AER/AGS Report 102

Regional Shallow Stratigraphy and Hydrogeology of the Grande Prairie–Valleyview Area, Northwestern Alberta

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Abstract

Basal coarse-grained sediments (sand and gravel deposits overlying bedrock and underlying fine-grained glacial and glaciolacustrine sediments) constitute important regional aquifers and aggregate resources in the Peace River valley and adjacent plains and uplands. Previous studies have indicated that similar deposits are present in the Grande Prairie–Valleyview area, and may serve as aquifers there.

In this study, the three-dimensional geometry of a basal coarse-grained sediment unit in the Grande Prairie–Valleyview area was rendered from water well drill log reports, subsurface geological investigations, and field investigation. The hydrogeological conditions of the basal coarse-grained sediment unit, as well as adjacent units, including the overlying fine-grained sediments and the underlying uppermost bedrock, were then characterized. Although the basal coarse-grained sediment unit is widely distributed in the Grande Prairie–Valleyview area, it is generally thin and discontinuous. The vast majority of water wells completely penetrate the unit and are completed in underlying bedrock. Within buried bedrock valleys where basal coarse-grained sediment thickness exceeds 5 m, some wells are completed within the sediment unit. However, even in these areas, most wells are completed in bedrock or well completions include screens that bridge bedrock and basal coarse-grained sediments.

Groundwater chemistry in the Grand Prairie-Valleyview area extends from fresh Ca-Mg-HCO_3–type waters to older Na-SO_4–type waters, which are more prevalent. Groundwater chemistry samples show no clear distinction between wells completed in bedrock and those completed in basal coarse-grained sediments, possibly indicating that basal coarse-grained sediments are recharged by groundwater from underlying bedrock units and not by precipitation/snowmelt from above. Due to potential hydraulic connectivity between bedrock aquifer systems and basal coarse-grained sediments in the Grande Prairie–Valleyview area, it may be useful to consider bodies of basal coarse-grained sediments as extensions of bedrock aquifers rather than as discrete aquifers. Where the overlying fine-grained sediment unit is thin, basal coarse-grained sediments may serve as a hydraulic conduit between bedrock aquifers and the surface.

1 Introduction

The Grande Prairie–Valleyview area (GPVA; Figure 1) is an important region for agriculture, forestry, and energy resource development in northwestern Alberta and has recently experienced high rates of economic and population growth. It is anticipated that the rate of energy resource development will increase further as the area is underlain by the highly prospective Montney and Duvernay plays (Rokosh et al., 2012; Euzen et al., 2018). Development of these plays will likely use hydraulic fracturing completion techniques, which typically consume large volumes of nonsaline water from surface and groundwater sources (Rivard et al., 2014; Cai et al., 2018; Alberta Energy Regulator, 2019). In order to manage the orderly development of energy resources while maintaining water availability for natural systems and non-energy–related uses, a regional-scale characterization of nonsaline groundwater resources is required. This characterization may also inform land-use planning, cumulative environmental effects assessment, and regulation of other development activities.

The objective of this study was to characterize the nonsaline groundwater resources in the GPVA by 1) establishing a conceptual regional hydrostratigraphic framework; 2) three-dimensional geological modelling of hydrostratigraphic units; 3) assigning water well screen intervals to hydrostratigraphic units; and 4) assessing the physical and chemical properties of groundwater within each hydrostratigraphic unit. Recent regional hydrogeological studies partially within and proximal to the GPVA indicate that shallow sandstone-dominated bedrock units and basal coarse-grained sediments (sand and gravel deposits overlying bedrock and underlying fine-grained glaciogenic sediment) constitute important regional nonsaline aquifers (Hydrogeological Consultants Ltd., 2004; Slomka et al., 2018; Babakhani et al., 2019; Smerdon et al., 2019). Therefore, this study was focused mainly on the basal coarse-grained sediment unit and uppermost bedrock units.

This report and associated digital products provide a regional hydrogeological characterization for the GPVA within the context of the shallow geological framework in which accessible, nonsaline groundwater is hosted. The work has been conducted as part of the Alberta Geological Survey’s (AGS) Provincial Groundwater Inventory Program (PGIP) and is intended to inform management, regulation, exploration, and protection of groundwater resources in the GPVA.

2 Study Area Characteristics and Background

The study area encompasses 24 680 km^2 of northwestern Alberta herein referred to as the GPVA (Figure 1). The boundary of the study area comprises several elements including 1) drainage divides along the north and east (respectively, the drainage divides between the Smoky River and the upper Peace River, and the Smoky River and Lesser Slave Lake); 2) the boundary of the west-central Alberta study area (Atkinson and Hartman, 2017) along the southeast; 3) the Rocky Mountain Foothills physiographic region (Pettapiece, 1986) along the southwest; and 4) the British Columbia–Alberta provincial border along the west. The major urban centres are Grande Prairie, Valleyview, Sexsmith, Beaverlodge, and Wembley. Half of the study area (12 440 km^2) is designated as Green Area (forest lands and mountain areas), and the remainder is designated as White Area (agricultural and urban areas; Alberta Environment and Parks, 2011). Energy development, including wells, pipelines, processing and storage facilities, and disposal sites, is widespread across the study area and occurs in both Green and White areas. Chowdhury and Chao (2018) provide an overview of time-series land-use/land-cover classification for the Upper Peace Region between 1985 and 2015.

From the geological and hydrogeological perspectives of this study, the most important study area characteristics and background information pertain to its physiography, climate and hydrology, bedrock geology, Neogene–Quaternary geology, and hydrogeology, as discussed in the following sections.

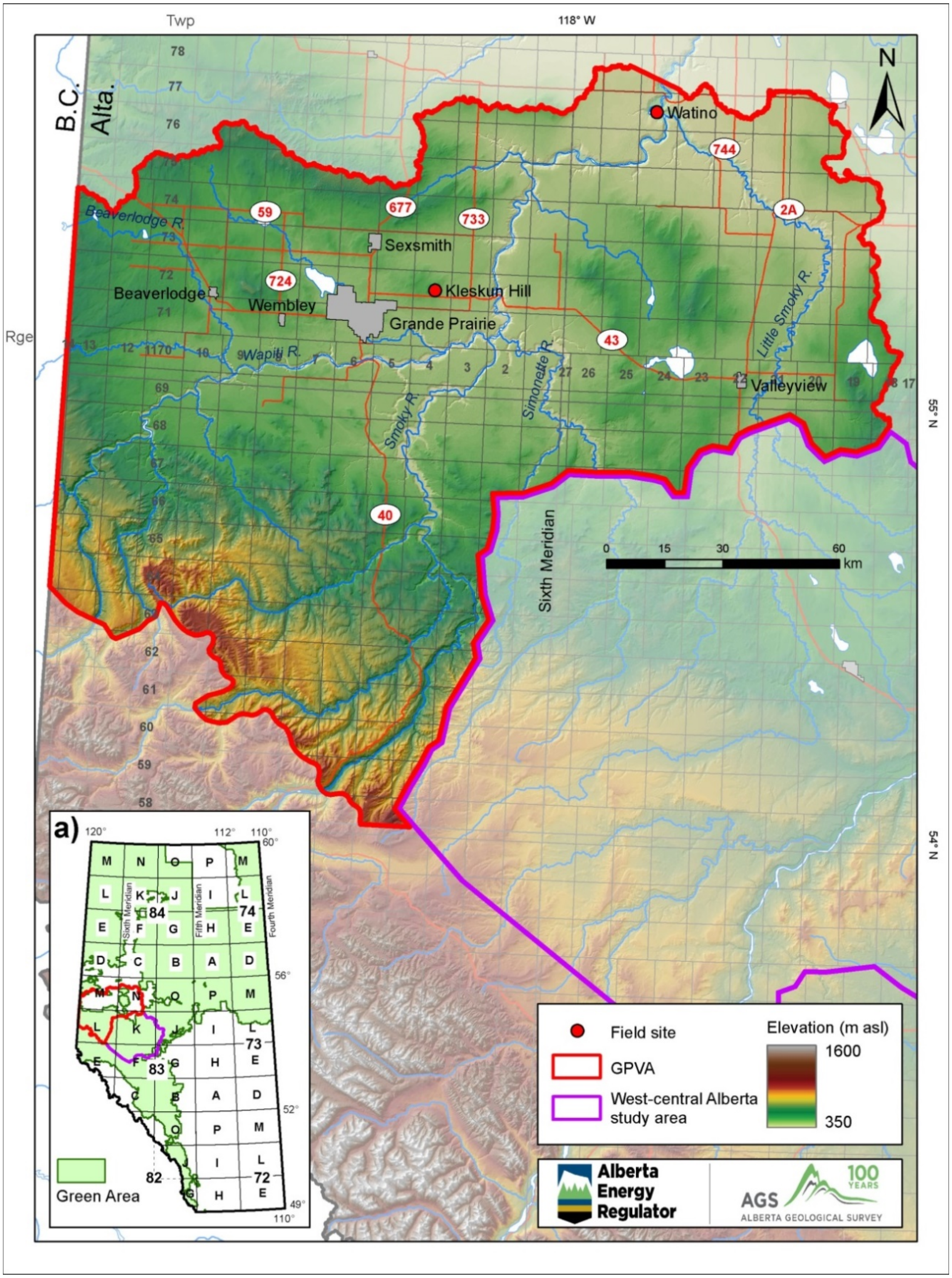

Figure 1. Grande Prairie–Valleyview area (GPVA) showing major topographic features, northwestern Alberta. Digital elevation model (DEM) provided by Alberta Environment and Parks (Alberta Environment and Parks, 2015b). Inset map a) shows the extents of the GPVA and west-central Alberta study area (Atkinson and Hartman, 2017), Green Area (Alberta Environment and Parks, 2011), and the National Topographic System grid in Alberta.

2.1 Physiography

The GPVA is located on the western edge of the Interior Plains (Bostock, 1970). Further physiographic subdivision in the study area (Pettapiece, 1986; Figure 2) includes the Grande Cache Benchlands (750–1600 m asl) in the southwest, the Saddle Hills Upland (680–1000 m asl) in the north, and the Swan Hills Upland (690–950 m asl) in the east. The central to northeastern parts of the study area consist of the Wapiti Plains (including Puskwaskau Hills; 600–940 m asl) and Peace River Lowland (390–750 m asl), respectively. Relief in the uplands and benchlands is generally much higher than that of the plains and lowlands. The major relief elements within the plains and lowlands are deeply incised river valleys and the proximal reaches of their tributaries (up to 180 m incision depth). The study area is drained by the Smoky River and its major tributaries including the Wapiti, Simonette, and Little Smoky rivers (Figure 1).

2.2 Climate and Groundwater Recharge

The study area has a continental climate with long cool summers, severe winters, and no dry season (Hydrogeological Consultants Ltd., 2004). The Alberta Climate Information Service (ACIS) reports annual precipitation of between 450 and 550 mm/yr (Alberta Climate Information Service, 2020) and Hydrogeological Consultants Ltd. (2004) report average precipitation at 436 mm/yr using data from six meteorological stations from 1961 to 1993. Jones (1966) estimates recharge in the Peace River district at about 2% of annual precipitation (equivalent to 9 mm/yr) and Hydrogeological Consultants Ltd. (2004) estimate recharge to the upper bedrock to be 0.2% of annual precipitation (equivalent to about 1 mm/yr). The AGS adapted an approach to assess groundwater availability at a regional scale. This approach uses baseflow and a one-dimensional soil water balance model to estimate recharge in the upper Peace region, which overlaps the GPVA, and presents the data at a watershed scale (Figure 3; Klassen and Liggett, 2019). Recharge estimates range between 3 and 21 mm/yr with the majority of watersheds between 5 and 10 mm/yr.

2.3 Upper Cretaceous–Paleogene Bedrock Geology

Bedrock in the GPVA comprises a heterogeneous assemblage of terrestrial, marginal marine, and offshore deposits. Subcropping units and their equivalents include (from oldest to youngest) the Smoky Group, and the Wapiti/Brazeau, Scollard, Battle, and Paskapoo formations. These units range from Late Cretaceous to Paleogene in age. Progressively older units subcrop in a general south to north trend (Figure 4a and b).

The uppermost formations of the Smoky Group assessed in this study include (from oldest to youngest) the Kaskapau, Cardium, Bad Heart, and Lea Park / Puskwaskau formations (Figure 4b). Lower formations were considered too deep to provide accessible nonsaline groundwater within the GPVA and were not assessed. The Kaskapau Formation is dominantly composed of silty offshore deposits (e.g., Varban and Plint, 2007). Hart and Plint (2003) interpret that the Cardium Formation, from Twp. 58 to 78, Rge. 20, W 5th Mer. to Rge. 13, W 6th Mer., represents shoreface, river mouth, and fluvial depositional environments. The Bad Heart Formation was deposited within a shallow-marine shelf setting above wave base (Donaldson et al., 1998). Deposition was significantly affected by tectonic activity (regional tilting and bevelling as well as localized block faulting) related to the Peace River Arch (Donaldson et al., 1999). The Puskwaskau Formation, with the exception of the Chungo Member, represents deposition controlled by numerous transgressive-regressive cycles in a relatively shallow offshore zone. The Chungo Member represents shoreface sand deposition. The western Puskwaskau and the eastern Lea Park formations are equivalent and included in the same model zone within version 3 of the Geological Framework of Alberta (GFA v3; Alberta Geological Survey, in progress, 2020; Figure 4b).

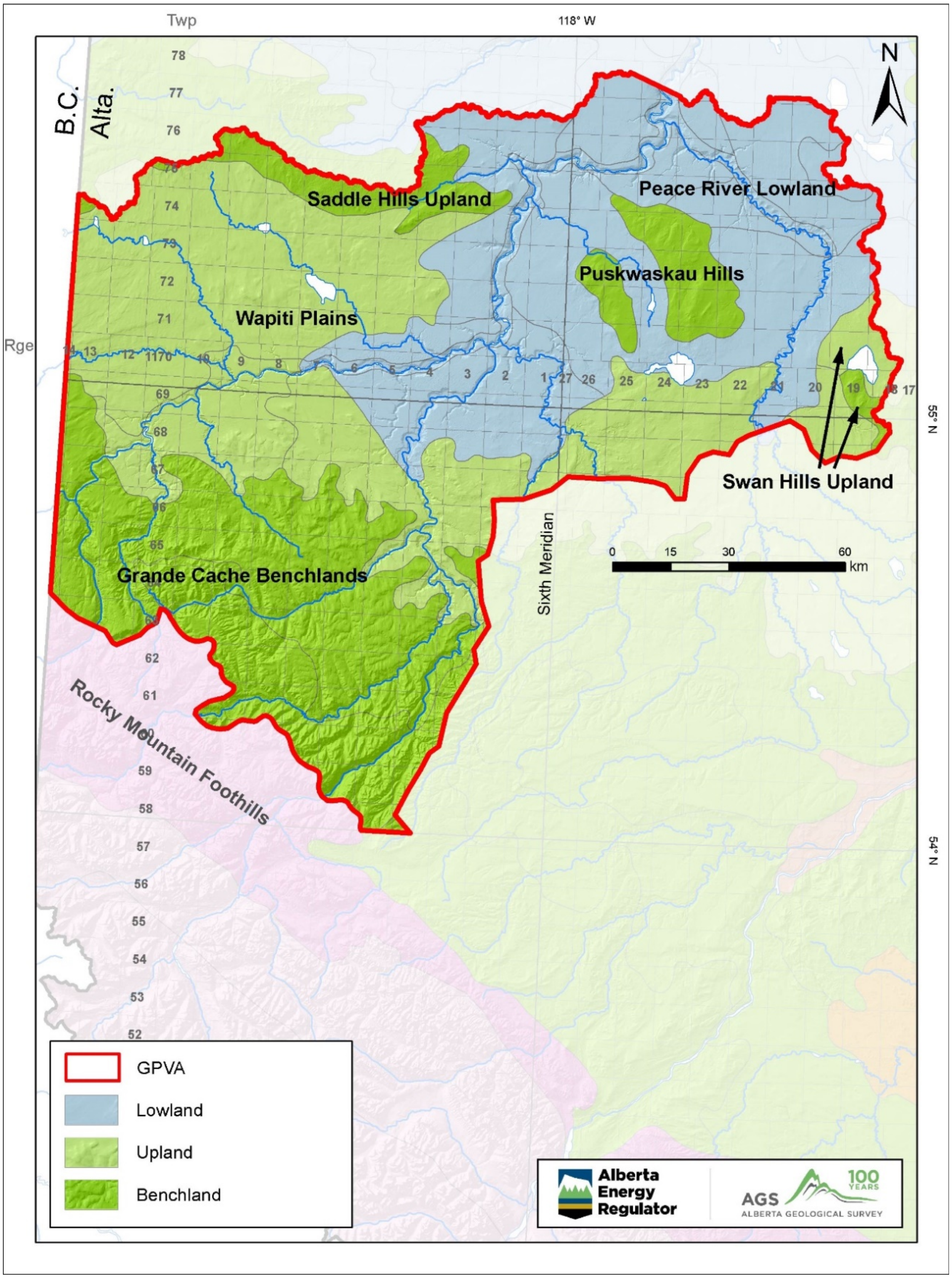

Figure 2. Physiographic divisions in the Grande Prairie–Valleyview area (GPVA), northwestern Alberta (from Pettapiece, 1986). Hill-shaded relief based on digital elevation model (Alberta Environment and Parks, 2015b).

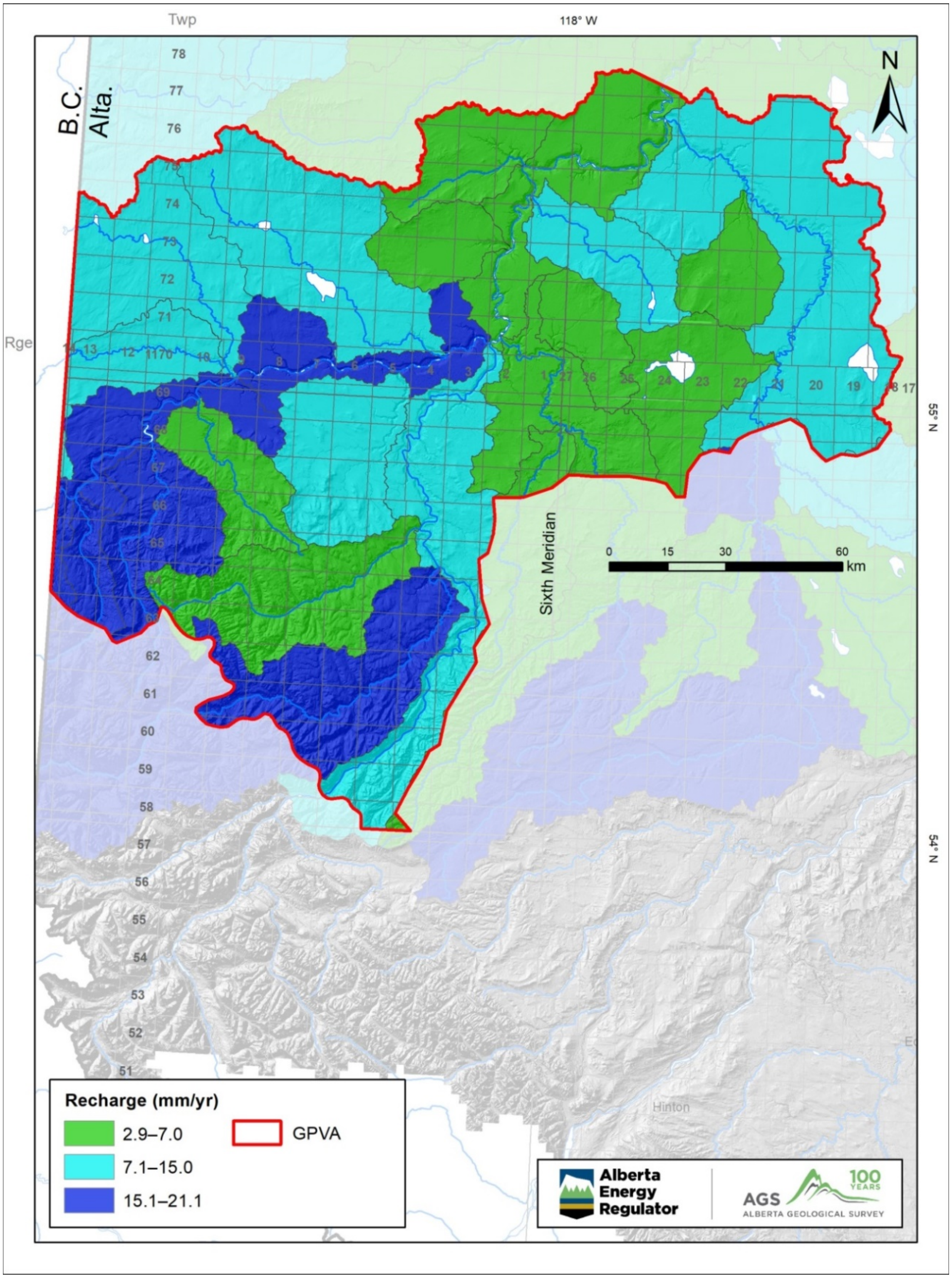

Figure 3. Watershed-scale recharge estimates in the Grande Prairie–Valleyview area (GPVA), northwestern Alberta (from Klassen and Liggett, 2019). Hill-shaded relief based on digital elevation model (Alberta Environment and Parks, 2015b).

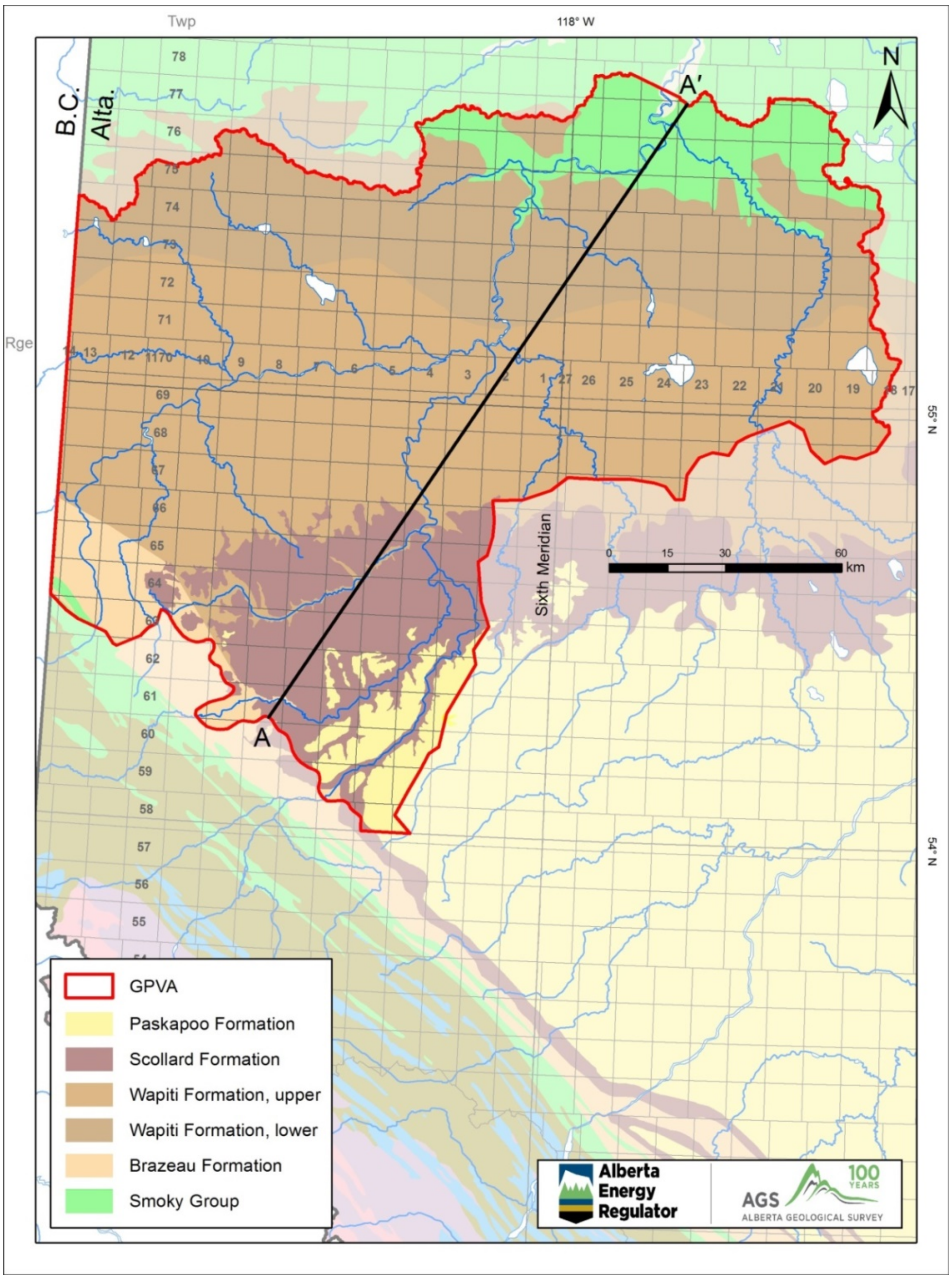

Figure 4a. Bedrock geology of the Grande Prairie–Valleyview area (GPVA), northwestern Alberta (from Prior et al., 2013). Line A–A′ corresponds with geological cross-section A–A′ in Figure 4b.

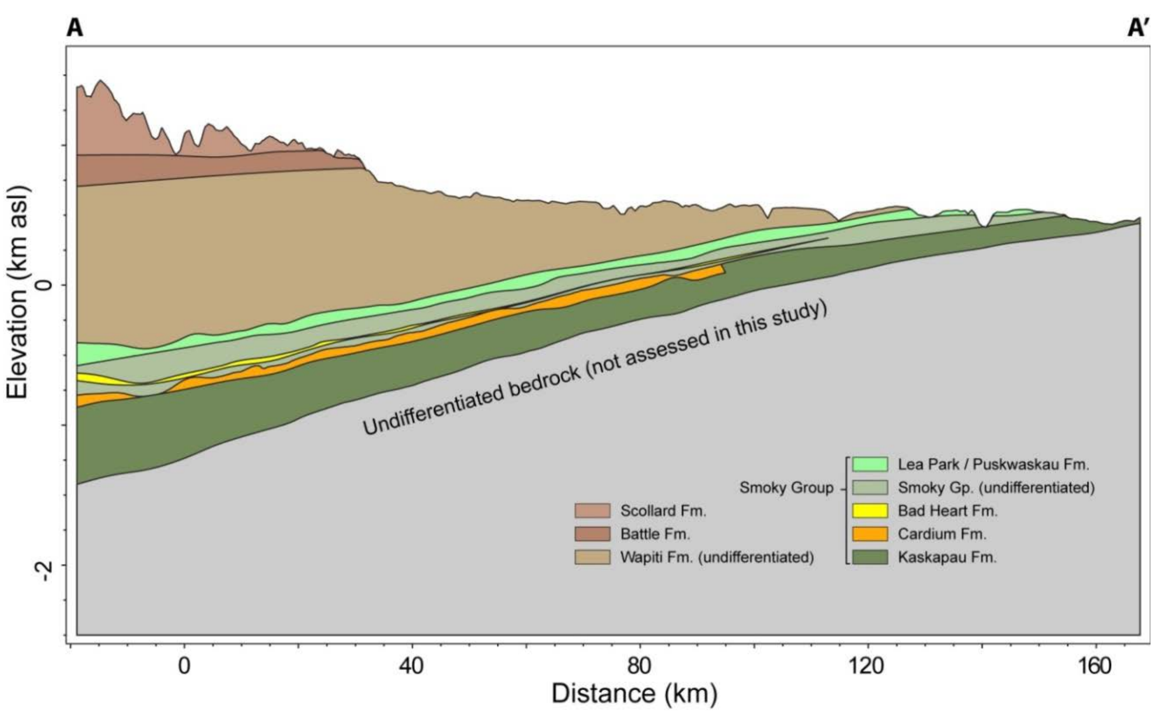

Figure 4b. Geological cross section A–A′ through the bedrock of the Grande Prairie–Valleyview area (GPVA; 24 times vertical exaggeration), northwestern Alberta, based on version 3 of the Geological Framework of Alberta (Alberta Geological Survey, in progress, 2020). Neogene–Quaternary units above bedrock are not shown. Bedrock below the Kaskapau Formation shown as undifferentiated and not assessed in this study.

Dawson et al. (1994) subdivided the Wapiti Formation into a lower and upper unit. The boundary between the two units is the base of the Cutbank coal measure. They defined the Wapiti Formation as the "specific stratigraphic interval lying above the marine sediments of the Puswaskau [sic] Formation and below the resistant massive sandstone (Entrance Member) at the base of the Coalspur/Scollard Formation". Following this early work, Fanti and Catuneanu (2009) subdivided the Wapiti Formation into five units (units 1–5) based on channel stacking patterns, coal zones, and bentonite layers from outcrop data and gamma-ray well log signatures from a subsurface dataset. The surfaces separating each of the units were interpreted within a fluvial sequence stratigraphic framework by Fanti and Catuneanu (2010).

The Battle Formation is interpreted as a marsh or lacustrine deposit (Hathway, 2011). The base of the Battle Formation has been interpreted to represent a significant disconformity, interpreted as a third order sequence boundary (Catuneanu et al., 2000). The top of the Battle Formation is more difficult to define as it is sometimes described as erosional and other times as conformable (cf. Hathway, 2011).

The Scollard Formation can be subdivided into the lower Scollard Formation, which represents braided fluvial systems, and the upper Scollard Formation, which represents meandering fluvial systems and includes the thick coal beds of the Ardley coal zone (Khidir and Catuneanu, 2003). Within the study area, the Scollard Formation comprises isolated fluvial sandstone bodies encased in interfluvial sediments. The base of the Scollard Formation is defined as the transition from mauve-coloured mudstone of the Battle Formation, to greener sediment of the Scollard Formation (Khidir and Catuneanu, 2003). The upper contact of the Scollard Formation is defined as the first prominent sandstone body (belonging to the Paskapoo Formation) above the Ardley (or equivalent) coal zone. The base of the Ardley coal zone can be used as a regional datum (Langenberg et al., 2007; Quartero et al., 2015).

The Paskapoo Formation comprises fluvial-associated strata. The lowest unit is characterized by amalgamated fluvial channel deposits, whereas the middle unit is characterized by silty interfluvial deposits interspersed with isolated sandstone channels. The upper unit consists of northeast-trending fluvial deposits corresponding to either a large fan-shaped distributive fluvial system or a fixed-outlet individual avulsing channel (Quartero et al., 2015).

2.4 Neogene–Quaternary Geology

Neogene–Quaternary sediment in the GPVA includes preglacial fluvial sand and gravel deposits overlying planar bedrock surfaces and the floors of bedrock valleys as well as broadly distributed glacial sediments deposited during or immediately after the Late Wisconsinan glaciation. Postglacial sediments, including fluvial deposits along modern rivers and organic deposits in modern bogs, swamps, and fens, constitute a relatively minor component of Neogene–Quaternary sediments in the GPVA.

2.4.1 Preglacial Geological History

The preglacial geological history of the western Interior Plains is dominated by erosion via episodic fluvial incision and lateral planation, as indicated by the presence of thick deposits of fluvial gravel upon relatively planar bedrock surfaces above, at, and below the modern plains (cf. Alden, 1932; Vonhof, 1969; Osborn and du Toit, 1991; Edwards and Scafe, 1996; Leckie, 2006). These processes resulted in a step-form landscape architecture in which younger planation surfaces are incised below older planation surfaces. To the south of the study area, four partially gravel-covered planation surfaces were recognized (Roed, 1968, 1975; St-Onge, 1972; Edwards and Scafe, 1996; Atkinson and Hartman, 2017):

- the Swan Hills, Entrance, and Mayberne benchlands (up to 600 m above the modern plains);
- the Berland, Little Smoky, and Simonette benchlands (up to 350 m above the modern plains);
- the Edson, Windfall, and Iosegun plains (approximately equivalent to the average modern plains surface); and
- buried valleys (incised up to 100 m below the modern plains).

Four partially gravel-covered planation surfaces were also recognized to the north of the study area (Tokarsky, 1967; Mathews, 1978; Edwards and Scafe, 1996; Hartman and Clague, 2008; Hartman and Slomka, 2017; Slomka et al., 2018) and, following the nomenclature of Slomka et al. (2018), they are

- the Clear Hills (up to 450 m above the modern plains);
- the Grimshaw strath (up to 100 m above the modern plains);
- the Old Fort strath (approximately equivalent to the average modern plains surface); and
- the Shaftesbury valley (incised up to 200 m below the modern plains).

The planation surfaces to the north and south of the study area are associated with, respectively, the ancestral equivalents of the modern Peace and Athabasca rivers (Tokarsky, 1967; Vonhof, 1969; Edwards and Scafe, 1996; Hartman and Clague, 2008; Atkinson and Hartman, 2017; Hartman and Slomka, 2017; Slomka et al., 2018), which are primary drainage elements of the western Interior Plains. Within the study area, which is drained by the second order Smoky River (Figure 1), gravel-covered planation surfaces have not been reported. However, gravel-floored, buried preglacial valleys have been identified (Jones, 1960, 1966; Tokarsky, 1967, 1977; Westgate et al., 1971, 1972; Barnes, 1977; Hackbarth, 1977; Borneuf, 1980; Liverman, 1989). The absence of thick upland gravel caps may reflect second order ancestral drainage that was incapable of transporting and emplacing thick deposits of large-calibre gravel. Nonetheless, steps can be recognized in the landscape architecture of the study area suggesting that it too is, primarily, a product of episodic fluvial incision and lateral planation.

2.4.2 Glacial Geological History

During the Late Wisconsinan, the GPVA was glaciated by both the Cordilleran and Laurentide ice sheets (Atkinson et al., 2016; Hickin et al., 2016). Atkinson et al. (2016) provides a detailed reconstruction of ice sheet dynamics and a relative chronology of glacial events based on the geomorphic analysis of landforms and associated sediments. The major events identified by Atkinson et al. (2016) include (from oldest to youngest):

1) Initially, the topographically unconstrained Cordilleran Ice Sheet (CIS) flowed in a northeast direction, across the Rocky Mountains and onto the Interior Plains. Concurrently, the Laurentide Ice Sheet (LIS) advanced towards the southwest (Figures 2 and 5).
2) The ice sheets converged and mutually deflected against one another.
3) The convergence zone between the ice sheets migrated westward towards the Rocky Mountain Foothills (Figures 2 and 5) as the LIS displaced the CIS.
4) The LIS retreated and progressively decoupled from the CIS. Debuttressing of the CIS led to localized expansion of outlet glaciers from major mountain valleys including the modern Smoky and Athabasca river valleys.
5) Moraines, eskers, and ice-marginal meltwater channels within foothills valleys record thinning and retreat of the CIS. Glacial Lake Peace (Mathews, 1980; Hickin et al., 2015) formed against the margin of the LIS as it retreated from the study area resulting in the widespread distribution of glacial lake sediments across the Wapiti Plains and Peace River Lowland (Figures 2 and 5).

The glacial history outlined by Atkinson et al. (2016) is broadly similar to Late Wisconsinan glacial histories outlined by Hickin et al. (2016) and Roed (1968, 1975) based on stratigraphic analyses to the north and south of the GPVA, respectively. In addition, the western limit of the LIS in the Rocky Mountain Foothills, and the eastern limit of the CIS on the Interior Plains outlined by Atkinson et al. (2016) are supported by the distribution of glacially transported erratics unique to each ice sheet (Roed, 1968, 1975; Catto et al., 1996; Andriashek, 2001).

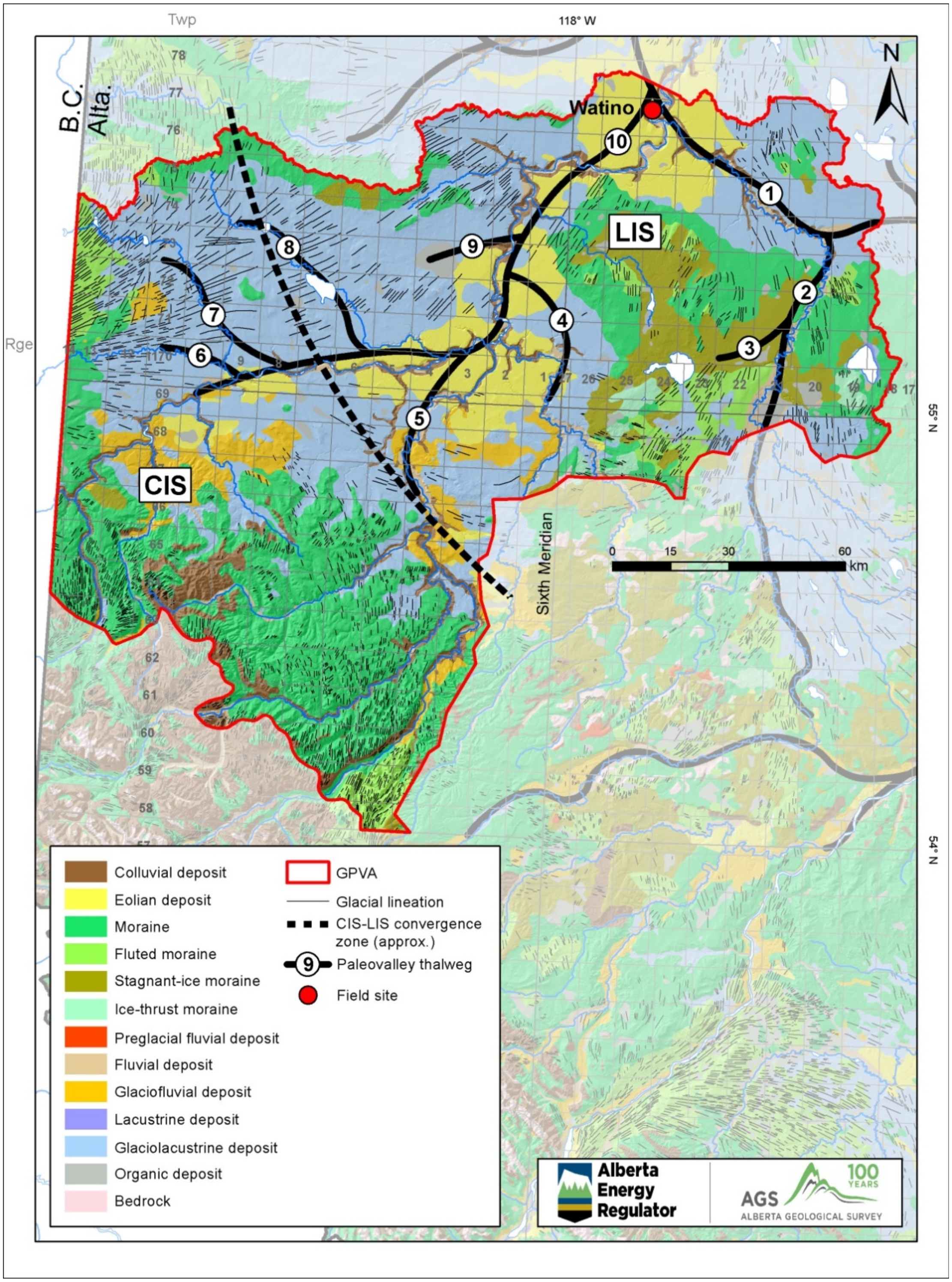

Figure 5. Surficial geology (from Fenton et al., 2013) of the Grande Prairie–Valleyview area (GPVA), northwestern Alberta, with Cordilleran Ice Sheet (CIS) and Laurentide Ice Sheet (LIS) glacial lineations (from Atkinson et al., 2018), approximate convergence zone (modified from Atkinson et al., 2016), and buried paleovalley thalwegs (modified from Andriashek, 2018) including 1) High Prairie valley, 2) Valleyview valley, 3) Stump valley, 4) Misery valley, 5) Tolstad valley, 6) Diamond valley, 7) Wembley valley, 8) Grande Prairie valley, 9) Kleskun valley, and 10) Bezanson valley. Hill-shaded relief based on digital elevation model (Alberta Environment and Parks, 2015b).

The glacial history outlined by Atkinson et al. (2016) is largely restricted to events immediately prior to, during, and following the last glacial maximum (LGM) because geomorphic analysis is based on landforms and sediments visible at surface. From a hydrostratigraphic perspective, an important glacial event that is not captured by surface geomorphic analysis is the impoundment of regional drainage and burial of valleys with glacial deposits upon the advance of the LIS. These events are documented within the study area through the analysis of sections and core by Westgate et al. (1971, 1972), Liverman (1989), and Slomka and Utting (2017). The identification and distribution of buried valleys within the study area is captured in assessments of bedrock topography (Carlson and Hackbarth, 1974; Carlson and Green, 1979; Pawlowicz and Fenton, 1995; MacCormack et al., 2015) and hydrogeology (Jones, 1960, 1966; Barnes, 1977; Hackbarth, 1977; Tokarsky, 1977; Borneuf, 1980). Andriashek (2018) compiled all mapped thalwegs of bedrock valleys in Alberta, including buried valleys within the study area (Figure 5). Liverman (1989) and Slomka and Utting (2017) outline the typical buried valley infill succession consisting of (from base to top)

- a gravel fluvial unit emplaced prior to the LGM (Westgate et al., 1971, 1972; Liverman, 1989; Slomka and Utting, 2017);
- a fine-grained advance-phase glaciolacustrine unit emplaced upon the advance of the LIS;
- a regional till diamicton deposited during the Late Wisconsinan by the CIS/LIS; and
- a regional fine-grained retreat-phase glaciolacustrine unit.

Pre–Late Wisconsinan CIS glacial sediments have been described in stratigraphic studies of the Foothills and westernmost Interior Plains, to the north and south of the study area, by Hickin et al. (2016) and Roed (1968, 1975), respectively. Within the study area, however, no pre–Late Wisconsinan CIS deposits have been described. It is noted that the pre–Late Wisconsinan sediments described by Hickin et al. (2016) and Roed (1968, 1975) are associated with major valleys that extend through the Rocky Mountains and Foothills. Potentially, the lack of a similar conduit for CIS expansion towards the study area prevented its glaciation prior to the LGM. It is also possible that pre-LGM CIS deposits are simply not exposed within the study area. The well documented stratigraphy at Watino (Westgate et al., 1971, 1972; Liverman, 1989; Catto et al., 1996; Figure 5) indicates that the LIS did not reach the study area prior to the Late Wisconsinan.

The genesis of surficial materials across the province, including within the study area, is portrayed by Fenton et al. (2013; Figure 5). In general, glacial till and colluvium mantle uplands and benchlands, whereas glaciolacustrine deposits occur in lowlands and plains within the basins of former glacial lakes. Glaciofluvial deposits are located at the edges of glacial lakes adjacent to major river valleys and spillways. Glaciofluvial deposits are also found on high terraces of major rivers, which have incised into the plains and lowlands. Fluvial deposits are found adjacent to modern rivers on low terraces and floodplains. Eolian deposits are centred in the low portions of former glacial lake basins. The sediments from which they are comprised were presumably scavenged from the bare glacial lake plains following drainage of the glacial lakes, as well as from fluvial deposits emplaced following lake drainage (Pawley and Atkinson, 2012).

2.5 Hydrogeology

Previous regional hydrogeological work in this area includes Jones (1961, 1966), Tokarsky (1966), Barnes (1977), Hackbarth (1977, 1978), and most recently Hydrogeological Consultants Ltd. (2004). Hydrogeological Consultants Ltd. (2004) conducted a groundwater assessment within the White Area of the Peace River watershed, which overlaps with the northern portion of the GPVA. They identified aquifers in surficial deposits and uppermost bedrock, and described the quality and quantity of groundwater within each aquifer. The term aquifer was applied to saturated permeable sand and gravel deposits or bedrock units that are able to transmit groundwater to water wells in economic quantities.

Hydrogeological Consultants Ltd. (2004) found that sand and gravel deposits occur throughout the surficial deposits in their study area but are generally thin and discontinuous. Sand and gravel thickness is typically less than 10 m but can be up to 20 to 30 m in some areas, such as the gravels in the Grimshaw area directly north of the GPVA (see Slomka et al., 2018). The majority of water wells completed in the sand and gravel deposits (66%) have an apparent yield of less than 50 m^3/day, but the long-term yields are expected to be less due to the limited areal extent of individual sand and gravel deposits. Groundwater chemistry in sand and gravel deposits is diverse and is characterized as sodium-bicarbonate, sodium-sulphate, calcium-bicarbonate, or calcium-sulphate–type waters.

Hydrogeological Consultants Ltd. (2004) characterized the hydrogeological conditions in bedrock aquifers on a formation by formation basis. However, collectively, uppermost bedrock aquifers have apparent yields of less than 20 m^3/day and most bedrock-sourced groundwater is sodium-bicarbonate– or sodium-sulphate–type water (although some areas have calcium as the dominant ion).

Regional hydraulic head within the Wapiti / Belly River hydrostratigraphic unit was mapped by Singh and Nakevska (2019; Figure 6). The general trend of groundwater flow is from the west/southwest to northeast. Hydrogeological Consultants Ltd. (2004) created a recharge/discharge map for the upper bedrock aquifers by subtracting the nonpumping water level surface (wells completed in upper bedrock) from an interpolated bedrock surface. Areas were designated as recharge areas where the water level was more than 5 m below the bedrock surface and discharge areas where the water level was less than 5 m below the bedrock surface. The majority of the study area (62%) was interpreted to be under discharge conditions (mostly around bedrock lows) and 38% of the study area was interpreted to be under recharge conditions (mostly around bedrock highs).

Four GOWN (Groundwater Observation Well Network; maintained by Alberta Environment and Parks) wells were sampled in the GPVA around the city of Grande Prairie (Smerdon, 2019). Three of the four GOWN wells are completed in bedrock and the other is completed in surficial material. Isotopic results (high ^{3}H and ^{14}C) indicate that the groundwater sampled in the GOWN well completed in surficial material is relatively young whereas the groundwater sampled in GOWN wells completed in bedrock have ^{14}C values of <15% of modern carbon (pMC) and <0.8 tritium units (TU), which could indicate a groundwater age in the order of 15 000 to 25 000 years before present.

3 Methodology

Regional hydrogeological characterization of the GPVA was accomplished by establishing a conceptual regional hydrostratigraphic framework and three-dimensional geological modelling of hydrostratigraphic units. Water wells were then assigned to hydrostratigraphic units based on completion depths (screen intervals). Physical and chemical properties of groundwater were assessed within each hydrostratigraphic unit.

The conceptual hydrostratigraphic framework of bedrock units in the GPVA parallels lithostratigraphic divisions of shallow bedrock units provided in the GFA v3 (Alberta Geological Survey, in progress, 2020). Therefore, the three-dimensional (3D) hydrostratigraphic model of the bedrock units in the GPVA was extracted directly from the GFA v3 as outlined in Section 3.1. Four conceptual regional hydrostratigraphic units could be identified in Neogene–Quaternary sediments based on previous work and subsurface data assembled in this project. However, only a basal coarse-grained unit and overlying fine-grained units could be modelled in 3D at a regional scale (Section 3.2). Water well completions (screened intervals) were intersected with the 3D hydrostratigraphic model to determine the hydrostratigraphic unit(s) being produced on a well-by-well basis (Section 3.3.1). These data were used to interpolate decadal potentiometric surfaces, which enabled the assessment of regional water level fluctuations over time (Section 3.3.2), estimate vertical hydraulic head gradient and groundwater flow potential (Section 3.3.3), and interpret the evolution of groundwater chemistry throughout the GPVA (Section 3.3.4).

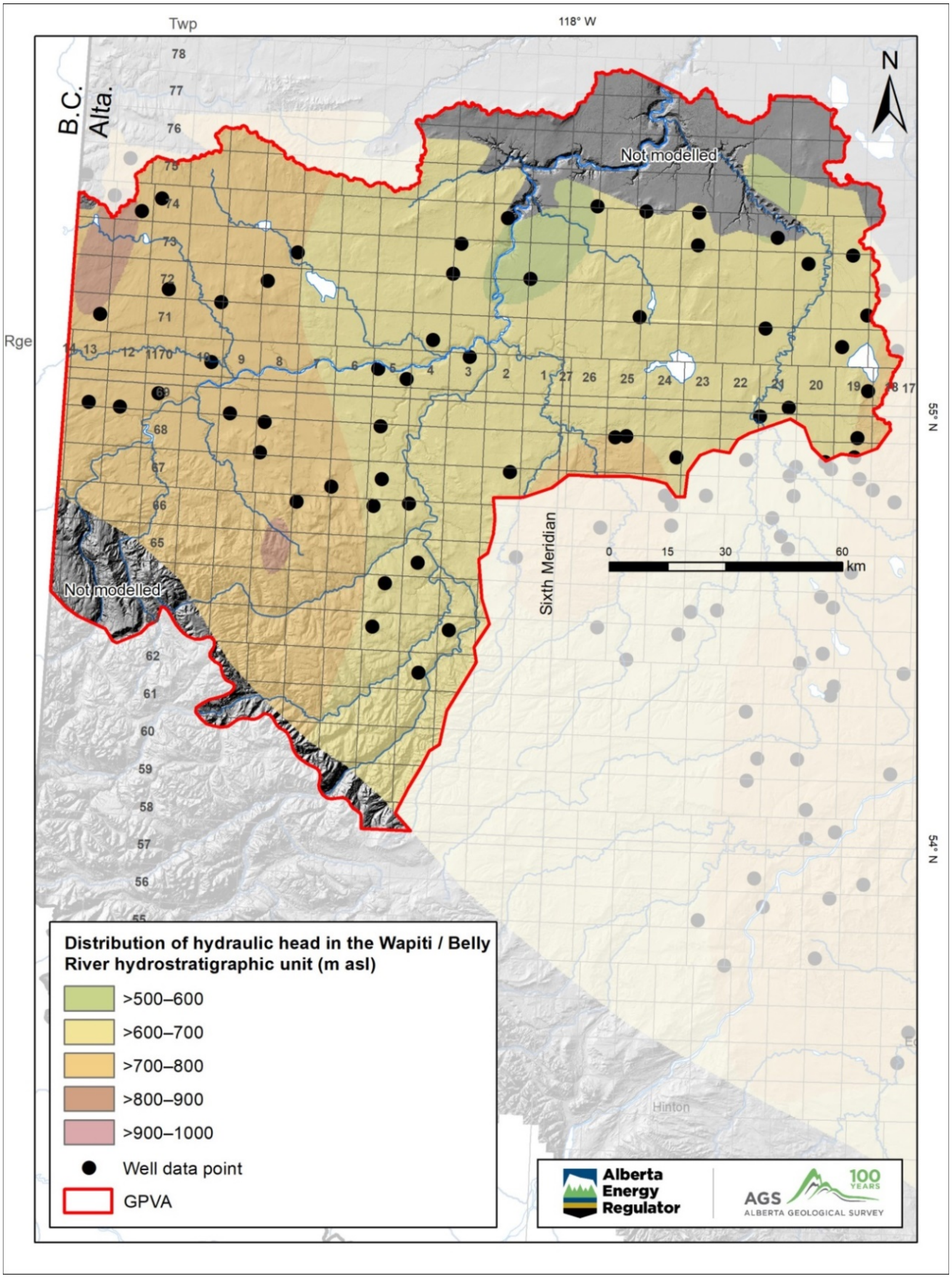

Figure 6. Regional hydraulic head in the Wapiti / Belly River hydrostratigraphic unit (from Singh and Nakevska, 2019), Grande Prairie–Valleyview area (GPVA), northwestern Alberta. Hill-shaded relief based on digital elevation model (Alberta Environment and Parks, 2015b).

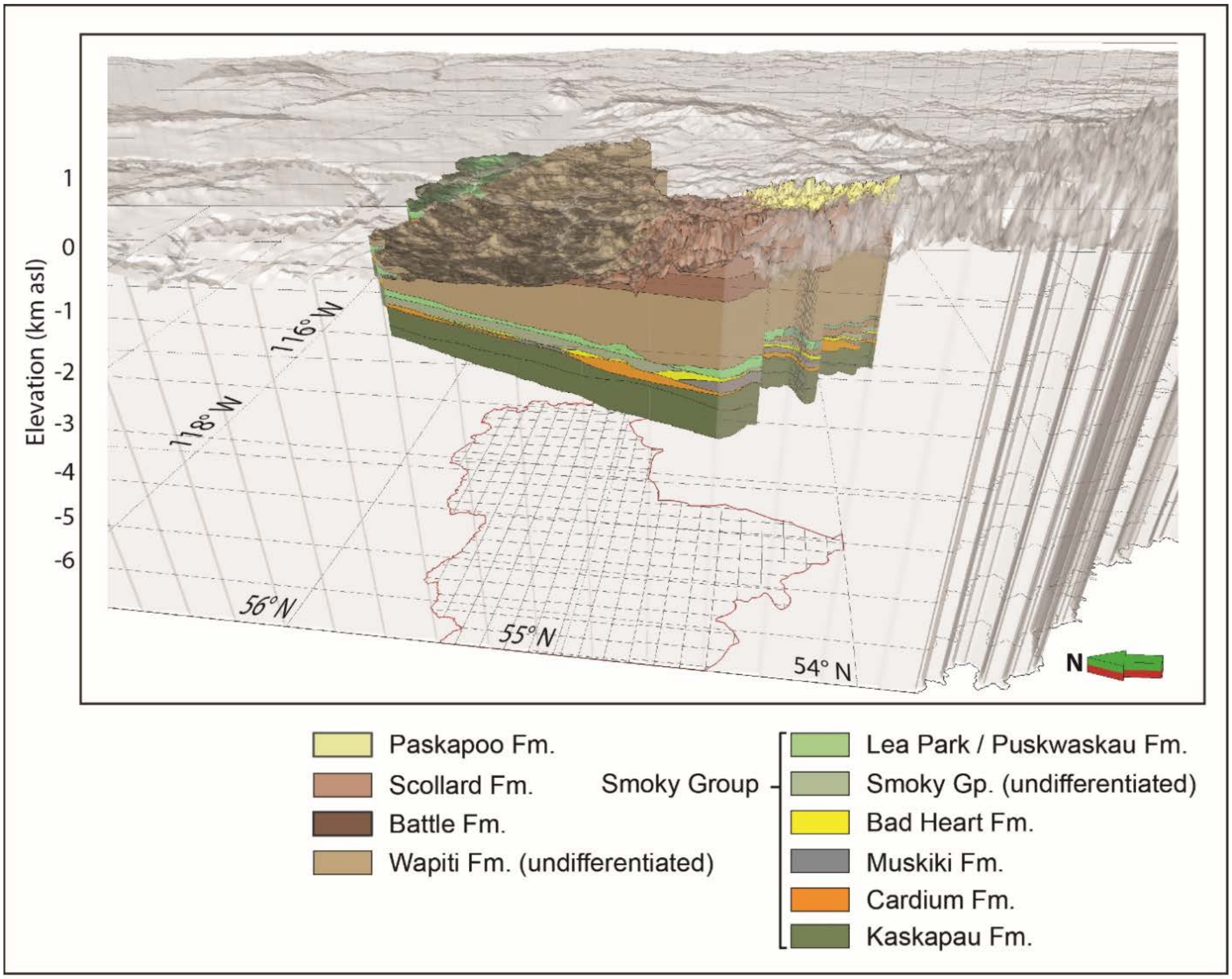

Figure 7. Geological model of the Grande Prairie–Valleyview area, northwestern Alberta, extracted from version 3 of the Geological Framework of Alberta (Alberta Geological Survey, in progress, 2020).

3.1 Bedrock Geological Modelling

The lithostratigraphic/hydrostratigraphic model units extracted from the GFA v3 include the Paskapoo, Scollard, Battle, and Wapiti formations, and the Smoky Group including the Lea Park / Puskwaskau, Bad Heart, Cardium, and Kaskapau formations (Figure 7).

The GFA v3 is modelled at a 500 by 500 m grid resolution, and is composed of zones that represent geological groups, formations, members, or combinations thereof. Elevation tops and bases of zones are represented by two-dimensional (2D) grids built using interpolation algorithms to infer grid values between wellbore pick locations. Zone boundaries are defined by using a combination of the provincial border, unit erosional edges, lateral nomenclature changes, and/or the limit of current stratigraphic pick interpretation. Each zone is composed of a single layer of 3D cells.

3.2 Neogene–Quaternary Geological Modelling

The methodology employed to model Neogene–Quaternary units in this study broadly follows that described in the west-central Alberta report (Atkinson and Hartman, 2017) and included

1) development of a conceptual hydrostratigraphic framework based on the Neogene–Quaternary geological history;

2) assimilation of subsurface, surface, and gridded information in a geographic information system (GIS) database (herein termed the lithological database);
3) field investigation to calibrate subsurface geological descriptions;
4) analysis and correlation of subsurface information in cross-section, and picking of hydrostratigraphic unit tops;
5) computer interpolation (gridding) of regionally significant hydrostratigraphic units in 3D; and
6) superposition of Neogene–Quaternary hydrostratigraphic model units above bedrock hydrostratigraphic model units to complete the 3D hydrostratigraphic model of the study area.

Output grids portray the modelled location, elevation, and thickness of Neogene–Quaternary hydrostratigraphic units within the limits of uncertainty inherent in the input data and the modelling procedure (discussed in Section 6.2). Interpolation of the bedrock topography is typically a primary component of Neogene–Quaternary hydrostratigraphic modelling because 1) the bedrock topography provides the base of Neogene–Quaternary units and the top of bedrock units, 2) the interface between the bedrock and the Neogene–Quaternary sediments is one of the few surfaces that may be present everywhere in the study area, and 3) the bedrock top is typically a less uncertain pick than the tops of other units. These characteristics make the bedrock topography surface a good starting point for further stratigraphic subdivision. The bedrock topography of the GPVA was provided by an update to the provincial bedrock topography grid (Alberta Geological Survey, 2020a) that was concurrent with the GPVA study and, within the GPVA study area, used data that was generated or evaluated as part of this study. Data used in the bedrock topography update includes bedrock top picks, buried valley thalweg positions, and evaluation of proxy data. Although the bedrock topography grid is provincial in scale (500 m grid cell size), its production used a novel machine-learning methodology that resulted in high accuracy overall.

3.2.1 Lithological Database

Subsurface information in the GPVA was collected in a lithological database. Data sources included drillers' logs compiled in the Alberta Water Well Information Database (AWWID; Alberta Environment and Parks, 2015a); Alberta Research Council (ARC) and AGS geological test hole logs; downhole geophysical logs from geological test holes, water wells, and oil and gas wells; AGS gravel assessment borehole and pit section logs; AGS bedrock and Neogene–Quaternary section logs and mapped outcrops; and bedrock outcrop positions remotely assessed from imagery (Figure 8). All depths/elevations were related to the provincial 25 m digital elevation model (DEM; Alberta Environment and Parks, 2015b). Due to a large quantity of co-located data, only the deepest and shallowest logs were retained at any single location. Certain locations were investigated in the field including Kleskun Hill, and natural exposures along the Smoky River between its confluence with the Wapiti River and Watino (Figures 1 and 9). All data sources listed above were considered high quality with the exception of remotely assessed bedrock outcrops and drillers' logs extracted from the AWWID (which represent the majority of data). These data sources were considered medium quality because of 1) the remote nature of remotely assessed bedrock outcrops, and 2) inconsistency in the terminology used in drillers' logs to describe subsurface units as well as uncertainty inherent in the location descriptions of water wells (often undefined beyond the quarter section). Water well lithologs comprise 93% of subsurface data (14 802 lithologs, after selection of the shallowest and deepest lithologs where multiple wells are co-located; Figure 8). Medium-quality data sources make up the majority of data, and have the most widespread distribution in the study area. In order to leverage the relatively small number of high-quality data sources, cross-sections were drawn to incorporate high-quality data wherever possible. Subsurface hydrostratigraphic picks made on cross-sections (discussed below) were stored in the lithological database.

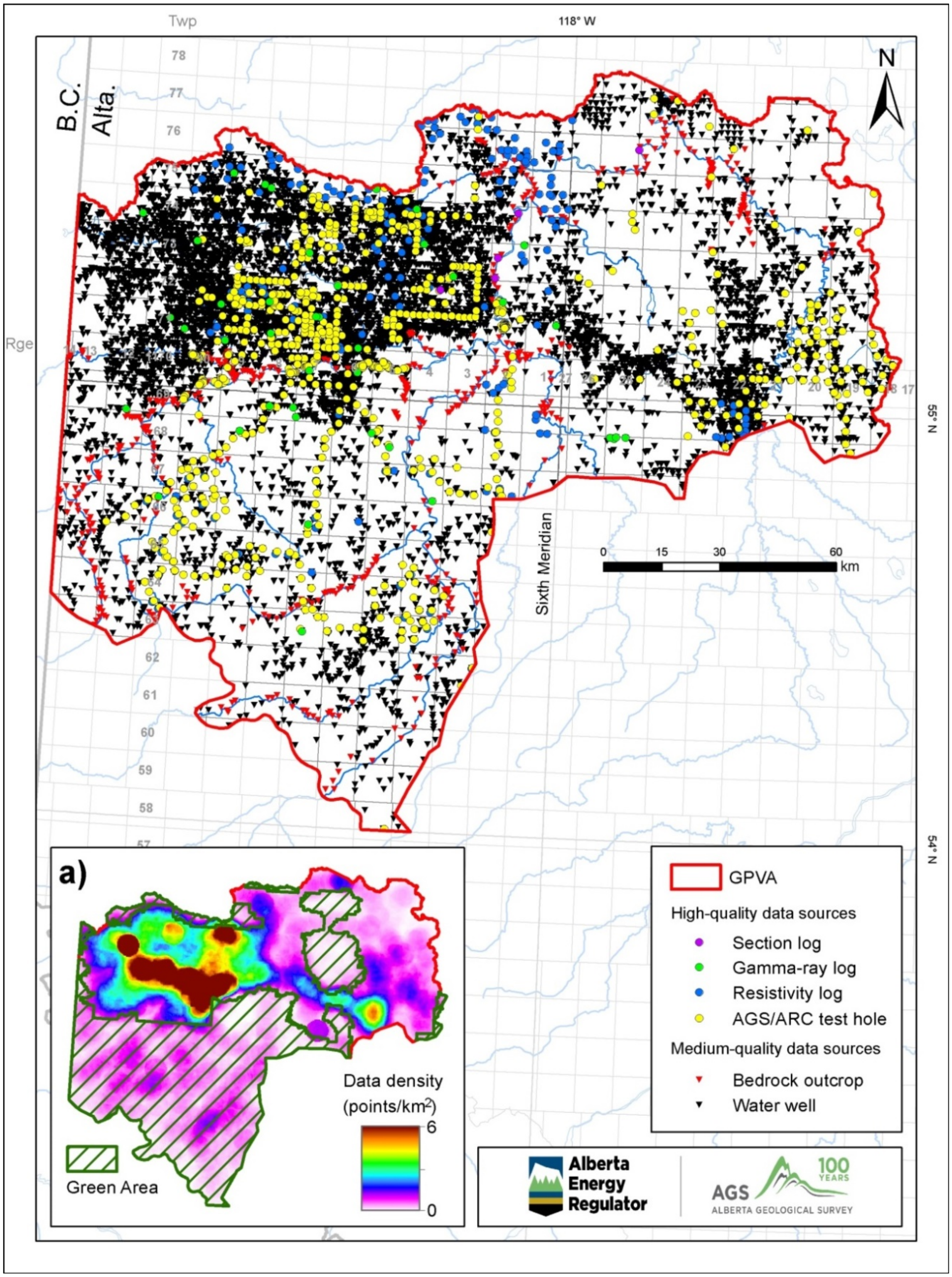

Figure 8. Sources and locations of high- and medium-quality subsurface lithological data in the Grande Prairie–Valleyview area (GPVA), northwestern Alberta. Inset a) Density of high- and medium-quality data (number of points/km^2) and Green Area (Alberta Environment and Parks, 2011). Abbreviations: AGS, Alberta Geological Survey; ARC, Alberta Research Council.

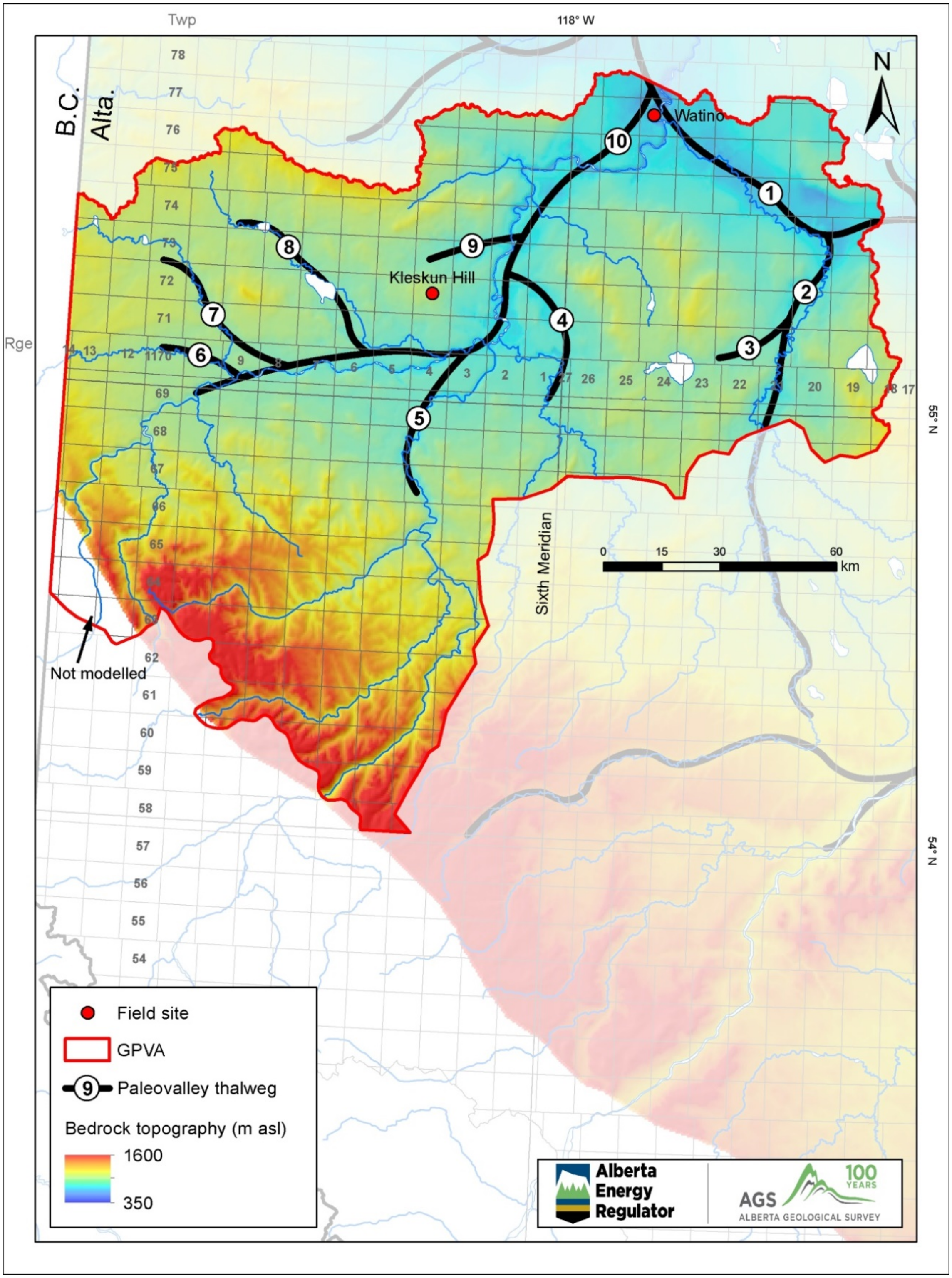

Figure 9. Bedrock topography in the Grande Prairie–Valleyview area (GPVA; from Alberta Geological Survey, 2020a), northwestern Alberta, and buried paleovalley thalwegs (modified from Andriashek, 2018) including 1) High Prairie valley, 2) Valleyview valley, 3) Stump valley, 4) Misery valley, 5) Tolstad valley, 6) Diamond valley, 7) Wembley valley, 8) Grande Prairie valley, 9) Kleskun valley, and 10) Bezanson valley.

3.2.2 Cross-Section Analysis and Model Construction

Hydrostratigraphic unit top picks were made in cross-section in Earthfx Inc.'s VIEWLOG software, and stored in the lithological database. Picks were imported into RockWare Inc.'s RockWorks software to interpolate grids of the upper surfaces of regional hydrostratigraphic units using inverse distance weighting (IDW). The model was built from the base (top of bedrock / bottom of stratigraphically lowest Neogene–Quaternary hydrostratigraphic unit) up to ensure that onlapping units did not cross over underlying units. The grids were then truncated by the bedrock topography grid and land surface DEM. Hydrostratigraphic unit grids were reimported into VIEWLOG and edited via Boolean logic grids. The main objective of this editing was to remove interpolation artifacts, grid components that were considered to be outliers or otherwise erroneous, and grid components that had an area below the resolution of the model.

3.3 Hydrogeology

The hydrostratigraphic model provided the framework for hydrogeological characterization within the GPVA. The development of the model included

1) assigning water wells to hydrostratigraphic units based on completion depths (screen intervals), where information was available;
2) interpolating hydraulic head and producing decadal potentiometric surfaces, which enabled the assessment of regional water level fluctuations over time;
3) estimating vertical hydraulic head gradient and groundwater flow potential, which can be used to infer potential recharge/discharge locations; and
4) plotting groundwater chemistry data to understand groundwater evolution paths and compare with groundwater age dating analysis in the region (Smerdon, 2019; Smerdon et al., 2019).

3.3.1 Water Well Assignment

As of January 2019, there were 15 108 water well records in the AWWID for the GPVA. Of these, 5379 well records provided completion information including water level, well depth, and well screen information; these wells were used for analyzing potentiometric surfaces and potential groundwater flow directions. An additional 3735 records (9114 wells total) provided only well depth and water level information and were used to supplement the groundwater chemistry analysis. Out of the 9114 well records, 1043 records included the full suite of major ions and only 241 of these had screen information.

Well screen information includes upper and lower screen depths. For wells with multiple screens, the screen interval includes the uppermost depth of the shallowest screen and the lowest depth of the deepest screen. The elevation of the ground surface at well locations was extracted from the provincial 25 m DEM (Alberta Environment and Parks, 2015b) and was used to calculate the elevations of the well bottoms, water levels, and screen interval tops and bottoms. For wells with completion information and a litholog upon which hydrostratigraphic picks were made, the top/bottom elevations of the screen intervals were assigned to hydrostratigraphic units based on corresponding hydrostratigraphic picks in the lithological database (discussed in Section 3.2.1). For wells with completion information but without a litholog, hydrostratigraphic assignments were made based on intersections of screen intervals with modelled hydrostratigraphic units (3D hydrostratigraphic surface elevation grids). Lithological assignments at the top/bottom of screen intervals facilitated identification of well screens that bridge units.

3.3.2 Potentiometric Surface

Potentiometric surface maps provide information on lateral hydraulic head gradients and groundwater flow potential. To augment the regional hydraulic head mapping of the Wapiti / Belly River hydrostratigraphic unit by Singh and Nakevska (2019; Figure 6), hydraulic head within the GPVA was analyzed over several decades. Wells completed in bedrock and water levels of major perennial rivers (extracted from the DEM; Alberta Environment and Parks, 2015b) were analyzed. Potentiometric surfaces were created using the Topo to Raster function in Esri's ArcGIS, which is an interpolation method similar to inverse distance weighted interpolation and creates hydrologically correct DEMs. The potentiometric surfaces are provided on a decade-by-decade basis enabling the evaluation of water level fluctuations over time. The decades examined include 1980–1989 (921 wells), 1990–1999 (1321 wells), 2000–2009 (1721 wells), and 2010–2018 (943 wells).

3.3.3 Vertical Hydraulic Head Gradient

Vertical hydraulic head gradients indicate groundwater flow potential in the vertical direction, which can then be used to infer the recharge/discharge potential. Following a similar approach to Atkinson et al. (2017), two methods were used to map vertical gradients: 1) a tomographic-like approach (e.g., Tóth and Almási, 2001), and 2) determination of the vertical gradient on a township-by-township and section-by-section basis (Alberta Township System [ATS]). The first approach interpolates data continuously, whereas the second approach aggregates all available data within a township and a section. Both methods require well screen depth information and well location within a legal subdivision (LSD; 2068 wells).

For the first approach, potentiometric surfaces were interpolated using hydraulic head measurements at mid-screen depths, in 20 m depth intervals from land surface; this interval is large enough to contain a sufficient number of wells for interpolation, but small enough to determine meaningful vertical gradients. The difference between two potentiometric surfaces from specified depth intervals reveals the locations of upward or downward vertical gradients. However, evaluation of a true gradient would require division by the distance between the two units (e.g., 20 m). The difference between the two (interpolated) potentiometric surfaces is a residual, which may have high uncertainty where data is sparse, so care must be taken when interpreting the results.

The second approach is resolved upon the ATS grid and provides assessments of vertical gradient on a township-by-township and section-by-section basis. Within a township or section, hydraulic head versus mid-screen elevation was plotted for all wells that could be located within an LSD. The slope of the linear best-fit line through these points is representative of the vertical gradient: positive slopes indicate downward flow potential and negative slopes indicate upward flow potential. Steeper line slopes indicate larger gradients. Coefficient of determination (R^2) gives an indication of the goodness of fit of the best-fit line. Low R^2 values indicate data that does not strongly follow a linear hydraulic gradient trend. Conversely, high R^2 values indicate a strong linear trend in the data. Only townships and sections with more than two wells and an R^2 greater than 0.6 were included in the vertical gradient analysis.

3.3.4 Groundwater Chemistry

Groundwater chemistry was evaluated in RockWorks and plotted on a piper diagram to provide a better understanding of the chemical composition and potential groundwater evolution paths within the GPVA. Concentrations of all major ions including Ca, Mg, Na, K, SO_4, HCO_3, CO_3, and Cl were required for this analysis. The complete suite of ion concentrations was recorded from samples recovered from only 1043 wells. Twenty-one of these wells are completed in surficial deposits, 220 are completed in bedrock, and 802 wells do not report screen information.

4 Results of Geological Modelling

The 3D hydrostratigraphic model of the GPVA includes bedrock units extracted from the GFA v3 (Alberta Geological Survey, in progress, 2020; Section 2.3) superposed by Neogene–Quaternary units modelled during this study (Section 4.2). The interface between bedrock and Neogene–Quaternary units is the bedrock topography. This topographic surface records erosional events such as episodic fluvial incision and lateral planation, which can provide context for understanding the stratigraphy of overlying Neogene–Quaternary units. Furthermore, the relative height of the bedrock topography is a major control on the type of and total thickness of Neogene–Quaternary units, as discussed below.

4.1 Bedrock Topography and Sediment Thickness

Physiographic interpretation of bedrock topography is essential for understanding the stratigraphy of the overlying Neogene–Quaternary hydrostratigraphic units and their subsurface relationships with the underlying bedrock. Identifiable physiographic features such as eroded uplands, fluvial planation surfaces, and buried valleys inform the stratigraphy of overlying coarse-grained units, which may otherwise be indistinguishable based only on lithological descriptions from drillers' logs.

The bedrock topography of the GPVA (Figure 9) largely mimics the land surface topography and descends from 1575 m asl in the Grande Cache Benchlands (Figure 2) to 365 m asl below the Smoky River at the study area boundary in the northeast. Uplands and benchlands are underpinned by bedrock that is higher in both elevation and relief than that below plains and lowlands.

The step-form architecture of the landscape, resulting from episodic fluvial incision and lateral planation (described in Section 2.4.1), is discernible in the bedrock topography of the study area. However, in contrast to areas to the north and south of the study area (Tokarsky, 1967; Vonhof, 1969; Edwards and Scafe, 1996; Hartman and Clague, 2008; Atkinson and Hartman, 2017; Hartman and Slomka, 2017; Slomka et al., 2018), higher fluvial planation surfaces in the GPVA are difficult to resolve. Potentially, the lack of thick caps of large-calibre gravel upon these surfaces left them unprotected and more susceptible to erosion than adjacent gravel-capped surfaces. Alternatively, fluvial planation surfaces in the GPVA, being carved by second order ancestral rivers (e.g., ancestral Smoky and Little Smoky rivers), may not have been as extensive as those carved by primary ancestral rivers (e.g., ancestral Peace and Athabasca rivers to the north and south of the study area, respectively).

Four planation surfaces can be delineated in the study area and are numbered one through four, in order of decreasing relative topographic height and presumed age (Figure 10). The step-form architecture of the bedrock and delineation of individual planation surfaces is important for characterizing overlying coarse-grained units, which may have been deposited after each planation surface was excavated. As such, coarse-grained units overlying different planation surfaces could comprise discrete hydrostratigraphic units due to spatial and temporal differences in their deposition.

The floors of all buried valleys identified in the study area are associated with the lowest (no. 4) planation surface (Figure 10). Buried valleys form a dendritic network, which likely represents the regional drainage system immediately prior to its disruption by Laurentide glaciation in the Late Wisconsinan (Westgate et al., 1971, 1972; Liverman, 1989; Catto et al., 1996; Slomka and Utting, 2017). The elevations of the floor of the High Prairie valley (Figure 10) and Shaftesbury valley at their confluence 30 km beyond the northeastern boundary of the study area (cf. Slomka and Hartman, 2019; Slomka et al., 2018) are consistent at approximately 400 m asl. This observation supports the inference that the High Prairie valley and its tributaries within the study area were, in turn, tributaries of the Shaftesbury valley. With the exception of up to 100 m of incision by the modern drainage network, relief of the no. 4 planation surface is low.

The no. 3 planation surface includes benches adjacent to buried valleys (Figure 10), with an average relative topographic height of 40 m above the valleys (Figure 10). The terrace-like morphology of the no. 3 planation surface suggests that it may constitute the floors of a fluvial system that predated the fluvial system that formed the buried valleys. The relief of the no. 3 planation surface is relatively low. Buried valleys and adjacent benches (nos. 4 and 3 planation surfaces) largely underlie the Peace River Lowland physiographic section (Pettapiece, 1986; Figure 2) within the study area.

The no. 2 planation surface (Figure 10) occurs at an average relative topographic height of 110 m above the no. 3 planation surface and is the most extensive in the study area. It largely underlies the Wapiti Plains physiographic section (Pettapiece, 1986; Figure 2). At up to 65 km wide, the no. 2 planation surface is plateau-like in form. Although still relatively subdued, relief within the no. 2 planation surface is higher than that of the nos. 3 and 4 planation surfaces suggesting that it has undergone more extensive erosion and dissection.

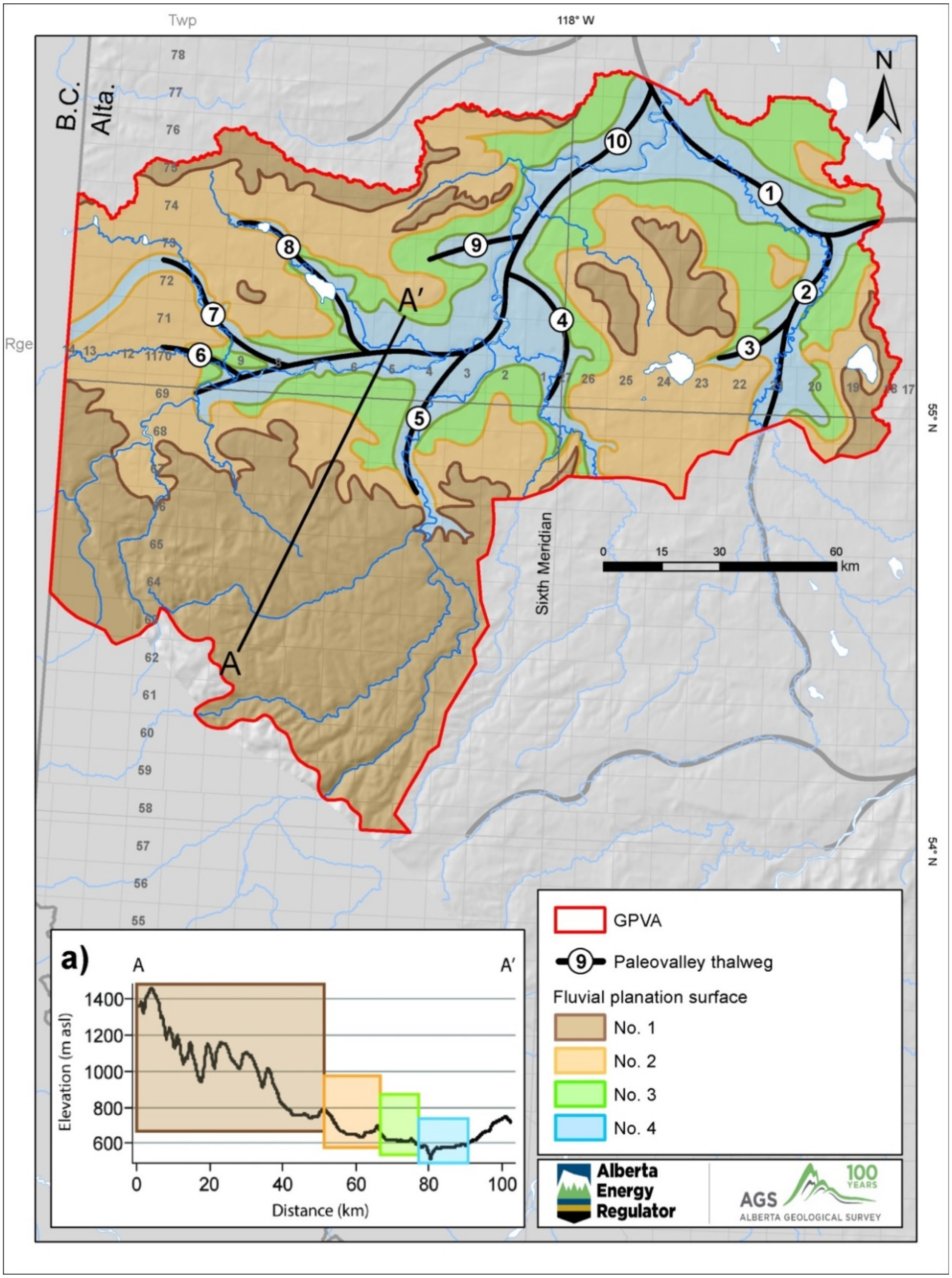

Figure 10. Fluvial planation surfaces in the Grande Prairie–Valleyview area (GPVA), northwestern Alberta, and buried paleovalley thalwegs (modified from Andriashek, 2018) including 1) High Prairie valley, 2) Valleyview valley, 3) Stump valley, 4) Misery valley, 5) Tolstad valley, 6) Diamond valley, 7) Wembley valley, 8) Grande Prairie valley, 9) Kleskun valley, and 10) Bezanson valley. Line A–A′ corresponds with bedrock topographic profile A–A′ (inset a). Fluvial planation surfaces are generalized and include eroded areas and intervening transitional slopes between surfaces. Hill-shaded relief based on bedrock topography grid (Alberta Geological Survey, 2020a).

The no. 1 planation surface (Figure 10) largely underpins benchland and upland physiographic sections (Pettapiece, 1986; Figure 2), which bound the study area. The no. 1 planation surface occurs at an average relative topographic height of 250 m above the no. 2 planation surface, but has been heavily eroded and dissected. Consequently, relief is high and the planar character of this surface has been almost completely erased, especially in the northern and eastern parts of the study area. Its designation as a fluvial planation surface is supported by the occurrence of fluvial gravel upon flat-topped hills and ridges that are interpreted to be erosional remnants of a formerly extensive fluvial plain. However, it is possible that parts of the no. 1 planation surface have a genesis other than fluvial planation.

Mean sediment thickness in the study area is 30 m. However, sediment is unevenly distributed (Figure 11). The thinnest sediment generally overlies the highest bedrock, such as in the Grande Cache Benchlands, where exposed bedrock is not uncommon. The thickest sediment (up to 220 m) overlies buried valleys in the lowlands. Despite thick sediment cover in lowland areas, bedrock may be exposed in steep valley walls where the modern drainage system has incised into bedrock. For example, bedrock exposures are common adjacent to outside bends of the Smoky River below its confluence with the Wapiti River where the modern river does not superpose a buried valley.

4.2 Neogene–Quaternary Hydrostratigraphy

Neogene–Quaternary deposits (nonlithified sediments overlying bedrock) were classified into informal hydrostratigraphic units (Table 1) based on lithology, stratigraphic position, depositional setting, and topographic position relative to the bedrock topography (Figures 9 and 10) and the modern land surface (Figure 1). Hydrostratigraphic units from the bottom up include basal coarse-grained sediments (HSU1), fine-grained glaciogenic sediments (HSU2), surficial coarse-grained sediments (HSU3), and organic sediments (HSU4). Of these, only HSU1 and HSU2 could be modelled in 3D at the scale of the study area. HSU3 and HSU4 could be locally identified on cross-sections, but could not be rendered in 3D due to an insufficient number of intersections of these units in the lithological database.

Table 1. Neogene–Quaternary hydrostratigraphic units (HSU), Grande Prairie–Valleyview area, northwestern Alberta.

Hydrostratigraphic Unit	Mappable (at Regional Scale)	Generalized Unit Description
HSU1	Yes	Coarse-grained sediments (dominantly sand and gravel) overlying bedrock and underlying other HSUs. Typically fluvial or glaciofluvial genesis. Preglacial, interglacial, or early last (Late Wisconsinan) glaciation in age.
HSU2	Yes	Fine-grained (dominantly silt and clay) sediments. May overlie bedrock or HSU1. Typically glacial or glaciolacustrine genesis. Last glaciation in age.
HSU3	No	Coarse-grained sediments (dominantly sand and gravel) exposed at surface. May overlie bedrock or other HSUs. Typically fluvial or glaciofluvial genesis. Late glacial or Holocene in age.
HSU4	No	Organic sediments exposed at surface. May overlie bedrock or other HSUs. Holocene in age.

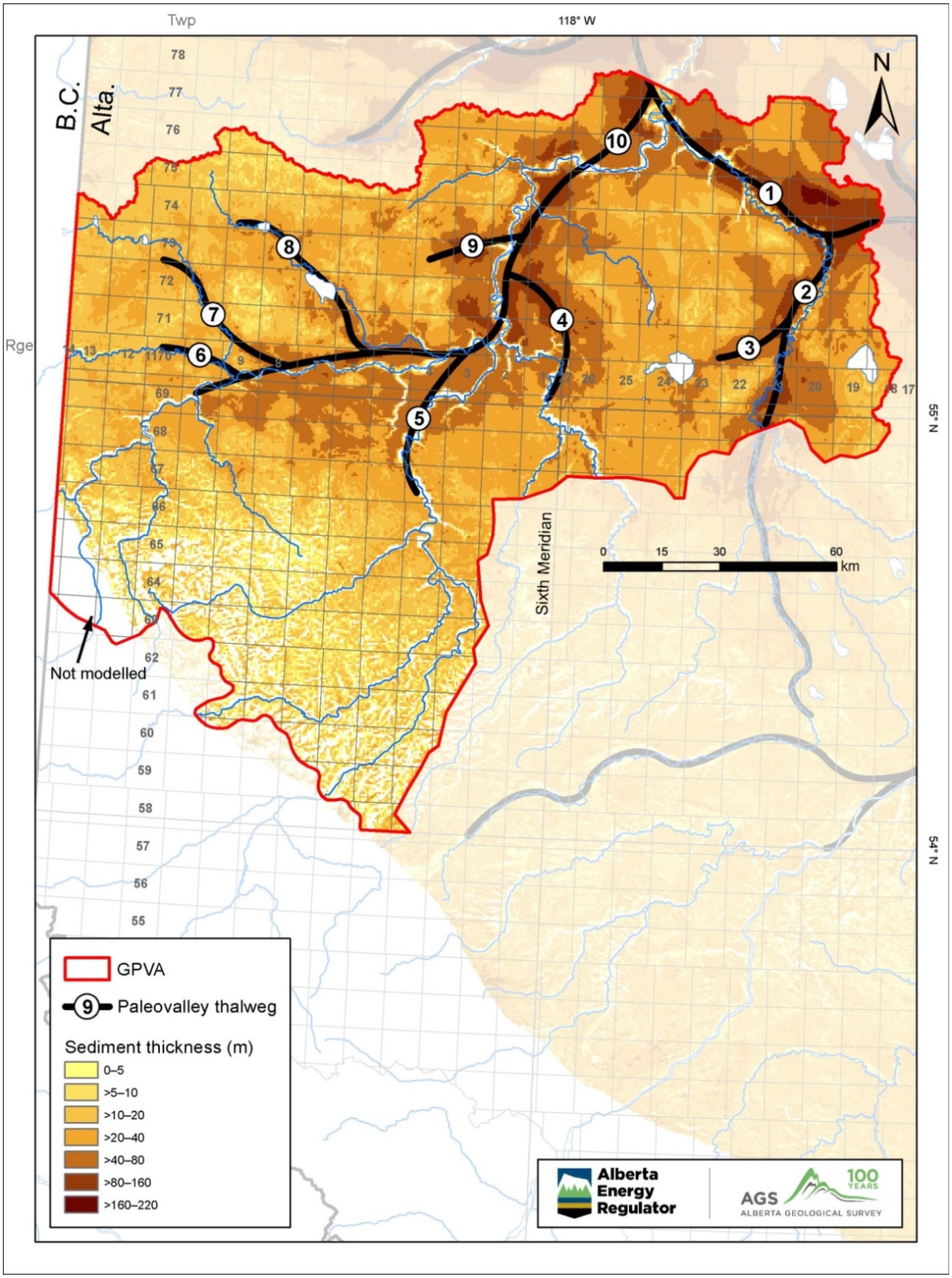

Figure 11. Sediment thickness in the Grande Prairie–Valleyview area (GPVA; from Alberta Geological Survey, 2020b), northwestern Alberta, and buried paleovalley thalwegs (modified from Andriashek, 2018) including 1) High Prairie valley, 2) Valleyview valley, 3) Stump valley, 4) Misery valley, 5) Tolstad valley, 6) Diamond valley, 7) Wembley valley, 8) Grande Prairie valley, 9) Kleskun valley, and 10) Bezanson valley.

4.2.1 HSU1: Basal Coarse-Grained Sediments

Basal coarse-grained sediments of HSU1 (Figure 12) overlie bedrock and are, in turn, typically overlain by fine-grained sediments of HSU2. Descriptions of HSU1 from exposures such as the Watino section (Westgate et al., 1971, 1972; Liverman, 1989; and this study) indicate that it may be composed of massive to crudely bedded clast- to matrix-supported gravel or massive to horizontally bedded sand. At the Watino section in particular, where much of the High Prairie valley infill sequence can be observed in an approximately 60 m tall exposure, 4 m of basal gravel grades upwards into sand (approximately 2 m thick), which is sharply overlain by laminated clay and silt (incorporated in HSU2). Clast lithologies observed within HSU1 at Watino include quartzite (up to cobble size), chert (up to pebble size), and some concretions and local bedrock fragments. Clast shape is dominantly round to subround. Sand, either in lenses in the gravel unit, within the matrix of the gravel unit, or in the sand units, is composed of quartz, chert, mica, and lithic fragments. The absence of granite-gneiss clasts (derived from the Canadian Shield) in the gravel portion of HSU1 at Watino indicates that it was deposited prior to the Late Wisconsinan Laurentide glaciation (Westgate et al., 1971, 1972; Liverman, 1989; Catto et al., 1996).

The distribution of HSU1 is strongly associated with the step-form fluvial planation surfaces described in Section 4.1 (Figures 10 and 12). The distribution, as well as the stratigraphic position of HSU1 (at the base of the Neogene–Quaternary sequence), suggests that much of the unit was likely deposited by the same fluvial systems that excavated the planation surfaces. HSU1 may also have been deposited as glacial outwash in pre-existing valleys (Liverman, 1989). In some rare cases, the advance-phase glaciolacustrine deposits that overlie HSU1 in buried valleys (Slomka and Utting, 2017) are sand-dominated and thus difficult to differentiate from HSU1 based on lithological descriptions. As such, and because of presumed hydraulic connectivity between the two deposits, the sand component of the glaciolacustrine stratigraphic unit is incorporated within HSU1. The well-established stratigraphy at Watino (Westgate et al., 1971, 1972; Liverman, 1989; Catto et al., 1996) suggests that those parts of HSU1 that are composed of glacial outwash or advance-phase glaciolacustrine sediments are Late Wisconsinan in age whereas those that are composed of fluvial gravel, within which exotic clasts derived from the Canadian Shield have not been found, are pre–Late Wisconsinan in age.

HSU1 deposits that overlie the floors of buried valleys and adjacent benches (no. 4 and 3 planation surfaces) were modelled as a single subunit (HSU1-low) due to the close spatial association of these planation surfaces and their similarly low topographic position in the landscape (Figure 10). HSU1 deposits that mantle the no. 1 and 2 planation surfaces were incorporated in a single subunit (HSU1-high) based on their similarly high topographic positions. However, due to wider distribution and more extensive erosion of these units they are, in places, spatially distal. As outlined in Section 2.4.1, the relative age of fluvial planation surfaces and the fluvial units that overlie them correspond with their relative topographic height. Consequently, HSU1-low stratigraphically overlies HSU1-high, and was modelled to onlap that unit even though its relative topographic height is lower.

Both HSU1-high and HSU1-low are widespread but discontinuous across the no. 2, 3, and 4 planation surfaces (Figures 10 and 12). The distribution may reflect nondeposition or erosion of the unit. Certainly, the many logs in the lithological database in which HSU1 is not present indicate that its distribution is variable. However, the discontinuous distribution of HSU1 is also, in part, a function of the modelling process. In particular, the HSU1 top elevation grids were truncated by the land surface DEM and bedrock topography grids, and subsequently edited by a Boolean logic grid to eliminate areas where 1) the grid contained obvious errors and artifacts, 2) the data did not support the presence of HSU1, or 3) a body of HSU1 had an area of less than 100 ha and thus was not considered mappable at the scale of this study. Only isolated occurrences of HSU1-high are found on the no. 1 planation surface (Figures 10 and 12).

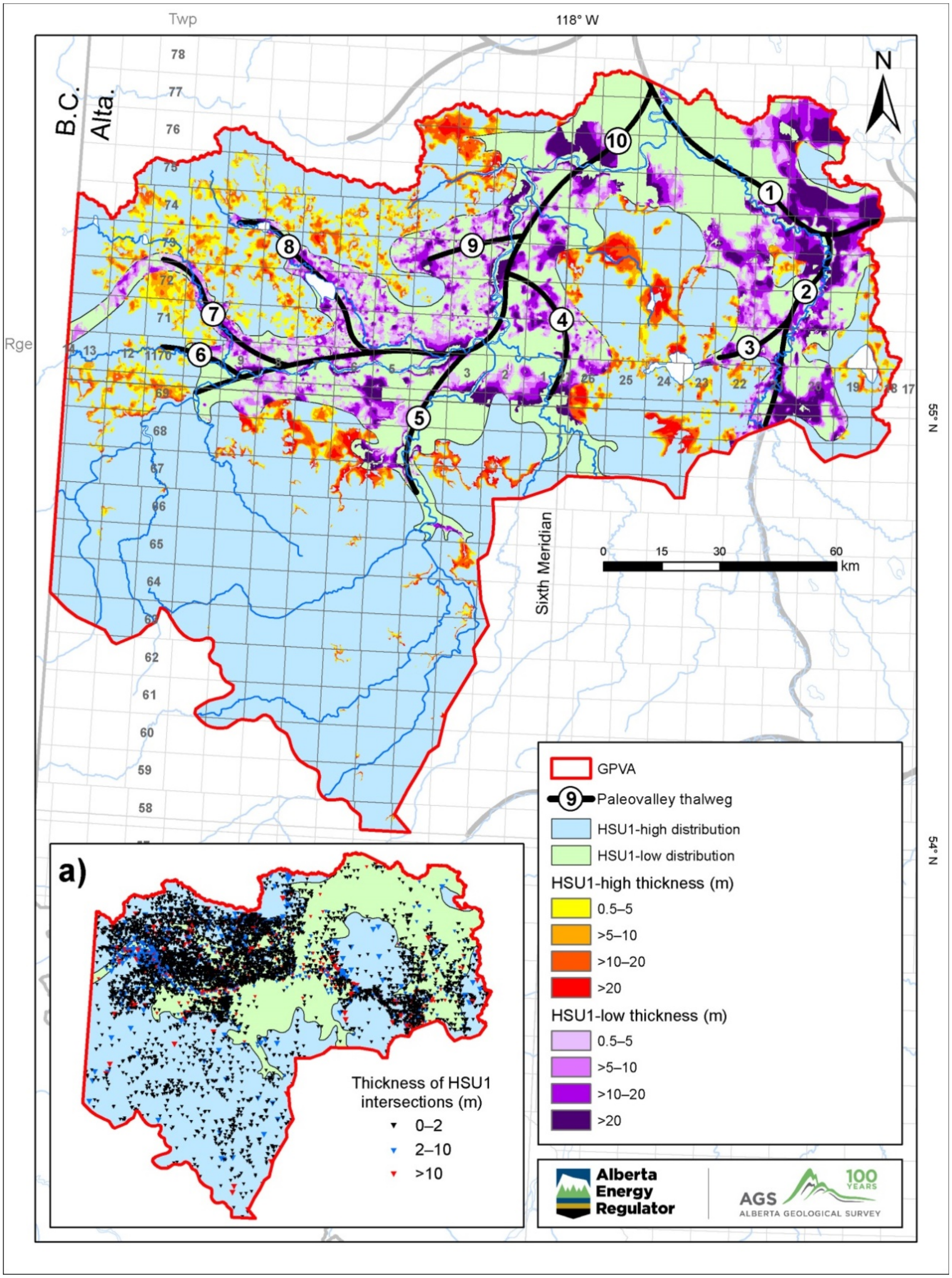

Figure 12. Isopach map of hydrostratigraphic unit (HSU) 1-high and HSU1-low from grid interpolation, Grande Prairie–Valleyview area (GPVA), northwestern Alberta, and buried paleovalley thalwegs (modified from Andriashek, 2018) including 1) High Prairie valley, 2) Valleyview valley, 3) Stump valley, 4) Misery valley, 5) Tolstad valley, 6) Diamond valley, 7) Wembley valley, 8) Grande Prairie valley, 9) Kleskun valley, and 10) Bezanson valley. Inset a) Thickness of HSU1 intersections in the lithological database.

The maximum and mean thicknesses of HSU1-high intersections in boreholes assembled in the lithological database are 49 and 6.2 m, respectively, whereas the maximum and mean thicknesses of HSU1-low are 97 and 8.8 m, respectively (Figure 12, inset a). The maximum and mean thicknesses of HSU1-high calculated from its isopach grid (Figure 12) are 70 and 1.6 m, respectively, whereas the HSU1-low isopach grid indicates that maximum and mean thicknesses of that subunit are 120 and 5.9 m, respectively. The maximum and mean thickness values for each HSU1 subunit calculated from borehole intersections are considered more reliable than values calculated from the interpolated grids as uncertainty inherent in the modelling process (discussed in Section 6.2) may affect thickness values represented by the isopach grids; especially in areas where data density and/or quality is low (Figure 8).

The greater maximum and mean thicknesses of HSU1-low as compared to HSU1-high are, in part, a function of amalgamation of sand-dominated parts of the overlying advance-phase glaciolacustrine sediments within HSU1-low. The greater mean thickness of HSU1-low may also reflect lower net erosion of the unit due to its relatively young geological age and the erosion protection provided by overlying advance-phase glaciolacustrine sediments, which were deposited within the same buried bedrock valleys and adjacent benches (nos. 4 and 3 planation surfaces) in which HSU1-low is found. Also, HSU1-high's position below glacial till suggests that a portion of that subunit may have been eroded during glaciation.

4.2.2 HSU2: Fine-Grained Glaciogenic Sediments

Fine-grained glaciogenic sediments of HSU2 are dominantly fine-grained glacial tills and glaciolacustrine deposits that were distributed across the study area during Laurentide and Cordilleran glaciation (Liverman, 1989; Fenton et al., 2013; Atkinson et al., 2016; Slomka and Utting, 2017; Figure 13). The amalgamation of at least two till and two glaciolacustrine stratigraphic units into a single hydrostratigraphic unit is a gross oversimplification of Neogene–Quaternary stratigraphy in the study area. However, from a hydrostratigraphic perspective, the dominantly fine-grained matrix material of these units, irrespective of their genesis, differentiates them from the dominantly coarse-grained HSU1 and HSU3, which may underlie or overlie them, respectively.

A further oversimplification of the lithology of HSU2 was the incorporation of coarse-grained intervals within the otherwise dominantly fine-grained unit. These intervals may represent lenses, thin interbeds, or other discontinuous bodies of coarse-grained sediments within the glaciolacustrine and till sequence that could not be modelled due to scale limitations and the irregular presence and/or elevation of coarse-grained intervals between boreholes. Intersections of coarse-grained intervals within HSU2 have been flagged in the lithological database (intra-HSU2 coarse-grained sediments; Figure 13).

Modelling HSU2 required only the subtraction of the combined HSU1-high and HSU1-low isopach grids from the total Neogene–Quaternary sediment isopach grid (calculated by subtracting the bedrock topography grid from the land surface DEM). This procedure ignored the presence of HSU3; however, as outlined below, there were too few intersections of HSU3 in the lithological database to facilitate modelling that unit in 3D. The resulting isopach grid indicates that HSU2 ranges from 0 to 220 m thick, with a mean thickness of 28 m (Figure 13). HSU2 intersections in the lithological database indicate that the maximum and mean thicknesses of HSU2 are 230 and 28 m, respectively (Figure 13, inset a). There is a discrepancy between maximum HSU2 thicknesses derived from grid interpolations and those measured in borehole intersections, however, thickness values measured in borehole intersections are considered more reliable due to uncertainties inherent in the modelling process (discussed in Section 6.2).

HSU2 is thickest in buried valleys that were successively occupied by glacial lakes (Slomka and Utting, 2017; Figure 5); these valleys were buried beneath thick deposits of glaciolacustrine sediment, as well as till. Conversely, HSU2 upon benchlands and uplands (Figure 2), at elevations above glacial lake shorelines, is generally less than 20 m thick. Many areas of exposed bedrock occur in these areas.

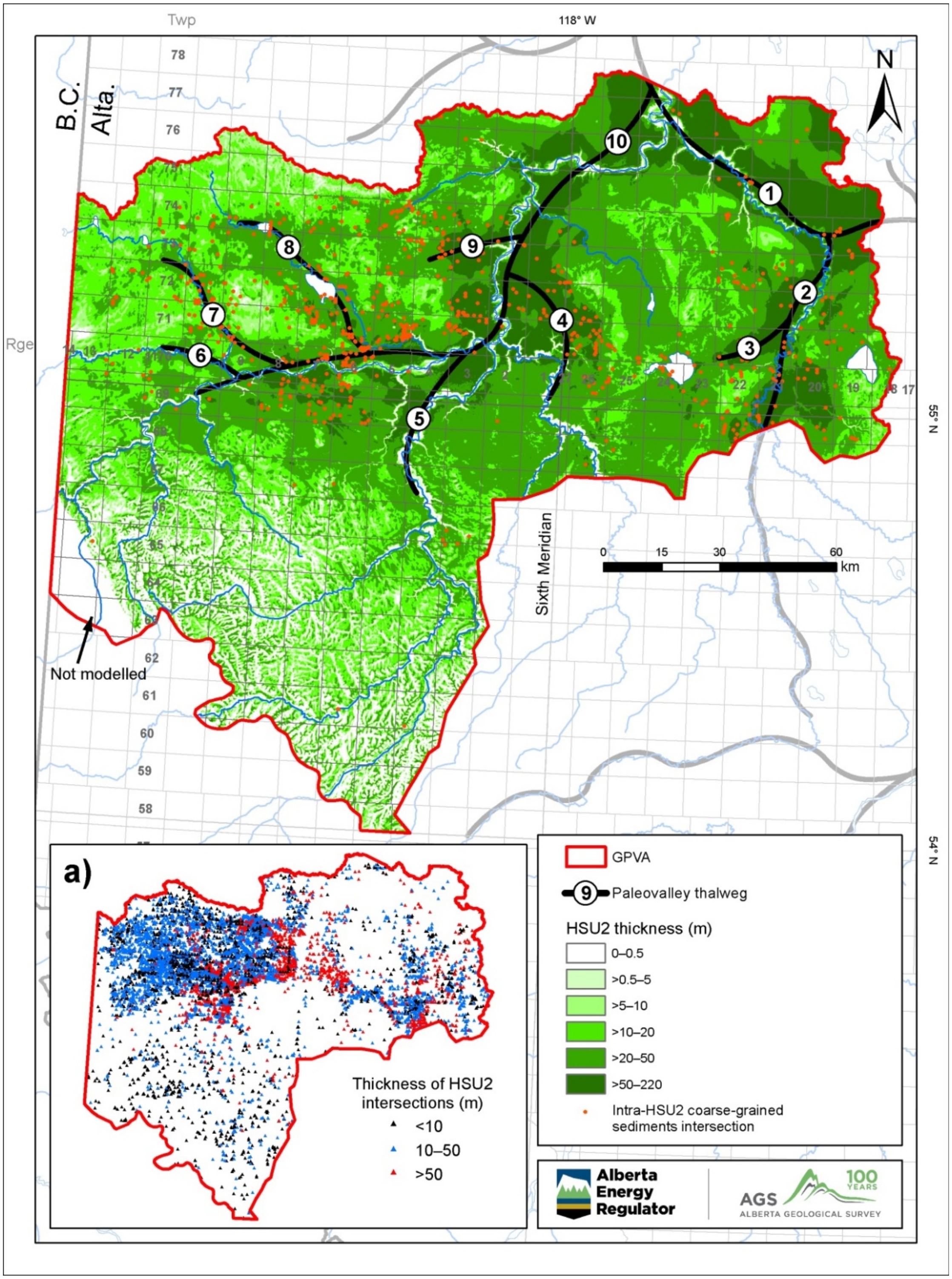

Figure 13. Isopach map of hydrostratigraphic unit (HSU) 2 (from grid interpolation) and intersections of coarse-grained intervals within HSU2 (locations posted as orange dots) in the Grande Prairie–Valleyview area, northwestern Alberta, with buried paleovalley thalwegs (modified from Andriashek, 2018) including 1) High Prairie valley, 2) Valleyview valley, 3) Stump valley, 4) Misery valley, 5) Tolstad valley, 6) Diamond valley, 7) Wembley valley, 8) Grande Prairie valley, 9) Kleskun valley, and 10) Bezanson valley. Inset a) Thickness of HSU2 intersections in the lithological database.

4.2.3 HSU3: Surficial Coarse-Grained Sediments

Surficial coarse-grained sediments of HSU3 include sand and/or gravel deposits that are exposed at surface. Too few HSU3 intersections (only 631; Figure 14) were identified in the lithological database to model this unit in three dimensions throughout the study area. However, previous surficial mapping (compiled in the provincial-scale surficial geology mosaic by Fenton et al., 2013) shows the distribution of surficial genetic units, from which the distribution of surficial coarse-grained units were reinterpreted by Pawley et al. (2015).

Within the study area, Pawley et al. (2015; Figure 14) indicate that surficial coarse-grained sediments consist of fluvial, glaciofluvial, eolian (e.g., sand dunes), and some nearshore glaciolacustrine deposits. For the most part, glaciofluvial and nearshore glaciolacustrine deposits are located where uplands or benchlands meet the plains adjacent to major river valleys. Conceivably, glaciofluvial sediment was transported along these valleys and deposited on the plains due either to occupation of the plains by a glacial lake, or flow expansion and velocity reduction as rivers spilled out onto the plains. Another area of glaciofluvial deposition is on the high terraces along major modern rivers such as the Wapiti and Smoky. Lower terraces and floodplains, which were established after glaciation, are mantled by fluvial coarse-grained deposits. Extensive eolian sand dune fields are found across the central lowlands and plains.

Although the intersections of HSU3 in the lithological database are too few to model the unit in 3D, they do provide thickness information. The maximum thickness of HSU3 is 74 m whereas its mean thickness is 8 m (Figure 14).

4.2.4 HSU4: Organic Deposits

There were too few intersections of HSU4 (organic deposits consisting of undifferentiated peat) in the lithological database (only one) to model the unit in 3D. However, organic deposits are common in the study area where they overlie poorly drained materials such as clay-rich glaciolacustrine or till deposits (Fenton et al., 2013; Figure 5).

5 Results of Hydrogeological Characterization

Hydrogeological characterization of the GPVA includes the assignment of wells to hydrostratigraphic units (Section 5.1), decadal potentiometric surface (hydraulic head) mapping (Section 5.2), mapping of vertical hydraulic gradients (Section 5.3), and analysis of groundwater chemistry within each hydrostratigraphic unit (Section 5.4).

5.1 Well Assignment

The assignment of water well screen intervals to hydrostratigraphic units indicates which units are being used for groundwater production. Water level, well depth, and screen depth information is available for 5379 wells in the GPVA. The spatial distribution of the unit intersected by the screen top in the GPVA is provided in Figure 15. Of the 5379 wells, only 224 wells are completed exclusively in Neogene–Quaternary sediment, 5117 wells are exclusively completed in bedrock, and the screens of the remaining 38 wells bridge bedrock and one or more overlying Neogene–Quaternary units.

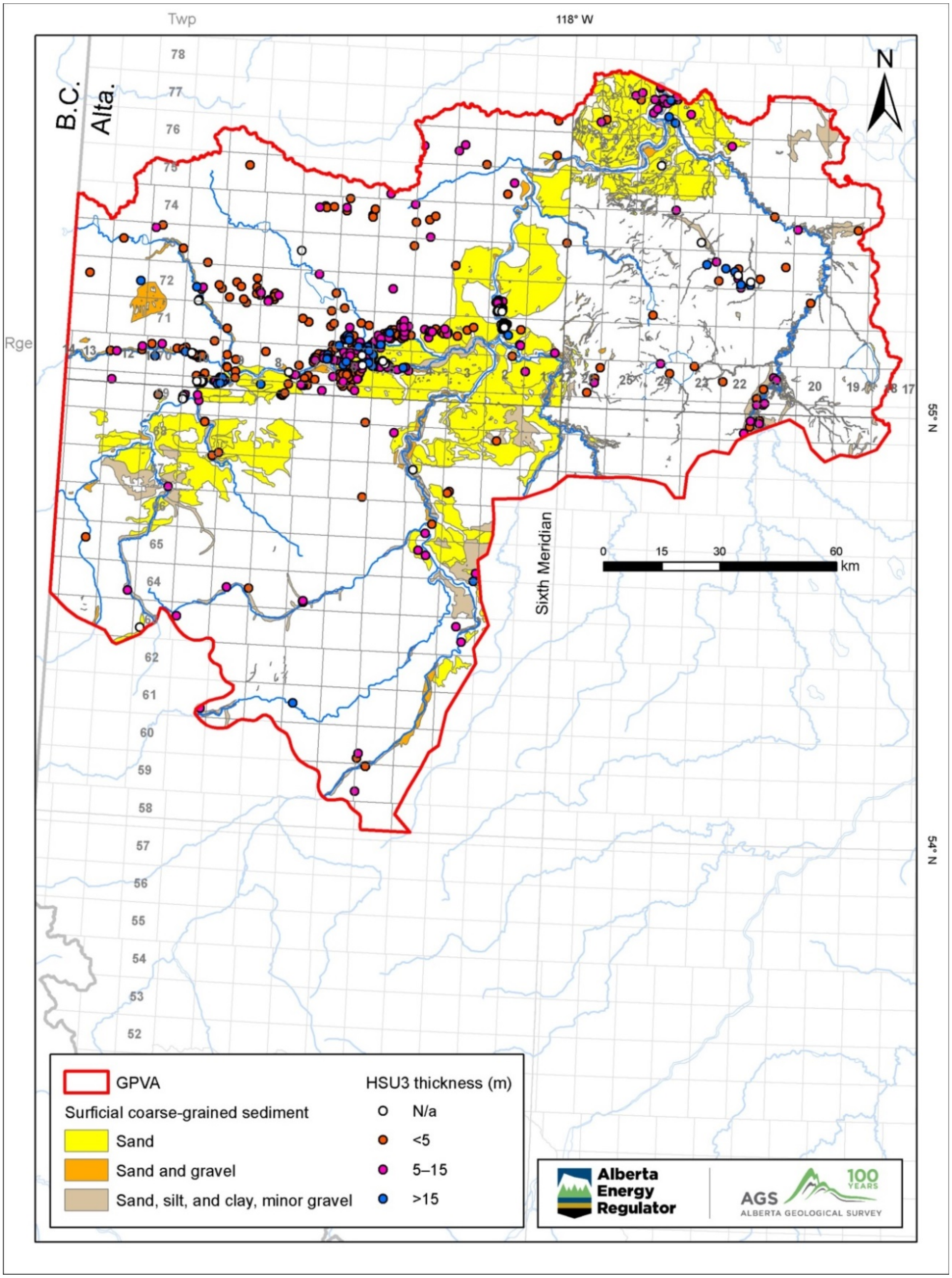

Figure 14. Location and thickness of hydrostratigraphic unit (HSU) 3 intersections in the lithological database and surficial coarse-grained sediments mapped in the Grande Prairie–Valleyview area (GPVA), northwestern Alberta (from Fenton et al., 2013, and modified by Pawley et al., 2015).

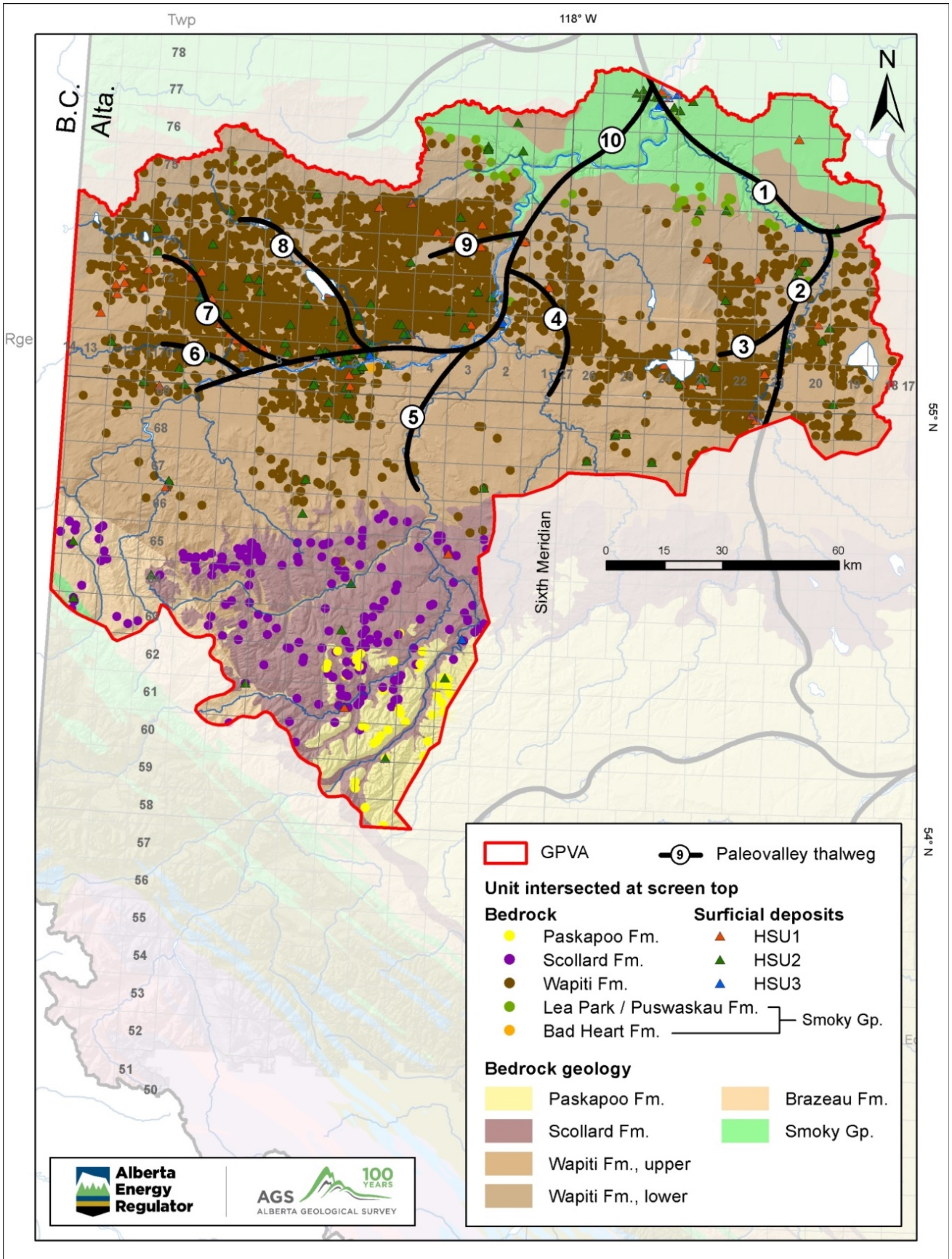

Figure 15. Hydrostratigraphic unit (HSU) intersected at water well screen top for wells with screen depth information (5379 wells) in the Grande Prairie–Valleyview area (GPVA), northwestern Alberta, with bedrock geology (from Prior et al., 2013) and buried paleovalley thalwegs (modified from Andriashek, 2018) including 1) High Prairie valley, 2) Valleyview valley, 3) Stump valley, 4) Misery valley, 5) Tolstad valley, 6) Diamond valley, 7) Wembley valley, 8) Grande Prairie valley, 9) Kleskun valley, and 10) Bezanson valley.

The distribution of wells completed in HSU1 (55 wells) or bridging HSU1 and bedrock (9 wells) show a spatial association with buried valleys, especially west of Grande Prairie along the buried Wembley valley (Figure 15). However, wells completed in HSU1 are also present in plains and uplands (Figures 2 and 12). Importantly, even within buried valleys where HSU1 is relatively thick (Figure 12), wells penetrate Neogene–Quaternary units to access groundwater sourced from underlying bedrock units. Wells completed exclusively within HSU2 (160 wells), bridging HSU2 and bedrock (28 wells), or bridging HSU2 and HSU1 (3 wells) are commonly associated with buried valleys, especially south of Grande Prairie along the Bezanson and Grande Prairie buried valleys (Figure 13). The six wells completed in HSU3 are associated with mapped surficial coarse-grained deposits including eolian dunes and fluvial deposits (Figures 5 and 14). The one well with a screen that bridges all units including HSU3, HSU2, HSU1, and bedrock is located east of Grande Prairie in the Bezanson valley.

The distribution of wells completed in bedrock indicates that all subcropping bedrock units are used for groundwater production in the GPVA (Figure 15). For the most part, wells are completed within the uppermost bedrock unit. However, some exceptions occur near the mapped boundaries of bedrock units where, presumably, the uppermost unit is thin and may be fully penetrated by a well. Alternatively, uncertainty inherent in the bedrock modelling process (discussed in Section 6.1) or in the well location (discussed in Section 6.3) may affect the assignment of hydrostratigraphic units to well screen intervals, especially near the top or bottom of bedrock unit grids. The distribution of water well screens (Figure 15) and the distribution of all water wells (Figure 8), including those for which screen depth information is not available (3735 wells), indicates that there are few areas where bedrock units are not used for groundwater production. Potentially, one area where bedrock units are not used is the subcrop of the mud-dominated marine Smoky Group. Wells completed in this unit occur mainly at the top of the unit (near the mapped boundary between the Smoky Group and overlying Wapiti Formation; Figure 15). Further north where lower portions of the Smoky Group constitute the uppermost bedrock, water wells have been installed, but screen information is unavailable (Figure 8). These wells may be completed in bedrock, or they may be completed in the thick sediment infill of the High Prairie and Bezanson buried valleys, which overlies bedrock in this area (Figure 11). An examination of hydrostratigraphic picks made on water wells in the High Prairie and Bezanson buried valleys shows that many wells terminate above bedrock indicating that screens, if installed, could only intersect Neogene–Quaternary units.

5.2 Potentiometric Surface

Potentiometric surface maps were created for four decades, starting with the 1980s. Each potentiometric surface shows high values in the southwestern part of the GPVA and low values in the northeastern part, indicating consistent groundwater flow in a general northeastward direction, following the topographic trend of the landscape. The most recent data (2010–2018) are shown in Figure 16. In order to compare water levels over time, water levels were extracted from each decadal potentiometric surface at seven point locations in the northern half of the GPVA (Figure 17). These point locations were placed in data dense areas within the GPVA (typically in close proximity to urban areas; Figure 17) to reduce the uncertainty of the interpolated potentiometric surface for each decade. Water levels near Grande Prairie and west of Smoky River remain stable over the four decades. East of Smoky River, water level remains constant from the 1960s to 2000s, but within the last decade there is a decrease of about 20 m. Near Wembley, water levels decrease about 15 m over time. At Sturgeon Lake and Valleyview, water levels vary over time and both show an overall increase of 15 m. Water level at Beaverlodge consistently increases with a 30 m difference over time.

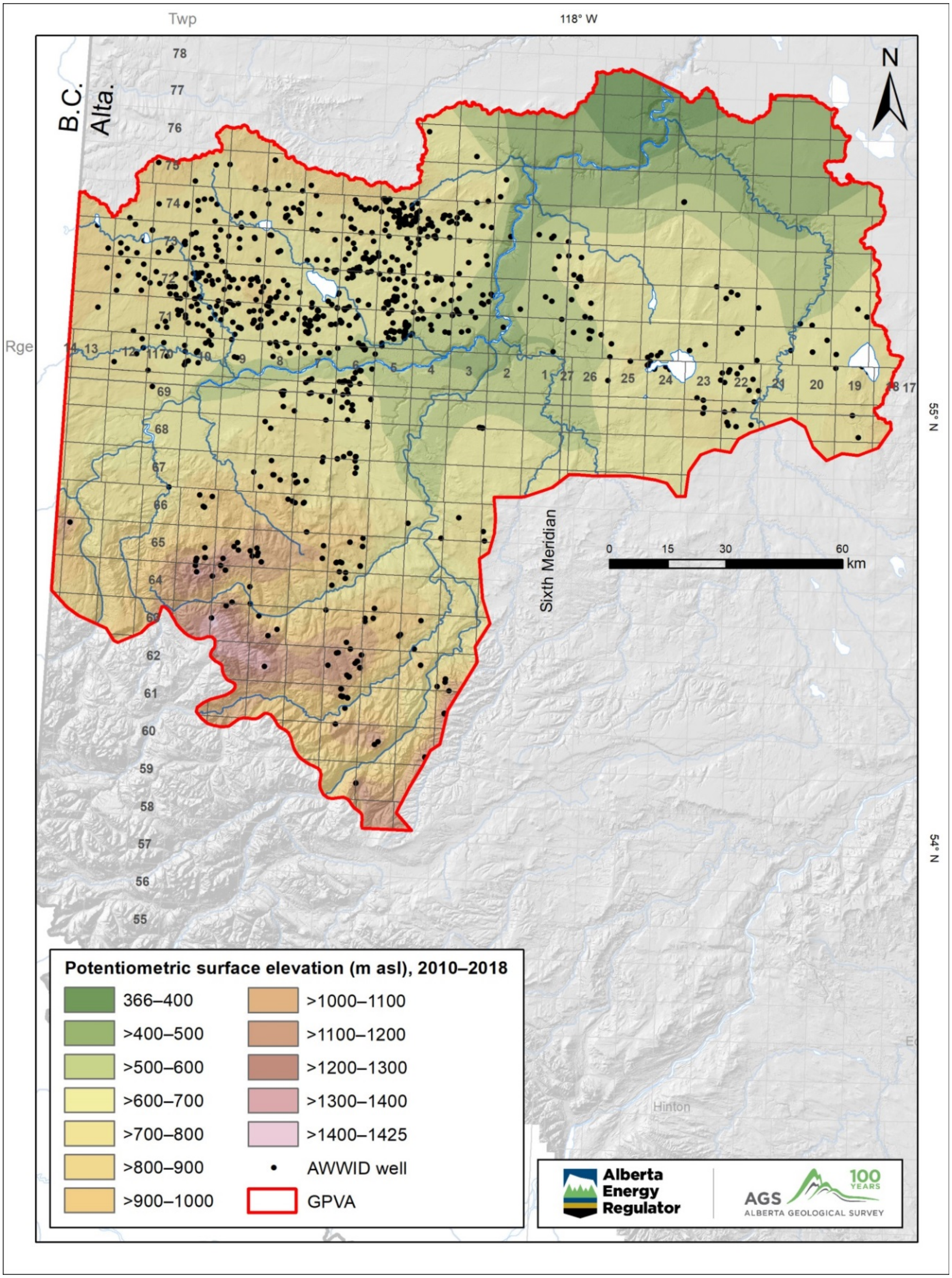

Figure 16. Potentiometric surface in the Grande Prairie–Valleyview area (GPVA), northwestern Alberta (2010–2018). Hill-shaded relief based on digital elevation model (Alberta Environment and Parks, 2015b). Abbreviation: AWWID, Alberta Water Well Information Database.

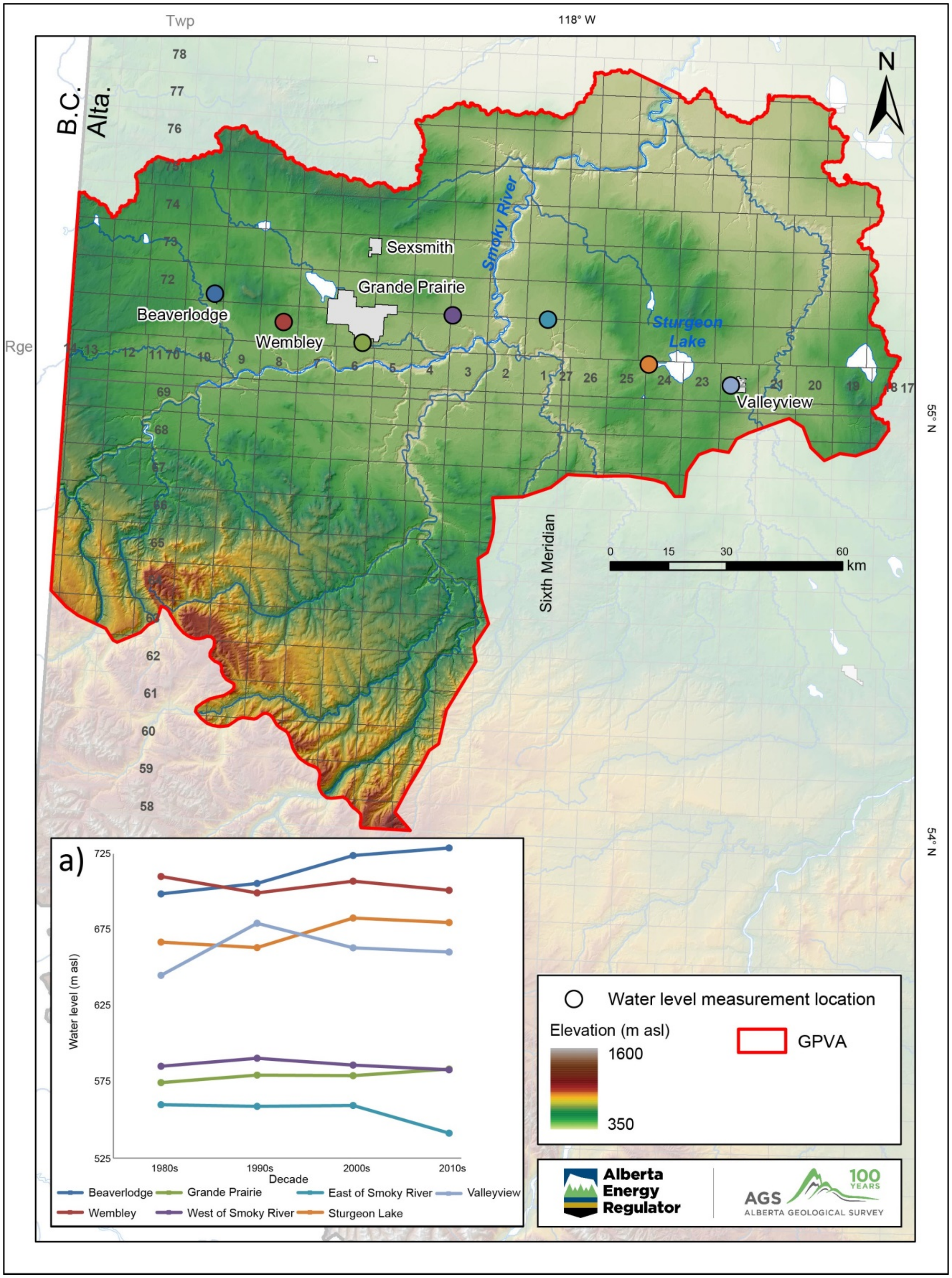

Figure 17. Locations where water levels were extracted from potentiometric surfaces for six decades from 1980–2018, Grande Prairie–Valleyview area (GPVA), northwestern Alberta. Inset a) Comparison of water levels for seven locations throughout the GPVA. Digital elevation model provided by Alberta Environment and Parks (2015b).

5.3 Vertical Hydraulic Head Gradients

Two assessments of vertical hydraulic gradient using the tomographic-like approach were conducted. The first shows the difference between potentiometric surfaces interpolated from wells with mid-screen depths between 21 to 40 m and 61 to 80 m (Figure 18) and the second shows the difference between potentiometric surfaces interpolated from wells with mid-screen depths between 41 to 60 m and 81 to 100 m (Figure 19). The resulting surfaces were clipped to areas of contiguous 2500 m buffers around wells to prevent subtraction of two interpolated surfaces from areas where data is sparse and the potentiometric surfaces are not well constrained.

The ATS approach assesses vertical gradient information from all wells within a township and section via a plot of hydraulic heads versus mid-screen elevations. The slope of the linear best-fit line through these data points represents the vertical gradient in that township or section (Figure 20). Within the GPVA, the vertical gradients in all but three townships show the potential for downward flow. Groundwater discharge is typically local in scale and directed towards surface waterbodies including lakes, rivers, streams, wetlands, and springs. These local areas are better captured by analysis of vertical gradients on a per-section basis (Figure 20).

The tomographic-like approach results were compared with the vertical gradient approach results, mapped at the section scale, and with spring locations (which indicate upward flow potential; Figure 21). The two approaches did not produce the exact same results; however, several areas correlate and may indicate potential areas of upward groundwater flow potential. These areas are located around Beaverlodge, west Grande Prairie, and just southwest of Sexsmith (Figure 21). It is important to note that these maps show only the potential for upward groundwater flow. Confirmation of upward flow at these locations would require additional field investigation.

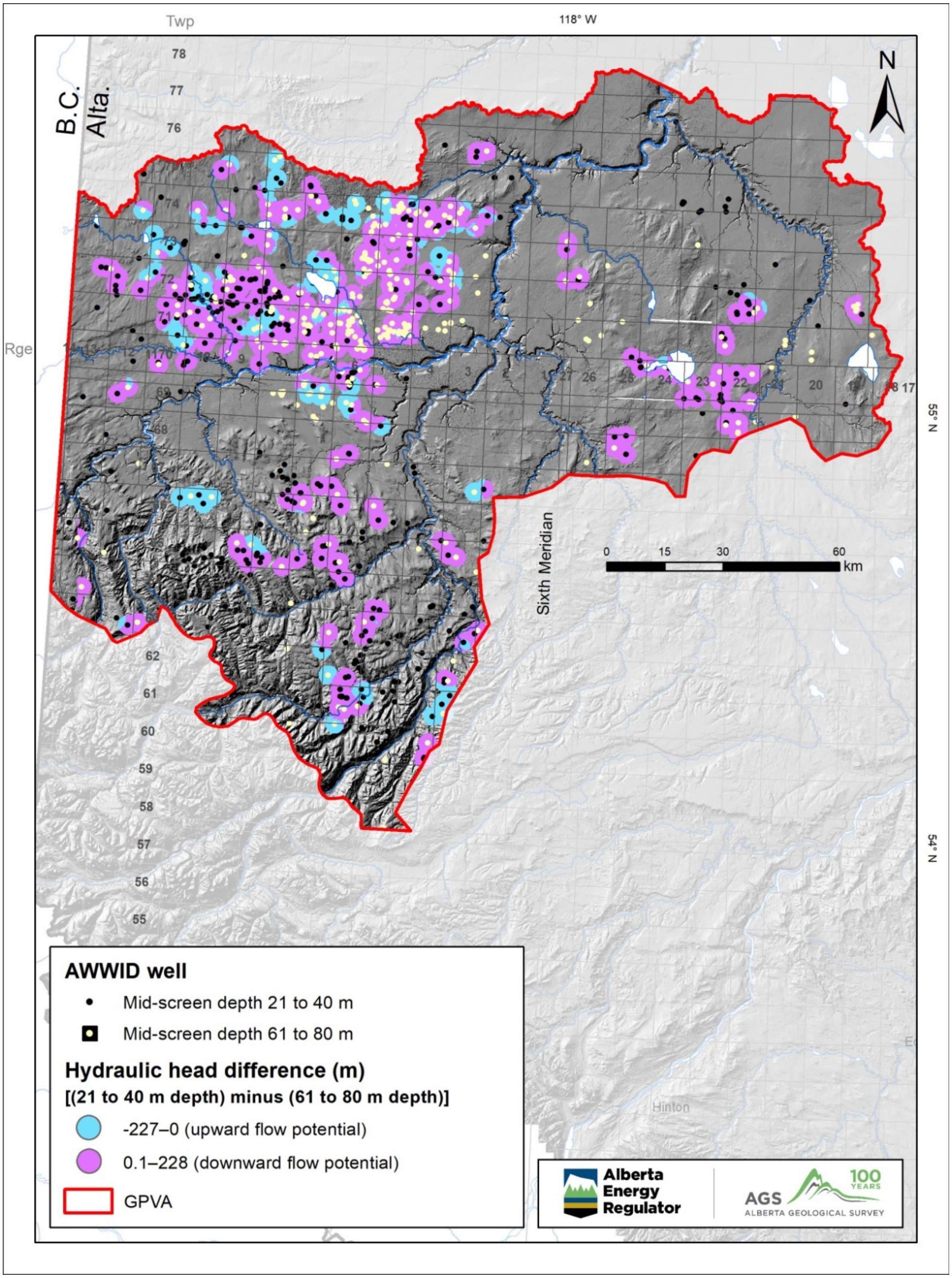

Figure 18. Hydraulic head difference between two potentiometric surfaces, one created at the 21 to 40 m depth interval and the other at 61 to 80 m depth interval, Grande Prairie–Valleyview area (GPVA), northwestern Alberta. Hill-shaded relief based on digital elevation model (Alberta Environment and Parks, 2015b). Abbreviation: AWWID, Alberta Water Well Information Database.

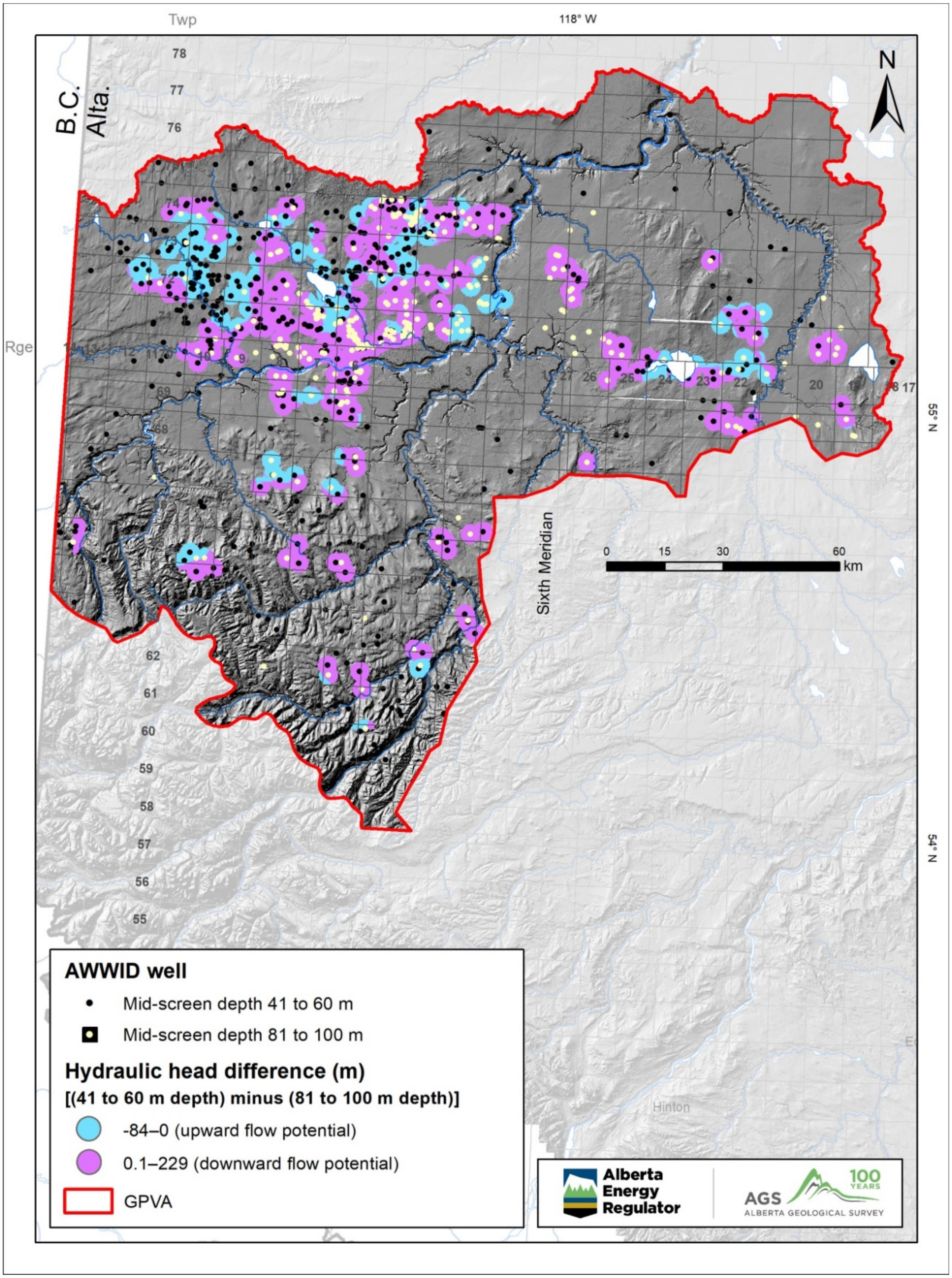

Figure 19. Hydraulic head difference between two potentiometric surfaces, one created at the 41 to 60 m depth interval and the other at 81 to 100 m depth interval, Grande Prairie–Valleyview area (GPVA), northwestern Alberta. Hill-shaded relief based on digital elevation model (Alberta Environment and Parks, 2015b). Abbreviation: AWWID, Alberta Water Well Information Database.

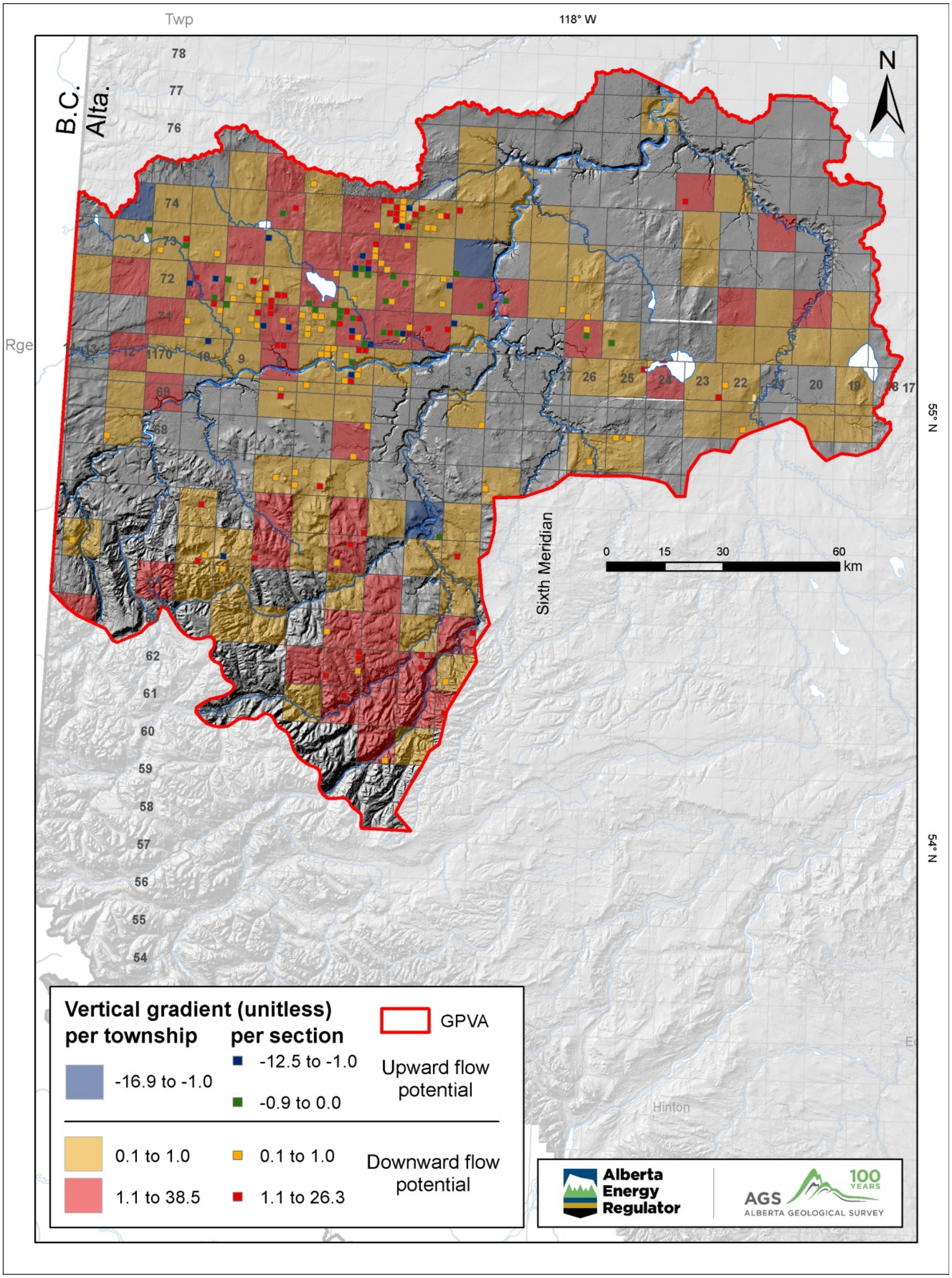

Figure 20. Vertical gradient at the township and section scale, Grande Prairie–Valleyview area (GPVA), northwestern Alberta. Hill-shaded relief based on digital elevation model (Alberta Environment and Parks, 2015b).

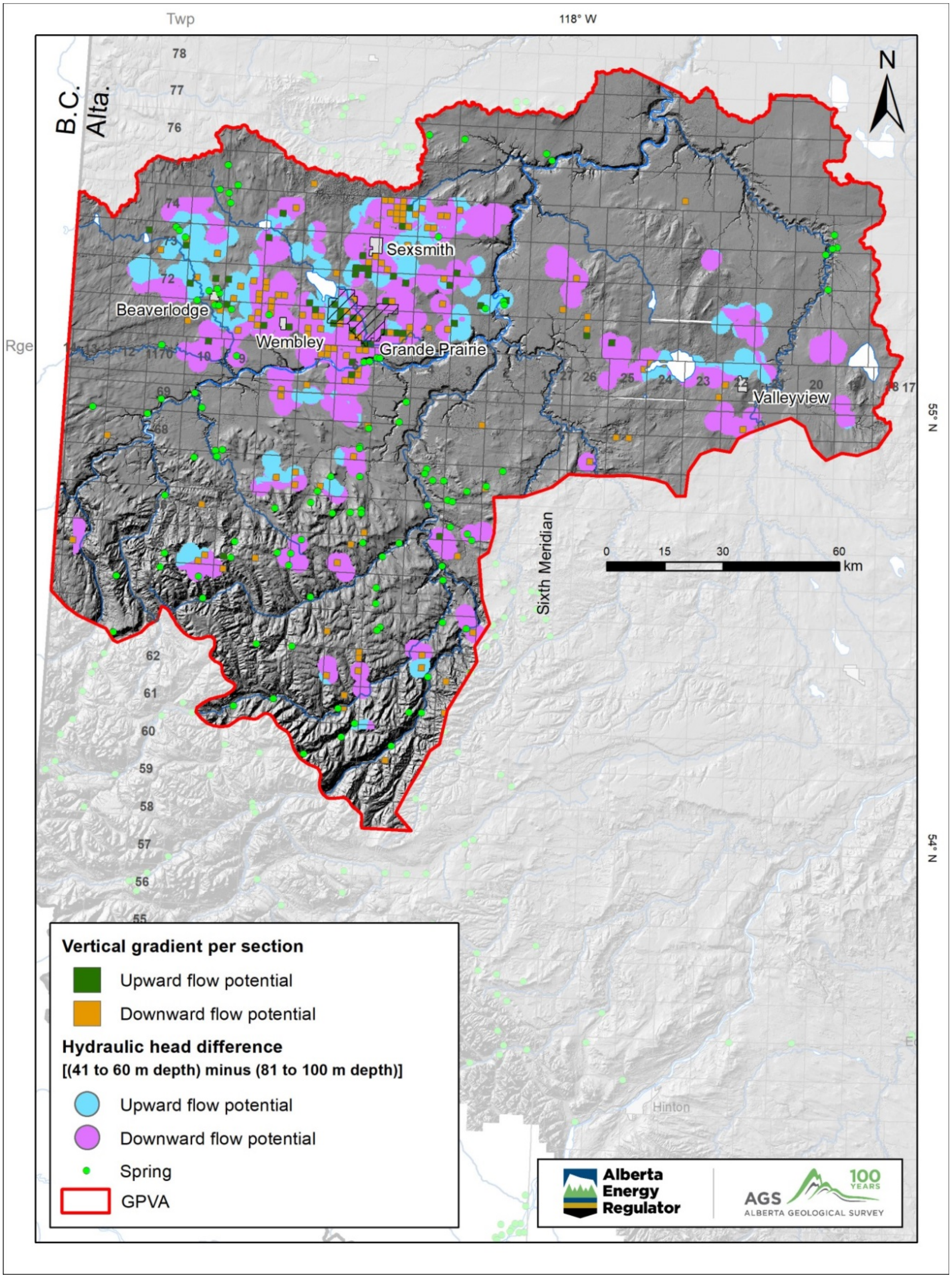

Figure 21. Comparison of vertical gradients from tomographic-like approach and Alberta Township System approach, Grande Prairie–Valleyview area (GPVA), northwestern Alberta. Springs from Stewart (2009). Hill-shaded relief based on digital elevation model (Alberta Environment and Parks, 2015b).

5.4 Groundwater Chemistry

Figure 22 shows a piper diagram that summarizes groundwater chemistry for each hydrostratigraphic unit based on wells with both screen information and full chemistry (241 wells). Figure 23 shows a piper diagram that summarizes groundwater chemistry based on wells without screen information (802 wells) and thus without knowledge of the hydrostratigraphic unit from which groundwater is sourced. Both plots show similar trends and indicate that groundwater samples in the GPVA are mixed from relatively young, fresh Ca-Mg-HCO_3–type waters (20% of samples) to more evolved Na-SO_4–type waters (80% of samples). Chemistry samples from wells with screen information showed similar trends between wells completed in HSU1 and HSU2 and wells completed in bedrock (Scollard, Lea Park, and Wapiti formations), potentially indicating hydraulic connectivity between Neogene–Quaternary and bedrock hydrostratigraphic units. Chemistry information for HSU3 was only available from one sample. This sample was characterized by fresh (Ca-Mg-HCO_3–type) water, which is expected as HSU3, being exposed at surface, typically receives recharge from precipitation or snowmelt (relatively young water).

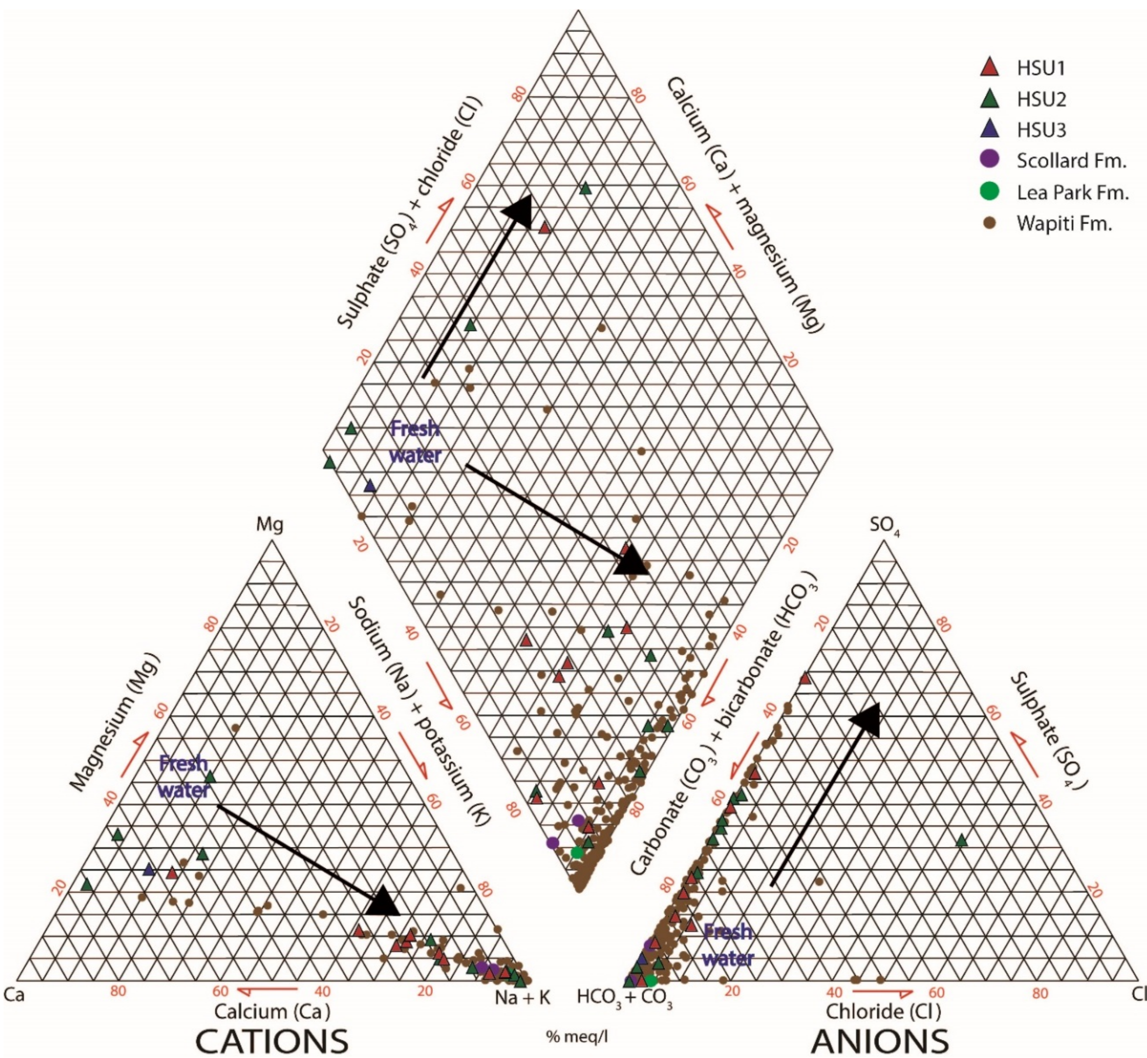

Figure 22. Piper diagram of groundwater chemistry of Grande Prairie–Valleyview area, northwestern Alberta. The source wells had screen information and were assigned to lithological units. Abbreviations: meq, milliequivalent; HSU, hydrostratigraphic unit.

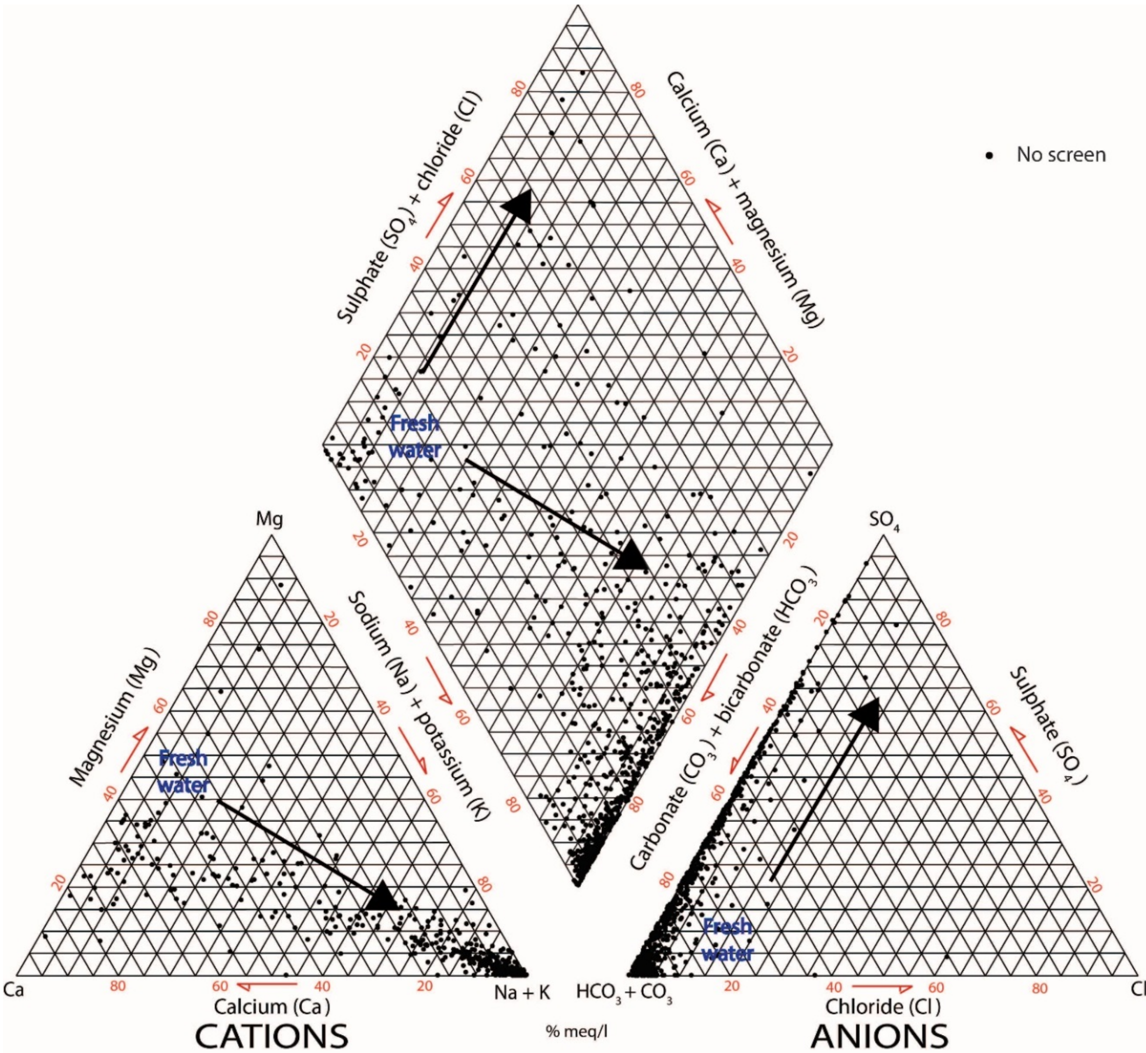

Figure 23. Piper diagram of groundwater geochemistry for Grande Prairie–Valleyview area, northwestern Alberta. The source wells did not have screen depth information and therefore not assigned to a lithological unit. Abbreviation: meq, milliequivalent.

6 Model Limitations and Uncertainty

Each major component of this study, including the bedrock geological model, the Neogene–Quaternary hydrostratigraphic model, and the regional hydrogeological characterization, are subject to limitations and uncertainty in the ability to understand and portray their characteristics. As each component uses different input data and analysis techniques, the limitations and uncertainty for each component differ and are described separately below.

6.1 Bedrock Geology

The limitations and uncertainty of the bedrock model in the GPVA are the same as those of its parent model, the GFA v3, and will be discussed in detail in the documentation of the parent model (Alberta Geological Survey, in progress, 2020). Notable limitations of the model include 1) structural features (such as faults) are not explicitly modelled, and 2) model zone erosional edges are simplified (vertical edges within the modelled area, as opposed to transitional areas or pinch-outs for example).

Uncertainty analysis is carried out as part of the GFA v3 workflow, and includes both a provincial uncertainty calculation as well as calculation of the local uncertainty of each 2D grid (Alberta Geological Survey, in progress, 2020). At the provincial level, global uncertainty is evaluated by calculating the root mean square error for each 2D grid. Local uncertainty is evaluated for each 2D grid by gridding a standard deviation map for each of the input 2D grids used for modelling. Data quality, data density, structural complexity, and geostatistical parameters are the main sources of uncertainty for the GFA v3 (Alberta Geological Survey, in progress, 2020).

6.2 Neogene–Quaternary Geology

The limitations and uncertainties inherent in the 3D characterization of Neogene–Quaternary sediments include, but are not limited to, 1) the scale and resolution of the model, 2) variability in the quality and distribution of input data, 3) modelling methodologies, 4) the stratigraphic conceptualization of the area, and 5) the translation of the conceptual stratigraphy to hydrostratigraphy, and finally into unit picks on cross-section.

The scale and geometry of the model area was selected to meet the project objective of mapping regionally significant hydrostratigraphic units in 3D. In addition, the units were selected to be compatible with adjacent project models to facilitate broader investigations that may be conducted in the future. As such, the resolution of hydrostratigraphic units is fairly simplistic compared to the number of stratigraphic units recognized in the literature (outlined in Section 2.4). Furthermore, two of the four hydrostratigraphic units picked on cross-sections (HSU3 and HSU4) could not be modelled due to insufficient data. However, one unit (HSU1) could be subdivided based on its relationship with the bedrock topography. The final top elevation and thickness grids satisfy the project objective by defining mappable, regionally significant hydrostratigraphic units in unconsolidated sediment. However, stratigraphic information remains unresolved at subregional scales.

A significant source of model uncertainty is inherent within the datasets upon which the model is based, and pertains to their distribution and quality as discussed in Section 3.2.1. Importantly, from the perspective of 3D model generation, the data is highly clustered (Figure 8). Model uncertainty is inversely related to data density, and thus large regions of the model are relatively unconstrained where data density is low. On average, there are 0.6 data points per km^2. However, data density ranges from 0 to 6 data points per km^2. The data density within 68% of the GPVA (16 710 km^2) is less than 0.5 points per km^2 (Figure 8).

Grid interpolation is an inevitable source of model uncertainty. The inverse distance weighting interpolation method was selected for grid interpolation of the tops of the HSU1-high and HSU1-low grids. This methodology calculates the value of a grid cell as the average of surrounding values weighted by their proximity to the cell in question. The resolved grid is a mathematical construction that may not reflect the features and relief of geological surfaces, especially where the relief of those surfaces is high and sample point density is low. Due to the limitations and uncertainty inherent within the data, inverse distance weighting (a relatively simple interpolation method) provided predictable results. In addition to uncertainty inherent in grid interpolation, the HSU1-high and HSU1-low grids were further manipulated by truncation by the land surface DEM and bedrock topography grids. These grids, being interpolations of datasets with a far greater data density, include relief that may not be represented in the HSU1-high and HSU1-low grids. The truncation process therefore introduces relief that portrays a more complex distribution of the HSU1 units than can be ascertained from borehole interception data alone.

The stratigraphic conceptualization of Neogene–Quaternary sediments in the study area, and the translation of that conceptualization into hydrostratigraphic picks on cross-sections are further sources of model uncertainty. Stratigraphic conceptualization is based on 1) previous investigations at various scales (summarized in Section 2.4), 2) field observations, and 3) the authors' assessment of the data compiled within this project. None of these sources of information are based on evenly distributed sampling or investigation of the study area and thus stratigraphic units are gross regional generalizations. The sediments encountered within any particular borehole may represent a different geological history than that of regional stratigraphic units depending on geological events that occurred at that location. In this study, intra-HSU2 coarse-grained sediments (Figure 13) provide an example of a unit that was not captured in the conceptual stratigraphy of the area and thus was not resolved as a hydrostratigraphic unit despite frequent intersections in boreholes. Presumably, intra-HSU2 coarse-grained sediments, although common in the study area, are local in extent and disconnected from one another. Thus they would not, in fact, represent a regional stratigraphic unit.

6.3 Hydrogeological Characterization

The assignment of well screen intervals to lithological units was based on 1) picks from the lithological database (3698 wells), or 2) grids from the bedrock and Neogene–Quaternary hydrostratigraphic models in wells where picks were unavailable or ambiguous (1681 wells). Because the grids are products of interpolation there is some uncertainty inherent in the assignment of the latter group of well screen intervals to lithological units. There were 543 wells with multiple screen intervals. In these cases, the assigned screen interval extended from the top of the upper screen to the bottom of the lower screen (discrete screens were not considered). This amalgamation of screen intervals may introduce uncertainty where water entering wells is derived from a single unit, but is assigned to multiple units.

Uncertainty is inherent in the decadal potentiometric surfaces and the vertical gradient estimates. As outlined in Section 3.3.2, water levels were extracted from decadal potentiometric surface grids in data dense areas to minimize the effects of incomplete decadal water level records in individual wells, and to minimize the effects of poorly constrained grids in areas where data is sparse. The vertical gradient (from a tomographic-like approach) grid was clipped to a contiguous 2500 m buffer around wells that were used in the two input surfaces. Grid clipping restricted the analysis to areas with sufficient data density to produce reliable estimates of vertical gradient.

7 Discussion

The distribution of water wells (Figure 8) and assignment of water well screens to hydrostratigraphic units (Section 5.1; Figure 15) indicates that overwhelmingly, bedrock units are used for groundwater production in the GPVA (95% of wells with screen information are completed in bedrock). With the possible exception of parts of the mud-dominated marine Smoky Group (discussed in Section 2.3), all bedrock units that subcrop within the GPVA are used for groundwater production. Relatively few wells are completed in Neogene–Quaternary units. Even within areas where small clusters of wells are completed in Neogene–Quaternary units, such as HSU1 within the Wembley valley (Figure 15), adjacent wells are completed in bedrock, or well screens bridge bedrock and overlying units.

Although all terrestrial bedrock formations that subcrop within the GPVA are used for groundwater production, lithological heterogeneity within and between formations suggests that they are not equally productive throughout the GPVA. For example, the lower Haynes and upper Dalehurst members of the Paskapoo Formation (Demchuk and Hills, 1991) have been characterized as sand-dominated aquifer zones (Haynes and Sunchild aquifers) whereas the mud-dominated middle Lacombe Member has been characterized as an aquitard, without implying a direct correlation between the lithostratigraphic members and informal hydrostratigraphic units (Lyster and Andriashek, 2012). Recent regional-scale property modelling of bedrock units underlying the west-central Alberta (WCAB) study area (Babakhani et al., 2019; Figure 1) identified potential aquifers (defined as zones in which the net-to-gross sand ratio exceeds 0.86) within the upper Paskapoo Formation and lower Wapiti Formation. In contrast to Demchuk and Hills (1991) and Lyster and Andriashek (2012), Babakhani et al. (2019) did not identify a Haynes Member–equivalent sand-dominated unit at the base of the Paskapoo Formation in the WCAB study area.

Property modelling (net-to-gross sand ratios) of bedrock units in the GPVA could potentially identify regional aquifers. However, it is noted that the distribution of water wells in the GPVA is correlated with settlement patterns (Figure 8) and does not appear to reflect strong geological control (i.e., there are no populated/developed areas with anonymously low well densities). This may indicate that economically productive wells can be installed in terrestrial bedrock units in the GPVA irrespective of broader regional sandiness trends. The lithological heterogeneity that characterizes terrestrial bedrock units (described in Section 2.3) suggests that sandstone bodies are present throughout terrestrial units. Sandstone bodies within broader mud-dominated units may be isolated and disconnected, or stacked, amalgamated, or otherwise interconnected. Permeable coal seams and impermeable bentonite layers further complicate the hydraulic characterization of bedrock units. Therefore, the productivity of any particular well may be a function of the number, size, and interconnectedness of sandstone bodies intercepted by the well (Figure 24).

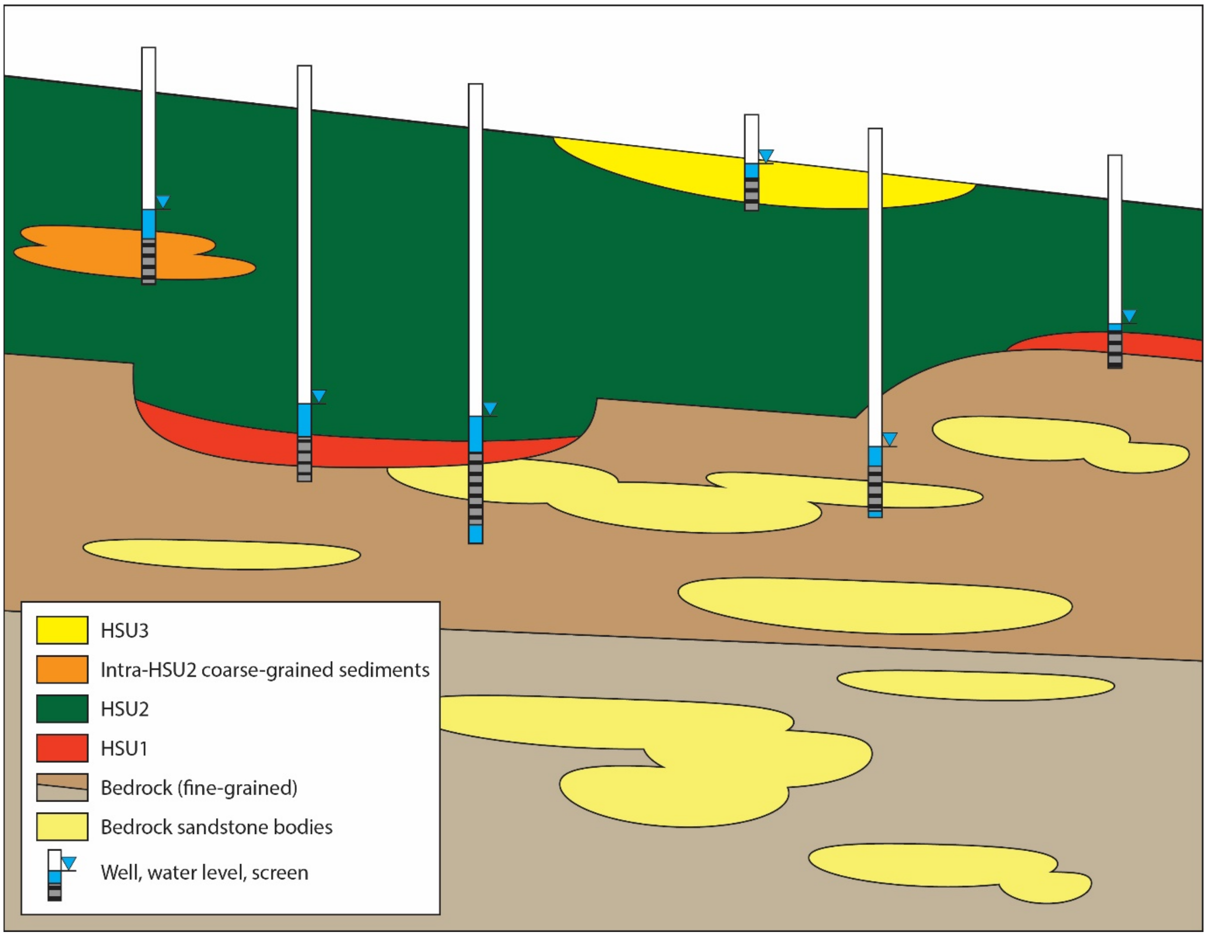

Figure 24. Schematic cross-section of aquifers within the Grande Prairie–Valleyview area (GPVA), northwestern Alberta, which includes interconnected and isolated permeable sandstone bodies surrounded by less permeable mudstone. Bedrock aquifers may be hydraulically connected to basal coarse-grained sediments (hydrostratigraphic unit [HSU] 1) in places. Isolated bodies of coarse-grained sediments (intra-HSU2 coarse-grained sediments) that occur within unconsolidated clay-rich overburden (HSU2) may also function as aquifers. Surficial coarse-grained sediments (HSU3) may function as local unconfined aquifers and recharge zones.

Throughout most of the study area, HSU1 is thin and discontinuous, which may render it difficult to target and unproductive as a water source. Although some wells are fully or partially completed in HSU1, adjacent wells are more often completed in underlying bedrock. Therefore, it may be useful to conceptualize HSU1 deposits as potentially hydraulically connected to bedrock aquifers (Figure 24). Conceptualization of HSU1 in this way is supported by groundwater chemical characterizations that show no difference between groundwater sourced from HSU1 or bedrock at a regional scale (Figure 22). Locally however, HSU1 may host independent or partially independent flow systems (areas A, B, and C on Figure 25) as discussed below. Coarse-grained units within HSU2 appear to be discontinuous and could not be evaluated in 3D at the scale of this study. Wells completed within HSU2 (160 wells) likely intercept these units, which may produce water locally (Figure 24). Very few wells are completed in HSU3 but the broad distribution of coarse-grained sediment at surface in the GPVA (Figure 14) suggests that it may function as an important regional conduit for recharge.

Figure 25 illustrates the spatial distribution and state of evolution of groundwater from all wells with groundwater chemistry in the GPVA (1043 wells). The state of evolution is correlated with groundwater age and is expressed as the relative concentration of sodium (Na) and potassium (K) in percent where high values indicate older more evolved $Na\text{-}SO_4$–type waters and low values indicate younger fresh $Ca\text{-}Mg\text{-}HCO_3$–type water. Approximately 80% of wells sampled produce older, more evolved $Na\text{-}SO_4$–type water (more than 80% Na and K). These wells largely coincide with the subcrop of the Wapiti Formation (Figures 4a and 25). Less evolved, intermediate groundwater (between 40% and 80% Na and K) near Beaverlodge River and Little Smoky River (areas A and C on Figure 25) indicate flow systems that are intermediate in relative length and residency time. Fresh, relatively young water (0–20% Na and K) near Wapiti River (area B on Figure 25) indicates a local flow system. These three areas coincide with relatively thick and continuous HSU1 deposits (Figure 12) where high relief elements are adjacent to modern and buried valleys (Figure 10). This suggests the flow systems are at least partially hosted within surficial hydrostratigraphic units and they recharge at higher elevations and discharge at lower elevations, including to springs and present-day rivers. Area B, which yields the freshest and youngest water in the study area, is also coincident with a large deposit of HSU3 (Figure 14), which likely acts as a conduit for recharge from surface.

The geological setting (illustrated in Figure 24), spatial distribution and state of evolution of groundwater from sampled wells (Figure 25), and potentiometric surface mapping (Figure 16) provide context for conceptualization of groundwater flow patterns in the GPVA, which include both regional and local flow systems (illustrated in Figure 26). At a regional scale, recharge occurs in elevated areas underlain by the Paskapoo Formation within and beyond the southern part of the GPVA and discharge occurs in low areas underlain by the Wapiti Formation in the central part of the GPVA. This inference is supported by estimated groundwater residence time based on isotopic analysis of groundwater samples conducted by Smerdon et al. (2019; per cent of modern carbon and helium-4) in the WCAB study area (to the south of the GPVA; Figure 1) and by Smerdon (2019; per cent of modern carbon) in the GPVA. In the WCAB study area, estimated groundwater residence time in the Paskapoo Formation is from 1000 to 10 000 years. By comparison, estimated groundwater residence time in the Wapiti Formation is greater than 30 000 years, and potentially closer to 100 000 years (Smerdon et al., 2019). Smerdon (2019) estimated the ages of groundwater samples recovered from three GOWN wells completed in the Wapiti Formation in the GPVA to be between 15 000 to 25 000 years BP (Figures 25 and 26). These older, more evolved groundwater samples are indicative of regional flow systems. One GOWN well completed in surficial deposits and sampled by Smerdon (2019; Figure 25) showed 95% of modern carbon, which is associated with younger water and indicative of a local flow system.

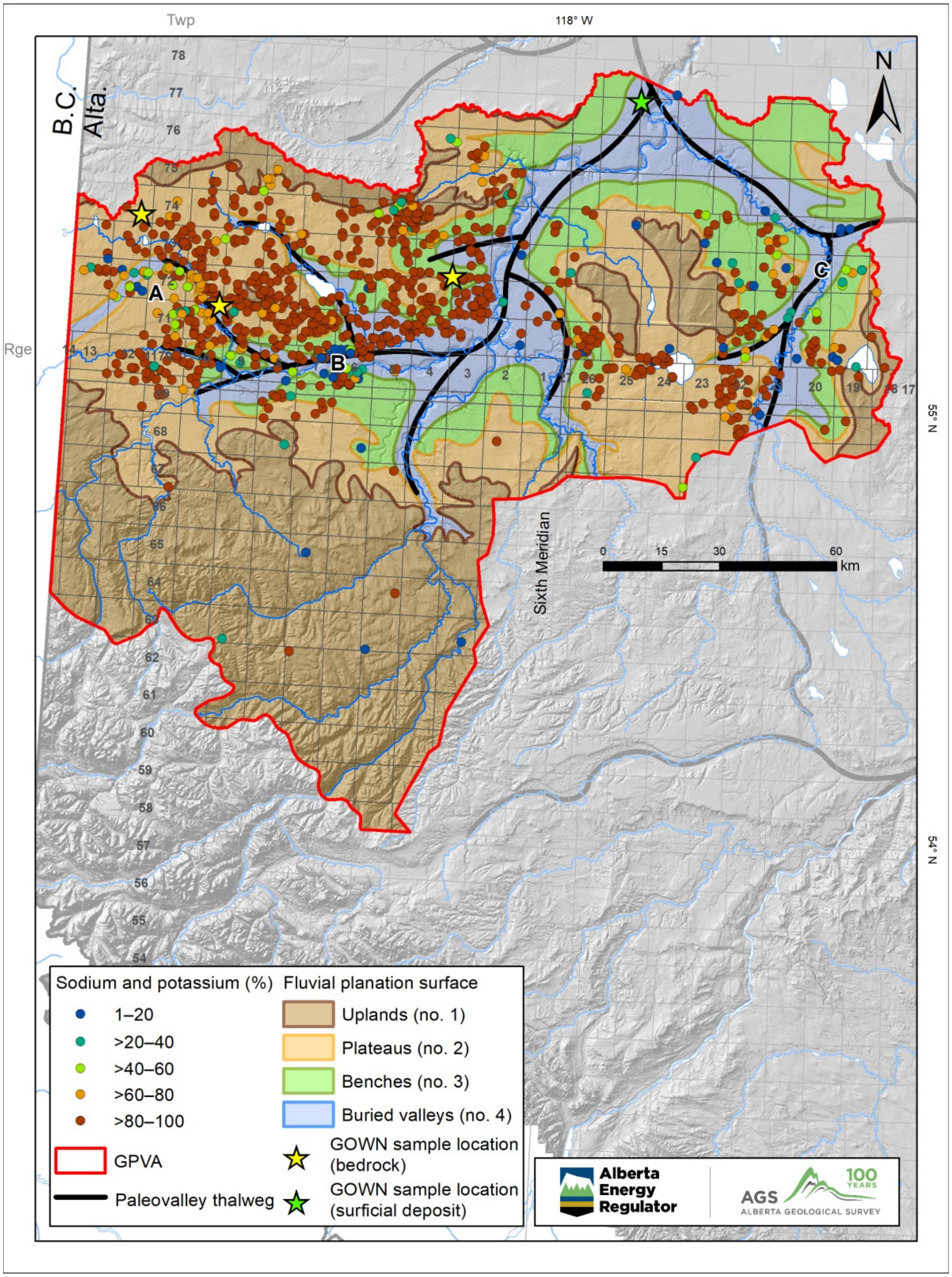

Figure 25. Spatial distribution and relative concentration of sodium and potassium in the Grande Prairie–Valleyview area (GPVA), northwestern Alberta. Smerdon (2019) conducted isotope analysis on samples from four GOWN (Groundwater Observation Well Network) wells, three completed in bedrock and one completed in surficial deposits; groundwater samples from wells completed in bedrock are estimated to be 15 000 to 25 000 years BP and are located where sodium and potassium is >80%. 'A' and 'C' highlight areas of intermediate flow (sodium and potassium between 40 and 80%), and 'B' highlights an area of local flow where groundwater is relatively young (0–20% sodium and potassium). Hill-shaded relief based on bedrock topography grid provided by Alberta Geological Survey (in progress, 2020).

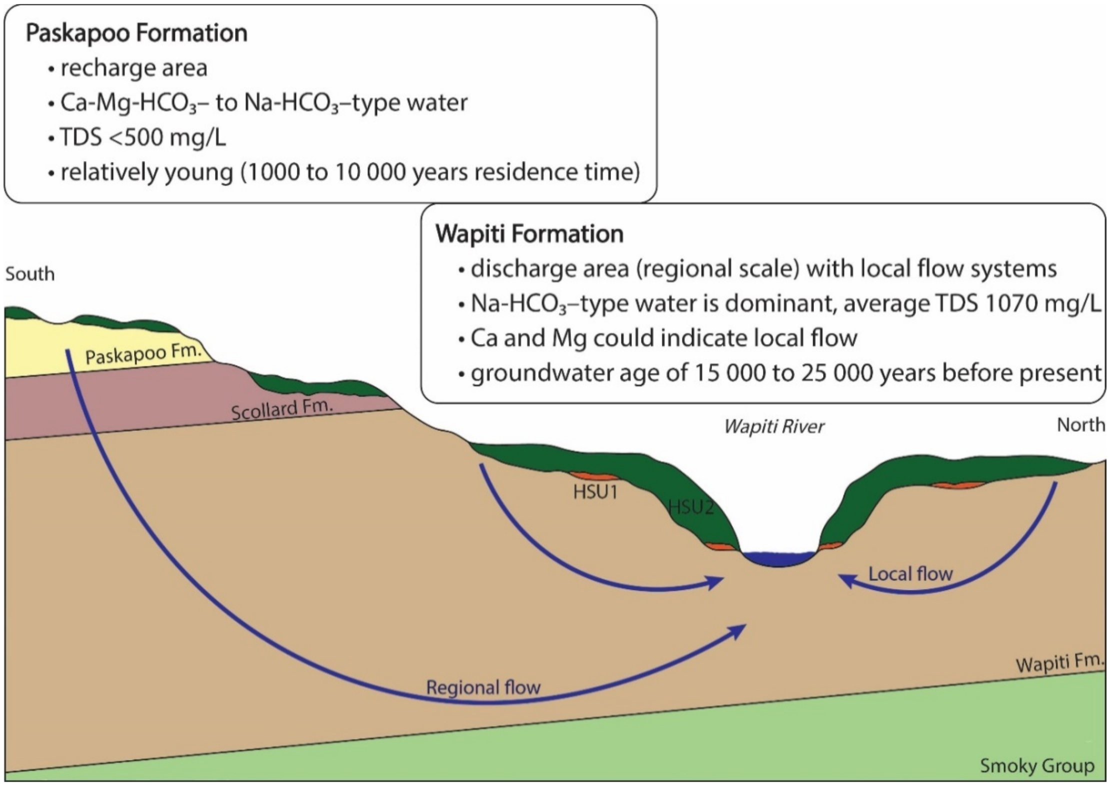

Figure 26. Conceptualization of regional and local flow systems in the Grande Prairie–Valleyview area (GPVA), northwestern Alberta. Although recharge occurs at the surface throughout the study area, it may support shallow, local flow systems rather than recharging to deeper (regional) flow systems. Groundwater in the Wapiti Formation is most likely recharged from the Paskapoo Formation in the south of, and beyond the southern and western boundaries of the GPVA, and chemically evolves over time as it travels through the bedrock. Abbreviations: HSU, hydrostratigraphic unit; TDS, total dissolved solids.

8 Conclusions

The main hydrogeological conclusions from this study include

- the distribution of wells and well screens in the Grande Prairie–Valleyview area indicate that all bedrock units, with the possible exception of parts of the Smoky Group, are used for groundwater production;
- basal coarse-grained Neogene–Quaternary sediments (hydrostratigraphic unit 1) do not appear to form regionally significant aquifers, but may instead be hydraulically connected to bedrock aquifer systems consisting of interconnected sand bodies;
- coarse-grained units isolated within clay-rich overburden (hydrostratigraphic unit 2) and surficial coarse-grained units (hydrostratigraphic unit 3) may function as local aquifers; hydrostratigraphic unit 3 deposits may also function as recharge zones.
- regional, intermediate, and local flow systems occur throughout the Grande Prairie–Valleyview area;
- regional flow systems are recharged in the Paskapoo Formation, which underlies the elevated southern part of the Grande Prairie–Valleyview area and areas beyond the southern and western boundaries of the study area; discharge occurs in lower areas underlain by the Wapiti Formation in the central part of the Grande Prairie–Valleyview area;
- most groundwater is recovered from regional flow systems hosted primarily in bedrock;
- local to intermediate flow systems occur adjacent to high-relief elements such as uplands and river valleys and may be, at least partially, hosted within surficial hydrostratigraphic units.

9 References

Alberta Climate Information Service (2020): Alberta climate and atlas maps; Alberta Agriculture and Forestry, URL <https://agriculture.alberta.ca/acis/climate-maps.jsp> [September 2019].

Alberta Energy Regulator (2019): Alberta water use performance report, 2017 water summary; URL <https://www2.aer.ca/t/Production/views/AlbertaWaterUseReport_0/WaterSummary?:embed=y&:display_count=no&:showShareOptions=true&:showVizHome=no> [May 2019].

Alberta Environment and Parks (2011): 2M base map plus land-use framework planning regions, municipalities, green/white area; URL <https://geodiscover.alberta.ca/geoportal/rest/metadata/item/cf7f0363b8994d8da973f5b66f4e1fe8/html> [December 2019].

Alberta Environment and Parks (2015a): Alberta Water Well Information Database; URL <https://www.alberta.ca/alberta-water-well-information-database-overview.aspx> [August 2016].

Alberta Environment and Parks (2015b): Provincial DEM; AltaLIS Ltd., 25 m cell, Esri grid format, URL <http://www.altalis.com/products/terrain/dem.html> [December 2016].

Alberta Geological Survey (2020a): Bedrock topography of Alberta, version 2 (gridded data, ASCII format); Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Digital Data 2020-0022.

Alberta Geological Survey (2020b): Sediment thickness of Alberta, version 2 (gridded data, ASCII format); Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Digital Data 2020-0023.

Alden, W.C. (1932): Physiography and glacial geology of eastern Montana and adjacent areas; U.S. Geological Survey, Professional Paper 174, 133 p.

Andriashek, L.D. (2001): Surficial geology of the Wapiti area, NTS 83L; Alberta Energy and Utilities Board, EUB/AGS Map 239, scale 1:250 000.

Andriashek, L.D. comp. (2018): Thalwegs of bedrock valleys, Alberta (GIS data, line features); Alberta Energy Regulator, AER/AGS Digital Data 2018-0001.

Atkinson, L.A. and Hartman, G.M.D. (2017): 3D rendering of the regional stratigraphy of Paleogene−Quaternary sediments in west-central Alberta; Alberta Energy Regulator, AER/AGS Report 93, 44 p.

Atkinson, L.A., Liggett, J.E., Hartman, G., Nakevska, N., Mei, S., MacCormack, K.E. and Palombi, D. (2017): Regional geological and hydrogeological characterization of the Calgary-Lethbridge Corridor in the South Saskatchewan regional planning area; Alberta Energy Regulator, AER/AGS Report 91, 175 p.

Atkinson, N., Pawley, S. and Utting, D.J. (2016): Flow-pattern evolution of the Laurentide and Cordilleran ice sheets across west-central Alberta, Canada: implications for ice sheet growth, retreat and dynamics during the last glacial cycle; Journal of Quaternary Science, v. 31, p. 753–768.

Atkinson, N., Utting, D.J. and Pawley, S.M. (2018): Glacial landforms of Alberta, Canada, version 3.0 (GIS data, line features); Alberta Energy Regulator, AER/AGS Digital Dataset 2014-0022.

Babakhani, M., Mei, S., Atkinson, L.A. and Smerdon, B.D. (2019): 3D property modelling of the bedrock hydrostratigraphy in the Fox Creek area, west-central Alberta; Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Open File Report 2019-03, 19 p.

Barnes, R.G. (1977): Hydrogeology of the Mount Robson-Wapiti area, Alberta; Alberta Research Council, Alberta Geological Survey, Earth Sciences Report 1976-05, 37 p.

Borneuf, D.M. (1980): Hydrogeology of the Winagami area, Alberta; Alberta Research Council, Alberta Geological Survey, Earth Sciences Report 1979-03, 14 p.

Bostock, H.S. (1970): Physiographic regions of Canada; Geological Survey of Canada, Map 1254A, scale 1:5 000 000.

Cai, J., Cole, J. and Young, A. (2018): Practical application of neural networks in assessing completion effectiveness in the Montney unconventional gas play in northeast British Columbia, Canada; Bulletin of Canadian Petroleum Geology, v. 66, no. 2, p. 552–574.

Carlson, V.A. and Green, R. (1979): Bedrock topography of the Iosegun Lake map area, NTS 83K, Alberta; Alberta Research Council, Alberta Geological Survey, Map 65, scale 1:250 000.

Carlson, V.A. and Hackbarth, D.A. (1974): Bedrock topography of the Grande Prairie area, NTS 83M, Alberta; Alberta Research Council, Alberta Geological Survey, Map 61, scale 1:250 000.

Catto, N.R., Liverman, D.G.E., Bobrowsky, P.T. and Rutter, N. (1996): Laurentide, cordilleran, and montane glaciation in the western Peace River–Grande Prairie region, Alberta and British Columbia, Canada; Quaternary International, v. 32, p. 21–32.

Catuneanu, O., Sweet, A.R. and Miall, A.D. (2000): Reciprocal stratigraphy of the Campanian–Paleocene western interior of North America; Sedimentary Geology, v. 134, p. 235–255.

Chowdhury, S. and Chao, D.K. (2018): Time-series land-use/land-cover classifications of the Upper Peace Region of Alberta, derived from 1985 to 2015 Landsat multispectral data (image data, TIFF format); Alberta Energy Regulator, AER/AGS Digital Data 2018-0004.

Dawson, F., Kalkreuth, W. and Sweet, A. (1994): Stratigraphy and coal resource potential of the Upper Cretaceous to Tertiary strata of northwestern Alberta; Geological Survey of Canada, Bulletin 466, 60 p.

Demchuk, T.D. and Hills, L.V. (1991): A re-examination of the Paskapoo Formation in central Alberta Plains; the designation of three new members; Bulletin of Canadian Petroleum Geology, v. 39, no. 3, p. 270–282.

Donaldson, W.S., Plint, A.G. and Longstaffe, F.J. (1998): Basement tectonics control on distribution of the shallow marine Bad Heart Formation: Peace River Arch area, northwest Alberta; Bulletin of Canadian Petroleum Geology, v. 46, p. 576–598.

Donaldson, W.S., Plint, A.G. and Longstaffe, F.J. (1999): Tectonic and eustatic control on deposition and preservation of Cretaceous ooidal ironstone and associated facies: Peace River Arch area, NW Alberta, Canada; Sedimentology, v. 46, p. 1159–1182.

Edwards, D.W.A. and Scafe, D. (1996): Mapping and resource evaluation of the Tertiary and preglacial sand and gravel formations of Alberta; Alberta Energy, Alberta Geological Survey, Open File Report 1994-06, 246 p., URL <http://ags.aer.ca/publications/OFR_1994_06.html> [June 2016].

Euzen, T.E., Moslow, T.F. and Caplan, M. (2018): The Montney Play of western Canada: deposition to development; Bulletin of Canadian Petroleum Geology, v. 66, no. 1, p. 1–5.

Fanti, F. and Catuneanu, O. (2009): Stratigraphy of the Upper Cretaceous Wapiti Formation, west-central Alberta, Canada; Canadian Journal of Earth Sciences, v. 46, p. 263–286.

Fanti, F. and Catuneanu, O. (2010): Fluvial sequence stratigraphy: the Wapiti Formation, west-central Alberta, Canada; Journal of Sedimentary Research, v. 80, p. 320–338.

Fenton, M.M., Waters, E.J., Pawley, S.M., Atkinson, N., Utting, D.J. and Mckay, K. (2013): Surficial geology of Alberta; Energy Resources Conservation Board, ERCB/AGS Map 601, scale 1:1 000 000.

Hackbarth, D.A. (1977): Hydrogeology of the Grande Prairie area, Alberta; Alberta Research Council, Alberta Geological Survey, Earth Sciences Report 1976-04, 20 p.

Hackbarth, D.A. (1978): Groundwater conditions in the Grande Prairie-Beaverlodge area, Alberta; Alberta Research Council, Alberta Geological Survey, Earth Sciences Report 1977-04, 63 p.

Hart, B.S. and Plint, A.G. (2003): Stratigraphy and sedimentology of shoreface and fluvial conglomerates: insights from the Cardium Formation in NW Alberta and adjacent British Columbia; Bulletin of Canadian Petroleum Geology, v. 51, p. 437–464.

Hartman, G.M.D. and Clague, J.J. (2008): Quaternary stratigraphy and glacial history of the Peace River valley, northeast British Columbia; Canadian Journal of Earth Sciences, v. 45, p. 549–564.

Hartman, G.M.D. and Slomka, J.M. (2017): Regional Neogene–Quaternary stratigraphy of the Peace River Lowland, northwestern Alberta; Geological Society of America, Rocky Mountain Section Meeting 2017, June 9–10, 2017, Calgary, Alberta, Paper 20-4, URL <https://gsa.confex.com/gsa/2017RM/webprogram/Paper293187.html> [July 2017].

Hathway, B. (2011): Late Maastrichtian paleovalley systems in west-central Alberta: mapping the Battle Formation in the subsurface; Bulletin of Canadian Petroleum Geology, v. 59, p. 195–206.

Hickin, A.S., Lian, O.B., Levson, V.M. and Cui, Y. (2015): Glacial Lake Peace, NE British Columbia, Canada; Boreas, v. 44, p. 288–304.

Hickin, A.S., Lian, O.B. and Levson, V.M. (2016): Coalescence of late Wisconsinan Cordilleran and Laurentide ice sheets east of the Rocky Mountain Foothills in the Dawson Creek region, northeast British Columbia, Canada; Quaternary Research, v. 85, p. 409–429.

Hydrogeological Consultants Ltd. (2004): AAMD&C northern zone, part of the Peace River Basin, Tp 065 to 107, R 05 to 27, W5M & Tp 069 to 087, R 01 to 13, W6M, regional groundwater assessment; unpublished report prepared for AAMD&C, 80 p., URL <https://www.hcl.ca/public/download/documents/11720> [September 2019].

Jones, J.F. (1960): Groundwater geology, Beaverlodge district, Alberta; Research Council of Alberta, Alberta Geological Survey, Earth Sciences Report 1959-02, 53 p.

Jones, J.F. (1961): Water supply study for the City of Grande Prairie, Alberta; Research Council of Alberta, Alberta Geological Survey, Open File Report 1961-08, 157 p.

Jones, J.F. (1966): Geology and groundwater resources of the Peace River district, northwestern Alberta; Research Council of Alberta, Alberta Geological Survey, Bulletin 016, URL <http://ags.aer.ca/publications/BUL_016.html> [June 2017].

Khidir, A. and Catuneanu, O. (2003): Sedimentology and diagenesis of the Scollard sandstones in the Red Deer Valley area, central Alberta; Bulletin of Canadian Petroleum Geology, v. 51, no. 1, p. 45–69.

Klassen, J. and Liggett, J.E. (2019): First-order groundwater availability assessment for the upper Peace region; Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Open File Report 2019-10, 28 p.

Langenberg, C., Berhane, W.H., Sweet, A.R., Marchioni, D. and Heaman, L.M. (2007): Regional correlations of the Ardley coal zone, Alberta; Alberta Energy and Utilities Board, EUB/AGS Earth Sciences Report 2007-05, 21 p.

Leckie, D.A. (2006): Tertiary fluvial gravels and evolution of the western Canadian prairie landscape; Sedimentary Geology, v. 190, p. 139–158.

Liverman, D.G.E. (1989): The Quaternary geology of the Grande Prairie area, Alberta; Ph.D. thesis, University of Alberta, 360 p.

Lyster, S. and Andriashek, L.D. (2012): Geostatistical rendering of the architecture of hydrostratigraphic units within the Paskapoo Formation, central Alberta; Energy Resources Conservation Board, ERCB/AGS Bulletin 66, 115 p.

MacCormack, K.E., Atkinson, N. and Lyster, S. (2015): Bedrock topography of Alberta, Canada; Alberta Energy Regulator, AER/AGS Map 602, scale 1:1 000 000.

Mathews, W.H. (1978): Quaternary stratigraphy and geomorphology of Charlie Lake (94A) map-area, British Columbia; Geological Survey of Canada, Paper 78-20, 25 p.

Mathews, W.H. (1980): Retreat of the last ice sheets in northeastern British Columbia and adjacent Alberta; Geological Survey of Canada, Bulletin 331, 22 p.

Osborn, G. and du Toit, C. (1991): Lateral planation of rivers as a geomorphic agent; Geomorphology, v. 4, p. 249–260.

Pawley, S.M. and Atkinson, N. (2012): Surficial geology and Quaternary history of the southern Lesser Slave Lake area, Alberta (NTS 83O/S); Energy Resources Conservation Board, ERCB/AGS Open File Report 2012-16, 33 p.

Pawley, S.M., Atkinson, N., Kendall, A.N. and Utting, D.J. (2015): Surficial sand and gravel deposits of Alberta: digital mosaic (GIS data, polygon features); Alberta Energy Regulator, AER/AGS Digital Data 2015-0027.

Pawlowicz, J.G. and Fenton, M.M. (1995): Bedrock topography of Alberta; Alberta Energy and Utilities Board, EUB/AGS Map 226, scale 1:2 000 000.

Pettapiece, W.W. (1986): Physiographic subdivisions of Alberta; Agriculture Canada, Research Branch, Land Resources Research Centre, scale 1:1 500 000, URL <http://sis.agr.gc.ca/cansis/publications/surveys/ab/abp/index.html> [June 2017].

Prior, G.J., Hathway, B., Glombick, P.M., Pană, D.I., Banks, C.J., Hay, D.C., Schneider, C.L., Grobe, M., Elgr, R. and Weiss, J.A. (2013): Bedrock geology of Alberta; Alberta Energy Regulator, AER/AGS Map 600, scale 1:1 000 000, URL <http://ags.aer.ca/publications/MAP_600.html> [June 2015].

Quartero, E.M., Leier, A.L., Bentley, L.R. and Glombick, P. (2015): Basin-scale stratigraphic architecture and potential Paleocene distributive fluvial systems of the Cordilleran Foreland Basin, Alberta, Canada; Sedimentary Geology, v. 316, p. 26–38.

Rivard, C., Lavoie, D., Lefebvre, R., Séjourné, S., Lamontagne, C. and Duchesne, M. (2014): An overview of Canadian shale gas production and environmental concerns; International Journal of Coal Geology, v. 126, p. 64–76.

Roed, M.A. (1968): Surficial geology of the Edson-Hinton area, Alberta; Ph.D. thesis, University of Alberta, 201 p.

Roed, M.A. (1975): Cordilleran and Laurentide multiple glaciation west-central Alberta, Canada; Canadian Journal of Earth Sciences, v. 12, no. 9, p. 1493–1515.

Rokosh, C.D., Lyster, S., Anderson, S.D.A., Beaton, A.P., Berhane, H., Brazzoni, T., Chen, D., Cheng, Y., Mack, T., Pana, C. and Pawlowicz, J.G. (2012): Summary of Alberta's shale- and siltstone-hosted hydrocarbon resource potential; Energy Resources Conservation Board, ERCB/AGS Open File Report 2012-06, 327 p.

Singh, A. and Nakevska, N. (2019): Distribution of hydraulic head in the Wapiti / Belly River hydrostratigraphic unit; Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Map 543, scale 1:1 750 000.

Slomka, J.M. and Hartman, G.M.D. (2019): Sedimentary architecture of a glaciolacustrine braidplain delta: proxy evidence of a pre-Middle Wisconsinan glaciation (Grimshaw gravels, Interior Plains, Canada); Boreas, v. 48, p. 215–235.

Slomka, J.M. and Utting, D.J. (2017): Glacial advance, occupation, and retreat sediments associated with multi-stage ice-dammed lakes: north-central Alberta, Canada; Boreas, v. 47, p. 150–174.

Slomka, J.M., Hartman, G. and Klassen, J. (2018): Architecture and geometry of basal sand and gravel deposits including the 'Grimshaw gravels', northwestern Alberta (NTS 84C and 84D); Alberta Energy Regulator, AER/AGS Open File Report 2018-04, 44 p.

Smerdon, B.D. (2019): Environmental isotope sampling of the Saddle River and the Groundwater Observation Well Network in the Upper Peace Region, northwestern Alberta; Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Open File Report 2019-08, 6 p.

Smerdon, B.D., Klassen, J. and Gardner, W.P. (2019): Hydrogeological characterization of the Upper Cretaceous-Quaternary units in the Fox Creek area, west-central Alberta; Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Report 98, 35 p.

Stewart, S.A. (2009): Locations of Alberta springs (GIS data, point features); Energy Resources Conservation Board, ERCB/AGS Digital Data 2009-0002.

St-Onge, D.A. (1972): Sequence of glacial lakes in north-central Alberta; Geological Survey of Canada, Bulletin 213, 16 p.

Tokarsky, O. (1966): Final results, Grande Prairie deep test hole, 11-24-70-6-W6; Research Council of Alberta, Alberta Geological Survey, Open File Report 1966-01, 16 p.

Tokarsky, O. (1967): Groundwater and groundwater resources of the Grimshaw-Cardinal Lake area, Alberta; M.Sc. thesis, University of Alberta, 179 p.

Tokarsky, O. (1977): Hydrogeology of the Iosegun Lake area, Alberta; Alberta Research Council, Alberta Geological Survey, Earth Sciences Report 1976-02, 13 p.

Tóth, J. and Almási, I. (2001): Interpretation of observed fluid potential patterns in deep sedimentary basin under tectonic compression: Hungarian Great Plain, Pannonian Basin; Geofluids, v. 1, no. 1, p. 11–36.

Varban, B.L. and Plint, A.G. (2007): Palaeoenvironments, palaeogeography, and physiography of a large, shallow, muddy ramp: Late Cenomanian–Turonian Kaskapau Formation, western Canada foreland basin; Sedimentology, v. 55, p. 201–233.

Vonhof, J.A. (1969): Tertiary gravels and sands in the Canadian Great Plains; Ph.D. thesis, University of Saskatchewan, 279 p.

Westgate, J.A., Fritz, P., Matthews, J.V., Jr., Kalas, L. and Green, R. (1971): Sediments of mid-Wisconsinan age in west-central Alberta; geochronology, insects, ostracodes, mollusca, and the oxygen isotope composition of molluscan shells; Geological Society of America, Rocky Mountain Section Annual Meeting, November 1–3, 1971, Washington, D.C., Abstracts with Program, v. 3, p. 419.

Westgate, J.A., Fritz, P., Matthews, J.V., Jr., Kalas, L., Delorme, L.D., Green, R. and Aario, R. (1972): Geochronology and paleoecology of mid-Wisconsinan sediments in west-central Alberta; International Geological Congress, 24th session, Montreal, Quebec, Abstracts, p. 380.