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Alberta Energy Regulator

First-Order Groundwater Availability Assessment for the Upper Peace Region

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J. Klassen and J.E. Liggett

Alberta Energy Regulator
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Abstract

Groundwater is an important resource in Alberta. It is necessary to quantify the amount of groundwater available to compare with total groundwater allocation, and evaluate the risk associated with potential groundwater withdrawals due to increased development. The Alberta Geological Survey (AGS) has adopted an approach to provide a regional first-order assessment of groundwater availability in Alberta based on an aquifer yield continuum concept. Groundwater yield within 150 m below ground surface is quantified along a spectrum of total groundwater availability and is bound by two extremes: nonuse and maximum mining. The aquifer yield continuum depends on hydrogeological parameters such as recharge, discharge, and aquifer volume, and the method of quantifying these parameters may vary depending on scale, data availability, hydrogeological regime, climate, and landscape characteristics of the study area. Other governing factors such as environmental flow needs, and input from the community and local stakeholders can be accounted for to manage the degree of impact of groundwater withdrawal on the hydrogeological system.

This report documents the work completed in part of the upper Peace region and is the third area in Alberta mapped using the aquifer yield continuum approach. The aquifer yield continuum can be divided into five classes: nonuse, permissive sustained yield, maximum sustained yield, permissive mining yield, and maximum mining yield. The permissive sustained and permissive mining yields fall along the continuum at some point between nonuse and maximum sustained yield, and maximum sustained yield and maximum mining yield, respectively. The nonuse, maximum sustained yield, and maximum mining yield are constrained by the physical hydrogeological system. This study focuses primarily on the maximum sustained yield, which is equated to the natural rate of recharge. It is the maximum amount of groundwater that is available in the hydrogeological system without mining groundwater. Previous studies in central and southern Alberta used two different approaches for quantifying recharge. This report describes how both methods were used in the upper Peace region, as the data availability and hydrogeological regime varies throughout the study area. In the agricultural areas of the upper Peace region, recharge was modelled using a one-dimensional soil water balance code that accounts for the process of depression-focused recharge. However, in the forested non-agricultural areas, a baseflow approach was used to assess recharge because a comparable recharge modelling approach has not been developed for use in forested boreal settings. Results show that recharge is generally between 5 and 10 mm/yr, with a maximum of just over 20 mm/yr.

Groundwater yields are calculated on a watershed basis and results show that the maximum sustain yield varies from 2.45×10^4 to 6.94×10^7 m^3/yr. Groundwater abstraction equal to the maximum sustained yield would have a significant impact on the hydrogeological system, including major impacts to surface water bodies. The aquifer yield results of this study can be used to assess potential, order of magnitude, regional groundwater yields, and to compare relative differences between watersheds. Additionally, results can be used as a screening or risk assessment tool to identify watersheds of interest, where further groundwater assessments could be conducted considering local knowledge and specific scenarios. The aquifer yield continuum methodology can be adapted and utilized to focus the assessment of aquifer yield to the specific area of interest, incorporating local knowledge of the groundwater system and desires of the community, stakeholders, and environment.

1 Introduction

Groundwater is an important resource in Alberta. It is necessary to quantify the amount of groundwater available to compare with total groundwater allocation, and evaluate the risk associated with potential groundwater withdrawals due to increased development. The Alberta Geological Survey (AGS) has adopted an approach to provide a regional first-order assessment of groundwater availability in Alberta based on an aquifer yield continuum concept (e.g., Pierce et al., 2013). Groundwater yield is quantified along a spectrum of total groundwater availability and is bound by two extremes: nonuse and maximum mining. The aquifer yield continuum depends on hydrogeological parameters such as recharge, discharge and aquifer volume. Other governing factors such as environmental flow needs, and input from the community and local stakeholders can be accounted for to manage the degree of impact of groundwater withdrawal on the hydrogeological system.

There are a variety of different methods to quantify these hydrogeological parameters. Data availability, hydrogeological regime, climate and landscape characteristics may influence the method chosen for a given study area. The aquifer yield continuum concept was first applied to map groundwater availability in central Alberta (Klassen and Smerdon, 2018), where groundwater discharge to rivers (baseflow) was the method used to estimate recharge, one of the key hydrogeological parameters. This method was used because the central Alberta area was characterized by near surface bedrock aquifers with thin overlying sediment, the presence of generally unregulated rivers with no significant water withdrawals, and the abundance of river gauging data. The aquifer yield continuum concept was then applied in southern Alberta (Klassen et al., 2018); which is characterized by thicker sediments than in central Alberta, the climate is warmer and dryer, agriculture is the dominant land use type, rivers are often regulated, and hydrometric gauging data was more variable. Depression-focussed recharge is also the dominant recharge mechanism in the Canadian Prairies of the southern Alberta study area; therefore a one-dimensional recharge modelling approach was used to estimate recharge.

This report describes the application of the aquifer yield continuum approach to mapping regional first-order groundwater availability to a depth of 150 m below ground surface (bgs) in the upper Peace region area in northwest Alberta. Both the baseflow and recharge modelling approaches used in the two previous study areas (Klassen and Smerdon, 2018; Klassen et al., 2018) were used to estimate recharge in the upper Peace region.

2 Study Area

2.1 Study Area

The study area is approximately 70 000 km^2 and is located northwest of Edmonton, extending from the British Columbia–Alberta border in the west to Lesser Slave Lake in the east, and covering most of the area between the Town of Peace River in the north to Grande Cache in the south (Figure 1). The study area includes most of the Upper Peace Land Use Framework Region (Figure 1: inset; AEP, 2011a); with information on land cover, surficial geology, sediment thickness, and bedrock geology available throughout the study area (Figures 2–5). The upper bedrock geology of the study area consists of Cretaceous–Paleogene sediments deposited during marine or continental sedimentation (Figure 5; Prior et al., 2013). The bedrock geology consists of sandstones, shales, and siltstones that dip in a southwest direction along the Alberta syncline towards the mountains and foothills in the southwest corner of the study area, where there is folding of strata along the deformation belt.

The study area was divided into two parts, which generally coincide with the green (non-agricultural) and white (agricultural) areas (Figure 1; AEP, 2011b). Different methods were used to estimate recharge in each of these two parts. The green area is heavily forested (Figure 2), sediment thickness is relatively thin

(<25 m; Figure 4), and there are many types of surficial deposits (Figure 3), with the dominant type being morainal deposits. The southern portion of the study area overlaps with the study area of Klassen and Smerdon (2018). In the white area, the dominant land use is cropland, sediments above bedrock are generally thick and infill paleovalleys where present, and the surficial deposits are mostly glaciolacustrine.

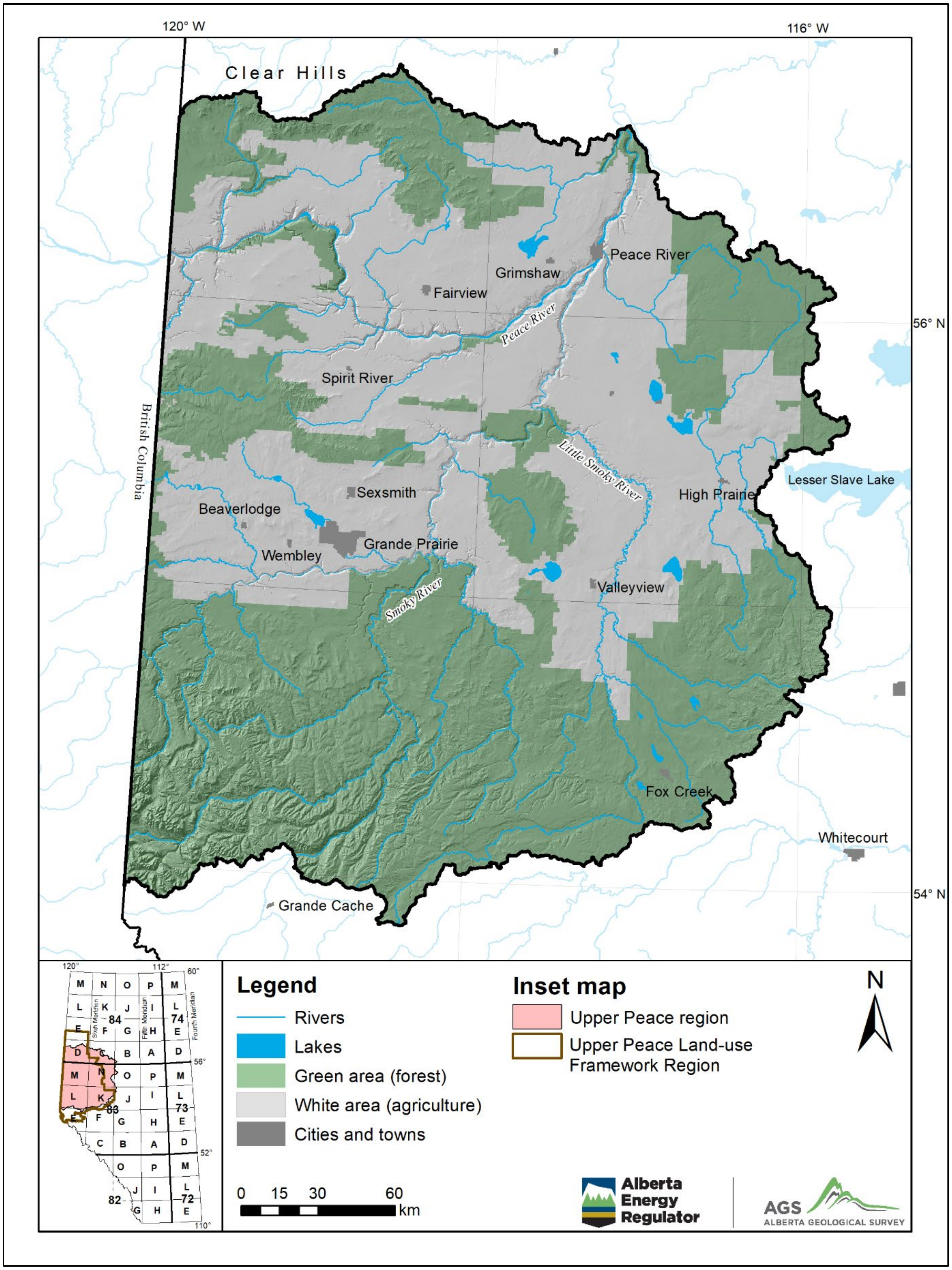

Figure 1. Study area in the upper Peace region of Alberta coincides with the Upper Peace Land-Use Framework Region (AEP, 2011a).

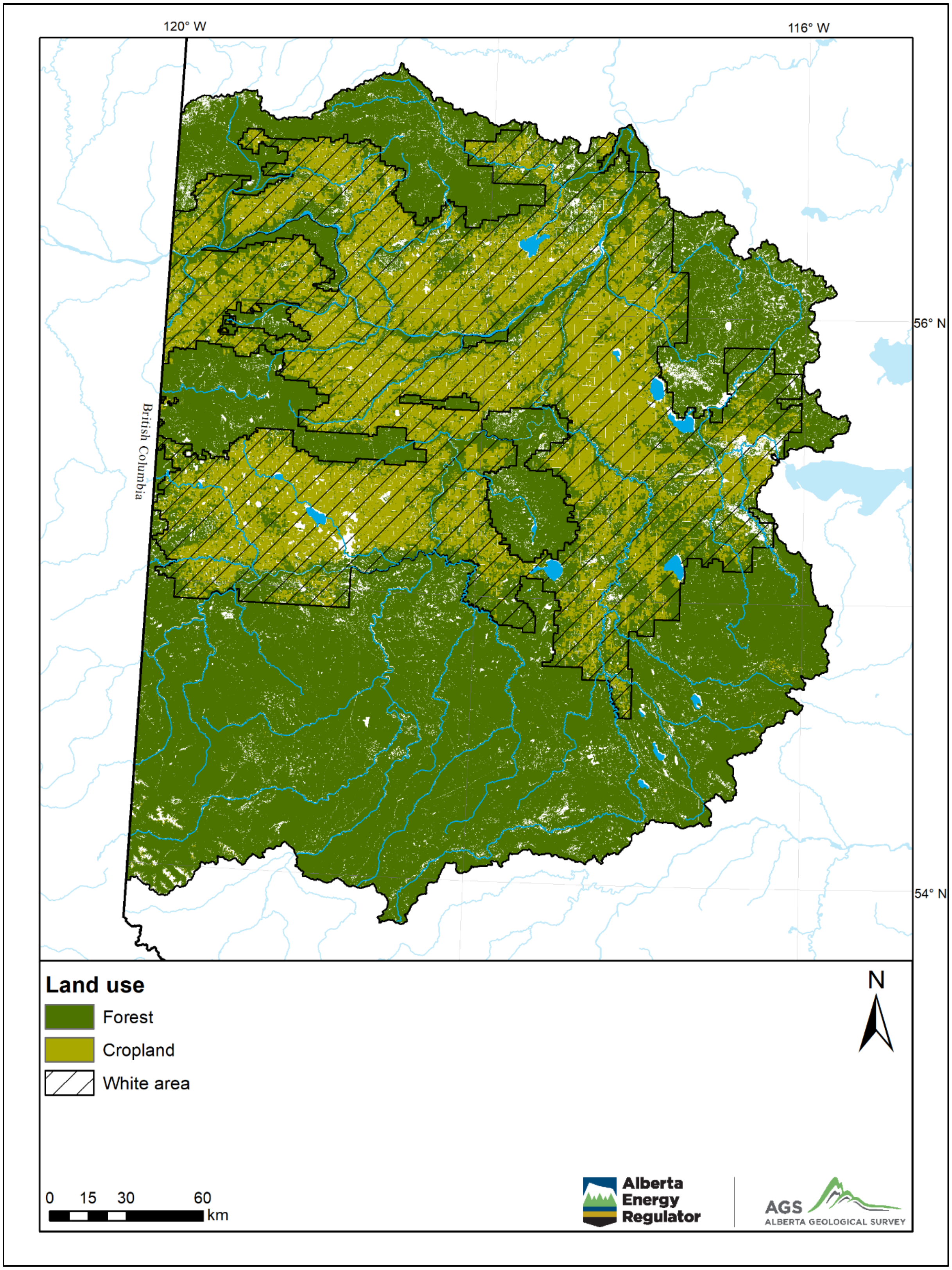

Figure 2. Land use in the upper Peace region of Alberta (Agriculture and Agri-Food Canada, 2015). White area corresponds to the agricultural areas. A more detailed time-series land-use/land-cover classification for a portion of the study area is provided in Chowdhury and Chao (2018).

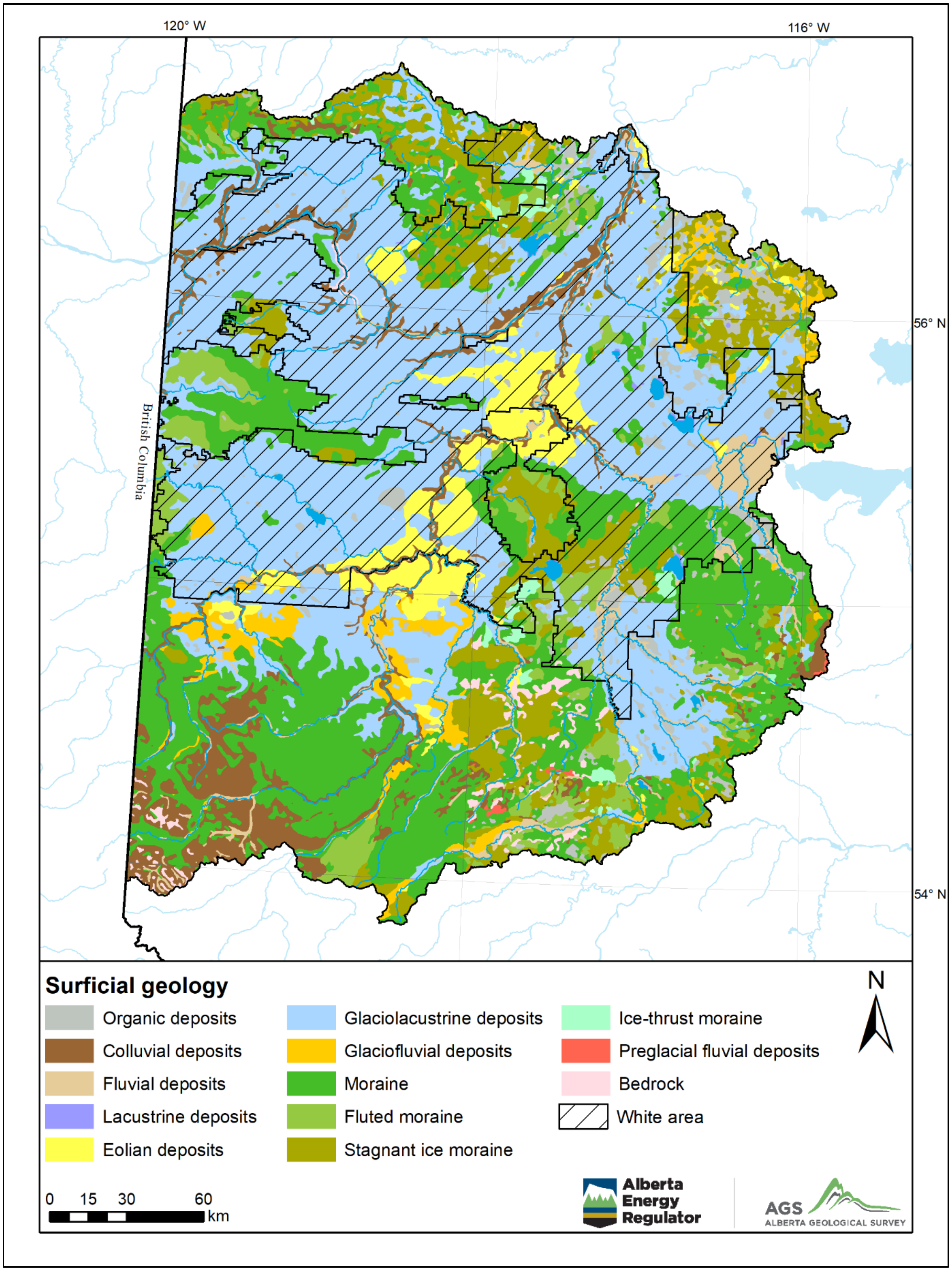

Figure 3. Surficial geology within the upper Peace region of Alberta (Fenton et al., 2013).

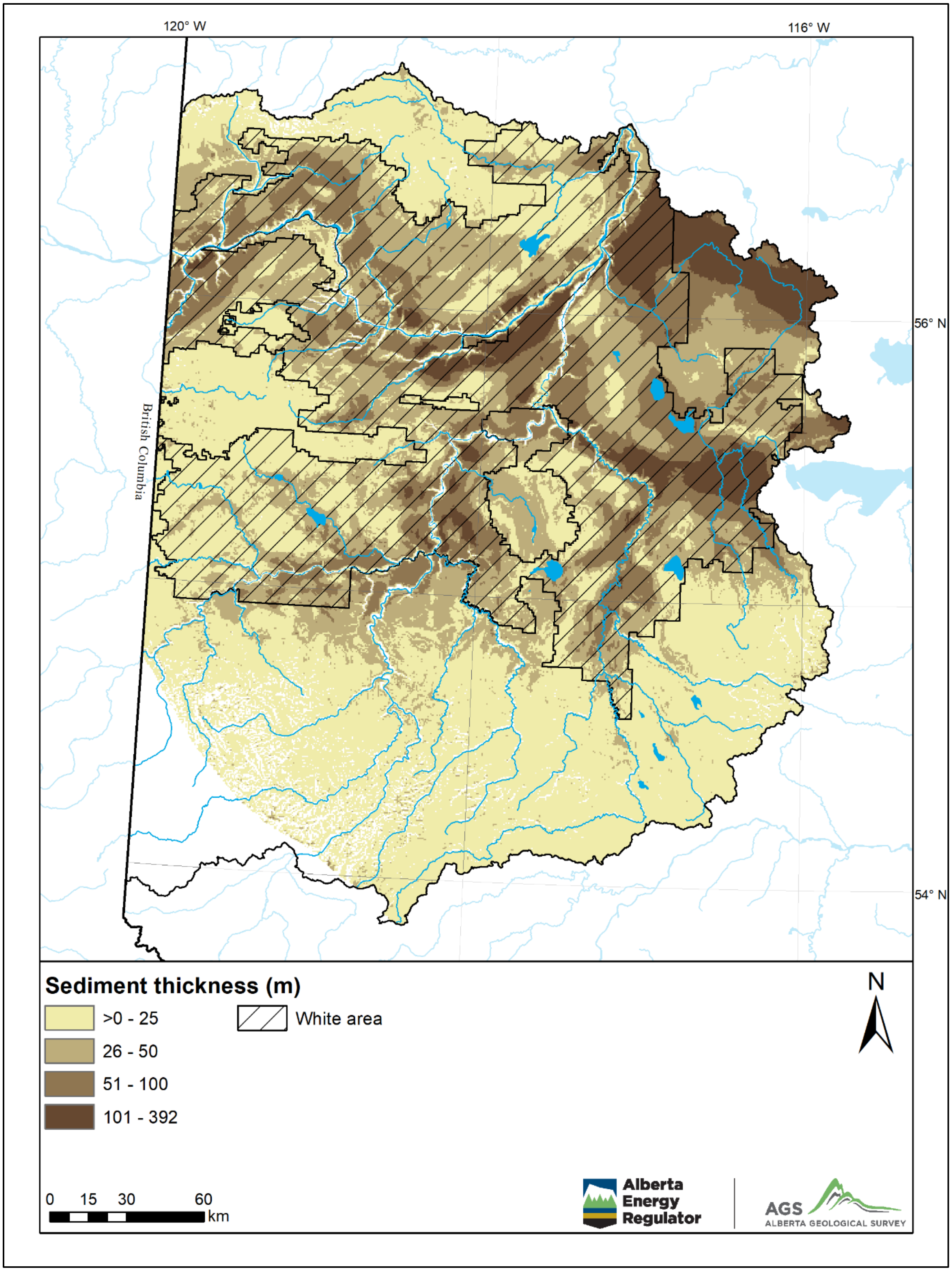

Figure 4. Thickness of sediment in the upper Peace region of Alberta (AGS, in prep).

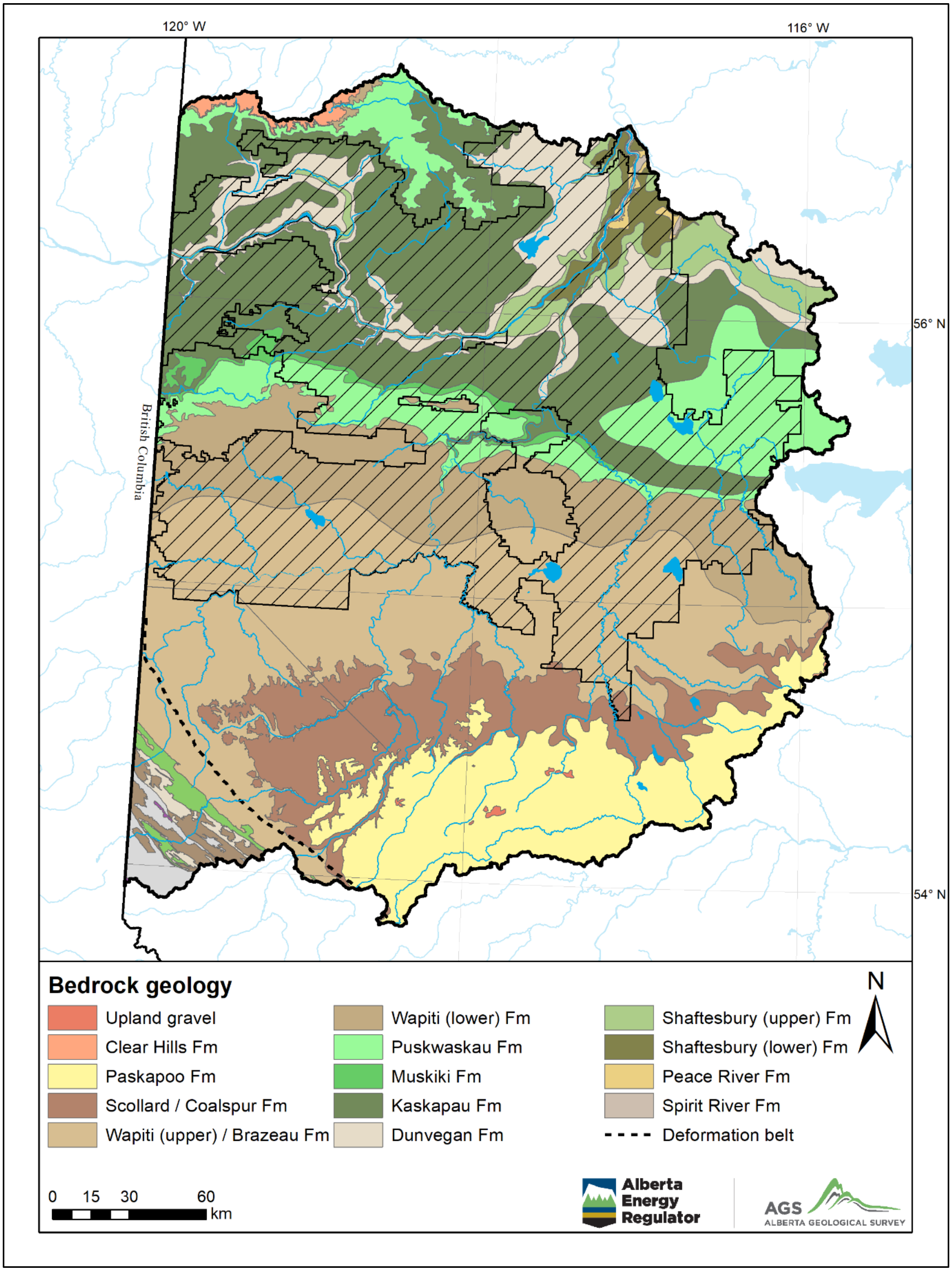

Figure 5. Bedrock geology of the plains in the study area, upper Peace region (Prior et al., 2013). Bedrock geology of the foothills and mountains, southwest of the deformation belt are not shown in the legend.

2.2 Yield Mapping

Groundwater yield within Alberta has been previously determined by the Alberta Research Council (ARC) from 1968–1983. The previous maps show estimated rates of groundwater abstraction based on the geology, available pumping or aquifer test information, and the concept of a 20-year safe yield for a well (Maathius and van der Kamp, 2006; Lemay and Guha, 2009). Although these maps are useful for estimating groundwater abstraction rates throughout the province, they were not intended for regional groundwater inventory or management purposes (Lemay and Guha, 2009), they are limited to a time horizon, and provide a single estimate of yield for a single well. The AGS has adopted a different approach to mapping groundwater yield based on an aquifer yield continuum concept (Kalf and Wooley, 2005; Pierce et al., 2013), which takes into account the total amount of groundwater available in the system. This approach has been applied in central Alberta (Klassen and Smerdon, 2018) and southern Alberta (Klassen et al., 2018). Klassen et al. (2018) provides more background on the development of the aquifer yield continuum concept.

Rather than using one value to estimate yield of a groundwater supply, the AGS has modified the approach of the aquifer yield continuum by Pierce et al. (2013) to also incorporate other definitions of groundwater yield (e.g., Bredehoeft, 2002; Devlin and Sophocleous, 2005; Kalf and Woolley, 2005; Zhou, 2009). The five classes of aquifer yield used in this study (and Klassen et al., 2018) are defined as:

1) **nonuse (NU):** no human induced groundwater abstraction from system;
2) **permissive sustained yield (PSY):** can be quantified as any value between nonuse and maximum sustained yield. Use of groundwater resource is limited, permitting discharge to surface water bodies albeit at a reduced rate. The desired PSY is a social and environmental boundary rather than a physical system boundary;
3) **maximum sustained yield (MSY):** pumping is balanced by the maximum amount of capture which includes induced recharge of streamflow and zero discharge. Surface water bodies will be seriously affected. Pumping above this value means water is continuously removed from storage and significant impacts to the hydrogeological system will occur. In this study MSY is equal to natural recharge as a proxy for maximum capture, which excludes induced recharge of streamflow and is therefore less than the maximum rate of capture;
4) **permissive mining yield (PMY):** includes the maximum amount of capture plus partial mining of the aquifer, without fully depleting the theoretically recoverable volume of stored water over a planned time horizon. The amount of aquifer mining permitted is governed as a social boundary;
5) **maximum mining yield (MMY):** represents the maximum amount of capture plus all theoretically available water stored within the aquifer over a planned time horizon. It is unlikely that this yield would ever be reached as not all water in an aquifer in technically recoverable and would result in significant alterations to the hydrogeological system.

Given the regional focus of this study, a simple water balance method is used to determine the aquifer yield classes. This simplifies the hydrogeological system by assuming that the maximum sustained yield is equal to the natural state of recharge rather than taking into consideration capture (discussed in Klassen et al., 2018). Table 1 summarizes the equations used to quantify each of the aquifer yield classes described above and are based on equations presented in Kalf and Woolley (2005) and Pierce et al. (2013).

Table 1. Equations used for calculating the yields for each aquifer yield class.

Nonuse	Permissive Sustained Yield	Maximum Sustained Yield	Permissive Mining Yield	Maximum Mining Yield
$P_{NU} = 0$	$P_{PSY} = R - D_x$	$P_{MSY} = R$	$P_{PMY} =$ $R + (V_0 - V_x)$	$P_{MMY} = R + V_0$

P = groundwater withdrawal (pumping)
R = inflow into the groundwater system (i.e., recharge)
D_x = desired discharge from the groundwater system (other than pumping)
V_0 = initial volume of water-saturated aquifer prior to the planning horizon
V_x = desired volume of water to remain in storage at the end of the planning horizon

The values for MSY and MMY are limited by the hydrogeological system, whereas the values for PSY and PMY can vary within a range on the continuum depending on aquifer management decisions, including incorporating social, environmental, and economic aspects. Current groundwater use and desired future use can be compared to values along the continuum to provide a first-order evaluation of the degree of groundwater development (Figure 6).

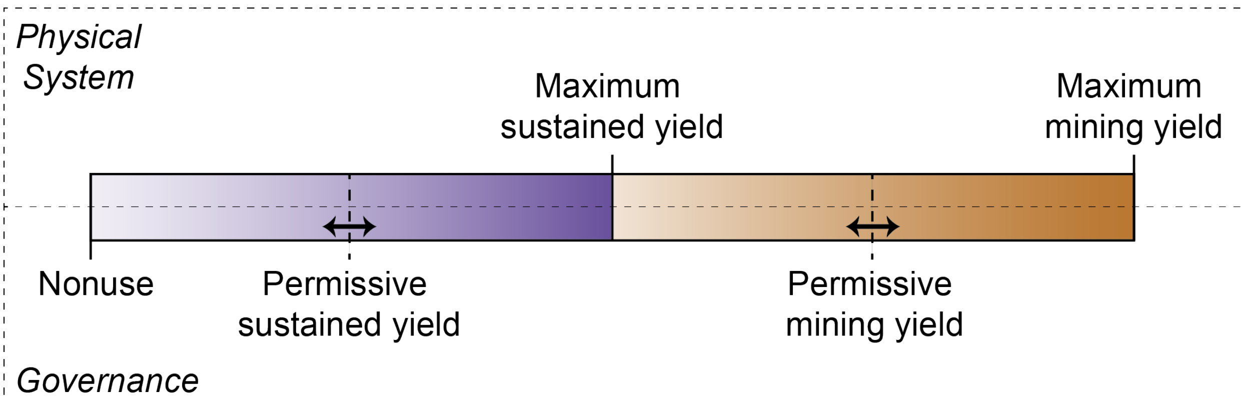

Figure 6. Aquifer yield classes, modified after Kalf and Woolley (2005) and Pierce et al. (2013).

The methods used to determine the hydrogeological parameters used in the aquifer yield continuum (Table 1) can be adapted to fit many different hydrogeological systems.

3 Aquifer Yield Mapping Methods

The aquifer yield continuum was applied at a watershed level. Watersheds are reflective of Hydrologic Unit Code Watersheds of Alberta level 8 (HUC8) (Alberta Environment and Parks, 2017). Values for the four aquifer yield classes greater than nonuse are calculated for 45 HUC8 watersheds within the study area, as well as two calculations for PSY to illustrate possible permissive yield values.

The three hydrogeological parameters required to determine the aquifer yield for each class are recharge (R), discharge (D_x), and volume of groundwater in storage (V_0, V_x). In this study, recharge was estimated using both groundwater discharge to rivers (baseflow) (Klassen and Smerdon, 2018) and a modelling method developed by the University of Calgary (e.g., Pavlovskii et al., 2019; Noorduijn et al., 2018) with some slight modifications (Klassen et al., 2018). Discharge is based on the assumptions of a closed basin, steady-state system where recharge eventually makes its way out of the system as discharge. Aquifer volumes were obtained using the AGS's 3D Provincial Geological Framework Model of Alberta, Version 2 (3D PGF model v2; Alberta Geological Survey, 2019). Detailed methods on determining each of the hydrogeological parameters are described in the following sections.

3.1 Recharge

Recharge was estimated using two methods, the baseflow approach used by Klassen and Smerdon (2018) and the one-dimensional recharge modelling approach used by Klassen et al. (2018). The following two subsections outline how these two approaches were used in the upper Peace region. For more detailed background information on these two approaches, please refer to the previous reports. Generally, the baseflow approach was used to estimate recharge within the green area and the recharge modelling approach was used in the white area (Figure 1); although, both approaches were used in some watersheds, which allowed for a comparison between the two methods. Different approaches are needed because the recharge modelling approach has been developed for use in agricultural and prairie settings (i.e., the white area) and has not been tested for use in a forested boreal setting (i.e., the green area). Additionally, the baseflow approach could not be used across the entire study area because of a breakdown of the underlying assumptions in the method for parts of the study area, particularly along the Peace River: the Peace River is a major hydrogeological feature that receives regional groundwater discharge from deeper bedrock units; it is regulated by numerous large dams in British Columbia; and it is affected by ice cover in the winter.

3.1.1 Baseflow Approach

The baseflow approach relies on equating the values of recharge and discharge using the long-term steady-state water balance within a watershed, which may be written as:

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

where R is recharge, D is natural discharge to surface water, P is pumping and G_{in} and G_{out} are groundwater flow from neighbouring watersheds. To simplify the equation, it was assumed that G_{in} and G_{out} are the same and the amount of pumping is negligible compared to the amount water in the aquifer; therefore, recharge is equivalent to natural discharge or “baseflow”, assuming all groundwater discharge occurs to rivers. The volume of baseflow can be divided by the surface area of the watershed to give an average rate [L/t] that is then equated to areal recharge.

Hydrometric data collected at gauging stations along streams and rivers have been 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, 2018). The Agriculture and Agri-Food Canada (AAFC) Watershed Project (Agriculture and Agri-Food Canada, 2013) delineated incremental drainage areas, which can be defined as a particular hydrometric station’s drainage basin, and is between itself and the next upstream station(s).

Within the study area, the number of years of recorded data (up to the year 2014) varies for each hydrometric station, with a minimum, mean, and maximum of 7, 43, and 74 years, respectively. The frequency of observations varies depending on the station and throughout the lifetime of a station; additionally, data may be collected all year round or only seasonally (summer only). The daily data were aggregated to average monthly flows for each station and monthly percent exceedance curves were calculated. The lowest monthly Q95 value was between September and April, meaning that 95% of the average monthly flows are higher than this value, was chosen to represent baseflow for each station within the study area. This low flow value provides a conservative approach to estimating groundwater discharge. A limitation of this method is that when a station has very low flows or is only recorded seasonally, data is not sufficient to determine a value for Q95 for that month. To overcome this limitation, the lowest average monthly streamflow value was used as an alternate to the lowest monthly Q95 value (see Klassen and Smerdon, 2018). In addition to the Q95, the Q80 was also determined for a basic uncertainty analysis discussed in Section 4.1.

The Q95 value determined for each hydrometric station is not representative of the baseflow generated within that incremental drainage basin; rather, it is an accumulation of baseflow up until that point along the river and may include baseflow from incremental drainage basins upstream. To obtain the baseflow for a particular incremental drainage area the Q95 value(s) of the hydrometric station(s) immediately upstream of a given station were subtracted from that station's Q95 value. In some cases this resulted in a negative Q95, which may indicate that the particular reach of stream is a losing section, where river water enters the groundwater (i.e., no baseflow is expected to enter the river). The hydrometric stations and their corresponding incremental drainage basin are shown in Figure 7. Baseflow is measured in m^3/yr and was divided by the surface area of the incremental drainage basins in order to get a recharge value in mm/yr.

The incremental drainage areas associated with the hydrometric stations are not always congruent with the HUC8 watersheds. In order to assign a recharge value to the HUC8 watersheds, a spatial average of recharge in (mm/yr) was aggregated to HUC8 watersheds from incremental drainage basins. Then the recharge (mm/yr) for each HUC8 watershed was multiplied by its area to obtain a MSY in m^3/yr.

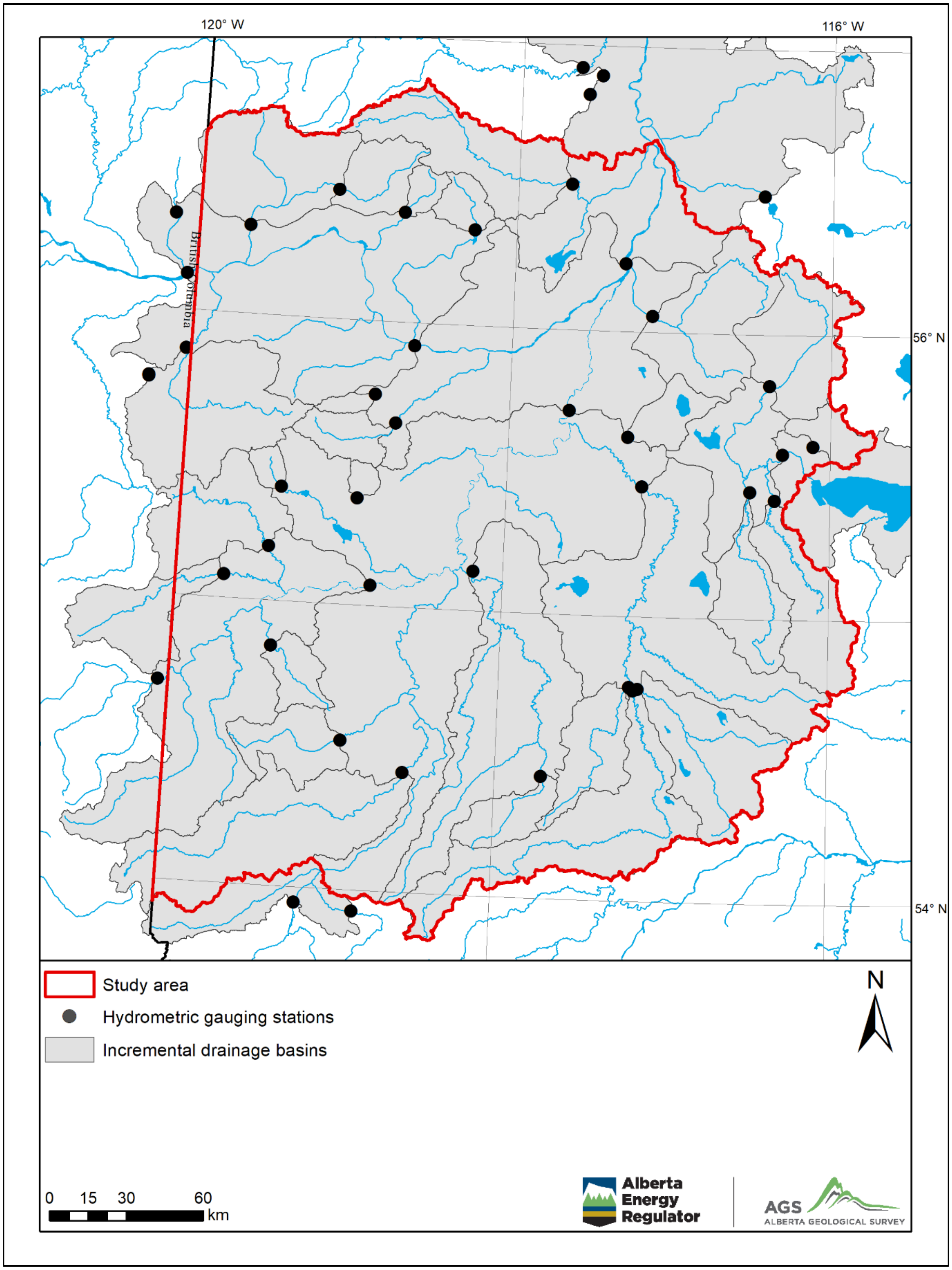

Figure 7. Incremental drainage basins within the upper Peace region. Only major rivers are shown, therefore some gauging stations on smaller rivers (not shown) will not appear to be connected to the river network.

3.1.2 Recharge Modelling Approach

Spatially-distributed recharge across the white area of the study area was determined using a recharge modelling approach developed at the University of Calgary (Pavlovskii et al., 2019; Noorduijn et al., 2018) and used in the southern Alberta groundwater availability assessment (Klassen et al., 2018). This approach accounts for the process of depression-focused recharge, which is a dominant mechanism of recharge in the prairie pothole region of the Canadian Prairies (Hayashi et al., 2003; Mohammed et al., 2013). The modelling approach consists of three steps:

1. Terrain analysis of individual depressions and their catchments in order to derive upland-depression characteristics for the area. These characteristics include a generalised relationship between depression area and volume, and probabilities of given catchment areas, depression areas and ratios between them in 4 types of surficial deposits (glaciolacustrine, moraine, stagnant-ice moraine, and fluted moraine; Fenton et al., 2013)
2. Modelling recharge using a suite of simulations with varying catchment and depression areas, crop types (evapotranspiration parameters), and meteorological data from different stations. This is achieved using the Versatile Soil Moisture Budget (VSMB) model, which is a multilayer, one dimensional, soil water balance code. VSMB has undergone many modifications to improve its simulation of recharge on the Canadian Prairies (e.g., Akinremi et al., 1996; Hayashi et al., 2010; Mohammed et al., 2013) including accounting for the process of depression-focused recharge with a VSMB-DUS (-depression-upland storage) version (Noorduijn et al., 2018)
3. Spatially distributing the VSMB recharge results based on the surficial deposit type, which have differing probabilities of particular catchment and depression areas, and proximity to meteorological station. Finally, the recharge results are averaged over each HUC8.

Pavlovskii et al. (2019) developed and applied the terrain analysis methodology described above in an area of southern Alberta. Klassen et al. (2018) expanded on the work of Pavlovskii et al. (2019) by analysing a larger area, surrounding the original analysed area, and found similar upland-depression characteristics. Southern Alberta contains a mixture of glacial deposits, including a high proportion of morainal deposits, whereas the upper Peace region is characterised by extensive glaciolacustrine deposits (Figure 3) and is on the edge of the prairie pothole region. Therefore, rather than applying the same upland-depression characteristics to the upper Peace region, a terrain analysis was completed for the current study and upland-depression characteristics were compared to southern Alberta. The terrain analysis requires a high resolution (2 m or 5 m) digital elevation model (DEM) in order to accurately capture what can be very small depressions on the landscape. Unfortunately, for the upper Peace region, the AGS has limited high-resolution LiDAR DEM data in the white area (Figure 8). Although discontinuous, the total area of high resolution DEM coverage was sufficient to perform a terrain analysis similar to Pavlovskii et al. (2019) and Klassen et al. (2018).

The relationship between depression area (DA) and volumetric capacity (C) for the 4 types of surficial deposits for the upper Peace region is:

$$C = 0.17(DA)^{1.03}$$

Comparing the terrain analysis results of the upper Peace region to those from southern AB, the DA-C relationship is different, with the southern Alberta study area DA-C relationship shown below:

$$C = 0.054(DA)^{1.21}$$

Additionally, for each of the 4 types of surficial deposits, there were differences in the probability of finding a particular catchment area and depression to catchment area ratio (DA-C). While the change in the DA-C relationship leads to an increase in simulated recharge, the upper Peace region has a higher proportion of catchments that are larger, but that have smaller depression areas. This ultimately leads to an overall decrease in the simulated recharge compared to the southern Alberta.

A suite of VSMB simulations were run with the upper Peace DA-C relationship, a range of catchment areas and depression to catchment area ratios, two different vegetation types (grass and crop), and 8 different weather stations. The model simulated 9 years of recharge from 2009 to 2018 using weather data obtained from station data from the Alberta Climate Information Service (https://agriculture.alberta.ca/acis/). Recharge was distributed spatially based on the upland-depression characteristics of the 4 types of surficial deposits and proximity to a particular weather station. In order to apply the recharge modelling results to a particular HUC8, a zonal average of recharge (in mm/yr) was calculated in Esri ArcMap.

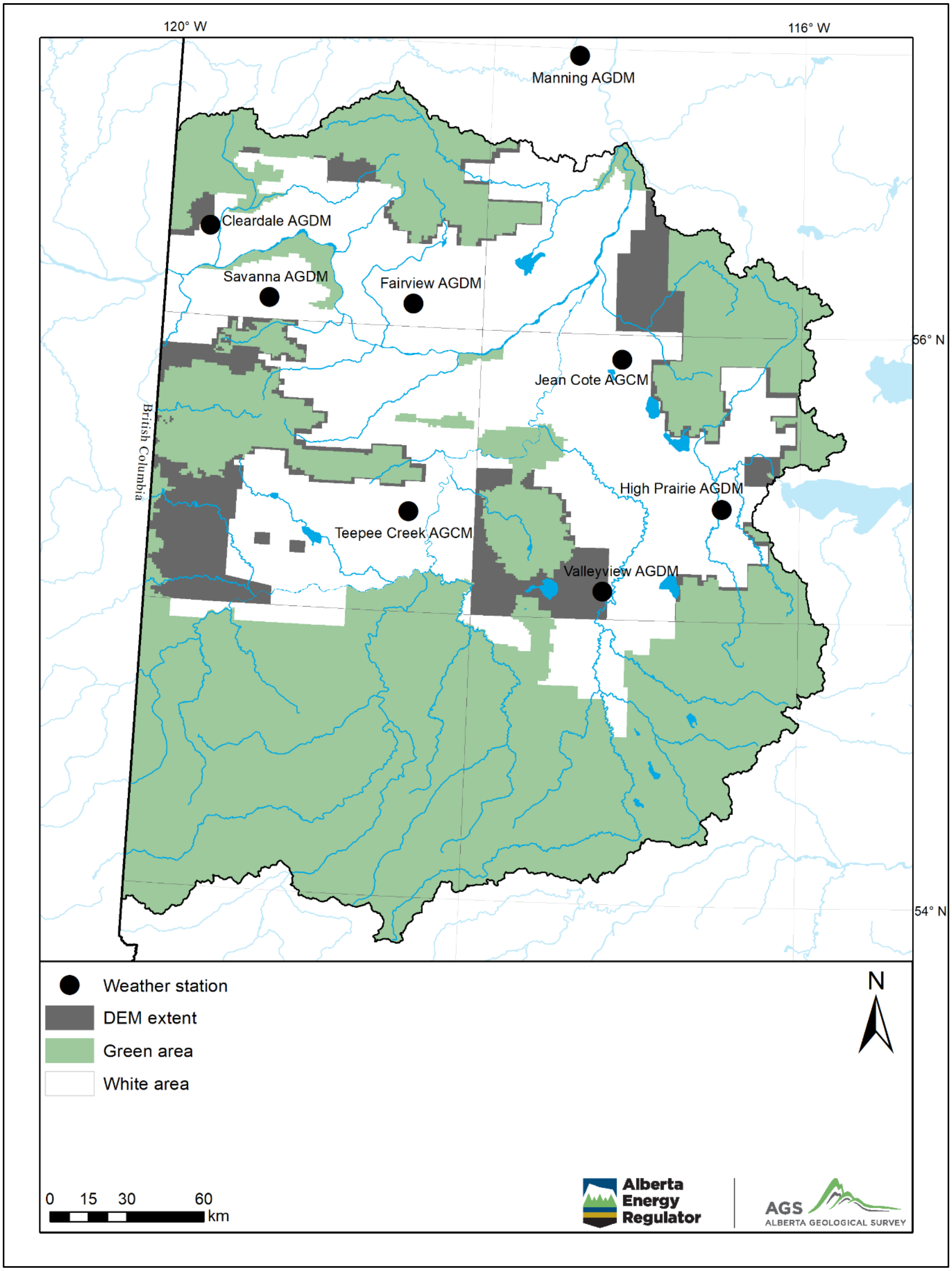

Figure 8. Location of high-resolution LiDAR DEMs used for the terrain analyses and locations of weather stations used for VSMB-DUS recharge modelling. LiDAR DEMs used for the terrain analysis were located in the white area only.

3.2 Discharge

Discharge is the hydrogeological parameter used to quantify the PSY class and D_x is the residual discharge that is not captured by pumping (Table 1). D_x can be equal to recharge during a non-pumping steady-state, and decrease to zero when it is fully captured during MSY pumping conditions. The actual desired values for discharge are not available for this study and would be the result of a management decision process. Values were assumed to show how discharge can be incorporated into the aquifer yield continuum. Values can be modified to be site specific, depending on the hydrogeological system, environmental flow needs, and desires of the community.

Under the assumption that in a steady-state, closed basin, inputs are equal to outputs; the rate of natural discharge within each HUC8 watershed would be equivalent to recharge. To be consistent with Klassen and Smerdon (2018) and Klassen et al. (2018), two PSY values were calculated to illustrate how PSY will fall on the continuum. In the first scenario, 90% of natural discharge is desired for D_x; this is described by Gleeson and Richter (2018) to be a presumptive standard for ecological protection in the absence of more detailed assessments. The second scenario falls in the middle of PSY range, where 50% of natural discharge is for D_x desired. These scenarios are equivalent to assuming pumping (P) represents 10% and 50% of the simulated recharge for the PSY class (Table 1).

3.3 Volume

The hydrogeological parameter used to quantify the PMY and MMY classes is volume of water in the subsurface. To be consistent with Klassen et al. (2018), V_0 was considered to a depth of 150 m bgs. Region-wide, detailed mapping of permeable geobodies that could be productive aquifers is unavailable; therefore, water volumes are determined on a geological formation basis from the 3D PGF model for this first-order assessment of groundwater availability. In the future, the volumetric assessment could be refined in areas where detailed aquifer mapping exists.

The 3D PGF model is a province-wide multi-layer model of the stratigraphy of Alberta that is divided into zones representing geological members, formations, groups, or mixes of these entities depending on data availability (Alberta Geological Survey, 2019). The upper Peace region covers 23 individual model zones within the upper 150 m, with the uppermost bedrock zone being the Paskapoo Formation, and the lowermost bedrock zone being the model zone with the Mannville Group (excluding Grand Rapids, Clearwater, and McMurray formations), Spirit River, and lower Loon River formations. Generally bedrock units dip to the south-southwest and Figure 9 shows the bedrock geology in the study area, along with a cross section, from the 3D PGF v2 model.

Volume for each geological zone within 150 m bgs was determined in Schlumberger's Petrel 2015 software (Figure 9). Water volume for each zone was determined by assuming effective porosity based on geological characteristics. Aquitards were assigned a porosity of 0.1, aquifers were assigned a porosity of 0.3, and formations which are a mixture of sandstone, siltstone, mudstone and shales were assigned a porosity of 0.2 (Figure 9). The overlying Neogene–Quaternary sediments are assigned a porosity value of 0.2.

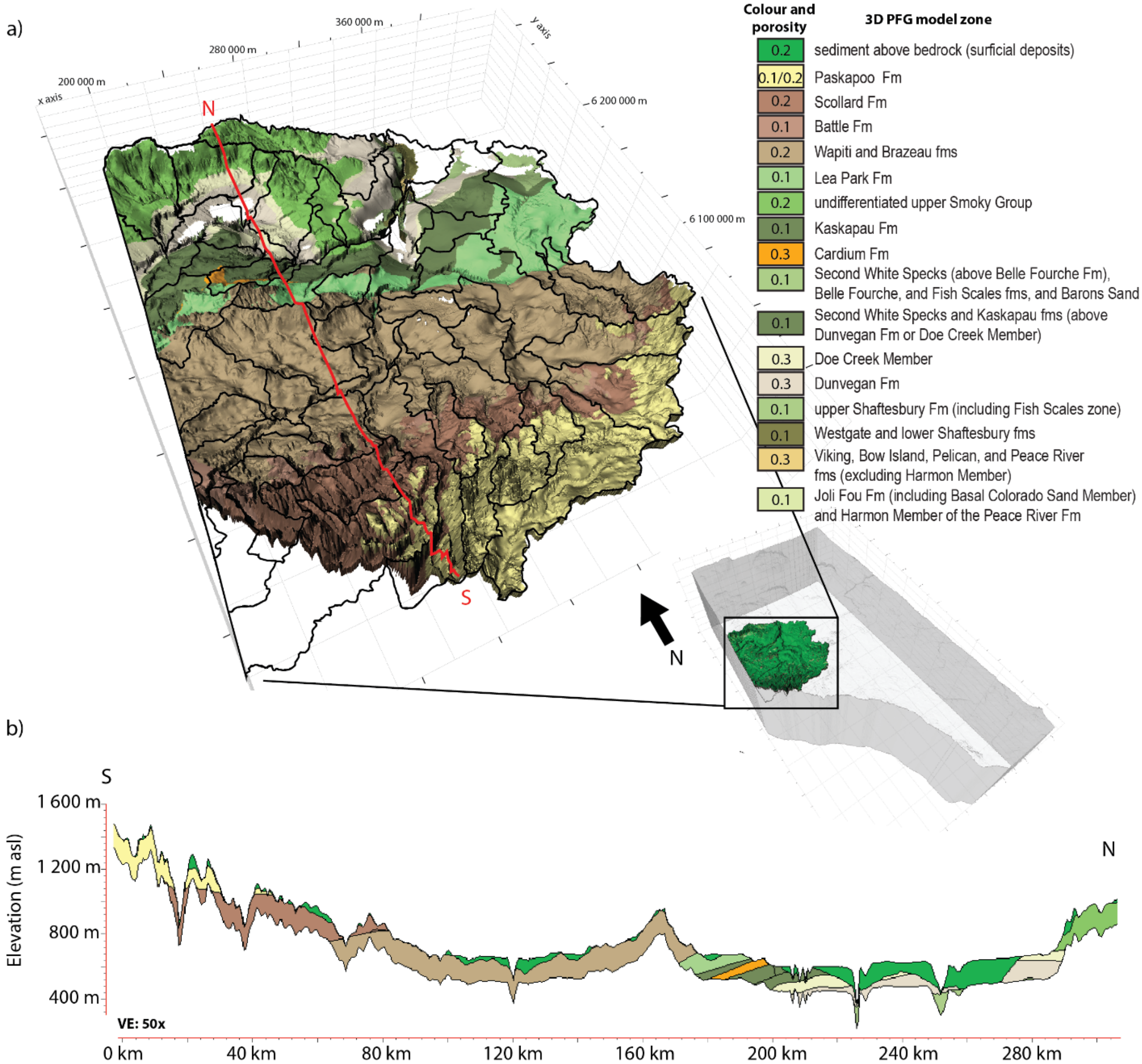

Figure 9. a) Bedrock units in the study area from the 3D PGF model v2 to a depth of 150 m below the ground surface with the HUC8 watersheds overlain (black outlines). Bedrock units not shown are masked by Neogene−Quaternary sediment, which can exceed 150 m in thickness. b) S–N cross-section identified by red line in a).

There are several watersheds in the southeast that overlap with Klassen and Smerdon (2018). In Klassen and Smerdon (2018) the water volume was not estimated using the 3D PGF model, instead it was constrained to the uppermost bedrock unit which varied in depth. For consistency, the water volume was recalculated for these watersheds using the 3D PGF model.

4 Results and Discussion

4.1 Recharge

Figure 10 shows the extent where each recharge approach (baseflow and recharge modelling) was applied, as well as which approach was ultimately used to estimate recharge in each HUC8. Figure 10a shows where recharge was estimated using the baseflow approach (blue areas) and the recharge modelling approach (grey areas). As mentioned in Section 3.1, recharge in each HUC8 was determined using a zonal average of recharge, in mm/yr. Areas shown in white on Figure 10a had no recharge estimate and were not included in the zonal average. In the southern part of the study area (green areas, Figure 10b) the baseflow approach was the only method of assessing recharge; recharge results for these watersheds range from 3 to 21 mm/yr as shown by the points in Figure 11 (baseflow approach only). For the watersheds close to the Peace River (yellow areas, Figure 10b) the recharge modelling approach was the only method of assessing recharge, and results range from 5 to 9 mm/yr (green points in Figure 11 limited to the recharge modelling approach). In these watersheds the assumptions inherent to the baseflow assessment are not valid. One such assumption of the baseflow approach is that the basin is closed. However, the Peace River is a major hydrological feature on the landscape that receives regional groundwater discharge from deeper bedrock units and more distinct sources such as the Whitemud and Clear Hills in the north (Borneuf, 1981; Ozoray, 1982). The capture of regional discharge, in addition to the discharge contributed by the local incremental drainage area, inflates the apparent value of recharge that is attributed to that local area. Additionally, the Peace River is regulated by numerous large dams in neighbouring British Columbia and is affected by ice cover in the winter, which can affect the average Q95 values.

For the remainder of the watersheds (orange areas, Figure 10b), the baseflow and recharge modelling approaches were compared (blue and green points in Figure 11 using both approaches). Recharge results using the baseflow approach range from essentially zero to 15 mm/yr, and from 5 to 9 mm/yr using the recharge modelling approach. There are a number of watersheds with very low, near zero, recharge values using the baseflow approach. In these watersheds it appears as though the assumptions inherent to the baseflow method are not valid. These include HUC8 watersheds that are close to the Peace River (but do not contain the Peace River) and are also topographically high. Recharge in these watersheds is most likely not discharging within the boundaries of the surface watershed, but is instead moving outside the watershed boundaries to discharge in other areas, like the Peace River. Thus, the recharge results are under predicted in the head watershed areas. Whereas, the apparently large recharge results using the baseflow method on the Peace River watersheds are likely capturing groundwater from the adjacent watersheds as discussed above. Lastly, some of the low baseflow results are also found in areas that have a high number of wetlands that would capture groundwater through evapotranspiration, again violating the assumption that all groundwater discharge is captured by the main gauged stream. Consequently, for the watersheds that have very low recharge values using the baseflow method, the recharge modelling method was selected to represent the recharge for the aquifer yield continuum, even if the area covered by the recharge modeling approach within a particular HUC8 was limited. Figure 10c shows the method that was ultimately used to assign the recharge value for each particular HUC8 in the study area.

Figure 11 also provides an indication of the uncertainty of the recharge results. For recharge calculated using the baseflow approach, the upper bound of the shaded blue area shows the recharge if the lowest average monthly Q80 was used instead of the Q95. While in some watersheds this involves the recharge value doubling, it is still within the range of recharge of watersheds in the area. For the recharge calculated using the recharge modelling approach, the green shading represents the range between the recharge results using evapotranspiration parameters that consider a grass vegetation (lower bound) and those considering a wheat crop (upper bound).

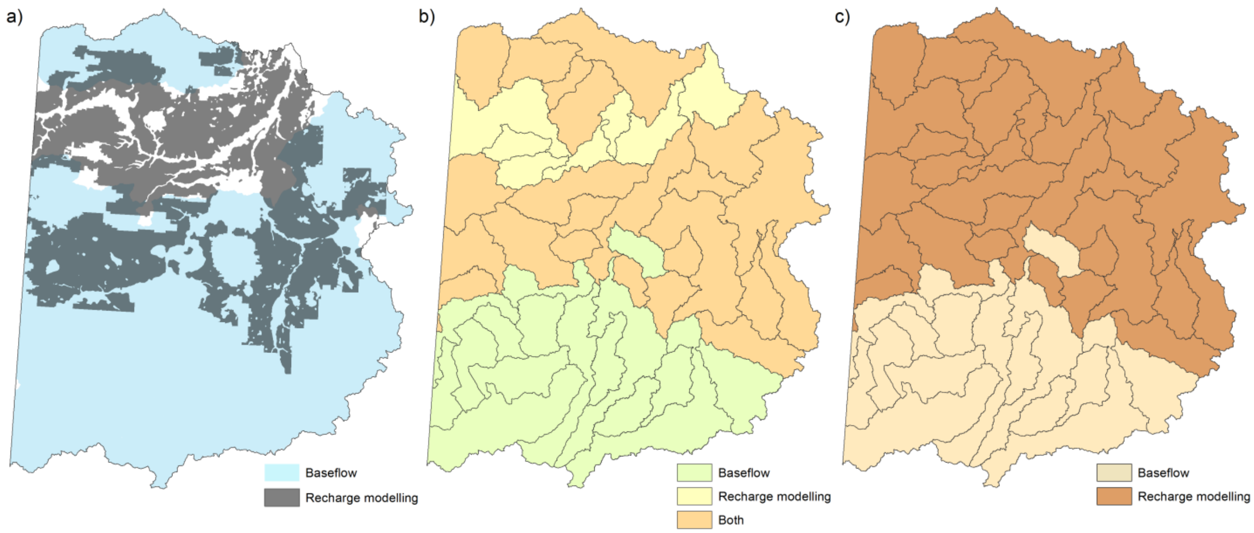

Figure 10. a) Identifies areas where recharge was estimated using the baseflow approach (blue) and recharge modelling approach (gray). b) Identifies HUC8 watershed polygons where the two approaches were used to estimate recharge. c) The recharge approach that was chosen to represent each HUC8 watershed.

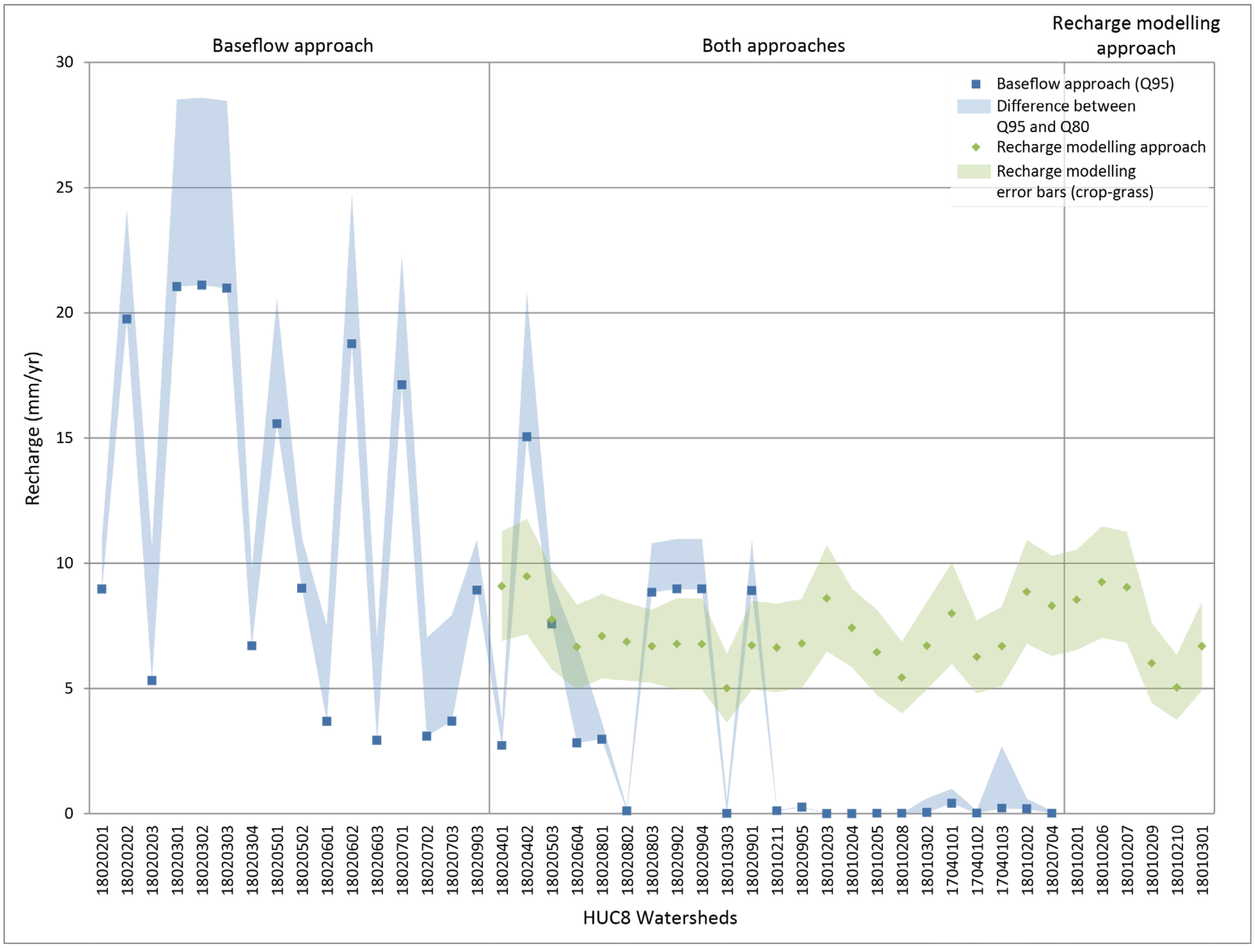

Figure 11. Recharge estimates from the baseflow approach and the recharge modelling approach. The points indicate the recharge value and the shading shows an estimate of uncertainty. The baseflow shading shows the difference between the Q95 (lower bound) and Q80 (upper bound). Recharge modelling shading shows the value of recharge using evapotranspiration parameters considering different vegetation types. The lower estimate is reflective of grass, and the higher estimate is reflective of a crop (wheat). The mean recharge was used to apply to the HUC8, but the two different vegetation types provide a range of possible recharge results. (Map of the HUC8 watersheds ID numbers on the x-axis are in Appendix 1: Figure 13 and referenced in Table 2).

As mentioned in Section 3.1.2, this study uses different upland-depression characteristics than the study in southern Alberta by Klassen et al. (2018). If the same upland-depression characteristics from the southern Alberta study area were applied to the simulations in the current study area, the recharge results for the HUC8 watersheds would be between 4 and 10 mm/yr higher than shown in Figure 11. Given that the purpose of this study is to assess groundwater availability, the lower recharge values using the updated upland-depression characteristics are useful in erring on the more conservative side of availability.

There are a limited number of other estimates of recharge in the upper Peace region. Jones (1966) estimated recharge at about 9 mm/yr (or 2% of annual precipitation) based on an earlier estimate for the Edmonton area, which he argues has similar recharge conditions as the upper Peace region. Hydrogeological Consultants Ltd. (2004) estimated recharge to the upper bedrock (e.g., deeper than the surficial deposits) in the white area at 0.2% of the annual precipitation, which is about 1 mm/yr. In general, the results of this study agree well with these previous results.

Figure 12 shows the final value of recharge attributed to each HUC8, along with the volume of annual recharge in a given watershed, which is equivalent to the MSY. Recharge is below 10 mm/y across much of the study area, with higher values in the south and west, closer to the mountains.

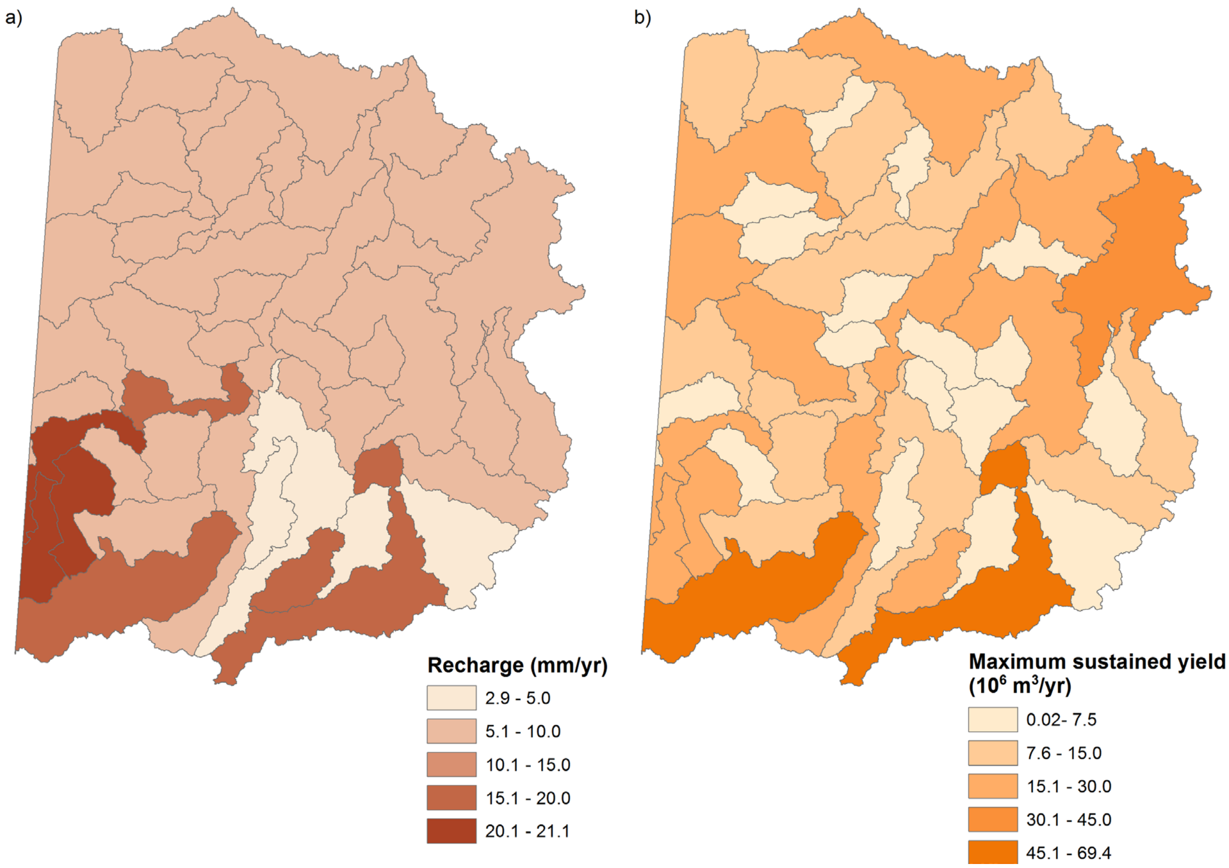

Figure 12. a) Areal recharge and b) volumetric recharge for each HUC8 in the upper Peace region. Volumetric recharge is equivalent to the MSY in this study.

4.2 Aquifer Yield Continuum

Values for each of the four aquifer yield classes were calculated (equations in Table 1) for each watershed and can be found in Appendix 1. In this study, the groundwater yields are presented as average annual volume per watershed, since recharge (and therefore discharge) is often reported as an average annual rate; however, when considering the PMY and the MMY this assumes that the stored water volume is extracted within a single year, which is highly unrealistic. Appendix 1 shows average annual yield volume of PMY and MMY both with this unrealistic assumption ($PMY_{(1\ yr)}$ and $MMY_{(1\ yr)}$) as well as with a more realistic average annual yield volume assuming a 20 year management horizon ($PMY_{(20\ yr)}$ and $MMY_{(20\ yr)}$). That is, only 1/20th of the water volume is extracted per year.

The MSY represents the maximum amount of water that can be extracted without mining groundwater storage, although it still would have a significant impact on the hydrogeological system and surface water bodies. Figure 12b shows the MSY as an annual volume of yield. Unlike with the estimates of areal recharge (Figure 12a), the distribution of volumetric MSY values are affected by both recharge and the watershed size.

The methods used to quantify each of the points along the aquifer yield continuum can be adapted to focus the assessment on specific areas of interest by incorporating local knowledge of the groundwater system, desires of the community and local stakeholders, and environmental flow needs. The results of this study are intended to provide a regional, first-order assessment of groundwater yield rather than exact values for quantitative management decisions. Results can be used as a screening or risk assessment tool to focus on areas in need of further attention and for examining the relative differences between watersheds along the continuum. For example, current or projected groundwater use can be compared to yield values in a particular watershed to gauge the potential for water resource development or issues. An example of this is the Alberta Energy Regulator's (AER) water use performance report (https://www.aer.ca/protecting-what-matters/holding-industry-accountable/industry-performance/water-use-performance), which compares licences groundwater use to the availability results of this study (and the previously mapped areas).

The aquifer yield continuum approach does not take into account the spatial or temporal response of the groundwater flow system to pumping; it assumes a new steady-state has been reached. Therefore, although actual groundwater withdrawals in a watershed may be below a particular aquifer yield class (e.g., PSY), negative effects may still occur if the withdrawal occurs next to a sensitive receptor such as another well or a surface water body. The aquifer volumes derived in this study represent a regional, theoretically recoverable estimate and do not take into account actual measured porosity values, specific storage, heterogeneity, hydraulic conductivity, or water quality of a particular formation. Technically recoverable volumes have the potential to be much smaller, especially in low hydraulic conductivity formations.

5 Summary

The aquifer yield continuum provides a flexible approach for estimating groundwater yield throughout Alberta. The hydrogeological parameters (recharge, discharge, volume) can be quantified by various methods depending on the scale of the study, data available, environmental flow needs, and input from local stakeholders and the community. For part of the upper Peace region, two approaches were used to estimate recharge (baseflow and recharge modelling) and regional scale geology and volumes were accounted for using the 3D PGF model v2. Recharge was estimated between 3 to 20 mm/yr throughout the study area. The baseflow approach is conservative as it is equating discharge to recharge and although there is the assumption of a closed basin, groundwater tends to flow into neighbouring watersheds or into deeper units and therefore may not be accounted for at hydrometric gauging stations. Additionally, evapotranspiration in riparian areas may decrease apparent discharge. The recharge modelling approach produced fairly consistent results throughout the study area (6 to 9 mm/yr), this is because the surficial sediments are fairly consistent (glaciolacustrine is dominant) and there is not a lot of variation in climate in the modelled area. Within the study area there is a large influence of regional groundwater flow systems. Recharge occurs in the north at the Clear Hills and most likely discharges in the Peace River; this was observed by the tributary watersheds that flow into the Peace River having low baseflow and the Peace River having substantially baseflow results (higher than precipitation). Results of this study can be used as a screening or risk assessment tool to identify watersheds of interest, where further, more local sale groundwater yield assessment could be conducted.

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Appendix 1 – Aquifer Yield Continuum Classes

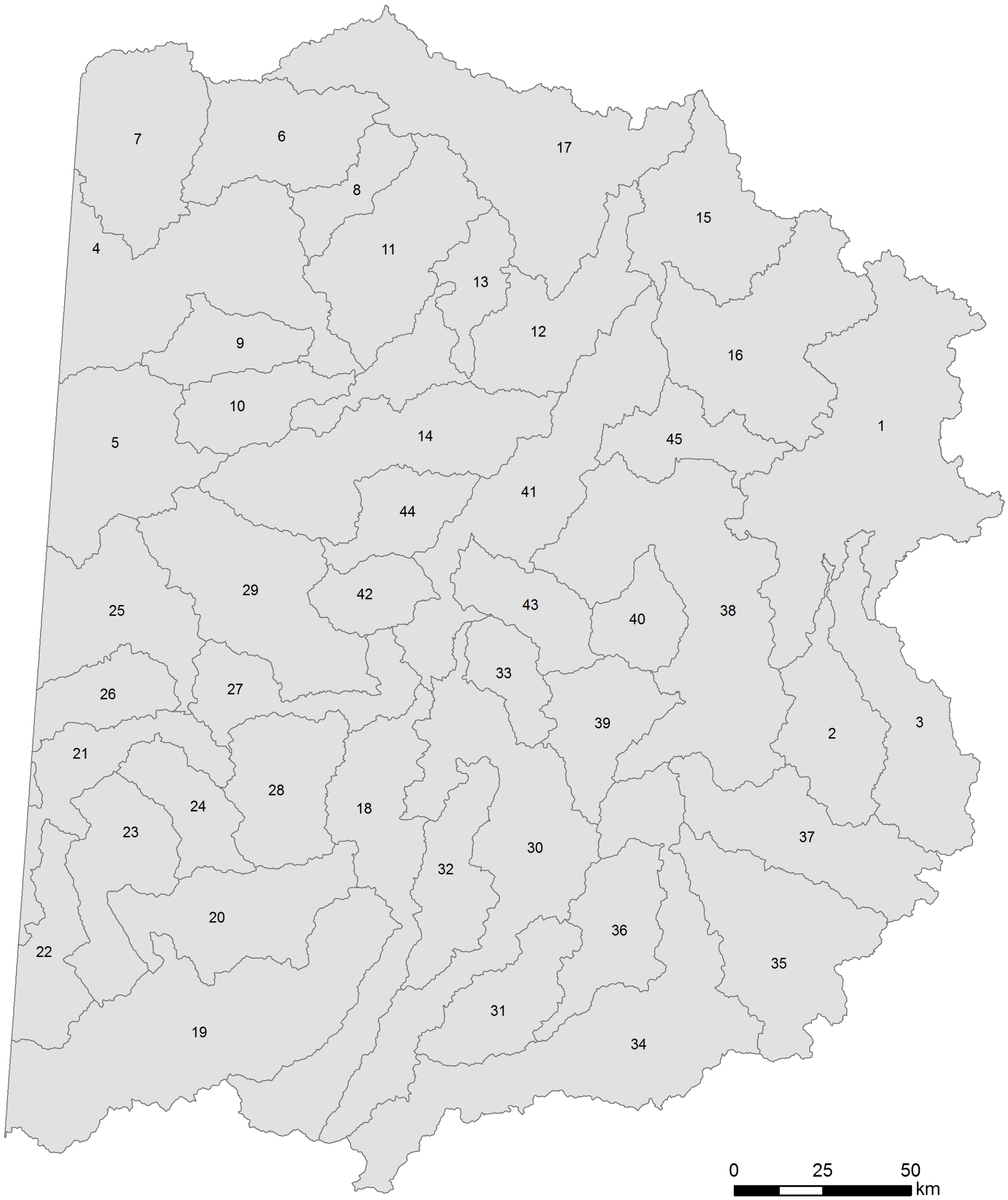

Figure 13. HUC8 watersheds labelled with ID numbers used in Table 2.

Table 2. Aquifer yield continuum classes for the upper Peace region of Alberta. $P_{PSY(10\%)}$ and $P_{PSY(50\%)}$ use 10% and 50% of natural discharge for pumping, respectively. $P_{PMY(1yr)}$ & $P_{PMY(20yr)}$ and $P_{MMY(1yr)}$ & $P_{MMY(20yr)}$ assume water is removed from storage over 1 and 20 years, respectively.

ID	HUC8	$P_{PSY(10\%)}$ (m^3/yr)	$P_{PSY(50\%)}$ (m^3/yr)	P_{MSY} (m^3/yr)	$P_{PMY(1\ yr)}$ (m^3/yr)	$P_{MMY(1\ yr)}$ (m^3/yr)	$P_{PMY(20\ yr)}$ (m^3/yr)	$P_{MMY\ (20\ yr)}$ (m^3/yr)
1	17040101	3.21E+06	1.61E+07	3.21E+07	8.70E+08	8.38E+10	7.40E+07	4.22E+09
2	17040102	7.31E+05	3.65E+06	7.31E+06	3.51E+08	3.43E+10	2.45E+07	1.72E+09
3	17040103	1.06E+06	5.32E+06	1.06E+07	4.43E+08	4.33E+10	3.23E+07	2.17E+09
4	18010201	2.28E+06	1.14E+07	2.28E+07	8.42E+08	8.20E+10	6.38E+07	4.12E+09
5	18010202	1.52E+06	7.59E+06	1.52E+07	3.70E+08	3.55E+10	3.29E+07	1.79E+09
6	18010203	1.17E+06	5.87E+06	1.17E+07	5.39E+08	5.28E+10	3.81E+07	2.65E+09
7	18010204	1.25E+06	6.23E+06	1.25E+07	6.29E+08	6.16E+10	4.33E+07	3.09E+09
8	18010205	3.42E+05	1.71E+06	3.42E+06	1.92E+08	1.89E+10	1.28E+07	9.46E+08
9	18010206	6.43E+05	3.22E+06	6.43E+06	1.61E+08	1.55E+10	1.42E+07	7.79E+08
10	18010207	7.21E+05	3.60E+06	7.21E+06	1.98E+08	1.91E+10	1.67E+07	9.60E+08
11	18010208	9.06E+05	4.53E+06	9.06E+06	6.36E+08	6.27E+10	4.04E+07	3.14E+09
12	18010209	1.21E+06	6.03E+06	1.21E+07	1.12E+09	1.11E+11	6.77E+07	5.57E+09
13	18010210	2.91E+05	1.45E+06	2.91E+06	2.34E+08	2.32E+10	1.45E+07	1.16E+09
14	18010211	1.47E+06	7.33E+06	1.47E+07	5.35E+08	5.21E+10	4.07E+07	2.62E+09
15	18010301	9.90E+05	4.95E+06	9.90E+06	4.44E+08	4.34E+10	3.16E+07	2.18E+09
16	18010302	1.52E+06	7.59E+06	1.52E+07	6.63E+08	6.48E+10	4.76E+07	3.26E+09
17	18010303	1.66E+06	8.29E+06	1.66E+07	1.23E+09	1.22E+11	7.75E+07	6.11E+09
18	18020201	1.90E+06	9.50E+06	1.90E+07	5.53E+08	5.35E+10	4.57E+07	2.69E+09
19	18020202	6.94E+06	3.47E+07	6.94E+07	6.26E+08	5.57E+10	9.72E+07	2.85E+09
20	18020203	8.00E+05	4.00E+06	8.00E+06	4.33E+08	4.25E+10	2.92E+07	2.13E+09
21	18020301	2.09E+06	1.04E+07	2.09E+07	2.69E+08	2.48E+10	3.33E+07	1.26E+09
22	18020302	1.84E+06	9.18E+06	1.84E+07	3.97E+07	2.15E+09	1.94E+07	1.25E+08
23	18020303	2.60E+06	1.30E+07	2.60E+07	2.89E+08	2.63E+10	3.92E+07	1.34E+09
24	18020304	4.80E+05	2.40E+06	4.80E+06	2.06E+08	2.02E+10	1.49E+07	1.01E+09
25	18020401	1.33E+06	6.63E+06	1.33E+07	4.46E+08	4.33E+10	3.49E+07	2.18E+09
26	18020402	6.64E+05	3.32E+06	6.64E+06	2.13E+08	2.06E+10	1.69E+07	1.04E+09
27	18020501	1.48E+06	7.41E+06	1.48E+07	2.99E+08	2.85E+10	2.90E+07	1.44E+09

28	18020502	1.07E+06	5.33E+06	1.07E+07	3.60E+08	3.49E+10	2.81E+07	1.75E+09
29	18020503	1.57E+06	7.87E+06	1.57E+07	6.14E+08	5.99E+10	4.57E+07	3.01E+09
30	18020601	1.08E+06	5.38E+06	1.08E+07	7.71E+08	7.60E+10	4.88E+07	3.81E+09
31	18020602	1.82E+06	9.08E+06	1.82E+07	1.97E+08	1.80E+10	2.71E+07	9.15E+08
32	18020603	2.88E+05	1.44E+06	2.88E+06	2.84E+08	2.81E+10	1.69E+07	1.41E+09
33	18020604	3.64E+05	1.82E+06	3.64E+06	1.68E+08	1.64E+10	1.19E+07	8.25E+08
34	18020701	5.94E+06	2.97E+07	5.94E+07	1.10E+09	1.04E+11	1.11E+08	5.24E+09
35	18020702	6.62E+05	3.31E+06	6.62E+06	5.90E+08	5.83E+10	3.58E+07	2.92E+09
36	18020703	3.83E+05	1.91E+06	3.83E+06	2.55E+08	2.52E+10	1.64E+07	1.26E+09
37	18020704	1.32E+06	6.61E+06	1.32E+07	4.49E+08	4.36E+10	3.50E+07	2.19E+09
38	18020801	2.48E+06	1.24E+07	2.48E+07	8.87E+08	8.63E+10	6.79E+07	4.34E+09
39	18020802	6.59E+05	3.29E+06	6.59E+06	2.94E+08	2.88E+10	2.10E+07	1.45E+09
40	18020803	3.95E+05	1.97E+06	3.95E+06	1.65E+08	1.61E+10	1.20E+07	8.09E+08
41	18020901	1.51E+06	7.57E+06	1.51E+07	6.17E+08	6.02E+10	4.53E+07	3.03E+09
42	18020902	3.83E+05	1.91E+06	3.83E+06	1.73E+08	1.69E+10	1.23E+07	8.49E+08
43	18020903	7.12E+05	3.56E+06	7.12E+06	2.40E+08	2.33E+10	1.88E+07	1.17E+09
44	18020904	4.92E+05	2.46E+06	4.92E+06	1.59E+08	1.54E+10	1.26E+07	7.74E+08
45	18020905	5.41E+05	2.70E+06	5.41E+06	1.93E+08	1.88E+10	1.48E+07	9.43E+08