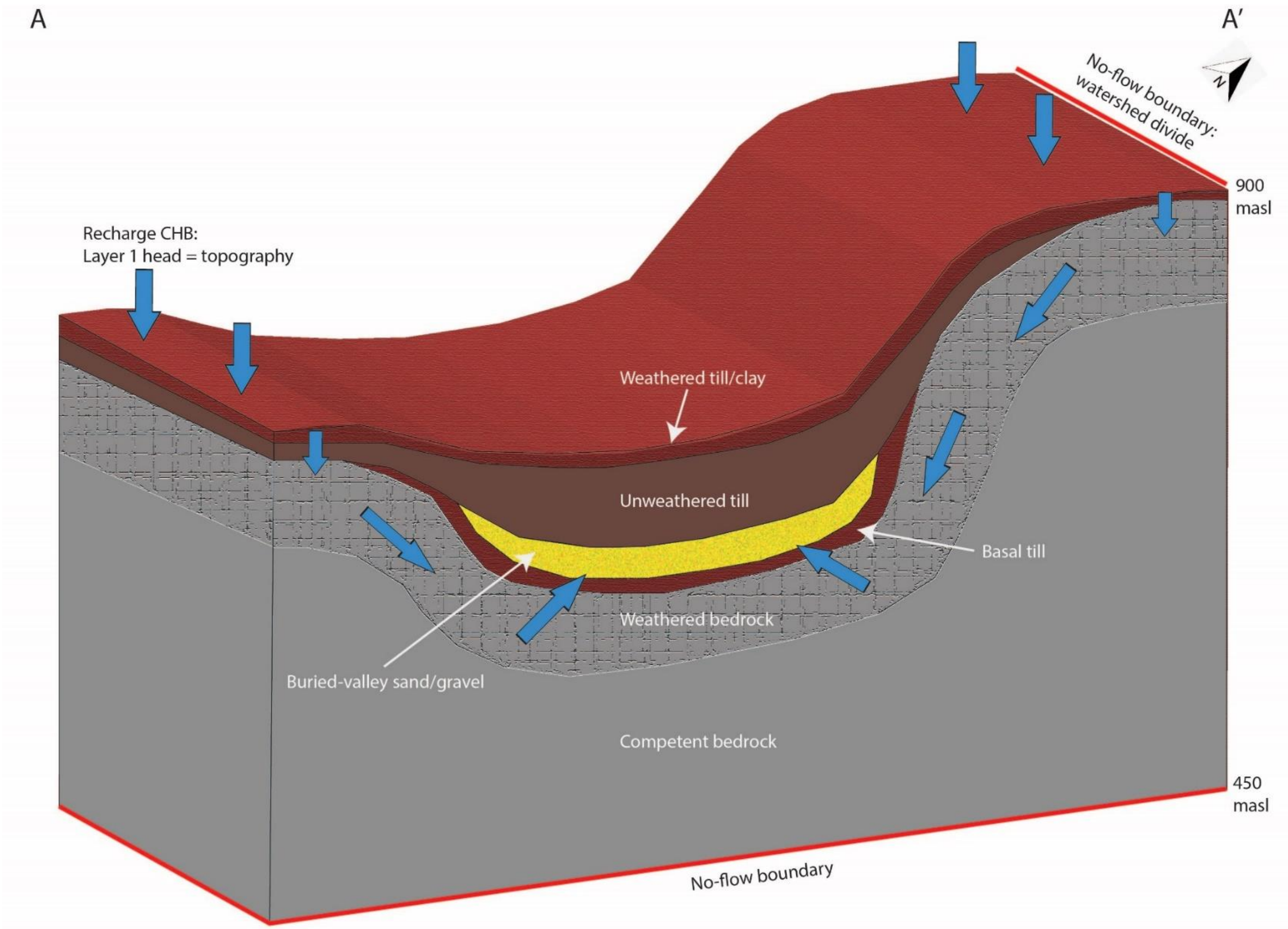


**Fig. 4** Conceptual block model of the hydrostratigraphy of the Sunset Paleovalley. Transect A-A'B shown in Fig. 2. Hydrostratigraphic units are labeled, along with hypothesized recharge flow path from surface to buried valley sand/gravel aquifer, and broad locations of some of the boundary conditions.

Weathered till/clay is the top most HSU and is categorized as a leaky aquitard with groundwater flow primarily occurring through fracture flow created by secondary processes (Cravens & Ruedisili, 1987; Cummings et al., 2012).

The alluvial HSU has the highest hydraulic conductivity in the model and acts as an unconfined aquifer.

This unweathered till HSU acts as the main confining unit in the model; having the same matrix permeability as the unweathered till, but lacking the enhanced secondary fracture permeability and oxidized matrix (Hendry, 1982).

The buried sand/gravel HSU acts as a confined aquifer and is modeled along the longitudinal axis (thalweg) of the paleovalley, pinching out against where bedrock topography steepens. In reality, the true size, hydraulic conductivity, grainsize distribution, and lateral connectivity of this HSU is incredibly variable, as variations between gravel, sand, mud, and diamict can cause aquifer compartmentalization (Cummings et al., 2012). For this study, a simplifying assumption is made for the lateral connectivity and homogeneity of this HSU. The lateral extent of the buried-valley sand/gravel HSU was roughly estimated based on domestic and EERI well logs, and shape based off the Groundbirch paleovalley study (Hickin et al., 2016). The shape (Fig. 2) roughly encompasses any grid block in the center of the paleovalley with a drift thickness value of roughly 25 meters of greater. A drift thickness value of 25 meters was chosen on a trial-and-error basis, with 25 meters being the value that most conservatively captured all hydraulic head data points that intercepted the buried sand/gravel HSU.

The basal till HSU is a highly reworked, oxidized till that directly overlies weathered bedrock.

The weathered bedrock HSU is split between Dunvegan Fm. and Kaskapau Fm. based on bedrock maps and are both modeled as to being regionally extensive aquifer units. Other modeling studies considers this fractured layer of bedrock as the key regional groundwater aquifer, estimating 30-50m depth before reaching more competent, less conductive material (Nastev et al., 2005).

The competent bedrock HSU underlies the weathered bedrock HSU and is characterized by a strong decrease in fracture frequency from its overlying bedrock counterparts. The contact of bedrock/weathered bedrock is roughly estimated from drilling experience of EERI wells in the Peace Region, and from the literature. The competent bedrock is not broken out by mapped formation, it is assumed to having the very low hydraulic conductivity of an unweathered shale. This was done due to the absence of deep lithological logs in the study area that determine the contacts between Kaskapau Formation, underlying Dunvegan Formation, and underlying Fort St. John Group.

#### *3.3.2. Material Properties*

The hydraulic conductivity of each of the eight HSUs is based on estimates from various sources: range of values from the literature, grain-size distribution results and pumping tests (Table 1). In all units, the two horizontal components of hydraulic conductivity are assumed equal, $K_h = K_x = K_y$. A vertical anisotropy factor of Kh/Kv = 10 is set for the alluvial, buried-valley sand/gravel and all bedrock HSUs to represent the horizontal preferential permeability common to sedimentary rocks (Freeze and Cherry, 1979). The three till HSUs are assumed to be isotropic based on the assumption that both vertical and horizontal fractures are equally common, in combination with extremely low expected matrix permeability (Grisak & Cherry, 1975; Shaw & Hendry, 1998). However, it is expected that flow through the till material will always be vertical due to flow-line refraction.

Grain-size distribution was analyzed using a Mastersizer particle-size analyzer developed by Malvern Panalytical Ltd. on select Quaternary samples from EERI-1. The hydraulic conductivity

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of two samples within the EERI-1 buried-valley sand/gravel was estimated using the Kozeny-Carman and Terzaghii equations (Odong, 2007), with values ranging between 60 and 130 m/d.

In a prior study by Baye et al. (2016), 24-hour pumping tests were performed at the provincial monitoring wells within the model domain. Using both the Theis, Cooper-Jacob, and recovery analyses (Theis, 1935; Cooper & Jacob, 1946), the hydraulic conductivity at provincial monitoring well OBS 416 was estimated to range between 9.0 and 30 m/d and at well OBS 417 between 0.70 and 0.81 m/d. These ranges of values are representative of both the weathered-bedrock Dunvegan Formation and weathered Kaskapau Formation, respectively.

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**Table 1** Hydrostratigraphic units, with corresponding layer number, calibrated hydraulic conductivities and literature ranges. HSU's in blue represent aquifer material

| Hydrostratigraphic Unit | Model Layer # | Model Kx/Ky (m/day) | Model Kz (m/day) | Literature range Min (m/day) | Literature range Max (m/day) |
|---|---|---|---|---|---|
| **Weathered till/clay [a]** | 1 | 1.5 x $10^{-3}$ | 1.5 x $10^{-3}$ | 1.6 x $10^{-4}$ | 1.7 x $10^{-2}$ |
| **Alluvial [b]** | 1 | 430 | 43 | 260 | 8.6 x $10^{-4}$ |
| **Unweathered till [a]** | 2 | 8.6 x $10^{-6}$ | 8.6 x $10^{-6}$ | 4.3 x $10^{-6}$ | 8.6 x $10^{-5}$ |
| **Buried valley sand/gravel [ac]** | 3 | 110 | 11 | 1.0 | 140 |
| **Basal till [a]** | 4 | 1.5 x $10^{-3}$ | 1.5 x $10^{-3}$ | 1.6 x $10^{-4}$ | 1.7 x $10^{-2}$ |
| **Dunvegan Fm. sandstone (weathered) [bd]** | 5 | 8.0 | 0.80 | 8.6 x $10^{-5}$ | 8.6 |
| **Kaskapau Fm. shale (weathered) [bd]** | 5 | 0.10 | 1.0 x $10^{-2}$ | 8.6 x $10^{-9}$ | 8.6 x $10^{-5}$ |
| **Kaskapau Fm. shale (competent) [b]** | 6 | 1.0 x 10-7 | 1.0 x $10^{-8}$ | 8.6 x $10^{-9}$ | 8.6 x $10^{-5}$ |

[a] estimated from literature values from Cummings et al (2012)

[b] estimated from literature values from Freeze and Cherry (1979)

[c] estimated from grain size analysis (Goetz, UBC, unpublished thesis, 2021)

[d] estimated from pumping test analysis (Baye 2016)

## 3.4. Numerical Model

The active model domain covers approximately 235 km$^2$. The model grid consists of six layers, each with 23 448 gridblocks 100 m in length and width. The gridblock size was chosen to adequately represent variations in hydraulic properties, while maintaining a manageable run time

(Reilly & Harbaugh, 2004). All gridblocks are set to 'convertible' as the default value, with the wetting option enabled for all layers.

#### ***3.4.1. Layer Structure***

The six model layers extend from ground surface down to a planar, horizontal base at an elevation of 450 m asl. The top four layers represent Quaternary HSUs and the bottom two layers represent bedrock HSUs.

The upper surface of the grid was interpolated from digital elevation data (DEM; USGS, 2015) and the top of the bedrock was interpolated using an existing bedrock topography DEM (Hickin & Fournier, 2011b). In a previous study of drift thickness in the Peace Region, Hickin and Fournier (2011b) digitized a bedrock DEM using primarily lithological descriptions from water-well driller logs, oil and gas petrophysical logs, and surface exposures. Both bedrock and surface topography DEMs were reclassified (Resample raster function in ArcMap) to the same 100 m cell size. Since the DEMs came from different sources, bedrock elevations at some gridblocks were greater than surface elevations. To eliminate this incongruence, Raster Calculator was used in ArcGIS to locate cells where bedrock DEM elevation was greater than ground surface DEM elevation. The bedrock elevation in these selected cells was set to 1 m deeper than the surficial DEM. The resulting DEMs were then imported into MODFLOW 6 as layer boundaries.

It was not possible to define precise lithological contacts based on the few lithology logs publicly available for the model domain area. In an attempt to approximate as precisely as possible the thicknesses of the overburden layers (layers 1–4), each layer was assigned a constant fraction of the total drift thickness dependent on spatial location. These constant fractions for the four Quaternary layers were estimated based primarily on hydrogeological interpretations from monitoring wells EERI-1 and EERI-11 (Fig. 3). The surficial geology of layer 1 at the surface is based on mapped surficial geology data from Hickin and Fournier (2011) and consists of either weathered till/clay or the alluvial HSU. The thickness of this layer accounts for 13% of the total drift thickness value. Layer 2 is composed entirely of unweathered till, representing the main confining unit of the model. The thickness of this layer corresponds to 52% of the total drift thickness. Layer 3 is defined as buried-valley sand/gravel HSU if within the thalweg shape or unweathered till if it lies outside the thalweg shape (Fig. 2). The thickness of this layer is 25% of the total drift thickness. Layer 4 consists entirely of basal till HSU and accounts for 10% of the total drift thickness. Layer 5 is defined as either weathered bedrock Dunvegan Formation sandstone or Kaskapau Formation shale, depending on mapped bedrock (BC Ministry of Energy, Mines and Petroleum Resources and BC Geological Survey, 2020). The thickness of this layer is uniformly set at 20 m. Layer 6 is entirely composed of competent-bedrock shale HSU (layer 6), ranging from the bottom of the weathered bedrock to 450 m asl.

### *3.4.2. Boundary Conditions*

The lateral model boundaries were assigned no-flow, primarily defined by major regional watershed divides, or, between the Sunset Creek, Groundbirch and Kiskatinaw River valleys, as flow divides (Fig. 2). Indeed, these three valleys are likely separated by groundwater divides, with no interbasin groundwater flow assumed for this study. The northern and western no-flow boundaries follow the boundary between the Pine River and Kiskatinaw River watersheds (Fig. 1). The Pine River, ~10km west of the model's western boundary, is likely a major regional discharge zone and groundwater divide (Fig. 1), collecting deep regional groundwater flow sourced from the Rocky Mountains. This justifies the model's western no-flow boundary.

The southern no-flow boundary was investigated using the particle-tracking program in MODFLOW 6. A larger model domain was established and the groundwater-divide boundaries between Sunset and Groundbirch paleovalleys identified by the particle tracks.

Inflow from deep groundwater into the model domain is not expected to be significant, as the deeper bedrock hydraulic conductivities are low, less than 8.6 x $10^{-5}$ m/d. Therefore no-flow boundaries were applied to the bottom plane of the model, at sufficient depth to not affect simulation results in the shallow zone.

Although several small lakes and ephemeral streams are located within the study area, these features occupy a small portion of the total model area and are not represented in the model (Fig. 2). These surface water features are likely perched, isolated from regional groundwater systems by the generally thick (up to ~60m), impermeable (K= $10^{-6}$ m/day) clay/till confining material, which blankets most of the model surface (Cummings et al., 2012).

Hydrological data within the study area show hydraulic heads are close to the topographic surface, indicating that recharge is controlled by the thickness and the low hydraulic conductivity of the confining-layer till (the conductance of the unit). Accordingly, a specified-head boundary (SHB) condition was applied to the top of layer 1, except for areas mapped as alluvial HSU (Sanford, 2002). The head in layer 1 was set equal to the elevation of the model top, allowing the model to compute recharge rates and flow paths through confining layers. Therefore, the resultant recharge/discharge outputs are a result of the required flows at the upper boundary to sustain the SHB condition.

A specified – head boundary condition is not appropriate for the HSU unit which has a hydraulic conductivity of 43 m/d. For this unit, a specified-rate–recharge (SRR) boundary condition, based on material type, of 68 mm/a was applied. This rate was determined by Baye et al. (2016) in study in the adjacent Groundbirch region.

The regional groundwater discharge locations, where the Sunset paleovalley meets the Kiskatinaw River valley, were represented in the model as specified-head boundaries applied to two of the aquifer layers (Fig. 2).

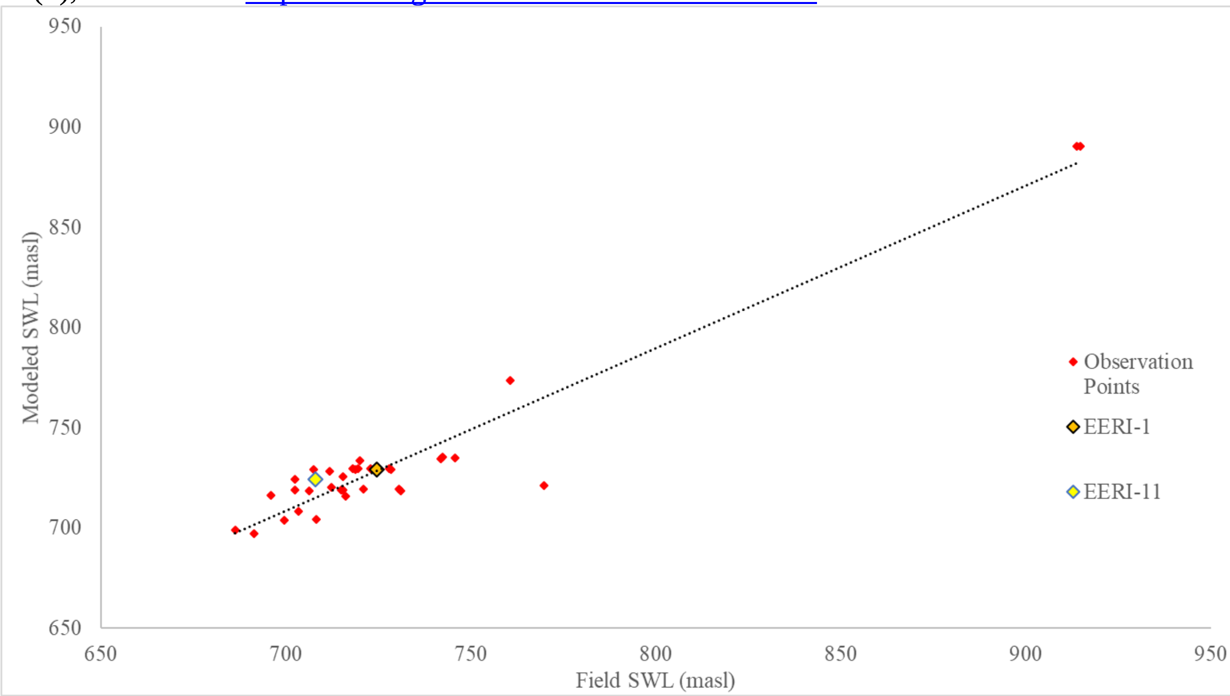
The specified-head value of 693 m asl at the outflow boundary for the buried-valley sand/gravel aquifer (layer 3) was estimated based on the head gradient of gravel-thalweg domestic wells west of the outflow boundary. Based on hydraulic head data in domestic wells, GW Solutions Inc. (2016, p. 62) indicated potential connection between the Kiskatinaw River buried-valley aquifer, with the Kiskatinaw River alluvial unconfined aquifer. Although this occurs outside the model area, it is assumed that flow exiting the model via the layer 3 specified head boundary enters the adjacent Kiskatinaw buried-valley aquifer, then into the unconfined Kiskatinaw River alluvial aquifer and ultimately discharges to the Kiskatinaw River.

The specified head in the weathered-bedrock aquifer (layer 5) was set at the estimated Kiskatinaw River elevation (665 m) near the model outflow point. The outflow boundary for layer 5 was located at the intersection of the Sunset paleovalley bedrock catchment with the Kiskatinaw River. No stream-gauge data were available on the Kiskatinaw River near the Sunset paleovalley outflow point to constrain the head or flux value.

#### ***3.4.3. Model calibration***

The only model calibrated parameters were the hydraulic conductivities of each HSU (assumed uniform throughout the HSU), with two exceptions, (Table 1): the alluvial HSU was not calibrated, because it occupies a small portion of the total model volume, and no observation points exist within the alluvial areas, and the competent bedrock HSU was not calibrated because no observation points are screened within this HSU it does not affect the modeled observations points in the sensitivity analysis (Table 2). Other parameters such of layer thicknesses, boundary condition values/locations, and grid block size, were not calibrated.

The model was calibrated by trial-and-error using the 35 observation-well static water levels as calibration targets (Fig. 5). The model generally over-predicts head values, with a root mean squared error (RMSE) of 14.7 m, and a normalized root mean squared error (NRMSE) of 7.6%, compared to the threshold NMRSE value of 5% recommended by Anderson (2015). The simulated heads more closely match those from bedrock observation wells (NRMSE of 8.1%) than those from buried valley wells (NRMSE 46.9%). Some of the variance can be explained by the model's steady-state assumption, whereas the observed data is from a dynamic system, with measurements taken during different seasons over the course of multiple decades. The post-calibration potentiometric surface of Layer 5 is shown in Fig. 8.



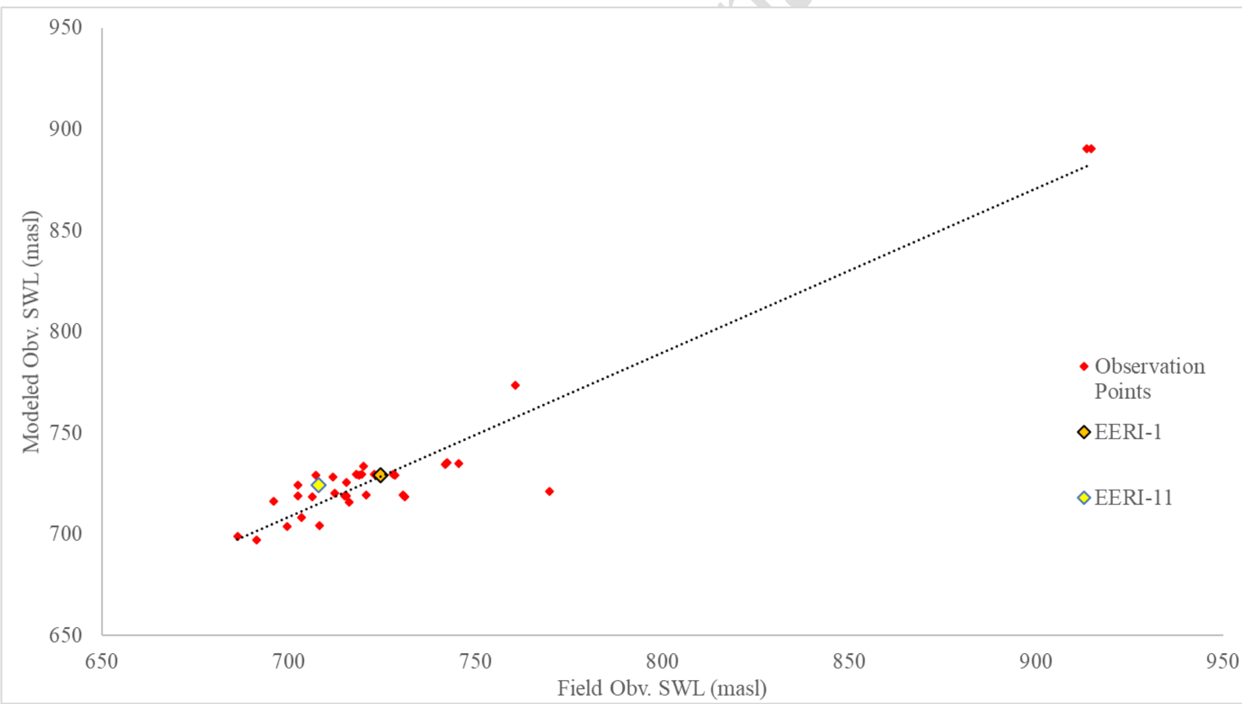




**Fig. 5** Calibration results, compared modeled hydraulic head observation points with field measurements

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### *3.4.4. Sensitivity analysis*

The sensitivities were computed at each calibration location by changing the value of the hydraulic conductivity of a HSU under examination by an order of magnitude and determining the head change at the calibration points. Average sensitivities were computed at all calibration points, in the bedrock and in the Quaternary sediments, as shown in Table 2 in order of decreasing sensitivity. These sensitivity coefficients, (M. P. Anderson et al., 2015), represent the ratio of the change in simulated head to a change in the value of hydraulic conductivities in the HSU.  Of the seven parameters, the hydraulic conductivity of the competent bedrock was found to be the only parameter with no effect on the head observations. The hydraulic conductivity of the weathered Kaskapau Fm. is most sensitive parameter for bedrock wells, having a higher sensitivity than the weathered Dunvegan Fm.

**Table 2** Results of the sensitivity analysis, with the average of the sensitivity coefficients ranked in descending order of magnitude. The columns Bedrock. Quaternary and All calibration locations refer to sensitivities computed for head observations in those respected HSU categories.

| **Hydraulic conductivity of HSU** | **# Obv. location** | **Bedrock calibration locations $\frac{m}{\frac{m}{d}}$** | **Quaternary calibration locations $\frac{m}{\frac{m}{d}}$** | **All calibration locations $\frac{m}{\frac{m}{d}}$** |
|---|---|---|---|---|
| **Weathered Kaskapau Fm.** | 16 | -157.0 | -3.6 | -105.8 |
| **Weathered Dunvegan Fm.** | 9 | -83.1 | -77.7 | -81.3 |
| **Buried valley sand/gravel** | 10 | -12.4 | -11.8 | -12.2 |
| **Basal till** | 0 | -5.1 | -4.4 | -4.8 |
| **Unweathered till** | 0 | -1.0 | -2.9 | -1.7 |
| **Weathered till/clay** | 0 | -0.1 | -0.1 | -0.1 |
| **Competent bedrock** | 0 | 0.0 | 0.0 | 0.0 |

#### ***3.4.5. Chloride Mass Balance***

To compare recharge rate model results, a simple chloride mass balance (CMB) was calculated using available geochemical data from precipitation and domestic and EERI groundwater wells (n=18) within the study area (Kirste, Simon Fraser University, unpublished data, 2020). This simple analysis was performed using modified methods from Manna et al. (2016). Average annual recharge is calculated by multiplying the average precipitation rate by the geometric average of Cl concentration in precipitation, then dividing by the geometric average of Cl concentration in groundwater. Mass inputs of Cl were assumed to be from atmospheric sources only, with measured atmospheric Cl including only wet deposition, since dry deposition was not measured. This dry deposition exclusion induces a 50% uncertainty range to this recharge estimate, since it is the largest source of uncertainty in CMB estimates (Gates et al., 2014). The average annual precipitation rate from the Dawson Creek station (43km from the study area) is 453 mm/yr., with a [Cl] geometric average of 0.345 mg/L (38 rain samples collected from 2012-2015). The geometric averages of [Cl] in groundwater ranges from 0.73-4.7 mg/L, for gravel and bedrock screened wells, respectively.

#### ***3.4.6. MODPATH***

The flow directions and travel times originating from all observation wells within the model domain were investigated using the MODPATH utility within MODFLOW-6. Three vertically stacked particles were placed at the approximated screen locations of the 35 observation wells used for model calibration. These particles were backward tracked until a strong-source condition was met (corresponding to infiltration points).

# 4. Results

## 4.1 Recharge distribution

Simulated recharge within the model domain is shown in Fig. 6. Orange/red represent recharge areas, whereas those in different shades of green represent modelled discharge areas (negative values). The observed spatial pattern of recharge/discharge is consistent with the hypothesis of highland recharge and valley discharge, except for several localized discharge areas associated with topographic lows in the northern part of the model. The spatial-average recharge rate of the model is 16 mm/a, with a standard deviation of 32 mm/a and values ranging from -78 to 500 mm/a, with the normalized distribution of all rates denoted by the bell curve (Fig. 7). As this is a steady-state simulation, these values represent temporal averages and instantaneous values will vary about them. The maximum value of steady-state–gridblock discharge (78 mm/a) is lower than the 400 mm/a evapotranspiration rate estimated for the Kiskatinaw River watershed (Foundry Spatial, 2011) suggesting that, on average, that the rate of groundwater discharge does not exceed evapotranspiration, therefore groundwater discharge will not sustain stream flow in the model domain will not supply creeks within the model domain, although on shorter time scales instantaneous discharge may exceed evapotranspiration. This is consistent with the ephemeral nature of the mapped streams in the model area, which flow during freshet when surface runoff is greatest. Extreme outlier gridblocks with high recharge values (>100 mm/a), which occur mostly within regions with <10 m of Quaternary cover (total thickness of layers 1–4), are unrealistic giving the low hydraulic-conductivity values of layer 1 and are likely numerical artifacts caused by misalignment of adjacent gridblocks with large differences in elevation, as explained in Hughes et al. (2017, p. 54).

Recharge was studied by Baye et al. (2016) using the Hydrologic Evaluation of Landfill Performance (HELP) model, which assumes recharge is based on the properties of surficial confining material. They calculated average annual recharge rates for vadose zones of till (33 mm/a), glaciolacustrine (2 mm/a) and alluvial (46–68 mm/a) materials. Since layer 1 in the Sunset paleovalley model domain consists primarily of till and glaciolacustrine material, the results of this study are consistent with the range of values presented in the Baye et al. (2016) study.

The recharge estimated by the chloride mass balance range between 36-213 mm/yr. (78.1 mm/yr. average). Including the 50% error induced by excluded dry deposition, this CMB estimate is much higher than the results from the groundwater model, and this discrepancy could be due to neglect of the runoff component of [Cl], or due to other geochemical processes during infiltration removing [Cl] from solution. The average recharge rate from the CMB of 78.1 mm/yr. was applied to the calibrated groundwater model as a constant recharge boundary condition to the top of the model, replacing original head in layer 1 = topography constant head boundary condition. The resulting head values in this simulation are much higher than the observed heads, indicating an unrealistic recharge condition. The input/output volume from this simulation is 50,125 $m^3$/day, compared to 11,139 $m^3$/day for the initial calibrated mode

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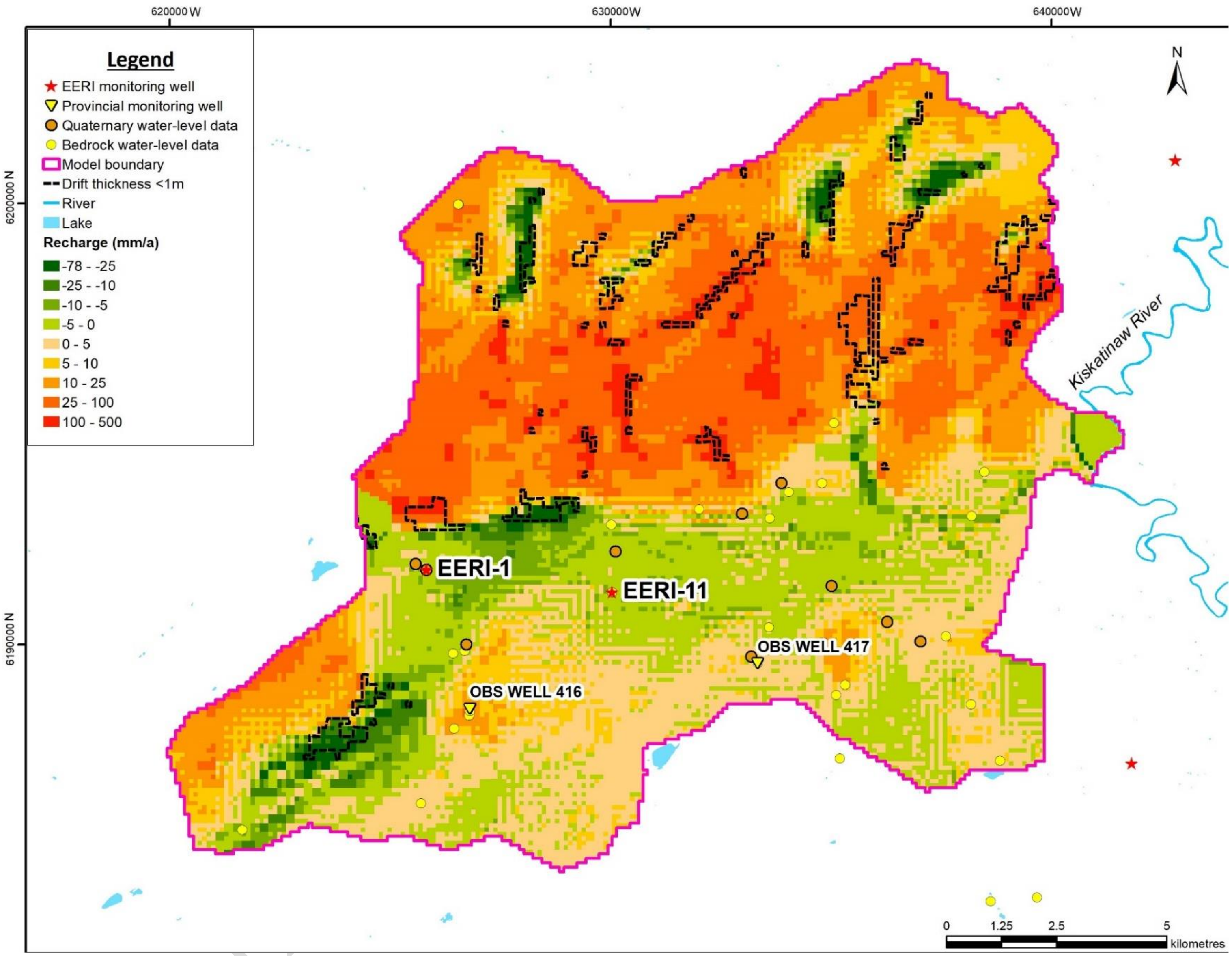
518 


519 **Fig. 6** Spatial distribution of recharge/discharge rates in Layer 1. Dotted black lines indicates zones of thinest drift (<1m)

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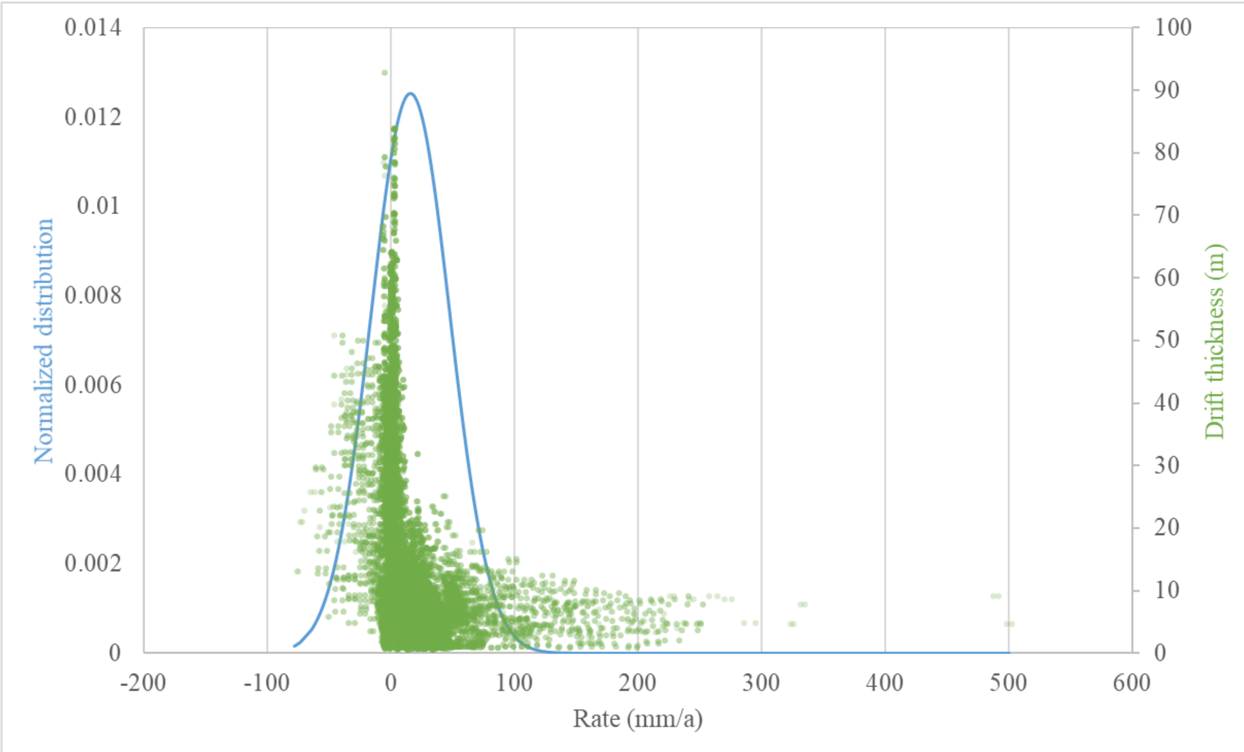


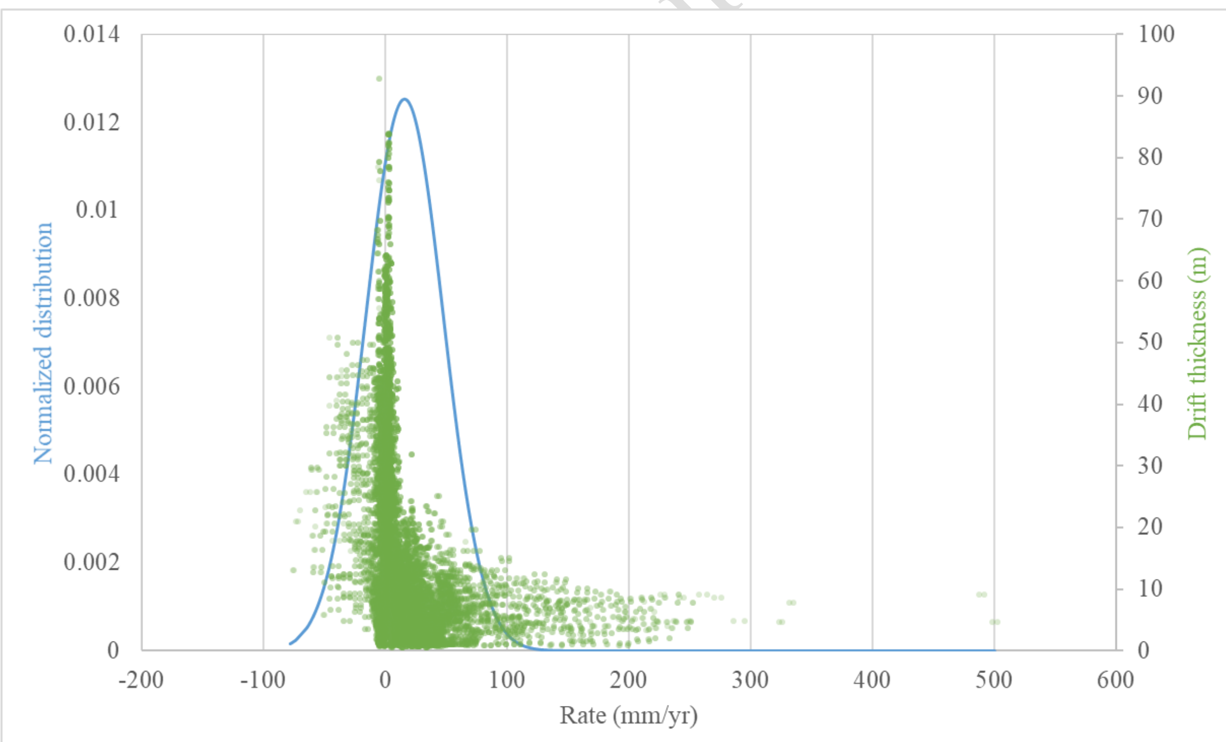


**Fig. 7** Normalized distribution of recharge/discharge rates within the model domain by gridblock (blue line). Recharge/discharge rates of all gridblocks plotted against drift thickness (green dots).

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### 4.2 Groundwater budget

Using the Zone Budget tool within MODFLOW-6, a water balance for the model was generated (Table 3). The components of the model groundwater flow budget include: recharge from precipitation, outflow from the buried valley sand/gravel Layer 3 at the SHB exit, and outflow of the weathered bedrock Layer 5 into the Kiskatinaw River SHB. Table 3 shows that inflow to the weathered bedrock aquifer comes primarily from overlying units (infiltration recharge), with negligible contribution from the underlying competent bedrock HSU. Regions with little to no drift (>1m) interpreted as outcropping weathered bedrock, account for 3% of the model surface area. These areas were found to account for 15% of recharge to the weathered bedrock aquifer.

Results show that the buried-valley aquifer receives 99% of its inflow from the underlying weathered bedrock aquifer. This finding agrees with the result from the buried valley studies by Nastev et al. (2005) and Seyoum and Eckstein (2014), which found that the buried-valley aquifer functions as a drain for the adjacent bedrock aquifers. A total of 58% of the model's flow occurs via Layer 3 SHB, with a further 33% of total flow volume exiting via the Layer 5 Kiskatinaw River SHB and 9% being discharged to the model top as surface water.

Flux exiting the model via the Kiskatinaw River CHB can be compared to data from the nearest river gauge, located approximately 15km downstream from this boundary condition. Hydrometric data from this station (id 07FD001) indicates a baseflow occurs from approximately November to March, when freezing temperatures prevent runoff from precipitation to contribute to the Kiskatinaw River flow (Environment Canada, 2017). Baseflow averages at around 2 $m^3/s$ (172,800 $m^3/d$) and occurs from approximately November to March (Environment Canada, 2017). The model results show an output value of 3,777 $m^3/d$, compared to 172,800 $m^3/d$ from the

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hydrometric river gauge. The difference in these values is because the Sunset Paleovalley accounts for only 5.3% of the cumulative land area upstream from this river gauge. Therefore, a conservative estimate of the Sunset Paleovalley groundwater outflow to the Kiskatinaw River would only account for 5.3% of the baseflow at the hydrometric station, which is equivalent to 9,158 $m^3$/d. The output total of the Sunset Paleovalley model closely approximates this value, assuming the total flux of both Layer 3 and Layer 5 boundary conditions eventually discharge to the Kiskatinaw River (10,423 $m^3$/d) based on the assumptions made in the Boundary Conditions section.



#### ***4.2.1. Groundwater budget discussion***

The long-term sustainable yield of aquifers is mainly dependent on the rate of extraction as a proportion of total discharge from the aquifer (Bredehoeft, 2002; Sanford, 2002). The existing groundwater allowance volumes within the Sunset Creek Catchment are roughly 11,000 $m^3$/year (30 $m^3$/day) used primarily for oil and gas activity (Northeast Water Tool, 2020). This total does not include allocations from domestic wells within the study area because this data was not available but are hypothesized as a small total volume compared to the listed allowances. This groundwater extraction volume is far less than the modeled total output from both exit SHB conditions to the Kiskatinaw River (10,423 $m^3$/day). In addition, although located distal (9 - 15 km) from the Kiskatinaw River in a recharge area, the two provincial wells within the study area with 8 years of water-level data show a steady increase in water level, with no signs of long-term drawdown (Fig. SI-1). This and the model results indicate that current groundwater extraction has a minimal impact on this reach of the Kiskatinaw River.

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**Table 3** Summarized groundwater budget for the model. Zone budgets are shown for the entire model, the buried valley gravel HSU (layer 3), and the weathered bedrock (layer 5). Inflow/outflows are either hydrostratigraphic units (HSU), specified recharge rates (SRR) or specified head boundary (SHB). The weathered bedrock HSU includes both weathered Dunvegan and Kaskapau HSU's.

| **Zone** | **Component** | **Inflow ($m^3$/day)** | **Outflow ($m^3$/day)** | **Inflow (%)** | **Outflow (%)** |
|---|---|---|---|---|---|
| **Model Domain** | Weathered till/clay SHB | 11139 | 1013 | 97% | 9% |
| | Alluvial SRR | 298 | 0 | 3% | 0% |
| | Kiskatinaw River SHB | 0 | 3777 | 0% | 33% |
| | Buried valley gravel SHB | 0 | 6646 | 0% | 58% |
| | Total flow | 11436 | 11436 | | |
| **Buried valley gravel (HSU)** | Weathered + unw. till/clay HSU | 116 | 131 | 1% | 1% |
| | Weathered bedrock HSU | 9172 | 2929 | 99% | 31% |
| | Buried valley gravel SHB | 0 | 6264 | 0% | 67% |
| | Total flow | 9288 | 9324 | | |
| **Weathered bedrock (HSU)** | Weathered + unw. till/clay HSU | 11125 | 812 | 79% | 6% |
| | Buried valley gravel HSU | 2928 | 9515 | 21% | 68% |
| | Kiskatinaw River SHB | 0 | 3726 | 0% | 27% |
| | Total flow | 14053 | 14053 | | |

### 4.3. Flow paths and travel times

Fig. 8 shows the potentiometric surface of the weathered bedrock layer, showing flow from topographic highs in the north and south of the model flow towards the valley center, then east towards the Kiskatinaw River CHB exit. This groundwater flow pattern is similar to a regional bedrock potentiometric map generated in 2016 (GW Solutions Inc., 2016, p. 68), which used

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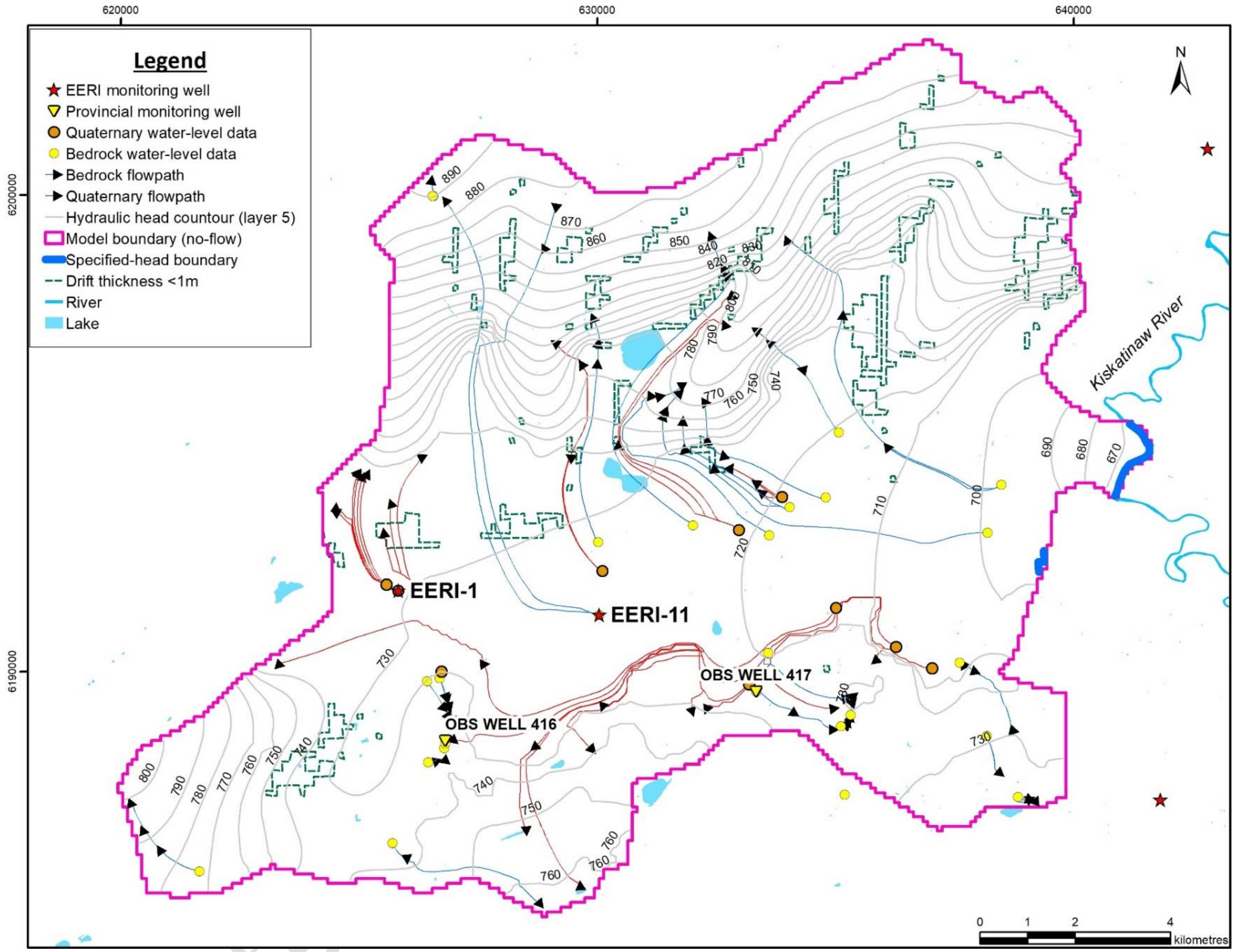
hydraulic head data from domestic wells to broadly characterize flow in the larger Dawson-Groundbirch region.

The results from particle tracking show that although most infiltration is in topographic highs, most particle path termination points do not fall directly within the areas of <1m drift thickness. Travel times in the buried valley sand/gravel aquifer were an average of 3,200 years, with a range of 37 to 30,000 years. Average travel times from the weathered bedrock aquifer were 2,900 years with a range of 49 to 20,000 years. Some of these values exceed the age of the confining clay and till units, hypothesized to have been deposited during the Late Wisconsinan age (14,000 – 16,000 years ago), whereas the buried valley sand/gravel were deposited between 16,000-22,000 years ago (P. Clark et al., 2009; Hickin et al., 2017). Therefore, original connate water likely is still in place in some units (Shaw & Hendry, 1998). Travel times within the weathered bedrock HSUs are likely biased high, since fracture porosities are not taken into account in the model, which would normally see higher groundwater velocity in fractured bedrock.

The hydrogeochemistry of groundwater in the Sunset Valley is also consistent with long residence times, where longer residence times and poor flushing lead to higher total dissolved solids (TDS). The average TDS in groundwater collected from 15 domestic wells within the study area was 1,300 mg/l; averages of 1,800 mg/L TDS in bedrock and 950 mg/L in quaternary samples (Kirste, Simon Fraser University, unpublished data, 2020). These relatively high values are indicative of a poorly flushed, slow flowing system.

Residence time ages can be compared and constrained by groundwater ages calculated from tritium concentrations in groundwater samples collected between 2011-2015 from the study area. Six tritium samples contain between 0.04 to 1.4 TU, indicative of residence times greater than ~50 years (I. Clark & Fritz, 1997; Plummer, 2005).




601

602 **Fig. 8** Potentiometric surface of layer 5 (weathered bedrock), and particle flow paths with infiltration locations, resultant of the calibrated model

# 5. Model assessment

While the geometry of the HSUs and study area are well constrained, the relatively sparse geological and hydrological data does not allow us to describe considerable smaller-scale heterogeneity in the complex real-world system. The model is fit for the purpose of large-scale estimates of recharge and system water balance but is not appropriate for sub-kilometer-scale predictions. The properties of the HSUs should be interpreted as large-scale, effective properties. Effective medium properties will likely yield reasonable predictions for total fluxes but will not properly account for rapid travel that can occur through fractures or other preferential pathways. Domestic well static water levels used in calibration were likely measured shortly after installation of the wells and may not have equilibrate with the local formation.

Although difficult to accurately conceptualize, smaller scale, intertill aquifers could be included to simulate potential permeable pathways through confining unweathered till. These interconnected permeable lenses within the confining layer have been hypothesized as potential pathways for buried-valley recharge (Cummings et al., 2012).

Finer mesh size, leading to longer run times, could have helped improve spatial recharge-rate resolution and potentially deal with the large outlier values seen in the model. The model domain could be expanded to incorporate adjacent Kiskatinaw and Groundbirch paleovalleys to gain a better understanding of the flow budget between these regional features.

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# 6. Conclusions

A regional groundwater flow model of a paleovalley based confined aquifer system in NEBC was constructed with the purpose of simulating and then constraining the spatial distribution of recharge and discharge. This modeling study utilized data from newly installed monitoring wells and synthesized available hydrogeological data for buried-valley aquifer systems in NEBC and the WCSB to construct a simplified conceptualization of the Sunset Paleovalley. Using MODFLOW-6, groundwater flow models were constructed and calibrated, adjusting parameters within literature ranges. Within the study area, the model quantitatively estimates the spatial distribution and magnitude of groundwater recharge and discharge, the water balance between HSU's, and residence times of aquifers. The simulation results were consistent with the general conceptual model, showing relatively low recharge rates, constrained by the low hydraulic conductivity of the surface diamicton. The average recharge in the study area is 16 mm/yr., which falls within the range of results from another study in the same region (Baye et al., 2016). The total flow in the study amounts to 11,000 $m^3$/day, with 58% outflow exiting via the buried-valley aquifer SHB, 33% exiting the weathered bedrock SHB into the Kiskatinaw River and 9% to surface water within the model domain. The buried-valley aquifer receives 99% of its inflow from the underlying weathered bedrock aquifer, which less than 1% coming vertically downwards through the thick, impermeable confining till units. Using particle tracking the average residence times of particles originating in the buried-valley aquifer was 3,200 years, and 2,900 years in the weathered bedrock aquifer. These average travel times results fall within the 1000-10,000 year range of results from studies that use groundwater carbon-14 data from buried gravel aquifers with confining till material to estimate residence time (Cravens & Ruedisili, 1987; Keller et al., 1989).

The model results add to the understanding of buried-valley aquifer systems and their recharge. These hydrogeological settings are common to the Interior Plains region of North America and important sources of water for domestic, agricultural, and industrial use. As a next step, modeled flow budget results can be used as a basis for groundwater management strategies within the region. Similar to study by Pétré et al. (2019), this study's model can be used for groundwater exploitation scenario modeling, to better provide estimates on sustainable extraction of this finite resource.

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**Conflict of interest statement**
On behalf of all authors, the corresponding author states that there is no conflict of interest.

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## Supporting Information

### Geological conceptualization

EERI-1 lithological interpretation: The top ~13 m is a sequence of coarse sharp sand, overlain by diamicton interbedded with a thin clay layer, overlain by continuous clay interpreted as sediments deposited by retreat-phase glacial Lake Peace, a proglacial lake which typically formed the surface units in areas of northeastern BC with elevations less than 1000 m asl (Hickin et al., 2016). The subglacial till below this unit (~13–42 m) is a poorly sorted, silt- to clay-rich, matrix-supported diamicton with granule- to boulder-sized clasts of western provenance (chert and quartzite), indicative of Cordilleran ice-sheet transport. This subglacial till forms an abrupt contact with the underlying glaciofluvial sandy gravel, which consists of a poorly sorted and clast-supported gravel, with minor sand interbeds. Underlying the glaciofluvial gravel is a fining-upward sequence of laminated silty clay to diamicton, interpreted as deposits associated with the advance-phase glacial Lake Mathews (Hartman & Clague, 2008).

EERI-11 lithological interpretation: Like EERI-1, the uppermost 10 m consist of fining-upward glaciolacustrine clay indicative of retreat-phase glacial Lake Peace. Below this, lies subglacial till (10–27 m) consisting mainly of poorly sorted, silt- to clay-rich matrix-supported diamicton with granule- to boulder-sized clasts. Below this, a massive fine-sand unit (27–37 m) is interpreted to be of glaciofluvial origin. The lowermost portion (37–40 m) consists of a thin layer of diamicton interpreted as deposits associated with glacial Lake Mathews. These Quaternary sediments lie unconformably atop the Cretaceous bedrock, which is composed of medium-grained sandstone interlayered with siltstone that matches the Dunvegan Formation bedrock mapped at this location.

## Groundwater flow

At both sampling times, the vertical gradient between consecutive ports was less than ±0.02 m/m in seven of the nine ports. This small vertical gradient is within the ±0.01 m error tolerance of the Westbay® pressure-profile tool (Meyer et al., 2008, 2014), and indicates horizontal flow along these intervals, relatively high vertical hydraulic conductivity (Kv) and good vertical connection in this section of weathered bedrock (Meyer et al., 2014). The hydraulic head at the bottom port was 12 cm greater than at the top port, with a vertical separation of 25 m, corresponding to a total vertical gradient of 0.0048 m/m downward (Fig. 3). The lack of large resolvable head changes between ports indicates the absence of aquitard units within this section of sandstone interlayered with siltstone. It is important to note that the top 4 m of bedrock (directly underlying the

Quaternary units) are not screened by Westbay® ports. Without head measurements in the top 4 m, it is difficult to interpret the vertical-flow direction through the bedrock/overburden interface.

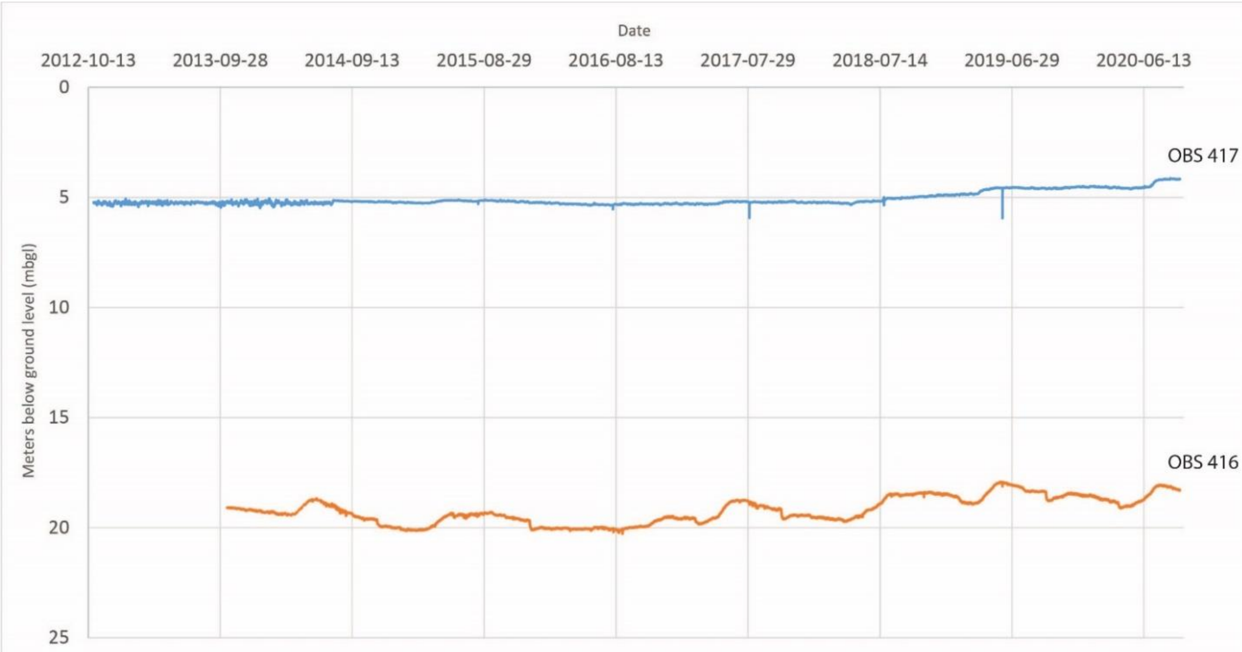


**Fig. SI-1** Hydrograph data showing static water level fluctuations in OBS 416 (top) and 417 (bottom).

## Hydrogeological Conceptual Model

### *1. Weathered till/clay*

Genetically, these clays and diamict were likely deposited from retreat-phase proglacial Lake Peace (Hickin et al., 2016). In the study area, surficial weathered till is most common in the topographic highs as the surficial top unit by extent, whereas glaciolacustrine clay which is typically found in capping the valley center. There is likely a large variation in pore water velocities in near surface weathered till, likely due to complex fracture network (Keller et al., 1988; Nastev et al., 2005). Potential mechanisms on the formations of fractures leading to increased secondary permeability in weathered till include: regional extension of the earth's crust due to crustal rebound following glacial loading, primarily vertical stress release of Quaternary deposits following retreat of glaciers during late Wisconsin, and volume changes due to desiccation during warm climatic conditions of post-Wisconsin time (Grisak & Cherry, 1975). Further development of secondary porosity can result from osmotic, ion-exchange processes and freeze-thaw cycles. The flow regime through surficial tills depends on vertical groundwater flux, depth to water table and depth of the weathered/unweathered boundary (Keller et al., 1988).

***2. Alluvial***

Alluvial sediments are found only in the modern alluvial plain of the Kiskatinaw River plain, with the exception of a small patch of alluvial cover on the eastern-central part of the model area.

***3. Unweathered till***

Genetically, this unit is a subglacially deposited diamict and has a poorly-sorted silt to clay rich matrix, with granule to boulder sized clasts (Hickin et al., 2016). The interface between weathered and unweathered till typically varies between 4.6 and 18m below ground level, and mimics the surface topography (Cravens & Ruedisili, 1987; Grisak & Cherry, 1975; Keller et al., 1988). Horizontal gradients through unweathered till are found to be very small compared to vertical gradients, with very low vertical pore water velocities ~0.8 mm/yr. (Keller et al., 1988).

***4. Buried valley sand/gravel***

Genetically, this unit is glaciofluvially deposited, with poorly-sorted clast supported gravel, with lesser sand interbeds (Hickin et al., 2016). Studies on buried-valley aquifers have indicated large drawdown responses at great distances from the pumping well in buried valley, indicating a laterally continuous aquifer (Kamp & Maathuis, 2012; Russell et al., 2004). In contrary, a study by (Troost & Curry, 1991) found interconnections of permeable buried valley sands to be in weak response from aquifer pumping testing, likely due to a high proportional of silt and clay in the valley fill. Hydraulic barriers, preventing lateral continuity of buried aquifers are also possible in reality, but not considered in this study (Korus et al., 2017; Shaver & Pusc, 1992).

***5. Basal till***

Genetically, this unit is likely deposited by the advanced-phase proglacial Lake Mathews (Hartman & Clague, 2008; Hickin et al., 2016). The increased oxidation compared to unweathered till suggests water flow through this unit. From domestic and EERI well logs in the model area, permeable sand/gravel deposits are typically not directly overlying bedrock, with this basal till HSU separating the gravel/sand aquifer from the weathered bedrock aquifer (~5 meters based on EERI-11). This can be interpreted that the two aquifers are at least somewhat disconnected, depending on the leakiness of the basal till unit.

***6-7. Weathered bedrock (Dunvegan Fm. sandstone and Kaskapau Fm. shale)***

This HSU is intended to encompass the "critical zone", which encompasses the downward weathering front of top of bedrock layer (S. P. Anderson et al., 2007; Welch & Allen, 2014). During drilling investigation in the EERI project, a layer of saprolite-like material was commonly encountered before reaching fresher bedrock. For fine clastic formations such as Kaskapau Fm. shales, bedrock weathering is anticipating to be less intense, due to dissolution enlargement of fractures being less effective because of rock composition being enriched in low mobility clay elements (Al, Fe, K) and depleted in higher mobility elements (Ca, Na, Mg) (Worthington et al., 2016). However, preferential flow on bedding planes in fine clastic sedimentary rocks can still be a cause for enhanced permeability (Worthington et al., 2016). For coarse clastic rocks such as the Dunvegan Fm., flow through matrix is considerable (Worthington et al., 2016).

***8. Competent bedrock shale***

A groundwater flow modeling study in Quebec, Canada found that most of the total bedrock groundwater flux occurs within the topmost 30-50m section of fractured bedrock, with underlying competent bedrock far less influential on regional flow regimes (Nastev et al., 2005).