AER/AGS Open File Report 2020-05

First-Order Groundwater Availability Assessment for the Lower Athabasca Region, Eastern Alberta

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Alberta Geological Survey

March 2021

ISBN 978-1-4601-4926-3

If you use information from this publication in other publications or presentations, please acknowledge the AER/AGS. We recommend the following reference format:

Klassen, J. (2021): First-order groundwater availability assessment for the lower Athabasca region, eastern Alberta; Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Open File Report 2020-05, 19 p.

Publications in this series have undergone only limited review and are released essentially as submitted by the author.

Published March 2021 by:
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Acknowledgements

The author would like to thank Alberta Environment and Parks for allowing us to use the groundwater models for the North and South Athabasca Oil Sands areas.

From within the Alberta Energy Regulator / Alberta Geological Survey, the author would like to thank Amandeep Singh for working with the models from Alberta Environment and Parks and extracting recharge surfaces; Laurence Jayawardane for extracting geological volumes from version 3 of the Geological Framework of Alberta; and Ernst Kerkhoven for sharing the exceedance-flow calculation tool that analyzes data from the Water Survey of Canada's HYDAT database.

Abstract

Groundwater is an important resource in Alberta. In order to evaluate the impact of potential groundwater withdrawals on groundwater availability, it is necessary to quantify the amount of available groundwater and compare this to the total groundwater allocations. The Alberta Geological Survey 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 water volume, and the method of quantifying each parameter 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 the lower Athabasca region, the fourth 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 Alberta used two different approaches, baseflow and a one-dimensional soil moisture model, to quantify recharge. This report uses the recharge parameter from groundwater models created for the North Athabasca Oil Sands and South Athabasca Oil Sands areas. Results show that average recharge is 7 mm/yr with a range from 2 to 21 mm/yr.

Groundwater yields are calculated on a watershed basis and results show that the maximum sustained yield varies from 1.5×10^6 to 65.7×10^6 m^3/yr. Groundwater abstraction equal to the maximum sustained yield would have a significant impact on the hydrogeological system, including major impacts on 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, after which 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. In order to evaluate the impact of potential groundwater withdrawals on groundwater availability, it is necessary to quantify the amount of available groundwater and compare this to the total groundwater allocations. The Alberta Geological Survey (AGS) has developed an approach for regional first-order assessment of groundwater availability in Alberta based on an aquifer yield continuum (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 is dependent on three hydrogeological parameters: recharge, discharge, and water 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.

The hydrogeological parameters (recharge, discharge, and water volume) can be quantified using several different methods depending on data availability, hydrogeological regime, climate, and landscape characteristics. For example, the AGS used different methods of assessing recharge in three previously mapped areas of groundwater availability (central Alberta, southern Alberta, and the upper Peace region). The aquifer yield continuum was first applied to map groundwater availability in central Alberta (Klassen and Smerdon, 2018); where groundwater discharge to rivers (baseflow) was used to estimate recharge. This method was chosen because the study area is characterized by near-surface bedrock aquifers with thin overlying sediment, generally unregulated rivers with no significant water withdrawals, and abundant river gauging data. The aquifer yield continuum concept was then applied to southern Alberta (Klassen et al., 2018) where, when compared to central Alberta, the sediments are thicker, the climate is warmer and dryer, agriculture is the dominant land-use type, rivers are often regulated, and hydrometric gauging data are more variable. Depression-focused recharge is also the dominant recharge mechanism in the Canadian Prairies of southern Alberta; therefore, a one-dimensional recharge modelling approach was used to estimate recharge. In the upper Peace region (Klassen and Liggett, 2019), both baseflow and recharge modelling approaches were used to estimate recharge.

The fourth and current study area is the lower Athabasca region, which is home to one of the largest hydrocarbon resources in the world, with a complex geology that includes a combination of evaporites, carbonates, sandstones, shales, oil sands, and thick Neogene–Quaternary deposits. There has been extensive research and characterization of this region, which informed the development of two groundwater models created by WorleyParsons Canada (2010, 2012). These models were used to determine the recharge hydrogeological parameter, which is essential for the aquifer yield continuum.

2 Background

2.1 Study Area

The lower Athabasca region is approximately 58 000 km^2 and located within the Athabasca River basin in eastern Alberta, extending from Lac La Biche in the south to the confluence of the Athabasca and Firebag rivers in the north (Figure 1). The study area is located in the physiographic region of the Interior Plains (Bostock, 1970) and is further divided into the physiographic subregions of the Kazan Upland, Northern Plains, Saskatchewan Plains, Northern Alberta Lowlands, Eastern Alberta Plains, and Northern Alberta Uplands (Figure 1; Pettapiece, 1986). Several smaller uplands include the Birch Mountains (850 m asl) in the northwest, Muskeg Mountain (650 m asl) in the northeast, and Stony Mountain (750 m asl) south of Fort McMurray (Figure 1; Pettapiece, 1986). The study area is within the Central Mixedwood Natural Subregion of the Boreal Forest Natural Region (Natural Regions Committee, 2006). The uplands contain forests and the lowlands are characterized by poorly drained wetlands. The natural drainage patterns of the wetlands are modified in some areas due to mining (Andriashek and Atkinson, 2007; WorleyParsons Canada, 2012).

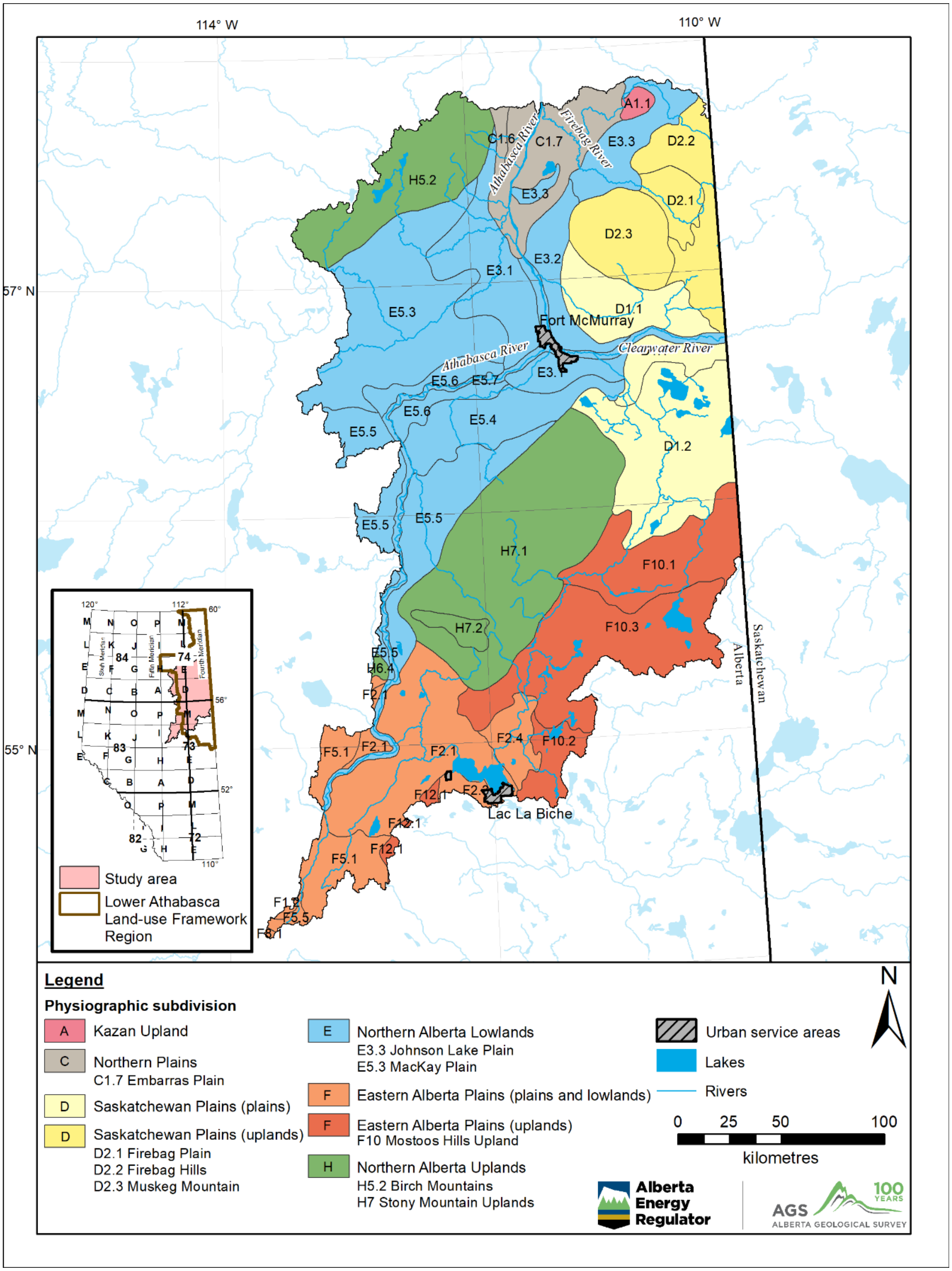

Figure 1. The study area of the lower Athabasca region partially overlaps with the Lower Athabasca Land-use Framework Region (Alberta Environment and Parks, 2011). Physiographic subdivisions (from Pettapiece, 1986) are divided into regions (e.g., A), sections (e.g., A1), and districts (e.g., A1.1).

The lower Athabasca region is characterized by long cold winters and short wet summers. Average precipitation ranges from 376 mm/yr at the Aurora Climate Station to 456 mm/yr at the Fort McMurray International Airport as calculated by WorleyParsons Canada (2010, 2012) from Environment and Climate Change Canada climate data archives. Snowfall is between 23% and 28% of annual precipitation, most occurs between November and March. Snowmelt occurs between March and May, resulting in significant contributions of meltwater to springs and rivers during that time (WorleyParsons Canada, 2010). Groundwater recharge rates for sand- and till-covered settings in the Plains Region of North America range from 1.5% to 17% of annual precipitation (Meyboom, 1967; Rehm et al., 1982; Fortin et al., 1991; Smerdon, 2007; WorleyParsons Canada, 2010, 2012).

2.2 Geology and Athabasca Oil Sands

The Alberta oil sands are one of the largest hydrocarbon resources in the world and development related to bitumen extraction has been occurring for over 40 years. Consequently, there has been extensive study of the geology of the region; some examples include Hackbarth and Nastasa (1979), Andriashek and Fenton (1989), Bachu et al. (1991, 1992, 1993), Andriashek (2003), Andriashek and Atkinson (2007), and Utting and Andriashek (2020). From a hydrogeological perspective, Bachu et al. (1991) describes four basic hydrostratigraphic types in the bedrock overlying the crystalline Precambrian basement: 1) evaporitic beds, which do not allow fluid movement (aquicludes), 2) shale aquitards, 3) carbonate aquifers, and 4) sandstone aquifers, although the latter two lithologies may also act as aquitards where bitumen is present (Bachu et al., 1991). The bedrock geology of the lower Athabasca region is shown in Figure 2. Andriashek and Atkinson (2007) describe the buried channel systems that can act as aquifers in the sediments above the bedrock.

There are generally two methods of bitumen extraction, each of which have different impacts on groundwater and occur in different areas. Surface mining of the oil sands occurs in the north and disturbances to the land surface associated with surface mining operations impact groundwater quantity at a local to subregional scale; active mines must be dewatered, which could result in large areas of drawdown and could impact groundwater quantity close to the surface (Alberta Environment and Sustainable Resource Development, 2012). In the south, in situ oil sands developments recover bitumen by injecting steam into reservoirs so that bitumen viscosity is reduced to a point where it can flow into a well. In situ areas may experience physical and chemical effects from localized heating of subsurface formations, and drilling could create new pathways for groundwater to travel (Alberta Environment and Sustainable Resource Development, 2012).

In addition to bitumen extraction, there are a variety of other activities in the lower Athabasca region that could impact the quality or quantity of groundwater, such as gas development, municipal development, aggregate mining operations, forestry cut blocks or wood processing mills, agriculture, or natural disturbances such as forest fires or climate variability (Alberta Environment and Sustainable Resource Development, 2013a, b).

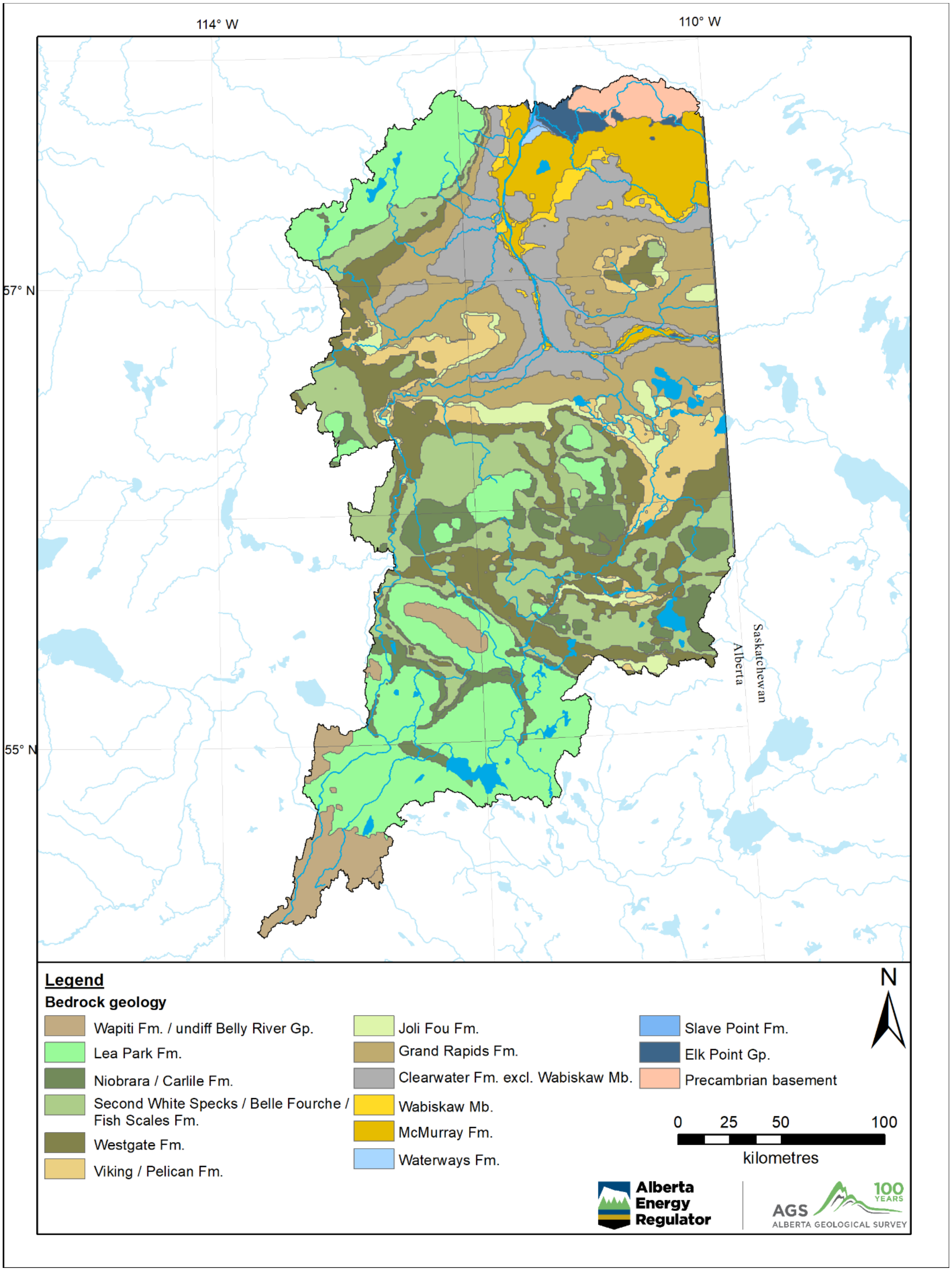

Figure 2. Bedrock geology within the lower Athabasca region, eastern Alberta (Alberta Geological Survey, 2019). Abbreviations: excl., excluding; undiff, undifferentiated.

2.3 SAOS and NAOS Groundwater Models

Two groundwater models were created by WorleyParsons Canada for Alberta Environment to assist in regional groundwater management of the oil sands area (WorleyParsons Canada, 2010, 2012). The South Athabasca Oil Sands (SAOS) model (WorleyParsons Canada, 2010) covers the area where bitumen is extracted in situ, and the North Athabasca Oil Sands (NAOS) model (WorleyParsons Canada, 2012) covers the area around the surface mineable bitumen. The extents of the SAOS and NAOS models are shown in Figure 3. The purpose of the groundwater models was to 1) facilitate understanding of cumulative effects of groundwater extraction, injection, and diversions on regional groundwater quantity and quality; 2) assist in future environmental impact assessments (EIAs); 3) enhance understanding of hydrogeology in natural and developed scenarios; 4) support a monitoring network (locations and targets); 5) assist in management decisions regarding stress and risk to the groundwater system; and 6) support further development of the groundwater management framework for the region (WorleyParsons Canada, 2010, 2012). The groundwater models are meant for regional-scale, not site-specific decisions, therefore, they are not meant for groundwater allocation purposes, to identify local-scale groundwater pathways, or to aid in land-use decisions (WorleyParsons Canada, 2010, 2012).

The groundwater models were created in DHI-WASY Gmbh's FEFLOW (Finite Element subsurface FLOW system) versions 5.4 (SAOS) and 6.0 (NAOS). They were calibrated using a parameter estimate tool (PEST), and the water balance error was 1% and 0.004% for the SAOS and NAOS models, respectively, which represents well-converged models (WorleyParsons Canada, 2010, 2012). Calibrated recharge values from the models were used to determine groundwater availability in the lower Athabasca region. The recharge parameter was initially based on previous studies for similar geographic locations (till-covered setting in the Plains Region of North America), where groundwater recharge rates range from 1.5% to 9% of annual precipitation for till-covered settings and 5% to 17% of annual precipitation for sand-covered settings (Meyboom, 1967; Rehm et al., 1982; Fortin et al., 1991; Smerdon, 2007), and calibrated along with other model parameters using hydrogeological data provided by industry that span over 40 years. Calibrated recharge was within acceptable ranges as was simulated discharge to the Athabasca River compared to measured baseflow.

2.4 Yield Mapping

Groundwater yield in Alberta was determined by the Alberta Research Council (ARC) from 1968–1983 and the resultant maps were digitized by the AGS in 2009 (Lemay and Guha, 2009). The maps show estimated rates of groundwater abstraction based on 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 are useful for estimating groundwater abstraction rates throughout the province, but were not intended for regional groundwater inventory or management purposes because they are limited to a specific time and provide a single estimate of yield for a single well (Lemay and Guha, 2009). The AGS adapted an approach to mapping groundwater yield based on an aquifer yield continuum concept (Kalf and Woolley, 2005; Pierce et al., 2013), which considers the total amount of groundwater available in the system and a range of possible yield values. This approach has been applied in central Alberta (Klassen and Smerdon, 2018), southern Alberta (Klassen et al., 2018), and the upper Peace region (Klassen and Liggett, 2019). Klassen et al. (2018) provides more background on the development of the aquifer yield continuum concept.

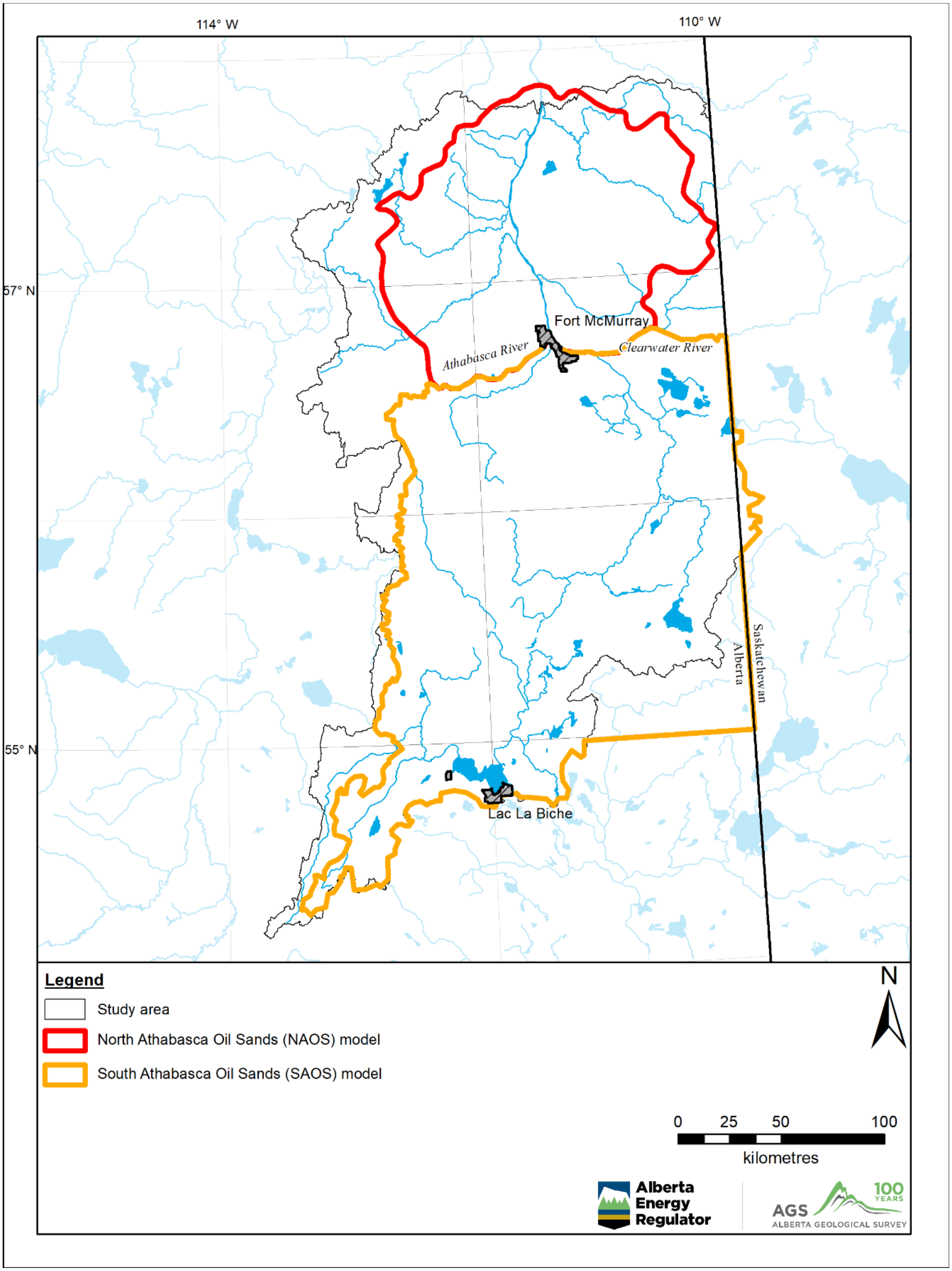

Figure 3. Model boundaries for the South Athabasca Oil Sands (SAOS) and North Athabasca Oil Sands (NAOS) models created by WorleyParsons Canada (2010, 2012), eastern Alberta.

The AGS approach modifies the aquifer yield continuum by Pierce et al. (2013) to incorporate other definitions of groundwater yield (e.g., Bredehoeft, 2002; Devlin and Sophocleous, 2005; Kalf and Woolley, 2005; Zhou, 2009). Five classes of aquifer yield are defined:

1) **Nonuse (NU):** no human-induced groundwater abstraction from the hydrogeological 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 a 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 continuum is applied at a regional scale; therefore, a water balance approach was used to determine the aquifer yield classes. The hydrogeological system is simplified by assuming maximum sustained yield is equivalent to the natural state of recharge instead of including capture (discussed in Klassen et al., 2018). Table 1 summarizes the equations used for calculating the yields for each aquifer yield class.

There is a single value for MSY and MMY and they are limited by the hydrogeological system. The PSY and PMY are variable and can range from NU to MSY, and MSY to MMY, respectively (Figure 4). The PSY and PMY will vary depending on aquifer management decisions, including social, environmental, and economic aspects. Current groundwater use and desired future use can be compared to values along the continuum to provide first-order evaluation of the degree of groundwater development.

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

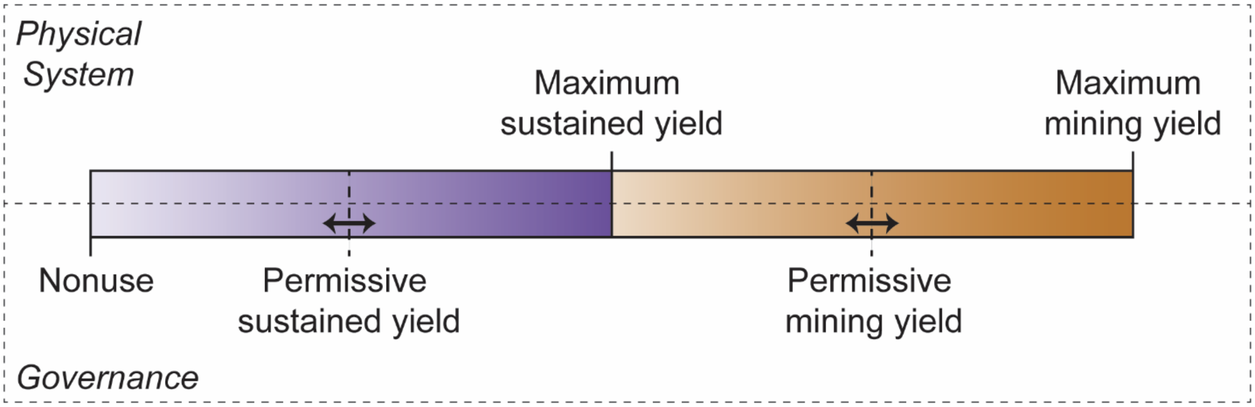

Figure 4. Aquifer yield classes, modified after Kalf and Woolley (2005) and Pierce et al. (2013).

3 Aquifer Yield Mapping Methods

The aquifer yield continuum was applied at a watershed level. Watersheds are reflective of the Hydrologic Unit Code (HUC) Watersheds of Alberta system of classification; all are at a level 8 (HUC8; Alberta Environment and Parks, 2017) for this study. Values for the four aquifer yield classes greater than NU are calculated for 30 watersheds within the study area, and two calculations for PSY are included to illustrate possible PSY values.

The three hydrological parameters used to determine aquifer yield for each class are recharge (R), discharge (D_x), and volume of groundwater in storage (V_0, V_x). In this study, the SAOS and NAOS models provided the recharge values. Discharge is based on the assumption of a closed, steady-state system where recharge eventually makes its way out of the system as discharge. Water volumes were obtained using data from version 3 of the Geological Framework of Alberta (GFA v3; Alberta Geological Survey, in progress, 2021). Detailed methods on determining each of the hydrogeological parameters are described in the following sections.

3.1 Recharge

Recharge was estimated using the calibrated recharge parameter from the SAOS and NAOS models. The spatially distributed recharge (in mm/yr) from the SAOS and NAOS models were brought into Esri's ArcMap as raster surfaces. Recharge was aggregated to the HUC8 level using the Zonal Statistics tool in ArcMap.

For comparison, modelled recharge was also compared to estimates using the baseflow approach, described in more detail by Klassen and Smerdon (2018) and Klassen and Liggett (2019). The following two sections outline how these two approaches were used in the lower Athabasca region. The baseflow approach was used to see if the range of recharge values from the SAOS and NAOS models were consistent with values from previous methods used in the province. There are some limitations to the baseflow approach, especially in the lower Athabasca region where thick Neogene–Quaternary sediments and poorly draining wetlands characterize the land surface. Therefore, not all of the water within HUC8 watersheds may discharge to gauged rivers and streams.

3.1.1 Model Approach

This section will discuss how the recharge parameter in the SAOS and NAOS models was determined.

3.1.1.1 SAOS Model

Groundwater recharge was applied to the top of the model domain (layer 1). For the initial steady-state calibration, recharge was distributed based on surficial deposits. After hydraulic conductivity values were finalized in the model, PEST was applied to optimize recharge distribution. The optimized recharge distribution was based on topography, surficial deposits, and the calibrated hydraulic conductivity (WorleyParsons Canada, 2010). Sandy morainal deposits of the Mostoos Hills Upland (F10, Figure 1) were determined to have the highest recharge rate of 55 mm/yr. A recharge rate of 26 mm/yr was determined for the Stony Mountain Upland (H7, Figure 1). Elsewhere in the model, morainal, glaciolacustrine, and till deposits were assigned a recharge rate of 6 mm/yr. On average, recharge within the SAOS model was 2.3% of annual precipitation or 10.3 mm/yr (WorleyParsons Canada, 2010).

3.1.1.2 NAOS Model

Groundwater recharge was applied to the top of the model domain (layer 1). The model was calibrated to match regional, predevelopment, groundwater flow patterns (static groundwater flow) from the conceptual model. For the steady-state calibration, recharge distribution was based on modified DRASTIC scores, surficial geology, and estimates from previous modelling studies (WorleyParsons Canada, 2010). Recharge distribution was optimized following calibration, both manually and using PEST. The highest recharge rate of 28.6 mm/yr was determined for Firebag Hills (D2.2, Figure 1) and Fort Hills (in the Northern Plains, C, Figure 1). Embarras Plain (C1.7, Figure 1), Johnson Lake Plain (E3.3, Figure 1), Firebag Plain (D2.1, Figure 1), and the eastern area of Muskeg Mountain (D2.3; Figure 1) were determined to have a recharge rate of 18.2 mm/yr. A recharge rate of 8.1 mm/yr was determined for Birch Mountains (H5.2, Figure 1) and MacKay Plain (E5.3, Figure 1). The ground moraine region of Muskeg Mountain was determined to have a recharge rate of 4.0 mm/yr. The remaining parts of the model were expected to have lower rates and were assigned a recharge rate of 1.1 mm/yr. Average recharge in the NAOS model was 2.4% of annual precipitation or 10.0 mm/yr (WorleyParsons Canada, 2012).

3.1.2 Baseflow Approach

The recharge values from the NAOS and SAOS models were compared to recharge values determined by the baseflow approach used in Klassen and Smerdon (2018) and Klassen and Liggett (2019). The baseflow approach assumes a long-term steady-state water balance within a watershed, where recharge and discharge are equal, 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. The equation is simplified by assuming that G_{in} and G_{out} are the same and the amount of pumping is negligible compared to the amount of water in the aquifer. The result is that recharge is equal to discharge or 'baseflow', assuming that all groundwater discharge occurs to rivers. The volume of baseflow can be divided by the surface area of the watershed to give an average [length/time], which is equated to areal recharge.

Data for the baseflow approach is collected at hydrometric gauging stations along streams and rivers. These data are catalogued by the Water Survey of Canada, and reviewed and published by Environment and Climate Change Canada in a digital database called HYDAT (Environment and Climate Change Canada, 2018). The Agriculture and Agri-Food Canada (AAFC) Watersheds Project (Agriculture and Agri-Food Canada, 2013) delineated incremental drainage areas, which can be defined as a particular hydrometric station's drainage basin with its boundary between its gauging station and the next upstream station(s).

Data from the hydrometric gauging stations within the study area were aggregated to average monthly flows and monthly percent exceedance curves were calculated. The lowest monthly Q95 value (i.e., 95% of the average monthly flows are higher than this value) between October and March 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 stations have very low flows or only record seasonally, data is not sufficient to determine a Q95 value for that month. To overcome this limitation, the lowest average monthly streamflow value was used as an alternative (see Klassen and Smerdon, 2018).

The Q95 value determined for each hydrometric station is not representative of the baseflow within each incremental drainage basin, rather it is an accumulation of baseflow up until that point along the river, which may include baseflow from other 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 value. In some cases, this resulted in a negative Q95, which could indicate that this particular section is a losing stream, where river water enters the groundwater system rather than groundwater entering the river. Baseflow is measured in m^3/yr and was divided by the surface area of the incremental drainage basin in order to get a recharge value in mm/yr. The incremental drainage areas are not the same as HUC8 watersheds, therefore a spatial average of recharge (mm/yr) was aggregated to HUC8 watersheds from incremental drainage basins. This recharge value for each HUC8 watershed was compared with the recharge values from the NAOS and SAOS models.

3.2 Discharge

The discharge hydrogeological parameter is used to quantify the PSY class, where D_x is the residual discharge not captured by pumping (Table 1). The D_x is equal to recharge during nonpumping steady-state conditions (NU class) and decreases to zero when fully captured (MSY class). The actual desired value for discharge would result from a management decision process and, therefore, was not available for this study. Residual discharge 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 hydrogeological system, environmental flow needs, and desires of the community.

To be consistent with previous work (Klassen and Smerdon, 2018; Klassen et al., 2018; Klassen and Liggett, 2019), two PSY values were calculated to illustrate how PSY will fall on the continuum. In the first scenario, D_x is equal to 90% of natural discharge; this is described by Gleeson and Richter (2018) to be a presumptive standard for ecological protection in the absence of a more detailed assessment. The second scenario falls in the middle of the PSY range, where 50% of natural discharge is desired for D_x. These two scenarios are equivalent to assuming pumping (P) represents 10% and 50% of simulated recharge for the PSY class (Table 1).

3.3 Water Volume

Volume of water within the subsurface is the hydrogeological parameter used to quantify the PMY and MMY classes. To be consistent with Klassen et al. (2018) and Klassen and Liggett (2019), the initial volume of a water-saturated aquifer (V_0) was considered to a depth of 150 m below ground surface (bgs). Region-wide detailed analysis of permeable geobodies within formations that could be used as aquifers is unavailable for this region, therefore, water volumes were determined on a formation-by-formation basis using the GFA v3. In the future, volumetric assessment could be refined in areas where more detailed aquifer mapping exists.

The GFA v3 is a province-wide multilayer model of the stratigraphy of Alberta and is divided into zones representing geological members, formations, groups, or mixes of these entities depending on data availability. The lower Athabasca region covers 25 individual model zones within 150 m of the surface, with the youngest bedrock unit being the Wapiti Formation and the oldest bedrock unit being the Precambrian basement. Generally, the bedrock units dip to the south-southwest, and the youngest units subcrop in the southwest and the oldest units subcrop in the northeast below Neogene–Quaternary sediments. Figure 5 shows the bedrock geology of the study area, along with a cross-section.

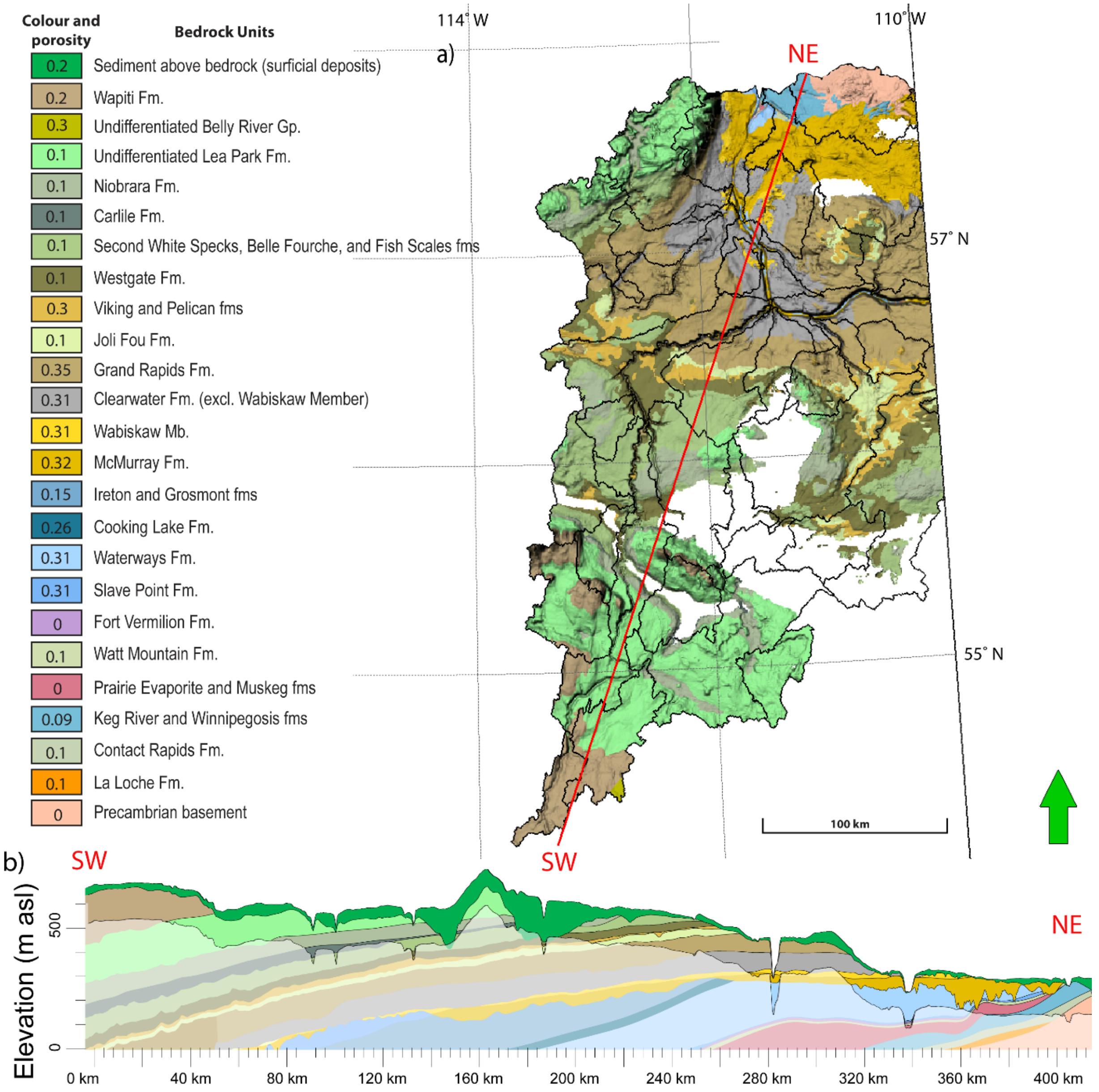

Figure 5. a) Bedrock units in the study area (eastern Alberta; from version 3 of the Geological Framework of Alberta, Alberta Geological Survey, in progress, 2021) to a depth of 150 m below ground surface. The Hydrologic Unit Code Watersheds of Alberta level 8 (HUC8) watersheds (black lines; Alberta Environment and Parks, 2017) are overlain. Bedrock units not shown (transparent areas) are overlain by Neogene–Quaternary sediments exceeding 150 m in thickness. b) Southwest (SW)-northeast (NE) cross-section identified by red line in a).

The volume for each geological zone within 150 m bgs was determined in Schlumberger’s Petrel 2015 software. Water volumes for each zone were determined by assuming effective porosity based on general geological characteristics (consistent with previous reports) or from Bachu et al. (1993) where hydrostratigraphic units had regional-scale porosity measurements obtained from core analyses (Figure 5). For zones that did not have porosity based on core analyses, aquitards were assigned a porosity of 0.1, aquifers assigned a porosity of 0.3, and formations that were a mixture of sandstone, siltstone, mudstone, and shale were assigned a porosity of 0.2 (Figure 5). Overlying Neogene–Quaternary sediments were assigned a porosity of 0.2.

4 Results and Discussion

4.1 Aquifer Yield Continuum

Recharge was determined for 30 HUC8 watersheds within the study area. Recharge results determined from the SAOS and NAOS models range from 2 to 21 mm/yr with an average recharge of 7 mm/yr. For comparison, recharge from the baseflow approach ranged from 0.3 to 71 mm/yr, with an average of 15 mm/yr. A comparison between the two methods is shown in Figure 6. The majority of recharge values from the model approach is between 2 and 10 mm/yr whereas values from the baseflow approach are typically between 1 and 30 mm/yr, with values in several watersheds up to 70 mm/yr.

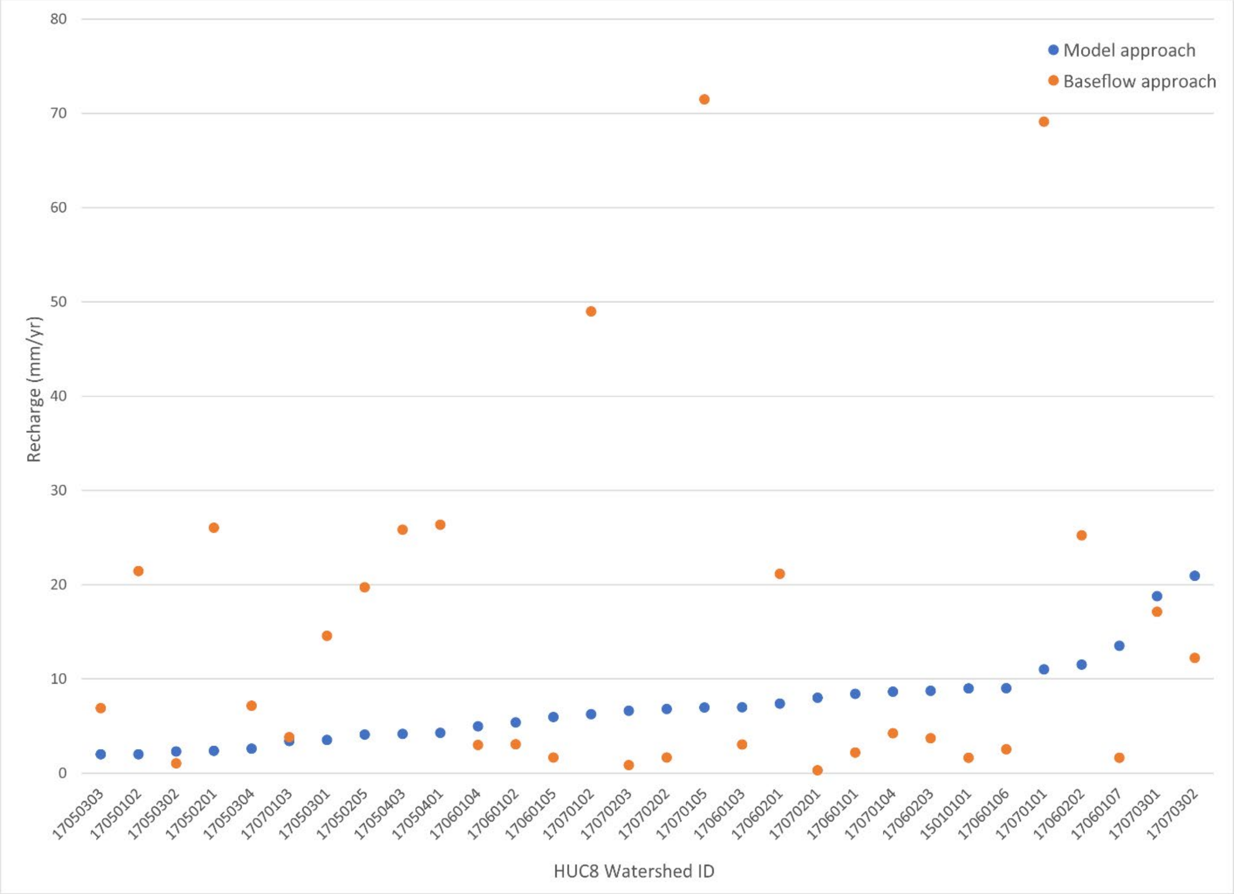

Figure 6. Recharge estimates from the model approach and baseflow approach for Hydrologic Unit Code Watersheds of Alberta level 8 (HUC8) watersheds (Alberta Environment and Parks, 2017) in lower Athabasca region, eastern Alberta.

There are limitations to the baseflow approach in this part of the province, which is why the model approach was used to determine recharge. For example, the baseflow approach assumes all groundwater discharge occurs to streams and rivers, where it is measured; however, there are many wetlands in this area that may receive discharge that is unaccounted for by measuring the baseflow. Data collected from the hydrometric gauging stations were quite variable; although data collected spanned from 1913 to 2018, they were not consistently collected and some stations only collected data seasonally. There was not a period of time when data were collected consistently, which could skew the results when flow at one station is subtracted from the flow at another station to determine flow within a watershed. Because most stations only collected data seasonally (not through the winter months), the data were skewed towards wetter seasons, which could be the reason why the baseflow approach produced recharge results that are quite higher than those from the model approach.

Figure 7a shows the recharge results from the model approach in mm/yr and Figure 7b shows the recharge results in m^3/yr, which is equivalent to the MSY class from the aquifer yield continuum. The results for the remaining classes of the yield continuum can be found in Appendix 1.

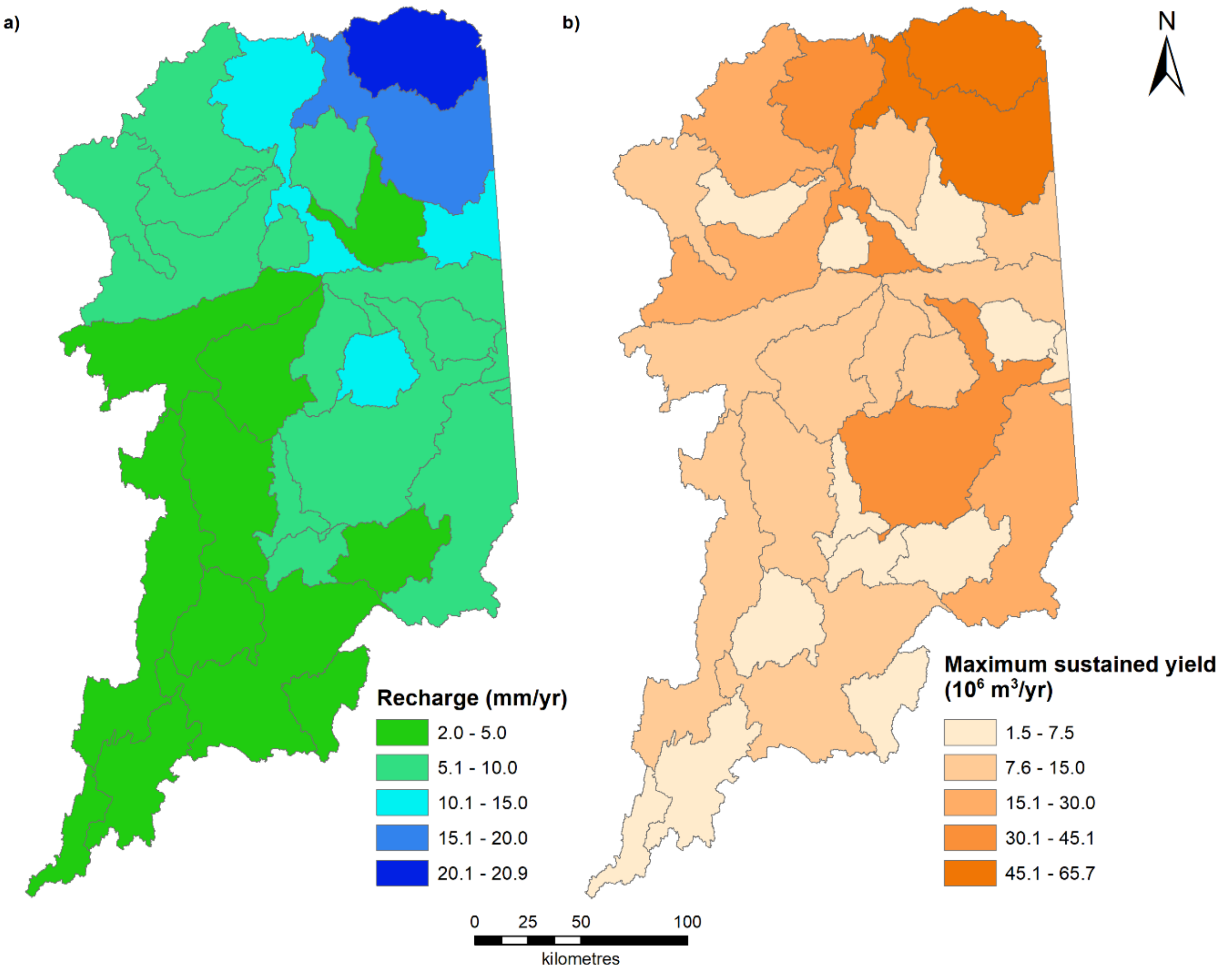

Figure 7. a) Areal recharge and b) volumetric recharge for each Hydrologic Unit Code Watersheds of Alberta level 8 (HUC8) watershed (Alberta Environment and Parks, 2017) in the lower Athabasca region, eastern Alberta. Volumetric recharge is equivalent to the maximum sustained yield in this study.

4.2 Limitations

There are several limitations to the model approach for estimating recharge and to presenting groundwater availability at a watershed scale. Limitations to this method include:

1) The recharge parameter from the SAOS and NAOS models is an input parameter and, therefore, was assigned rather than being a model result. The recharge parameter from the models was used because it was consistent with previous work in similar geographic areas and was optimized during calibration. It did take into consideration precipitation within the area as well as the type of surficial deposits (sand versus till) and topography (uplands versus lowlands). Unfortunately, because the area is heavily forested, the one-dimensional (1D) soil moisture model used in Klassen et al. (2018) and Klassen and Liggett (2019) is not applicable.
2) The results are limited to near-surface aquifers. The yield continuum, specifically for the mining classes (MSY and MMY), assesses groundwater volume within 150 m bgs. In this region, industry requires groundwater data for much deeper units that may not be recharged from surface but rather recharged through cross-formational flows or regional-scale flow. Future work in this area could include assessments of groundwater availability on a formation-by-formation basis.
3) Groundwater recharge results are at the HUC8 watershed level and do not provide site-specific groundwater availability. These results would not be useful for site-specific groundwater allocation but rather for providing estimates of how much groundwater is available per watershed.
4) The aquifer yield continuum assumes that the groundwater system reaches a new steady state and the PMY and MMY classes represent the volume of water that can be extracted in either one year or over 20 years. It is important to consider that groundwater extraction rates change over the lifetime of industry projects. The spatial distribution of groundwater extraction also changes over time as mines develop or are affected by nearby operations.

5 Summary

The aquifer yield continuum is one approach for estimating groundwater yield throughout Alberta and is easily modified by finding different methods to quantify the hydrogeological parameters (recharge, discharge, water volume). For the lower Athabasca region, recharge was estimated from FEFLOW groundwater models; regional-scale geology and geological zone volumes were determined using version 3 of the Alberta Geological Survey’s Geological Framework of Alberta. Average recharge was estimated to be 7 mm/yr and ranges from 2 to 21 mm/yr throughout the study area. Recharge was multiplied by the area of the watersheds to determine groundwater yields on a watershed basis and the maximum sustained yield varied from 1.5×10^6 to 65.7×10^6 m^3/yr. Results from this study can be used as a screening or risk assessment tool to identify watersheds of interest, after which more local-scale groundwater yield assessments could be conducted.

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Appendix 1 – Aquifer Yield Continuum Classes

Figure 8. Hydrologic Unit Code Watersheds of Alberta level 8 (HUC8) watersheds (Alberta Environment and Parks, 2017), eastern Alberta, labelled with HUC8 ID used in Table 2.

Table 2. Aquifer yield continuum classes for the lower Athabasca region of eastern Alberta. The $P_{PSY(10\%)}$ and $P_{PSY(50\%)}$ use 10% and 50% of natural discharge for pumping, respectively. The $P_{PMY(1yr)}$ and $P_{MMY(1yr)}$ and $P_{PMY(20yr)}$ and $P_{MMY(20yr)}$ assume water is removed from storage over 1 and 20 years, respectively. Abbreviations: HUC8, Hydrologic Unit Code Watersheds of Alberta level 8 watershed (Alberta Environment and Parks, 2017); MMY, maximum mining yield; MSY, maximum sustained yield; P, groundwater withdrawal (pumping); PMY, permissive mining yield; PSY, permissive sustained yield.

HUC8 ID	$P_{PSY(10\%)}$ (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)
15010101	2.19E+05	1.09E+06	2.19E+06	1.11E+08	1.09E+10	7.61E+06	5.45E+08
17050102	1.49E+05	7.46E+05	1.49E+06	2.11E+08	2.10E+10	1.20E+07	1.05E+09
17050201	8.68E+05	4.34E+06	8.68E+06	8.62E+08	8.53E+10	5.13E+07	4.27E+09
17050205	1.13E+06	5.67E+07	1.13E+07	7.72E+08	7.61E+10	4.94E+07	3.81E+09
17050301	1.50E+06	7.49E+06	1.50E+07	1.04E+09	1.02E+11	6.61E+07	5.13E+09
17050302	2.44E+05	1.22E+06	2.44E+06	2.40E+08	2.37E+10	1.43E+07	1.19E+09
17050303	3.76E+05	1.88E+06	3.76E+06	4.10E+08	4.06E+10	2.41E+07	2.03E+09
17050304	3.79E+05	1.90E+06	3.79E+06	3.63E+08	3.59E+10	2.18E+07	1.80E+09
17050401	1.34E+06	6.72E+06	1.34E+07	1.30E+09	1.28E+11	7.76E+07	6.43E+09
17050403	9.11E+05	4.55E+06	9.11E+06	8.35E+08	8.26E+10	5.04E+07	4.14E+09
17060101	3.73E+06	1.87E+07	3.73E+07	1.58E+09	1.54E+11	1.15E+08	7.76E+09
17060102	3.57E+05	1.78E+06	3.57E+06	2.00E+08	1.96E+10	1.34E+07	9.84E+08
17060103	5.13E+05	2.56E+06	5.13E+06	2.24E+08	2.19E+10	1.61E+07	1.10E+09
17060104	7.10E+05	3.55E+06	7.10E+06	4.27E+08	4.20E+10	2.81E+07	2.11E+09
17060105	2.37E+06	1.19E+07	2.37E+07	1.32E+09	1.29E+11	8.84E+07	6.49E+09
17060106	7.20E+05	3.60E+06	7.20E+06	3.73E+08	3.66E+10	2.55E+07	1.84E+09
17060107	1.36E+06	6.81E+06	1.36E+07	3.94E+08	3.81E+10	3.27E+07	1.92E+09
17060201	1.26E+06	6.32E+06	1.26E+07	7.17E+08	7.04E+10	4.78E+07	3.53E+09
17060202	1.15E+06	5.73E+06	1.15E+07	4.40E+08	4.28E+10	3.29E+07	2.15E+09
17060203	9.31E+05	4.66E+06	9.31E+06	4.25E+08	4.16E+10	3.01E+07	2.09E+09
17070101	3.14E+06	1.57E+07	3.14E+07	1.06E+09	1.03E+11	8.29E+07	5.19E+09
17070102	3.27E+05	1.64E+06	3.27E+06	2.38E+08	2.35E+10	1.50E+07	1.18E+09
17070103	4.60E+05	2.30E+06	4.60E+06	5.63E+08	5.59E+10	3.25E+07	2.80E+09
17070104	1.24E+06	6.18E+06	1.24E+07	6.01E+08	5.89E+10	4.18E+07	2.96E+09
17070105	1.89E+06	9.44E+06	1.89E+07	8.12E+08	7.93E+10	5.85E+07	3.98E+09
17070201	1.30E+06	6.51E+06	1.30E+07	5.04E+08	4.91E+10	3.76E+07	2.47E+09
17070202	2.04E+06	1.02E+07	2.04E+07	1.33E+09	1.31E+11	8.61E+07	6.59E+09
17070203	6.47E+05	3.24E+06	6.47E+06	4.49E+08	4.42E+10	2.86E+07	2.22E+09
17070301	6.57E+06	3.28E+07	6.57E+07	1.20E+09	1.13E+11	1.22E+08	5.73E+09
17070302	4.74E+06	2.37E+07	4.74E+07	3.11E+08	2.64E+10	6.06E+07	1.36E+09