AER/AGS Open File Report 2018-09

First-Order Groundwater Availability Assessment for Southern Alberta

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Abstract

Groundwater is an important resource for many stakeholders in Alberta. Quantifying the availability of groundwater is necessary for understanding current water use versus availability and evaluating risks associated with potential development scenarios. The Alberta Geological Survey (AGS) has used an aquifer yield continuum approach to quantify groundwater yield to a depth of 150 m below ground surface in southern Alberta. The aquifer yield continuum approach classifies yield along a spectrum, bound by non-use and maximum mining, rather than determining a single aquifer yield value. The concept depends on quantifying hydrogeological parameters such as recharge, discharge, and aquifer volume. Environmental flow needs, and input from local stakeholders and the community can be accounted for in order to manage the degree of impact of groundwater withdrawal on the hydrological system. Methods used to quantify each of these hydrogeological parameters depend on data availability, hydrogeological regime, climate, and landscape characteristics of the study area. As depression-focussed recharge is the dominant recharge mechanism on the Canadian Prairies, a method incorporating terrain analysis, identification of upland and depression characteristics, and simulation of surface runoff into depressions was used to estimate recharge throughout southern Alberta. Discharge was inferred based on recharge, and aquifer volumes to a depth of 150 m below ground surface were estimated from the AGS's 3D Provincial Geological Framework Model of Alberta. Aquifer yields are calculated on a watershed basis and results show that recharge ranges from 4 to 36 mm/yr with recharge decreasing from the northwest towards the southeast, following regional climatic gradients. Maximum sustained yield, after which groundwater mining will start to occur, ranges from 0.2E7 to 13E7 m^3/yr; however, there is less of a spatial trend in the yield values compared to recharge as volumetric yield is influenced by the size of a given watershed. Groundwater abstraction equal to the maximum sustained yield would have a significant impact on the hydrogeological system, including major impacts to surface water bodies. Permissive sustained yield, calculated as 10% of the maximum sustained yield in this study therefore provides an order of magnitude presumptive standard for yield in the absence of detailed studies in a given area. 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 throughout Alberta, and quantifying the amount of groundwater available throughout the province is necessary for understanding current water use versus availability and evaluating risks associated with potential development scenarios. The Alberta Geological Survey (AGS) has adopted a new approach to provide regional first-order assessments of groundwater availability in Alberta based on an aquifer yield continuum concept. This concept quantifies groundwater yield along a spectrum of total groundwater availability and is bound by two extremes: non-use and maximum mining. The concept depends on quantifying hydrogeological parameters such as recharge, discharge, and aquifer volume. Environmental flow needs and input from the community and local stakeholders can be accounted for in order to manage the degree of impact of groundwater withdrawal on the hydrological system.

There are a variety of methods to quantify each of these hydrogeological parameters. Data availability, hydrogeological regime, climate, and landscape characteristics of the study area may influence the methods chosen in any given study. The first area in Alberta mapped using the aquifer yield continuum concept was the near surface bedrock aquifers and overlying sediments in central Alberta (Klassen and Smerdon, 2018). Here, factors such as climate, the presence of generally unregulated rivers with no significant water withdrawals, and abundance of river gauging data contributed to the decision to use groundwater discharge to rivers (i.e., baseflow) as an estimate of 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 (m bgs) on the Canadian Prairies in southern Alberta. Differences in climate, recharge mechanisms, landscape characteristics, and availability of river flow data compared to the study area of Klassen and Smerdon (2018) lead to differences in the methods used to determine the values of the hydrogeological parameters required to quantify groundwater yield according to the continuum approach.

2 Background

2.1 Study Area

The study area covers approximately 180 000 km^2 of southern Alberta extending from the northern edge of the North Saskatchewan River Basin in the north to the Canada–U.S.A. border in the south (Figure 1). The western boundary is a combination of the western boundaries of the Edmonton–Calgary Corridor (ECC; Barker et al., 2011) and Calgary–Lethbridge Corridor (CLC; Atkinson et al., 2017) study areas, truncated by the deformation belt. The study area encompasses both the ECC and CLC and extends eastwards to the Alberta–Saskatchewan border. The northwest portion of the study area overlaps with the central Alberta study area of Klassen and Smerdon (2018), which allows for a comparison of the two different methods used to determine aquifer yield.

There are five Natural Regions present in the study area: Boreal Forest, Foothills, Grassland, Parkland, and Rocky Mountains; Grassland and Parkland being the most dominant (approximately 80 percent of study area) (Figure 2). Both regions consist mostly of glacial deposits (Figure 3) and are characterized by undulating plains and hummocky uplands. The region has been heavily cultivated and the dominant land uses includes cropland and grassland (Figure 2). The Grassland Natural Region is the warmest and driest region in Alberta, with maximum precipitation often occurring in June followed by a pronounced moisture deficit during the latter part of the growing season (Natural Regions Committee, 2006). The Parkland Natural Region climate is an intermediate zone between the dry, warm grasslands to the south and cooler, moisture boreal forests to west and north (Natural Regions Committee, 2006).

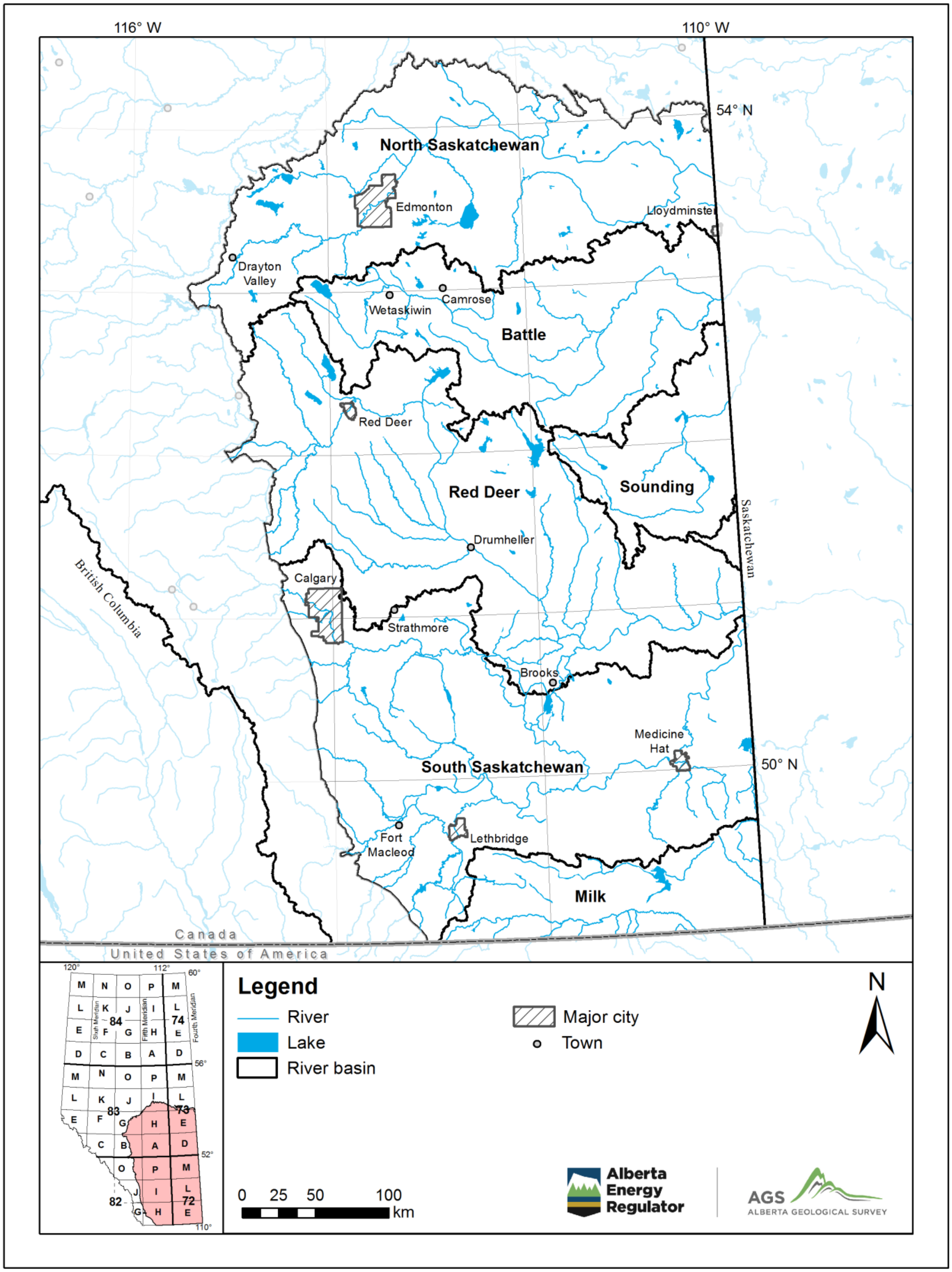

Figure 1. Study area, southern Alberta.

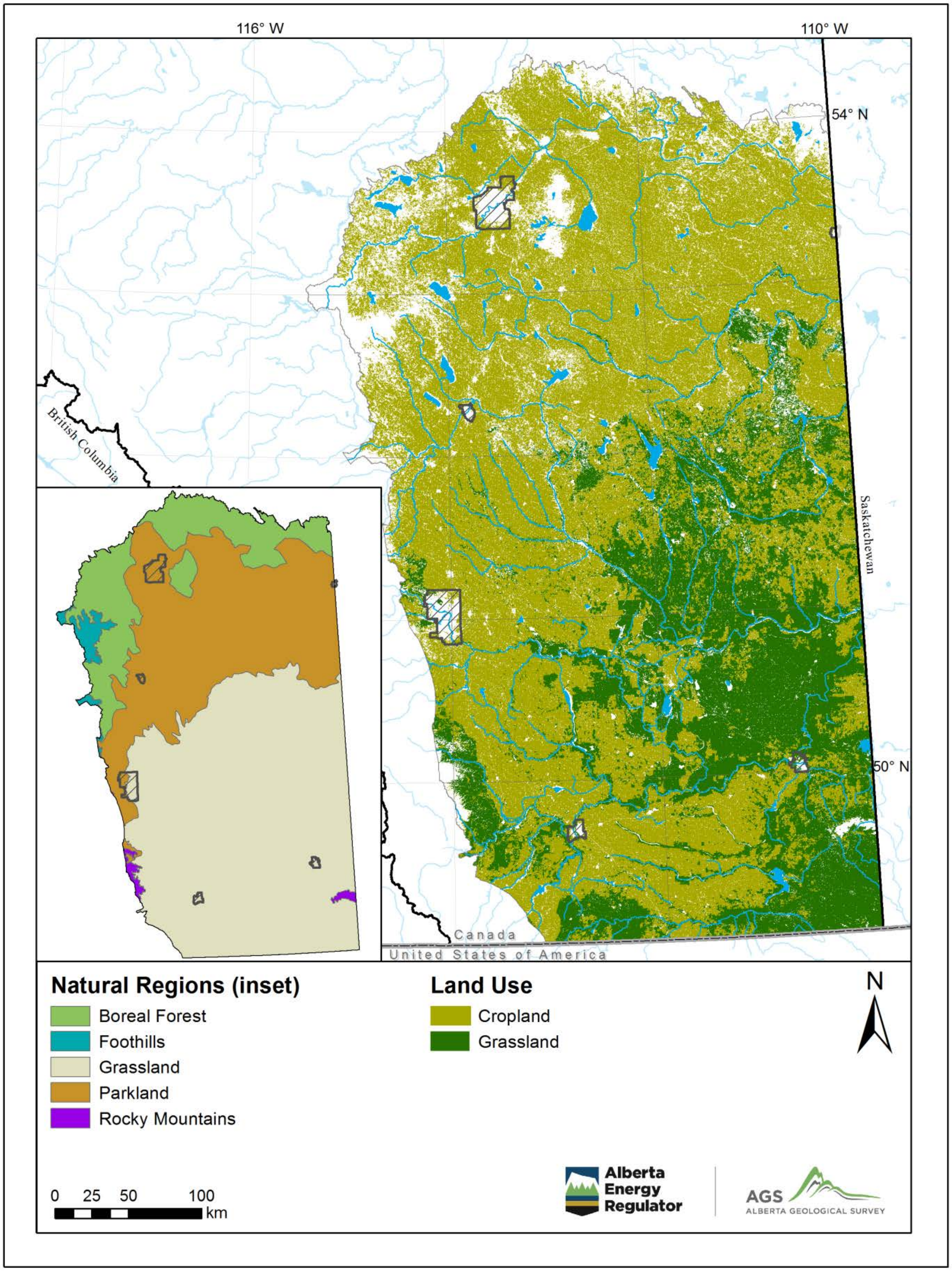

Figure 2. Natural regions of southern Alberta as defined by Natural Regions Committee (2006) and land use (Agriculture and Agri-Food Canada, 2015).

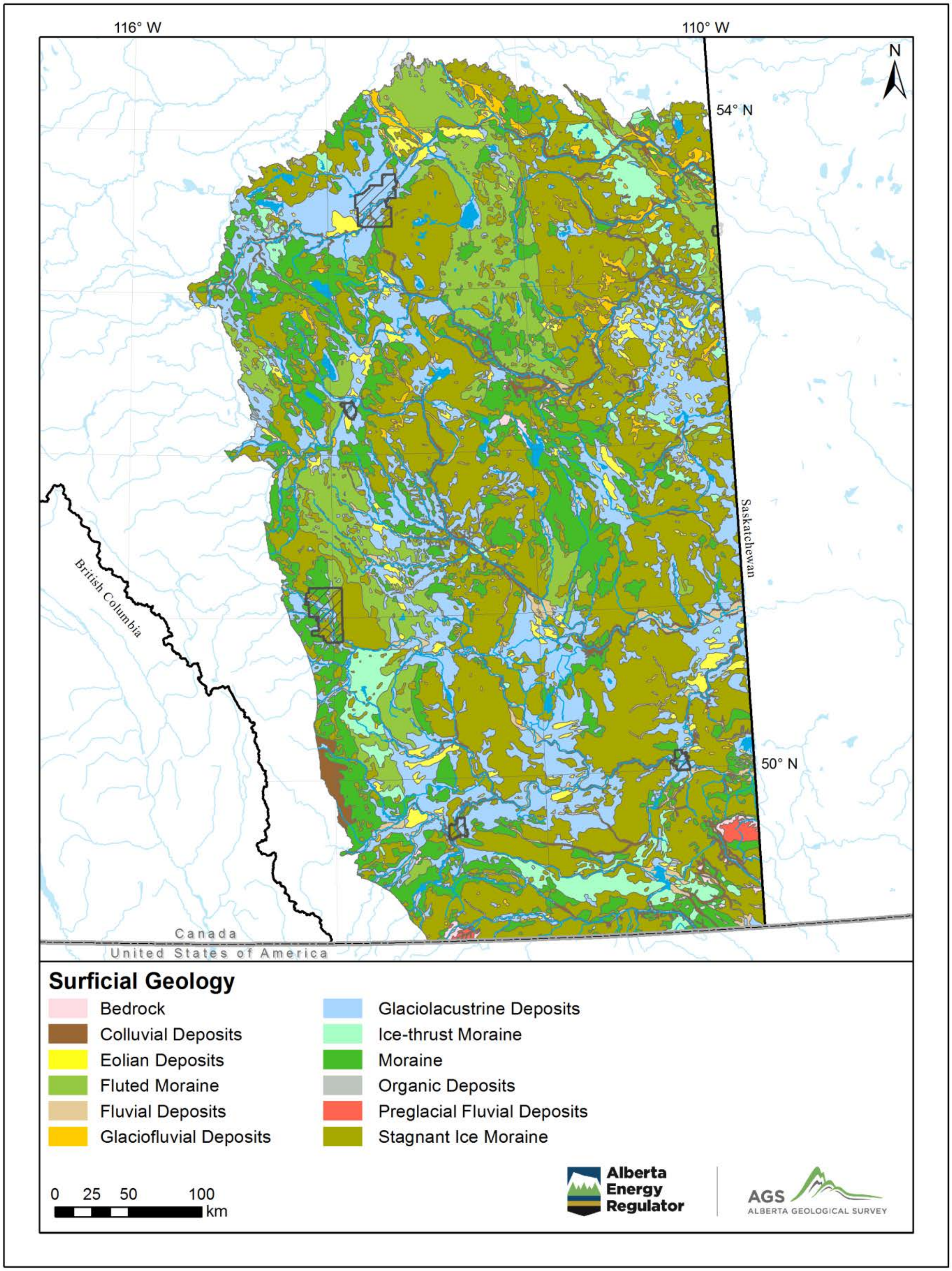

Figure 3. Surficial geology within the study area, southern Alberta (Fenton et al., 2013).

Snowmelt-driven depression focussed recharge is an important mechanism for recharge in the Canadian Prairies (Hayashi et al., 2003).With a moisture deficit occurring during the summer months, groundwater recharge occurs primarily during the spring, early summer, and sometimes fall months when snowmelt occurs and available water can exceed evaporation. During the winter months, the soil freezes and pore networks become limited, thereby reducing the infiltration capacity of the soil. Surface runoff is generated during spring snowmelt because the ground has not completely thawed and runoff is directed into small topographic depressions that are characteristic of this glacial landscape. When the ground underneath the depression partially thaws a recharge “window” occurs and ponded water infiltrates into the subsurface as depression focussed recharge (Hayashi et al., 2003; Mohammed et al., 2013; Noorduijn et al., in press). Potential evapotranspiration is also very low during the time of year when snowmelt and depression focussed recharge occurs.

The upper bedrock geology of the study area consists of upper Cretaceous–Paleogene sediments that were deposited during alternating events of limited sedimentation and/or marine events and continental sedimentation (Dawson et al., 1994). In southeast Alberta, the modern day surface has eroded down to the Bow Island Arch, exposing outcrops of the oldest formation (Milk River Formation) within the study area. Overlying the Milk River Formation is the Pakowki Formation which formed during a marine transgression (Dawson et al., 1994). The Lea Park Formation is the lateral equivalent to the Milk River and Pakowki formations. A gradational transition upwards leads into the Belly River wedge (lower Belly River, Foremost, Oldman and Dinosaur Park formations), which represents a period of continental sediment influx. A second transgression (Bearpaw Sea) and regression (Horseshoe Canyon Wedge) produced the Bearpaw, Blood Reserve, St. Mary River, Horseshoe Canyon, Eastend and Brazeau formations which are capped by the fine grained Battle Formation (Dawson et al., 1994). A regional disconformity separates these units from another clastic wedge made up of Frenchman, Coalspur, Scollard, Willow Creek, Porcupine Hills, Ravenscrag and Paskapoo formations (Dawson et al., 1994) (Figure 4).

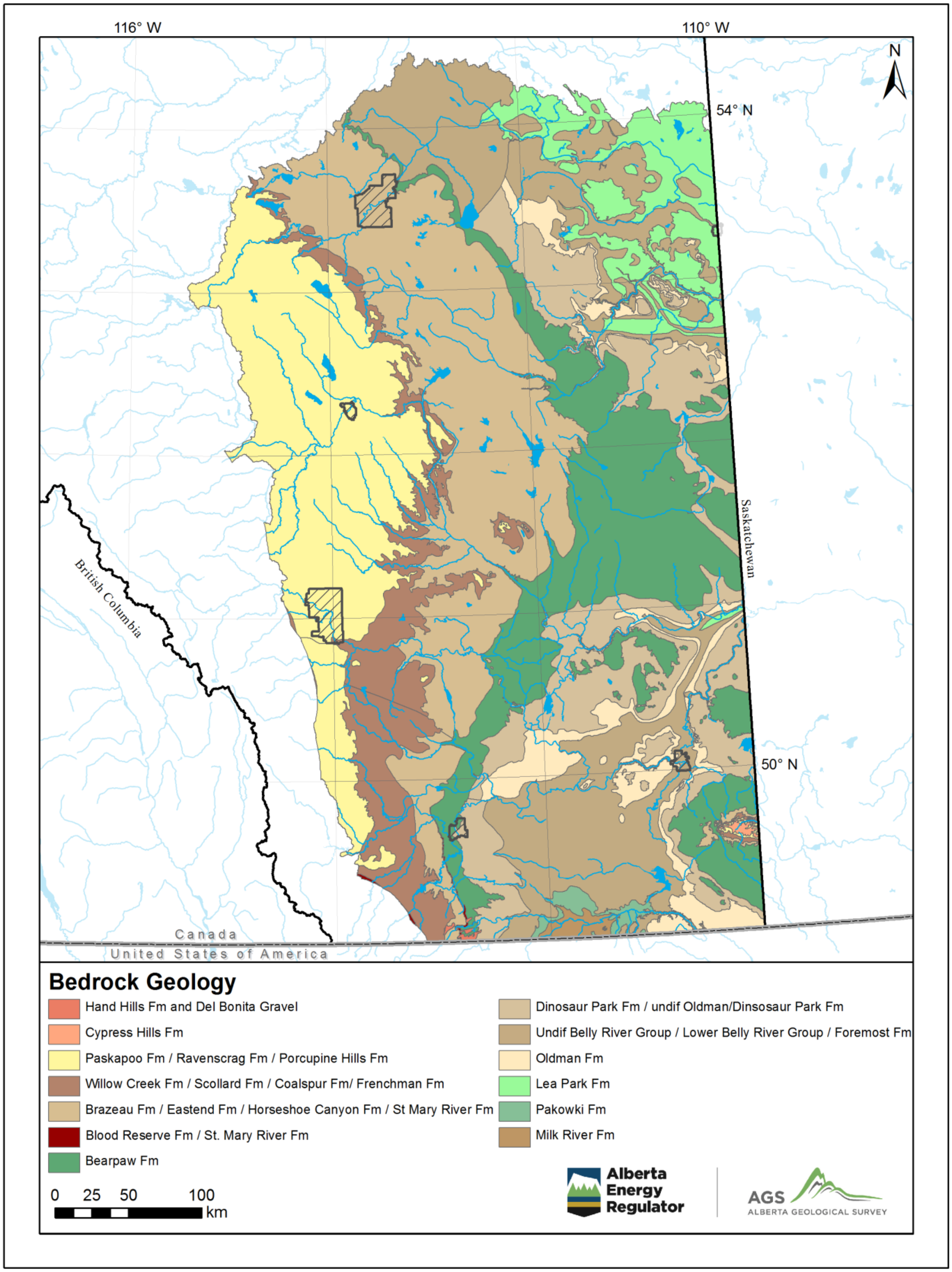

Figure 4. Bedrock geology with the study area, southern Alberta (Prior et al., 2013).

2.2 Yield Mapping

Previous determination of groundwater yield within Alberta includes maps created by the Alberta Research Council (ARC) from 1968–1983, which show the estimated rate 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). These maps were never intended for groundwater inventory or management purposes (Lemay and Guha, 2009), are limited to a time horizon, and provide a single estimate for yield. The AGS has adopted a new approach to mapping groundwater yield based on an aquifer yield continuum concept (Kalf and Woolley, 2005; Pierce et al., 2013).

The dialogue on the concepts of *safe* or *sustainable* groundwater yield has a long history, which is well summarized by Kalf and Woolley (2005). Over the past one hundred years there have been debates about terminology and how to best quantify sustainable yield, which includes both the physical system and social considerations. The water budget myth (Bredehoeft et al., 1982; Bredehoeft, 2002; Devlin and Sophocleous, 2005) states that from the physical system point of view it is incorrect to assume that the maximum size of a sustainable development can be determined by estimating the rate of natural recharge prior to initiation of pumping; in fact, it depends on the maximum amount of capture that occurs following pumping, which may or may not be equal to the initial natural recharge depending on the groundwater system (van der Gun and Lipponen, 2010). Capture is the decrease in discharge, increase in recharge, or a combination of both induced under pumping conditions (Lohman et al., 1972; Barlow et al. 2018). A decrease in discharge to or induced recharge from surface water bodies such as rivers, lakes, and wetlands may have a significant impact on the ecosystem health and downstream water availability.

The amount of pumped water coming from capture increases as pumping progresses and the groundwater system reaches a new steady state (or quasi-steady state). Figure 5 shows the source of water from a pumped well over time, separated into four phases. According to basic hydrogeological principles, when pumping is initiated all water extracted comes from storage as pressure at the well screen is reduced, lowering the potentiometric surface around the well and creating a cone of depression (Phase I). As the cone of depression grows, water can be captured that would have otherwise discharged from the groundwater system (e.g., into surface water bodies or via evapotranspiration) and/or recharge can be induced (e.g., from surface waterbodies), resulting in less water obtained from storage (Phase II). Eventually the maximum amount of capture attainable by the system for the given pumping rate is reached and a new equilibrium is established (Phase III). In the case of a sustainable scenario (upper chart) the rate of pumping is balanced entirely by capture of recharge and discharge, and no more water is removed from storage. This scenario can go on indefinitely (i.e., be sustained) without mining the aquifer, although it may result in a major change in the groundwater and surface water systems if the pumping rate is high enough. In the case of an unsustainable or groundwater mining scenario (lower chart), Phase III is a quasi-equilibrium, where the pumping rate is higher than the maximum amount of capture available from the physical system. The balance is made up by the continued removal of water from storage. Eventually the unsustainable scenario completely mines the aquifer (Phase IV) and pumping can no longer be sustained at the original rate. This comes at a great cost to both the groundwater and surface water systems.

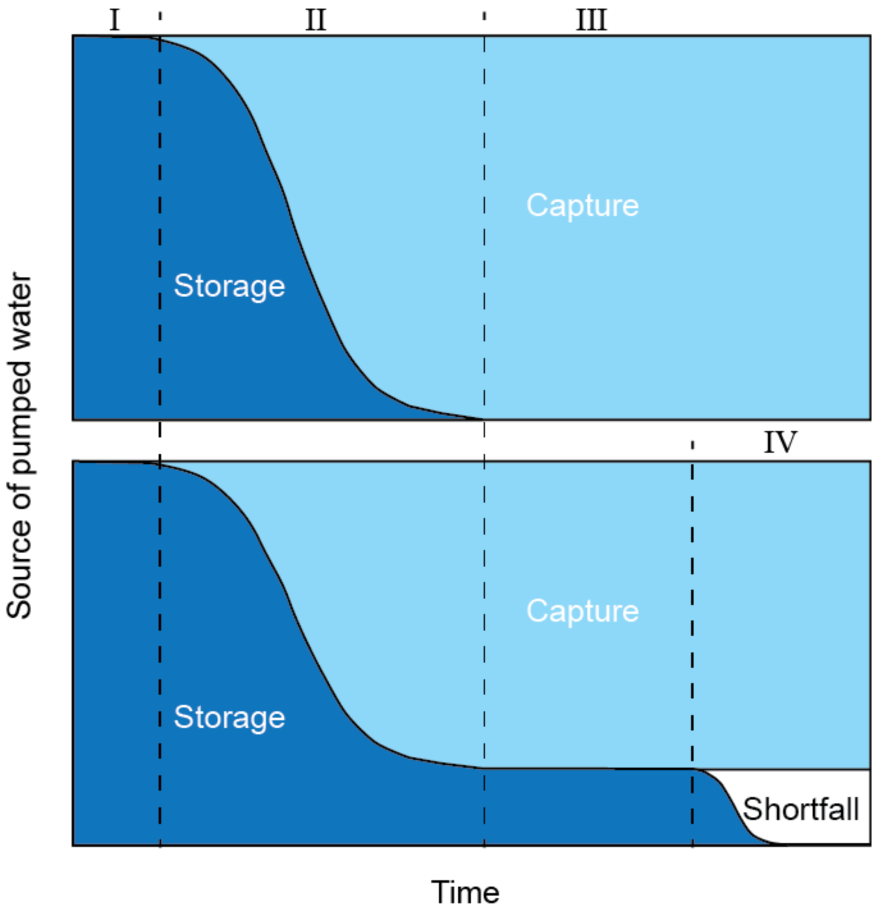

Figure 5. Schematic of the source of water to a pumping well over time. Upper chart shows a sustainable scenario and the lower chart shows an unsustainable or groundwater mining scenario.

Since any amount of groundwater abstraction will have some impact on the groundwater system, ultimately there should be no single value of groundwater yield for an area. Determining appropriate yields depends on the aquifer system as well as groundwater management decisions (e.g., Kalf and Woolley, 2005; Pierce et al., 2013). Pierce et al. (2013) discusses the merging of traditional hydrogeological information about aquifer performance with aquifer governance, and puts these in context of an aquifer yield continuum. Values of possible aquifer yield range from nonuse to a maximum mining scenario. The AGS has adopted a modified version of the aquifer yield continuum classes by Pierce et al. (2013) which also draws on other definitions of groundwater yield (e.g., Bredehoeft, 2002; Devlin and Sophocleous, 2005; Kalf and Woolley, 2005; Zhou, 2009). To summarize, the five classes of aquifer yield used for this study 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.

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 is technically recoverable and would result in significant alterations to the hydrogeological system.

The Pierce et al. (2013) study also includes a safe yield (SY), which lies between the MSY and PMY. However, there is some ambiguity in the mathematical definitions in the MSY, SY, and PMY classes defined by Pierce et al. (2013). Additionally, the term “safe yield” has been suggested by others to be abandoned due to its implication that a yield of that magnitude is “safe” when in reality; it will have significant consequences on the groundwater system and surface water bodies. Therefore, this report aligns with the terms outlined by Kalf and Woolley (2005) as described above.

Considering the physical system, there are many methods that could be used to determine the aquifer yield classes. These range from simple water balance, to complex numerical modelling methods. While numerical modelling methods may provide detailed analysis of the spatial and transient effects of pumping, they are time and data intensive and thus are usually developed for specific areas rather than regional applications. Water balance methods are not able to account for the spatial and temporal impacts of pumping (i.e., Phases I and II in Figure 5), but can provide information on the long-term yield once the system has reached a new (quasi-)steady-state (i.e., Phase III in Figure 5).

Given the regional focus of this study, water balance methods are used to define each of the aquifer yield classes. Table 1 summarizes the equations used to quantify each of the aquifer yield classes described above. They are based on equations presented in Kalf and Woolley (2005) and Pierce et al. (2013), with some modification. The equations can be adjusted such that yields can be quantified as rates or volumes over a given planning horizon.

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

There are a number of points to consider about the equations listed in Table 1:

- Quantifying R under a scenario of maximum capture would require an analysis of the groundwater and surface water system that is beyond the scope of this study. Therefore, it is assumed that in the MSY class, R is equal to the current rate of natural recharge. This is likely an underestimate of the maximum capture; however, given that the study area is semi-arid, the availability of additional surface water to induce recharge under a scenario of maximum capture is limited. Additionally, the rate of natural recharge provides a conservative value of MSY by not including induced recharge.

- The PSY and MSY of Pierce et al. (2013), and Klassen and Smerdon (2018) are captured under one class (PSY) in this report, with different values of D_x. The term SY of Pierce et al. (2013), and Klassen and Smerdon (2018) is replaced by MSY in this report.
- Kalf and Woolley (2005) define MMY under the condition that the aquifer is a non-renewable resource, similar to minerals or oil and gas. Therefore the yield comes only from storage and does not consider inflow/outflow. In this study, MMY includes full abstraction of recharge and aquifer storage;
- It is important to note that the equations in Table 1 relate to Phase III in Figure 1, neglecting the volume of water that would initially be depleted from storage. If actual volumes removed from storage vs capture during Phase I and II are desired, a more local, transient analysis of the pumping system must be performed.

The value of each yield class is determined according to the equations shown in Table 1. The MSY and MMY classes are limited by the hydrogeological system, whereas the PSY and PMY scenarios can slide within a range along the continuum depending on aquifer management decisions, including incorporating social, environmental, and economic decisions. 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).

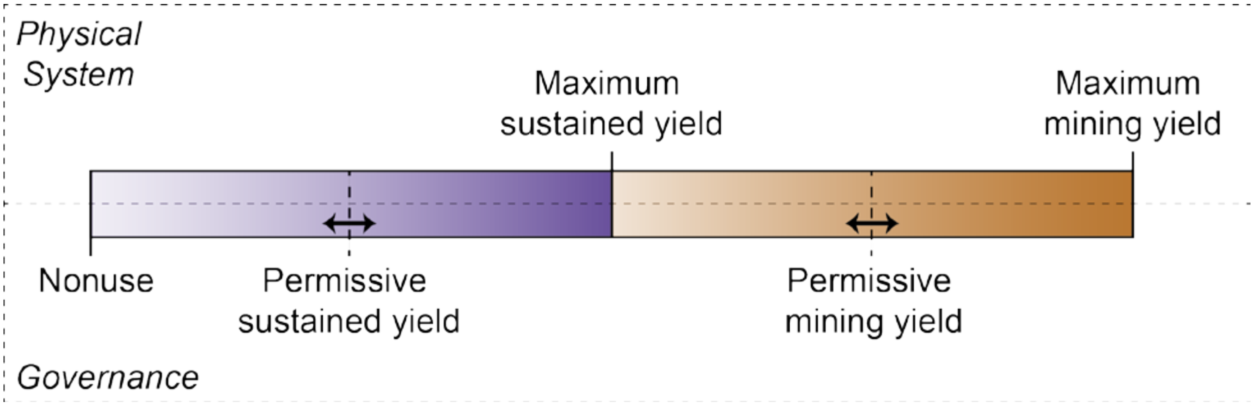

Figure 6. Aquifer yield classes, modified after Kalf and Woolley (2005) and Pierce et al. (2013).

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. For central Alberta, the aquifer yield continuum method was applied to near-surface bedrock formations containing nonsaline groundwater and used a baseflow approach to estimate recharge (Klassen and Smerdon, 2018). The baseflow approach for estimating recharge is not suitable for southern Alberta because compared to central Alberta, southern Alberta has thicker surficial sediment cover, more regulated (dammed) rivers, stream gauge data is minimal, and higher evapotranspiration (e.g., in riparian areas). As a result, a new approach to quantifying recharge is required in order to apply the aquifer yield continuum.

3 Aquifer Yield Mapping Methods

The aquifer yield continuum is applied at a watershed level in this study. The watersheds are reflective of the Hydrologic Unit Code Watersheds of Alberta level 8 watersheds (HUC8) (Alberta Environment and Parks, 2017), with level 2 being equivalent to major rivers basins (e.g., Figure 1), followed by level 4, 6, and 8. Values for aquifer yield classes above nonuse are calculated for each of the 121 HUC8 watersheds within the study area, including two calculations for PSY to illustrate more and less conservative yield values (see Section 3.2).

The three types of hydrogeological parameters required to determine the aquifer yield in each class are recharge (R), discharge (D_x) and volume of groundwater in storage (V_0, V_x) (Table 1). In this study, spatially variable recharge was modelled using a methodology developed by the University of Calgary (e.g., Pavlovskii et al., 2017, Noorduijin et al., in press) with some slight modification. Discharge is based on the knowledge of modelled recharge and an assumption that recharge eventually discharges in a closed-basin, steady-state system. Aquifer volumes are obtained using the AGS's 3D Provincial Geological Framework Model of Alberta, Version 1 (3D PGF model v1; Branscombe et al., 2018a). Detailed methods on determining each of these hydrogeological parameters from Table 1 are described in the sections below.

3.1 Recharge

Figure 7 shows the workflow involved in determining spatially distributed recharge (R in Table 1) throughout the study area. The workflow follows methods developed at the University of Calgary by Farrow et al. (2014), Pavlovskii et al. (2017), and Noorduijn et al. (in press). Initially, a terrain analysis was performed to delineate individual depressions in the landscape and their associated catchment area. From this analysis upland–depression characteristics such as the depression area (DA), catchment area (CA), and depression area to catchment area ratio (DA:CA) could be extracted. Results of the terrain analysis were used in two ways: first, a generalized relationship between DA and volumetric capacity (C) of the depression was developed (i.e., the DA-C relationship). Second, a matrix of the likelihood of finding a particular combination of two particular upland–depression characteristics, CA and DA:CA, in a given surficial geology type was determined.

The DA-C relationship was used as an input parameter for simulating recharge with the VSMB-DUS soil water balance code (see Section 3.1.2). A large suite of one-dimensional VSMB-DUS models were created in order to reflect varying upland–depression characteristics and land use types. Finally, the results of the one-dimensional recharge modelling were spatially distributed using the probability matrices of upland–depression characteristics for each surficial geology type, and aggregated to provide simulated recharge within each HUC8 watershed.

The following sections detail the methods within each of the terrain analysis, VSMB-DUS modelling, and spatial distribution of modelling results steps.

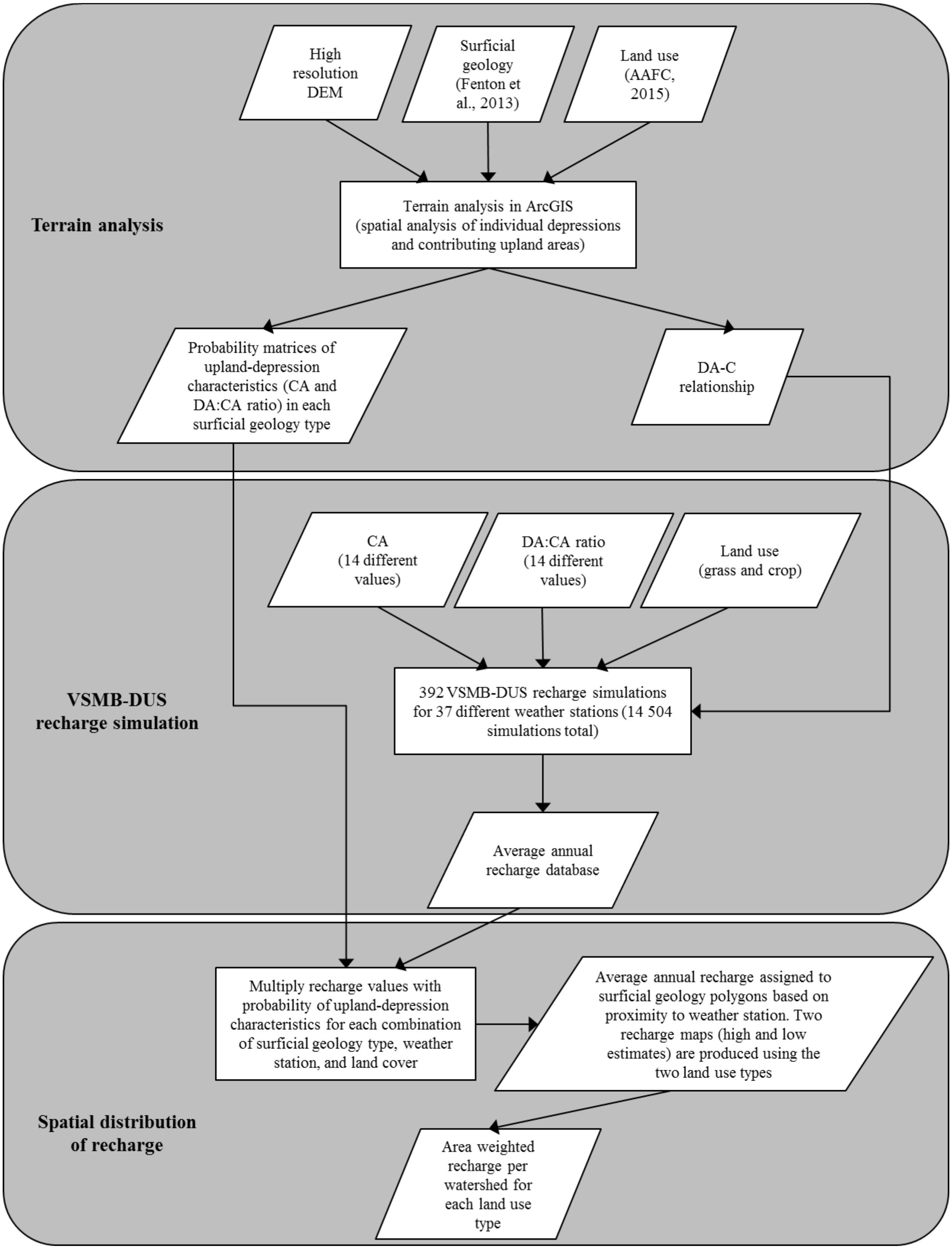

Figure 7. Workflow for determining spatially distributed recharge.

3.1.1 Terrain Analysis

The terrain analysis method of Pavlovskii et al. (2017) utilizes a 2 m resolution LiDAR digital elevation model (DEM) acquired by ESRD (2007), surficial geology (Fenton et al., 2013), and land use (Agriculture and Agri-Food Canada, 2015) to identify the upland–depression characteristics in a portion of the ECC. The land use and surficial geology maps are used to identify catchments that are not intersected by roads and fall completely within each surficial geology type. Probability matrices of the CA and DA:CA are created for each surficial geology type. Additionally, the volumetric capacity of each depression is determined across which a best-fit line for a generalised DA-C relationship can be fitted.

Pavlovskii et al. (2017) conducted a terrain analysis on a DEM within the ECC (Figure 8; NTS mapsheet 82P). Their analysis considered four surficial geology types (glaciolacustrine deposits, fluted moraine, moraine and stagnant ice moraine) and two land use types (cropland and grassland). The terrain analysis resulted in a DA-C relationship for all depressions, regardless of surficial geology type, of:

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

In the current study, the terrain analysis was expanded north and south of the area used by Pavlovskii et al. (2017) (Figure 8). The expanded terrain analysis allows for the inclusion of more surficial geology types (i.e., colluvial, eolian, fluvial, and glaciofluvial) and to explore the sensitivity of the DA-C relationship. The terrain analysis resulted in a DA-C relationship for all depressions, for the four surficial geology types from Pavlovskii et al. (2017) and four new surficial geology types, of:

$$C = 0.053(DA)^{1.23}$$

The DA-C relationship from the expanded terrain analysis area was very similar to Pavlovskii et al. (2017) therefore the original equation was used in the VSMB-DUS recharge simulation. Figure 9 shows the DA-C results of the expanded terrain analysis area as well as the generalized best-fit DA-C relationship from Pavlovskii et al. (2017). The results from the expanded terrain analysis area were used to determine the probability matrices of upland–depression characteristics for the eight surficial geology types within the DEM extent type. These were used later to spatially distribute the results of the VSMB-DUS recharge modelling.

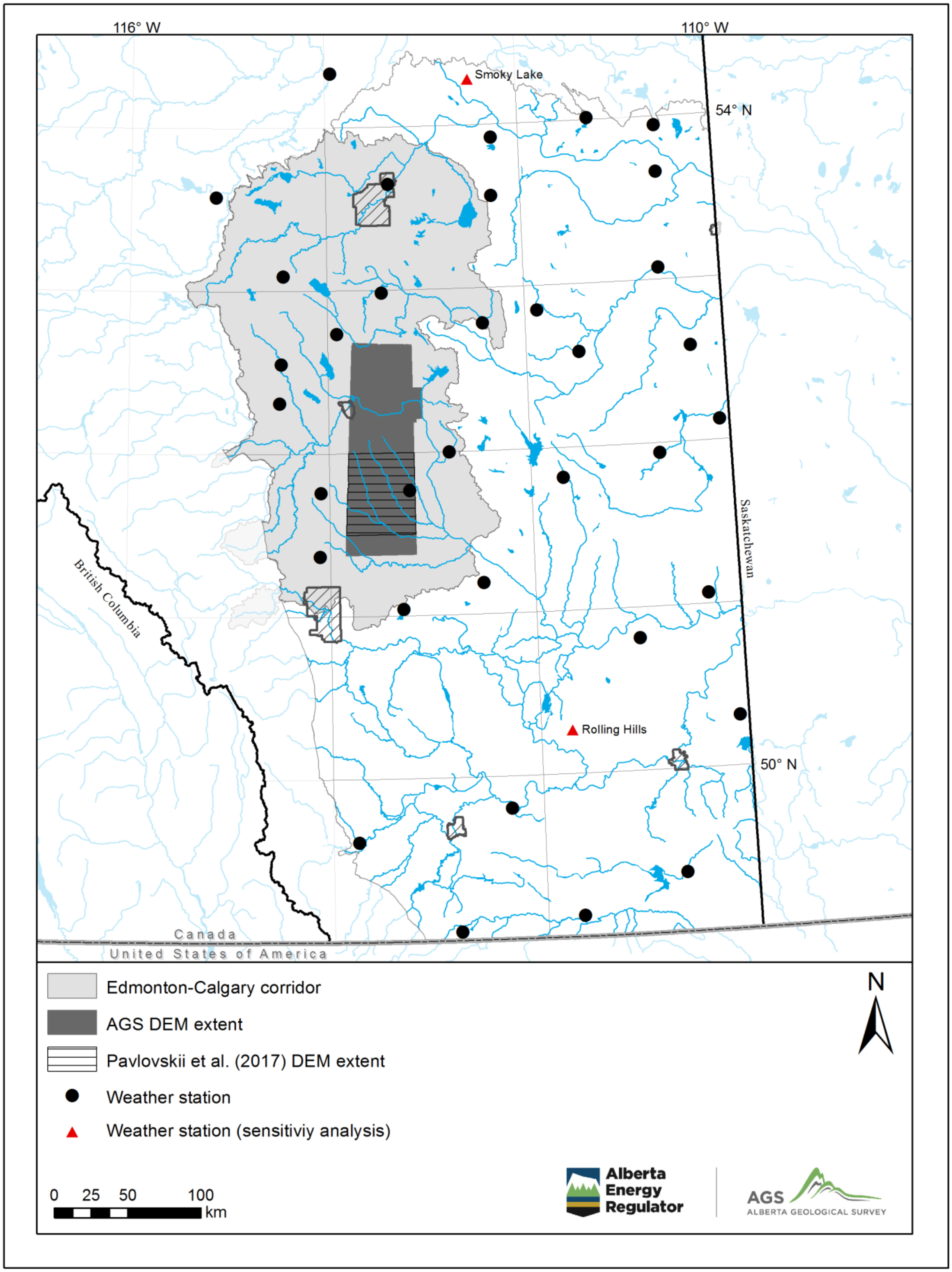

Figure 8. Location of DEMs used for the terrain analyses, and locations of weather stations used for VSMB-DUS recharge modelling and sensitivity analysis.

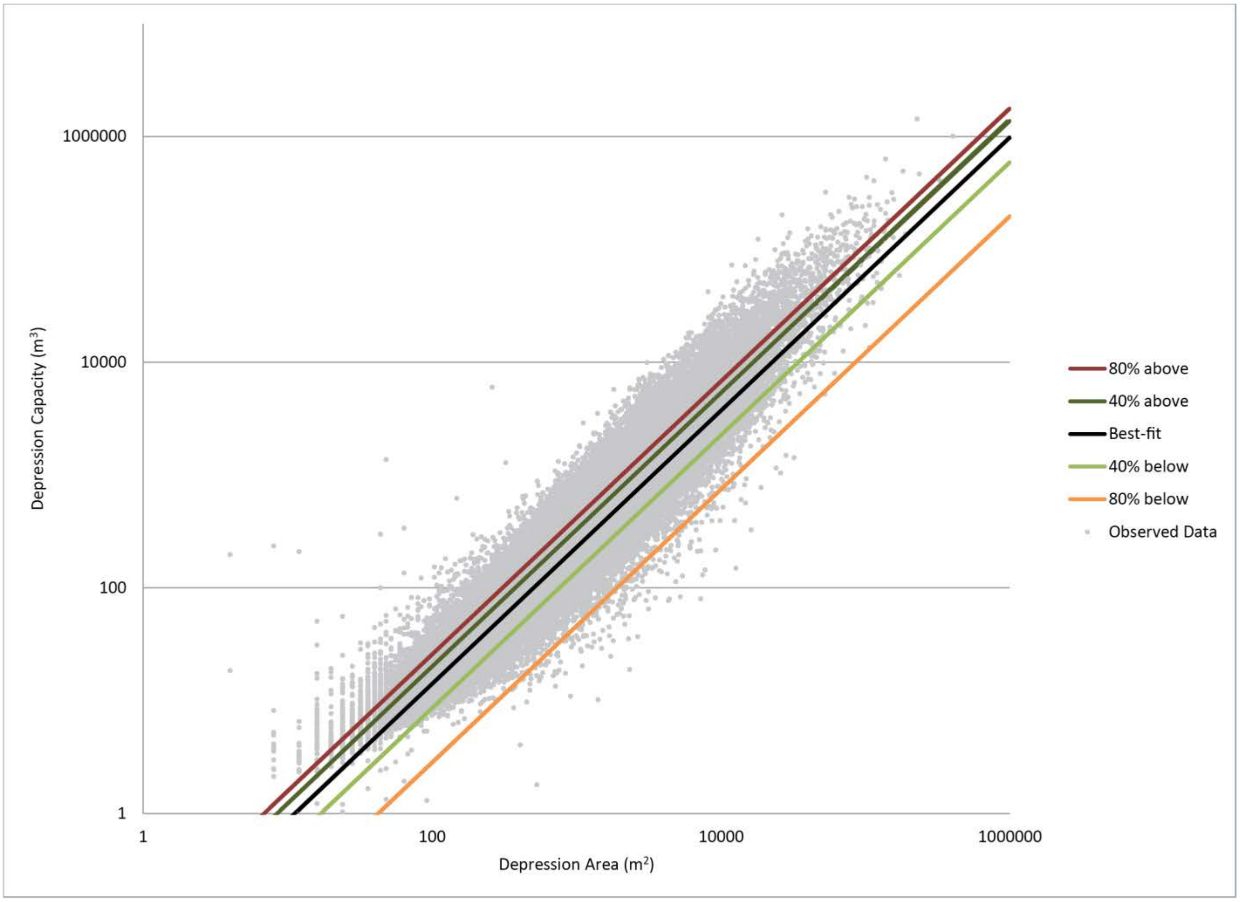

Figure 9. Depression area capacity results of the expanded terrain analysis area. The best-fit line is illustrated along with those representing an 80% and 40% departure above and below the best-fit line.

3.1.2 VSMB-DUS Recharge Simulation

The Versatile Soil Moisture Budget (VSMB) is a multilayer, one dimensional, soil water balance code originally developed by Baier and Robertson (1966). It has been used widely to model soil moisture dynamics in the Canadian Prairies (Mohammed et al., 2013). Leakage out the bottom of the simulated soil column can be viewed as groundwater recharge (Noorduijn et al., in press). VSMB has undergone numerous modifications, including improvements to the simulation of rainfall runoff and evapotranspiration (Akinremi et al., 1996, and Hayashi et al., 2010), and improvements to snow accumulation/melt and frozen soil processes (Mohammed et al., 2013). The most recent modification incorporates the concept of depression focussed recharge by linking two VSMB simulations: one representing the soil and ponding conditions in a local depression (VSMB$_d$) and one representing the contributing upland area to the depression (VSMB$_u$), where surface runoff from the VSMB$_u$ simulation is added to the VSMB$_d$ simulation (Figure 10) (Noorduijn et al., in press). This new version of the code is called VSMB-DUS (-Depression Upland Storage) (Noorduijn et al., in press).

Inputs to VSMB-DUS include meteorological data (e.g., hourly precipitation, air temperature, relative humidity), evapotranspiration parameters (e.g., growth curves), and soil properties (e.g., wilting point, field capacity). VSMB-DUS includes additional parameters describing depression characteristics and the relationship between the upland and depression simulations. These include the CA, DA:CA, and the DA-C relationship.

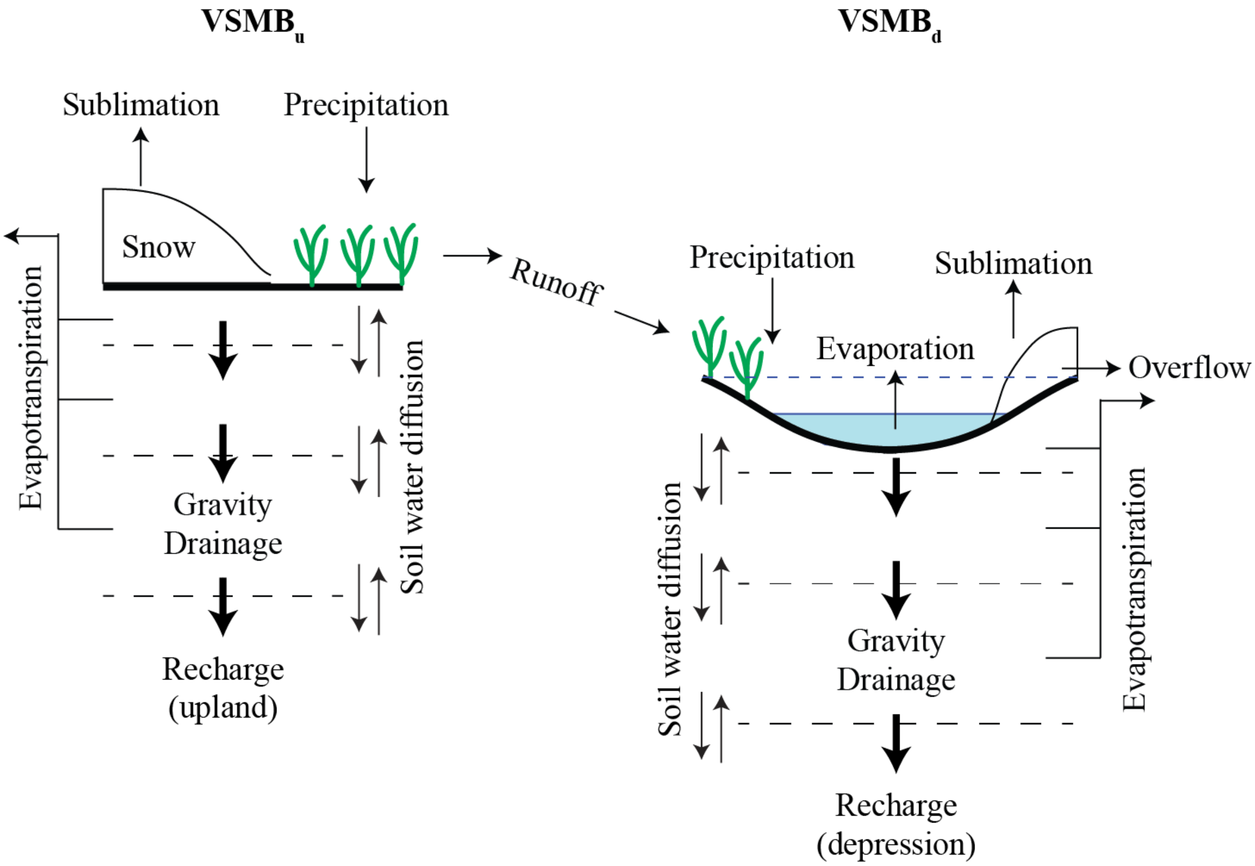

Figure 10. Schematic of VSMB-DUS showing the relationship between the upland (VSMB$_u$) and depression (VSMB$_d$) simulations.

In order to obtain spatially-distributed values of recharge a large suite of VSMB-DUS models were simulated with varying input parameters considering different upland–depression characteristics, land use, and meteorological data. The parameters describing the upland–depression characteristics in VSMB-DUS were informed by the terrain analysis (Section 3.1.1). Hourly data from 37 weather stations was obtained from Alberta Agriculture and Forestry’s Alberta Climate Information Service (ACIS, https://agriculture.alberta.ca/acis/) (Figure 8). The precipitation data were processed to correct any bias due to wind-induced undercatch (Smith, 2007). Following the procedure in Pavlovskii et al. (2017), 392 simulations were completed for each weather station considering 14 different CAs (100, 200, 400, 800, 1600, 3200, 6400, 12 800, 25 600, 51 200, 102 400, 204 800, 409 600, 819 200 m^2), 14 different DA:CA (0.01, 0.03, 0.05, 0.07, 0.09, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, 0.95), and two land use types (crop and grass).With 37 weather stations, this totals 14 504 VSMB-DUS simulations.

The VSMB simulations were run on an hourly time-step for seven hydrological years: from October 1, 2009 to September 30, 2016. The simulations also include a spin-up period of 14 years prior to October 1, 2009, which was achieved by repeating the input meteorological data twice. The runoff parameters used in these simulations were the same as those of Pavlovskii et al. (2017), which were calibrated based on a field site north of Calgary, Alberta. The soil properties (e.g., field capacity, porosity, hydraulic conductivity) are similar to those outlined in Noorduijun et al. (in press) and are held constant. Results of the VSMB-DUS simulations were compiled in a database such that for each weather station a recharge value reflecting a specific CA and DA:CA for either cropland or grassland could be referenced. The cropland recharge represents a high estimate of recharge, whereas the grassland recharge estimate represents a low estimate of recharge.

Early tests of VSMB-DUS indicated that the DA-C relationship can have a large impact on recharge results; therefore, in order to evaluate the effect of the DA-C relationship on recharge rates a sensitivity analysis was performed using 4 additional DA-C relationships. Figure 9 shows 4 DA-C relationships with the same slope as the best-fit line, but different x-intercepts. The equations with the highest and lowest x-intercept show the DA-C relationships 80% higher and lower than the best-fit line, respectively, while the equations with the next highest and lowest x-intercept show a difference of 40% above and below the best-fit line. If the generalized DA-C relationships are determined for each surficial geology type, they mostly fall between the lines which lie 80% above the best-fit line and 40% below.

The suite of 392 VSMB-DUS simulations (i.e., with 14 different CAs, 14 different DA:CAs, and 2 land use types) were run for each of the 4 additional DA-C relationships using meteorological data from two weather stations: Smoky Lake AGDM and Rolling Hills AGCM, which represent a wetter area in the northern section of the study area and a drier area in the south, respectively (Figure 8). Results show that of the three upland–depression parameters tested (CA, DA:CA, and DA-C relationship), the DA:CA has the largest influence on the recharge results, rather than the DA-C relationship. Figure 11 shows box and whisker plots of the range of recharge within each DA:CA tested. The variability between different DA:CAs is larger than the variability between different DA-C relationships. The results of the sensitivity analysis show that using the terrain analysis to account for the probability of finding a particular DA:CA (and CA) within a particular surficial geology type is beneficial.

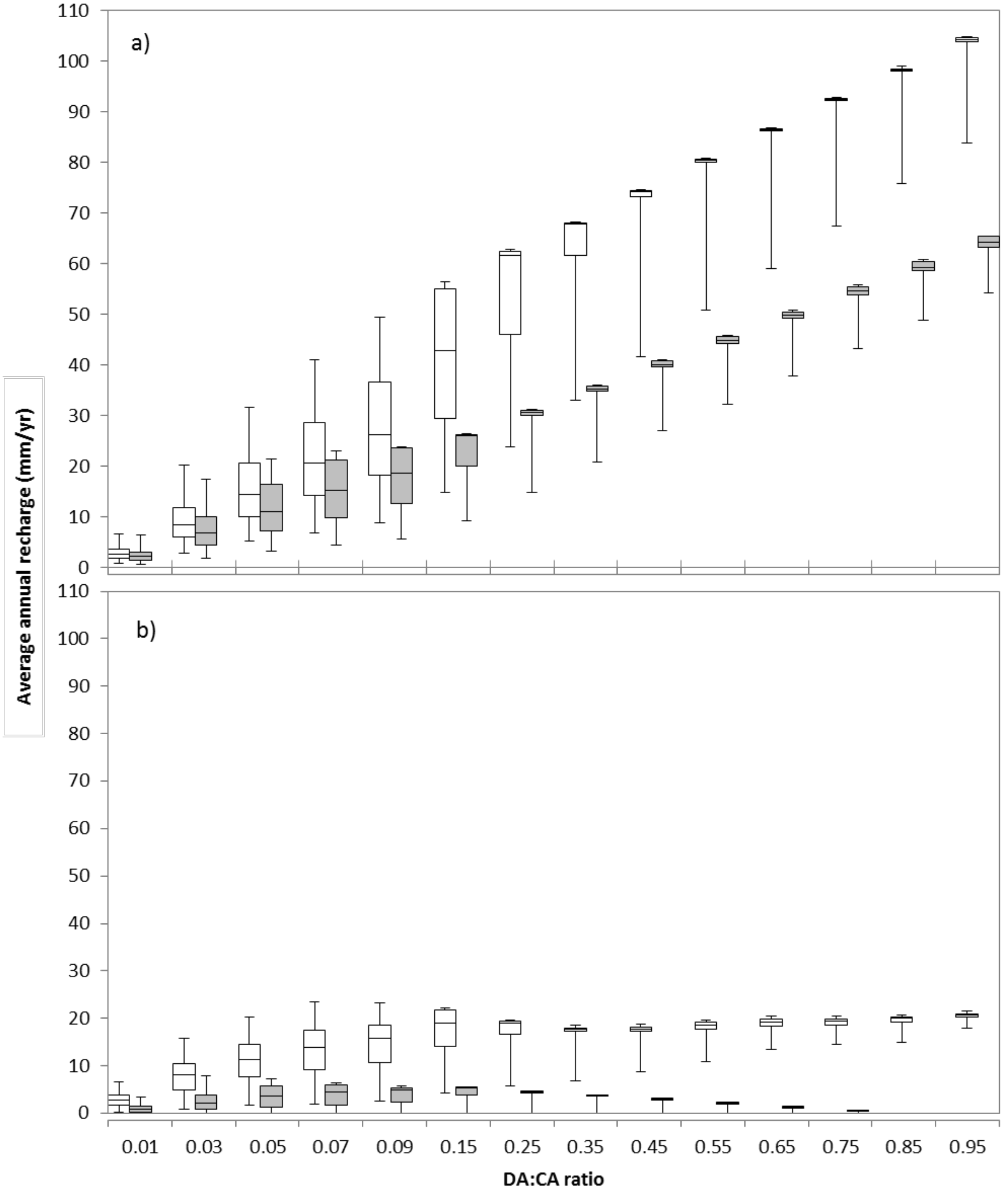

Figure 11. Box and whisker plots showing the minimum, 25th percentile, median, 75th percentile, and maximum recharge for a given DA:CA using 14 different catchment areas and 5 different DA-C relationships for a) the Smoky Lake weather station, and b) the Rolling Hills weather station. The white boxplots are for simulations with cropland ET parameters and the gray boxplots are for simulations with grassland ET parameters.

3.1.3 *Spatial Distribution of Recharge*

The expanded terrain analysis area contained nine surficial geology types (colluvial, eolian, fluted moraine, fluvial, glaciofluvial, glaciolacustrine, ice thrust moraine, moraine, and stagnant ice moraine), the percent coverage of each material type was more similar to the distribution of percent coverage throughout the entire southern Alberta study area compared to the terrain analysis area used by Pavlovskii et al. (2017). Ice thrust moraine was the only surficial geology type to be excluded from the expanded terrain analysis for two reasons: firstly, the percent coverage of ice thrust moraine in the expanded terrain analysis area was very small (<1%) although this surficial geology covers large, continuous portions of the southern Alberta study area; secondly, the DA-C relationship was very different from the other surficial geology types and did not fall between the sensitivity analysis bounds (i.e., 80% above the best-fit line and 40% below). Therefore the results of the terrain analysis for ice thrust moraine may not be representative of the average upland–depression characteristics for that surficial geology type.

In order to spatially distribute the VSMB-DUS recharge results the high (crop) and low (grass) recharge results for each weather station were multiplied by the upland–depression characteristic probability matrix for each surficial geology type. The high and low recharge values were then attributed to their corresponding surficial geology polygons based on the proximity to weather stations to create high and low recharge maps for southern Alberta. Since the aquifer yield continuum in this study is a first-order assessment and is applied at a watershed scale, area weighted average low and high recharge values were calculated for each of the HUC8 watersheds.

3.2 Discharge

In the aquifer yield continuum, D_x is the residual discharge that is not captured during pumping under the PSY class (Table 1). The value of D_x can vary from being equal to recharge during a non-pumping steady state to zero, where it is fully captured during MSY pumping conditions. For this study, actual desired values of discharge are not available, therefore, values were assumed. These values can be modified to be site specific, depending on the hydrogeological system, environmental flow needs, and desires of the community.

In a steady-state, closed basin, inputs are equal to outputs; therefore, the natural discharge rate in each HUC8 watershed was assumed to be equivalent to recharge (simulated with VSMB-DUS). To be consistent with the approach by Klassen and Smerdon (2018), two PSY values are calculated to illustrate how it will fall on the continuum. The first was a scenario where 90% of natural discharge was desired to remain in the system, which 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 was in the middle where 50% of natural discharge was desired. These two scenarios are equivalent to assuming that pumping (P) represents 10% and 50% of the simulated recharge for the PSY class (Table 1).

3.3 Volume

The V_0 was considered to a depth of 150 m bgs. This depth was selected because the vast majority of water wells in the study area are completed above this depth, and drilling deeper requires well blow-out prevention measures. In lieu of region-wide detailed mapping of permeable geobodies that could represent productive aquifers, water volumes were determined on a geological formation basis according to the 3D Provincial Geological Framework Model, Version 1 (3D PGF model v1) (Branscombe et al., 2018a).

The 3D PGF model v1 is a province-wide multi-layer model of the stratigraphy of Alberta. The 3D PGF model v1 is divided into zones representing geological members, formations, groups or mixes of these entities depending on data availability (Branscombe et al., 2018b). The modelled zones relevant to the study area include the sediment above bedrock, Paskapoo Formation, Scollard Formation, Battle Formation, undifferentiated Horseshoe Canyon Formation / Wapiti Formation / St. Mary River Formation / Belly River Group / Bearpaw Formation equivalent interval, upper Bearpaw interval, Strathmore Member, lower Bearpaw interval, Dinosaur Park Formation, Oldman Formation, Foremost Formation, undifferentiated Lea Park Formation / Colorado Group / Smoky Group / Fort St. John Group equivalent interval, the Pakowki Formation, and the Milk River Formation to base of the Fish Scales Formation interval. The stratigraphic relationships between these zones in the 3D PGF model v1 are shown in Figure 12. It is important to note that Version 1 of the 3D PGF model v1 does not have the same geological divisions as the bedrock subcrop map of Alberta (Figure 4), with some geological members/formations/groups being undifferentiated in the 3D PGF model v1 due to the unavailability of regionally mapped geological tops and bottoms of each division. For example, the Bearpaw Formation is differentiated in the 3D PGF model v1 only where the intervening Strathmore member has been mapped, rather than based on its actual geological extent. Subsequent versions of the 3D PGF model v1 aim to incorporate more geological divisions based on regional geological mapping.

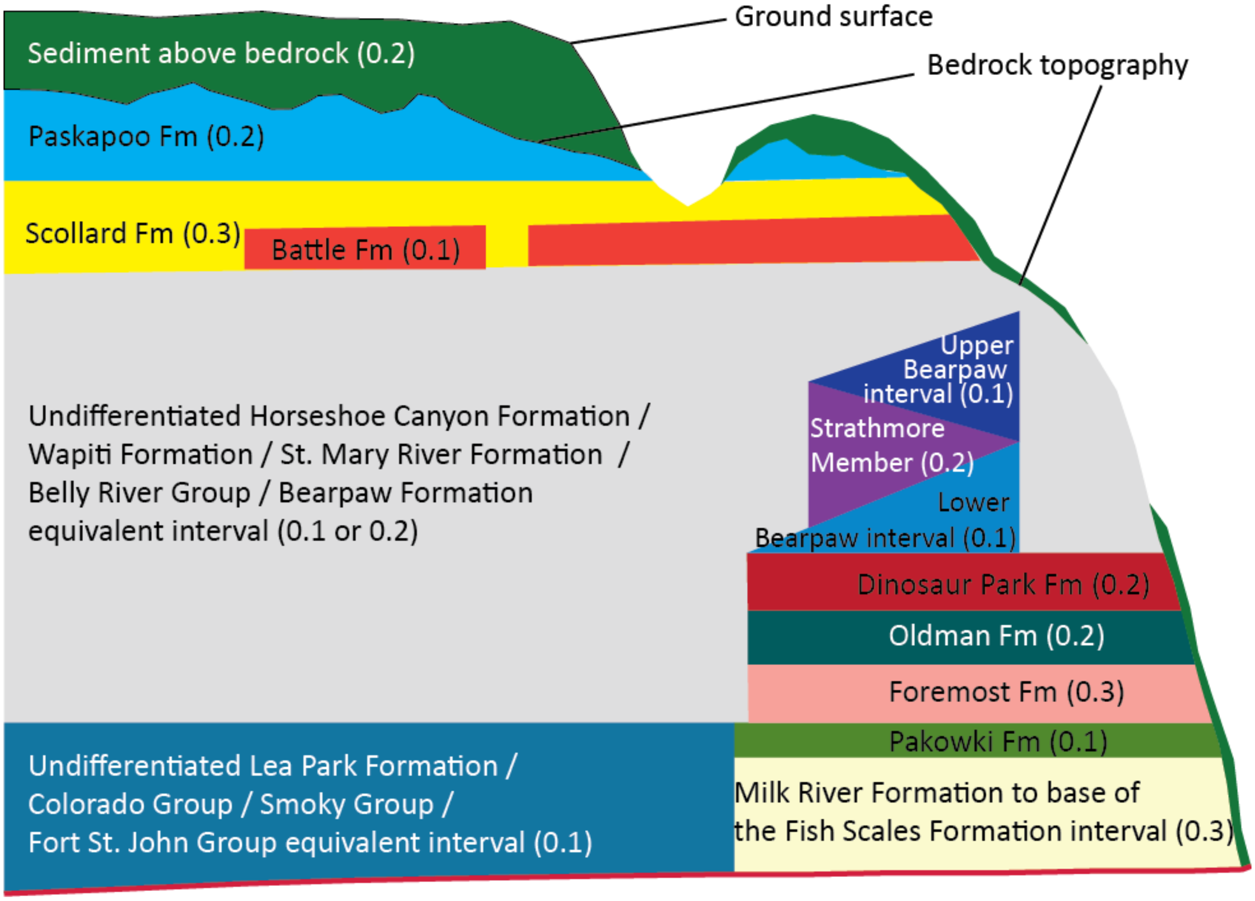

Figure 12. Geological zones and stratigraphic relationships from the 3D PGF model v1 found within 150 m of the ground surface (modified from Branscombe et al., 2018b). Geological zones are based on the availability of stratigraphic picks. Values in parentheses indicate the effective water-filled porosity of each zone used in the calculations of aquifer yield.

For each watershed, the volume of each geological zone within 150 m bgs was determined using the 3D PGF model v1 in Schlumberger's Petrel 2015 software (Figure 13). Water volume within each zone was determined by assuming an effective porosity based on its geological characteristics (Figure 12). Zones in the 3D PGF model v1 that are typically composed of fine-grained shale and mudstone, which are generally considered aquitards, are assigned an effective porosity of 0.1. This includes the Battle Formation, upper and lower Bearpaw intervals, the Pakowki Formation, and the undifferentiated Lea Park / Colorado Group / Smoky Group / Fort St. John Group equivalent interval. Note that although the Colorado and Smoky groups do contain some coarser grained siltstone and sandstone formations, these units are likely to be found deeper than 150 m bgs within the study area. Zones which are typically composed of coarser-grained siltstones and interbedded sandstones, and generally considered aquifers, are assigned an effective porosity of 0.3. This includes the Strathmore Formation, Foremost Formation, and Milk River Formation to base of the Fish Scales Formation interval. Zones which are a mixture of sandstone and siltstone with interbedded mudstones and shales are assigned an effective porosity of 0.2. This includes the Paskapoo Formation (because the Sunchild and Haynes aquifers have not been differentiated in Version 1 of the 3D PGF model v1), the Scollard Formation, Dinosaur Park Formation, and Oldman Formation. The undifferentiated Horseshoe Canyon Formation / Wapiti Formation / St. Mary River Formation / Belly River Group / Bearpaw Formation equivalent interval was assigned a porosity of 0.1 in watersheds where only the Bearpaw Formation subcrops according to Map 600 (i.e., no Horseshoe Canyon Formation subcrop), as it likely that the shallowest undifferentiated zone in the 3D PGF model v1 consists mainly of the Bearpaw Formation in these areas. The overlying Neogene-Quaternary sediments are assigned a porosity value of 0.2, because they have not been differentiated across the entire study area.

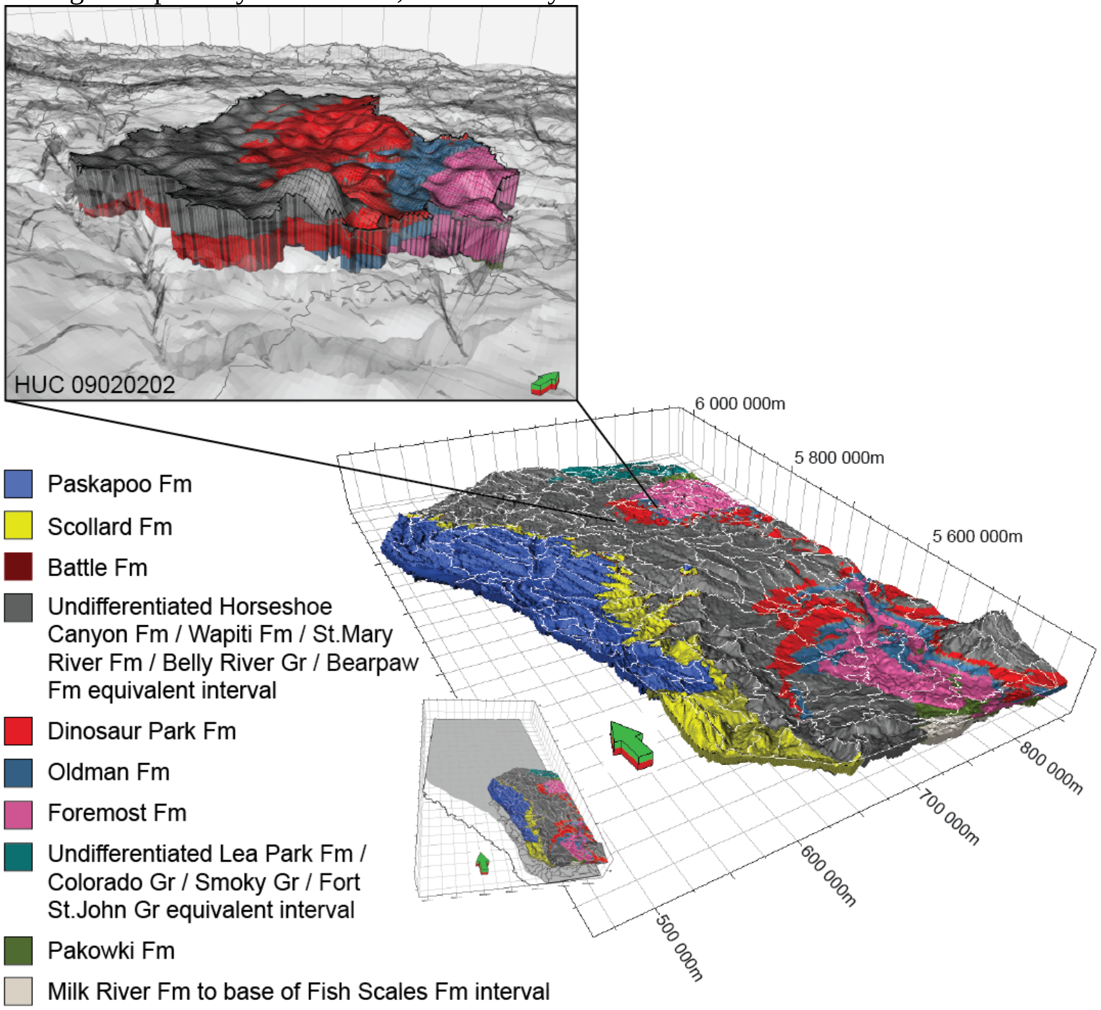

Figure 13. Bedrock units in the study area from the 3D PGF model v1 to a depth of 150 m bgs. Upper inset shows an example watershed and the modelled geological units within.

The porosities for each of these zones can be adjusted based on additional differentiation within the 3D PGF model v1, detailed property modelling, or other geological knowledge about the zone. Likewise, the porosity values for each zone could be adjusted on a watershed-by-watershed basis to reflect local knowledge of the porosity, heterogeneity of the geological unit(s) in question, and technically available water. Detailed aquifer mapping in specific study areas could improve estimates of locally available aquifer storage.

The value of V_0 for each watershed was determined by summing the water volumes for each geological zone within the upper 150 m bgs. The value of V_x was considered as 99% of V_0 (i.e., 1% of storage is extracted), although this value may change depending on the desires of the community and stakeholders.

4 Results

Results of the recharge modelling, aggregated to the 121 HUC8 watersheds in southern Alberta are shown in Figure 14a and Figure 14b for the low and high estimates of recharge, respectively. For both estimates, results show higher values of recharge in the northwest and lower values of recharge towards the southeast, where precipitation is low and evapotranspiration is high. For the low recharge estimate, values of 10 to 15 mm/yr throughout the study area are common with up to 22 mm/yr in the northwest down to 4 mm/yr in the south. For the high recharge estimate, recharge values of 20 to 30 mm/yr are common with up to 36 mm/yr in the northeast and 13 mm/yr in the south. Differences between the high and low recharge estimates in any particular watershed range from 6 to 20 mm/yr.

Values for each of the four aquifer yield classes were calculated for each watershed using the equations described in Table 1. Two yield values for each of the four classes were calculated using both the high and low recharge values (Appendix 1), which reflects the two main land use types within the study area (cropland and grassland) and provides an estimate of uncertainty in recharge estimation. Yield can be calculated as either total volume or annual rate over the selected time period, in this study, groundwater yields are presented as average annual volume per watershed (Appendix 1) since recharge (and therefore discharge) is often reported as an average annual rate. This presents a problem when considering the PMY and MMY classes, as extracting either partial ($V_0 - V_x$) or the complete aquifer volume (V_0) within a single year is highly unlikely if not impossible. Although average annual yield volumes extracted assuming one year are shown in Appendix 1 ($\text{PMY}_{(1\text{ yr})}$ and $\text{MMY}_{(1\text{ yr})}$), a more realistic value of average annual yield volume are also shown as average annual yield volume assuming a 20 year management horizon ($\text{PMY}_{(20\text{ yr})}$ and $\text{MMY}_{(20\text{ yr})}$). That is, only 1/20th of the ($V_0 - V_x$) or V_0 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. Figures 14c and 14d show the low and high MSY values, respectively, as annual volumes of yield based on the low and high estimates of recharge in each watershed. Unlike with the estimates of recharge, the distribution of volumetric MSY values are affected by both recharge and the watershed size, so that larger watersheds in the southern part of the study area can have higher values of MSY than smaller watersheds in the north.

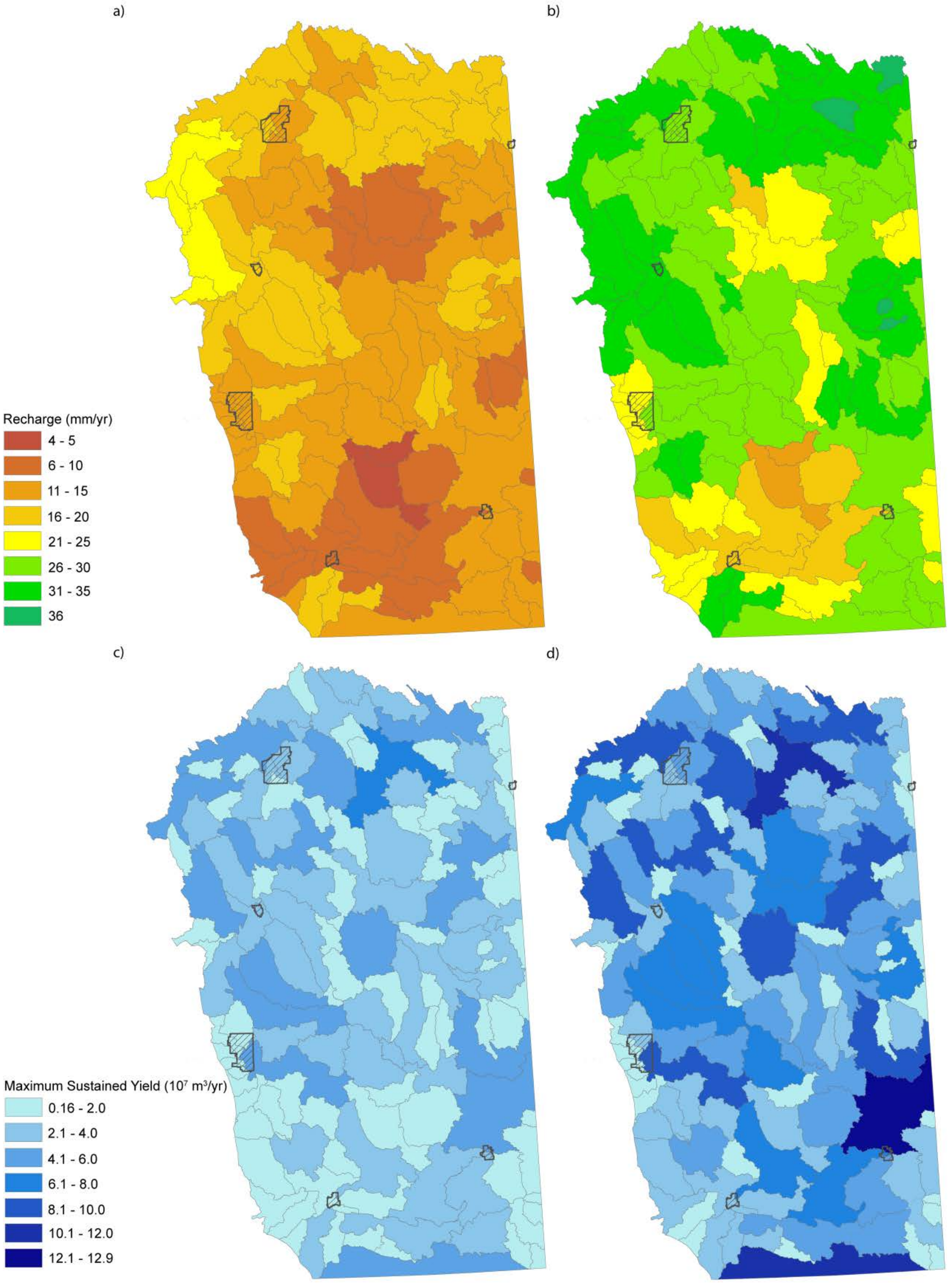

Figure 14. a) Low simulated recharge, considering grassland evapotranspiration parameters b) high simulated recharge, considering cropland evapotranspiration parameters c) low MSY, calculated using recharge from A and the area of the watershed d) high MSY, calculated using recharge from B and the area of the watershed.

5 Discussion

The aquifer yield continuum results of this study are intended to provide a regional, first-order assessment of groundwater yield in southern Alberta, rather than exact values for quantitative management decisions. The aquifer yield continuum methodology can be adapted and utilized to focus the assessment of aquifer yield to specific areas of interest, incorporating local knowledge of the groundwater system, desires of the community and local stakeholders, and environmenal flow needs. The results of this study can be used as a screening or risk assessment tool for focusing on specific areas in need of further attention and for examining the relative differences between watersheds along the continuum. For example, current or projected groundwater use in a particular watershed can be compared to yield values to gauge the potential for water resource development or issues. As a proxy for water use, Figure 15 shows the number of water wells within each watershed from the Alberta Water Well Information, considering wells with a total depth less than 150 m which are for domestic, stock, irrigation, industrial, or municipal purposes. Watersheds with the highest amount of wells are located within the ECC and decrease to the southeast. The amount of water wells within a watershed is driven by a number of factors, including population and geology. A comparison of Figure 14 and Figure 15 show watersheds in the ECC have many wells but lower relative MSY. These watersheds may be candidates for further investigation. Additionally, although MSY in the southeast corner of Alberta are low, the amount of water wells within the watershed (and possibly water use) is also low.

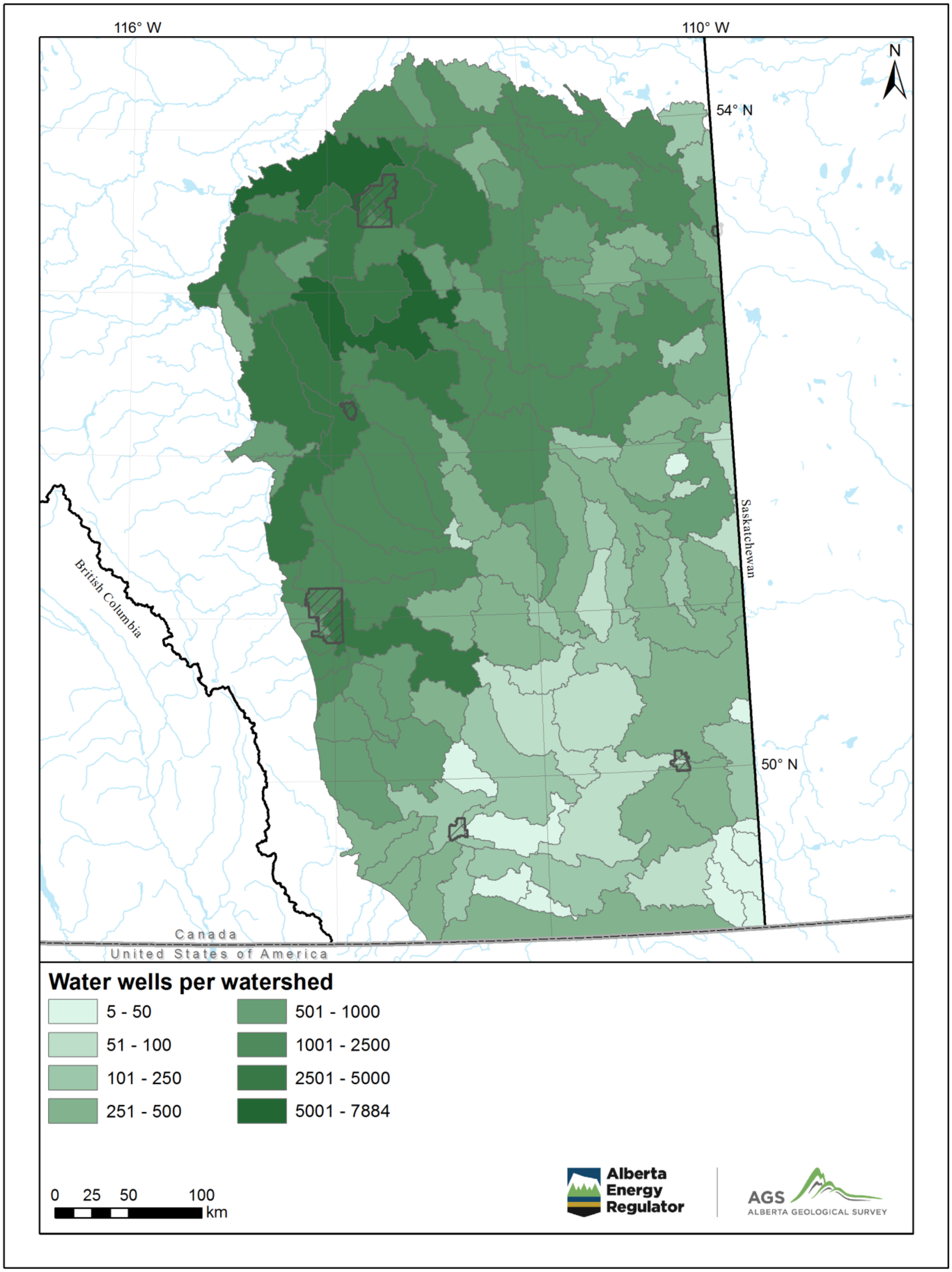

Figure 15. Water wells per watershed, southern Alberta. Only reports from newly constructed wells (i.e., not deepened, reconstructed, abandoned, etc.) with total depth less than 150 m which are for domestic, stock, irrigation, industrial or municipal purposes are included.

The aquifer yield continuum approach is a water balance method that does not take into account the spatial or temporal response of the groundwater flow system to extractions. 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 (e.g., another well, surface water body). Additionally, the aquifer volumes derived in this study represent a first-order 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 such as the Bearpaw (Figure 4). For example, although there is a decline in population towards the southeast there are also different near-surface bedrock formations, which may explain some of the variation in the amount of water wells in this area (Figure 15).

The methods used in this study rely on a closed-basin approach and use surficial watersheds to define groundwater basins: a limitation in this approach is that all recharge for an aquifer occurs within that particular basin, and subsequently either discharges to the rivers or is extracted within that basin. We assume no flow of groundwater in or out of the basin defined by the surface watershed. This closed-basin assumption may affect the aquifer yield values as the effect of recharge or discharge from outside a particular surface watershed is not considered. For example, the recharge area for the Milk River aquifer in southeast Alberta is recharged in Montana (Meyboom, 1960; Pétré, 2016). Alternately, values of discharge in this study may represent total discharge from the basin, as the combination of flow to rivers and net groundwater flow out of the basin, rather than just discharge to rivers alone.

Previous work by Riddell et al. (2014) calculated recharge within the ECC using a residual water balance method where recharge estimation was based on the residual between precipitation and evapotranspiration and runoff. The recharge estimates in the ECC from Riddell et al. (2014) were between 0 to 235 mm/yr which is in high contrast to estimates of 0 to 5 mm/yr by Klassen and Smerdon (2018) that were calculated using baseflow to rivers as a proxy for recharge. The recharge estimates from this study fall between these previous methods, with low estimates within the ECC between 10 to 20 mm/yr and high estimates between 20 to 35 mm/yr. The recharge rates from the current study are also comparable to previous work by Pavlovskii et al. (2017), Atkinson et al. (2017), Farrow (2014), and van der Kamp and Hayashi (1998). The recharge rates for three watersheds within the Sylvan Lake area near Red Deer (HUC8 08010301 – 32 mm/yr, 08010302 – 35 mm/yr, 08010303 – 30 mm/yr) are also comparable to the 35–40 mm/yr of recharge used in a numerical groundwater model of the same area (Liggett and Singh, in press).

Like the aquifer yield continuum results, the results of the recharge modelling are intended to provide an estimate of regional recharge. Many simulation parameters are held constant between the simulations including the soil type. The recharge results from VSMB-DUS represent recharge to shallow groundwater flow systems, which may be quite localized; therefore, it is possible that recharge values presented overestimate regional recharge to deeper bedrock aquifers.

The recharge modelling approach using the combination of terrain analysis and VSMB-DUS allows for accounting of the depression focussed recharge process which is the dominant recharge mechanism on the Canadian prairies. However, in areas where this mechanism is not dominant, recharge values may vary from the VSMB-DUS results. Areas where depression focussed recharge may not be dominant within the study area include those with higher permeability soils and sediments, such as the colluvial or glaciofluvial surficial deposits. In these cases, recharge may infiltrate in the upland rather than running off to pond and infiltrate in depressions. Additionally, less cropland and grassland is present in the north and northeast parts of the study area, where the boreal natural region starts to become more dominant. Thus, the evapotranspiration parameters in the VSMB-DUS simulations would not be appropriate.

The depression focussed recharge mapping methodology used in this study was developed as part of the University of Calgary's Groundwater Recharge in the Prairies (GRIP) project. An extension of this project is currently underway with one of the goals being to examine the role of the depression focussed recharge mechanism in the southeast portion of Alberta, where the landscape is extremely flat, precipitation is very low, and evapotranspiration is very high. The results of this second GRIP project could cause a re-examination of the groundwater yield results of this study for the southeast portion of Alberta.

6 Conclusions

The aquifer yield continuum method provides a flexible approach to determining groundwater yield in southern Alberta. Environmental flow needs, and input from local stakeholders and the community can be accounted for, and methods for quantifying the hydrogeological parameters (recharge, discharge, and aquifer volume) can be modified depending on the hydrological regime and data availability. The depression focussed recharge mechanism, common on the Canadian Prairies, is accounted for by upscaling the results of the VSMB-DUS simulations according to typical upland–depression characteristics found in different surficial geology types. The 3D PGF model v1 provides regional-scale geology and aquifer volumes. Recharge estimates are consistent with previous studies and show a decrease from the northwest to the southeast. Annual volumetric permissive and maximum sustained yields are influenced by watershed size as well as recharge. As groundwater abstraction at the rate of the MSY would have a significant impact on the hydrogeological system, including surface water bodies, the PSY_{10} provides an initial order of magnitude estimate of yield in the absence of more detailed analysis for a given area. The results can be used to assess 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, more local-scale groundwater yield assessments could be conducted. The aquifer yield continuum methodology can also 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.

7 References

Agriculture and Agri-Food Canada (2015): Land Use 2010; URL <https://open.canada.ca/data/en/dataset/9e1efe92-e5a3-4f70-b313-68fb1283eadf> [August 2017].

Alberta Environment and Parks (2017): Hydrologic unit code watersheds of Alberta; Government of Alberta; URL <http://aep.alberta.ca/forms-maps-services/maps/resource-data-product-catalogue/hydrological.aspx> [August 2017].

Alberta Environment and Parks (2015): Alberta water well information database; Government of Alberta; URL <http://aep.alberta.ca/water/reports-data/alberta-water-well-information-database/default.aspx> [August 2017].

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

Baier, W. and Robertson, G. W. (1966): A new versatile soil moisture budget; Canadian Journal of Plant Science, v. 46, p. 299–315.

Barker, A.A., Riddell, J.T.F., Slattery, S.R., Andriashek, L.D., Moktan, H., Wallace, S., Lyster, S., Jean, G., Huff, G.F., Stewart, S.A. and Lemay, T.G. (2011): Edmonton-Calgary Corridor groundwater atlas; Energy Resources Conservation Board, ERCB/AGS Information Series 140, 98 p., URL <http://ags.aer.ca/publications/INF_140.html> [September 2017].

Branscombe, P., MacCormack, K.E., Corlett, H., Hathway, B., Hauck, T.E. and Peterson, J.T. (2018a): 3D Provincial Geological Framework Model of Alberta, Version 1 (dataset, multiple files); Alberta Energy Regulator, AER/AGS Model 2017-03, URL <https://ags.aer.ca/data-maps-models/3D_PGF_model_v1.html> [October 2018].

Branscombe P., MacCormack, K.E. and Babakhani, M. (2018b): 3D Provincial Geological Framework model of Alberta version 1 – methodology; Alberta Energy Regulator, AER/AGS Open File Report 2017-09, 114 p., URL <https://ags.aer.ca/publications/OFR_2017_09.html> [October 2018].

Dawson, F.M., Evans, C.G., Marsh, R. and Richardson, R. (1994): Uppermost Cretaceous and Tertiary strata of the Western Canada Sedimentary Basin; in Geological atlas of the Western Canada Sedimentary Basin; Canadian Society of Petroleum Geologists and Alberta Research Council, URL <http://ags.aer.ca/publications/chapter-24-uppermost-cretaceous-and-tertiary-strata> [January 2018].

Farrow, C.R. (2014): Winter surficial processes and groundwater recharge in the southern Alberta Prairies; MSc thesis, University of Calgary, 195 p.

Fenton, M.M., Waters, E.J., Pawley, S.M. Atkinson, N., Utting, D.J. and Mckay, K. (2013): Surficial geology of Alberta; Alberta Energy Regulator, AER/AGS Map 601, scale 1:1 000 000, URL <http://ags.aer.ca/publications/MAP_601.html> [August 2017].

Gleeson, T. and Richter, B. (2018): How much groundwater can we pump and protect environmental flows through time? Presumptive standards for conjunctive management of aquifers and rivers; River Research and Applications, v. 34, p. 83–92, doi: 10.1002/rra.3185.

Hayashi, M., van der Kamp, G., Schmidt, R. (2003): Focused infiltration of snowmelt water in partially frozen soil under small depressions; Journal of Hydrology, v. 270, p. 214–229, doi: 10.1016/S0022-1694(02)00287-1.

Hayashi, M., Jackson, J.F. and Xu, L. (2010): Application of the Versatile Soil Moisture Budget model to estimate evaporation from prairie grassland; Canadian Water Resources Journal, v. 35, no. 2, p. 187–208, doi: 10.4296/cwrj3502187.

Kalf, F.R.P and Woolley, D.R. (2005): Applicability and methodology of determining sustainable yield in groundwater systems; Hydrogeology Journal, v. 13, no. 1, p. 295–312, doi: 10.1007/s10040-004-0401-x.

Klassen, J. and Smerdon, B.D. (2018): First-order groundwater availability assessment for central Alberta; Alberta Energy Regulator, AER/AGS OFR 2017-07, URL <https://ags.aer.ca/OFR_2017_07.html> [February 2018].

Liggett, J. E. and Singh, A. (in press): Numerical groundwater flow model of the Sylvan Lake sub-basin in the Edmonton–Calgary Corridor, central Alberta; Alberta Energy Regulator, AER/AGS Report 96.

Maathius, H. and van der Kamp, G. (2006): The Q20 concept: sustainable well yield and sustainable aquifer yield; Saskatchewan Research Council, Publication No. 10417-4E06, 110 p.

Meyboom, P. (1960): Geology and groundwater resourced of the Milk River Sandstone in southern Alberta; Research Council of Alberta, Memoir 2.

Mohammed, G. A., Hayashi, M., Farrow, C.R. and Takano, Y. (2013): Improved characterization of frozen soil processes in the Versatile Soil Moisture Budget model; Canadian Journal of Soil Science, v. 93, p. 511–531, doi: 10.4141/cjss2012-005.

Natural Regions Committee (2006): Natural regions and subregions of Alberta; D.J. Downing and W.W. Pettapiece (comp.), Government of Alberta, Publication No. T/852, 254 p.

Noorduijn, S., Hayashi, M., Mohammed, G., and Mohammed A. (in press): A coupled soil water balance model for simulating depression-focused groundwater recharge; Vadose Zone Journal.

Pavlovskii, I., Noorduijn, S. and Hayashi, M. (2017): Regional-scale mapping of a depression-focussed groundwater recharge rate in the prairie landscape of Alberta.; GeoOttawa 2017, 70th Canadian Geotechnical Conference and the 12th Joint CGS/IAH-CNC Groundwater Conference, October 1-4, 2017, Ottawa, Canada, 6 p.

Pétré, M.-A. (2016): Étude hydrogéologique de l'aquifére transfrontalier Milk River (Canada-USA) modéles géologique, conceptual et numérique pour la gestion raisonnée se la resource; PhD Thesis, Université du Québec, Institut National de la Recherche Scientifique Centre Eau Terre Environment, 235 p.

Pierce, S.A., Sharp, J.M., Guillaume, J.H.A., Robert, E.M., and Eaton, D.J. (2013): Aquifer-yield continuum as a guide and typology for science-based groundwater management; Hydrogeology Journal, v.21, no. 2, p. 331–340, doi: 10.1007/s10040-012-0910-y.

Prior, G.J., Hathway, B., Glombick, P.M., Pana, D.I., Banks, C.J., Hay, D.C., Schneider, C.I., Grobe, M., Elgr, R. and Weiss, J.A. (2013): Bedrock geology of Alberta, Canada; Alberta Energy Regulator, AER/AGS Map 600, scale 1:1 000 000, URL <http://ags.aer.ca/publications/MAP_600.html> [January 2018].

Riddell, J.T.F., Moktan, H. and Jean, G. (2014): Regional hydrology of the Edmonton–Calgary Corridor, Alberta; Alberta Energy Regulator, AER/AGS Open File Report 2014-02, 31 p., URL<http://ags.aer.ca/publications/OFR_2014_02.html> [October 2017].

Smith, C.D. (2007): Correcting the wind bias in snowfall measurements made with a Geonor T-200B precipitation gauge and alter wind shield; 87th American Meteorological Society Annual Meeting, San Antonio, TX, January 13–18, 2007.

van der Kamp, G. and Hayashi, M. (1998): The groundwater recharge function of small wetlands in the semi-arid northern prairies; Great Plains Research: A Journal of Natural and Social Sciences, v. 8, no. 1, p. 39–56.

Van der Gun, J. and Lipponen, A. (2010): Reconciling groundwater storage depletion due to pumping with sustainability; Sustainability, 2, p. 3418–3435, doi: 10.3390/su2113418.

Appendix 1 – Aquifer Yield Continuum Classes

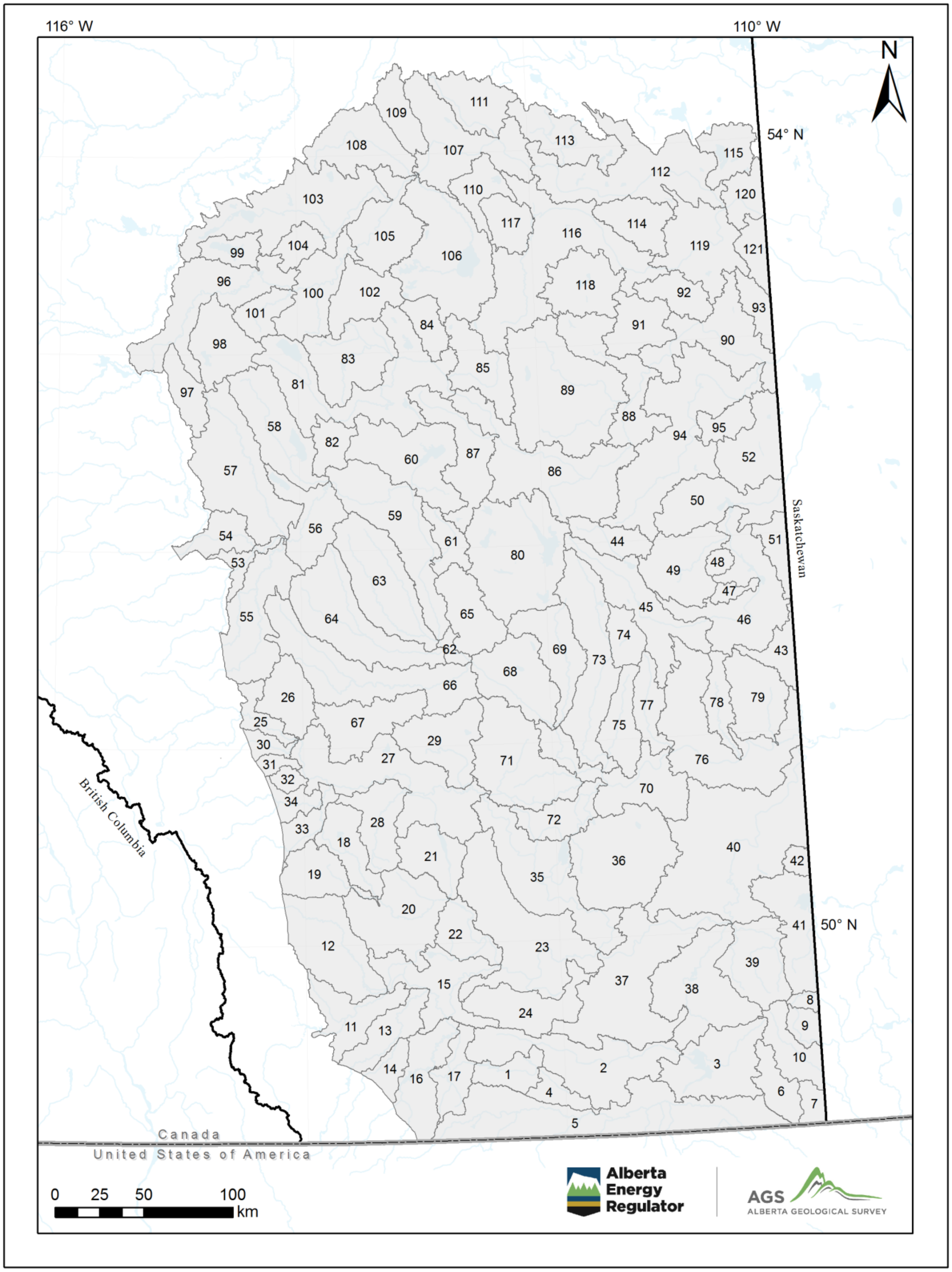

Figure 16. HUC8 watersheds labelled with ID number.

Table 2. Aquifer yield continuum classes for southern Alberta using the high estimate of recharge. $P_{PSY(10\%)}$ and $P_{PSY(50\%)}$ use 10% and 50% of natural discharge for pumping, respectively. $P_{PMY(1yr)}$ and $P_{PMY(20yr)}$ 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	2010101	2.01E+06	1.01E+07	2.01E+07	2.07E+08	1.87E+10	2.95E+07	9.55E+08
2	2010102	5.64E+06	2.82E+07	5.64E+07	8.35E+08	7.79E+10	9.53E+07	3.95E+09
3	2010103	4.86E+06	2.43E+07	4.86E+07	5.47E+08	4.99E+10	7.36E+07	2.54E+09
4	2020101	9.46E+05	4.73E+06	9.46E+06	1.61E+08	1.52E+10	1.70E+07	7.67E+08
5	2020102	1.09E+07	5.44E+07	1.09E+08	1.37E+09	1.27E+11	1.72E+08	6.43E+09
6	2020103	1.64E+06	8.22E+06	1.64E+07	2.09E+08	1.93E+10	2.61E+07	9.79E+08
7	2020104	8.92E+05	4.46E+06	8.92E+06	9.21E+07	8.32E+09	1.31E+07	4.25E+08
8	2020201	3.80E+05	1.90E+06	3.80E+06	6.22E+07	5.84E+09	6.72E+06	2.96E+08
9	2020202	8.16E+05	4.08E+06	8.16E+06	1.07E+08	9.87E+09	1.31E+07	5.01E+08
10	2020203	2.30E+06	1.15E+07	2.30E+07	2.79E+08	2.56E+10	3.58E+07	1.30E+09
11	4010105	2.34E+06	1.17E+07	2.34E+07	4.95E+08	4.72E+10	4.70E+07	2.38E+09
12	4010201	3.78E+06	1.89E+07	3.78E+07	8.33E+08	7.95E+10	7.75E+07	4.01E+09
13	4010301	1.95E+06	9.73E+06	1.95E+07	3.69E+08	3.50E+10	3.69E+07	1.77E+09
14	4010302	9.13E+05	4.57E+06	9.13E+06	1.91E+08	1.82E+10	1.82E+07	9.19E+08
15	4010303	3.21E+06	1.60E+07	3.21E+07	5.58E+08	5.26E+10	5.84E+07	2.66E+09
16	4010401	4.00E+06	2.00E+07	4.00E+07	4.67E+08	4.27E+10	6.13E+07	2.17E+09
17	4010402	2.33E+06	1.17E+07	2.33E+07	2.54E+08	2.31E+10	3.49E+07	1.17E+09
18	4010501	2.62E+06	1.31E+07	2.62E+07	3.37E+08	3.11E+10	4.17E+07	1.58E+09
19	4010502	2.03E+06	1.02E+07	2.03E+07	3.13E+08	2.93E+10	3.49E+07	1.48E+09
20	4010503	4.57E+06	2.28E+07	4.57E+07	7.42E+08	6.97E+10	8.05E+07	3.53E+09
21	4010504	2.96E+06	1.48E+07	2.96E+07	3.48E+08	3.18E+10	4.55E+07	1.62E+09
22	4010505	1.67E+06	8.35E+06	1.67E+07	2.66E+08	2.49E+10	2.91E+07	1.26E+09
23	4010601	6.54E+06	3.27E+07	6.54E+07	1.18E+09	1.12E+11	1.21E+08	5.64E+09
24	4010602	2.76E+06	1.38E+07	2.76E+07	4.48E+08	4.21E+10	4.86E+07	2.13E+09
25	4020801	1.09E+06	5.43E+06	1.09E+07	1.51E+08	1.40E+10	1.78E+07	7.10E+08
26	4020803	2.33E+06	1.16E+07	2.33E+07	3.17E+08	2.94E+10	3.80E+07	1.49E+09
27	4020901	8.26E+06	4.13E+07	8.26E+07	1.06E+09	9.74E+10	1.31E+08	4.95E+09
28	4020902	3.17E+06	1.59E+07	3.17E+07	4.33E+08	4.02E+10	5.18E+07	2.04E+09
29	4020903	4.08E+06	2.04E+07	4.08E+07	4.85E+08	4.45E+10	6.30E+07	2.26E+09
30	4021001	6.23E+05	3.11E+06	6.23E+06	6.64E+07	6.03E+09	9.24E+06	3.07E+08
31	4021101	3.84E+05	1.92E+06	3.84E+06	4.57E+07	4.19E+09	5.93E+06	2.13E+08
32	4021102	4.54E+05	2.27E+06	4.54E+06	6.43E+07	5.98E+09	7.53E+06	3.03E+08
33	4021201	1.31E+06	6.57E+06	1.31E+07	1.60E+08	1.47E+10	2.05E+07	7.48E+08
34	4021202	9.52E+05	4.76E+06	9.52E+06	1.05E+08	9.54E+09	1.43E+07	4.86E+08
35	4021301	3.73E+06	1.86E+07	3.73E+07	9.36E+08	8.99E+10	8.22E+07	4.53E+09
36	4021302	5.06E+06	2.53E+07	5.06E+07	1.04E+09	9.89E+10	1.00E+08	4.99E+09
37	4030101	6.17E+06	3.09E+07	6.17E+07	1.23E+09	1.17E+11	1.20E+08	5.91E+09
38	4030201	5.77E+06	2.89E+07	5.77E+07	7.75E+08	7.18E+10	9.36E+07	3.65E+09
39	4030202	3.78E+06	1.89E+07	3.78E+07	4.97E+08	4.60E+10	6.07E+07	2.33E+09
40	4030301	1.29E+07	6.47E+07	1.29E+08	1.74E+09	1.61E+11	2.10E+08	8.18E+09

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)
41	4030401	3.32E+06	1.66E+07	3.32E+07	4.85E+08	4.52E+10	5.58E+07	2.29E+09
42	4030501	4.53E+05	2.26E+06	4.53E+06	5.77E+07	5.32E+09	7.18E+06	2.70E+08
43	4030601	1.52E+06	7.61E+06	1.52E+07	1.55E+08	1.40E+10	2.22E+07	7.13E+08
44	7010101	1.81E+06	9.06E+06	1.81E+07	2.19E+08	2.01E+10	2.82E+07	1.02E+09
45	7010102	5.23E+06	2.62E+07	5.23E+07	6.18E+08	5.66E+10	8.06E+07	2.88E+09
46	7010103	7.84E+06	3.92E+07	7.84E+07	7.53E+08	6.75E+10	1.12E+08	3.45E+09
47	7010104	7.11E+05	3.56E+06	7.11E+06	5.87E+07	5.16E+09	9.69E+06	2.65E+08
48	7010105	6.55E+05	3.28E+06	6.55E+06	5.90E+07	5.25E+09	9.17E+06	2.69E+08
49	7010106	5.03E+06	2.51E+07	5.03E+07	3.75E+08	3.25E+10	6.65E+07	1.67E+09
50	7010107	5.06E+06	2.53E+07	5.06E+07	5.09E+08	4.59E+10	7.35E+07	2.34E+09
51	7010108	1.31E+06	6.55E+06	1.31E+07	1.37E+08	1.24E+10	1.93E+07	6.32E+08
52	7010109	3.28E+06	1.64E+07	3.28E+07	5.03E+08	4.70E+10	5.63E+07	2.38E+09
53	8010201	1.23E+06	6.14E+06	1.23E+07	1.24E+08	1.11E+10	1.78E+07	5.68E+08
54	8010202	2.38E+06	1.19E+07	2.38E+07	2.29E+08	2.06E+10	3.40E+07	1.05E+09
55	8010203	5.95E+06	2.98E+07	5.95E+07	6.41E+08	5.82E+10	8.86E+07	2.97E+09
56	8010301	3.95E+06	1.97E+07	3.95E+07	4.10E+08	3.71E+10	5.80E+07	1.89E+09
57	8010302	9.60E+06	4.80E+07	9.60E+07	9.27E+08	8.32E+10	1.37E+08	4.25E+09
58	8010303	5.47E+06	2.74E+07	5.47E+07	5.94E+08	5.39E+10	8.17E+07	2.75E+09
59	8020101	7.11E+06	3.56E+07	7.11E+07	8.58E+08	7.88E+10	1.10E+08	4.01E+09
60	8020102	5.50E+06	2.75E+07	5.50E+07	6.85E+08	6.31E+10	8.65E+07	3.21E+09
61	8020103	1.73E+06	8.65E+06	1.73E+07	1.87E+08	1.70E+10	2.58E+07	8.66E+08
62	8020201	5.21E+05	2.61E+06	5.21E+06	6.06E+07	5.54E+09	7.98E+06	2.82E+08
63	8020202	6.62E+06	3.31E+07	6.62E+07	8.26E+08	7.60E+10	1.04E+08	3.86E+09
64	8020203	7.46E+06	3.73E+07	7.46E+07	8.93E+08	8.19E+10	1.15E+08	4.16E+09
65	8020204	3.38E+06	1.69E+07	3.38E+07	3.83E+08	3.50E+10	5.13E+07	1.78E+09
66	8020205	7.94E+06	3.97E+07	7.94E+07	1.02E+09	9.44E+10	1.27E+08	4.80E+09
67	8020206	4.13E+06	2.07E+07	4.13E+07	5.60E+08	5.19E+10	6.72E+07	2.63E+09
68	8030101	4.34E+06	2.17E+07	4.34E+07	5.28E+08	4.85E+10	6.77E+07	2.47E+09
69	8030102	3.45E+06	1.73E+07	3.45E+07	4.23E+08	3.89E+10	5.39E+07	1.98E+09
70	8030201	5.65E+06	2.82E+07	5.65E+07	6.55E+08	5.99E+10	8.64E+07	3.05E+09
71	8030202	6.52E+06	3.26E+07	6.52E+07	7.79E+08	7.14E+10	1.01E+08	3.63E+09
72	8030203	1.24E+06	6.19E+06	1.24E+07	2.78E+08	2.66E+10	2.57E+07	1.34E+09
73	8030301	5.83E+06	2.92E+07	5.83E+07	7.80E+08	7.23E+10	9.44E+07	3.67E+09
74	8030302	1.34E+06	6.69E+06	1.34E+07	1.20E+08	1.07E+10	1.87E+07	5.47E+08
75	8030303	2.85E+06	1.43E+07	2.85E+07	2.89E+08	2.61E+10	4.16E+07	1.33E+09
76	8030401	9.91E+06	4.95E+07	9.91E+07	1.06E+09	9.63E+10	1.47E+08	4.91E+09
77	8030402	2.47E+06	1.23E+07	2.47E+07	2.06E+08	1.82E+10	3.37E+07	9.31E+08
78	8030403	1.84E+06	9.22E+06	1.84E+07	1.67E+08	1.49E+10	2.59E+07	7.63E+08
79	8030404	3.79E+06	1.90E+07	3.79E+07	3.82E+08	3.44E+10	5.51E+07	1.76E+09
80	8040101	8.57E+06	4.29E+07	8.57E+07	1.02E+09	9.39E+10	1.33E+08	4.78E+09
81	9010101	8.68E+06	4.34E+07	8.68E+07	1.10E+09	1.02E+11	1.38E+08	5.17E+09
82	9010102	1.67E+06	8.37E+06	1.67E+07	1.96E+08	1.79E+10	2.57E+07	9.11E+08
83	9010103	4.26E+06	2.13E+07	4.26E+07	5.61E+08	5.19E+10	6.85E+07	2.63E+09
84	9010104	1.52E+06	7.59E+06	1.52E+07	1.80E+08	1.65E+10	2.34E+07	8.39E+08

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)
85	9010105	2.38E+06	1.19E+07	2.38E+07	3.72E+08	3.48E+10	4.12E+07	1.76E+09
86	9020101	6.67E+06	3.33E+07	6.67E+07	9.99E+08	9.33E+10	1.13E+08	4.73E+09
87	9020102	3.59E+06	1.80E+07	3.59E+07	4.80E+08	4.45E+10	5.81E+07	2.26E+09
88	9020201	4.18E+06	2.09E+07	4.18E+07	6.70E+08	6.28E+10	7.32E+07	3.18E+09
89	9020202	7.90E+06	3.95E+07	7.90E+07	1.27E+09	1.19E+11	1.39E+08	6.05E+09
90	9030101	5.49E+06	2.74E+07	5.49E+07	7.85E+08	7.30E+10	9.13E+07	3.70E+09
91	9030102	2.94E+06	1.47E+07	2.94E+07	4.27E+08	3.98E+10	4.93E+07	2.02E+09
92	9030103	2.10E+06	1.05E+07	2.10E+07	2.44E+08	2.23E+10	3.21E+07	1.14E+09
93	9030104	1.40E+06	7.01E+06	1.40E+07	1.73E+08	1.59E+10	2.20E+07	8.09E+08
94	9030201	9.90E+06	4.95E+07	9.90E+07	1.37E+09	1.27E+11	1.62E+08	6.44E+09
95	9030202	1.19E+06	5.97E+06	1.19E+07	2.12E+08	2.00E+10	2.20E+07	1.01E+09
96	11020101	6.87E+06	3.43E+07	6.87E+07	8.02E+08	7.34E+10	1.05E+08	3.74E+09
97	11020102	2.05E+06	1.02E+07	2.05E+07	2.21E+08	2.00E+10	3.05E+07	1.02E+09
98	11020103	3.50E+06	1.75E+07	3.50E+07	4.14E+08	3.79E+10	5.40E+07	1.93E+09
99	11020104	1.59E+06	7.96E+06	1.59E+07	1.73E+08	1.58E+10	2.38E+07	8.04E+08
100	11020201	3.57E+06	1.78E+07	3.57E+07	4.51E+08	4.16E+10	5.64E+07	2.11E+09
101	11020202	1.49E+06	7.43E+06	1.49E+07	2.13E+08	1.98E+10	2.47E+07	1.00E+09
102	11020203	2.81E+06	1.41E+07	2.81E+07	3.50E+08	3.22E+10	4.42E+07	1.64E+09
103	11020301	8.97E+06	4.48E+07	8.97E+07	9.89E+08	9.00E+10	1.35E+08	4.58E+09
104	11020302	1.25E+06	6.26E+06	1.25E+07	1.53E+08	1.40E+10	1.95E+07	7.14E+08
105	11030101	4.10E+06	2.05E+07	4.10E+07	4.86E+08	4.45E+10	6.32E+07	2.26E+09
106	11030102	8.77E+06	4.38E+07	8.77E+07	9.62E+08	8.76E+10	1.31E+08	4.46E+09
107	11030201	5.95E+06	2.98E+07	5.95E+07	6.28E+08	5.69E+10	8.79E+07	2.90E+09
108	11030202	4.48E+06	2.24E+07	4.48E+07	5.29E+08	4.84E+10	6.90E+07	2.46E+09
109	11030203	2.09E+06	1.05E+07	2.09E+07	2.44E+08	2.23E+10	3.21E+07	1.13E+09
110	11030204	1.88E+06	9.40E+06	1.88E+07	2.15E+08	1.96E+10	2.86E+07	9.99E+08
111	11030205	3.71E+06	1.85E+07	3.71E+07	2.88E+08	2.51E+10	4.96E+07	1.29E+09
112	11040101	9.74E+06	4.87E+07	9.74E+07	7.23E+08	6.27E+10	1.29E+08	3.23E+09
113	11040102	4.01E+06	2.01E+07	4.01E+07	3.36E+08	2.96E+10	5.49E+07	1.52E+09
114	11040103	3.17E+06	1.59E+07	3.17E+07	2.37E+08	2.05E+10	4.20E+07	1.06E+09
115	11040104	2.79E+06	1.39E+07	2.79E+07	2.37E+08	2.10E+10	3.83E+07	1.07E+09
116	11040201	1.18E+07	5.92E+07	1.18E+08	1.17E+09	1.05E+11	1.71E+08	5.38E+09
117	11040202	2.28E+06	1.14E+07	2.28E+07	2.22E+08	1.99E+10	3.28E+07	1.02E+09
118	11040203	3.98E+06	1.99E+07	3.98E+07	4.76E+08	4.37E+10	6.16E+07	2.22E+09
119	11040204	5.67E+06	2.83E+07	5.67E+07	4.74E+08	4.18E+10	7.75E+07	2.14E+09
120	11040301	2.11E+06	1.05E+07	2.11E+07	1.31E+08	1.10E+10	2.66E+07	5.72E+08
121	11040302	1.49E+06	7.47E+06	1.49E+07	1.23E+08	1.08E+10	2.03E+07	5.53E+08

Table 3. Aquifer yield continuum classes for southern Alberta using the low estimate of recharge. $P_{PSY(10\%)}$ and $P_{PSY(50\%)}$ use 10% and 50% of natural discharge for pumping, respectively. $P_{PMY(1yr)}$ and $P_{PMY(20yr)}$ 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)	$P_{PMY(1yr)}$ (m^3/yr)	$P_{MMY(1yr)}$ (m^3/yr)	$P_{PMY(20yr)}$ (m^3/yr)	$P_{MMY(20y)}$ (m^3/yr)
1	2010101	1.12E+06	5.60E+06	1.12E+07	1.98E+08	1.87E+10	2.05E+07	9.46E+08
2	2010102	2.17E+06	1.09E+07	2.17E+07	8.00E+08	7.79E+10	6.07E+07	3.92E+09
3	2010103	2.01E+06	1.00E+07	2.01E+07	5.19E+08	4.99E+10	4.50E+07	2.51E+09
4	2020101	3.35E+05	1.67E+06	3.35E+06	1.55E+08	1.52E+10	1.09E+07	7.61E+08
5	2020102	5.20E+06	2.60E+07	5.20E+07	1.32E+09	1.26E+11	1.15E+08	6.37E+09
6	2020103	6.94E+05	3.47E+06	6.94E+06	2.00E+08	1.93E+10	1.66E+07	9.70E+08
7	2020104	3.65E+05	1.83E+06	3.65E+06	8.68E+07	8.32E+09	7.81E+06	4.19E+08
8	2020201	1.60E+05	8.01E+05	1.60E+06	6.00E+07	5.84E+09	4.52E+06	2.94E+08
9	2020202	3.47E+05	1.73E+06	3.47E+06	1.02E+08	9.87E+09	8.40E+06	4.97E+08
10	2020203	9.54E+05	4.77E+06	9.54E+06	2.65E+08	2.56E+10	2.23E+07	1.29E+09
11	4010105	1.09E+06	5.43E+06	1.09E+07	4.82E+08	4.71E+10	3.44E+07	2.37E+09
12	4010201	1.79E+06	8.94E+06	1.79E+07	8.13E+08	7.95E+10	5.76E+07	3.99E+09
13	4010301	8.95E+05	4.48E+06	8.95E+06	3.59E+08	3.50E+10	2.64E+07	1.76E+09
14	4010302	4.60E+05	2.30E+06	4.60E+06	1.87E+08	1.82E+10	1.37E+07	9.15E+08
15	4010303	1.27E+06	6.34E+06	1.27E+07	5.38E+08	5.26E+10	3.90E+07	2.64E+09
16	4010401	2.31E+06	1.15E+07	2.31E+07	4.50E+08	4.27E+10	4.44E+07	2.16E+09
17	4010402	1.34E+06	6.71E+06	1.34E+07	2.44E+08	2.30E+10	2.49E+07	1.16E+09
18	4010501	1.38E+06	6.88E+06	1.38E+07	3.24E+08	3.11E+10	2.93E+07	1.57E+09
19	4010502	9.94E+05	4.97E+06	9.94E+06	3.02E+08	2.93E+10	2.46E+07	1.47E+09
20	4010503	2.06E+06	1.03E+07	2.06E+07	7.17E+08	6.97E+10	5.54E+07	3.50E+09
21	4010504	1.48E+06	7.41E+06	1.48E+07	3.33E+08	3.18E+10	3.07E+07	1.61E+09
22	4010505	5.81E+05	2.90E+06	5.81E+06	2.55E+08	2.49E+10	1.82E+07	1.25E+09
23	4010601	2.18E+06	1.09E+07	2.18E+07	1.14E+09	1.11E+11	7.76E+07	5.59E+09
24	4010602	9.63E+05	4.81E+06	9.63E+06	4.30E+08	4.21E+10	3.07E+07	2.11E+09
25	4020801	5.22E+05	2.61E+06	5.22E+06	1.45E+08	1.40E+10	1.22E+07	7.04E+08
26	4020803	1.13E+06	5.64E+06	1.13E+07	3.05E+08	2.93E+10	2.59E+07	1.48E+09
27	4020901	4.22E+06	2.11E+07	4.22E+07	1.02E+09	9.74E+10	9.08E+07	4.91E+09
28	4020902	1.68E+06	8.42E+06	1.68E+07	4.19E+08	4.02E+10	3.69E+07	2.03E+09
29	4020903	2.15E+06	1.08E+07	2.15E+07	4.66E+08	4.44E+10	4.37E+07	2.24E+09
30	4021001	3.01E+05	1.50E+06	3.01E+06	6.32E+07	6.03E+09	6.02E+06	3.04E+08
31	4021101	1.87E+05	9.35E+05	1.87E+06	4.37E+07	4.19E+09	3.96E+06	2.11E+08
32	4021102	2.25E+05	1.13E+06	2.25E+06	6.20E+07	5.98E+09	5.24E+06	3.01E+08
33	4021201	7.04E+05	3.52E+06	7.04E+06	1.54E+08	1.47E+10	1.44E+07	7.42E+08
34	4021202	5.00E+05	2.50E+06	5.00E+06	1.00E+08	9.54E+09	9.77E+06	4.82E+08
35	4021301	1.14E+06	5.70E+06	1.14E+07	9.10E+08	8.99E+10	5.63E+07	4.50E+09
36	4021302	1.94E+06	9.68E+06	1.94E+07	1.01E+09	9.89E+10	6.88E+07	4.96E+09
37	4030101	2.06E+06	1.03E+07	2.06E+07	1.19E+09	1.17E+11	7.91E+07	5.87E+09
38	4030201	2.32E+06	1.16E+07	2.32E+07	7.41E+08	7.18E+10	5.91E+07	3.61E+09
39	4030202	1.60E+06	8.00E+06	1.60E+07	4.75E+08	4.59E+10	3.90E+07	2.31E+09
40	4030301	5.74E+06	2.87E+07	5.74E+07	1.67E+09	1.61E+11	1.38E+08	8.11E+09

ID	HUC8	$P_{PSY(10\%)}$ (m^3/yr)	$P_{PSY(50\%)}$ (m^3/yr)	P_{MSY} (m^3/yr)	$P_{PMY(1yr)}$ (m^3/yr)	$P_{MMY(1yr)}$ (m^3/yr)	$P_{PMY(20yr)}$ (m^3/yr)	$P_{MMY(20y)}$ (m^3/yr)
41	4030401	1.46E+06	7.31E+06	1.46E+07	4.67E+08	4.52E+10	3.72E+07	2.28E+09
42	4030501	2.03E+05	1.01E+06	2.03E+06	5.52E+07	5.32E+09	4.68E+06	2.68E+08
43	4030601	5.16E+05	2.58E+06	5.16E+06	1.45E+08	1.40E+10	1.21E+07	7.03E+08
44	7010101	8.92E+05	4.46E+06	8.92E+06	2.09E+08	2.01E+10	1.89E+07	1.01E+09
45	7010102	2.40E+06	1.20E+07	2.40E+07	5.89E+08	5.66E+10	5.23E+07	2.85E+09
46	7010103	3.43E+06	1.72E+07	3.43E+07	7.09E+08	6.75E+10	6.80E+07	3.41E+09
47	7010104	3.33E+05	1.67E+06	3.33E+06	5.49E+07	5.16E+09	5.91E+06	2.61E+08
48	7010105	3.10E+05	1.55E+06	3.10E+06	5.55E+07	5.24E+09	5.72E+06	2.65E+08
49	7010106	2.38E+06	1.19E+07	2.38E+07	3.48E+08	3.25E+10	4.01E+07	1.65E+09
50	7010107	2.37E+06	1.18E+07	2.37E+07	4.82E+08	4.59E+10	4.66E+07	2.32E+09
51	7010108	6.01E+05	3.00E+06	6.01E+06	1.30E+08	1.24E+10	1.22E+07	6.25E+08
52	7010109	1.37E+06	6.86E+06	1.37E+07	4.83E+08	4.70E+10	3.72E+07	2.36E+09
53	8010201	7.23E+05	3.61E+06	7.23E+06	1.18E+08	1.11E+10	1.28E+07	5.63E+08
54	8010202	1.50E+06	7.50E+06	1.50E+07	2.21E+08	2.06E+10	2.53E+07	1.04E+09
55	8010203	3.19E+06	1.60E+07	3.19E+07	6.14E+08	5.82E+10	6.10E+07	2.94E+09
56	8010301	2.36E+06	1.18E+07	2.36E+07	3.94E+08	3.70E+10	4.22E+07	1.87E+09
57	8010302	5.93E+06	2.96E+07	5.93E+07	8.90E+08	8.31E+10	1.01E+08	4.21E+09
58	8010303	3.24E+06	1.62E+07	3.24E+07	5.71E+08	5.39E+10	5.94E+07	2.73E+09
59	8020101	3.74E+06	1.87E+07	3.74E+07	8.24E+08	7.87E+10	7.67E+07	3.97E+09
60	8020102	2.58E+06	1.29E+07	2.58E+07	6.56E+08	6.30E+10	5.73E+07	3.18E+09
61	8020103	8.97E+05	4.49E+06	8.97E+06	1.79E+08	1.70E+10	1.75E+07	8.58E+08
62	8020201	2.75E+05	1.37E+06	2.75E+06	5.81E+07	5.54E+09	5.52E+06	2.80E+08
63	8020202	3.52E+06	1.76E+07	3.52E+07	7.95E+08	7.60E+10	7.32E+07	3.83E+09
64	8020203	4.05E+06	2.02E+07	4.05E+07	8.58E+08	8.18E+10	8.14E+07	4.13E+09
65	8020204	1.75E+06	8.76E+06	1.75E+07	3.67E+08	3.50E+10	3.50E+07	1.76E+09
66	8020205	4.11E+06	2.05E+07	4.11E+07	9.84E+08	9.44E+10	8.82E+07	4.76E+09
67	8020206	2.18E+06	1.09E+07	2.18E+07	5.40E+08	5.18E+10	4.77E+07	2.61E+09
68	8030101	2.26E+06	1.13E+07	2.26E+07	5.07E+08	4.85E+10	4.69E+07	2.45E+09
69	8030102	1.74E+06	8.71E+06	1.74E+07	4.06E+08	3.88E+10	3.68E+07	1.96E+09
70	8030201	2.82E+06	1.41E+07	2.82E+07	6.26E+08	5.98E+10	5.81E+07	3.02E+09
71	8030202	3.33E+06	1.67E+07	3.33E+07	7.47E+08	7.14E+10	6.90E+07	3.60E+09
72	8030203	3.84E+05	1.92E+06	3.84E+06	2.69E+08	2.65E+10	1.71E+07	1.33E+09
73	8030301	3.04E+06	1.52E+07	3.04E+07	7.52E+08	7.22E+10	6.65E+07	3.64E+09
74	8030302	6.77E+05	3.38E+06	6.77E+06	1.14E+08	1.07E+10	1.21E+07	5.41E+08
75	8030303	1.48E+06	7.41E+06	1.48E+07	2.76E+08	2.61E+10	2.79E+07	1.32E+09
76	8030401	4.13E+06	2.07E+07	4.13E+07	1.00E+09	9.62E+10	8.94E+07	4.85E+09
77	8030402	1.25E+06	6.27E+06	1.25E+07	1.94E+08	1.81E+10	2.16E+07	9.19E+08
78	8030403	5.93E+05	2.96E+06	5.93E+06	1.55E+08	1.49E+10	1.34E+07	7.51E+08
79	8030404	1.22E+06	6.09E+06	1.22E+07	3.56E+08	3.44E+10	2.94E+07	1.73E+09
80	8040101	4.37E+06	2.18E+07	4.37E+07	9.82E+08	9.39E+10	9.06E+07	4.73E+09
81	9010101	4.50E+06	2.25E+07	4.50E+07	1.06E+09	1.02E+11	9.59E+07	5.13E+09
82	9010102	8.78E+05	4.39E+06	8.78E+06	1.88E+08	1.79E+10	1.77E+07	9.03E+08
83	9010103	2.14E+06	1.07E+07	2.14E+07	5.40E+08	5.19E+10	4.73E+07	2.61E+09
84	9010104	6.91E+05	3.46E+06	6.91E+06	1.72E+08	1.65E+10	1.52E+07	8.31E+08

ID	HUC8	$P_{PSY(10\%)}$ (m^3/yr)	$P_{PSY(50\%)}$ (m^3/yr)	P_{MSY} (m^3/yr)	$P_{PMY(1yr)}$ (m^3/yr)	$P_{MMY(1yr)}$ (m^3/yr)	$P_{PMY(20yr)}$ (m^3/yr)	$P_{MMY(20y)}$ (m^3/yr)
85	9010105	8.13E+05	4.06E+06	8.13E+06	3.56E+08	3.48E+10	2.55E+07	1.75E+09
86	9020101	2.74E+06	1.37E+07	2.74E+07	9.60E+08	9.33E+10	7.41E+07	4.69E+09
87	9020102	1.39E+06	6.97E+06	1.39E+07	4.58E+08	4.44E+10	3.62E+07	2.24E+09
88	9020201	1.60E+06	7.98E+06	1.60E+07	6.44E+08	6.28E+10	4.74E+07	3.15E+09
89	9020202	3.07E+06	1.53E+07	3.07E+07	1.22E+09	1.19E+11	9.04E+07	6.00E+09
90	9030101	2.63E+06	1.31E+07	2.63E+07	7.56E+08	7.30E+10	6.28E+07	3.68E+09
91	9030102	1.37E+06	6.86E+06	1.37E+07	4.11E+08	3.98E+10	3.36E+07	2.00E+09
92	9030103	1.01E+06	5.06E+06	1.01E+07	2.33E+08	2.23E+10	2.13E+07	1.13E+09
93	9030104	6.86E+05	3.43E+06	6.86E+06	1.66E+08	1.59E+10	1.48E+07	8.02E+08
94	9030201	4.20E+06	2.10E+07	4.20E+07	1.31E+09	1.27E+11	1.05E+08	6.38E+09
95	9030202	4.84E+05	2.42E+06	4.84E+06	2.05E+08	2.00E+10	1.49E+07	1.01E+09
96	11020101	4.93E+06	2.47E+07	4.93E+07	7.83E+08	7.34E+10	8.60E+07	3.72E+09
97	11020102	1.34E+06	6.72E+06	1.34E+07	2.14E+08	2.00E+10	2.35E+07	1.01E+09
98	11020103	2.57E+06	1.28E+07	2.57E+07	4.05E+08	3.79E+10	4.46E+07	1.92E+09
99	11020104	1.10E+06	5.49E+06	1.10E+07	1.69E+08	1.58E+10	1.89E+07	7.99E+08
100	11020201	2.05E+06	1.02E+07	2.05E+07	4.36E+08	4.16E+10	4.13E+07	2.10E+09
101	11020202	1.10E+06	5.50E+06	1.10E+07	2.09E+08	1.98E+10	2.09E+07	1.00E+09
102	11020203	1.40E+06	7.02E+06	1.40E+07	3.36E+08	3.22E+10	3.01E+07	1.62E+09
103	11020301	5.21E+06	2.61E+07	5.21E+07	9.51E+08	8.99E+10	9.70E+07	4.55E+09
104	11020302	7.21E+05	3.61E+06	7.21E+06	1.48E+08	1.40E+10	1.42E+07	7.09E+08
105	11030101	2.08E+06	1.04E+07	2.08E+07	4.65E+08	4.45E+10	4.30E+07	2.24E+09
106	11030102	4.87E+06	2.44E+07	4.87E+07	9.23E+08	8.75E+10	9.25E+07	4.42E+09
107	11030201	3.18E+06	1.59E+07	3.18E+07	6.00E+08	5.68E+10	6.02E+07	2.87E+09
108	11030202	2.49E+06	1.24E+07	2.49E+07	5.09E+08	4.84E+10	4.91E+07	2.44E+09
109	11030203	1.23E+06	6.13E+06	1.23E+07	2.35E+08	2.23E+10	2.34E+07	1.13E+09
110	11030204	9.97E+05	4.98E+06	9.97E+06	2.06E+08	1.96E+10	1.98E+07	9.90E+08
111	11030205	2.08E+06	1.04E+07	2.08E+07	2.72E+08	2.51E+10	3.33E+07	1.28E+09
112	11040101	5.47E+06	2.73E+07	5.47E+07	6.81E+08	6.26E+10	8.60E+07	3.18E+09
113	11040102	2.24E+06	1.12E+07	2.24E+07	3.18E+08	2.96E+10	3.71E+07	1.50E+09
114	11040103	1.78E+06	8.92E+06	1.78E+07	2.23E+08	2.05E+10	2.81E+07	1.04E+09
115	11040104	1.53E+06	7.64E+06	1.53E+07	2.25E+08	2.09E+10	2.57E+07	1.06E+09
116	11040201	6.80E+06	3.40E+07	6.80E+07	1.12E+09	1.05E+11	1.21E+08	5.33E+09
117	11040202	1.39E+06	6.97E+06	1.39E+07	2.13E+08	1.99E+10	2.39E+07	1.01E+09
118	11040203	2.13E+06	1.06E+07	2.13E+07	4.58E+08	4.36E+10	4.31E+07	2.20E+09
119	11040204	3.02E+06	1.51E+07	3.02E+07	4.48E+08	4.18E+10	5.11E+07	2.12E+09
120	11040301	1.16E+06	5.82E+06	1.16E+07	1.22E+08	1.10E+10	1.71E+07	5.63E+08
121	11040302	8.00E+05	4.00E+06	8.00E+06	1.16E+08	1.08E+10	1.34E+07	5.46E+08