AER/AGS Open File Report 2017-07

First-Order Groundwater Availability Assessment for Central Alberta

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Alberta Energy Regulator
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Abstract

The need to quantify groundwater inventory, to better understand potential development risks and the current state of water use versus water availability, has grown with the increase in economic activity and population over the last decade in Alberta. Previous hydrogeological mapping for most of Alberta was completed during 1968–1983 by the Alberta Research Council; these maps show a range of expected average groundwater yield for groundwater wells within different regions of Alberta. These maps provide guidance for water sourcing but were never intended to be used for groundwater inventory or groundwater management. A new approach to mapping groundwater yield in Alberta, based on an aquifer-yield continuum, was applied to an area of approximately 120 000 km^2 in central Alberta, specifically to near-surface bedrock formations containing nonsaline groundwater. The aquifer-yield continuum classifies groundwater yield along a spectrum that helps define total groundwater availability and is bound by two extremes: non-use and maximum mining. Safe yield is considered to be the maximum amount of groundwater that can be extracted without depleting groundwater storage and was the chosen parameter used for creating water yield maps for central Alberta. The northern part of the study area is characterized by larger yields, up to 1.0E9 m^3/yr, and yields decrease towards the southeast, with values up to 1.0E06 m^3/yr. There are several areas that have a safe yield of zero resulting in water extraction that would not be sustainable over the long period and where groundwater would likely be mined from aquifer storage. This report demonstrates a conservative application of the aquifer-yield continuum concept for a large portion of the province underlain by relatively near-surface bedrock aquifers. Future work will focus on adapting the aquifer-yield continuum for other regions in Alberta to estimate groundwater availability.

1 Introduction

The demand for Alberta's potable water supply has grown with the increase in economic activity and population over the last decade, resulting in the need to rapidly quantify groundwater inventory to understand potential development risks and the current state of water use versus availability. Hydrogeological mapping across most of Alberta was completed during 1968–1983 by the Alberta Research Council (ARC), and the resultant maps were digitized by the Alberta Geological Survey (AGS) in 2009 (Lemay and Guha, 2009). These hydrogeological maps show a range of expected average groundwater yields from groundwater wells within different regions for most of Alberta. Average groundwater yield estimates were based on the geology or specific properties of rock and sediments, if these were known, or from available pumping or aquifer test information. Although this information provides some guidance for water sourcing, it is outdated and was never intended to be used for groundwater inventory or groundwater management (Lemay and Guha, 2009).

This report describes a new approach to mapping groundwater yield in Alberta that is based on the aquifer-yield continuum outlined by Pierce et al. (2013). The aquifer-yield continuum classifies groundwater yield along a spectrum that helps define total groundwater availability and is bound by two extremes: non-use and maximum mining. The benefit to using the aquifer-yield continuum is that it incorporates aquifer performance with groundwater governance to delineate a range of physically possible yields and can be modified depending on human preference, use, and adaptive response (Pierce et al., 2013). In this study, the approach was applied to near-surface bedrock formations containing nonsaline groundwater as they provide a more consistent yield across a larger portion of central Alberta compared to surficial sediments, such as sand or gravel, which are locally important but not regionally prevalent.

2 Background

2.1 Study Area

The region of interest covers approximately 120 000 km^2 of central Alberta between Slave Lake in the north and Calgary in the south (Figure 1). The study area was delineated based on a combination of watersheds on the ground surface and subsurface geological boundaries. Watershed boundaries were defined by Agriculture and Agri-Food Canada (2012) and the following geological boundaries were included: the western edge of the Paskapoo Formation, the northern edge of the Wapiti Formation, the eastern edge of the Horseshoe Canyon Formation, and the southern edge of the Scollard Formation. The major geological units include the Paskapoo Formation (54% of the study area), Horseshoe Canyon/upper Wapiti Formation (29%), Scollard Formation (9%) and lower Wapiti Formation (8%; Figure 2). The study area contains multiple river basins, including the Peace, Athabasca, North Saskatchewan, Battle, Red Deer, and South Saskatchewan.

2.2 Geological Overview

During the Late Cretaceous, there was a major seaway that extended from the Arctic to the Gulf of Mexico between the Canadian Shield and active Cordilleran belt (Stott, 1984; Hamblin, 2004a). At the end of the Cretaceous, the marine environment regressed to the edge of what is now known as the Western Canada Sedimentary Basin (WCSB) in present day Manitoba and North Dakota; this resulted in a nonmarine environment that stretched hundreds of kilometres within the former seaway (Stott, 1984; Hamblin, 2004a). The rising cordillera led to high-energy sedimentation in the foreland basin, which created an eastward-thinning wedge in the WCSB, with strata near horizontal and dipping slightly to the west (Stott, 1984; Hamblin, 2004b; Grasby et al., 2008; Burns et al., 2010).

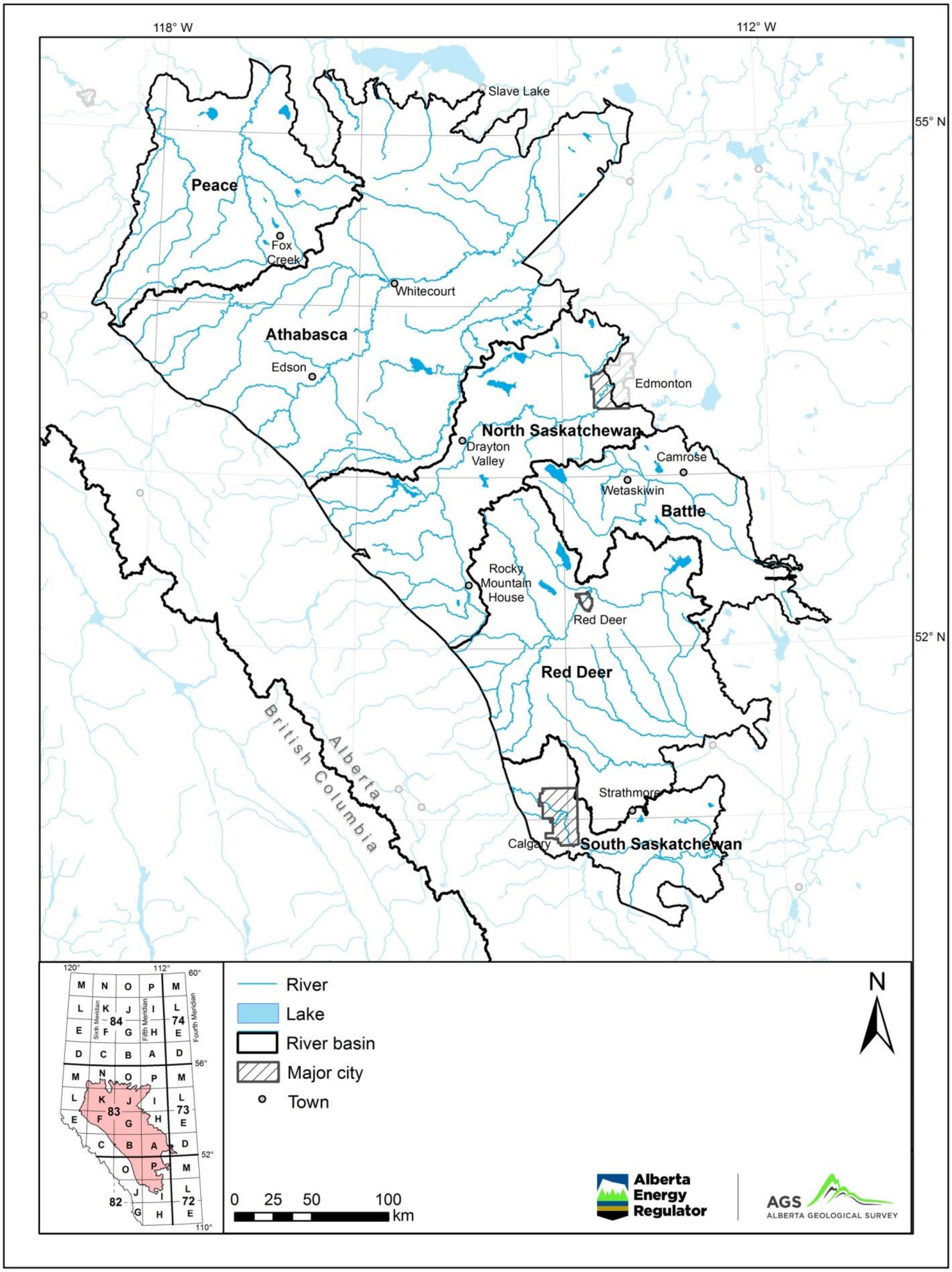

Figure 1. Study area, central Alberta.

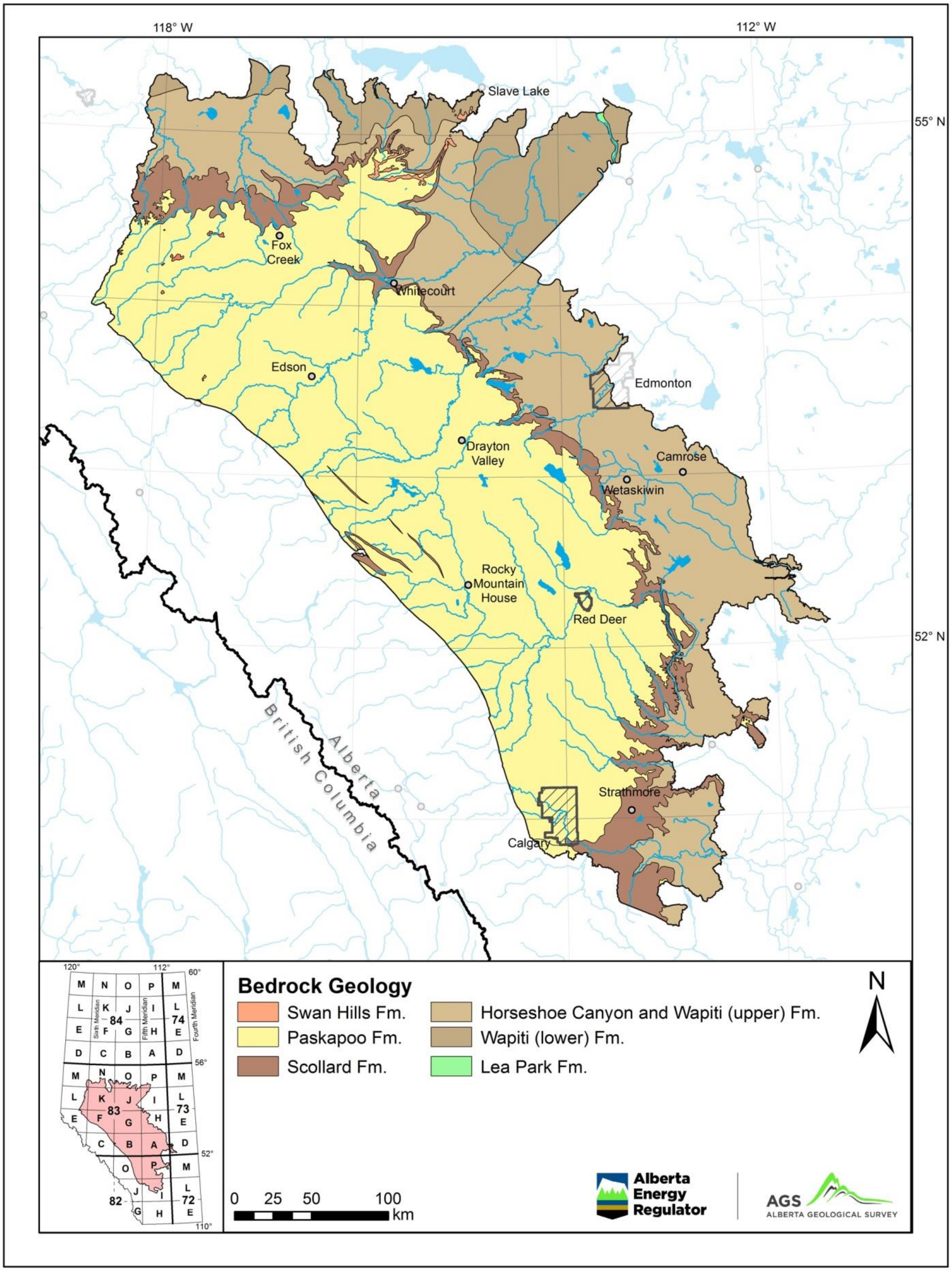

Figure 2. Bedrock geology within study area, central Alberta; major geological units include the Paskapoo, Scollard, Horseshoe Canyon, and upper Wapiti and lower Wapiti formations (Prior et al., 2013).

The Wapiti Formation was deposited during the Cretaceous in a mostly fluvial environment with a few local areas of lacustrine influence (Dawson et al., 1994). The Wapiti Formation is divided into the lower Wapiti and upper Wapiti and the contact between the two is defined by the lowermost coal seam. The lower Wapiti consists of medium-grained, light grey to brown sandstone, light grey-green siltstone, dark shale, and is without coal (Dawson et al., 1994). The upper Wapiti Formation, located in northern Alberta, is laterally equivalent to the Horseshoe Canyon Formation in central Alberta, and consists of interbedded medium to light grey, fine-grained sandstone and dark grey mudstone with carbonaceous horizons. The Horseshoe Canyon Formation was deposited towards the end of the Cretaceous and in a variety of environments, ranging from meandering rivers to estuarine channels to laterally extensive floodplains along the western margin of the western interior seaway. It is characterized by thin, interbedded, fine-grained sandstone, siltstone, shale, and coal (Dawson et al., 1994).

The Whitemud and Battle formations lie immediately above the Wapiti and Horseshoe Canyon formations. These units were deposited when the basin was stable and there was limited sedimentation. The Whitemud Formation is easily recognized by the kaolinitic siltstone while the Battle Formation is characterized by dark grey shale (Dawson et al., 1994). Both units are relatively thin with an average thickness of about 10 m, as a result they were not considered in this study.

The Scollard Formation, Cretaceous to Paleogene in age, lies disconformably above the Battle Formation and was deposited during continental sedimentation as the marine environment was restricted in southwestern Manitoba (Dawson et al., 1994; Parks and Andriashek, 2009). It can be divided into two units: the lower unit consists of thin, fining-upwards cycles of fine-grained sandstone overlain by mudstone and siltstone and the upper unit consists of clastic zones similar to the lower unit but with the presence of an extensive development of coal. Up to 10 coal zones have been observed in the upper unit of the Scollard Formation (Dawson et al., 1994; Parks and Andriashek, 2009), and the presence of coal easily marks the boundary between the two units.

The Paskapoo Formation overlies the Scollard Formation, separated by an erosional unconformity, which represents a hiatus of 1–2.5 Ma (Hamblin, 2004b; Grasby et al., 2008). Overall, the Paleocene Paskapoo Formation fines upwards, from coarse-grained sandstone to siltstone and mudstone (Hamblin, 2004b; Lyster and Andriashek, 2012). Demchuk and Hills (1991) were the first to give internal structure to the Paskapoo Formation: in ascending order, the Haynes, Lacombe, and Dalehurst members. The lowermost member, the Haynes, consists of thick massive conglomerate sandstone and stacked, medium- to coarse-grained, channel sandstone, which are regionally extensive and apparently continuous units up to 100 m thick (Burns et al., 2010; Lyster and Andriashek, 2012). The sandstones are light grey and interbedded with grey to greenish siltstone and mudstone (Hamblin, 2004b). The Lacombe Member makes up most of the middle of the Paskapoo Formation and consists of interbedded grey to green siltstone, mudstone, and thin argillaceous coal with lenticular channel sand (Hamblin, 2004b; Burns et al., 2010; Lyster and Andriashek, 2012). The Dalehurst Member, the uppermost layer, consists of interbedded fine-grained sandstone, grey mudstone, and thick coal seams (Hamblin, 2004b; Lyster and Andriashek, 2012).

2.3 Physiographic and Natural Regions

Five main physiographic regions have been identified in the study area: Southern Alberta Uplands, Western Alberta Plains, Western Alberta Uplands, Eastern Alberta Plains, and Eastern Alberta Uplands (Figure 3). The physiographic regions also help define the natural regions and subregions of Alberta, outlined by the Natural Regions Committee (2006; Figure 4). The Foothills Natural Region makes up most of the Southern Alberta Uplands and is recognized by a cool climate that receives a relatively high amount of precipitation. The topography is varied, from sharp bedrock ridges to undulating terrain with deciduous or mixedwood forests at low elevations and coniferous forests at high elevations (Natural Regions Committee, 2006).

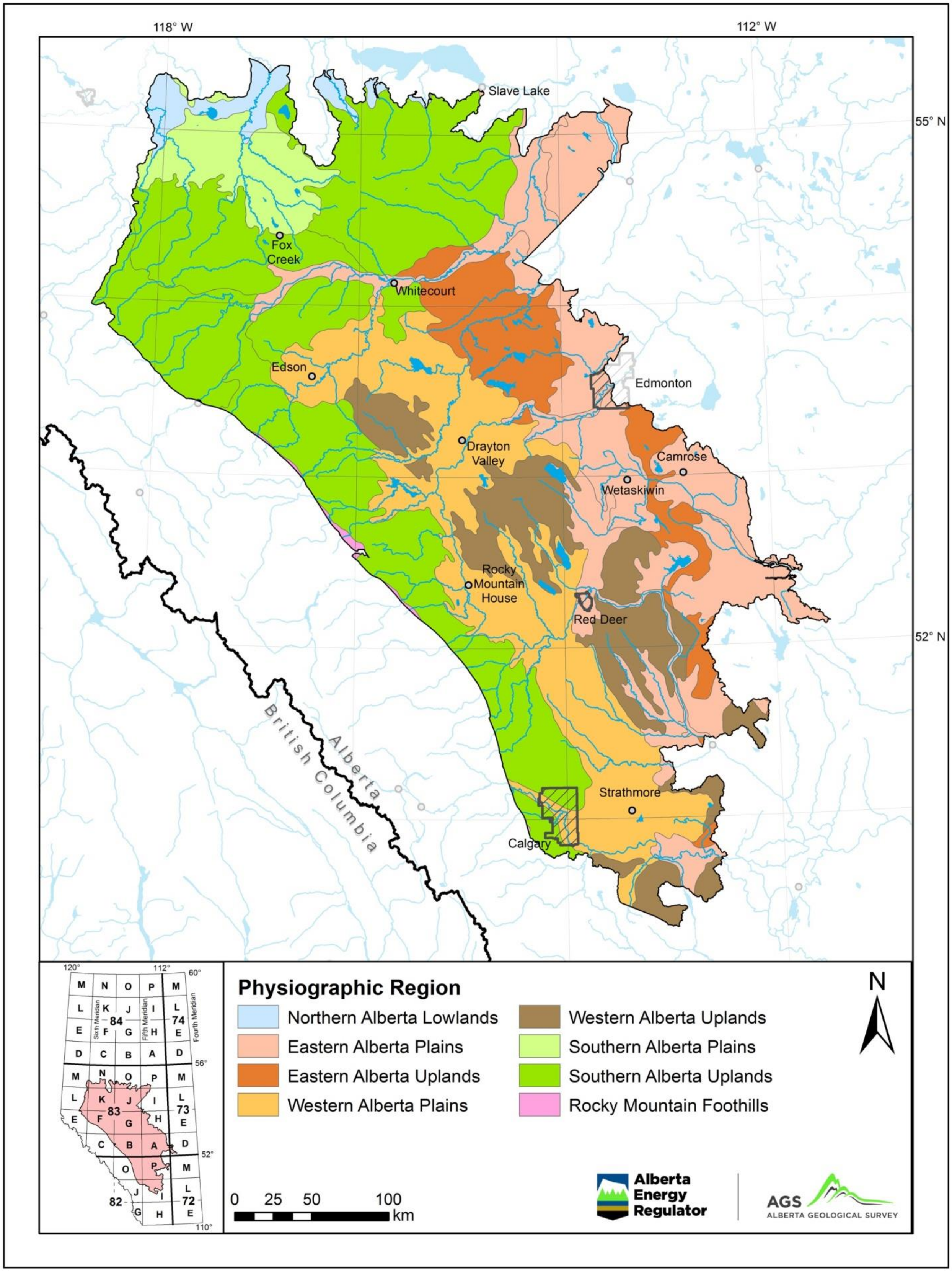

Figure 3. Physiographic regions of central Alberta as defined by Pettapiece (1986).

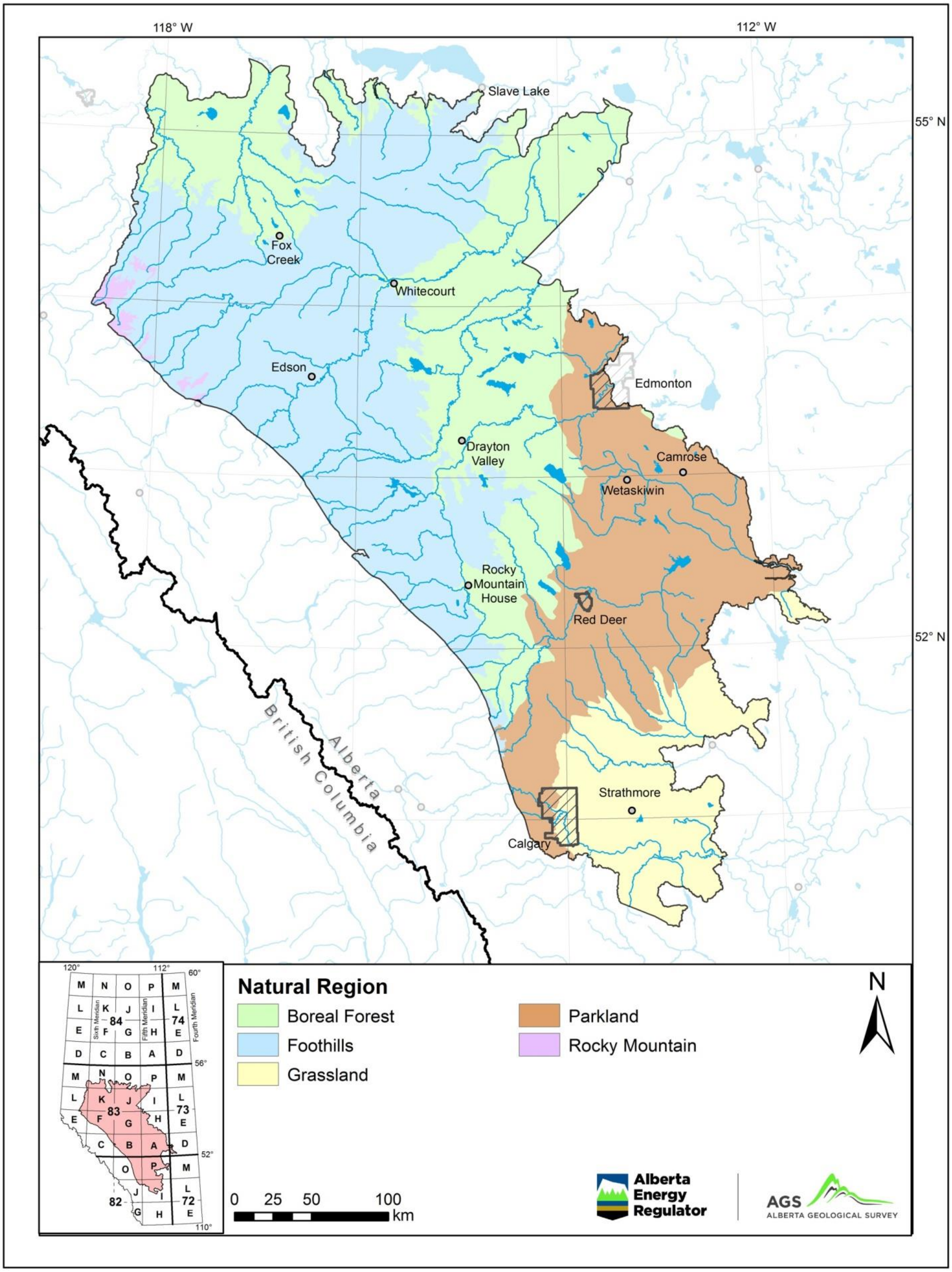

Figure 4. Natural regions of central Alberta as defined by Natural Regions Committee (2006).

Several natural regions cover the Western and Eastern Alberta plains and uplands, including Foothills (described above), Boreal Forest, Parkland, and Grassland. The Boreal Forest Natural Region is the largest region in Alberta (58% of province) and therefore the most diverse, with mean annual temperature varying up to 5°C between the warmer south and colder north. The region has short, cool summers and long, very cold winters and about 60–70% of annual rainfall occurs between April and August. The landscape is mostly undulating till and lacustrine plains although hummocky terrain, high elevation plateaus, and dune fields also occur. Vegetation is a mix of deciduous, mixedwood, and coniferous forests with extensive wetlands (Natural Regions Committee, 2006). The Grassland Natural Region is characterized by gently undulating, semi-arid prairie, with scattered coulees, valleys, badlands, and dune fields and a warm, dry climate. Vegetation found in this area includes drought-tolerant grasses, shrubs, and herbs and there are cultivated fields in moist or irrigated areas. Summers are hot with high solar inputs that cause high evapotranspiration and winters are long and cold with low snow cover (Natural Regions Committee, 2006). The Parkland Natural Region is characterized by temperature, precipitation, and growing season length that are intermediate between the warm grasslands in the south and moister boreal forest to the north. The terrain is mostly undulating till plains and hummocky uplands (Natural Regions Committee, 2006).

2.4 Thickness of Sediments

Overlying the bedrock in the study area are sediments that vary in thickness and distribution (Figure 5). The sediments range in thickness from 0–300 m, with the majority being 0–25 m thick, and include Neogene fluvial deposits, glaciogenic materials deposited during the Quaternary glaciation, and postglacial sediments. Sediments are thickest in the north and east, and thin towards the Rocky Mountains in the southwest. Thick sediments usually occur in paleovalleys or in the plains and lowlands, whereas sediments less than 5 m thick occur where bedrock is near the surface or forms modern landscapes (MacCormack et al., 2015).

2.5 Hydrogeological Characteristics

Based on geology and lithology, the following geological formations have been identified as aquifers in the context of this regional study: lower and upper Wapiti, Horseshoe Canyon, Scollard, and Paskapoo. Some of the thinner formations, such as Lea Park and Bearpaw as well as localized areas within the major formations, act as aquitards.

Regional hydrostratigraphic units have been identified within the Paskapoo Formation by Lyster and Andriashek (2012), and are similar to the members identified by Demchuk and Hills (1991). A geostatistical approach was used by Lyster and Andriashek (2012) to construct a three-dimensional (3D) model of the sandstone and mudstone distribution within the Paskapoo Formation. The results showed two aquifers, the Haynes and Sunchild, with >55% sandstone, and one aquitard, the Lacombe, with <35% sandstone (Figure 6; Lyster and Andriashek, 2012). The Haynes aquifer is the lowest unit, which disconformably overlies the Scollard Formation (Hamblin, 2004b). There are parts of the aquifer that are up to 100 m thick but on average, the thickness is about 50 m (Lyster and Andriashek, 2012). The Lacombe aquitard is the most extensive unit and consists of >65% nonsandy material, such as siltstone or mudstone. There are some sandy sections within the Lacombe aquitard but they are either isolated or poorly connected at a regional scale (Lyster and Andriashek, 2012). The Sunchild aquifer overlies the Lacombe aquitard in the central and western parts of the Paskapoo Formation (Lyster and Andriashek, 2012). The Sunchild aquifer is equivalent to the uppermost Dalehurst Member described by Demchuk and Hills (1991).

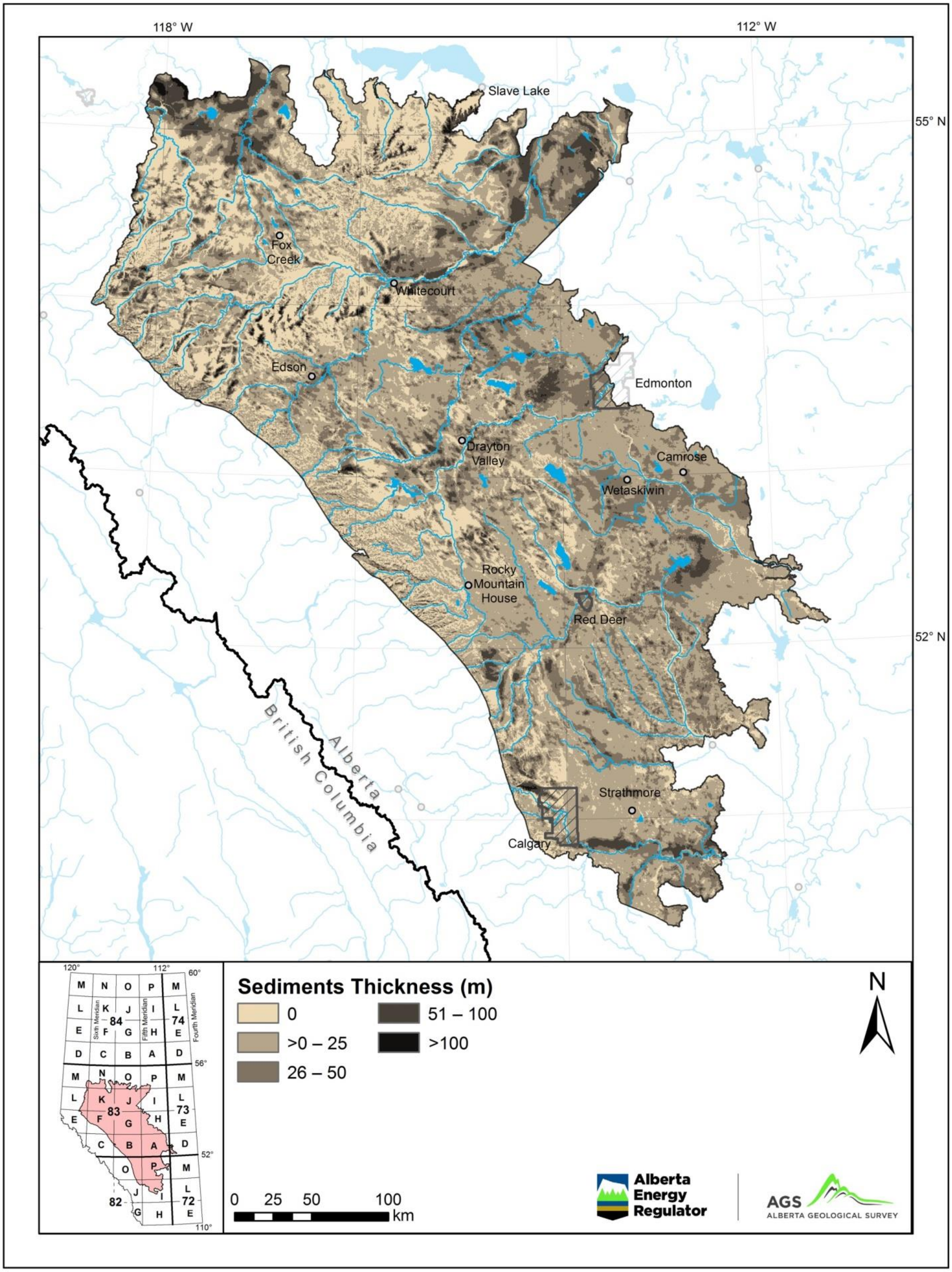

Figure 5. Thickness of sediments in study area, central Alberta (MacCormack et al., 2015).

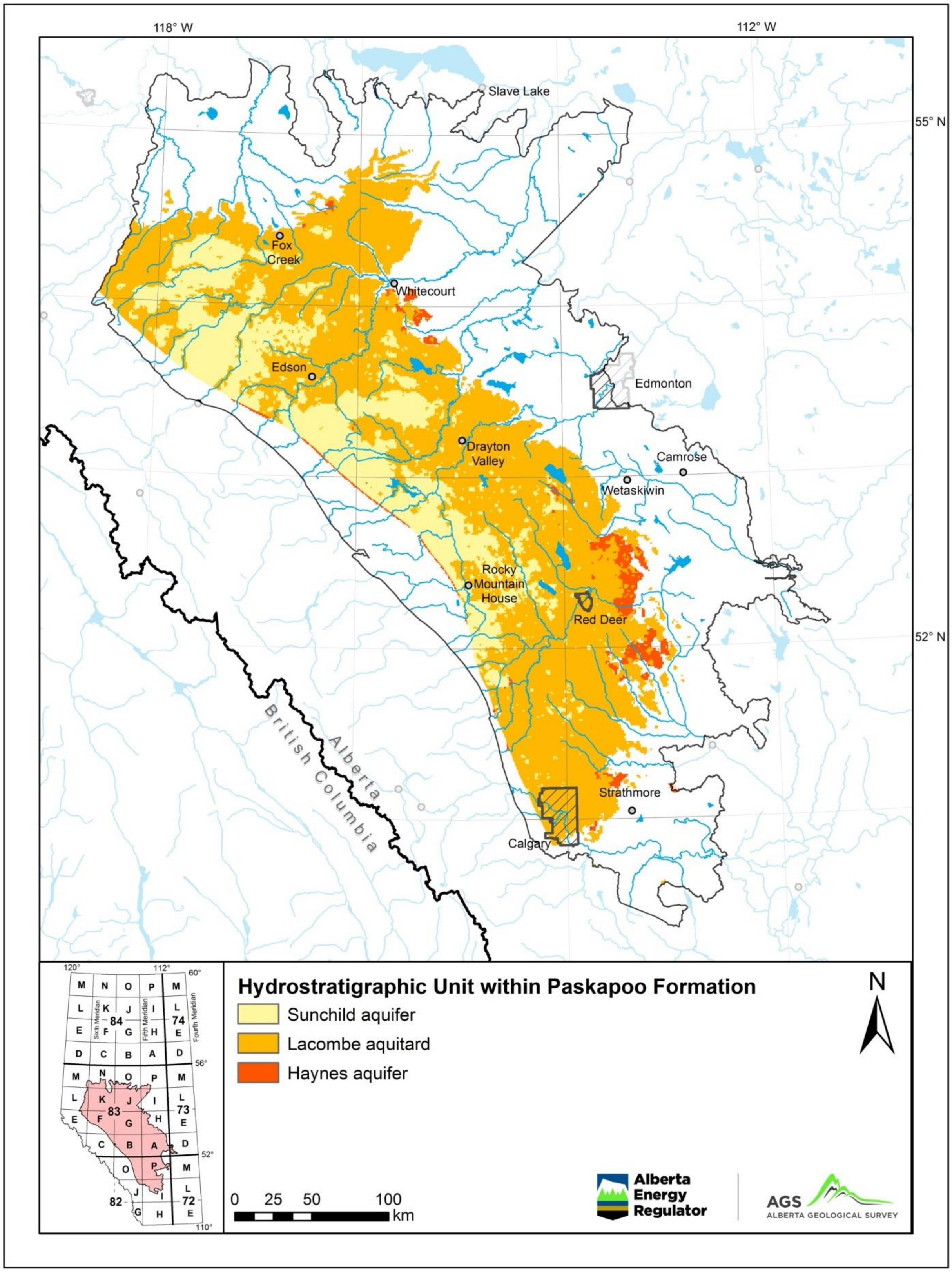

Figure 6. Plan view of aquifer systems within the Paskapoo Formation (central Alberta) as proposed by Lyster and Andriashek (2012). The Haynes aquifer underlies portions of the Lacombe aquitard.

2.6 Yield Mapping Approach

Alberta is water rich and according to Farvolden (1961), a natural renewable resource such as groundwater is of little benefit if it is not developed; however, it is important to use this resource in a sustainable matter. The idea of sustainable water development was initially discussed in literature in terms of safe yield, which was to limit the amount of water withdrawn on a regular and permanent basis to prevent dangerously depleting storage reserve (Lee, 1915; Meinzer, 1923). The concept of safe yield began to transition into sustainable yield as other factors, such as economic feasibility, rights to surface water, and greater impacts of pumping were taken into consideration (Pierce et al., 2013). Sustainable yield is influenced by the following factors: (1) recharge rates and storage conditions, (2) water quality, (3) discharge rates and environmental flows, (4) legal constraints, (5) economic feasibility, and (6) issues of intergenerational equity (Pierce et al., 2013).

Groundwater yield maps created by the ARC during 1968–1983 show the estimated amount of water that could be extracted from groundwater wells within a region based on the concept of a 20-year safe yield (Maathius and van der Kamp, 2006). Groundwater yield estimates were determined from geology and/or properties of rocks and sediments or available pumping test information. The groundwater maps provide general information regarding groundwater conditions for an area but were not intended for groundwater management purposes, rather as a starting point for groundwater inventory (Lemay and Guha, 2009).

A different method to classifying groundwater yield is the approach outlined by Pierce et al. (2013). Rather than a single yield value, the aquifer-yield continuum approach defines a range of physically possible yields that can be influenced by various factors for different regions and scenarios. The following five classes of aquifer yield describe impact, least to greatest (Figure 7):

1) **permissive sustained yield (PSY):** limited use of the resource permits some consumptive use but does not affect regional water levels and therefore has minimal impact on ecosystem, recreational, or other nonconsumptive or nonmarket use (Pierce et al., 2013); the pumped volume is small enough that the effects on the natural system are not observable or statistically significant;
2) **maximum sustained yield (MSY):** continuous withdrawal will not cause dewatering in the most productive water-yield formations but the potential for storage depletion over the planning horizon exists (Pierce et al., 2013); this class represents conditions where changes to the groundwater system and connected surface water bodies will be noticed, but have been deemed acceptable by regulating organizations;
3) **safe yield (SY):** represents the long-term capture of water that would otherwise have moved through the groundwater system to surface water bodies, resulting in significant impacts to those surface water bodies; both natural and human-induced recharge are eliminated and total storage will be depleted over time (Pierce et al., 2013), as a result, safe yield is not necessarily ‘safe’;
4) **permissive mining yield (PMY):** includes full capture of water that would discharge to surface water bodies and partial dewatering of the aquifer, without fully depleting the theoretically recoverable volume of water stored within the aquifer;
5) **maximum mining yield (MMY):** represents full depletion of all theoretically available water stored within the aquifer and full capture of the water that would discharge to surface water bodies.

The equations used to calculate the yields for different yield classes as outlined by Pierce et al. (2013) are shown in Table 1. Yields can be calculated as volumes or rates over a specific planning horizon (i.e., time frame).

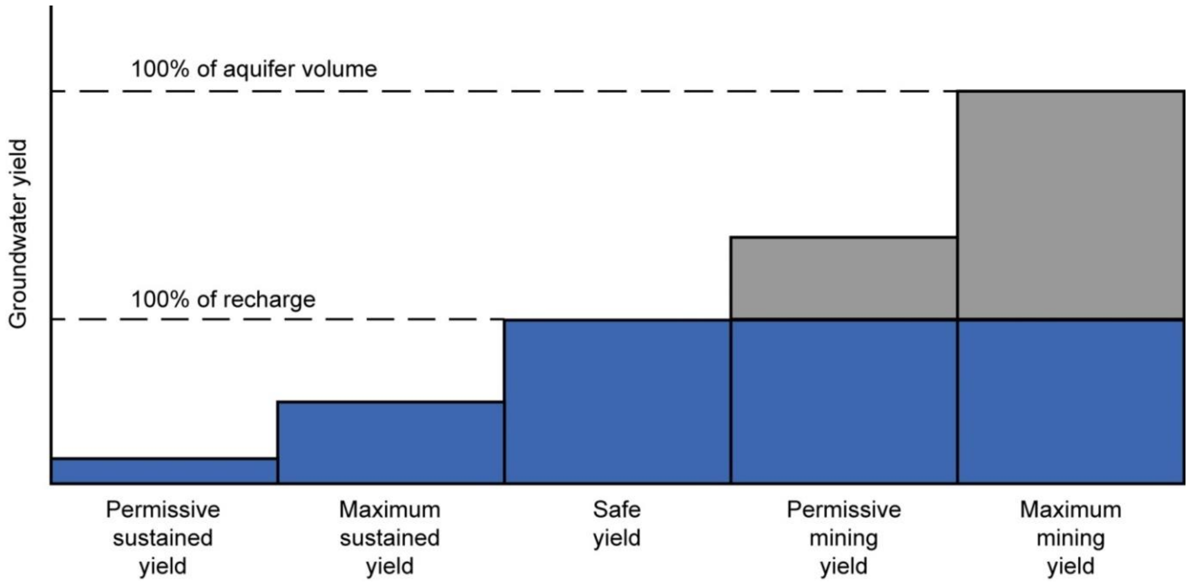

Figure 7. Aquifer-yield continuum as described by Pierce et al. (2013).

Table 1. Methodology for calculating the yields for aquifer-yield classes as outlined by Pierce et al. (2013).

Permissive Sustained Yield	Maximum Sustained Yield	Safe Yield	Permissive Mining Yield	Maximum Mining Yield
$P = R - D_{psy}$	$P = R - D_{msy}$	$P = R$	$P = V_0 - V_{min} + R - D_{min}$	$P = V_0 + R$

P = human-induced discharge (pumping) = 'yield'
R = recharge
D_{psy} = natural discharge required to maintain little to no impact on ecosystems, recreation, or other nonconsumptive uses of groundwater under the permissive sustained yield scenario [$D_{psy} > D_{msy}$]
D_{msy} = natural discharge required to maintain an acceptable impact on ecosystems, recreation, or other nonconsumptive uses of groundwater under the maximum sustained yield scenario [$D_{psy} > D_{msy}$]
V_0 = initial volume of water-saturated aquifer prior to the planning horizon
V_{min} = desired volume of water to remain in storage at the end of the planning horizon
D_{min} = minimum acceptable natural discharge

The Pierce et al. (2013) methodology for determining aquifer-yield continuum, in its current state, has the following strengths:

1) solid grounding in decades of research on sustainable yield
   a) the terminology, definitions, and values of the variables used in the calculation of the different classes of yield are consistent with what has been discussed in the literature on the subject (Domenico, 1972; Sophocleous, 1997; Devlin and Sophocleous, 2005; Kalf and Wooley, 2005)
2) potential to evaluate maximum groundwater allocation and use thresholds in the context of available yield
   a) the values of yield can be compared to groundwater allocations and uses within a region to see if these values exceed yield estimates
3) flexibility to evaluate multiple scenarios of groundwater allocation and use in order to test the influence of different development scenarios on availability of water and possible consequences of decision-making
   a) development scenarios can be proposed and tested against yield matrix values to see if they are likely to be feasible or if alternative licencing considerations might be required for allocating water in the region

4) means to view potential consequences and cumulative effects of water allocation and use in context of other decision criteria
    a) the aquifer-yield continuum can be presented as a yield matrix that is able to display information in a dashboard fashion, in addition to allowing for flexibility in adjusting the proportions assigned to use of recharge and aquifer storage

3 Yield Mapping Methods

3.1 Aquifer-Yield Continuum

The aquifer-yield continuum concept as outlined by Pierce et al. (2013) can be adapted to fit many different hydrogeological systems. For application in central Alberta, calculation of variables such as recharge, natural discharge, and volume of water within a saturated aquifer were tailored specifically for this region. No specific groundwater management time frame was considered, and yield values are reported as an annual volumetric flux.

3.1.1 Recharge

Groundwater recharge is difficult to quantify and a variety of methods can be used to determine appropriate values (Scanlon et al., 2002; Crosbie et al., 2010). One such method uses a water balance approach to equate recharge to discharge. If a majority of groundwater discharges to streams and rivers, discharge (and therefore recharge) can then be quantified by performing a baseflow separation.

The long-term steady-state water balance for groundwater within a watershed may be written as:

$R + G_{in} = D + P + G_{out}$

where R is recharge, D is natural discharge, P is pumping and G_{in} and G_{out} are groundwater flow from and to neighbouring watersheds. For the purpose of this study, two simplifying assumptions were made: (1) G_{in} and G_{out} are the same and (2) the amount of pumping is negligible compared to the volume of water contained with the aquifer. As a result, recharge is equivalent to natural discharge, or 'baseflow' (Figure 8). Baseflow is groundwater that discharges into streams when rain is absent or during dry periods (Rivard et al., 2007) and can be considered a suitable indicator of recharge in a long-term water balance. Baseflow can be divided by surface area of the watershed in order to derive an average rate in units of length per time (mm/yr), which is assumed to be equivalent to recharge. This method assumes that aquifer boundaries coincide with watershed boundaries and that the area that the aquifer contributes groundwater discharge to is the same as the surface drainage area (Healy, 2010). Several assumptions are made when using baseflow to estimate groundwater recharge (assumptions 1 and 2) within a basic water balance (assumptions 3–7):

1) aquifer boundaries coincide with surface watershed boundaries and the area that the aquifer contributes groundwater discharge to is the same as the surface drainage area (Healy, 2010)
2) all groundwater discharge from the aquifer occurs directly into a stream and does not re-infiltrate downstream
3) all water in a stream during low flow periods originates from groundwater discharge
4) no change in aquifer storage
5) no exchange with underlying aquifers
6) no underflow or deep groundwater flow that would discharge outside of the watershed boundaries
7) no influence on groundwater due to pumping or injection
8) no loss of groundwater due to evapotranspiration

To constrain the source of baseflow, interpretation of stream hydrographs can be completed for regions having a relatively uniform geological setting (e.g., predominantly bedrock). In the study area, the predominance of bedrock occurring close to the ground surface coincides with the extent of bedrock in the Cretaceous–Paleogene, resulting in streamflow hydrographs that generally indicate groundwater sourced from bedrock formations. Bedrock aquifers that are close to ground surface typically occur in the west and central areas of Alberta (Lemay and Guha, 2009, Figure 5).

3.1.1.1 Hydrometric Data and Zone Delineation

Hydrometric data along streams and rivers have been collected and catalogued by the Water Survey of Canada since 1908. These data are reviewed and published by Environment and Climate Change Canada in a digital database called HYDAT (Environment and Climate Change Canada, 2016). The HYDAT database contains measured and computed data for various hydrometric gauging stations. Data may include daily and monthly means of flow, water levels, and sediment concentrations for sediment stations. The Agriculture and Agri-Food Canada (AAFC) Watersheds Project (Agriculture and Agri-Food Canada, 2012) is based on data from hydrometric gauging stations in the HYDAT database. The AAFC watersheds are divided into sub-basin (e.g., 07A), sub-sub-basin (e.g., 07AG) or at the smallest level, an incremental drainage area, which is a particular hydrometric gauging station's drainage basin and is between itself and the next upstream gauging station(s) (e.g., 07AG004; Figure 9).

The AAFC incremental drainage areas form the basic unit for the aquifer-yield assessment in central Alberta. However, some gauging stations are either not currently active, are 'dummy' stations between distant hydrometric stations, or are influenced by the presence of control structures such as dams or reservoirs, which make it difficult to assess the natural flow of rivers. Therefore, zones were created within the study area based on incremental drainage areas that had corresponding hydrometric gauging station data and did not contain a dam or reservoir. When a station did not have flow data, incremental drainage areas were merged together at the sub-sub-basin level or sub-basin level depending on available data (Figure 9).

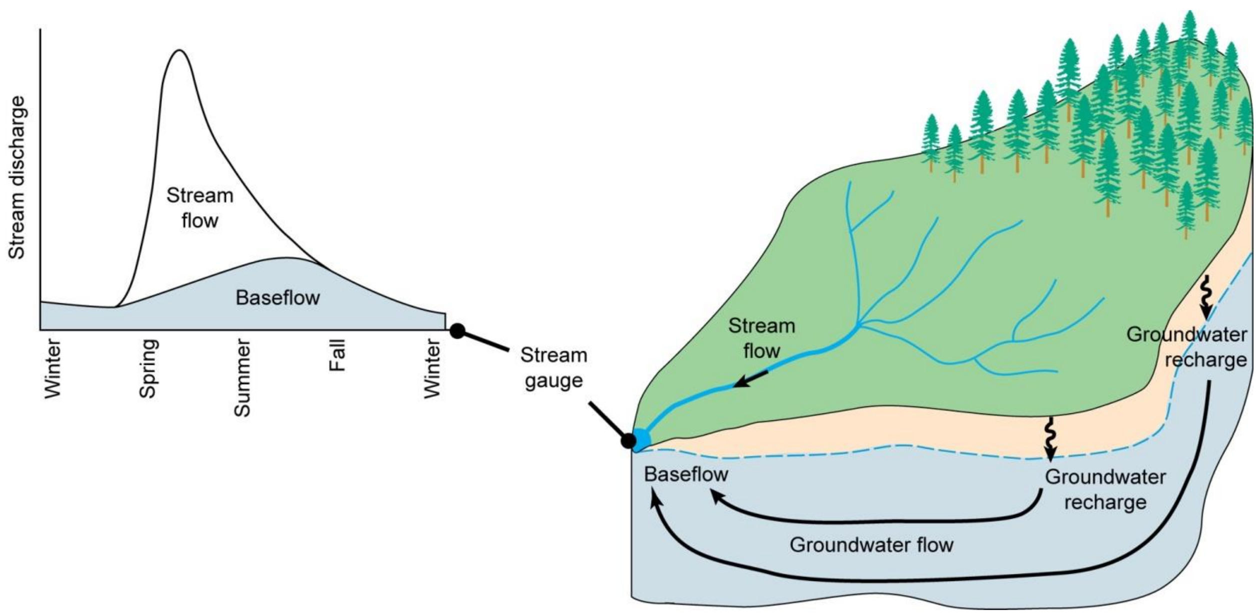

Figure 8. Conceptual diagram of baseflow recorded at hydrometric stream gauging stations.

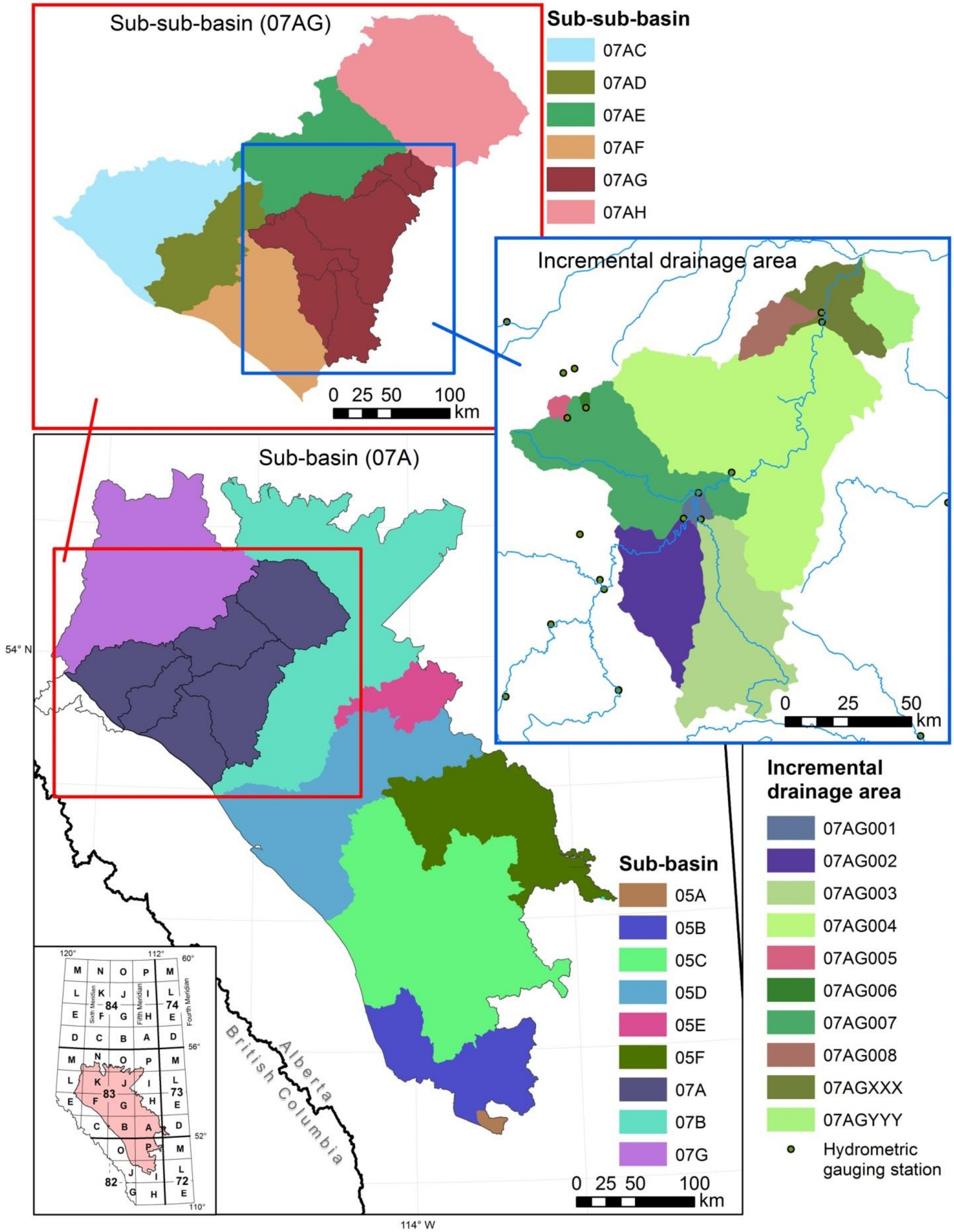

Figure 9. Agriculture and Agri-Food Canada watersheds divided into sub-basin, sub-sub-basin and incremental drainage area in central Alberta (Agriculture and Agri-Food Canada, 2012).

If an incremental drainage area extended past the geological boundaries considered in this study (i.e., western edge of Paskapoo Formation, northern edge of Wapiti Formation, eastern edge of Horseshoe Canyon Formation and southern edge of Scollard Formation; e.g., sub-basin 07A, Figure 9), the zone was truncated at that boundary. In total, 98 zones were created (Figure 10) and the aquifer yield values (Table 1) were calculated for each zone.

3.1.1.2 Estimating Baseflow for Recharge

Baseflow at each hydrometric gauging station is determined using recorded streamflow rates from the HYDAT database (Environment and Climate Change Canada, 2016). The number of years of streamflow data varies by station, with a minimum, median, and maximum of 3, 42, and 103 years, respectively for stations within the study area. Additionally, some hydrometric gauging stations are active year-round, while others are not active during the winter. The HYDAT database was brought into an internal statistical spreadsheet tool that aggregates daily data into weekly and monthly data to supplement record gaps. Monthly 50th, 20th, and 5th percentiles were calculated from average monthly flows for each year on record (e.g., Figure 11). These values are expressed as a percent exceedance and are referred to as the Q50, Q80, and Q95, respectively. A conservative approach was used for the aquifer-yield continuum, therefore, the lowest monthly Q95 (i.e., 5th percentile) streamflow value was chosen as being representative of baseflow for each hydrometric gauging station within the study area (e.g., Figure 11).

A limitation to the statistical spreadsheet tool is that when a station has very low flows or flows are only recorded seasonally, the data are not sufficient to determine a representative Q95 for that month. Instead the spreadsheet tool provides a default monthly Q95 value of 0.0001 m^3/s. To overcome this limitation, when a station had a monthly Q95 value of 0.0001 m^3/s for six months or more, the lowest average monthly streamflow value was used as an alternative to the lowest monthly Q95. This method was used on 27 stations and the alternative value assigned is shown in Figure 12.

The Q95 determined for each hydrometric station is not representative of baseflow generated solely within that zone; rather, it is an accumulation of baseflow up until that point and may include baseflow from many zones depending on how many tributary zones are located upstream. Therefore, the Q95 had to be modified in order to determine baseflow generated within each zone. To do so, the Q95 value(s) from hydrometric station(s) immediately upstream of each zone were subtracted from the Q95 of that zone. For zones derived from incremental drainage areas that are entirely within the study area boundary, the resulting value is considered representative of baseflow for that zone. For zones derived from incremental drainage areas that are partly outside the study area (i.e., at the edges, Figure 10), the resulting value was scaled based on the percentage of the incremental drainage area within the study area boundary in order to represent baseflow for that particular zone (Figure 13).

3.1.2 Discharge

For the aquifer-yield continuum, permissive sustained yield discharge (D_{psy}), maximum sustained yield discharge (D_{msy}), and minimum acceptable natural discharge (D_{min}) represent the natural discharge that is allowed to stay in the natural system and will not be used for anthropogenic sources under various yield scenarios. Actual values for the desired amount of natural discharge under each yield scenario are not available for this study area, therefore, values were assumed for the purpose of this study. These values can be modified to be site specific, depending on how conservative an approach is necessary.

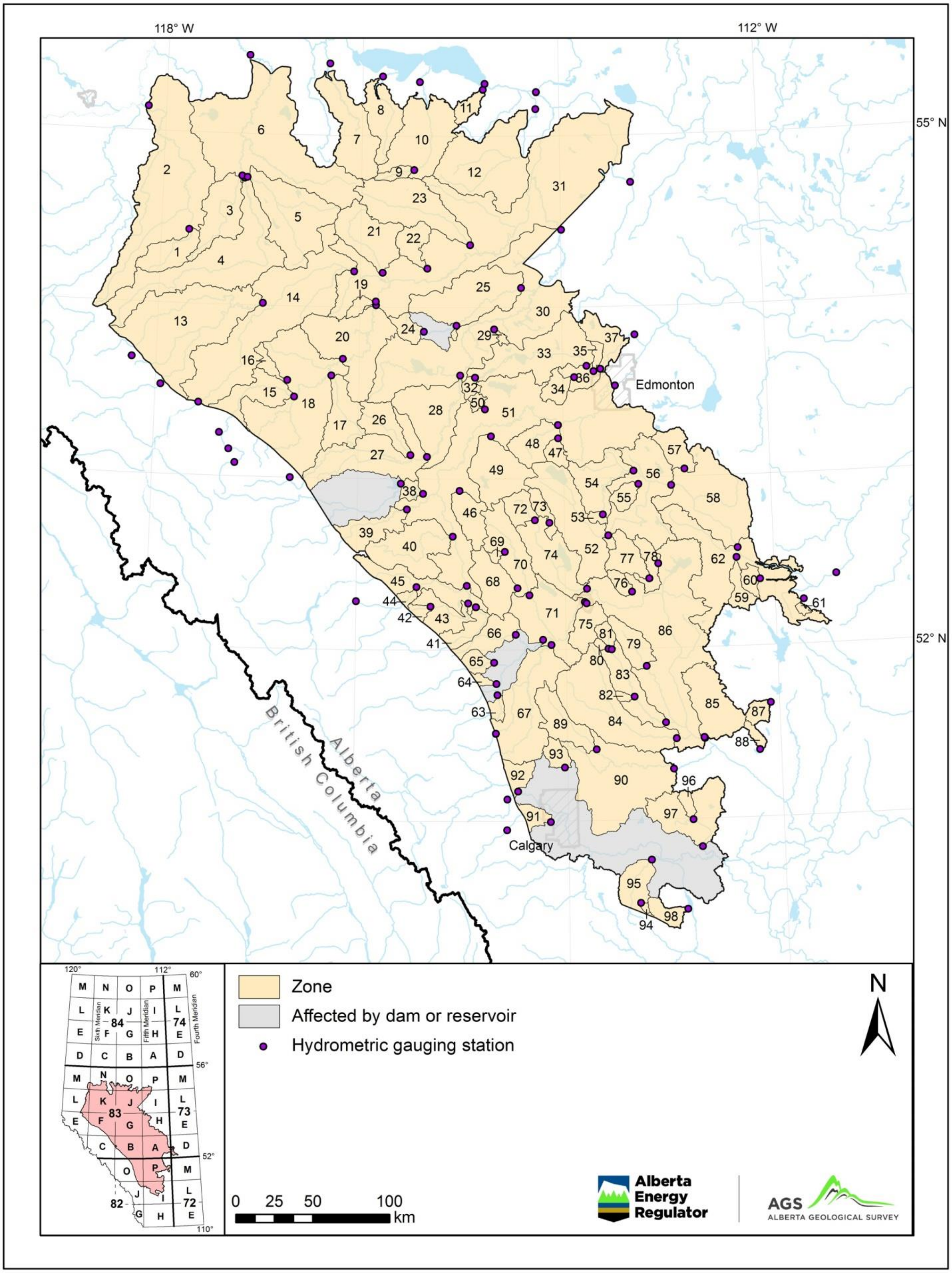

Figure 10. Designated zones and corresponding hydrometric gauging station, central Alberta.

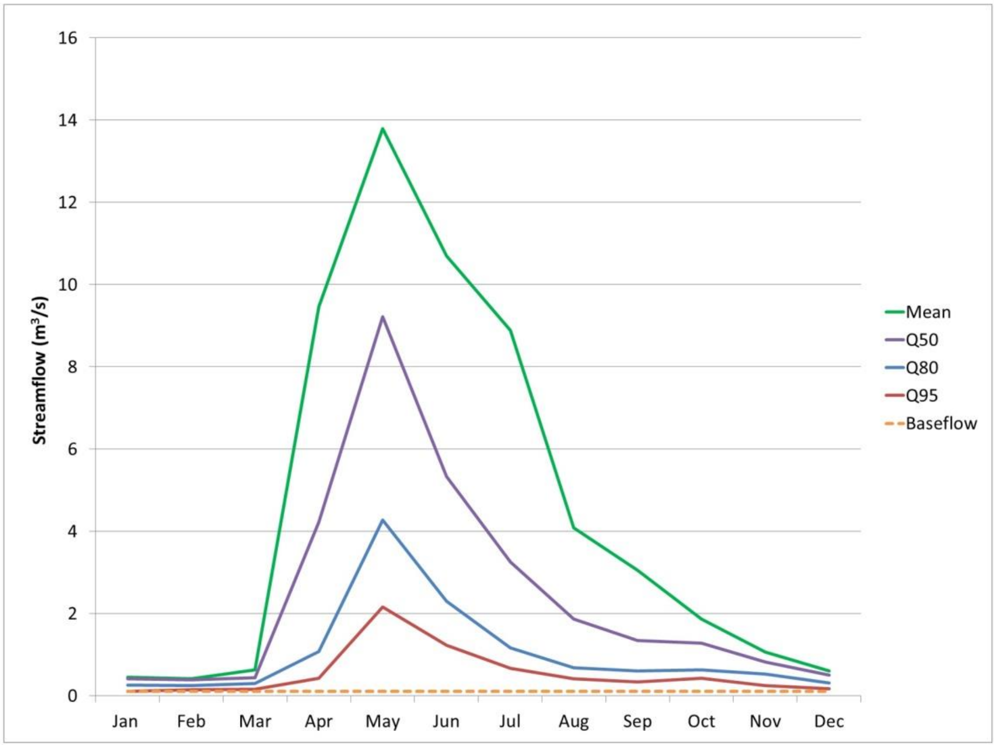

Figure 11. Average (mean) Q50, Q80, and Q95 (percent exceedance for the 50th, 20th, and 5th percentiles) monthly streamflow for hydrometric gauging station 07GG001, central Alberta (Zone 3 in Figure 10); in this case, the lowest monthly Q95 was 0.11 m^3/s and it occurred during the month of January.

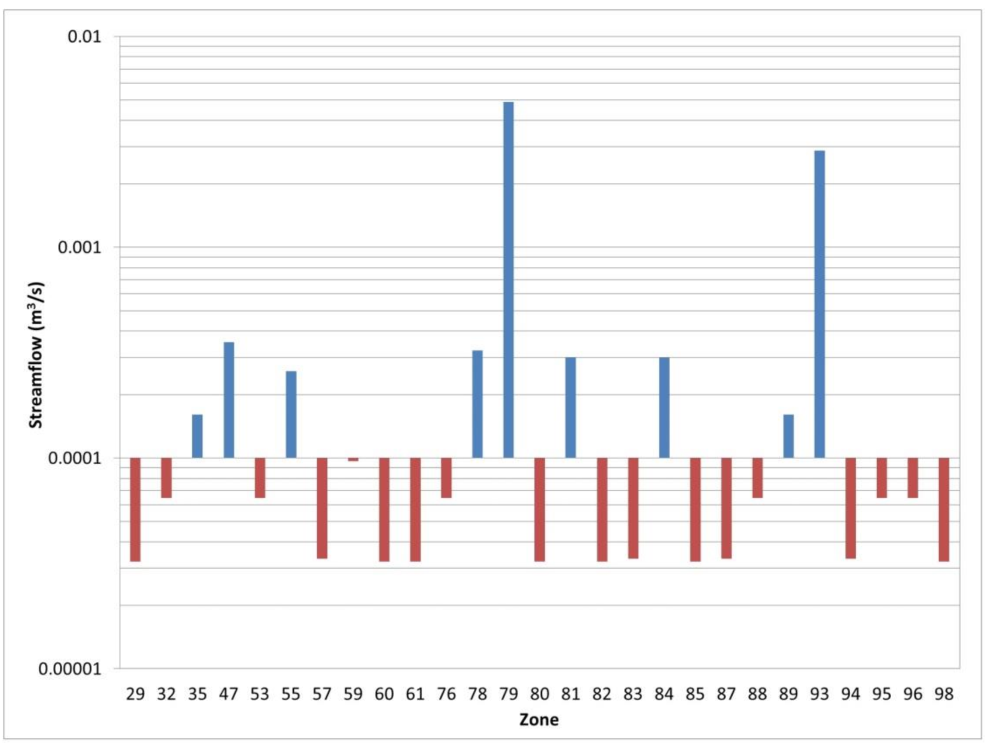

Figure 12. Lowest average monthly recorded streamflow used as alternative when Q95 was 0.0001 m^3/s for six months or more. Designated zones are shown on Figure 10 (central Alberta).

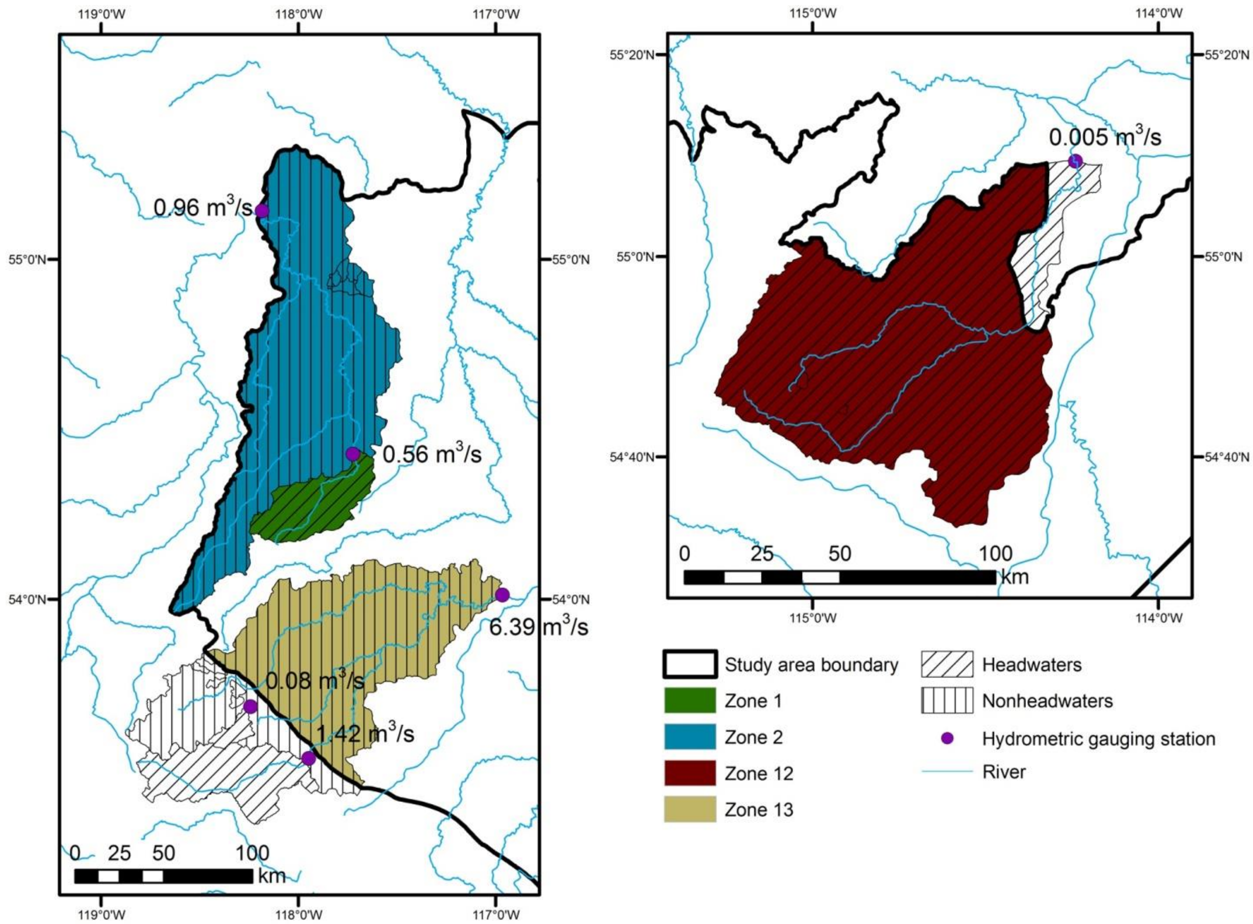

Figure 13. Zones 1 and 2 were created from incremental drainage basins that did not extend past the study area (geological) boundaries whereas Zones 12 and 13 were truncated (central Alberta). Diagonal lines represent headwater zones (Zones 1 and 12) and vertical lines represent zones that receive streamflow from zones upstream (Zones 2 and 13).

Assuming the baseflow determined previously for each zone (Section 3.1.1) is representative of current natural discharge (D), 50% of the value of D was permitted for the maximum sustained yield (MSY), whereas for permissive sustained yield (PSY), a conservative 90% of the value of D was permitted (Table 2). This method is equivalent to saying that under the PSY scenario, 10% of recharge is available for pumping, because baseflow values were also used to estimate recharge using the water balance approach.

Table 2. Calculation of discharge for permissive sustained and maximum sustained yields.

Permissive Sustained Yield	Maximum Sustained Yield
$P = R – D_{psy}$	$P = R – D_{msy}$
$P = R – (D \times 90\%)$	$P = R – (D \times 50\%)$

P = human-induced discharge (pumping) = 'yield'
R = recharge
D_{psy} = natural discharge required to maintain little to no impact on ecosystems, recreation, or other nonconsumptive uses of groundwater under the permissive sustained yield scenario [$D_{psy} > D_{msy}$]
D_{msy} = natural discharge required to maintain an acceptable impact on ecosystems, recreation, or other nonconsumptive uses of groundwater under the maximum sustained yield scenario [$D_{psy} > D_{msy}$]
D = current natural discharge

For determining permissive mining yield, D_{min} was excluded or considered to be zero because there is no way to distinguish if water that is extracted would have become natural discharge or if it came from aquifer storage. As a result, all water that was available to be extracted for this class was presumed to be from recharge and aquifer storage.

3.1.3 Volume of Water in Storage

For each zone (Figure 10), aquifer yield was determined considering the uppermost bedrock unit(s) and overlying sediments only (Figure 14). The extent of the uppermost bedrock unit was determined using the AGS's bedrock geology Map 600 (Prior et al., 2013). The AGS approach to calculating the initial volume of a water-saturated aquifer (V_0) was based on four assumptions: (1) water moves through, is stored, and extracted from the uppermost bedrock unit and overlying sediments; (2) a hydraulic connection between adjacent formations does not occur in response to pumping; (3) the estimate of porosity represents the effective porosity in the calculation of the quantity of recoverable water; and (4) the units are homogeneous.

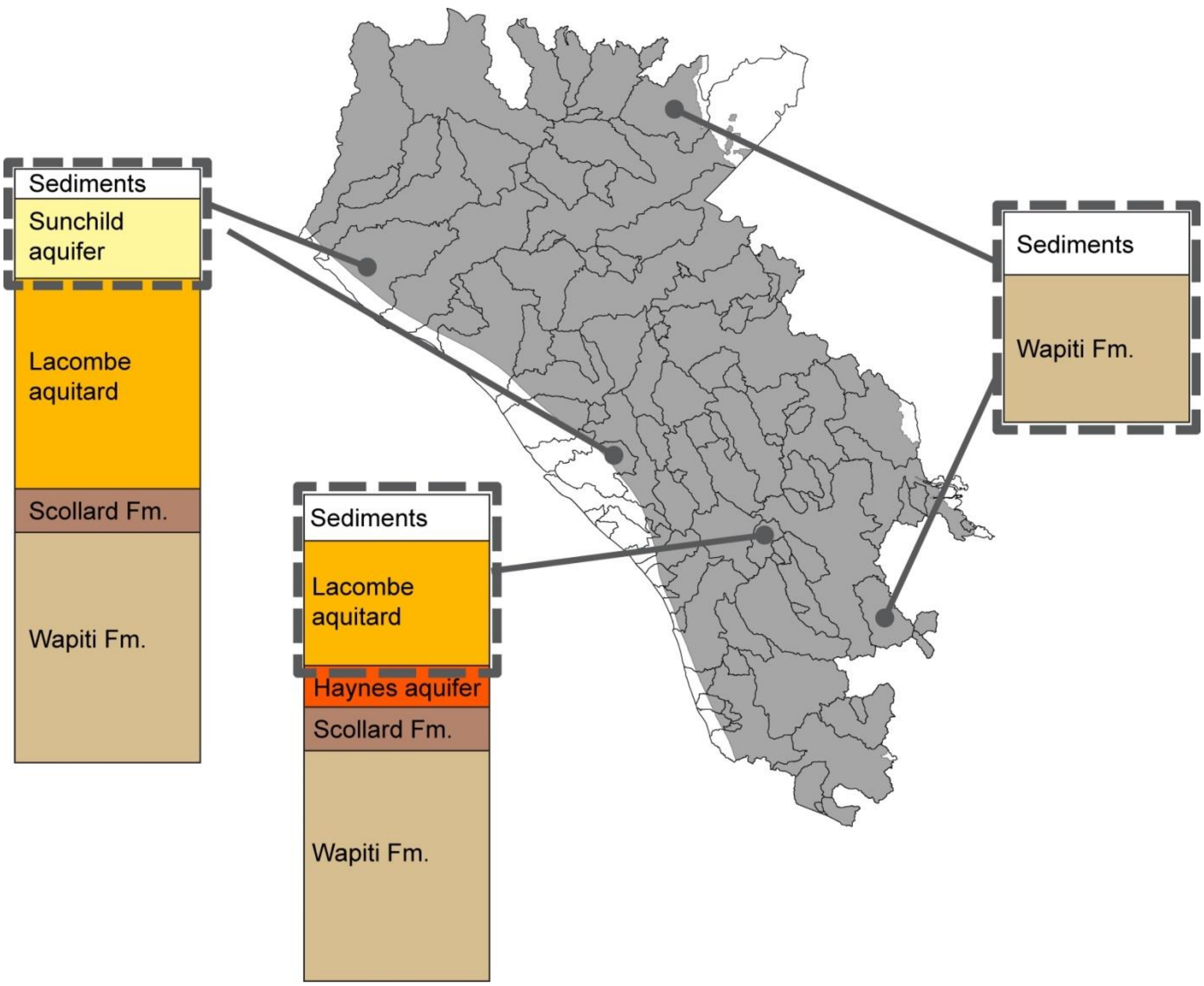

Figure 14. Examples of hydrostratigraphic columns from the study area (central Alberta), with the dashed line indicating the representative thickness of uppermost bedrock formation and sediments, which was used to calculate aquifer volume for each zone. The areal extent of the three-dimensional geological model (Lyster and Andriashek, 2012) used to calculate volume is shown in grey.

Bedrock thickness data were obtained using a 3D geological model from Lyster and Andriashek (2012) in addition to internal data sources at the AGS. Thickness data were available for the Paskapoo Formation, which was further divided into Sunchild, Lacombe, and Haynes units, and for the Scollard, Wapiti, and Horseshoe Canyon formations. However, the 3D geological model did not cover the entire extent of the study area (Figure 14) as the western edge of the model correlates with the deformation belt and along the eastern edge where formations pinch out there is some variability between the model and Map 600 (Prior et al., 2013). To account for the bedrock thickness that was missing along the western edge of Paskapoo Formation and eastern portions of lower Wapiti and Horseshoe Canyon formations, thickness of the uppermost bedrock unit was assumed based on the average bedrock thickness along the boundary of the 3D geological model for each zone. Thickness of the sediments overlying bedrock was obtained from MacCormack et al. (2015). Using the extent and thickness data, the volume of each uppermost bedrock unit and overlying sediments could be determined within each zone.

To calculate the amount of water stored in each zone (i.e., V_0), the uppermost bedrock unit(s) volume(s) and overlying sediments volume were multiplied by an effective porosity value. Aquifers (i.e., lower and upper Wapiti formations, Horseshoe Canyon Formation, Scollard Formation, and Sunchild and Haynes units of the Paskapoo Formation) were assigned a porosity of 0.3, aquitards (i.e., Lacombe unit of the Paskapoo Formation) were assigned a porosity of 0.1 and the overlying sediments were assigned a porosity of 0.2. Areas west of the deformation belt were assigned a porosity value of 0.2 because the 3D geological model did not cover that location and therefore could not be used to distinguish between the Sunchild and Haynes aquifers and the Lacombe aquitard.

The V_0 is used to calculate permissive mining yield (PMY) and maximum mining yield (MMY). The entire volume of stored water in addition to recharge is available for use in the MMY, whereas only a fraction of the aquifer volume is available for use in the PMY. For this study, the desired volume of water to remain in storage (V_{min}) was considered as 99% of V_0; therefore, only 1% of aquifer storage, in addition to recharge, can be extracted in the PMY class (D_{min} is zero). It should be noted that this study does not consider a specific water management planning time frame and therefore assumes that the volume of water stored in the aquifer is extracted within a single year. For management purposes, the volume of water removed from storage may be spread out over a designated time frame.

3.2 Limitations

Limitations to this aquifer-yield method include

1) removal of zones from the yield matrix calculations due to the presence of control structures, such as dams and reservoirs, which interfere with the natural flow of rivers and corresponding baseflow separation; the southern region of the study area, specifically around Calgary is heavily regulated along the Elbow and Bow rivers; watersheds not included in the study area include those that contain the Brazeau Reservoir, Bassano dam, Bearspaw dam, Carseland dam, Dickson dam, Glenmore Reservoir, and Paddle River reservoir;
2) limited spatial distribution and quantity of measurements of baseflow and aquifer properties;
3) assumptions around determining baseflow and aquifer properties which include
    a) recharge can be calculated using baseflow obtained from hydrometric gauging stations
    b) estimates of yield based on long-term average values of baseflow without accounting for seasonal variability or climatic trends
    c) hydrogeological units are homogeneous when in actuality hydrogeological units are heterogeneous; therefore, not all units have the same spatial ability to produce water at the yield rates in a sustainable fashion, with some portions of units not capable of producing water at rates usable for domestic, agriculture, or industrial purposes at all; even though broad-scale variability

within the Paskapoo Formation was taken into consideration (two aquifers and one aquitard), there is still variability within each of the units;

4) assumption that all water that recharges into, flows out of, and is stored in each unit is available to all wells in that unit regardless of where they are located; this can make it appear that more water is available within a unit than actually is, since portions of the unit far away from where pumping is occurring will contribute less water to pumping wells compared to portions that are closer to pumping wells;
5) aquifer-yield method is an analytical solution, not a calibrated model that allows for detailed analysis of scenarios where changes in recharge, baseflow, and use can be tested over a long period of time;
6) assumption that the uppermost bedrock unit and overlying sediments are saturated; the unsaturated zone was not included when calculating V_0:
   a) the unsaturated zone varies in thickness throughout the study area; this first-order study attempted to reduce complexity by not including the influence of the unsaturated zone on storage and rates of water movement
   b) an example volume calculation was done for Zone 1 with the assumption of an unsaturated zone 4 m thick; the water volume for an aquifer that included an unsaturated zone was 98% of the water volume without the unsaturated zone; as a result, it was assumed that including the unsaturated zone would not make a significant difference
   c) for future studies, the unsaturated zone could be incorporated in the volume calculation if more detailed information is available;
7) yield classes are reported as an annual volumetric flux, resulting in the permissive mining yield and maximum mining yield to be significantly larger than other yield classes because it assumes the entire volume of water in storage is available for use within a one-year time frame; for management purposes, the volume of water removed from storage should be spread out over a designated time frame.

4 Results

An aquifer-yield matrix was created for the 98 zones in the study area using the equations described in Table 1 (Appendix 1). For each zone, all five yield classes were calculated considering the uppermost bedrock unit and overlying sediments only. Safe yield is the midpoint of the yield matrix and represents the maximum amount of groundwater that can be extracted without quickly depleting groundwater storage (Figure 15). The northern part of the study area is characterized by larger safe yields, up to 1.0E9 m^3/yr along the Athabasca, McLeod, Pembina, and North Saskatchewan rivers. Yields decrease towards the southeast with values up to 1.0E6 m^3/yr. There are 10 zones that have a safe yield of zero, meaning that water extracted from these regions would not be sustainable and groundwater would be mined from aquifer storage.

Figure 16 shows safe yield as mm/yr, which accounts for the size of the watershed. Safe yield appears to be related to the physiographic and natural regions present in the study area (Figures 3 and 4). Zones within the Southern Alberta Uplands receive the most amount of recharge and therefore have the highest values of safe yield, which is equivalent to recharge (Table 1). As the physiographic regions transition eastwards into the Western and Eastern Alberta plains and uplands, recharge and safe yield decreases to 0–1 mm/yr. Only 10% of the study area has a safe yield of more than 25 mm/yr.

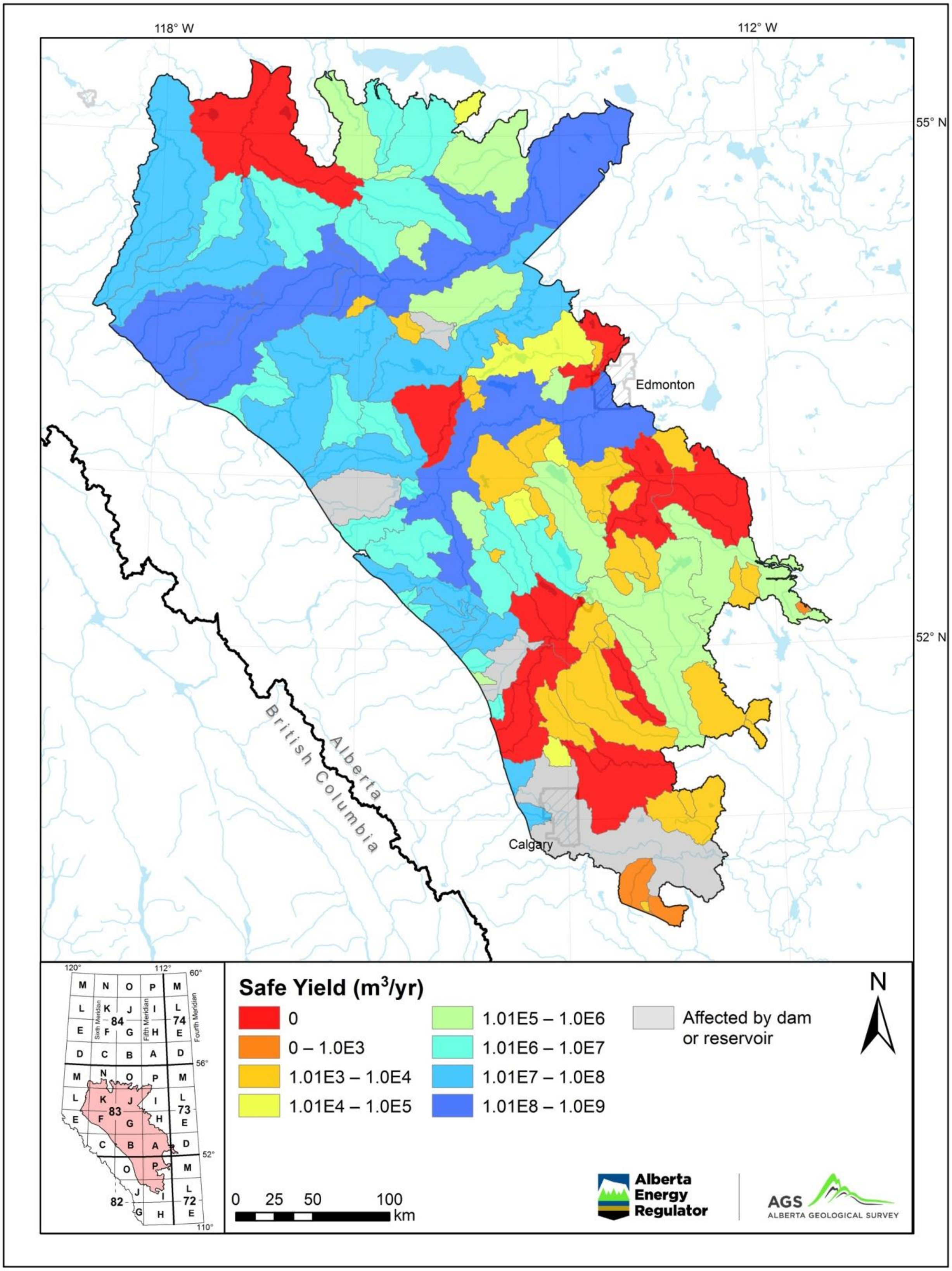

Figure 15. Safe yield expressed in m^3/yr for each watershed zone, central Alberta. Zones affected by a dam or reservoir are shown in grey.

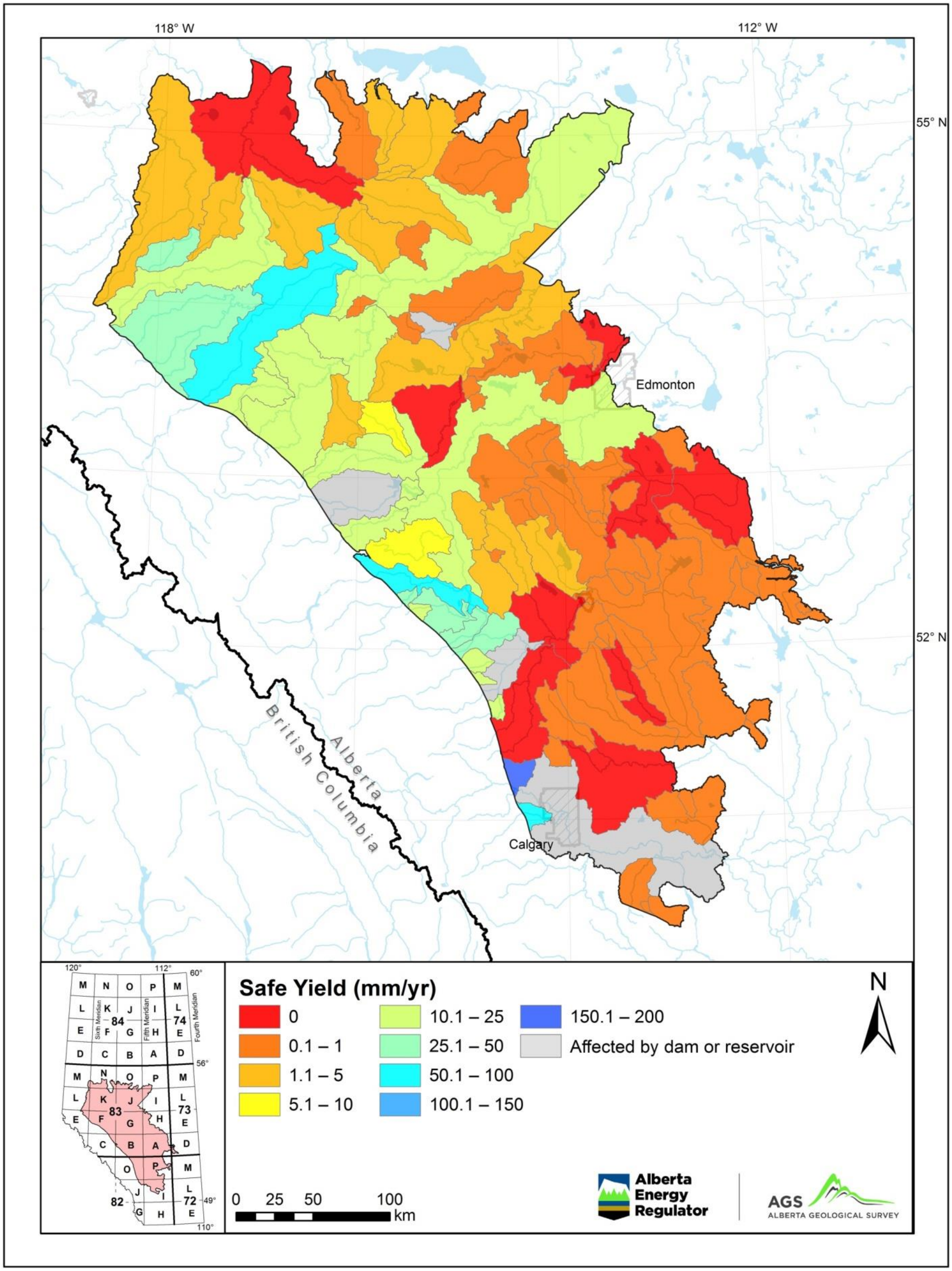

Figure 16. Safe yield expressed in mm/yr for each watershed zone, central Alberta. Zones affected by a dam or reservoir are shown in grey.

The significantly low recharge rates in the southeast between Edmonton and Calgary, and in turn safe yield results, contrast previous work by the AGS (Riddell et al., 2014) where recharge rates ranged from 0 to 235 mm/yr. Rather than using stream hydrographs to estimate recharge, Riddell et al. (2014) calculated recharge using a residual water balance method; where recharge was equal to precipitation minus actual evapotranspiration and sublimation and annual runoff divided by area of drainage basin. Recharge estimation was based on maps/gridded raster files for the various parameters and equations were calculated in ArcGIS. The baseflow approach used in the current study found relatively low recharge rates, and in some cases absence of recharge. For these specific zones, it is expected that although recharge is minimal, variations in precipitation would lead to some recharge occurring periodically. Additionally, the baseflow separation approach does not account for groundwater that discharges to riparian zones and is evapotranspired before reaching the river.

To examine the effect of using the simplified baseflow approach, which represents long-term averages as derived from streamflow records, a sensitivity analysis was performed. Baseflow was calculated from the 20th and 10th percentiles (expressed as Q80 and Q90 exceedances) for each hydrometric gauging station and compared to the Q95 values used in this study. Using Q80 and Q90 values would lead to an increase in the estimated baseflow and in turn, the safe yield. When Q90 values are used, the safe yield estimates increase by 0.02–10.8 mm/yr with a mean of 2.5 mm/yr. When Q80 values are used, the safe yield estimates increase by 0.002–26.9 mm/yr with a mean of 3.9 mm/yr. Although the resultant safe yield values are slightly higher, the general magnitude remains the same.

Future steps that could address the limitations and weakness identified in completing this first-order groundwater availability assessment include:

1) modifying the approach for estimating recharge as the baseflow approach is not suitable for all parts of Alberta;
2) optimize the level of detail necessary to adequately characterize the heterogeneity and extent of the hydrogeological units within the study area for the purpose of calculating aquifer yield values; and
3) implement a groundwater model within a recharge-constrained sub-basin to more closely examine groundwater availability under different recharge and development scenarios.

5 Summary

A new approach to mapping groundwater yield in Alberta, based on an aquifer-yield continuum, was applied in central Alberta, specifically to near-surface bedrock formations containing nonsaline groundwater. The aquifer-yield continuum classifies groundwater yield along a spectrum that helps define total groundwater availability. Safe yield is considered to be the maximum amount of groundwater that can be extracted without depleting groundwater storage and was the chosen parameter used for creating water yield maps for central Alberta. The northern part of the study area is characterized by larger yields up to 1.0E9 m^3/yr, which decrease towards the southeast with values up to 1.0E6 m^3/yr. There are several areas that have a safe yield of zero resulting in water extraction that would not be sustainable over long periods of time and where groundwater would likely be mined from aquifer storage. This report demonstrates a conservative application of the aquifer-yield continuum concept for a large portion of the province underlain by relatively near-surface bedrock aquifers. Future work will focus on adapting the aquifer-yield continuum for other regions in Alberta to estimate groundwater availability.

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Appendix 1 – Yield Matrix

Zone	PSY (m^3/yr)	MSY (m^3/yr)	SY (m^3/yr)	PMY (m^3/yr)*	MMY (m^3/yr)*
1	1.76E06	8.78E06	1.76E07	2.06E08	1.88E10
2	1.27E06	6.35E06	1.27E07	2.48E09	2.47E11
3	3.49E05	1.74E06	3.49E06	3.09E08	3.06E10
4	5.96E06	2.98E07	5.96E07	8.37E08	7.78E10
5	5.84E05	2.92E06	5.84E06	5.72E08	5.66E10
6	0	0	0	3.85E09	3.85E11
7	1.84E04	9.22E04	1.84E05	7.85E08	7.85E10
8	1.00E05	5.01E05	1.00E06	4.41E08	4.40E10
9	2.52E04	1.26E05	2.52E05	2.71E07	2.69E09
10	2.65E05	1.32E06	2.65E06	1.06E09	1.06E11
11	6.19E03	3.10E04	6.19E04	1.21E08	1.21E10
12	1.44E04	7.22E04	1.44E05	1.21E09	1.21E11
13	1.15E07	5.73E07	1.15E08	1.59E09	1.48E11
14	2.08E07	1.04E08	2.08E08	1.81E09	1.60E11
15	9.75E05	4.87E06	9.75E06	4.00E08	3.90E10
16	3.78E05	1.89E06	3.78E06	5.85E07	5.47E09
17	2.25E05	1.12E06	2.25E06	4.20E08	4.18E10
18	4.93E06	2.46E07	4.93E07	1.86E09	1.81E11
19	3.15E02	1.57E03	3.15E03	3.95E07	3.95E09
20	4.28E06	2.14E07	4.28E07	5.67E08	5.25E10
21	4.47E05	2.24E06	4.47E06	2.02E08	1.97E10
22	2.08E04	1.04E05	2.08E05	2.63E08	2.63E10
23	3.31E05	1.65E06	3.31E06	7.63E08	7.60E10
24	3.15E02	1.57E03	3.15E03	2.85E07	2.85E09
25	3.77E04	1.88E05	3.77E05	1.49E09	1.49E11
26	5.67E05	2.83E06	5.67E06	2.31E08	2.26E10
27	2.97E06	1.48E07	2.97E07	1.12E09	1.09E11
28	0	0	0	3.99E08	3.99E10
29	1.02E02	5.08E02	1.02E03	4.08E07	4.08E09
30	1.52E06	7.60E06	1.52E07	1.75E09	1.73E11
31	1.64E07	8.19E07	1.64E08	3.31E09	3.15E11
32	2.03E02	1.02E03	2.03E03	1.24E07	1.24E09
33	2.95E03	1.48E04	2.95E04	9.82E08	9.82E10
34	1.57E04	7.86E04	1.57E05	1.84E08	1.84E10
35	5.07E02	2.53E03	5.07E03	2.94E07	2.94E09
36	0	0	0	3.89E06	3.89E08
37	0	0	0	1.29E08	1.29E10
38	3.39E05	1.70E06	3.39E06	7.53E07	7.19E09
39	9.08E05	4.54E06	9.08E06	8.07E08	7.98E10
40	7.37E05	3.69E06	7.37E06	1.33E09	1.32E11
41	1.26E06	6.32E06	1.26E07	2.87E08	2.74E10
42	2.23E05	1.12E06	2.23E06	1.24E08	1.22E10
43	2.35E06	1.18E07	2.35E07	6.66E08	6.42E10
44	3.76E05	1.88E06	3.76E06	1.13E08	1.10E10
45	5.63E06	2.82E07	5.63E07	9.96E08	9.41E10
46	5.70E04	2.85E05	5.70E05	1.91E08	1.91E10
47	1.12E03	5.59E03	1.12E04	3.15E07	3.14E09
48	3.15E02	1.57E03	3.15E03	9.85E07	9.85E09
49	3.15E02	1.58E03	3.15E03	2.99E08	2.99E10
50	3.15E02	1.57E03	3.15E03	1.36E07	1.36E09
51	1.44E07	7.22E07	1.44E08	2.77E09	2.62E11
52	5.67E04	2.83E05	5.67E05	3.15E08	3.15E10
53	2.03E02	1.02E03	2.03E03	1.24E07	1.24E09
54	1.12E02	5.59E02	1.12E03	3.49E08	3.49E10
55	8.13E02	4.06E03	8.13E03	1.34E08	1.34E10
56	0	0	0	8.92E08	8.92E10
57	1.05E02	5.25E02	1.05E03	1.59E08	1.59E10
58	0	0	0	4.07E08	4.07E10
59	3.05E02	1.53E03	3.05E03	8.34E07	8.34E09

Zone	PSY (m^3/yr)	MSY (m^3/yr)	SY (m^3/yr)	PMY (m^3/yr)*	MMY (m^3/yr)*
60	1.02E02	5.09E02	1.02E03	3.79E07	3.79E09
61	6.50E01	3.25E02	6.50E02	2.66E06	2.66E08
62	2.05E04	1.02E05	2.05E05	7.12E08	7.12E10
63	2.24E05	1.12E06	2.24E06	1.04E08	1.02E10
64	7.70E04	3.85E05	7.70E05	8.03E07	7.96E09
65	4.62E05	2.31E06	4.62E06	2.18E08	2.13E10
66	2.04E06	1.02E07	2.04E07	2.93E08	2.73E10
67	0	0	0	1.05E09	1.05E11
68	1.51E05	7.56E05	1.51E06	2.42E08	2.41E10
69	3.15E02	1.57E03	3.15E03	1.99E07	1.99E09
70	1.32E05	6.60E05	1.32E06	3.13E08	3.11E10
71	0	0	0	3.80E08	3.80E10
72	9.45E03	4.72E04	9.45E04	1.15E08	1.14E10
73	3.15E02	1.57E03	3.15E03	5.31E07	5.31E09
74	1.70E05	8.49E05	1.70E06	2.77E08	2.75E10
75	3.15E02	1.57E03	3.15E03	8.69E07	8.69E09
76	2.03E02	1.02E03	2.03E03	2.18E07	2.18E09
77	3.15E02	1.57E03	3.15E03	7.20E07	7.20E09
78	6.76E02	3.38E03	6.76E03	1.06E08	1.06E10
79	1.55E04	7.73E04	1.55E05	8.28E07	8.27E09
80	1.02E02	5.08E02	1.02E03	9.37E06	9.37E08
81	8.43E02	4.22E03	8.43E03	3.28E07	3.28E09
82	1.02E02	5.08E02	1.02E03	9.65E06	9.65E08
83	0	0	0	1.30E08	1.30E10
84	9.10E02	4.55E03	9.10E03	5.03E08	5.03E10
85	1.02E02	5.09E02	1.02E03	4.70E08	4.70E10
86	8.59E04	4.30E05	8.59E05	1.40E09	1.40E11
87	1.05E02	5.25E02	1.05E03	4.31E07	4.31E09
88	2.03E02	1.02E03	2.03E03	9.31E06	9.31E08
89	5.07E02	2.53E03	5.07E03	2.48E08	2.48E10
90	0	0	0	5.36E08	5.36E10
91	2.04E06	1.02E07	2.04E07	1.13E08	9.24E09
92	5.58E06	2.79E07	5.58E07	2.81E08	2.26E10
93	9.04E03	4.52E04	9.04E04	9.11E07	9.11E09
94	1.05E02	5.24E02	1.05E03	5.49E06	5.49E08
95	6.80E01	3.40E02	6.80E02	1.43E08	1.43E10
96	2.03E02	1.02E03	2.03E03	4.55E07	4.55E09
97	1.12E02	5.59E02	1.12E03	3.87E08	3.87E10
98	8.06E01	4.03E02	8.06E02	7.37E07	7.37E09

*Assuming the total volume of water in aquifer storage can be extracted within a one-year time frame. For management purposes, the volume of water removed from storage may be spread out over a designated time frame.

Abbreviations: MMY, maximum mining yield; MSY, maximum sustained yield; PMY, permissive mining yield; PSY, permissive sustained yield; SY, safe yield.