Groundwater Recharge in a Confined Paleovalley Setting, Northeastern British Columbia (Part of NTS 093P)

A.M. Goetz[1], **The University of British Columbia, Vancouver, British Columbia, mgoetz@eoas.ubc.ca**

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

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Introduction

The Peace Region in northeastern British Columbia (BC) is located on the western edge of the Western Canada Sedimentary Basin (WCSB), bordering the Canadian Rocky Mountains (Figure 1). The hydraulic characteristics of major aquifers of the Peace Region in northeastern BC have been the subject of increasing interest over the last decade (Foundry Spatial Ltd., 2011; Baye et al., 2016; Morgan et al., 2019; Chao et al., 2020). Although groundwater is not the main source of drinking water for the over 60 000 residents of the Peace Region, as most large communities source their water supply from major rivers, nonetheless understanding sustainable yield of groundwater is important for domestic, industrial, agricultural and environmental purposes (Bredehoeft, 2002; Baye et al., 2016; Statistics Canada, 2017). Most groundwater wells in northeastern BC are constructed with a well screen installed in weathered/fractured bedrock, with fewer having the screen installed in buried-valley sand/gravel aquifers (Baye et al., 2016). Buried-valley, or paleovalley, aquifers commonly host significant sources of groundwater in those areas where they are thick and laterally continuous (Hickin et al., 2008). 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 gal/min) during a 72-hour constant-rate pumping test (Gardiner et al., 2020).

The objective of this study is to determine dominant recharge pathways through low-permeability, confining layers to both weathered bedrock and buried-valley aquifers in the Sunset paleovalley, an archetypical groundwater system that is located in the southern Peace Region, west of Dawson Creek, BC (Figure 1). The spatial distribution of recharge values, residence times of aquifers and the steady-state water balance of the system are analyzed using a groundwater-flow model.

[1]*The lead author is a 2020 Geoscience BC Scholarship recipient.*

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The distribution and magnitude of recharge is dependant on climate (precipitation/evapotranspiration rates), geological framework (confining thickness/conductivity) and topography (runoff/infiltration ratio; Winter, 2001; Sanford, 2002). Over much of the study area, the aquifers are confined by low-permeability tills, which limit recharge rates, but protect the aquifers from potentially degrading surficial processes such as drought and contamination (Cummings et al., 2012). The dominant factor controlling recharge for the Sunset paleovalley system is assumed to be lithology, with most recharge likely originating where 'windows' of thin surficial confining material (e.g., Quaternary diamict) exist, resulting in a shorter travel time to the aquifer below (Andriashek, 2003; Nastev et al., 2005; Cummings et al., 2012). These windows can provide pathways for focused recharge to weathered bedrock and buried-valley aquifers (Korus et al., 2017). Recharge dynamics in buried-valley aquifers depend greatly on the bulk permeability of the confining layer and groundwater residence times in till material has been shown to range from thousands to tens of thousands of years (Keller et al., 1989). The flow regime through surficial tills depends on vertical groundwater flux, depth to the water table and depth of the weathered/unweathered boundary (Keller et al., 1988).

There are no modelling studies with a primary focus on groundwater recharge of buried-valley settings in northeastern BC. This region is distinct from those of most other studies in the WCSB; it is characterized by undulating terrain near the Rocky Mountain Foothills and a lack of features common to the Prairie Pothole Region, which are hypothesized to be the dominant recharge mechanism found in many WCSB buried-valley systems (Meyboom, 1966; Berthold et al., 2004; Cummings et al., 2012).

Paleovalley systems are common in glaciated terrain and numerous other local (1–5 km scale) buried-valley systems have been studied using numerical models (Shaver and Pusc, 1992; Seifert et al., 2008; Seyoum and Eckstein, 2014). Morgan et al. (2019) used MODFLOW 6 software developed by the U.S. Geological Survey to simulate regional (60 km) groundwater flow for a paleovalley system in northeastern BC located in the Halfway River area, focusing on the continuity of buried-valley aquifers and their

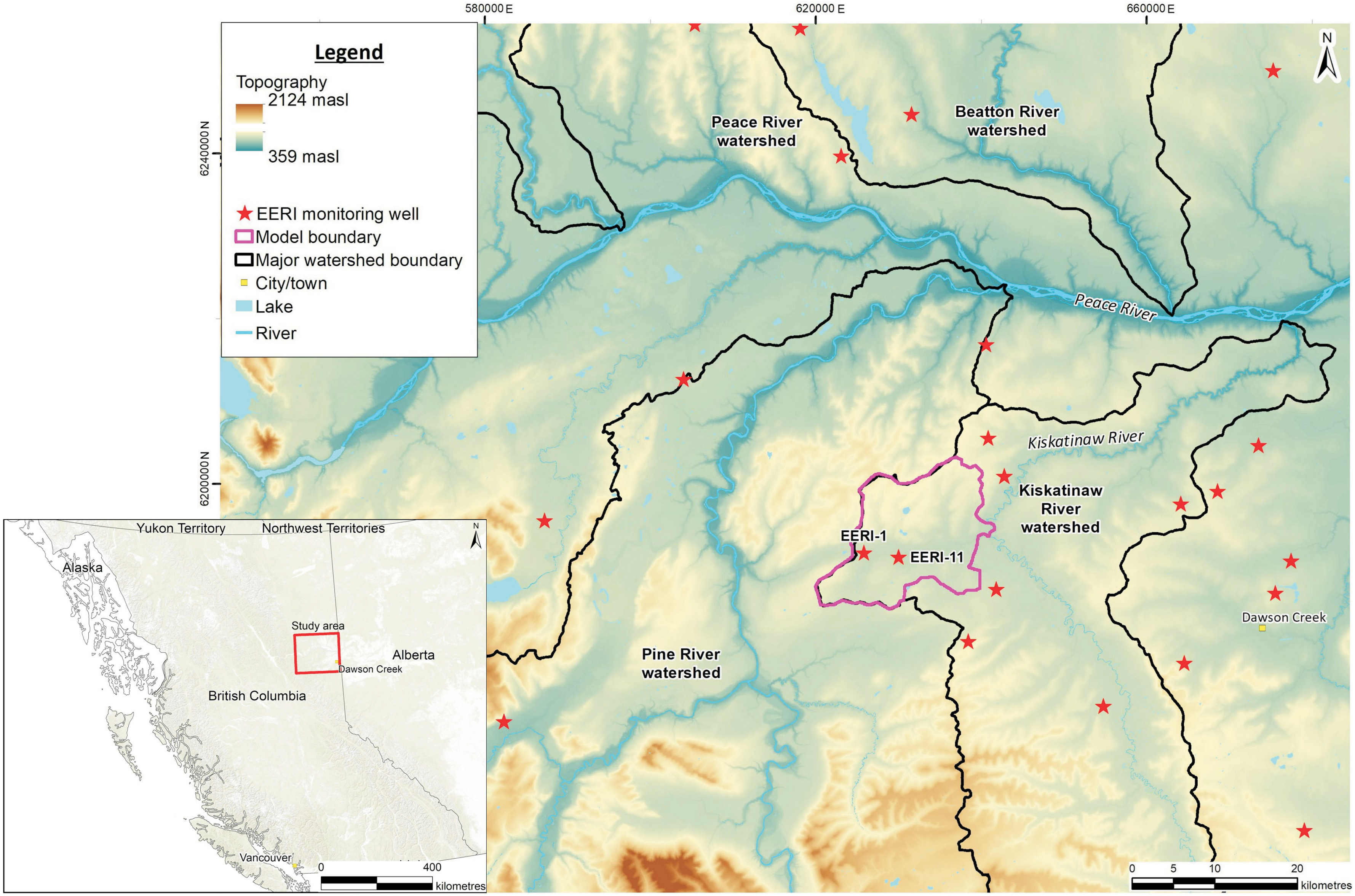

Figure 1. Digital elevation model of the study area in the southern Peace Region, showing major watershed boundaries. Inset shows the location of the study area in British Columbia. Abbreviations: EERI, Energy and Environment Research Initiative; m asl, metres above sea level.

importance on regional groundwater flow. Comparatively, this study by Morgan et al. (2019), focusing on a larger area, covered several distinct paleovalleys, had a large unconfined-aquifer component and described aquifers that were conceptualized to have considerable connection to surface water.

Since recharge is a major component of the groundwater budget, the interpreted model results will help inform sustainable extraction of this finite groundwater supply and have implications for advective transport of solutes and/or contaminants, such as dissolved fugitive gas being released from compromised energy wells (Bredehoeft, 2002; Cahill et al., 2019; Chao et al., 2020). As the Sunset paleovalley system is in an area of unconventional-gas development, it is important to understand typical regional-scale groundwater-flow patterns that will control the movement of potential dissolved-phase contaminants, including fugitive dissolved gases.

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 of the system using MODFLOW 6 software was developed (Hughes et al., 2017). The system was then modelled using methods that yielded a steady-state model, since only two long-term monitoring points were available within the model domain, and since 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 (Figure 2).

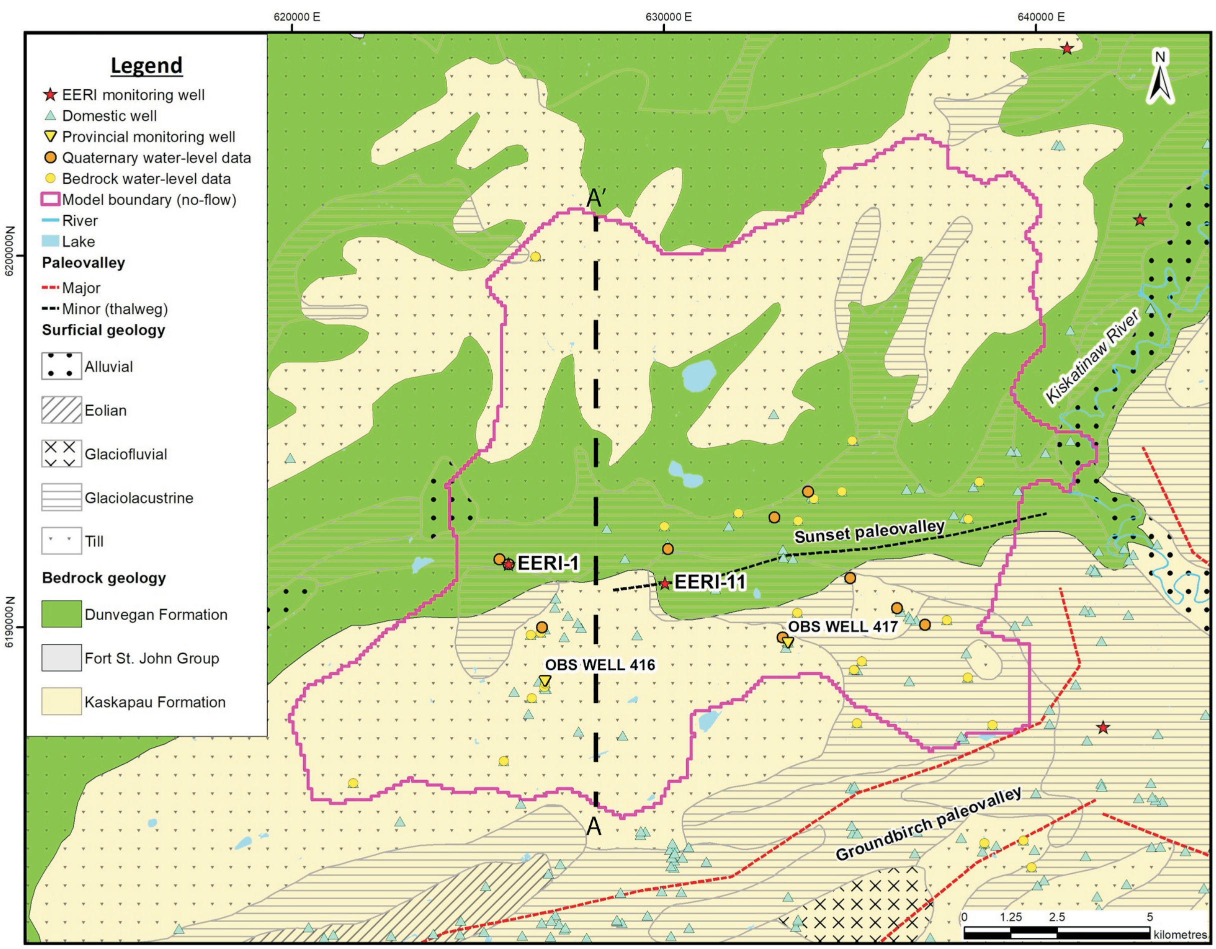

Figure 2. Surficial, bedrock and water well data of the study area in the southern Peace Region, west of Dawson Creek. The model area is outlined in pink and the vertical black dashed line represents a transect (A–A') indicating the location of the conceptual model cross-section shown in Figure 4. Abbreviation: EERI, Energy and Environment Research Initiative.

Study Area

Physiology

The Sunset paleovalley is a minor paleovalley (Figure 2) delineated by Hickin et al. (2008), with an elevation ranging from 660 to 900 m above sea level (asl). 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 (Figure 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 run-off for the Kiskatinaw River Basin (1966–2008) comes from precipitation (14.2%), with the remainder consisting of evapotranspiration and groundwater recharge (Foundry Spatial Ltd., 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 most important 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).

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 (Figure 2; Hickin and Fournier, 2011a; Riddell, 2012). The shallow bedrock formations are interpreted as 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 Low Carbon Innovation, 2020). The Dunvegan Formation is an Upper Cretaceous nonmarine 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 Ltd., 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 (Imrie, 1991; Gao, 2011). 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 and Clague, 2008; Hickin et al., 2008, 2016; Lowen Hydrogeology Consulting Ltd., 2011; Hickin and Best, 2013), 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, 2003; Pugin et al., 2014). Created glacially or interglacially, these paleovalleys sometimes mimic the shape of modern major river valleys, 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.

EERI Wells

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 EERI monitoring wells newly installed within the study area. 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, obtained from EERI-1 and EERI-11, were key to the development of the hydrogeological conceptual model. The 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 (Figure 2). The sequence stratigraphy of 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). It was assumed that through lateral continuity, given that the Sunset and Groundbirch paleovalleys share a similar elevation, the stratigraphic interpretations of the study by Hickin et al. (2016) could be applied to the Sunset paleovalley depositional setting. The generalized sequence stratigraphy 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.

Monitoring well EERI-1 consists of ~66 m of mainly till and sand/gravel intervals and does not reach bedrock (Figure 3). The top ~13 m is a sequence of coarse sharp sand, overlain by diamict 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 diamict 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 diamict, interpreted as deposits associated with the advance-phase glacial Lake Mathews (Hartman and Clague, 2008).

Monitoring well EERI-11 extends through 40 m of clay, diamict and sand overlying 37 m of medium sandstone interlayered with siltstone. 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 diamict 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 diamict 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

Hydraulic-head data was available from 35 groundwater wells, made up of domestic, provincial observation and EERI wells. Although 85 domestic well records entered in the WELLS database are located within the model domain, head data from only 31 wells were used to calibrate the numerical-model study since these were the only wells providing both reliable lithological and static-water records (22 in bedrock and 9 in Quaternary units).

The newly installed EERI monitoring wells provided more recent (2019–2020) and reliable hydraulic-head measurements than domestic wells. Most EERI monitoring wells located across the Peace Region were equipped with data-logged pressure transducers to record head through time. 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. Consequently, no data loggers were installed, and transient-head data is therefore unavailable. 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. 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 (Figure 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.

Conceptual Model

Hydrostratigraphy

A conceptual model, which identifies the most important hydrogeological processes, was developed considering the available information. A schematic hydrostratigraphic section for the Sunset paleovalley model is shown in Figure 4. The Sunset paleovalley has similar morphology and geology and, therefore, expected flow patterns similar to those identified in the study by Nastev et al. (2005). Precipitation

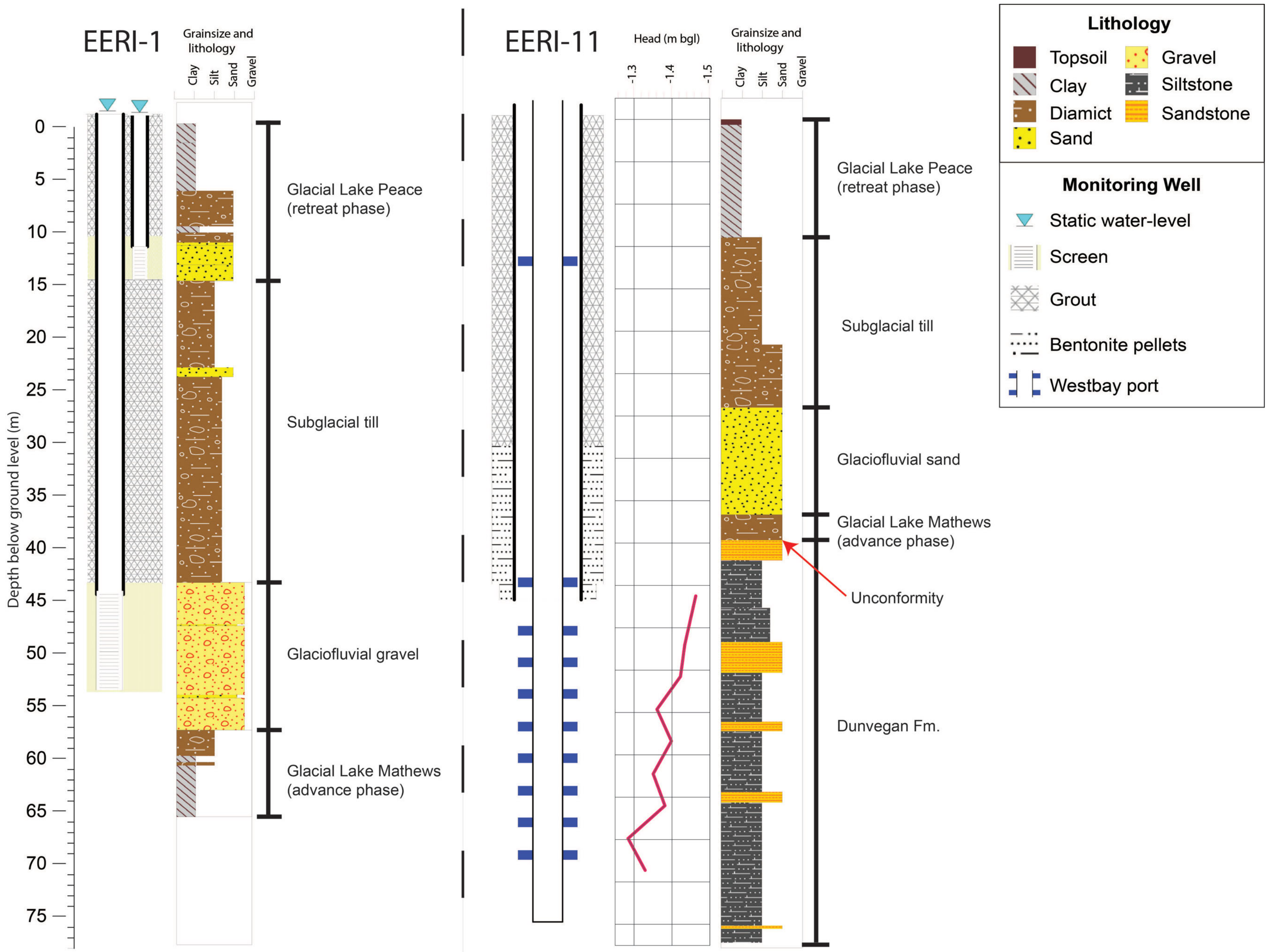

Figure 3. Well completion, hydraulic head, highly detailed lithological logs and depositional interpretation of monitoring wells EERI-1 and EERI-11 in the southern Peace Region, west of Dawson Creek. Abbreviations: EERI, Energy and Environment Research Initiative; Fm., Formation; m bgl, metres below ground level.

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

Eight hydrostratigraphic units (HSUs) have been identified for the conceptual model of the Sunset paleovalley: five Quaternary hydrofacies (weathered till/clay, alluvium, unweathered till, buried-valley sand/gravel and basal till) and three bedrock hydrofacies (weathered-bedrock Dunvegan Formation sandstone, weathered Kaskapau Formation shale and competent shale).

Aquifer 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, Kx is assumed equal to Ky. A vertical anisotropy factor of Kh/Kv = 10 is set for the alluvial, buried-valley sand/gravel and all bedrock HSUs to demonstrate 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. However, it is expected that flow-through 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 of two samples within the EERI-1 buried-valley sand/gravel was estimated using the Kozeny-Carman and Terzaghi equations (Odong, 2007), with values ranging between 60 and 130 m/d.

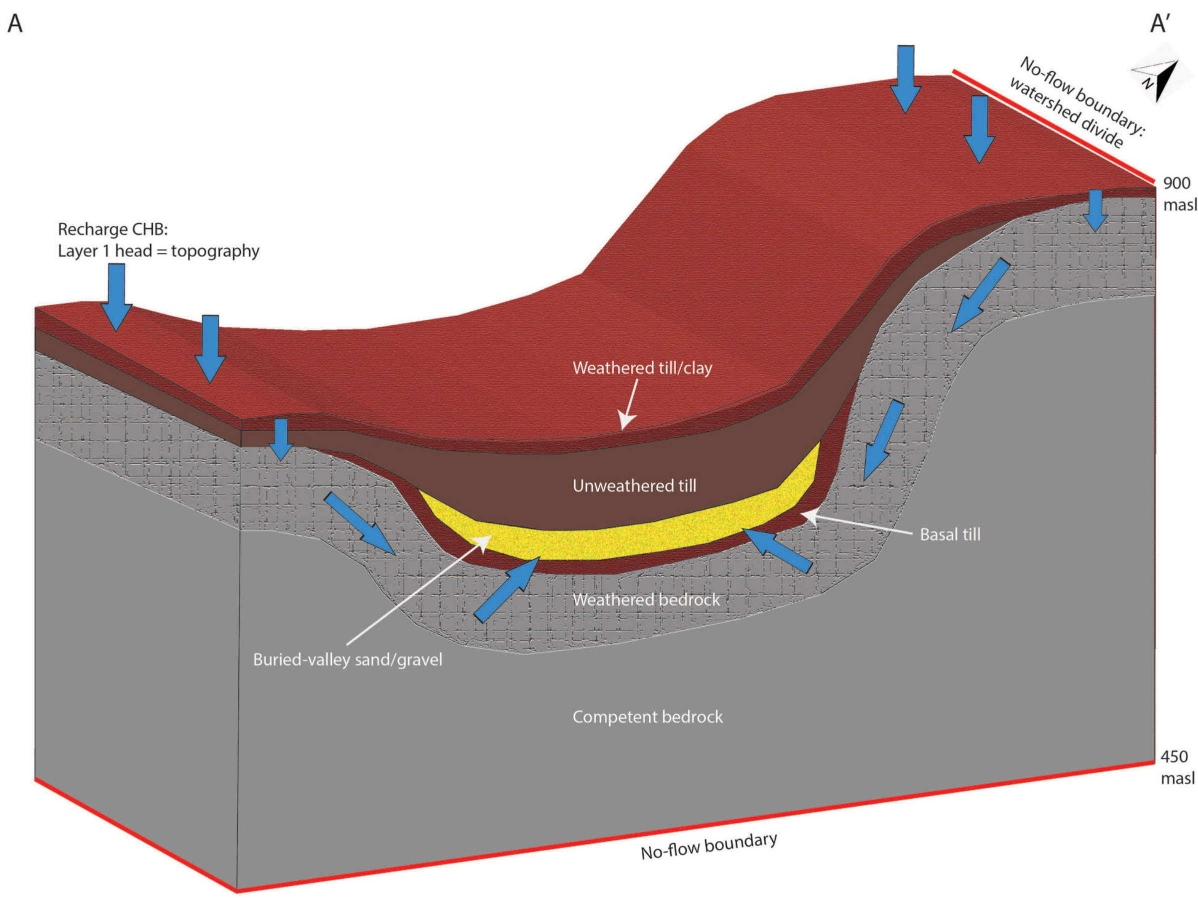

Figure 4. Conceptual block model of the hydrostratigraphy of the Sunset paleovalley study area, along transect A–A' shown in Figure 2. Hydrostratigraphic units are labelled, along with hypothesized recharge flow path (blue arrows) from surface to buried-valley sand/gravel aquifer and approximate locations of some of the boundary conditions. Abbreviations: CHB, constant-head boundary; m asl, metres above sea level.

Table 1. Hydrostratigraphic units, with corresponding layer number, calibrated hydraulic conductivities and range of values from the literature. Shaded hydrostratigraphic units represent aquifer material.

Hydrostratigraphic unit	Model layer no.	Model Kx/Ky	Model Kz	Literature range	
				Min	Max
		(m/d)	(m/d)	(m/d)	(m/d)
Weathered till/clay[1]	1	1.5×10^{-3}	1.5×10^{-3}	1.6×10^{-4}	1.7×10^{-2}
Alluvial[2]	1	430	43	260	8.6×10^{-4}
Unweathered till [1]	2	8.6×10^{-6}	8.6×10^{-6}	4.3×10^{-6}	8.6×10^{-5}
Buried-valley sand/gravel[1, 3]	3	110	11	1	140
Basal till [1]	4	1.5×10^{-3}	1.5×10^{-3}	1.6×10^{-4}	1.7×10^{-2}
Dunvegan Fm. sandstone (weathered)[2, 4]	5	8	0.8	8.6×10^{-5}	8.6
Kaskapau Fm. shale (weathered)[2, 4]	5	0.1	1.0×10^{-2}	8.6×10^{-9}	8.6×10^{-5}
Shale (competent)[2]	6	1.0×10^{-7}	1.0×10^{-8}	8.6×10^{-9}	8.6×10^{-5}

[1]Estimated from literature values (Cummings et al., 2012)

[2]Estimated from literature values (Freeze and Cherry, 1979)

[3]Estimated from grain size analysis (A.M. Goetz, unpublished data, 2020)

[4]Estimated from pumping-test analysis (Baye et al., 2016)

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 the Theis, Cooper-Jacob and recovery analyses (Theis, 1935; Cooper and Jacob, 1946), provincial monitoring well OBS 416 presented a range of hydraulic conductivities between 9.0 and 30 m/d and well OBS 417 ranged between 0.70 and 0.81 m/d. These values are representative of both the weathered-bedrock Dunvegan Formation and weathered Kaskapau Formation.

Groundwater-Flow Modelling

Model Structure

The grid of this model is formed of gridblocks each measuring 100 by 100 m; it consists of 23 448 gridblocks per layer and the active model domain covers approximately 235 km^2 (Figure 5). The gridblock size was chosen to adequately represent variations in hydraulic properties, while maintaining a manageable run time (Reilly and Harbaugh, 2004). All gridblocks are set to 'convertible' as the default value, with the wetting option enabled for all layers. The model is made up of six layers, extending from ground surface 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; Government of British Columbia, 2020) and the top of the bedrock was interpolated using an existing bedrock topography DEM (Hickin and 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 spots 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 (Seyoum and Eckstein, 2014; Morgan et al., 2019). 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. The surficial geology of layer 1 at the surface is based on mapped surficial geology data from Hickin and Fournier (2011a) 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 (yellow outline on Figure 5). 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 Low Carbon Innovation, 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.

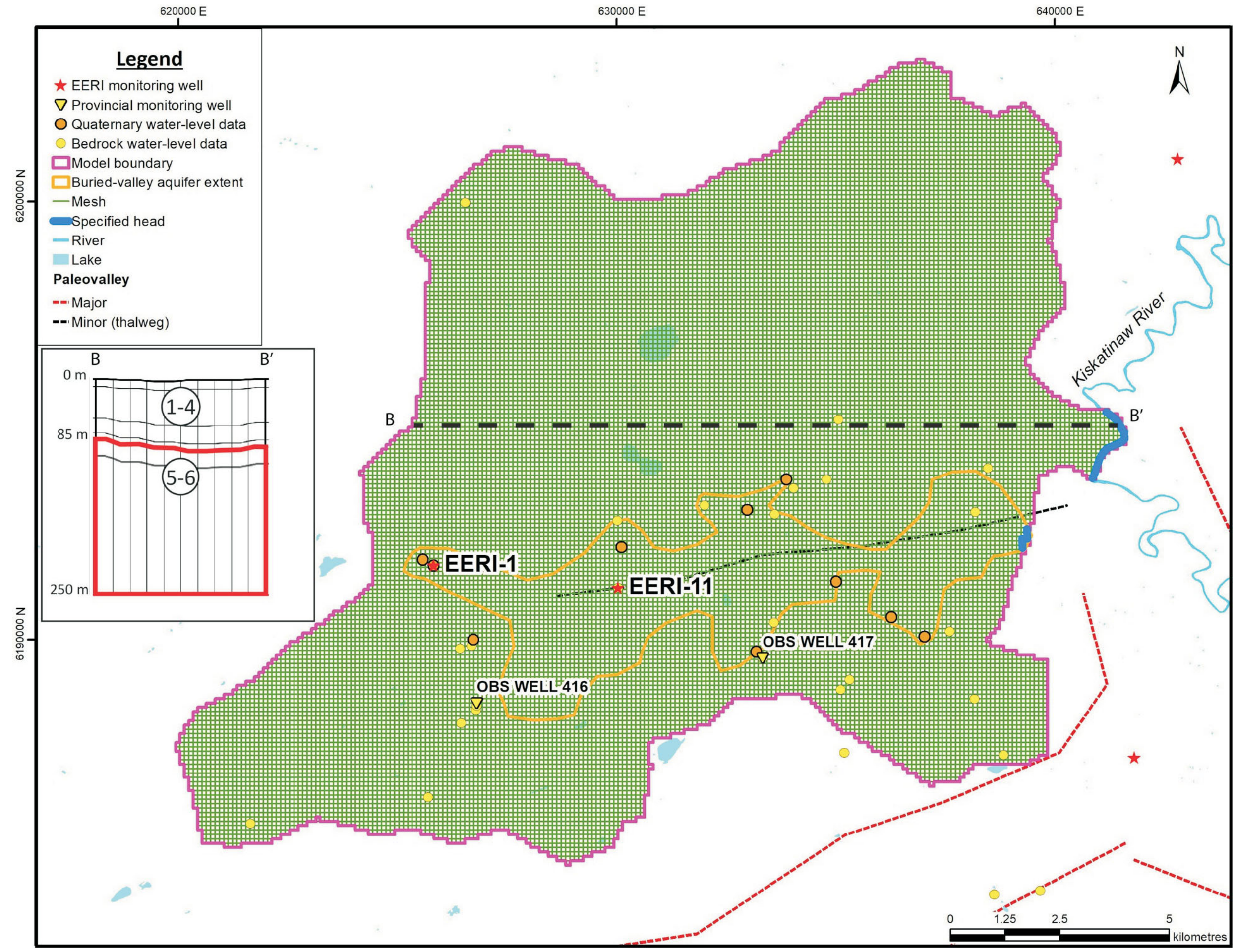

Figure 5. Model grid with boundary conditions built using MODFLOW 6 software (Hughes et al., 2017). Inset showing a simple cross-section (B–B') of layers 1–4 (Quaternary HSUs) and layers 5, 6 (bedrock HSUs). Abbreviations: EERI, Energy and Environment Research Initiative; HSU, hydrostratigraphic unit.

Boundary Conditions

In the case of the lateral limits of the model domain, no-flow boundaries were primarily defined by major regional watershed divides, with some boundaries being interpreted as flow divides between the Sunset Creek, Groundbirch and Kiskatinaw River valleys (Figure 2). A reasonable approximation is that these three valleys are likely separated by groundwater divides, with no interbasin groundwater flow. The northern and western no-flow boundaries follow the boundary between the Pine River and Kiskatinaw River watersheds (Figure 1). The Pine River likely acts as a groundwater divide, blocking the influence from the Rocky Mountain "water towers", which store and release large volumes of groundwater in 'pulses' during freshet (Viviroli and Weingartner, 2008; Marques et al., 2013). The southern no-flow boundary was determined 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.

No-flow boundaries were applied to the bottom section of the model. This boundary is not associated with a specific lithological change, but rather was set at a depth great enough to avoid it influencing the simulation of flow in the shallow aquifers.

Hydrological data within the study area show hydraulic heads are close to the topographic surface, suggesting infiltration rates exceed recharge rates. The thickness and the low hydraulic conductivity of the confining-layer till (the conductance of the unit) is assumed to act as a major control on the recharge rate. Under the assumption that recharge was largely limited by surface hydraulic conductivity (lithology-controlled recharge), a constant-head boundary (CHB) 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. This boundary condition allowed the model to implicitly calculate recharge rates and actually identify preferential pathways through confining layers. This boundary condition is beneficial in cases such as this study, where spatial measurements of rainfall, runoff and evapotranspiration data are unknown (Sanford, 2002).

A constant-rate–recharge boundary condition of 68 mm/a was applied to the alluvial HSU, which corresponded to the rate resulting from a recharge study based on material type by Baye et al. (2016). This boundary condition specific to the alluvial HSU was implemented due to the excessive amount of water entering this very permeable material (43 m/d) with the CHB applied, a value greater than precipitation, which was unrealistic.

To allow water to flow out of the model, specified head boundaries were applied to two of the aquifer layers (3 and 5) at the presumed paleovalley outflow point, where the Sunset paleovalley meets the Kiskatinaw River valley.

The specified head value 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. This specified head value was estimated to be 693 m asl at the outflow boundary.

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, since this represented bedrock outcropping at this boundary and groundwater flowing into the Kiskatinaw River according to drift-thickness data. The outflow boundary for layer 5 was defined as 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.

Results

Simulated recharge at each surface gridblock within the model domain is shown in Figure 6. Gridblocks in 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 gridblocks agrees with the hypothesis of highland recharge and valley discharge, except for several localized

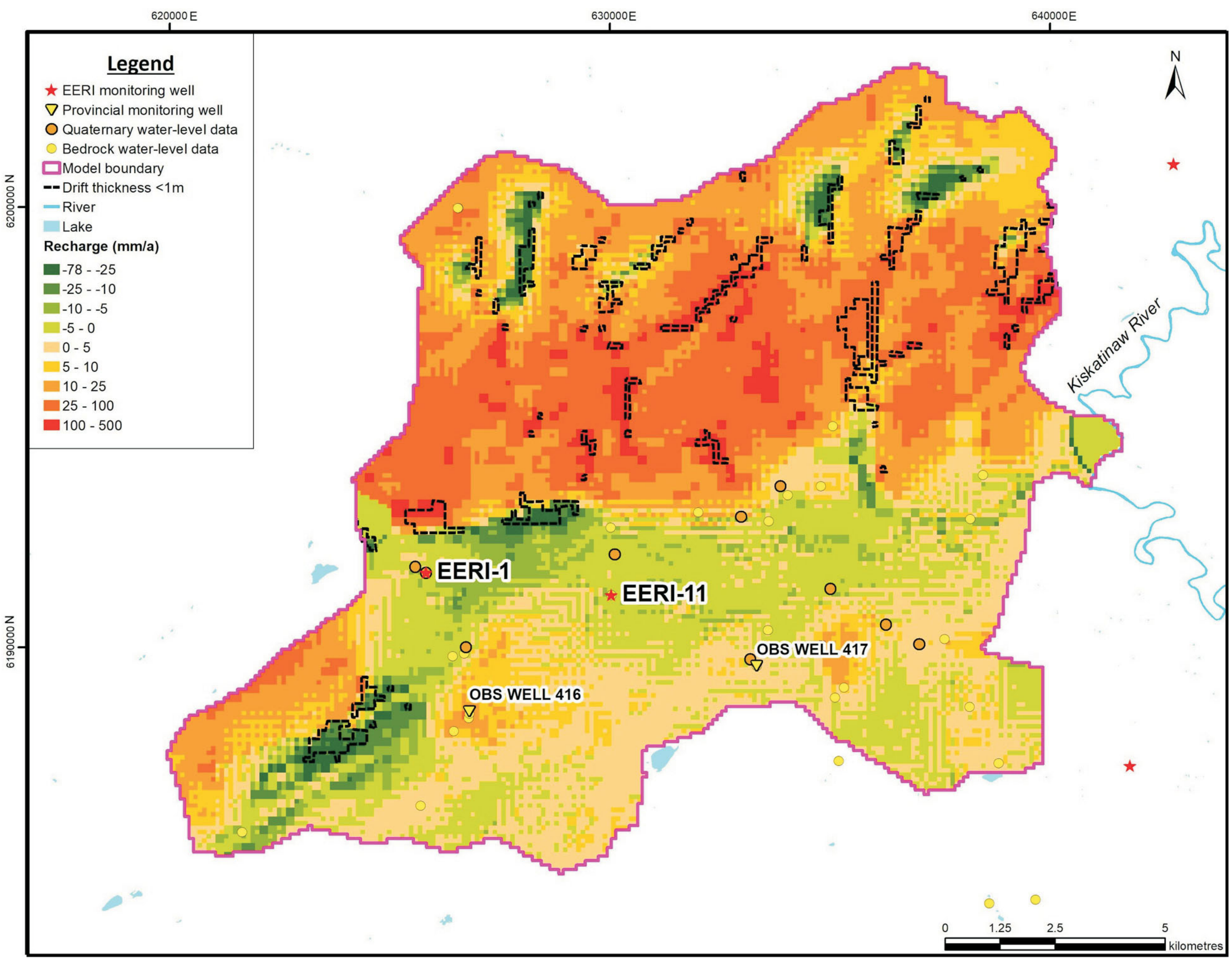

Figure 6. Spatial distribution of recharge/discharge rates in hydrostratigraphic unit layer 1 in the Peace Region, west of Dawson Creek. Dotted black lines indicate zones of thinnest drift (<1 m). Abbreviation: EERI, Energy and Environment Research Initiative.

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. 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 Ltd., 2011). The difference between discharge and evapotranspiration suggests that discharge areas would not result in groundwater-fed creeks within the model domain. This is consistent with the ephemeral nature of the mapped streams in the model area. Extreme outlier gridblocks with high recharge values (>100 mm/a) are unrealistic given 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). These outlier values could likely be dealt with by refining the grid mesh of these areas. Outlier recharge values occur mostly within regions with <10 m of Quaternary cover (total thickness of layers 1–4).

Recharge values based on surficial confining material in the region were studied by Baye et al. (2016) using the hydrologic evaluation of landfill performance (HELP) model developed for the Environmental Protection Agency by the U.S. Army Corps of Engineers Waterways Experiment Station. 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.

Discussion

Steady-state groundwater flow in the Sunset Creek valley groundwater system was analyzed. The simulation results were consistent with the general conceptual model, showing relatively low recharge rates, constrained by the low hydraulic conductivity of the surface diamict. Given the limited information, a pragmatic choice was made to assign uniform, effective properties to the units in the simulation domain, whereas the real system is heterogeneous at both the unit and subunit scale. 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.

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.

Although difficult to accurately conceptualize, 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).

Conclusion

A regional groundwater-flow model of a paleovalley-based confined-aquifer system in northeastern BC was constructed with the purpose of simulating the spatial distribution of recharge and discharge. This modelling study synthesized available hydrogeological data for buried-valley aquifer systems in northeastern BC and the WCSB, with data from newly installed monitoring wells, to construct a simplified conceptualization of the Sunset paleovalley. Using MODFLOW 6 software, groundwater-flow models were constructed and calibrated, adjusting parameters within the range of values identified in the literature. Within the study area, the model quantitatively estimated the spatial distribution and magnitude of groundwater recharge and discharge, the water balance between HSUs and residence times of aquifers. The average recharge in the study area was estimated at 16 mm/a, which falls within the range of results from another study in the same region (Baye et al., 2016).

In future work, the model's water budget will be analyzed to investigate flow volumes between HSUs and to compare model outflow to estimates of Kiskatinaw River baseflow, as determined from hydrometric data. Using the particle-tracking program of MODFLOW 6, average residence times for the aquifers will be calculated and evaluated based on residence times from similar paleovalley studies.

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 are important sources of water used for domestic, agricultural and industrial purposes. As a next step, modelled flow-budget results can be used as a basis for groundwater-management strategies within the region.

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