AER/AGS Open File Report 2019-11

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Abstract

Gravel deposits in the Grimshaw area form an important aquifer system and aggregate resource in northwestern Alberta. The stratigraphy and geometry of the gravel deposits were updated by the Alberta Geological Survey, and informally named the Grimshaw gravels, Old Fort gravel and Shaftesbury gravel from highest to lowest. Identification of three stratigraphically and geometrically distinct components of the gravel deposit provided an opportunity to re-examine the hydrogeological characteristics of the aquifer system that is hosted within the gravel deposits. The study focuses on variations in groundwater chemistry and spatial and temporal trends in groundwater levels across the three gravel units. A key finding of this assessment is that observations of varying groundwater quality and availability across the area are better explained by considering the aquifer as a terraced system corresponding with the three gravel units rather than a single aquifer.

This study found that groundwater levels are relatively flat across the Grimshaw gravels with Cardinal Lake receiving some groundwater discharge along the west and north shorelines, and recharging groundwater along the south and east shorelines. The groundwater in the Grimshaw gravels is generally of good quality and sourced primarily from snowmelt. Groundwater recharge was estimated to be in the range of 10 to 50 mm per year. The groundwater level across the Old Fort gravel slopes toward the Peace River valley and appears to have a consistent pattern of flow direction through time. Groundwater in the Old Fort gravel is sourced primarily from bedrock formations, leading to poorer water quality and zones of sodium- and/or sulphate-rich groundwater.

1 Introduction

Buried gravel deposits north of the Peace River near Grimshaw Alberta form a regionally important aquifer and aggregate resource (Figure 1). Two hydrogeological characterizations of the deposits have been previously conducted, the first by Tokarsky in 1967, the second by the Prairie Farm Rehabilitation Administration (PFRA) in 1998. Both studies recognized three adjacent gravel deposits at three different heights above the modern Peace River. Tokarsky (1967) termed these, from highest to lowest, the 'Grimshaw gravels', 'terrace gravels', and 'Shaftesbury gravels'. The PFRA delineated the uppermost gravel deposit and termed it the 'Grimshaw gravels aquifer'. Importantly, the PFRA identified the need to better understand the geometric and stratigraphic relationships between the three gravel deposits and underlying bedrock strata. Slomka et al. (2018) updated the geological framework of the Grimshaw gravels and adjacent sand and gravel units, along with their geometric distribution and stratigraphic history.

To build on the geological update by Slomka et al. (2018), the Alberta Geological Survey (AGS) completed a hydrogeological characterization of the Grimshaw area. The objective of hydrogeological characterization was to update the understanding of groundwater chemistry, examine spatial and temporal trends in groundwater levels at a greater resolution than reported in Slomka et al. (2018), and develop a conceptual model of groundwater circulation.

2 Study Area

The gravels in the Grimshaw area are located between the Whitemud Hills and the Peace River valley (Figure 1). Slomka et al. (2018) updated the stratigraphy and geometry of the gravel deposits by identifying and mapping three distinct bedrock straths (a term to describe river valley floors excavated in bedrock) and overlying gravel deposits. The straths and gravel deposits are the former valley floors of ancestral versions of the Peace River, each of which had incised and excavated more deeply than its predecessor. Slomka et al. (2018) assigned the informal names 'Grimshaw', 'Old Fort' and 'Shaftesbury' to the straths and overlying gravel deposits in order of decreasing relative height and age. In this report, the term 'Grimshaw gravels aquifer' is used to describe the collection of gravel deposits within the study area that are physically disconnected but interact together as a part of the larger aquifer system. The terms 'Grimshaw gravels', 'Old Fort gravel', and 'Shaftesbury gravel' will describe the individual gravel deposits in this report. The average heights above the modern Peace River of the top of the Grimshaw gravels, Old Fort gravel, and Shaftesbury gravel units are 320, 220, and 25 m, respectively (Slomka et al., 2018). The names of the highest and lowest straths and associated gravel deposits generally follow Tokarsky (1967). However, the intermediate strath is named 'Old Fort' for the community of Old Fort near Fort St. John, British Columbia where the gravel deposit is well exposed. The name 'Old Fort' replaces the term 'terrace' that was used by both Tokarsky (1967) and PFRA (1998).

The Grimshaw lobes (PRFA, 1998) are predominantly comprised of the uppermost Grimshaw gravels. The areas between the lobes are interpreted as glacial meltwater channels in which the gravel has presumably been eroded. The meltwater channels have been infilled with thicker accumulations of fine-grained glacial sediment (Figure 2a; PFRA, 1998) and are commonly overlain by small lakes and tributary streams that drain to the Peace River. In some areas, the Grimshaw gravels are overlain by a thin cover of fine-grained glacial sediments (Tokarsky, 1967, 1971; PFRA, 1998; Paulen, 2005). These relatively thin, discontinuous sediments leave the gravel aquifer unconfined and susceptible to contamination from surface sources (Tokarsky, 1967; PFRA, 1998).

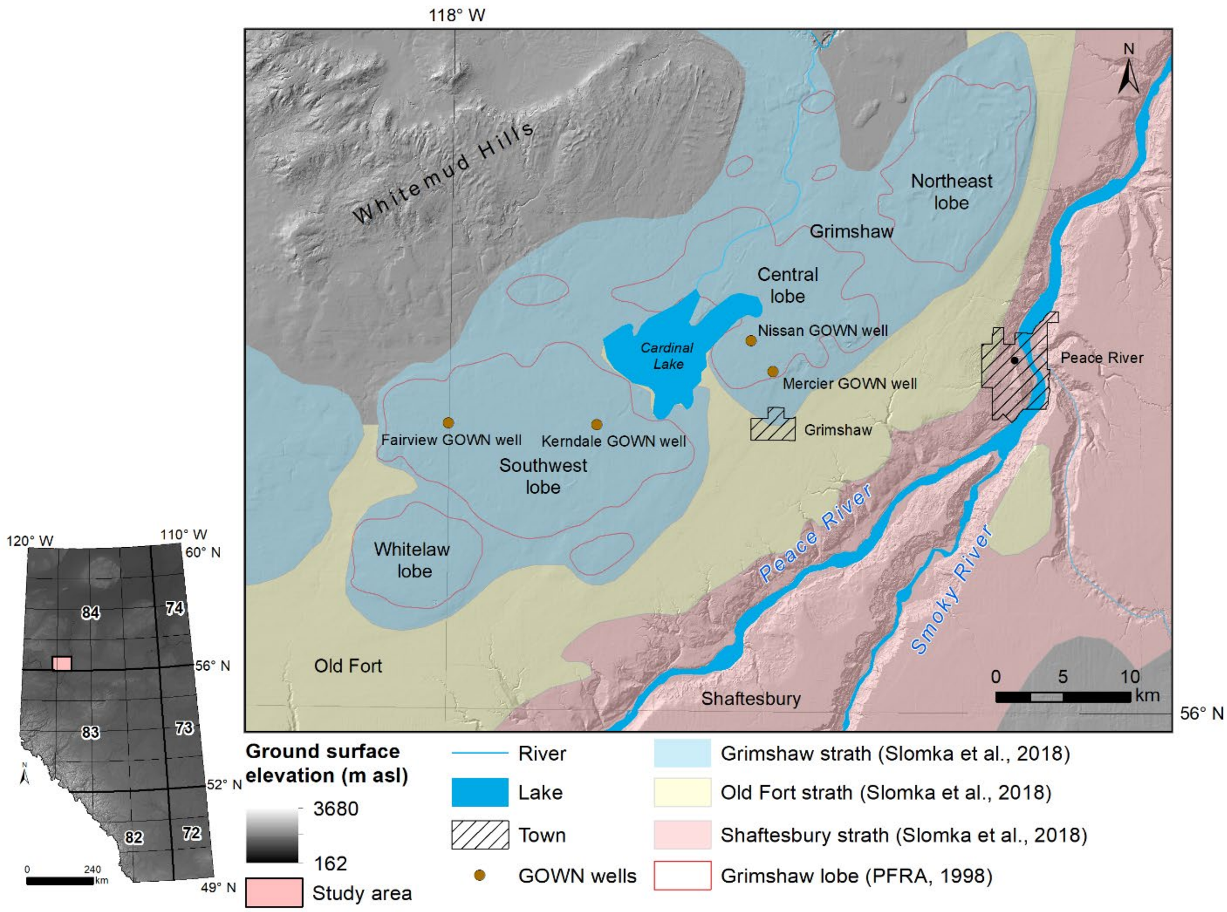

Figure 1. Grimshaw study area, including gravel deposits (Grimshaw lobes) mapped by PFRA (1998) and distribution of bedrock straths mapped by Slomka et al., (2018). Gravel deposits can be found within the bounds of the mapped bedrock straths. Alberta Environment and Parks Groundwater Observation Well Network (GOWN) wells are identified by location name.

Total sediment thickness above the Grimshaw strath (including the Grimshaw gravel where it is present) is typically >25 m, although thicker sediment (up to 50 m) exists west of Cardinal Lake (AGS, in prep b; Figure 2a). Bedrock units beneath the Grimshaw strath include the Kaskapau Formation west of Cardinal Lake and the Dunvegan Formation in the eastern part of the study area (Hathway et al., 2013; Prior et al., 2013; Figure 2b). The Kaskapau Formation is composed mostly of marine shale and siltstone while the Dunvegan Formation is composed of sandstone, siltstone, and shale.

The Old Fort gravel overlies the Old Fort strath, which occupies a 2–5 km wide strip between the Grimshaw gravel and Shaftesbury gravel in the study area (Figure 3). Within the study area, total sediment thickness overlying the Old Fort strath is generally between 25–75 m including gravel where it is present. The relatively thick cover of fine-grained glacial sediment confines the Old Fort gravel and provides protection from surface contamination. The Old Fort strath is underlain by the Kaskapau Formation in the west part of the study area, the Dunvegan Formation in the central part of the study area, and the upper Shaftesbury Formation in the east part of the study area and near the south-east edge of the Old Fort strath (Hathway et al., 2013; Prior et al., 2013; Figure 3b). The upper Shaftesbury Formation is mainly composed of marine mudstone.

The Shaftesbury gravel lies at the base of the Shaftesbury strath, which is the floor of the Shaftesbury bedrock valley described in Slomka et al. (2018). The total thickness of sediment that infills the Shaftesbury bedrock valley (including the thickness of the Shaftesbury gravel) is up to 200 m. The Shaftesbury bedrock valley is, through much of its length, superposed by the modern Peace River and the proximal reaches of its tributaries (Figure 1) which have eroded some of the Shaftesbury bedrock valley infill sediments including the Shaftesbury gravel. The floor of the modern Peace River valley is approximately 25 m below the Shaftesbury bedrock valley and thus the Shaftesbury gravel and overlying sediments are perched along the walls of the Peace River valley in many places (Figure 3). The Shaftesbury bedrock valley overlies the upper Shaftesbury Formation in the western part of the study area and the lower Shaftesbury Formation in the eastern part of the study area (Hathway et al., 2013; Prior et al., 2013; Figure 3b). The lower Shaftesbury Formation consists of marine mudstone and shale.

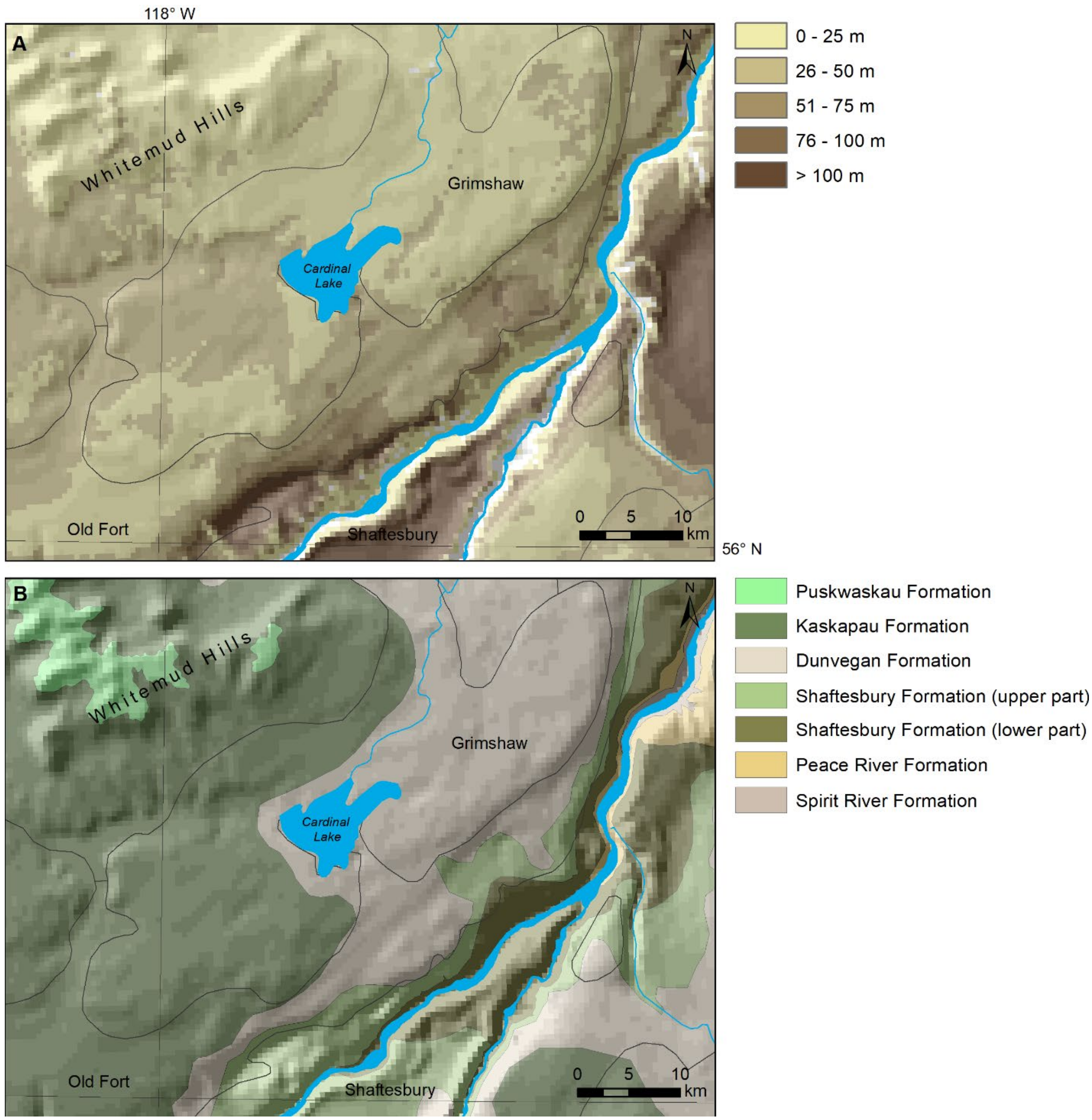

Figure 2. a) Sediment thickness (AGS, in prep b) (m) and b) bedrock geology (Prior et al., 2013) draped over a hill-shaded DEM of bedrock topography (AGS, in prep a).

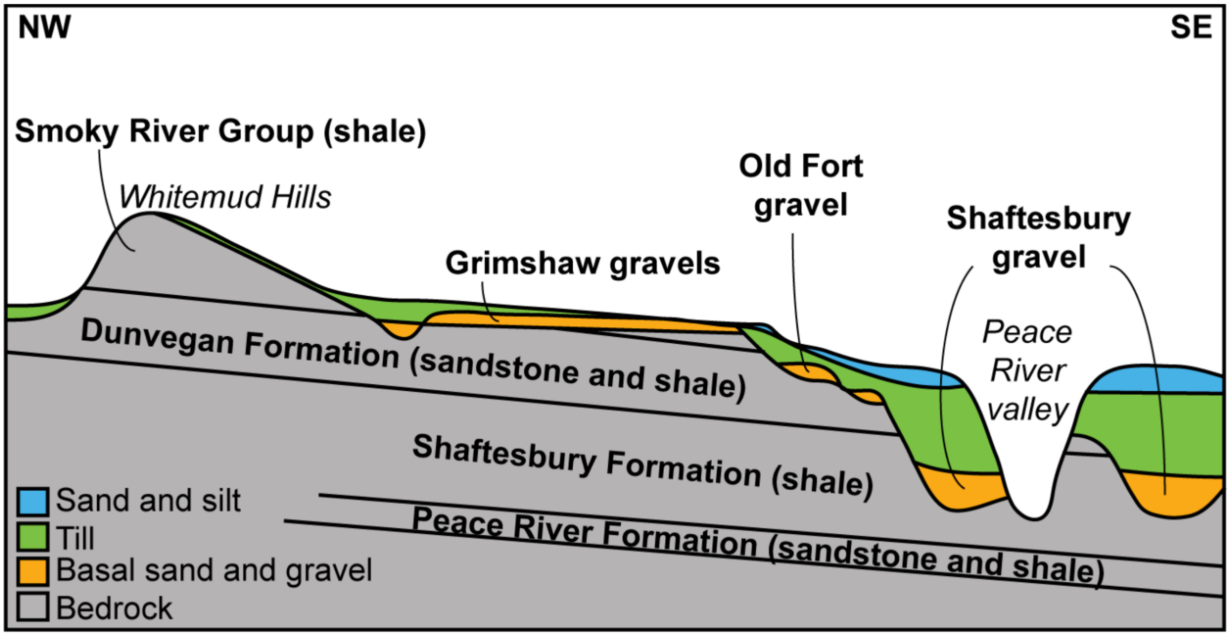

Figure 3. Conceptual geological cross-section identifying the location and elevation of the Grimshaw, Old Fort and Shaftesbury gravels (modified from Slomka et al., 2018).

3 Hydrogeological Characterization

To assess regional hydrogeological conditions in the Grimshaw area, groundwater data from the Alberta Water Well Information Database (AWWID; Alberta Environment and Parks, 2018), the Groundwater Observation Well Network (GOWN), and data from the Alberta Climate Information Service (ACIS; Alberta Agriculture and Forestry, 2018) were compiled to determine the following:

- an interpretation of hydraulic head data to produce potentiometric surface maps for the Grimshaw and Old Fort gravel deposits (the Shaftesbury gravel was excluded due to limited data); and
- an estimate of groundwater recharge.

3.1 Potentiometric Surface

A generalized potentiometric surface for the Grimshaw area was previously generated from water wells completed in the Grimshaw and Old Fort gravels, using AWWID data from 1996–2015 (Slomka et al., 2018). The generalized potentiometric surface map indicated that groundwater was relatively level across the Grimshaw gravels and generally followed the ground surface topography across the Old Fort gravel. The generalized potentiometric surface map indicated that groundwater moved from the northwest (Whitemud Hills) to the southeast (Peace River valley), consistent with the interpretation by Tokarsky (1971).

To more closely examine spatial and temporal trends in the potentiometric surface, a longer period of groundwater level data were divided into 10-year intervals (Figure 4). Potentiometric surfaces for the Grimshaw and Old Fort gravels were interpolated independently in ArcGIS using the ordinary kriging function of the Geostatistical Analyst extension. The distribution of the potentiometric surfaces within the Old Fort gravel vary throughout the decades due to differences in the spatial distributions of data points through time. Each 10-year interval represents the potentiometric surface as determined from water wells having a water level record during the same period (e.g., 1960–1969; Figure 4a).

The decadal intervals reveal minor variation in the potentiometric surface for the Grimshaw gravels, whereas the potentiometric surface for the Old Fort gravel is more consistent through time. Within the Old Fort gravel, there is a predominant northwest to southeast trend, with the lowest hydraulic heads occurring near the Town of Peace River.

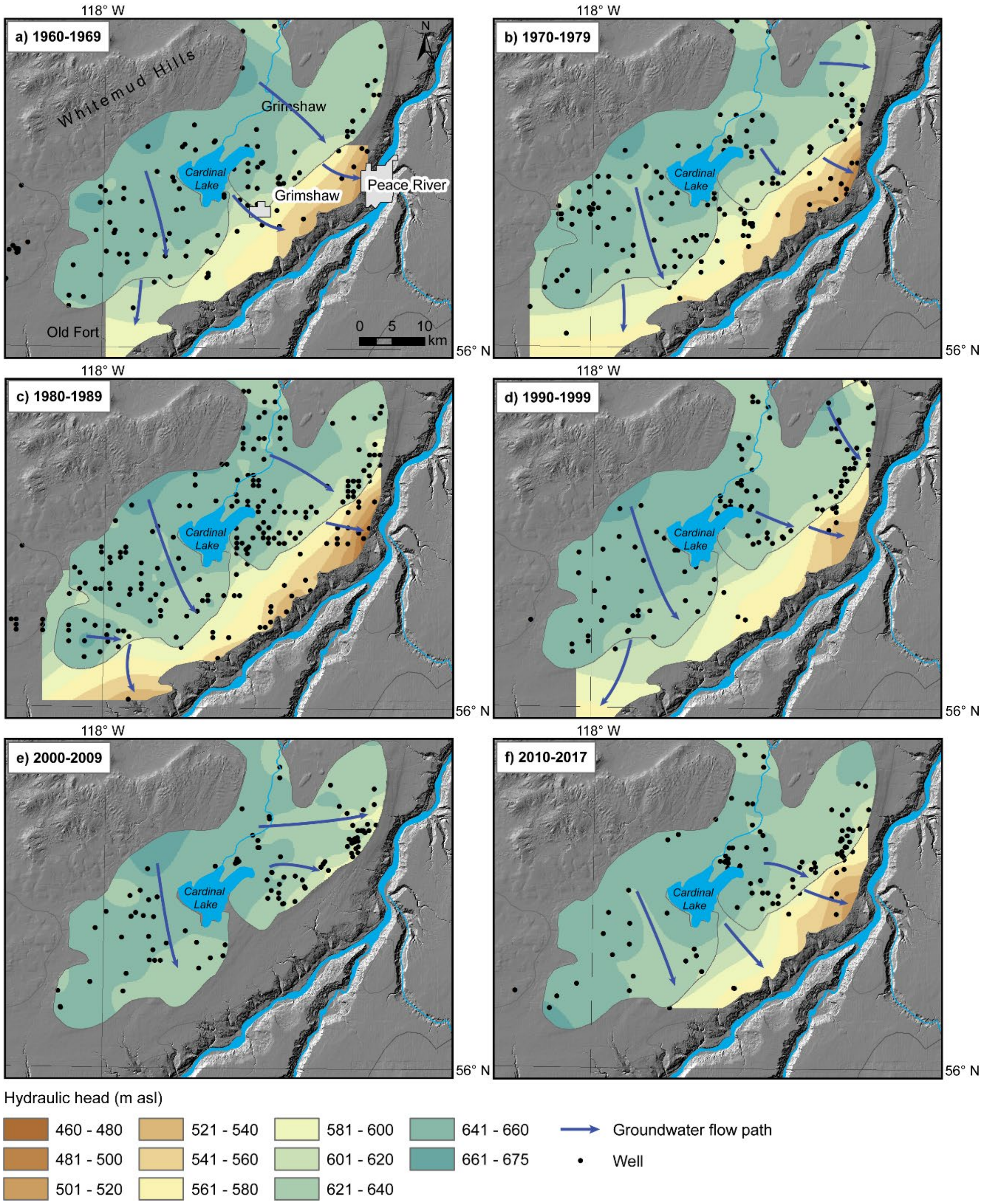

Figure 4. Maps of the potentiometric surface for Grimshaw and Old Fort gravels organized by decade. Coloured legend indicates ranges of hydraulic head (m asl). Arrows indicate groundwater flow direction. Data limitations prevent mapping of the potentiometric surface within the Old Fort gravel between 2000–2009 (e).

In the Grimshaw gravels southwest of Cardinal Lake, groundwater flow is dominantly from the north to the southeast, with hydraulic heads generally being higher than the lake level. The pattern of groundwater circulation southwest of the Cardinal Lake is complex, as a narrow depression (or trough) appears to develop immediately southwest of the lake during the 1970–1980 and 2010–2015 periods. This feature suggests that groundwater in the southwest part of the Grimshaw gravels (termed the "Whitelaw lobe" by Tokarsky, 1967; lobe shown in Figure 1) is constrained to the southwest. In the area immediately west of the lake, hydraulic heads are only slightly higher than the lake level, suggesting minimal interaction with the lake in the form of groundwater discharge. In the areas east and northeast of Cardinal Lake, groundwater flow is from the west to east and southeast. Here, hydraulic heads are consistently lower than the lake level and the distribution changes subtly through time, suggesting that recharge from the lake to the groundwater is consistently occurring. Although the potentiometric surface is relatively level, the decadal intervals indicate that Cardinal Lake receives some groundwater discharge along the west and north shorelines, and recharges groundwater along the south and east shorelines.

3.2 Groundwater Observation Time Series

There are four long-term groundwater observation network wells in the Grimshaw area (Figure 1). Two of these GOWN wells have been operational since 1965, with the second two wells being added in 1983 and 1986. Figure 5a illustrates the time series of hydraulic head for these GOWN wells and the water level of Cardinal Lake. These data confirm the spatial pattern in groundwater circulation near Cardinal Lake described above, and were used to establish the average horizontal hydraulic head gradient relative to the lake as shown on Table 1.

Table 1. Average horizontal hydraulic head gradients for Groundwater Observation Well Network (GOWN) wells relative to Cardinal Lake.

Location	Average water level for 1997–2017 (m asl)	Distance from lake (km)	Horizontal hydraulic head gradient	Groundwater flow direction
Cardinal Lake	644.11	-	-	-
Fairview GOWN well	647.52	12.3	0.00028	Toward lake
Kerndale GOWN well	644.65	3.8	0.00014	Toward lake
Nissan GOWN well	637.44	2.1	0.00317	Away from lake
Mercier GOWN well	641.49	5.0	0.00052	Away from lake

The groundwater observation time series (Figure 5a) shows that the lake and groundwater levels fluctuate similarly at most locations, in response to precipitation. For example, each hydrograph increases in 1997 because of high snowfall in the winter of 1996/1997, then declines from 1998–2001 because of subsequent years of low precipitation (Figure 5b). At the Mercier GOWN well, groundwater levels declined from approximately 641.2 m asl in 1980 to 640.2 m asl in 1981 before stabilizing. Although the lake level also decreased during this period, a similar decline was not observed in the Kerndale GOWN well.

The lower hydraulic head gradient values shown in Table 1 for Fairview and Kerndale GOWN wells support the idea of minimal groundwater interaction with the lake for areas west of the lake. The higher hydraulic head gradient values for Nissan and Mercier GOWN wells support evidence of recharge from the lake to the groundwater system.

3.3 Groundwater Recharge

The groundwater observation time series depicts notable increases in groundwater level in response to precipitation events, especially in the spring months as snowmelt percolates into the groundwater system. For unconfined aquifers, these water table fluctuations can be used to estimate groundwater recharge using the following equation (Healy and Scanlon, 2010):

$$R = S_y \Delta H \div \Delta t \qquad \text{Equation 1}$$

where R is the amount of groundwater recharge, S_y is an estimate of the specific yield for the aquifer material, and ΔH is the water level increase over a time interval Δt. Values of specific yield for gravel deposits vary between 0.2 and 0.3, and are closely related to porosity.

Three of the four GOWN wells exhibit notable groundwater level increase in spring only, typically between mid-March and late-April. The Mercier GOWN well, however, exhibits additional fluctuations in response to other events (assumed to be rainfall and localized pumping). The dominance of groundwater level increase in spring indicates that the majority of groundwater is recharged from snowmelt, which is common in the northern hemisphere (Jasechko et al., 2014) and has been observed elsewhere in the Peace Region (Smerdon et al., 2008).

Groundwater recharge was calculated from Equation 1 for groundwater level increases observed in the spring at each GOWN well, assuming a specific yield value of 0.25. Considering that groundwater level increases only appeared to occur in the spring when evapotranspiration would be minimal, the time interval was removed from Equation 1, so the resulting recharge values would represent the total amount of recharge for each given year.

The calculated recharge values varied from approximately 10–50 mm. To relate the recharge directly to snowmelt, snow water equivalent data (SWE; the amount of water contained within a snowpack) was obtained from the ACIS for the 1990–2017 period (Figure 5b). This timeframe corresponds to the groundwater observation time series of all four GOWN wells in the study area. The maximum (peak) snow water equivalent was plotted with calculated recharge values for the same year (Figure 6) to define an estimate of expected groundwater recharge occurring from snowmelt. The approximate relationship between SWE and groundwater recharge can be described by the following equation for the Grimshaw area:

$$R = 0.35 \times SWE - 17.5 \qquad \text{Equation 2}$$

where R is the amount of groundwater recharge, and SWE is the maximum snow water equivalent recorded for a given year.

The results shown on Figure 6 and described by Equation 2 demonstrate a relationship between the amount of snowfall and potential for replenishment of groundwater in the Grimshaw gravels aquifer. This approximation may be informative for regional planning and advancing the understanding of the groundwater balance for the Grimshaw gravels aquifer.

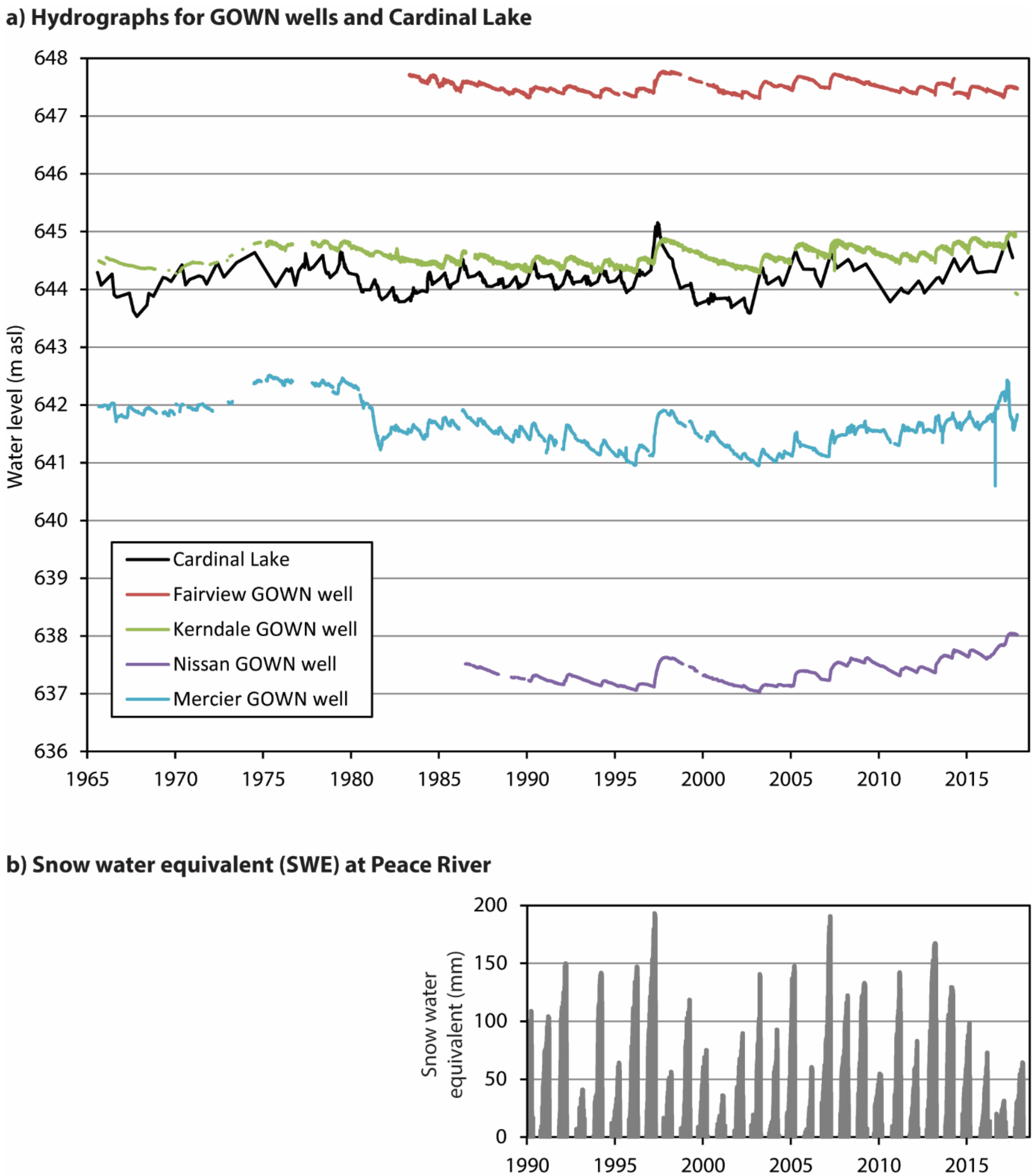

Figure 5. a) Time-series of Cardinal Lake and groundwater levels for each of the Groundwater Observation Well Network (GOWN) wells in the study area. b) Daily snow water equivalent (SWE) from Alberta Climate Information Service (ACIS; Alberta Agriculture and Forestry, 2018).

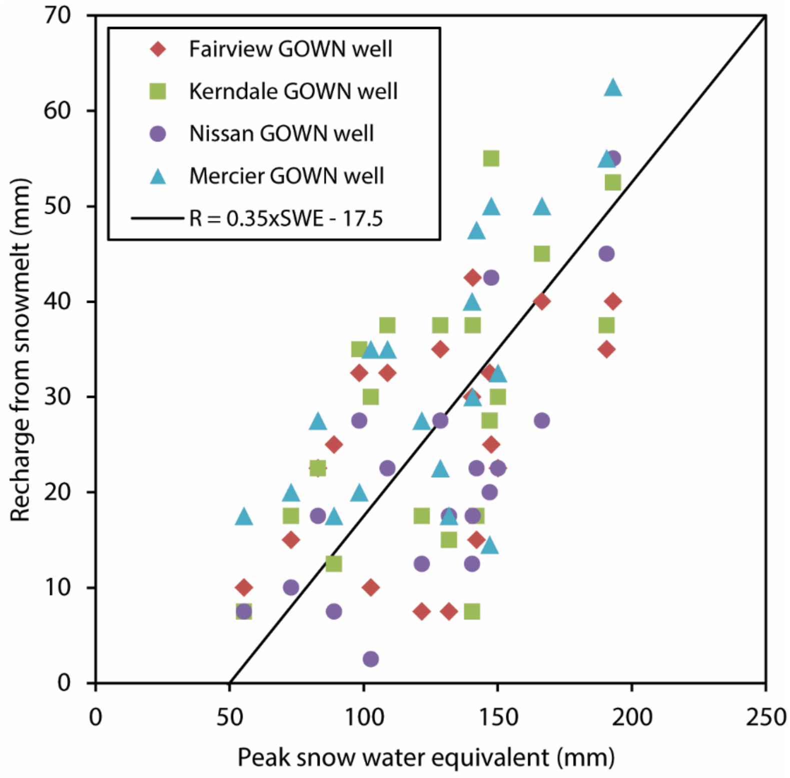

Figure 6. Summary of groundwater recharge calculated from observed groundwater level rises (Figure 5a) relative to the maximum amount of water contained within the snowpack during the same year.

4 Groundwater Chemistry

Groundwater within the Grimshaw gravels aquifer is of good quality (Tokarsky, 1971; PFRA, 1998; Slomka et al., 2018). The majority of the Grimshaw gravels aquifer is in an area of recharge and characterized by $CaMgHCO_3$ waters with low total dissolved solids (TDS). Areas of discharge (near rivers, streams and springs) show lower water quality which may contain higher concentrations of Na and SO_4 and an increase in TDS (Slomka et al., 2018; Figure 7).

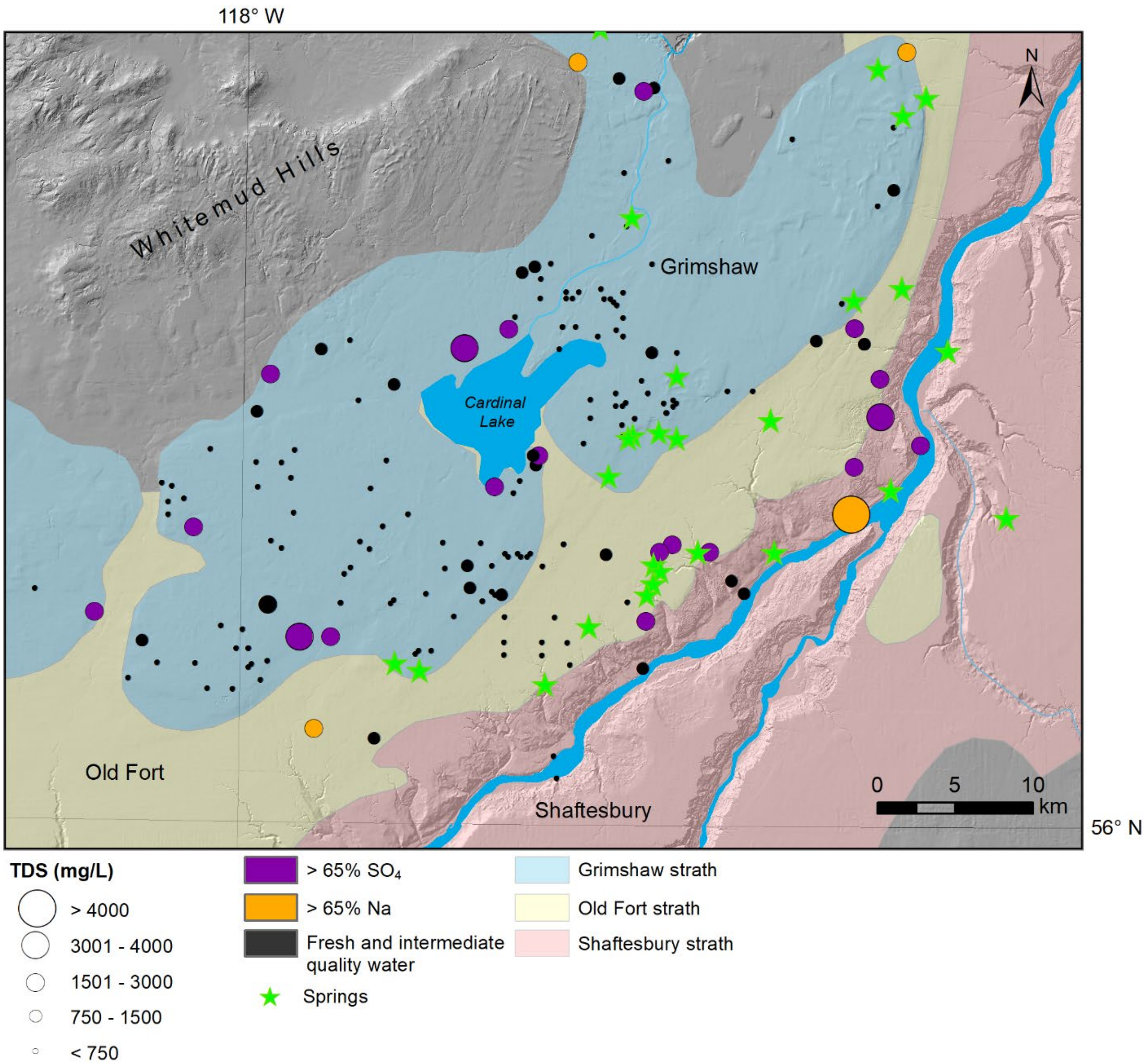

Figure 7. Groundwater chemistry, including total dissolved solids (TDS), SO_4, and Na for wells screened in the Grimshaw gravels aquifer, overlain on a hill-shaded DEM of the ground surface. Recharge areas are indicated by black wells with low TDS, and discharge areas are shown by purple and orange with high TDS (modified from Slomka et al., 2018).

4.1 Groundwater Sampling

To confirm the assessment of regional groundwater chemistry by Slomka et al. (2018) and learn more about the groundwater system, two groundwater sampling programs were completed in 2017 and 2018. Domestic water wells and local hydrologic features were sampled by the AGS in September 2017 for homeowners that volunteered in collaboration with the Grimshaw Gravels Aquifer Management Advisory Association. Subsequently, the GOWN wells in the Grimshaw area were sampled in February 2018 by Advisian under a contract with Alberta Environment and Parks (Advisian, 2018a). Each sampling program had the same analytical schedule including major and minor ions (i.e., routine water chemistry), dissolved metals, stable isotopes of water (^{18}O and ^{2}H), tritium (^{3}H), and carbon 14 (^{14}C).

Samples collected by the AGS included six domestic water wells, four community water wells, three creek samples, two lake samples, and a sample from Whitelaw spring. For domestic water wells, samples were collected from readily accessible taps as close to the well location as possible. Locations were typically an outdoor tap but in some cases were located within the home (e.g., kitchen sink). Taps were allowed to flow freely for at least 10 minutes attempting to ensure the pump was activated. Water was sampled after measurements of temperature, electrical conductivity (EC), and pH appeared stable. Creek and lake samples were collected using a peristaltic pump with the intake tubing located at the base of the surface water. Whitelaw spring was flowing and was sampled directly.

Groundwater samples from the five GOWN wells were collected using a variable speed submersible pump and a flow-through cell, where field parameters were measured (dissolved oxygen, oxidation/reduction potential, pH, temperature, and electrical conductivity) (Advisian, 2018a).

The sampling results in this report include major ions (bicarbonate, calcium, carbonate, chloride, magnesium, potassium, sodium, and sulphate) and isotopes (^{18}O, ^{2}H, ^{3}H, and ^{14}C). These data were supplemented with water level, basic groundwater chemistry data, and well completion information (e.g., screen depth) queried and extracted from the AWWID (Figure 8). The report by Slomka et al. (2018) showed that there was variation in groundwater chemistry regardless if the well was screened in the Grimshaw gravels aquifer or the overlying drift sediments (e.g., glaciolacustrine, lacustrine, outwash, and subglacial deposits) throughout the study area. As a result, all wells with water level, basic groundwater chemistry data, screen information and lithology were included in the analysis as shown in Figure 8. In the next section, only wells with known depth intervals were used to examine the composition of groundwater compared to the more generalized results of Slomka et al. (2018).

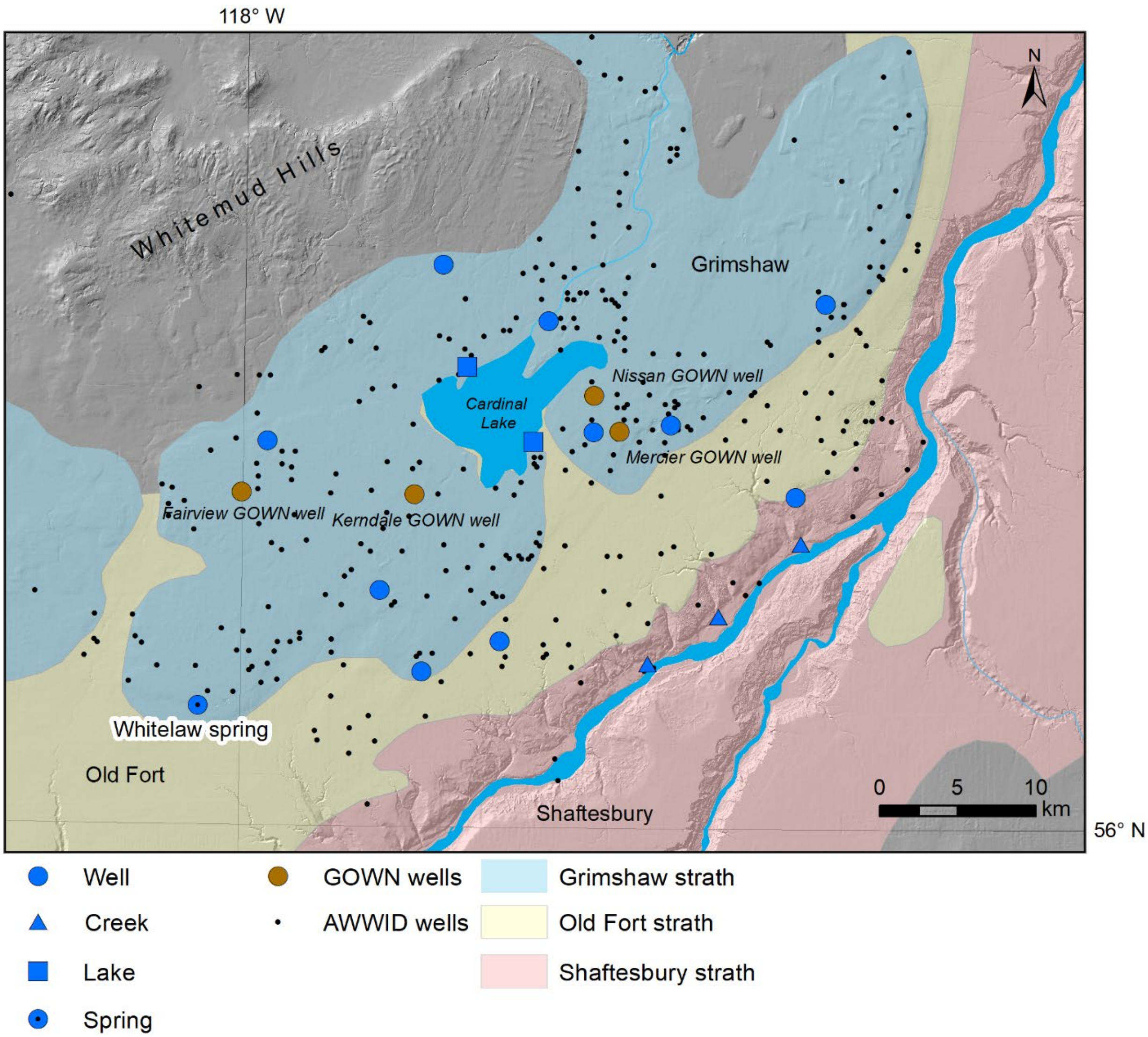

Figure 8. Sources of chemistry data (major ions) within Grimshaw study area include the Alberta Water Well Information Database (AWWID; Alberta Environment and Parks, 2018) and field samples collected by AGS (blue coloured symbols) and from the GOWN wells (brown coloured symbols).

4.2 Groundwater Composition Zones

Fresh groundwater is commonly Ca-Mg-HCO_3–type water and over time, depending on the groundwater residence time and materials which the water has travelled through, it can evolve into a Na-SO_4–type. The chemical composition of water samples in this study are shown as percent of meq/L for cations (Figure 9a) and anions (Figure 9b). Water within the study area is typically calcium and magnesium rich although there are a few areas with high sodium, mostly within the Old Fort gravel.

To differentiate groundwater composition, zones have been identified in Figure 9 that highlight distinct chemical composition including chloride, sodium, and sulphate rich waters. These zones are described as:

- Chloride zone: where chloride enrichment has occurred south of Cardinal Lake around the Mercier GOWN well (yellow polygon). An increasing trend in chloride was observed at Mercier GOWN well and noted in the review of groundwater data by Advisian (2018b).
- Sulphate zone: where waters are rich in calcium, magnesium and sulphate are located north of Cardinal Lake and in the northern end of the Old Fort gravel (green polygon).
- Sodium zone: where waters are enriched in sodium but also high in bicarbonate. These occur east of Cardinal Lake and as a lens that extends the length of the Grimshaw gravels along the border of the Grimshaw strath and Old Fort strath, east of Cardinal Lake (purple polygon).
- Sodium-sulphate zone: these waters are rich in sulphate but show a transition from calcium/magnesium to sodium and are located at the eastern base of the Whitemud Hills and on the western end of the Old Fort gravel (pink polygon).

Wells associated with the zones shown in Figure 9 were also plotted on a piper diagram to illustrate groundwater evolution paths (Figure 10). The zones show mixed waters varying from Ca-Mg-SO_4–type to Na-SO_4–type. Differing groundwater residence time typically results in different groundwater composition; relatively young waters are characterized as Ca-Mg-HCO_3–type and older waters are characterized as Na-SO_4–type (pink zone in Figures 9 and 10). The purple zones in Figure 9 identify intermediate waters (high in Na-HCO_3) which are found east of Cardinal Lake and along the border of the Grimshaw gravel strath and Old Fort gravel strath. East of Cardinal Lake, within the Grimshaw gravels an apparent increase in sodium is presumed to be relatively young water; the sodium increase may be the result of an unknown localized influence. Along the border of the Grimshaw gravel strath and Old Fort Gravel strath, groundwater is characterized by the transition from Na-HCO_3–type to Na-SO_4–type waters. Discharge from the underlying bedrock into the Old Fort gravel could be leading to the sodium increase in this area. The yellow zone indicates an increase in chloride within the Grimshaw gravels that was observed in the Mercier GOWN well. The chloride increase could be due to various reasons such as nearby infrastructure/activities, natural variation in water quality, or potential well integrity issues (Advisian, 2018b). The Mercier GOWN well has one of the highest chloride concentration values within the study area (168 mg/L of chloride; 90^{th} percentile = 37 mg/L). The high chloride concentration appears to be due to a localized source near the GOWN well. It is noted that nearby wells also show elevated chloride whereas the majority of the study area does not.

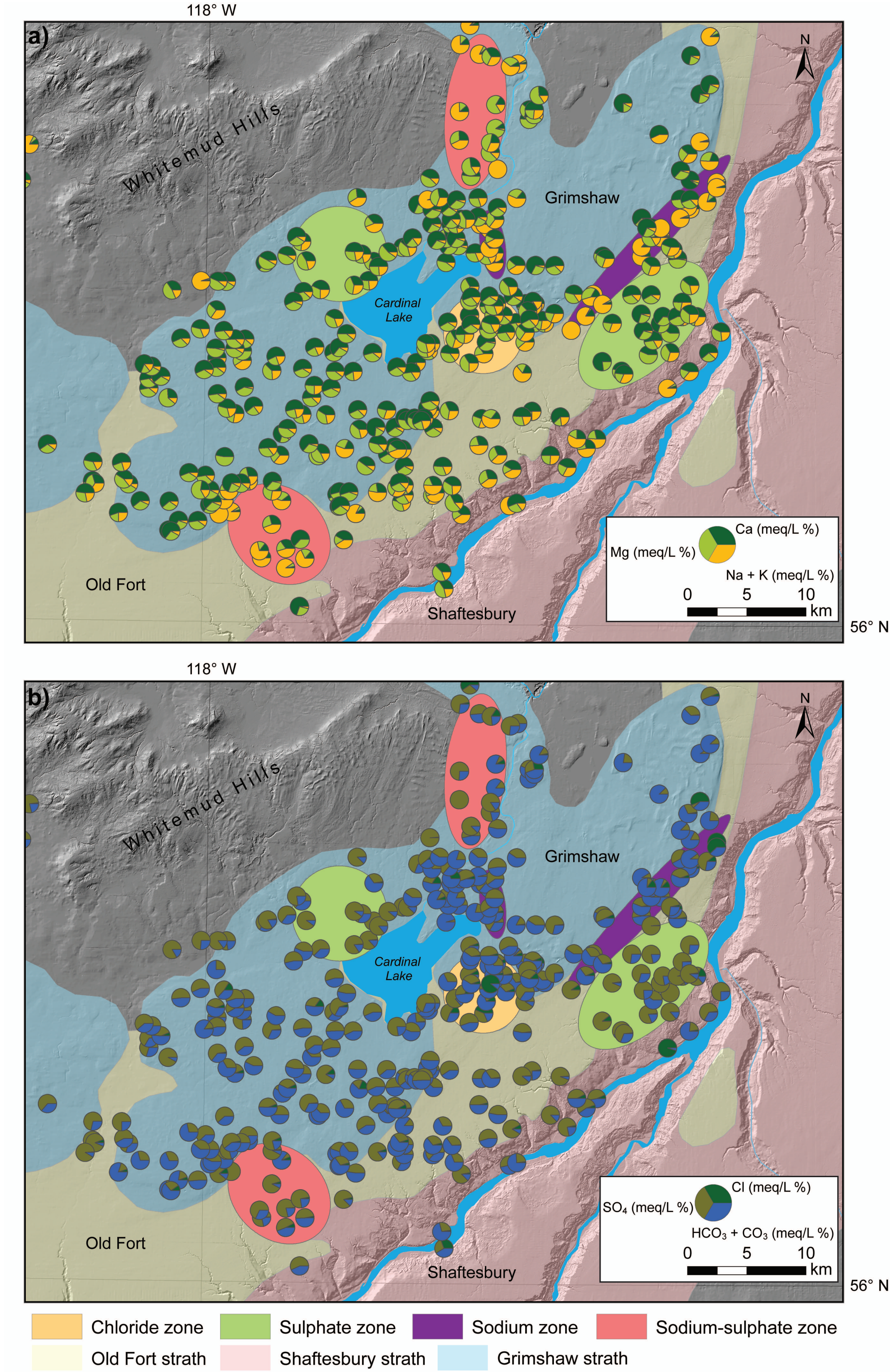

Figure 9. Distribution of a) cations and b) anions within the study area. Coloured zones are used to identify areas which are either rich in chloride, sodium, or sulphate.

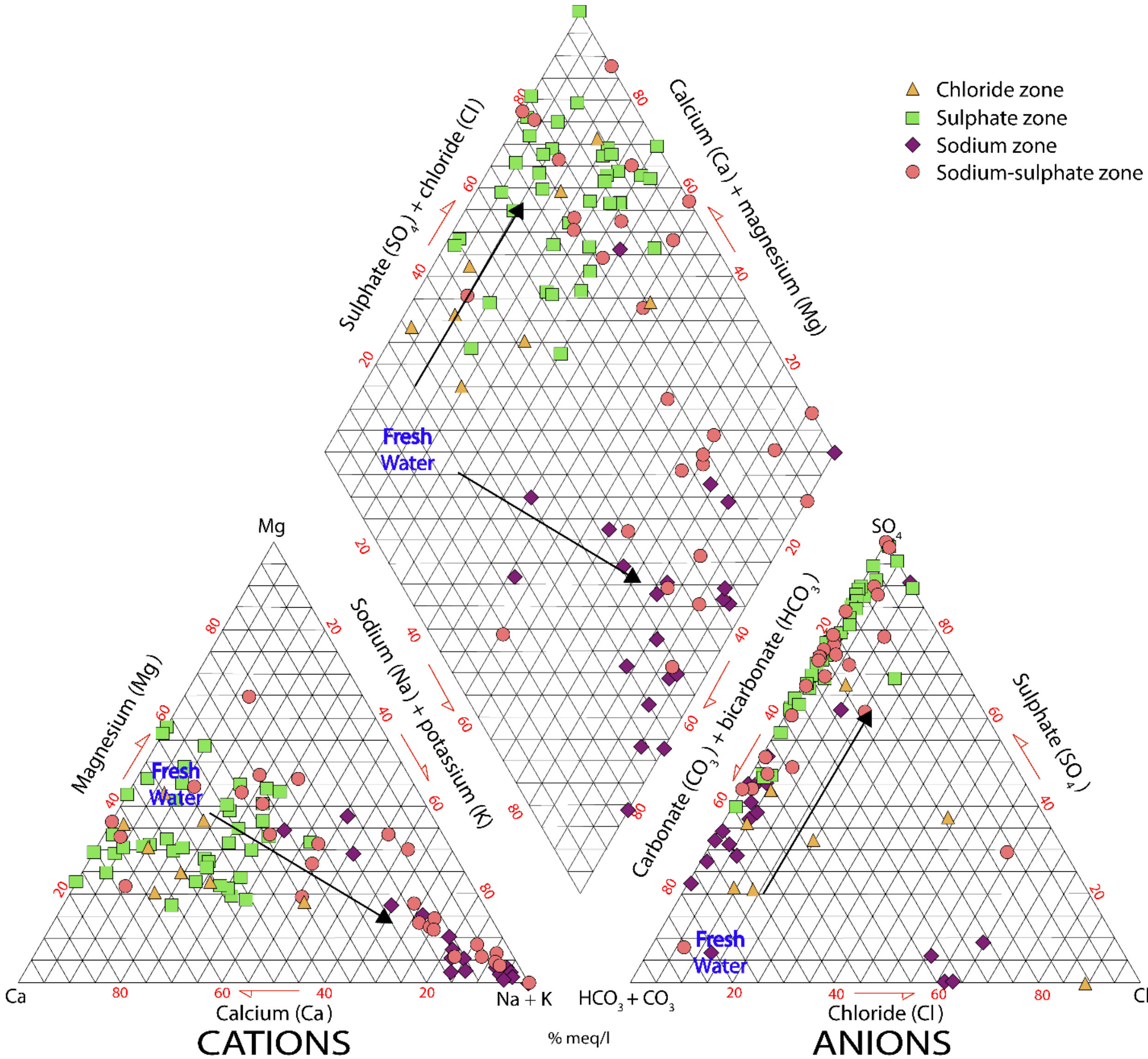

Figure 10. Piper plot illustrating groundwater evolution path showing enrichment in chloride, sulphate, and sodium.

4.3 Groundwater Residence Time

Presumably, water cycling through the Grimshaw gravels is relatively young, whereas water in the Old Fort and Shaftesbury gravels is older and may include a greater proportion of water derived from underlying bedrock formations. To test this hypothesis, naturally-occurring environmental tracers were analyzed to identify water of different relative ages and potential sources. Each tracer analyzed provides different information as outlined in Table 2.

Table 2. Summary of tracer sampling.

Tracer	Purpose
Stable isotopes of water ($\delta^{18}O$ and δ^2H)	Help understand the origin and movement within the hydrologic cycle. All values are expressed as δ values representing deviations in per mil from Vienna standard mean ocean water (VSMOW).
Tritium (^3H)	Present in the atmosphere with concentrations that peaked in the 1960s due to atmospheric atomic bomb testing. The decreasing concentration in the atmosphere helps distinguish pre-1960s waters from post-1960s waters.
Radiocarbon (^{14}C)	A radioactive isotope produced in the atmosphere that enters the subsurface through plant respiration. It is it an ideal tracer for groundwater movement on the time scale of thousands of years.

All geochemical and isotopic results are tabulated in Appendix 1. The results for stable isotopes of water are shown on Figure 11a relative to local meteoric water lines (LMWLs) developed for the Utikuma Region Study Area (URSA), which is located 140 km east of the study area (Smerdon et al., 2012) and Edmonton, which is located 400 km southeast of the study area (Maulé et al., 1994). Groundwater from the Grimshaw gravels, Old Fort gravel, and Whitelaw spring (Figure 8) plots at the transition between rainfall and snow segments of the URSA LMWL, confirming that the broadly held understanding that the majority of groundwater is recharged from snowmelt (Jasechko et al., 2014). The single groundwater sample from the bedrock (Kaskapau Formation) plots in the lower part of Figure 11a, suggesting it may be sourced from meteoric water under a slightly different climate than the present day. Water samples from Cardinal Lake plot in the upper part of Figure 11a and remain relatively close to the LMWL. The results for these lake samples indicates that evaporative enrichment has not occurred, suggesting a lake water budget that generally balances precipitation inputs and evaporation outputs.

The results for ^3H and ^{14}C are shown on Figure 11b and begin to reveal the relative age difference in waters. Many of the groundwater samples from the Grimshaw gravels have ^3H greater than 5 TU and ^{14}C greater than 50 percent of modern carbon (pMC). When viewed together, these results indicate water that is relatively young. For example, water samples from Cardinal Lake plot at the uppermost part of Figure 11b and would be sourced primarily from snowmelt and rainfall in recent years. In contrast, groundwater from the Old Fort gravel and bedrock show lower ^3H and ^{14}C values, indicative of older water. The distribution of results across Figure 11b demonstrates a gradient in groundwater residence time with some mixing occurring as suggested by the geochemistry. When mapped, it is apparent that groundwater with >50 pMC can be found across the Grimshaw gravels (Figure 12a); whereas groundwater with <50 pMC is generally limited to Old Fort gravel. The pattern for ^3H is similar; however there is greater variation across the Grimshaw gravels (Figure 12b). Two samples from wells screened in the Old Fort gravel and one from a well screened in bedrock (Kaskapau Formation) had tritium values less than the detection limit (<0.8 TU), these samples could be dated prior to the 1950s. Samples between 0.8 and 5 TU are most likely a mix of sub-modern and modern waters and samples with 5 TU are most likely modern waters.

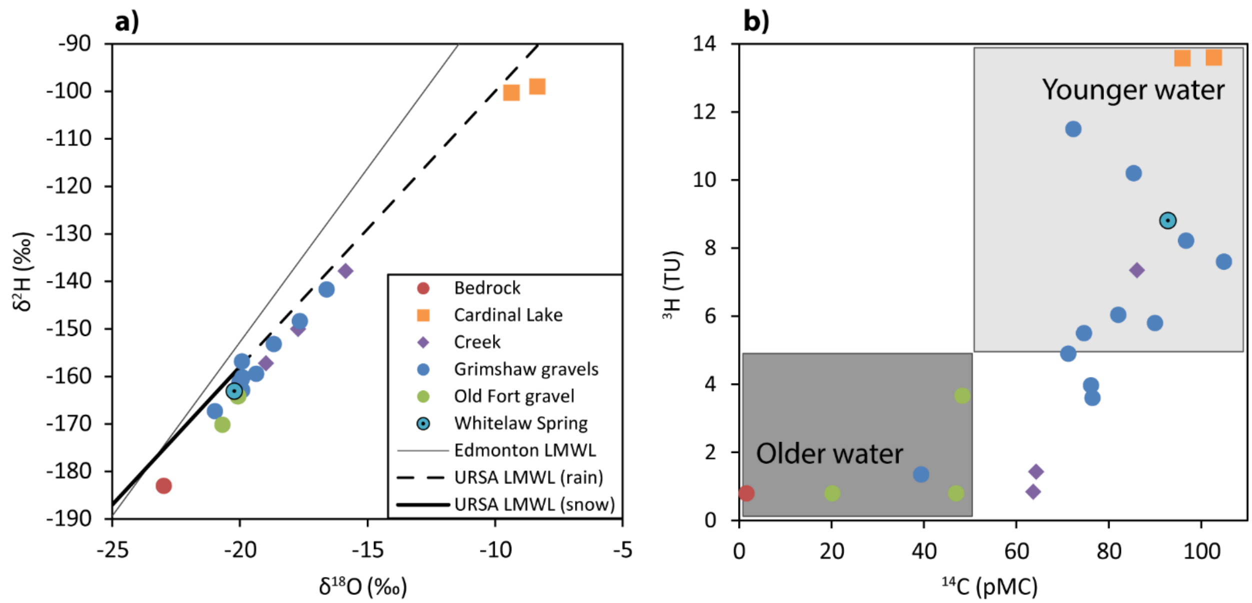

Figure 11. a) Stable isotopes of δ^2H and $\delta^{18}O$ for water samples relative to Local Meteoric Water Line (LMWL) from the Utikuma Research Study Area (URSA) reported in Smerdon et al. (2012) and for Edmonton by Maulé et al. (1994). b) ^3H and ^{14}C values for water samples indicating the relative age. Abbreviations: pMC, percent of modern carbon; TU, tritium units.

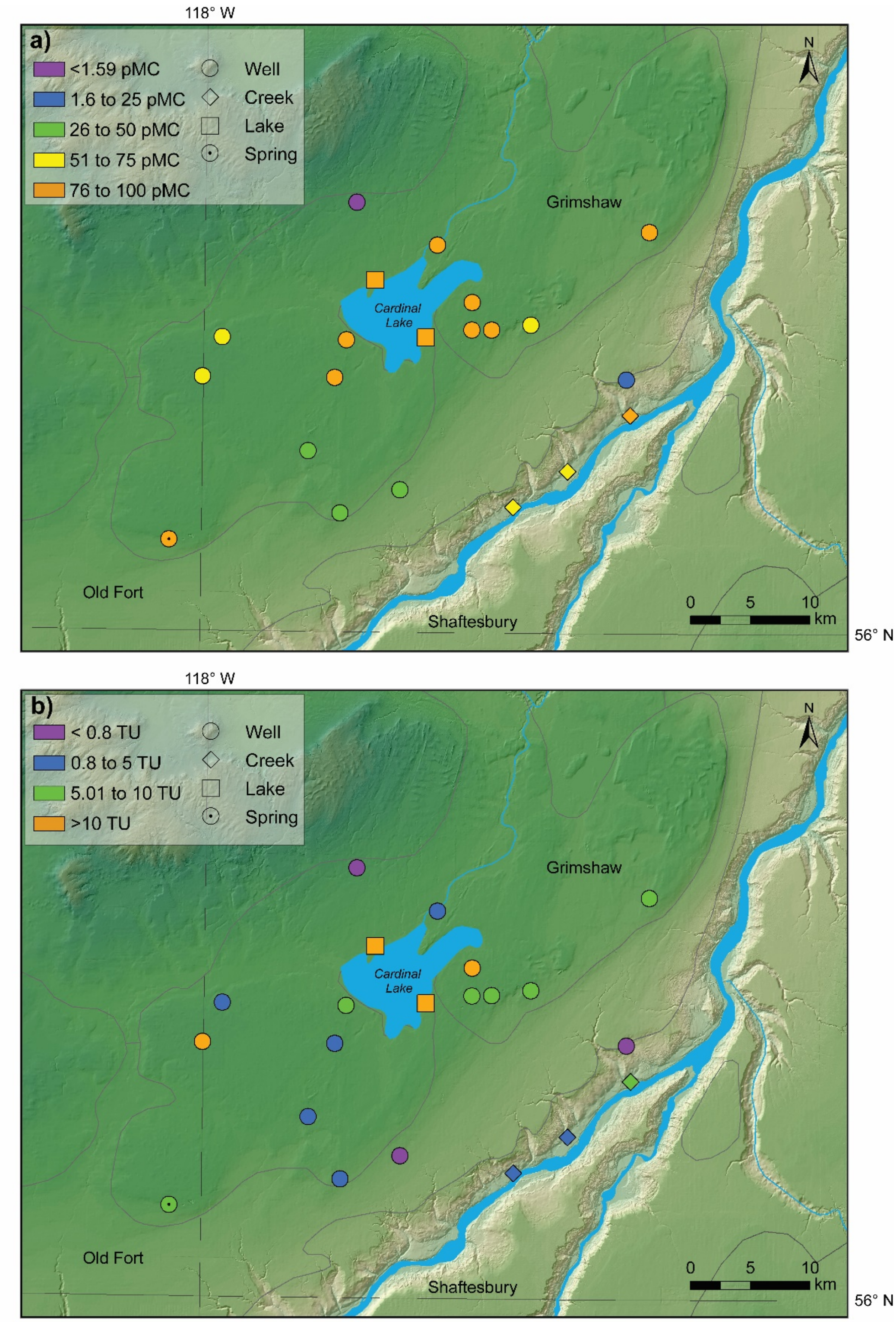

Figure 12. Distribution of a) ^{14}C and b) ^{3}H from water samples collected in the Grimshaw area. Orange coloured symbols indicate younger water and purple coloured symbols indicate older water. Blue, green and yellow coloured symbols indicate a mixture of groundwater residence time. Abbreviations: pMC, percent of modern carbon; TU, tritium units.

5 Conclusion

Building on the geological study by Slomka et al. (2018), this hydrogeological characterization provides an updated view of groundwater in the Grimshaw area. Most importantly, the key finding of these geology and hydrogeology investigations is that the gravel deposits in this area should be considered a terraced aquifer system, rather than a single aquifer. The geological framework helps explain spatially varying groundwater quality and availability observed locally. Groundwater in the Grimshaw gravels is of good quality and sourced from modern recharge, primarily snowmelt. The quality of groundwater in the Old Fort gravel (and lesser studied Shaftsbury gravel) is controlled by bedrock formations and tends to be poorer. Together, these gravel deposits form an aquifer system that is comprised of separate components, each having unique hydrogeological conditions.

The findings of this hydrogeological characterization confirm many of the previous findings made by Tokarsky (1971), with the added benefit of nearly 50 years of observations and advanced geochemical and isotopic analysis. The hydrogeological characteristics of the Grimshaw gravels aquifer system are summarized as follows:

- Groundwater levels (i.e., the potentiometric surface) are relatively flat across the Grimshaw gravels. The decadal intervals indicate that Cardinal Lake receives some groundwater discharge along the west and north shorelines, and recharges groundwater along the south and east shorelines.
- The Old Fort gravel has a potentiometric surface that consistently slopes toward the Peace River valley, resulting in localized springs where discharge from the groundwater system occurs.
- Time series of groundwater levels indicates that the majority of groundwater is recharged from snowmelt each spring season, in the range of 10–50 mm.
- Groundwater sampling confirmed that groundwater in the Grimshaw gravels is generally of good quality and relatively young. A localized chloride zone is emerging in the area southeast of Cardinal Lake; however, its source or cause is unknown.
- Zones of sodium- and/or sulphate-rich groundwater were found in the Old Fort gravel, leading to poorer water quality. Groundwater at these locations is older and sourced from bedrock.

These findings are further summarized in a conceptual model for the Grimshaw gravels aquifer system (Figure 13), which also depicts the major gains and losses for the groundwater budget and the direction and relative magnitude of groundwater flow. This conceptual model is intended to communicate the idea of a terraced aquifer system and justification for observed variation in groundwater quality in the Grimshaw area.

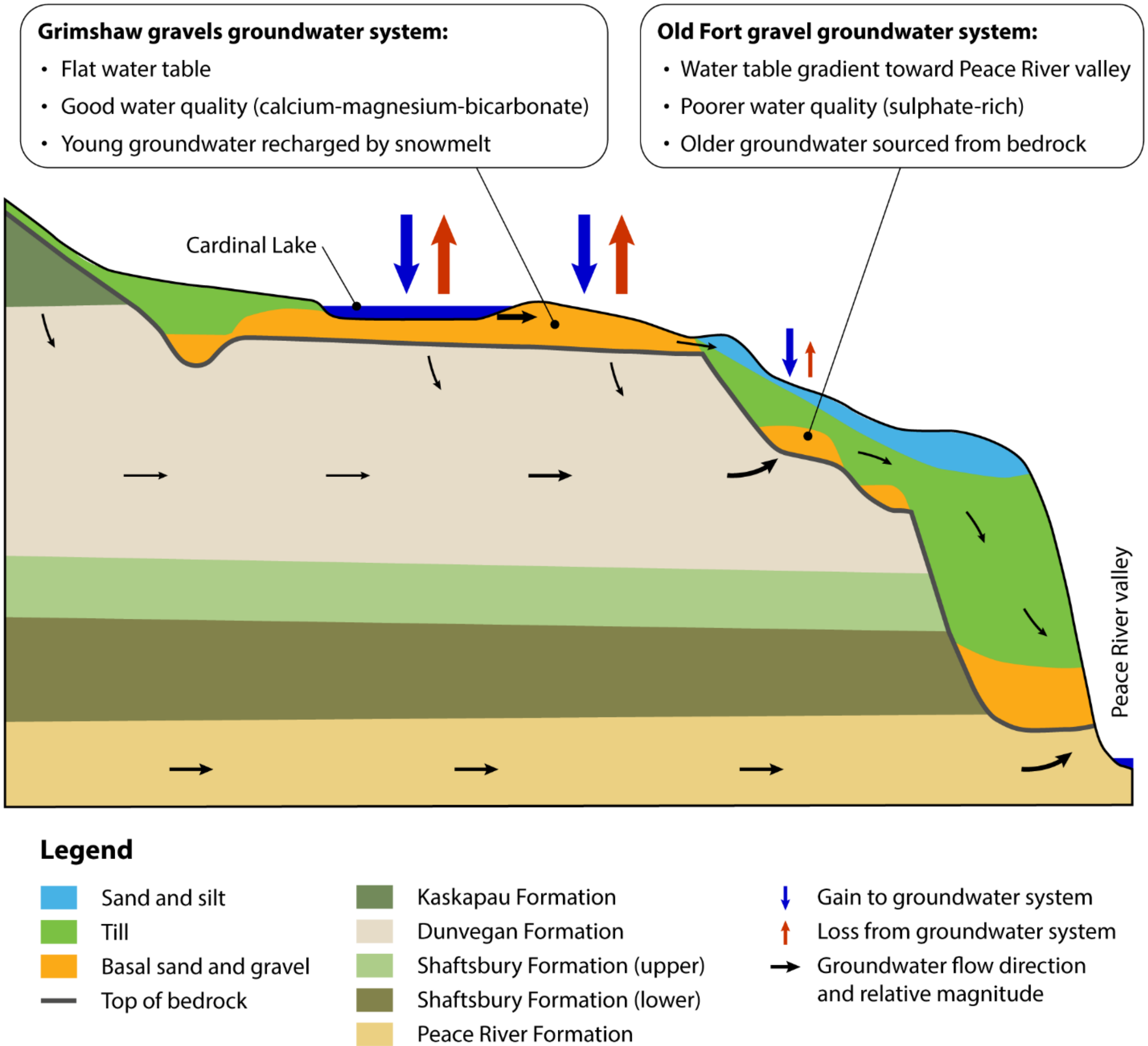

Figure 13. Conceptual model of the Grimshaw gravels aquifer system, illustrating terraced groundwater systems, major gains (e.g., recharge) and losses (e.g., evapotranspiration, pumping) for the groundwater budget. Shaftesbury gravel not included due to insufficient data.

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Appendix 1 – Geochemical and Isotopic Data

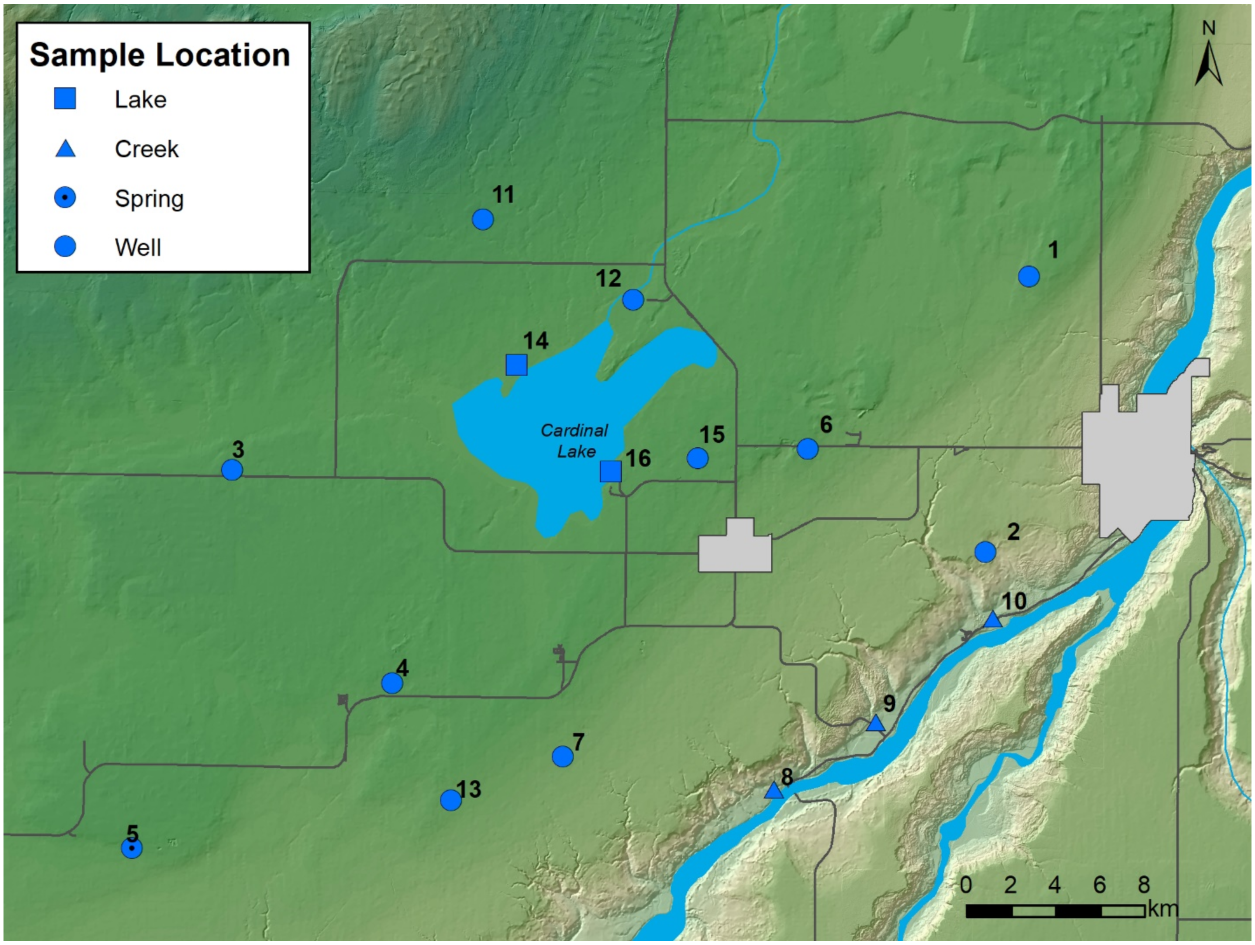

Figure 14. Location of groundwater and surface water samples in Grimshaw study area. Sample numbers correspond to tables of results.

Table 3. Field and lab parameters for water samples collected in the Grimshaw study area.

Sample ID	Location	Field pH	Field EC (µS/cm)	Field Temp. (°C)	Lab pH	Lab EC (µS/cm)	Lab TDS (mg/L)
1	Domestic Well	6.75	591	8.8	6.89	607	500
2	Domestic Well	7.71	1994	7.2	7.12	2042	1808
3	Domestic Well	6.38	416	9.3	6.51	419	298
4	Domestic Well	6.54	1939	7.4	6.82	2050	1954
5	Whitelaw Spring	6.73	521	5.3	6.92	535	424
6	Community Well (McInnis)	6.76	798	9.9	7.10	792	637
7	Domestic Well	7.15	687	10	7.34	714	602
8	Creek 1	8.18	943	14.1	8.16	983	814
9	Creek 2	8.07	1471	15.7	7.90	1549	1301
10	Creek 3	8.03	1366	15.2	8.16	1441	1209
11	Domestic Well	7.10	3737	5.3	7.25	4000	3587
12	Domestic Well	6.74	511	12.2	7.01	517	444
13	Community Well (Griffin Creek)	7.15	660	7.3	7.60	690	584
14	Cardinal Lake (north side)	6.77	570	10.7	7.15	594	530
15	Community Well (Grimshaw)	6.70	636	6.3	6.85	654	534
16	Cardinal Lake (south side)	7.94	456	14.6	7.85	460	362

Abbreviations:EC, electrical conductivity; TDS, total dissolved solids.

Table 4. Alkalinity results for water samples collected in the Grimshaw study area.

Sample ID	Location	Hydroxide (mg/L)	Carbonate (mg/L)	Bicarbonate (mg/L)	P-Alkalinity (mg/L as $CaCO_3$)	T-Alkalinity (mg/L as $CaCO_3$)
1	Domestic Well	<5	<6	300	<5.0	246
2	Domestic Well	<5	<6	480	<5.0	394
3	Domestic Well	<5	<6	92	<5.0	75.2
4	Domestic Well	<5	<6	554	<5.0	454
5	Whitelaw Spring	<5	<6	216	<5.0	177
6	Community Well (McInnis)	<5	<6	291	<5.0	239
7	Domestic Well	<5	<6	311	<5.0	255
8	Creek 1	<5	<6	322	<5.0	264
9	Creek 2	<5	<6	196	<5.0	161
10	Creek 3	<5	<6	265	<5.0	217
11	Domestic Well	<5	<6	382	<5.0	314
12	Domestic Well	<5	<6	287	<5.0	236
13	Community Well (Griffin Creek)	<5	<6	306	<5.0	251
14	Cardinal Lake (north side)	<5	<6	337	<5.0	276
15	Community Well (Grimshaw)	<5	<6	253	<5.0	208
16	Cardinal Lake (south side)	<5	<6	172	<5.0	141

Table 5. Anion water chemistry results for water samples collected in the Grimshaw study area.

Sample ID	Location	Cl (mg/L)	Br (mg/L)	SO_4 (mg/L)	F (mg/L)	NO_2 (mg/L)	NO_3 (mg/L)
1	Domestic Well	33.93	0.02	28.50	0.24	0.15	3.70
2	Domestic Well	15.90	0.06	803.97	0.26	0.12	0.03
3	Domestic Well	22.53	0.01	93.66	0.05	0.07	0.87
4	Domestic Well	13.21	0.03	886.97	0.15	0.10	0.67
5	Whitelaw Spring	18.83	0.01	68.57	0.16	0.09	4.93
6	Community Well (McInnis)	34.90	0.02	135.28	0.31	0.19	2.15
7	Domestic Well	13.23	0.01	116.73	0.30	0.22	0.04
8	Creek 1	19.66	0.03	252.43	0.22	0.13	0.03
9	Creek 2	19.71	0.03	746.37	0.14	0.18	0.04
10	Creek 3	41.25	0.03	569.96	0.21	0.25	0.09
11	Domestic Well	19.22	0.10	2148.87	0.07	0.02	0.05
12	Domestic Well	12.39	0.01	28.13	0.38	0.01	0.02
13	Community Well (Griffin Creek)	11.60	0.01	114.16	0.22	0.01	0.01
14	Cardinal Lake (north side)	24.19	0.02	12.94	0.08	0.01	0.02
15	Community Well (Grimshaw)	12.43	0.02	123.13	0.18	0.01	1.82
16	Cardinal Lake (south side)	20.59	0.02	69.94	0.31	0.01	0.02

Table 6. Cation water chemistry results for water samples collected in the Grimshaw study area.

Sample ID	Location	Ca (mg/L)	Na (mg/L)	Mg (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)
1	Domestic Well	92.90	9.60	19.80	3.40	<0.01	<0.005
2	Domestic Well	239.00	176.00	58.80	8.00	13.50	0.47
3	Domestic Well	44.90	9.10	17.50	7.60	2.28	0.16
4	Domestic Well	353.00	27.70	104.00	3.60	0.07	0.85
5	Whitelaw Spring	75.20	6.90	19.50	6.60	0.01	<0.005
6	Community Well (McInnis)	103.00	23.60	31.00	6.50	<0.01	<0.005
7	Domestic Well	94.50	20.80	30.30	4.50	1.27	0.73
8	Creek 1	70.20	90.00	42.70	9.40	0.09	0.02
9	Creek 2	157.00	87.40	78.20	10.20	0.07	0.01
10	Creek 3	168.00	75.40	73.40	10.80	0.17	0.03
11	Domestic Well	291.00	511.00	210.00	11.00	1.10	0.03
12	Domestic Well	76.60	5.20	20.60	5.30	0.12	0.70
13	Community Well (Griffin Creek)	95.30	15.40	29.20	4.70	0.20	0.44
14	Cardinal Lake (north side)	51.20	12.60	25.80	57.00	0.39	0.30
15	Community Well (Grimshaw)	87.60	12.90	27.50	7.30	0.03	<0.005
16	Cardinal Lake (south side)	40.60	16.20	18.60	21.30	0.17	0.06

Table 7. Isotopic analyses for water samples collected in the Grimshaw study area.

Sample ID	Location	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	^{3}H (TU)	^{14}C (pMC)
1	Domestic Well	-19.92	-156.85	8.22	96.70
2	Domestic Well	-20.68	-170.15	< 0.8	20.17
3	Domestic Well	-20.08	-163.73	4.90	71.23
4	Domestic Well	-19.94	-160.70	1.35	39.37
5	Whitelaw Spring	-20.22	-163.10	8.81	92.80
6	Community Well (McInnis)	-19.90	-160.20	5.50	74.63
7	Domestic Well	-20.06	-164.15	< 0.8	46.95
8	Creek 1	-18.97	-157.22	1.43	64.31
9	Creek 2	-17.71	-150.04	0.84	63.65
10	Creek 3	-15.85	-137.81	7.35	86.10
11	Domestic Well	-22.98	-183.03	< 0.8	<1.59
12	Domestic Well	-20.02	-161.25	3.97	76.17
13	Community Well (Griffin Creek)	-20.08	-164.20	3.67	48.32
14	Cardinal Lake (north side)	-8.35	-98.95	13.60	102.72
15	Community Well (Grimshaw)	-17.65	-148.36	6.04	82.05
16	Cardinal Lake (south side)	-9.36	-100.30	13.58	95.91

Abbreviations: pMC, percent of modern carbon; TU, tritium units.