

Guiding future research to support water management decisions in the Canadian Prairies using an  
integrated hydrologic model

by

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## **Author's Declaration**

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

## Abstract

Groundwater is the main source of water for most people in the Canadian Prairies. As the Canadian Prairies are prone to droughts, the need for additional water supplies is expected to increase as more changes to the climate in this region occur. With climate change, an increase in temperature and precipitation are anticipated. While an increase in precipitation should lead to an increase in infiltration of precipitation into the groundwater systems, this is not necessarily the case. As the temperature increases, it is expected that the already high rate of evapotranspiration will increase, limiting the chance for water to infiltrate the subsurface. This leads to the need for water management plans, which requires an understanding of the hydrologic flow system in the area. Hydrologic models are commonly used to help support water management decisions; however, they are often not developed until after most of the data collection and interpretation is completed. The utility of a preliminary hydrologic model to guide data collection efforts is not often employed, despite the opportunity for significant insight into key processes and data gaps. The goal of this research is to develop a preliminary integrated hydrologic model of an aquifer in the Canadian Prairies to identify research and data gaps that limit the creation of water management plans. The model, created using HydroGeoSphere, is based on the Dalmeny aquifer in Saskatchewan. A base model representing steady state historic conditions was developed, and then three climate change scenarios were simulated and compared to the results of this base model. These climate change scenarios were chosen based on their prevalent use by the Government of Canada using Representative Concentration Pathways. The three climate change scenarios are representative of (1) a significant reduction in global emissions of greenhouse gases, (2) there is no change to the current projected increase in global greenhouse gas emissions, and (3) a significant increase in global greenhouse gas emissions. The results of the base model indicate that groundwater flow is driven by topography, and yet updated, high-resolution topographical data is not readily available, indicating a data gap. The results of the climate scenarios indicate an overall decrease in hydraulic head in the aquifer due to increased estimated evapotranspiration. Evapotranspiration in this region is complex, as annual potential evapotranspiration is greater than precipitation, and so higher temporal resolution evapotranspiration data is necessary to capture infiltration. The direction of flow in some portions of the aquifer also change, leading to one of the boundaries, which is along the South Saskatchewan River, to change from a gaining river in the base scenario, to a losing river in the climate change

scenarios. The uncertainty along the river boundaries, particularly related to their connectedness to the aquifer and their temporal and spatial variability, are key data gaps that should be addressed.

In summary, this work shows that the preliminary integrated hydrologic model results indicate that , in order to support a more accurate simulation to support water management, additional data is necessary to improve: 1) the resolution of the topographical information of the study site, 2) the available methods of estimating temporally appropriate evapotranspiration and, 3) the understanding of groundwater-surface water interactions along the rivers, particularly South Saskatchewan River. With these alterations, a more robust water management plan can be developed, that will protect the availability of groundwater in the study area. By developing a preliminary model with limited information, improvements to the model development of the study area can be pursued.

## **Acknowledgements**

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## **Dedication**

For my parents, Ryan Wilson and Nancy Halverson. My dad sparked the fire and my mum made sure it kept burning when dad's was snuffed out.

For my partner, Matthew Lintaman, for always encouraging me, and helping me pick up the pieces of my life and keep me going. I would not be here if it were not for you.

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# Chapter 1

## Introduction

Global groundwater resources are vulnerable to depletion due to changes in climate, land-use, extraction, resources, and is an issue that is affecting many regions around the world (de Graaf et al. 2019). Sustainable management of groundwater resources is key to ensuring water security. The management of water resources has, and will continue to be, an issue as the climate changes and the demands for water increase (Castle et al. 2014). The increasing global population and the general increase in the quality of life in many populations has put a strain on water availability (Gorelick and Zheng 2015; Lemmen et al. 2008). Traditionally, surface water is first used for water requirements since it is easily accessible; however, in many areas, surface water is not sufficient to meet residential, industrial, agricultural, and commercial demands. Where available, groundwater is being used to supplement and, in some cases, replace the water previously drawn from surface water causing depletion of groundwater resources. This depletion can cause irreversible damage, including reduction in well yields, reduction in baseflow to surface water systems, loss of wetlands, and land subsidence. It is better to proactively manage groundwater resources before chronic groundwater depletion and water quality degradation occurs (Ramirez de la Parra et al. 2016).

Canada is fortunate to have relative abundance of freshwater; it possesses 7% of the world's renewable freshwater, and ranks third in a comparison of all other countries' total renewable freshwater resources (FDA and AQUASTAT 2019). This relative abundance does not mean the nation will be spared from issues in water availability caused by climate change. While most communities have reliable access to safe and clean drinking water, a significant number of Indigenous communities do not have such access (McLeod et al. 2020). The effects of climate change will do nothing to help this complex issue; droughts, floods, extreme heat, and extreme precipitation events can lead to a decrease in resources and an increase in drinking water contamination.

Freshwater reserves are distributed unevenly across Canada; apart from glaciers, freshwater is predominantly stored in surface water bodies such as in lakes and in subsurface aquifers. Most of the surface waters flow northwards, away from the denser populated areas, and away from regions with climates that can support agriculture (Huot et al. 2019). Regions dependent on agriculture are particularly sensitive to water security issues, as it could not only affect the general health and wellbeing of the residents, but also the economy at local, regional, provincial, and national scales. The heart of Canadian agriculture is in the Prairies, which makes this area particularly important when considering how water resources are managed with respect to water security (Lemmen et al.

2008). The Prairies are also the current and traditional lands of many Indigenous Peoples and therefore, Indigenous and rural communities' reliable access to safe and clean drinking water should be a high priority when developing a water management plan. In order to have a robust water management plan, it is important to develop tools to inform sustainable water use decisions.

There are many ways of informing water-use decisions including experimentally, analytically, and numerically. Experimental solutions can be quite accurate but are very time-consuming and only applicable for a single problem. Solving a problem analytically can provide an exact solution, however it can be unrealistic when considering complex problems. Analytical solutions are for very simplified conditions and numerical solutions are easier to conduct and allow more complex problems to be studied. To solve a problem, such as the domain considered in this study, analytically, would mean solving several complex equations for every single node at every single timestep simultaneously, which is impossible if trying to predict future solutions (Creosteanu et al. 2012). Numerical solutions are often used to capture more complex scenarios where flexibility and scenario testing is desired. Therefore, for this study, a numerical solution is the best way forward.

Numerical modelling is the solving of a set or selection of governing equations for the system being studied. The limitations of numerical modelling are the degree of accuracy, the computational power, as well as the uncertainty of the inputs, such as the initial and boundary conditions (Larson 2005). A model's result is only as good as its input. As any model is the representation of an object or a set of processes, there can be several ways to contextualize the object or set of processes that is being analyzed. A physically based distributed model contextualizes the study region based on the physics of hydrological processes as described by the corresponding equations. These types of models are effective at investigating the effects on climate change and land-use changes as they can use outside influences on the domain without extending the modelled area to unnecessary proportions. Process-based numerical methods are a common method of quantifying groundwater resources to predict how water resources will change in the future as other methods tend to fail at predicting outside of the calibrated conditions (Mishra et al. 2020).

Numerical modelling allows for the testing of water management plans before they are enacted, helping to optimize the effectiveness of the plan. Numerical models have been used in a wide variety of environments to consider the effects of groundwater availability when considering climate change. A few examples of these other studies include but are not limited to studies in the Czech Republic (Novicky et al. 2010), Belgium (Goderniaux et al. 2009), Pakistan (Usman et al. 2020), British Columbia, Canada (Allen et al. 2004), and even globally (Döll 2009). Other environments where numerical modelling has been used include northeast Thailand which is at risk of over-exploitation of

their water resources (Nettasana et al. 2012), Gozo (Malta) where the groundwater resources are in jeopardy with the consequences associated with climate change (Sapiano et al. 2017), and Canada where freezing and thawing can affect how oil-sands mines can be reclaimed (Nagare et al. 2022). Numerical models are used in water management to simulate scenarios based on predictions in climate and land-use changes in the area of interest (Thangarajan 2007).

There are several types of numerical models available, and they can be categorized by the hydrologic domains they simulate, including groundwater, surface water, and models which integrate both groundwater and surface water systems. An integrated hydrologic model is preferred when developing a conjunctive water management plan because by its very nature, it solves for the surface water and the groundwater at the same time. This means that integrated hydrologic models are preferred when dealing with groundwater surface water (GWSW) systems (Brunner and Simmons 2012). As explained in Huntington and Niswonger (2012), an integrated hydrologic model can provide greater insight into the effects of climate change between hydrologic processes that occur above and below the ground surface. While integrated hydrologic models do take considerably more computational power, treating the surface water in a coupled way means it can be more realistically simulated and a vague boundary condition is not needed to define the relationship between the groundwater and the surface water in the study domain.

In looking at previous research that study the effects of climate change on groundwater availability, there are few studies found that include the Canadian Prairies. A possible reason for this is that there is no shortage of fresh water in most of Canada, as there are a large number of freshwater bodies spread across the most populated areas of Canada. However, the Canadian Prairies are vulnerable to droughts, and if climate change will affect the amount of annual precipitation, this could put the reliable availability of safe drinking water and irrigation in jeopardy. The primary source for water in the Canadian Prairies is groundwater, as it is more resistant to droughts short-term (Berthold et al. 2004). To accommodate the increase in water necessary to keep up with the increase in population, anticipated in most climate scenarios, an increase in pumping for groundwater systems will be needed. This increase in pumping needs to be conducted safely so as to limit the irreparable damage that can be caused by over-pumping and the subsequent drying out of the groundwater system.

While large-scale integrated hydrologic models have been developed for the Canadian Prairies as part of Canada1Water (Kirkwood 2023), the large scale can make it more difficult to inform small-scale water management decisions. Decisions like groundwater pumping for irrigation or domestic water supply, are best made with local- to regional-scale models that can capture the relevant flow

processes, and the detail that is achieved from these smaller-scale models can better predict the effects of the groundwater usage. Small-scale integrated hydrologic models are limited in this region. Integrated hydrological models are typically calibrated with large data sets of historical groundwater and surface water measurements. However, the reliability of any future models is reliant on the availability of historical data. In Saskatchewan, which contains the study area, the Water Security Agency has an observational well network of approximately 70 monitoring wells and have been seasonally collecting water level data since wells in the network were drilled in 1964 (WSA 2021). While most of the monitoring wells are in the southern half of Saskatchewan, the area of interest for this study contains only one monitoring well, limiting the amount of data in the study area that can be used to develop the model. As a result, the objective of this research is to support the water security of the Canadian Prairies through the development of a preliminary integrated hydrologic model. This model will help identify data uncertainties that critically impact model development and limit model use for water management planning. To achieve this objective, the integrated hydrologic model is developed based on previous work on a shallow semi-confined aquifer northwest of Saskatoon, SK called the Dalmeny aquifer, to create a representative aquifer of the Canadian Prairies. In addition to developing a model based on the limited historic data, several climate change scenarios will then be used to determine the sensitivity of the model to changes in climate conditions over a set time span. The results of this work will provide a first step in prioritizing data collection programs for the region. The remainder of this thesis is laid out in three chapters. Chapter 2 describes the study site details, model development, rationale, and results of the baseline model simulation. Chapter 3 describes the climate scenarios chosen, discusses how they are implemented into the model and, the results of the climate scenarios, identifies the key data gaps in this basin, and also recommends future research directions. Chapter 4 provides a summary of the conclusions from this work.

## **Chapter 2**

### **Model Development**

#### **2.1 Introduction**

To identify and prioritize data needs in the study domain, a model is created based on the limited existing data, and several scenarios are then simulated to identify regions and processes that require better constraint. This is a unique approach as hydrologic models are typically developed once data collection is completed or quite advanced. This work aims to demonstrate how developing a baseline hydrologic model can help guide the data collection efforts near the beginning of study efforts. This chapter details the baseline model that is created before climate change scenarios are applied.

HydroGeoSphere (HGS) was chosen as the modelling framework for this project. HGS uses a physically based, fully-integrated approach, both of which are very important to developing a model that can realistically simulate a shallow aquifer's hydrogeological conditions. The benefit of a modelling framework being physically based is that the results are more likely to show good agreement with observations of the area of study while also allowing for climate scenario testing.

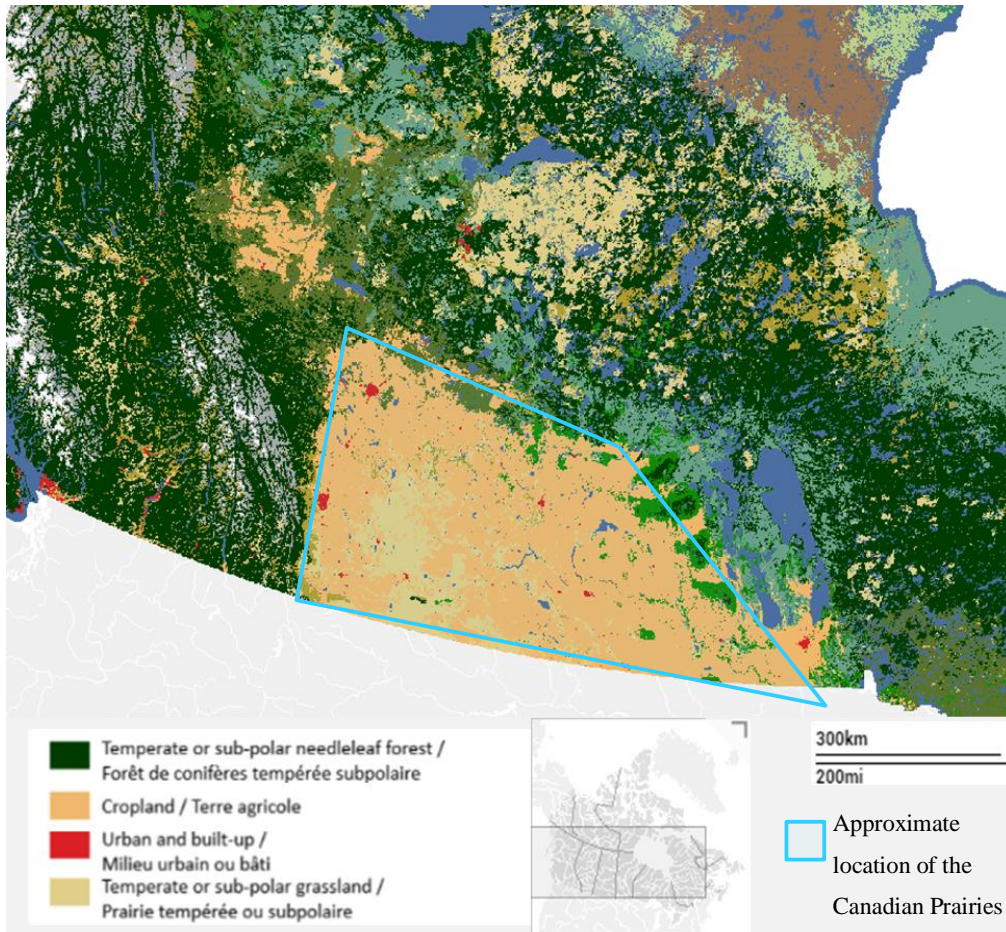
Before modelling frameworks were physically based, they were quasi-physical and semi-empirical, which led to model parameters that did not have a sound physical basis (Beven et al. 1982). The benefit of a modelling framework with a fully-integrated approach is that the surface and subsurface systems are both considered by solving as one system. In solving as one system, the changes in the surface will affect the subsurface in real- time and vice- versa (VanderKwaak 1999).

#### **2.2 Site Description (Conceptual model)**

The study area is in the Canadian Prairies, from this point forward referred to as the prairies, which include the provinces of Alberta, Saskatchewan, and Manitoba. The land cover of the prairies includes plains, grasslands, lowlands, and agriculture and over time, more natural grasslands have been converted for grazing or crop production (Acton et al. 2013). In general, this region is sensitive to droughts because of the low annual precipitation, high potential evapotranspiration, the length of time the ground surface is frozen throughout the year, and the low-permeability layers overlying the aquifers (McGinn 2010).

While low precipitation volumes significantly contribute to the risk of droughts, the low recharge rates due to high evapotranspiration makes the groundwater system particularly vulnerable to

depletion. As groundwater sustains human water needs for domestic use, industry and agriculture



**Figure 1: Land cover in the Canadian Prairies, which is mostly comprised of cropland and grasslands. Modified from the 2020 Land Cover of Canada Open Map available from (Natural Resources of Canada, 2020)**

(livestock production), particularly as surface water systems become less reliable with increased climate variability (Gleeson 2020; Taylor et al. 2013) and supports stable and favourable in-stream habitat conditions (Larsen et al. 2018), it is critical to understand how groundwater resources in the prairies may change in the future.

The infiltration of precipitation, and subsequently groundwater recharge, is controlled by the texture of the surface soils, geology of near-surface layers, and potential evapotranspiration (PET). In areas like the prairies, there has been a lot of previous glacial activity which deposited clay-rich soils on the surface (Ross et al. 2009). While clay-rich glacial deposits can have a large capacity for water, the speed at which water moves through clay-rich deposits is very slow (Freeze 1979). As the majority of precipitation in the Canadian Prairies falls as rain (~70%) during warmer months with higher PET as opposed to snow (~30%) during cooler months with lower PET (Akinremi et al. 1999), the rate of evapotranspiration is also a driver of groundwater recharge rates. High rates of evapotranspiration can

reduce recharge volumes, and variability in weather and vegetation can alter evapotranspiration patterns, both of which will affect groundwater levels. In the prairies the annual PET can exceed annual precipitation, however, because the rate of PET is not constant, and changes seasonally (and hourly) (Armstrong, 2015) there is still limited infiltration to the subsurface. The amount of recharge into the GW system is also limited by the clay-rich surface layers.

Prairie geology commonly features buried-valleys, which are depressions in the bedrock filled with glaciofluvial sediments. Buried-valleys occur all over the world, but are common in the prairie provinces of Alberta, Saskatchewan, and Manitoba, and extend into the bordering states of Montana and North Dakota. The glaciofluvial sediments within buried-valleys in this part of North America are commonly used as aquifers and have distinct hydrogeological properties due to their formation. Prairie buried-valley aquifers are commonly bounded by low-permeability units above and below the aquifer, fully encasing the porous media making up the aquifer and creating a confined aquifer. The units overlying the aquifer are typically clay-rich till, which does protect the aquifer from contamination and drought with the consequence of significantly reducing the recharge potential of the aquifer from surface water and precipitation (Cummings et al. 2012).

While the aquifer simulated in this work is not representative of other buried-valley aquifers that are common in the prairies, as it is bounded by 2 of the major rivers running through that part of Saskatchewan, it does share similarities with buried-valley aquifers on a smaller scale. The foundation of the simulated aquifer is the Dalmeny aquifer in Saskatchewan, which is close to the surface, semi-confined by clay-rich till, and lies atop glaciofluvial sediments that act as an aquitard. Due to a lack of data, a fully-calibrated hydrologic model of an aquifer in this region cannot currently be developed, and therefore, a representative approach is more appropriate for this work to inform future data collection efforts. Here, hydraulic measurements, geography, and geology from other previous studies are combined to create the basis of this model, and the model is broadly constrained to simulate observed and inferred general flow patterns as opposed to specific measurements.

### **2.2.1 Dalmeny Aquifer**

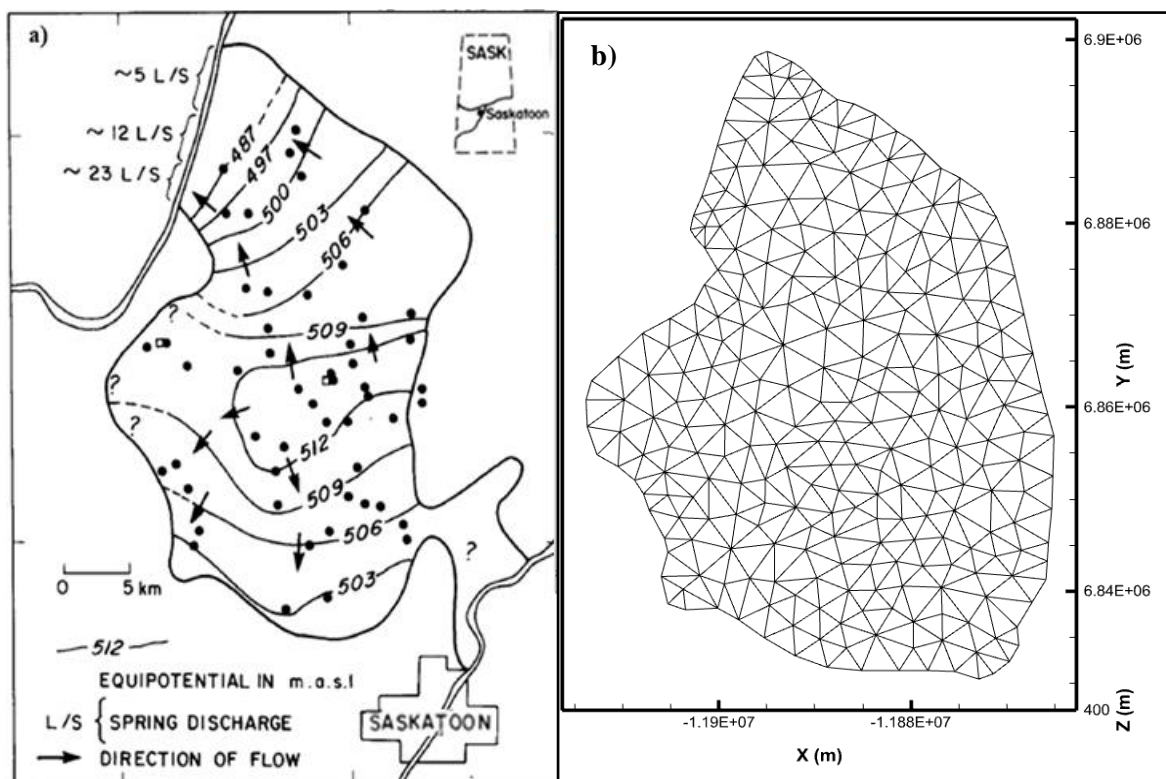
The Dalmeny aquifer is comprised of the Floral Formation and surrounded by the rest of the Saskatoon Group, and the Sutherland and Empress Groups; Pleistocene deposits which are very common in the Canadian Prairies. As the Dalmeny aquifer is comprised of the middle Floral Formation, capped by the Upper Floral Formation, Battleford Formation, and the Surficial Stratified Drift, the top of the Dalmeny aquifer ranges from 12 m to 1 m in depth. This is a shallow confined aquifer, which is ideal for determining the affect groundwater development has on streamflow (Keller et al. 1988).

As can be seen in Figures 3a and 3b, there are some differences between the aquifer extent in the previous study by Fortin et al. (1991), and the modelled domain in this study. The changes are to account for anticipated issues with the domain shape in HGS where pinched regions can lead to the model struggling to converge on a solution. While the previous work conducted by Fortin et al. (1991) is the main basis for this research, more recent studies and information were used to fill some gaps of knowledge, and augment the information presented in their research.



## 2.3 Methods

To create this model, the domain followed the extent of the aquifer provided by Fortin et al (1991) in ArcGIS Pro. The domain was then altered as described previously (Figure 3b) to ensure model convergence and to make the domain more representative of other prairie aquifers. A 2-dimensional mesh was then created using AlgoMesh, with 276 nodes and 478 elements. Then, by referencing cross-sections created for the Saskatchewan Water Agency, lithology can be categorized into layers in the model to create the 3D domain. The vertical delineation is based on the geology, with approximate distances as shown by the cross section (Figure 2). The final domain has 40 layers, resulting in a total of 11316 nodes and 19120 elements.



**Figure 3: a) A modified figure showing the domain's approximate location with respect to Saskatoon. The figure shows the hydraulic heads of the domain in the form of equipotential lines, and the direction of flow in the form of arrows which are correctly plotted perpendicular to the equipotential lines Fortin, van der Kamp, and Cherry (1991), b) A figure showing the extent of the domain that is being used for this study.**

The base of the model is uniform, located at 400 meters above sea level. This base elevation was selected to be deep enough to minimize the impact of the bottom boundary on the aquifer simulated.

The surface of the model domain follows the digital elevation model from Natural Resources Canada (Canada 2024). Sublayers between the surface and base were selected to allow for the representation of geologic units and to provide adequate resolution for analysis of the simulation results.

The hydraulic properties of the zones of porous media were taken from bulk estimates from Fortin et al (1991). The domain is broken up into four layers, the surface layer is treated separately, and their properties are described below. The remaining three layers are all in the subsurface domain and have been called: 1) the oxidized layer for the shallowest layer that has been exposed to oxygen and has weathered; 2) the aquifer layer for the layer containing the sediments that make up the aquifer, which are described as gravel and sand in a report of the Water Security Agency of Saskatchewan which was prepared by MDH Engineered Solutions (2011) and; 3) the unoxidized layer which is the layer that lies underneath the aquifer layer and is not exposed to the surface or any weathering. The unoxidized layer is isotropic, while the oxidized layer and the aquifer layer are anisotropic and the permeabilities and other properties are provided in Table 1 in order to show x direction's value, y direction's value, and z direction's value.

**Table 1: Hydraulic properties for the layers used in the model. Multiple values for a property are listed in x, y, and z directions respectively from WSA (2011).**

Porous Media Property	Oxidized Layer	Aquifer Layer	Unoxidized Layer
Porosity	0.25	0.34	0.25
Hydraulic Conductivity	$1 \times 10^{-7}$ m/s, $1 \times 10^{-7}$ m/s, $1 \times 10^{-8}$ m/s	$1 \times 10^{-5}$ m/s, $1 \times 10^{-5}$ m/s, $1 \times 10^{-6}$ m/s	$3.5 \times 10^{-9}$ m/s
Specific Storage	$1 \times 10^{-4} \text{m}^{-1}$	$1.2 \times 10^{-7} \text{m}^{-1}$	$1 \times 10^{-4} \text{m}^{-1}$

The unsaturated parameters for the aquifer layer was taken from a pre-existing unsaturated table for medium sands (Aquanty, 2024) as site specific information is not available. The other layers used Van Genuchten functions based on parameters from Aquanty, (2024) to generate unsaturated tables, as described in Table 2.

**Table 2: Van Genuchten values used to calculate unsaturation tables for the subsurface layers from Aquanty, (2024).**

Van Genuchten Property	Oxidized Layer	Unoxidized Layer
Alpha	-1.476	-1.801
Beta	11	140
Residual Saturation	0.117 m <sup>3</sup>	0.079 m <sup>3</sup>
Minimum Relative Permeability	1x10 <sup>-2</sup> m <sup>2</sup>	1x10 <sup>-2</sup> m <sup>2</sup>

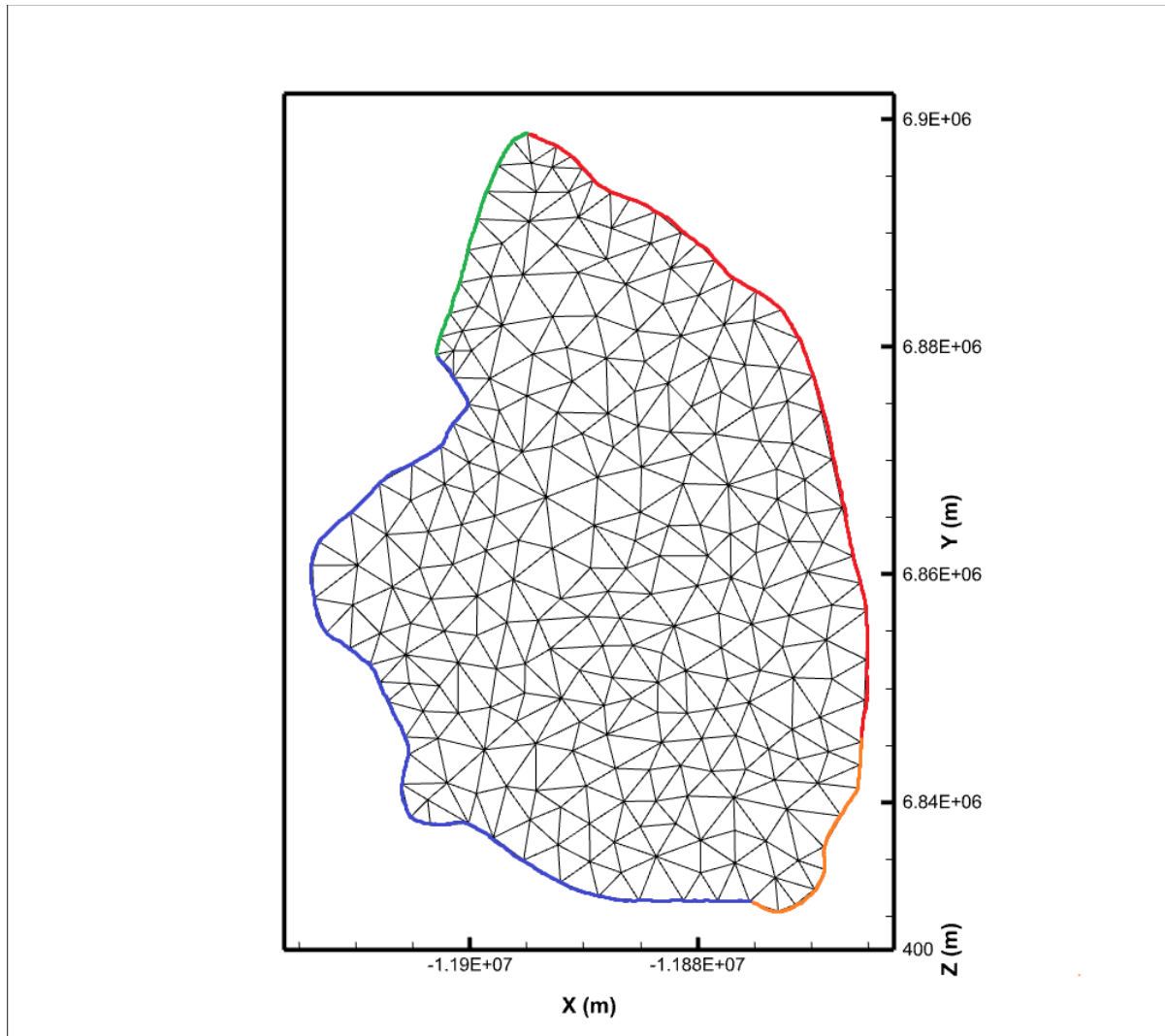
The surface domain is simplified to be homogeneous grassland/cropland, which is the dominant land cover type in the modelled region. The friction coefficients and rill storage heights from Aquanty, (2024) are used to characterize the subsurface, as described in Table 3.

**Table 3: Surface properties for the top face of the modelled domain from Aquanty (2024).**

Surface Property	Value
X-Friction	0.3
Y-Friction	0.3
Rill Storage Height	0.01m

### 2.3.1 Boundary Conditions

Boundary conditions are required along all edges of the surface and subsurface domains. Any boundaries not specified below are no flow boundary conditions. The surface boundary conditions include those capturing rain, the North and South Saskatchewan Rivers, and runoff out of the domain (Figure 4; Table 4). Across the top layer, a rain boundary is applied uniformly at a rate of  $1.58 \times 10^{-9}$  m/s, which is approximately 8% of the average annual precipitation. The rate selected for this boundary is based on work by Hayashi and van der Kamp (1998).



**Figure 4: The model domain and boundary conditions.**

**Boundary conditions are colour coded on this outline of the modelled domain to help with referencing their specifications.**

- North Boundary
- South Boundary
- North River Boundary
- South River Boundary

The river boundary conditions (shown in green and yellow Figure 4) are constant head boundaries, using values reflective of annual average streamflow depths of 465 meters above sea level and 490 meters above sea level for the North and South Rivers, respectively (Canada 2017). The river bounds the aquifer's domain on two sides, and a constant head surface boundary was used to capture the river stage. The remaining surface boundaries along the edge of the model (shown in red and blue in Figure 4) are critical depth boundaries, which allow water to flow out of the domain, as the hydraulic gradient dictates.

The subsurface boundaries are specified along all the edges and at the bottom of the domain. For all layers below the North and South Saskatchewan Rivers (green and yellow lines in Figure 4), a fluid transfer boundary condition is applied. These boundary conditions are vertically split in the subsurface as the influence of the surface conditions is anticipated to change with depth, given the deep incision of the riverbanks (Figure 5b). The large change in topography along the riverbanks yielded numerical issues, and therefore the boundaries along each river were truncated. For the top 15 layers, the fluid transfer boundary is applied to be at a distance of 50 m from the physical boundary, with a constant head of 490 meters above sea level and a hydraulic conductivity of  $1 \times 10^{-4}$  m/s, allowing water to move back and forth across the boundary depending on the conditions within the domain. The lower layers have the same type of boundary condition, however the hydraulic conductivity of the material between the edge of the domain and the 50 m boundary is reduced by an order of magnitude. The hydraulic conductivity of this boundary was reduced to try to match the flow patterns from Fortin et al (1991), and the lower hydraulic conductivity reflects the perceived disconnection from the rivers as depth increases. These boundary conditions allow the regional groundwater flow influence on the model domain to be represented. While it is unclear in previous work (Fortin, 1991) if the rivers are fully or even partially connected to the aquifer, there will still be an influence on the hydrologic conditions of the aquifer coming from beyond the specified domain which must be considered.

**Table 4: Boundary conditions used in the baseline model.**

Boundary	Type of Boundary Condition	Value(s)
Overland flow	Critical Depth	-
Climatic Input	Flux	1.58x10 <sup>-9</sup> m/s
South River – Surface	Head	490 masl
North River – Surface	Head	465 masl
South River - Subsurface Upper	Fluid Transfer	Head – 490 masl Hydraulic Conductivity - 1x10 <sup>-4</sup> m/s Distance - 50m
South River - Subsurface Lower	Fluid Transfer	Head – 490 masl Hydraulic Conductivity - 1x10 <sup>-5</sup> m/s Distance – 100 m
North River - Subsurface Upper	Fluid Transfer	Head – 465 masl Hydraulic Conductivity - 1x10 <sup>-4</sup> m/s Distance - 50m
North River - Subsurface Lower	Fluid Transfer	Head – 465 masl Hydraulic Conductivity - 1x10 <sup>-5</sup> m/s Distance - 100m
South Boundary	Flux	-6.4x10 <sup>-10</sup> m/s
North Boundary	Flux	6.4x10 <sup>-9</sup> m/s
Base	Fluid Transfer	Head – 483 masl Hydraulic Conductivity - 1x10 <sup>-5</sup> m/s Distance - 10m

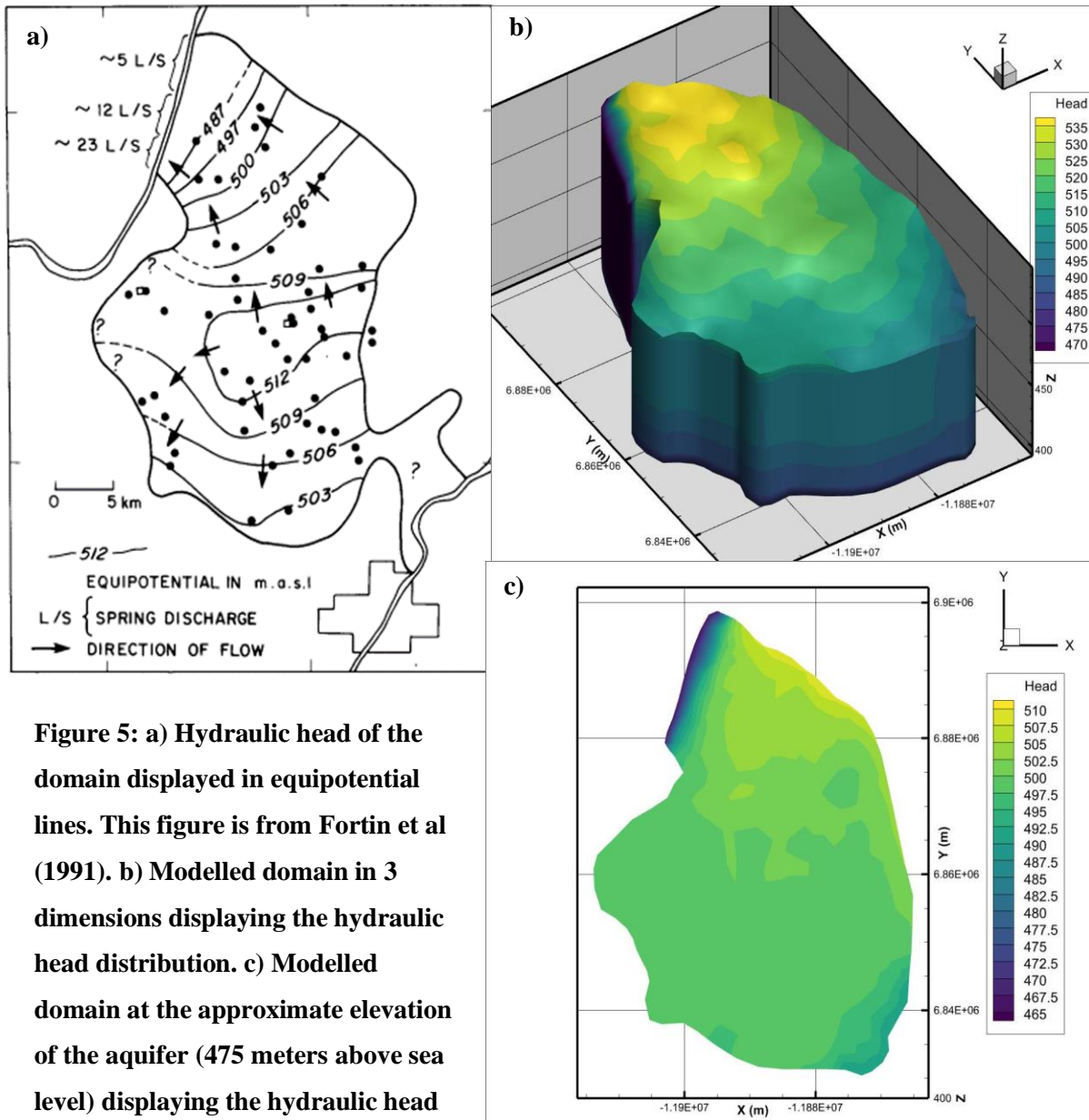
The other boundaries along the perimeter of the subsurface domain are flux boundaries. Following the flow field provided by Fortin et al. (1991), the Southern boundary is a negative flux, meaning the dominant direction of flow is out of the domain at a rate of  $-6.4 \times 10^{-10}$  m/s. The Northern boundary is an inflow boundary with a rate of  $6.4 \times 10^{-9}$  m/s. While the Northern boundary in Fortin et al (1991) is indicated to be a no-flow boundary, it was treated as a slight inflow in this model to allow for a better match between the model results and the flow patterns. There is also a boundary condition along the bottom of the domain, this is a fluid transfer boundary applied at a distance 10 m from the physical boundary, with a hydraulic conductivity of  $1 \times 10^{-5}$  m/s and a constant head of 483 meters above sea level. This boundary represents any downward flux through the porous media and fractures in the domain. All of these flux boundaries were selected to best match the head distribution and flow field shown in Figure 4. The data in Fortin et al (1991) was collected from sporadic historical water-level records from test-hole and farm well records and initial water-levels were taken at the time of installation of the 5 piezometers installed in the areas where historical data was scarce. The model was not calibrated to the exact measurements used to create this figure as they were all taken at different times throughout the basin, and their exact values likely do not represent head distribution of one point in time, as simulated by the model.

## **2.4 Model Results and Discussion**

Results of the steady state simulation outlined above are compared to the flow patterns presented by Fortin et al. (1991). As this model was developed to be a preliminary model of the region due to limited hydraulic head measurements taken at the same time, direct point-to-point comparisons are not provided, as previously discussed.

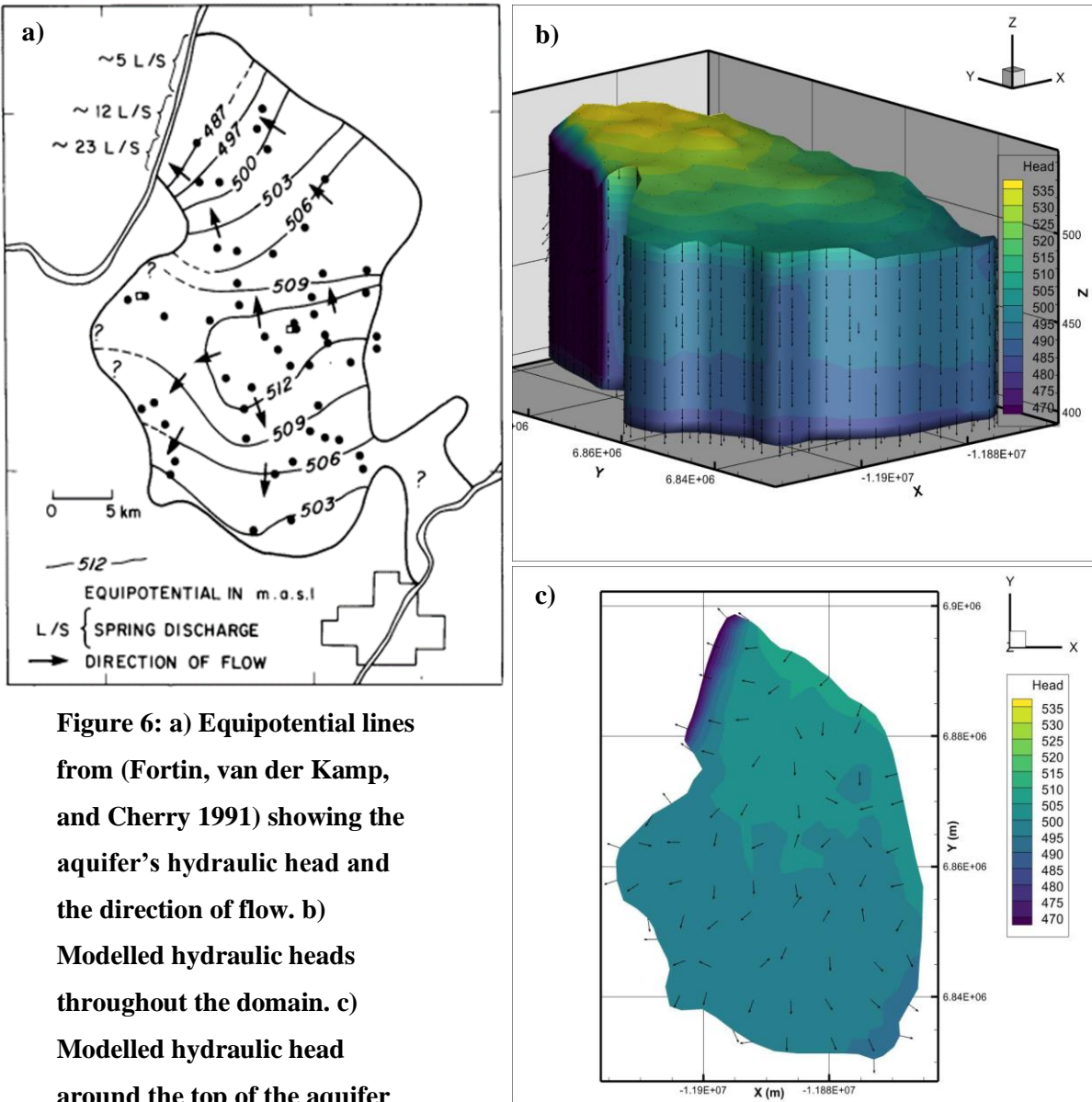
As can be seen by comparing Figures 5a and 5b, the representative aquifer that has been modelled does not perfectly match the data provided in Fortin et al (1991). The hydraulic heads are in the same range, and the dominant flow directions are consistent with each other, but the local topography is driving the simulated hydraulic head distributions more than in the figure depicted by Fortin et al (1991). There is mounding in the western, central part of the domain in the Fortin et al. (1991) depiction, as opposed to the mounding in the higher topographic regions in the simulated results. This may be due to the time difference in between the measurements (1991 to 2021 when first accessed), or this could be an accumulation of errors due to the method of analysis to create the Digital Elevation Model (DEM) by Natural Resources of Canada, as satellite images are the main source of the DEM's information for this area. In Figure 5a, it can be seen that the dominant direction of flow is towards the northwestern portion of the domain which leads towards the North River, the other directions of flow are following the topography. Updated, higher resolution topographic data, such as

Lidar, would benefit this model's development. As can be seen by comparing Figures 5a and 5b, the representative aquifer that has been modelled does not perfectly match the data provided in Fortin et al (1991), however, the hydraulic heads are in the same range between the two figures, and the dominant flow directions are consistent with each other. In comparing Figure 5a and c, where Figure 5c shows the hydraulic head distribution at the top of the aquifer unit (elevation = 475 masl), the similarities of the hydraulic heads are more apparent, even with the difference caused by the overlying topography.



**Figure 5: a) Hydraulic head of the domain displayed in equipotential lines. This figure is from Fortin et al (1991). b) Modelled domain in 3 dimensions displaying the hydraulic head distribution. c) Modelled domain at the approximate elevation of the aquifer (475 meters above sea level) displaying the hydraulic head distribution.**

Figure 6 compares the flow patterns from Fortin et al. (1991) with those from the simulation results. As can be seen in Figure 6b, the dominant direction of flow is downwards, something is not captured in Figure 6a. In Figure 6c, which shows the hydraulic head and flowpaths around the top of the aquifer (475 masl), demonstrates that the lateral flow paths are somewhat consistent with those from Fortin et al (1991).



**Figure 6:** a) Equipotential lines from (Fortin, van der Kamp, and Cherry 1991) showing the aquifer’s hydraulic head and the direction of flow. b) Modelled hydraulic heads throughout the domain. c) Modelled hydraulic head around the top of the aquifer (475m above the sea level).

## 2.5 Conclusions

The goal of this chapter was to create a preliminary integrated hydrologic model for a representative Canadian Prairie aquifer based on limited data and previous work conducted in the Dalmeny region. This was achieved by using hydrogeological properties found in previous work that has been published from the area, properties including, but not limited to, bulk porosity, bulk permeability, bulk hydraulic conductivity, and relative distance between layers, in addition to texture-based properties from other literature. All of the information that was gathered used to develop the baseline model, and minor edits were made to the literature values to get the model to achieve steady state conditions that are generally consistent with previously published flowpaths and hydraulic head distributions by Fortin et al (1991). As groundwater flow seems driven by topography, updated, higher resolution topographic data was identified as data that would improve this model.

One of the major problems that was encountered is that the surface layer of the glaciofluvial sediments that make up the top of the domain are clay-rich and significantly reduce the potential rate of groundwater and increase potential for runoff. In combination with the clay-rich surface layer, the high rates of evapotranspiration in the area reduce the potential recharge possible. Recharge in the domain's region is so low, it is more feasible to estimate the percentage rate of precipitation that is lost from the potential recharge via evapotranspiration calculations than trying to estimate the recharge into the domain. While this is not the most accurate method to estimate climatic input applied to the domain's surface, it is as accurate as possible given the limited information for the area. Alternate approaches to estimating the evapotranspiration would improve the accuracy of the model and therefore aid in informing future work. The effects of land use change on the domain's groundwater availability are outside the scope of this project due to time factors but would be recommended for further research. The following chapter further identifies areas of the domain and processes that are sensitive when climate change scenarios are applied, identifying further data collection efforts for supporting future water sustainability efforts.

## **Chapter 3**

### **Climate Change Scenarios**

#### **3.1 Introduction**

Groundwater is a critical source of water for human consumption, agriculture, and industry. The threat of groundwater security is compounded in regions where surface water is scarce or unreliable as more groundwater could be extracted to make up the difference. This can lead to an unsustainable level of extraction of groundwater which can deplete the groundwater resource and have repercussions for many years (Mukherjee et al. 2021). Groundwater recharge is typically governed by precipitation percolating through topsoil into the aquifer system, and the interchange between groundwater and surface waters (ECCC 2007). Climate change is anticipated to alter precipitation patterns and evaporations rates, which may lead to an overall reduction in recharge rates for most of the prairies (Negm et al. 2021). Changes in precipitation patterns, particularly snowmelt, can have profound effect on the local surface water systems. Increased amounts of rain in winter as well as the associated increase in air temperature may change the peak groundwater recharge rates to earlier in the spring than previously, and may exacerbate the issues with low summer flow in surface water systems (Taylor et al. 2013).

The use of integrated hydrologic models to assess the vulnerability of an area to water security is not a novel idea (Thangarajan 2007), but the results of the model assessments are unique to each study site. This chapter aims to determine the areas of the domain and processes that show significant differences between the baseline model developed in Chapter 2 and each of the climate change scenarios presented in this chapter. The areas and processes of difference are interpreted as the areas or processes where more information is necessary to be able to adequately support water management decisions in the future. This chapter explores how the baseline model produced in Chapter 2 has been changed to create three separate climate change scenarios.

#### **3.2 Climate Scenarios**

Climate models have been used for over 50 years to try to understand what is driving climate conditions or to try and predict future climate conditions. Climate models are often physically based, numerically solving the physical, chemical, and biological mechanisms that operate on Earth (McSweeney 2018). Simplifications to the equations used to represent these mechanisms, in addition to uncertainties associated with the data used to generate them, cause uncertainties in the results of the projections. Some of the uncertainties stem from the lack of information about the human effect on

the climate in the future (Hallegatte 2009). To help combat these uncertainties, different projections are created based on the assumption that humans will maintain different levels of emissions of greenhouse gases. These different projections based on different scenarios, are referred to as Representative Concentration Pathways (RCPs). While there are many possibilities in the future of global emissions, limiting the number of possible RCPs makes communication and research about climate change easier. The three most common RCPs used to describe emission scenarios by the Government of Canada are: RCP8.5, a high global emission scenario; RCP4.5, a medium global emission scenario; and RCP2.6, a low global emission scenario (Canada 2018). The RCPs described previously are projected until 2090 and include possible ranges of average global warming levels; for RCP8.5 the global average warming range of 3.2 to 5.4°C, RCP4.5 has a global average warming range of 1.7 to 3.2°C, and RCP2.6 has a global average warming range of 0.9 to 2.3°C (ECCC 2018). The climate change scenarios that will be used in this research are these three most commonly presented by the Government of Canada; RCP8.5, RCP4.5, and RCP2.6, which will now be referred to as High, Moderate, and Low, respectively.

### 3.3 Methods

To create the climate change scenarios that will be applied to the model developed in Chapter 2, the estimated percent change of precipitation and temperature will be used to alter the amount and rate of water applied to the surface of the domain. In this work, climatic input will be the calculation of precipitation minus evapotranspiration. The climatic input will be applied as a constant value across the entire domain in space, but given the uncertainty associated with the calculated values and the simplification of the numerical problem, is considered a reasonable approach for this preliminary model. Compared to Chapter 2, the evapotranspiration will be changed from an estimate of 92% of precipitation, to a temperature-based method for calculating the evapotranspiration, as described in the following paragraph. While the climatic input remains constant across the domain's surface, the difference between the climatic input for the baseline and climate models gradually applied through the model run to avoid a sudden change in climatic input.

In order to calculate the climatic input, the temperature-based Thornthwaite method is used to inform annual evapotranspiration estimates for the domain surface. The potential evapotranspiration was calculated by using the Thornthwaite equation (Thornthwaite 1948), and monthly averages of temperature and precipitation (Weather Spark 2024). The Thornthwaite equation (Thornthwaite 1948) given by:

$$E = 16 \left( \frac{10T_a}{I} \right)^a \left( \frac{d}{12} \right) \left( \frac{N}{30} \right) \quad (1)$$

Where  $E$  is the potential evapotranspiration,  $T_a$  is the average monthly temperature,  $d$  is the average daily number of sunlight hours for each month,  $N$  is the number of days in the month,  $I$  is a heat index which is calculated with the following formula:

$$I = \sum_{Jan}^{Dec} \left( \frac{\max [0, T_m]}{5} \right)^{1.514} \quad (2)$$

Where  $T_m$  is the monthly mean temperature [ $^{\circ}\text{C}$ ].

The exponent  $a$  of the Thornthwaite equations is calculated as follows:

$$a = (6.75 \times 10^{-7} \times I^3) - (7.71 \times 10^{-5} \times I^2) + (0.01792 \times I) + (0.49239) \quad (3)$$

(Tegos et al. 2013; Thornthwaite 1948; WSL 2024)

While Thornthwaite can lead to large over-underestimations or under-estimations based on the climatic data used for the calculation (Morton 1983), it provides a simple approach to estimate evapotranspiration. In this work, as shown in Table 5, the evapotranspiration as calculated by Thornthwaite is larger than the annual precipitation even after applying the increase of precipitation considered for each climate change scenario. For example, the Thornthwaite calculations for the baseline model yielded a potential evapotranspiration value of  $5.31 \times 10^{-7}$  m/s, while the annual precipitation of the area is  $1.98 \times 10^{-8}$  m/s. This shows that the potential evapotranspiration is an order of magnitude larger than the anticipated annual precipitation, and that the precipitation that is applied to the surface of the domain (climatic input) would be  $-5.11 \times 10^{-7}$  m/s. This is one of the many reasons that this area is difficult to model. There are other methods that could have yielded a more representative PET value, such as Penman-Monteith, however, they require more climatic data than was available for the study area (Subedi and Chavez 2015). In future work, a method that generates a more representative PET is recommended to improve the ability of the model to inform water management decisions.

An additional difficulty in assessing the impact of changing climate conditions on long term AET estimates is that this region is predicted to have increasing precipitation and temperature. This can potentially cause both an increase in AET and infiltration. Based on the climate model results for the Low scenario, there is a 6.3% increase of precipitation and an increase of temperature of  $1.8^{\circ}\text{C}$  for the study region. The Moderate scenario has an increase of precipitation of 7.3% and a temperature increase of  $3.3^{\circ}\text{C}$ , and the High scenario has an increase of precipitation of 11.4% and a temperature increase of  $6.7^{\circ}\text{C}$ . These changes are based on the historic average annual temperature of  $2.25^{\circ}\text{C}$  for the area and average annual precipitation of 0.0623 mm/yr (Canada 2023; Weather Spark 2024).

As previously indicated, most estimates of PET for this region indicate values larger than precipitation, insinuating no infiltration; however, the timing of precipitation events (during times of low PET) allows for some infiltration to occur. As such, the ratio between projected precipitation and PET calculated using Thornthwaite is used to scale the amount of water entering the subsurface for each scenario (P. Sullivan, personal communication). Therefore, while Thornthwaite was used to generate estimates of PET, the actual values resulting from the Thornthwaite equations were not used in the model, but instead the estimated PET values for the baseline and climate scenarios were used relative to each other and the precipitation to estimate the change in ET from the baseline calibrated value (P Sullivan, personal communication). The climatic inputs calculated for each scenario are provided in Table 5. These are calculated as precipitation minus actual evapotranspiration (AET). This results in infiltration ranging from 3.7% of precipitation in baseline scenario to 2.7% of precipitation for the ‘extreme’ scenario (Table 5). This allows the influence of ET on infiltration to scale relative to the projected precipitation in the region. For example, in the extreme scenario, precipitation increases by 11.4%, but PET as calculated by Thornthwaite increases by 75% over the baseline scenario. This causes a decrease in infiltration compared to the baseline despite an increase in precipitation. While this methodology may not accurately represent the AET and infiltration, it does capture the potential net influence of the projected scenarios on the hydrologic system.

The climatic input is the only thing that has been changed between the baseline model and each of the climate scenarios. The changes in climatic input were then applied gradually to the domain so as to not cause instabilities in the domain at the very first time step. The model is run with constant conditions for 50 years to represent a pseudo-steady state condition under the climate conditions.

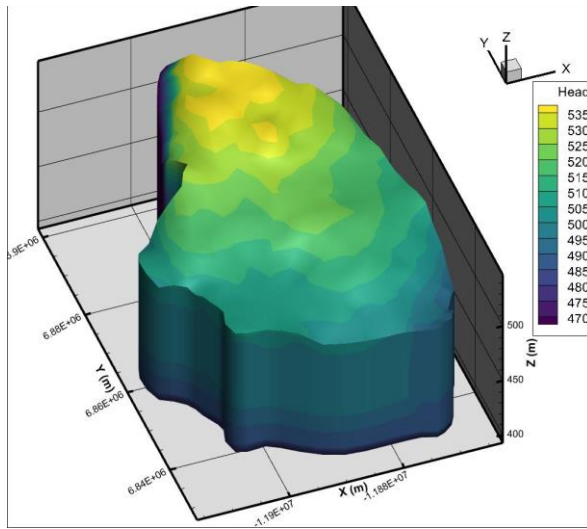
**Table 5: Data used for calculating the climatic input for the climate scenarios.**

	<b>Baseline</b>	<b>Low</b>	<b>Moderate</b>	<b>High</b>
<b>Annual Total Precipitation (m/s)</b>	1.98x10 <sup>-8</sup>	2.12x10 <sup>-8</sup>	2.25x10 <sup>-8</sup>	2.51x10 <sup>-8</sup>
<b>% increase of Precipitation over baseline scenario</b>		7%	6%	11%
<b>Average Annual Temperature [°C]</b>	2.25	4.05	5.55	8.95
<b>% increase of temperature over baseline scenario</b>		80%	147%	298%
<b>PET calculated as calculated by Thornwaite (m/s)</b>	5.31x10 <sup>-7</sup>	7.58x10 <sup>-7</sup>	6.97x10 <sup>-7</sup>	9.23x10 <sup>-7</sup>
<b>% increase in PET as calculated by Thornwaite (m/s)</b>		43%	31%	74%
<b>Ratio of Precipitation to ET (m/s)</b>		2.8%	3.2%	2.7%
<b>Climatic Input to the model (m/s)</b>	1.58x10 <sup>-9</sup>	5.93x10 <sup>-10</sup>	7.29x10 <sup>-10</sup>	6.83x10 <sup>-10</sup>
<b>AET (precip - climatic) (m/s)</b>	1.82x10 <sup>-8</sup>	2.06x10 <sup>-8</sup>	2.18x10 <sup>-8</sup>	2.44x10 <sup>-8</sup>
<b>Difference (m/s)</b>		9.87x10 <sup>-10</sup>	8.52x10 <sup>-10</sup>	8.98x10 <sup>-10</sup>
<b>Steps (m/s)</b>		4.11x10 <sup>-11</sup>	3.55x10 <sup>-11</sup>	3.74x10 <sup>-11</sup>

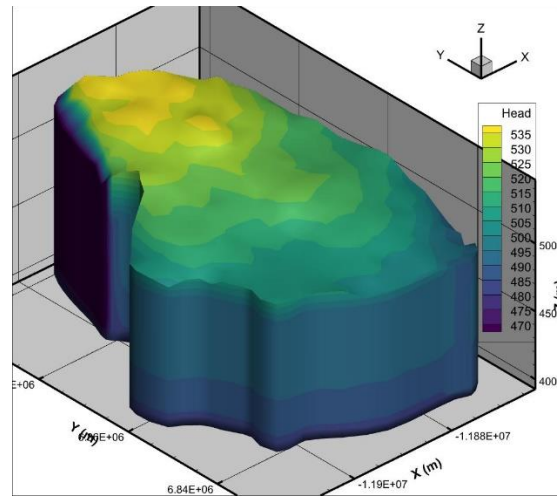
### 3.4 Model Results and Discussion

Model results between the baseline and climate scenarios are compared based on hydraulic head distributions and the final water balance at the end of the model simulations (50 years). The hydraulic head distributions indicate very little difference at the end time of the model (Figure 7), however, it does demonstrate that the consistent, dominant direction of movement of water is downwards and, to a lesser extent, out of the North River boundary, as can be seen by the low hydraulic heads displayed in those areas.

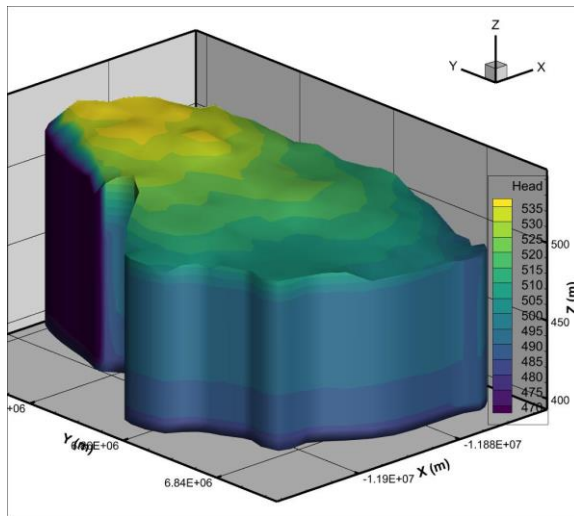
While there is not a significant change in the distribution of hydraulic head, as evident in the 3D distributions in Figure 7, when the distributions are plotted within the aquifer itself, at a depth of 50m from ground surface, the differences between scenarios becomes evident (Figure 8). As we can see Figure 8a, the average hydraulic head is larger than in Figures 8b-d, but at each point where there is a boundary between the aquifer and a river, the hydraulic head remains the same, as it is controlled by the boundary condition at those nodes. The hydraulic heads in all three of the scenarios are lower than in the baseline, as expected since the climatic input was reduced, and the changes in these hydraulic heads are more significant in the topographically high areas that experience some groundwater mounding.



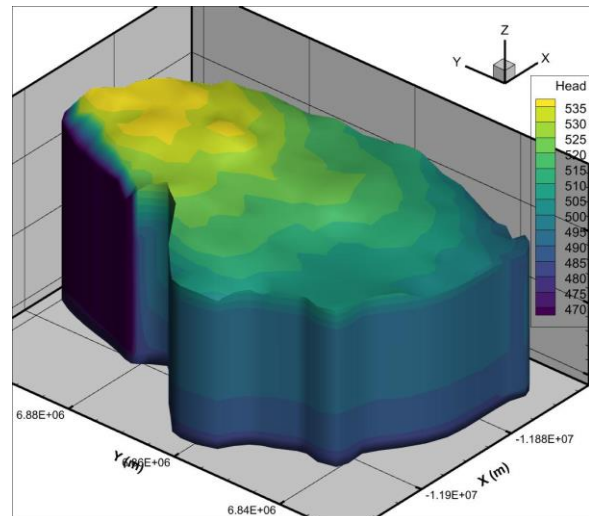
a) Baseline scenario 50 years 3D



b) High scenario 50 years 3D



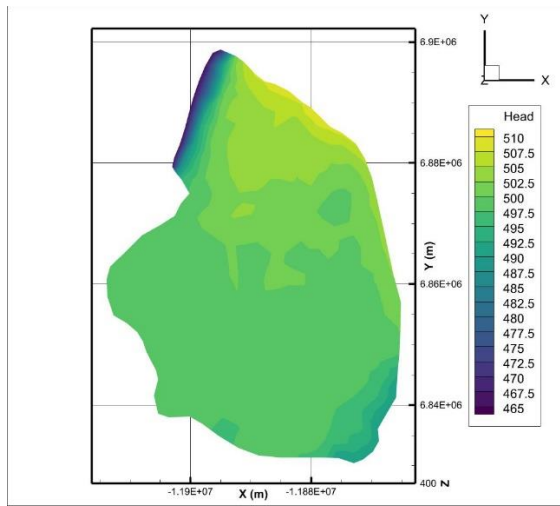
c) Low scenario 50 years 3D



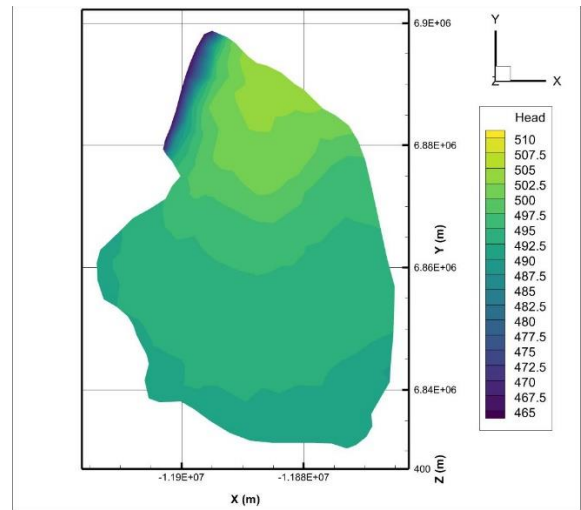
d) Moderate scenario 50 years 3D

**Figure 7: Hydraulic head results for the baseline model and the three climate scenarios that are considered in this chapter at the final output time of 50 years.**

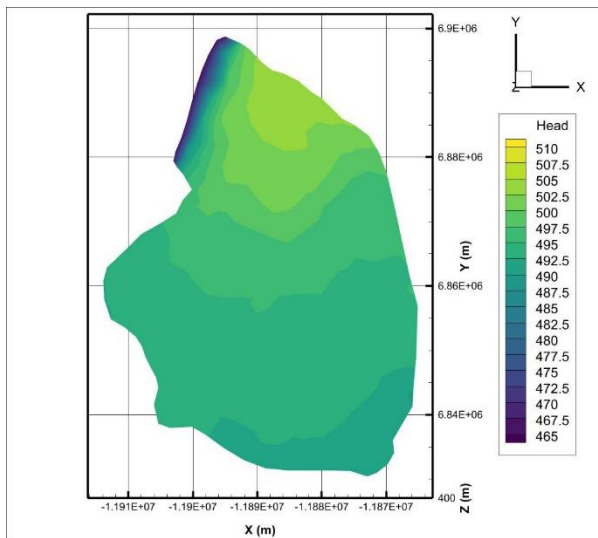
Figure 8 shows how the hydraulic head changes within the aquifer when the climate scenarios are simulated. The general trend is that there is a decrease in hydraulic head between the baseline and in order of the most reduction in global emissions (low scenario) to the lowest hydraulic heads shown in the least amount of reduction in global emissions (high scenario).



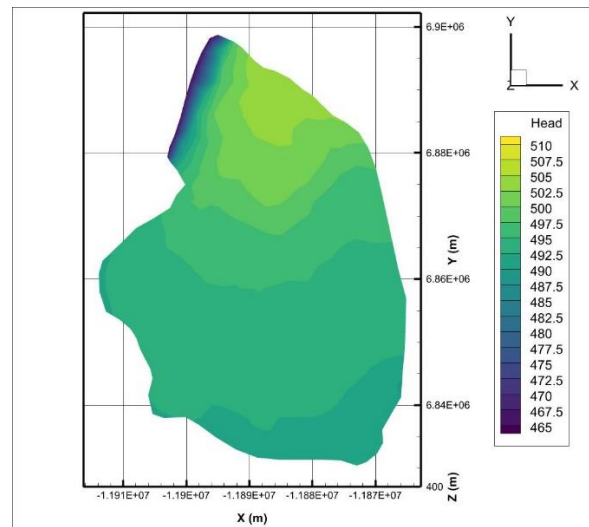
a) Baseline scenario 50 years 2D



b) High scenario 50 years 2D



c) Low scenario 50 years 2D

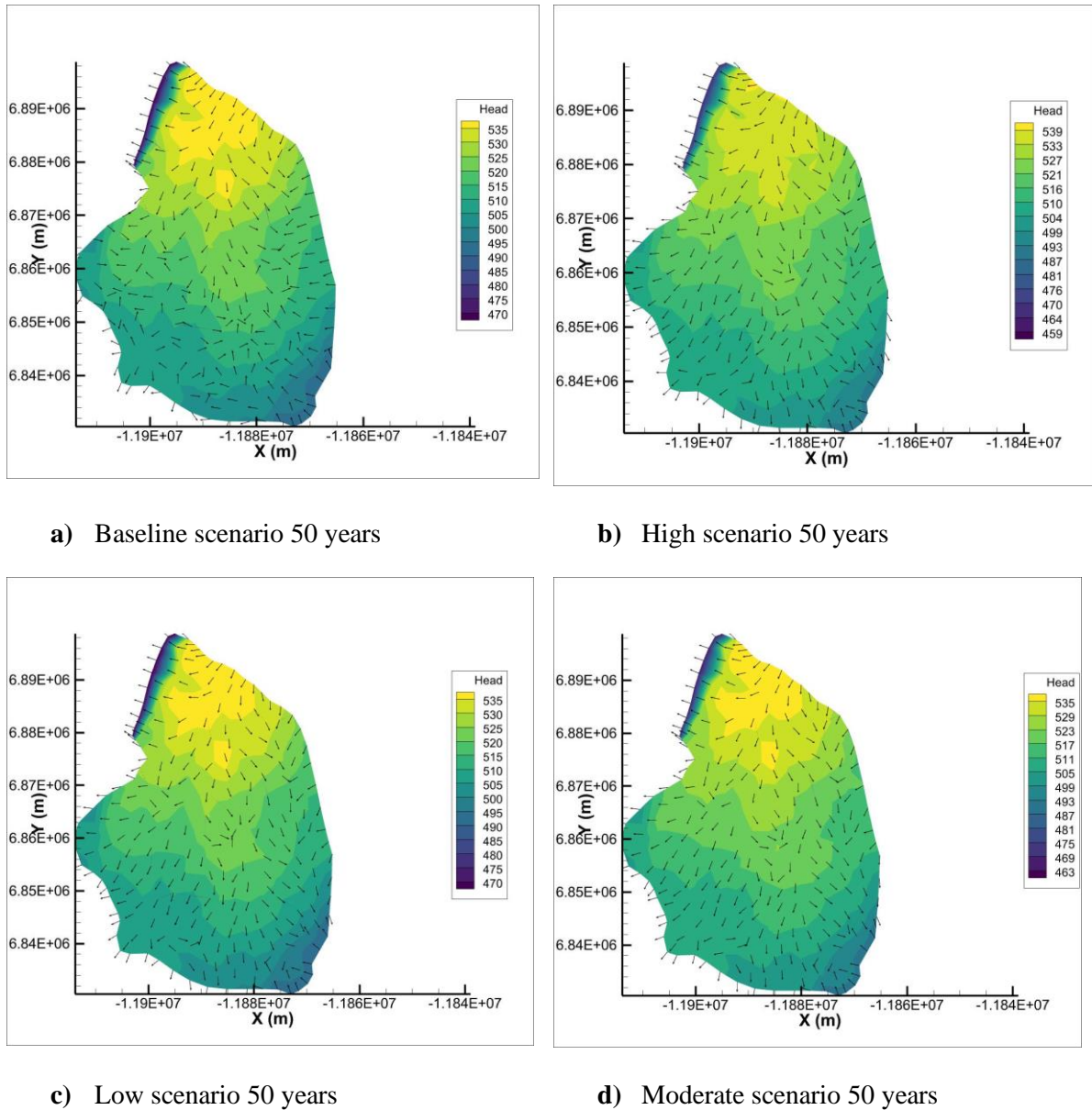


d) Moderate scenario 50 years 2D

**Figure 8: Hydraulic head results for the baseline model and the three climate scenarios that are considered in this chapter at the final output time of 50 years at 50 m below the ground surface.**

For all of the scenarios, the dominant direction of flow is downwards, however, as seen in Figure 9, there are the small variations in the directions of the flow. The baseline model results display more variability in the direction of flow, whereas the climate scenarios generally show more consistent flow trends. Figure 9a shows that the direction of movement of water changes rapidly over the surface of the domain, and often conflicts with neighbouring flow directions. In general, it is evident from Figure 9 that there is some small input from the South River boundary on the bottom left of the domain, particularly in the climate scenarios. There is also input along the top boundary until the

hydraulic head drops dramatically, indicating the start of the North River boundary, where the flow is out of the domain. The south boundary along the bottom of the domain is also an outflow boundary, however, at a lesser extent than the North River boundary. The rest of the flow paths inside the domain are typically governed by topography, and the small variations of topography in this domain is where there are some discrepancies as to the dominant direction of flow in the baseline scenario.



**Figure 9: Hydraulic head results and the associated 2D flowpaths for the baseline model and the three climate scenarios that are considered in this chapter at the final output time of 50 years at the ground surface.**

The water balance at the end of each scenario also demonstrates the differences between the baseline and climate scenarios (Table 6). As prescribed by the climatic input, the infiltration of precipitation decreases as the projected emissions increase. The overland flow component remains constant and exceptionally large in all the simulations. This indicates significant runoff from the domain, through the critical depth boundary conditions at the surface. This should be further investigated in future research through variation of overland flow properties which is beyond the scope of this research that focuses on the groundwater flow regime. The South River boundary at the surface goes from a sink in the baseline scenario to a source in all climate scenarios. This indicates that the reduction in climatic input has caused the hydraulic heads within the domain to fall below the boundary condition prescribed, causing water to flow into domain. The upper subsurface of the South River also changes direction of flow from a sink to a source between the baseline and the climate scenarios. This leads the South River to go from a gaining stream to a losing stream once the climatic input decreases. This may indicate the susceptibility of the South River to changes in climate and identifies this boundary as a region requiring further data collection. The other boundary conditions do not change direction of water flow, but they do show a general decrease in water leaving the domain and more water being retained within the domain, offsetting the reduction in climatic inputs. This response reduced the impact of the climate scenarios on the hydraulic head distributions shown in Figures 7 and 8.

**Table 6: Water balance of the models for each climate scenario.**

Boundary Condition	Net Rate of Fluid Exchange [m <sup>3</sup> /s]			
	Baseline	Low	Moderate	High
Overland flow	-7.63 x10 <sup>4</sup>	-7.63 x10 <sup>4</sup>	-7.63 x10 <sup>4</sup>	-7.63 x10 <sup>4</sup>
Climatic Input	3.42 x10 <sup>0</sup>	1.45 x10 <sup>0</sup>	1.37 x10 <sup>0</sup>	1.23x10 <sup>0</sup>
South River – Surface	-5.23 x10 <sup>-3</sup>	5.47 x10 <sup>-6</sup>	7.12 x10 <sup>-6</sup>	1.07 x10 <sup>-5</sup>
North River – Surface	-1.87 x10 <sup>-4</sup>	-4.37 x10 <sup>-5</sup>	-4.17 x10 <sup>-5</sup>	-3.82 x10 <sup>-5</sup>
South River - Subsurface Upper	-2.31 x10 <sup>-4</sup>	3.78 x10 <sup>-5</sup>	4.54 x10 <sup>-5</sup>	5.90 x10 <sup>-5</sup>
South River - Subsurface Lower	8.07 x10 <sup>-2</sup>	8.79 x10 <sup>-2</sup>	8.82 x10 <sup>-2</sup>	8.87 x10 <sup>-2</sup>
North River - Subsurface Upper	-7.85 x10 <sup>-5</sup>	-1.93 x10 <sup>-5</sup>	-1.83 x10 <sup>-5</sup>	-1.67 x10 <sup>-5</sup>
North River - Subsurface Lower	-3.52 x10 <sup>-1</sup>	-3.45 x10 <sup>-1</sup>	-3.45 x10 <sup>-1</sup>	-3.45 x10 <sup>-1</sup>
South Boundary	-5.74 x10 <sup>-3</sup>	-5.74 x10 <sup>-3</sup>	-5.74 x10 <sup>-3</sup>	-5.74 x10 <sup>-3</sup>
North Boundary	5.44 x10 <sup>-2</sup>	5.44 x10 <sup>-3</sup>	5.44 x10 <sup>-3</sup>	5.44 x10 <sup>-3</sup>
Base	-2.07 x10 <sup>0</sup>	-1.46 x10 <sup>0</sup>	-1.44 x10 <sup>0</sup>	-1.41 x10 <sup>0</sup>

The North River does not show changes quite as extreme as the South River, but there is still a decrease in water leaving the domain between the baseline and the climate scenario. The upper subsurface below the North River also has a reduction in the water leaving the domain. The amount

of water entering the domain from the North Boundary decreases by an order of magnitude, likely due to the increase in water coming in from the South River boundary at the surface and the subsurface. The bottom boundary shows a decrease in the amount of fluid leaving the domain through that boundary, presumably because there is less water in the system, or the water is preferentially leaving domain by other routes such as the surface of the North River.

### **3.5 Conclusions**

Three climate scenarios representing low, moderate and high carbon emissions were selected for identifying areas that may be sensitive to changes in climatic input compared to the baseline model developed in Chapter 2. In all three scenarios, the climatic inputs are lower than in the baseline scenario despite a predicted increase in precipitation. This is due to the increase in estimated AET that was greater than the increase in precipitation. The difficulty in estimating PET and AET in this region indicates that further data collection and research should be conducted to constrain this boundary condition.

The results of these scenarios, when simulated to 50 years, indicate that while changes to the hydraulic heads within the modelled domain are slight, that changes to the overall water balance of the domain is significant. Changes to the hydraulic heads were restricted to areas within the aquifer (at depth), and to regions of topographic highs. This is likely due to the dominance of topography in lateral flow within the domain and also to the distance of these regions from restrictive boundary conditions. This further supports the need to collect updated and refined topographic information in the region. The constant head boundary conditions used to simulate the North and South Rivers allowed for a water source that could adapt to the changing hydrologic conditions within the domain due to the change in climatic input, providing more water to the domain as recharge reduced. All of the boundary conditions, with the exception of the climatic input, either remained the same as the baseline scenario, had less water leaving the domain, or changed from a sink to a source of water to the domain. In particular, the South River switched from a gaining to a losing river between the baseline and all climate scenarios. This indicates that further work is needed to better parameterize and constrain the South River boundary condition to understand it's connection to the aquifer and susceptibility to changing climate conditions.

## Chapter 4

### Conclusions

The ability to predict how groundwater resources will be affected by any change, such as inputs like precipitation, recharge from surface water bodies, or outputs like groundwater discharge or pumping, is critical to any sustainable water management decision. Significant increases in computational power and accessibility have made numerical models a common approach for understanding how these resources may change under future climate and water use scenarios. In recent decades, integrated models that simulate the movement of both surface water and groundwater resources have become more readily available to improve this understanding. In this work, we demonstrated how a preliminary integrated model, based on limited data and information, can be used to inform future data collection and research efforts by identifying key areas and processes sensitive to climatic change. The integrated hydrological model, HydroGeoSphere, was used to simulate a representative shallow aquifer in the Canadian Prairies, based on the Dalmeny Aquifer in Saskatchewan, to determine data and research gaps to inform future work.

The baseline model represented historic climatic conditions and simulated 50 years to achieve steady state conditions. Results of this baseline model indicated that groundwater flow primarily followed topography, and that the resolution of available topographic datasets were not adequate to resolve flow directions throughout the aquifer. The first conclusion of this work was that updated, high resolution topographical information should be made available to ensure adequate representation of the surface elevations.

This baseline model was then modified to simulate climate scenarios that are based on the Representative Concentration Pathways 8.5, 4.5, and 2.6 as defined by the Government of Canada (Canada 2018). These climate scenarios are based on the temperature and precipitation change expected from high, moderate, and low annual global emissions (respectively). The temperature and precipitation changes for these scenarios are used to calculate the potential evapotranspiration in the domain so that the amount of actual evapotranspiration can be subtracted from the average annual precipitation before applied to the domain as the climatic input. A number of difficulties in the estimation of PET and AET, including spatial and temporal variability and data gaps, identified ET as a research focus that should be addressed for future work in this basin. Further to this, there was decrease in simulated hydraulic head in the modelled domain for the different climate scenarios, further indicating that it is a critical area of research towards understanding the influence of climate change on water resources in this area.

The decrease in climatic input in the climate scenarios also led to changes in the direction of water flow, the most notable being that the South River goes from a gaining to a losing stream between the simulations. This does not mean that South River will become a losing stream under future climate scenarios, but rather that the hydrologic properties and groundwater-surface water interactions in this region should be a key focus of future work to improve understanding of this basin, as compared to the North River which had relatively lesser changes compared to South River. Through comparing the results of the baseline model to the results of each of the climate change scenarios, it can be seen that certain areas, like the South River, show a lack of understanding of the true mechanisms that function in this system.

While there are several ways to improve the accuracy of these models, here we have demonstrated the benefits of using a preliminary model based on limited data towards informing areas or processes that can be targeted to make the biggest improvements in model development in the study area. The collection of additional data from the study area, as informed by this work, would likely yield a more accurate simulation. Specifically, three main target areas/processes are identified: 1) Update topographical information for this site with high spatial resolution; 2) Better capture temporal variability in PET/AET; and 3) Capture the interaction between the rivers and aquifer, focusing on the South River. It is recommended that data collection and interpretation occur concurrently, rather than consecutively, with model development to most effectively assign resources, simulate hydrologic conditions, and support water management decisions.

## References

- Acton, Donald F., and A. Bedard-Haughn. 2013. "Prairie." <https://www.thecanadianencyclopedia.ca/en/article/prairie> (February 6, 2024).
- Akinremi, O. O., S. M. McGinn, and H. W. Cutforth. 1999. "Precipitation Trends on the Canadian Prairies." *Journal of Climate* 12(10): 2996–3003. doi:10.1175/1520-0442(1999)012<2996:PTOTCP>2.0.CO;2.
- Allen, D. M., D. C. Mackie, and M. Wei. 2004. "Groundwater and Climate Change: A Sensitivity Analysis for the Grand Forks Aquifer, Southern British Columbia, Canada." *Hydrogeology Journal* 12(3): 270–90. doi:10.1007/s10040-003-0261-9.
- Aquanty. 2024. "Guide for New Users." *aquanty*. <https://www.aquanty.com/new-user-guide> (March 18, 2024).
- Armstrong, R. N., J. W. Pomeroy, and L. W. Martz. 2015. "Variability in Evaporation across the Canadian Prairie Region during Drought and Non-Drought Periods." *Journal of Hydrology* 521: 182–95. doi:10.1016/j.jhydrol.2014.11.070.
- Berthold, Susann, Laurence R. Bentley, and Masaki Hayashi. 2004. "Integrated Hydrogeological and Geophysical Study of Depression-Focused Groundwater Recharge in the Canadian Prairies." *Water Resources Research* 40(6). doi:10.1029/2003WR002982.
- Beven, K J, and P E O'Connell. 1982. *On the Role of Physically-Based Distributed Modelling in Hydrology*. Institute of Hydrology.
- Brunner, Philip, and Craig T. Simmons. 2012. "HydroGeoSphere: A Fully Integrated, Physically Based Hydrological Model." *Groundwater* 50(2): 170–76. doi:10.1111/j.1745-6584.2011.00882.x.
- Canada. 2018. "Representative Concentration Pathways." <https://climate-scenarios.canada.ca/?page=scen-rcp> (February 12, 2024).
- Canada. 2023. "Climate Data Viewer." <https://climate-viewer.canada.ca/climate-maps.html#/t=annual&v=tmean&d=dc&r=rcp45&cp=-107.09633060589455,52.24124593327408&z=8&ts=3> (May 24, 2023).
- Canada, Natural Resources. 2017. "Indexes of the National Topographic System of Canada - Open Government Portal." <https://open.canada.ca/data/en/dataset/055919c2-101e-4329-bfd7-1d0c333c0e62> (July 16, 2024).

- Canada, Natural Resources. 2024. "Open Maps Data Viewer."  
<https://search.open.canada.ca/openmap/957782bf-847c-4644-a757-e383c0057995> (March 15, 2024).
- Castle, Stephanie L., Brian F. Thomas, John T. Reager, Matthew Rodell, Sean C. Swenson, and James S. Famiglietti. 2014. "Groundwater Depletion during Drought Threatens Future Water Security of the Colorado River Basin." *Geophysical Research Letters* 41(16): 5904–11.  
doi:10.1002/2014GL061055.
- Creosteanu, A., G. Gavrilă, and L. Creosteanu. 2012. "Comparison between an Analytical Method and Two Numerical Methods on a given Electrostatic Potential Determination Problem." In *2012 15 International Symposium on Antenna Technology and Applied Electromagnetics*, , 1–6.  
doi:10.1109/ANTEM.2012.6262310.
- Cummings, Don I., Hazen A.J. Russell, and David R. Sharpe. 2012. "Buried-Valley Aquifers in the Canadian Prairies: Geology, Hydrogeology, and origin1Earth Science Sector (ESS) Contribution 20120131." *Canadian Journal of Earth Sciences* 49(9): 987–1004. doi:10.1139/e2012-041.
- Döll, Petra. 2009. "Vulnerability to the Impact of Climate Change on Renewable Groundwater Resources: A Global-Scale Assessment." *Environmental Research Letters* 4(3): 035006.  
doi:10.1088/1748-9326/4/3/035006.
- ECCC. 2007. "Water Sources: Groundwater." <https://www.canada.ca/en/environment-climate-change/services/water-overview/sources/groundwater.html> (March 24, 2023).
- ECCC. 2018. "Scenarios and Climate Models." <https://www.canada.ca/en/environment-climate-change/services/climate-change/canadian-centre-climate-services/basics/scenario-models.html> (February 12, 2024).
- FDA, and AQUASTAT. 2019. "Countries Ranked by Renewable Internal Freshwater Resources per Capita (Cubic Meters)." <https://www.indexmundi.com/facts/indicators/ER.H2O.INTR.PC/rankings> (May 8, 2023).
- Fortin, G., G. van der Kamp, and J. A. Cherry. 1991. "Hydrogeology and Hydrochemistry of an Aquifer-Aquitard System within Glacial Deposits, Saskatchewan, Canada." *Journal of Hydrology* 126(3): 265–92. doi:10.1016/0022-1694(91)90160-J.
- Freeze, R. Allan. 1979. *Groundwater*. Englewood Cliffs, N.J: Prentice-Hall.
- Gleeson, Tom. 2020. "Global Groundwater Sustainability." *Groundwater* 58(4): 484–85.  
doi:10.1111/gwat.12991.

- Goderniaux, Pascal, Serge Brouyère, Hayley J. Fowler, Stephen Blenkinsop, René Therrien, Philippe Urban, and Alain Dassargues. 2009. “Large Scale Surface–Subsurface Hydrological Model to Assess Climate Change Impacts on Groundwater Reserves.” *Journal of Hydrology* 373(1): 122–38. doi:10.1016/j.jhydrol.2009.04.017.
- Gorelick, Steven M., and Chunmiao Zheng. 2015. “Global Change and the Groundwater Management Challenge.” *Water Resources Research* 51(5): 3031–51. doi:10.1002/2014WR016825.
- de Graaf, Inge E. M., Tom Gleeson, L. P. H. (Rens) van Beek, Edwin H. Sutanudjaja, and Marc F. P. Bierkens. 2019. “Environmental Flow Limits to Global Groundwater Pumping.” *Nature* 574(7776): 90–94. doi:10.1038/s41586-019-1594-4.
- Hallegatte, Stéphane. 2009. “Strategies to Adapt to an Uncertain Climate Change.” *Global Environmental Change* 19(2): 240–47. doi:10.1016/j.gloenvcha.2008.12.003.
- Huntington, Justin L., and Richard G. Niswonger. 2012. “Role of Surface-Water and Groundwater Interactions on Projected Summertime Streamflow in Snow Dominated Regions: An Integrated Modeling Approach.” *Water Resources Research* 48(11). doi:10.1029/2012WR012319.
- Huot, Yannick, Catherine A. Brown, Geneviève Potvin, Dermot Antoniadis, Helen M. Baulch, Beatrix E. Beisner, Simon Bélanger, et al. 2019. “The NSERC Canadian Lake Pulse Network: A National Assessment of Lake Health Providing Science for Water Management in a Changing Climate.” *Science of The Total Environment* 695: 133668. doi:10.1016/j.scitotenv.2019.133668.
- Keller, C. K., G. Van Der Kamp, and J. A. Cherry. 1988. “Hydrogeology of Two Saskatchewan Tills, I. Fractures, Bulk Permeability, and Spatial Variability of Downward Flow.” *Journal of Hydrology* 101(1): 97–121. doi:10.1016/0022-1694(88)90030-3.
- Kirkwood, A. 2023. *Canada Water 2022 Progress Report*. doi:10.4095/331515.
- Larsen, Laurel G., and Cleo Woelfle-Erskine. 2018. “Groundwater Is Key to Salmonid Persistence and Recruitment in Intermittent Mediterranean-Climate Streams.” *Water Resources Research* 54(11): 8909–30. doi:10.1029/2018WR023324.
- Larson, Magnus. 2005. “Numerical Modeling.” In *Encyclopedia of Coastal Science*, Encyclopedia of Earth Science Series, ed. Maurice L. Schwartz. Dordrecht: Springer Netherlands, 730–33. doi:10.1007/1-4020-3880-1\_232.
- Lemmen, D S, FJ Warren, J Lacroix, and E Bush. 2008. *From Impacts to Adaptation: Canada in a Changing Climate 2007*. doi:10.4095/226455.

- McGinn, s. 2010. “Weather and Climate Patterns in Canada’s Prairie Grasslands.” *Arthropods of Canadian Grasslands (Volume 1): Ecology and Interactions in Grassland Habitats*. doi:10.3752/9780968932148.ch5.
- McLeod, Lianne, Lalita Anne Bharadwaj, Joanne Daigle, Cheryl Waldner, and Lori Elisabet Ann Bradford. 2020. “A Quantitative Analysis of Drinking Water Advisories in Saskatchewan Indigenous and Rural Communities 2012–2016.” *Canadian Water Resources Journal / Revue canadienne des ressources hydriques* 45(4): 345–57. doi:10.1080/07011784.2020.1831404.
- McSweeney, Robert. 2018. “Q&A: How Do Climate Models Work?” *Carbon Brief*. <https://www.carbonbrief.org/qa-how-do-climate-models-work/> (February 15, 2024).
- MDH Engineered Solutions. 2011. *Hydrogeology Mapping of NTS Mapsheet Saskatoon 73B*.
- Mishra, Binaya Kumar, Shamik Chakraborty, Pankaj Kumar, and Chitresh Saraswat. 2020. “Numerical Modeling and Simulation for Water Management.” In *Sustainable Solutions for Urban Water Security : Innovative Studies*, Water Science and Technology Library, eds. Binaya Kumar Mishra, Shamik Chakraborty, Pankaj Kumar, and Chitresh Saraswat. Cham: Springer International Publishing, 147–60. doi:10.1007/978-3-030-53110-2\_7.
- Morton, F. I. 1983. “Operational Estimates of Areal Evapotranspiration and Their Significance to the Science and Practice of Hydrology.” *Journal of Hydrology* 66(1): 1–76. doi:10.1016/0022-1694(83)90177-4.
- Mukherjee, Abhijit, Bridget R. Scanlon, Alice Aureli, Simon Langan, Huaming Guo, and Andrew McKenzie. 2021. “Chapter 1 - Global Groundwater: From Scarcity to Security through Sustainability and Solutions.” In *Global Groundwater*, eds. Abhijit Mukherjee, Bridget R. Scanlon, Alice Aureli, Simon Langan, Huaming Guo, and Andrew A. McKenzie. Elsevier, 3–20. doi:10.1016/B978-0-12-818172-0.00001-3.
- Nagare, Ranjeet M., Young-Jin Park, Rob Wirtz, Dallas Heisler, and Glen Miller. 2022. “Integrated Surface-Subsurface Water and Solute Modeling of a Reclaimed in-Pit Oil Sands Mine: Effects of Ground Freezing and Thawing.” *Journal of Hydrology: Regional Studies* 39: 100975. doi:10.1016/j.ejrh.2021.100975.
- Natural Resources of Canada. “2020 Land Cover of Canada - Open Government Portal.” <https://open.canada.ca/data/en/dataset/ee1580ab-a23d-4f86-a09b-79763677eb47> (January 23, 2024).

- Negm, Amro, Polina Abdrakhimova, Masaki Hayashi, and Kabir Rasouli. 2021. "Effects of Climate Change on Depression-Focused Groundwater Recharge in the Canadian Prairies." *Vadose Zone Journal* 20(5): e20153. doi:10.1002/vzj2.20153.
- Nettasana, Tussanee, James Craig, and Bryan Tolson. 2012. "Conceptual and Numerical Models for Sustainable Groundwater Management in the Thaphra Area, Chi River Basin, Thailand." *Hydrogeology Journal* 20. doi:10.1007/s10040-012-0887-6.
- Novicky, Oldrich, Ladislav Kasperek, and Jan Uhlík. 2010. "Vulnerability of Groundwater Resources in Different Hydrogeological Conditions to Climate Change." In *Groundwater Response to Changing Climate. International Association of Hydrogeologists Selected Paper*, , 1–10. doi:10.1201/b10530-2.
- Ramirez de la Parra, Roberto, Fernando J Gonzalez Villarreal, Timothy Kevin Parker, Ruben Chavez Guillen, and Adriana Palma Nava. 2016. *Sustainable Groundwater Management Policy Directives*. Comision Nacional del Agua. <https://recharge.iah.org/files/2016/08/SUSTAINABLE-DIRECTIVES-ISMAR9-call-to-action.pdf> (November 24, 2021).
- Ross, Martin, Janet E. Campbell, Michel Parent, and Roberta S. Adams. 2009. "Palaeo-Ice Streams and the Subglacial Landscape Mosaic of the North American Mid-Continental Prairies." *Boreas* 38(3): 421–39. doi:10.1111/j.1502-3885.2009.00082.x.
- Sapiano, Manuel, Michael Schembri, HENRY DEBATTISTA, and Nadia Theuma. 2017. "Integrating Numerical Models in River Basin Management Plans: The FREEWAT Project." In , 227–38. doi:10.2495/WRM170221.
- Subedi, Abhinaya, and Jose L Chavez. 2015. "Crop Evapotranspiration (ET) Estimation Models: A Review and Discussion of the Applicability and Limitations of ET Methods." *Journal of Agricultural Science* 7(6): 50–68.
- Taylor, Richard G., Bridget Scanlon, Petra Döll, Matt Rodell, Rens van Beek, Yoshihide Wada, Laurent Longuevergne, et al. 2013. "Ground Water and Climate Change." *Nature Climate Change* 3(4): 322–29. doi:10.1038/nclimate1744.
- Tegos, Aristoteles, Andreas Efstratiadis, Demetris Koutsoyiannis, Aristoteles Tegos, Andreas Efstratiadis, and Demetris Koutsoyiannis. 2013. "A Parametric Model for Potential Evapotranspiration Estimation Based on a Simplified Formulation of the Penman- Monteith Equation." In *Evapotranspiration - An Overview*, IntechOpen. doi:10.5772/52927.
- Thangarajan, M. 2007. "Groundwater Models and Their Role in Assessment and Management of Groundwater Resources and Pollution." In *Groundwater: Resource Evaluation, Augmentation*,

*Contamination, Restoration, Modeling and Management*, ed. M. Thangarajan. Dordrecht: Springer Netherlands, 189–236. doi:10.1007/978-1-4020-5729-8\_8.

Thornthwaite, C. W. 1948. “An Approach toward a Rational Classification of Climate.” *Geographical Review* 38(1): 55–94. doi:10.2307/210739.

Usman, Muhammad, Muhammad Uzair Qamar, Rike Becker, Muhammad Zaman, Christopher Conrad, and Shoaib Salim. 2020. “Numerical Modelling and Remote Sensing Based Approaches for Investigating Groundwater Dynamics under Changing Land-Use and Climate in the Agricultural Region of Pakistan.” *Journal of Hydrology* 581: 124408. doi:10.1016/j.jhydrol.2019.124408.

VanderKwaak, Joel E. 1999. “Numerical Simulation of Flow and Chemical Transport in Integrated Surface-Subsurface Hydrologic Systems.” Ph.D. University of Waterloo.  
<https://uwspace.uwaterloo.ca/bitstream/handle/10012/412/NQ38276.pdf?sequence=1&isAllowed=y>.

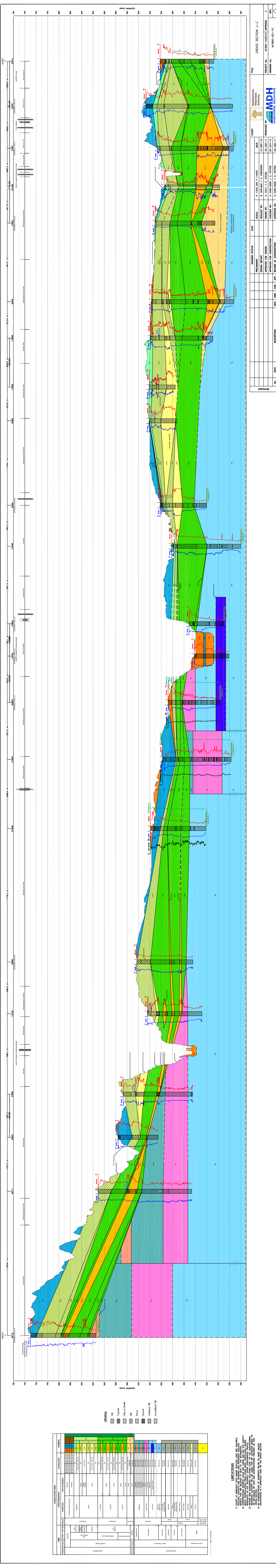
Weather Spark. 2024. “Dalmeny Climate, Weather By Month, Average Temperature (Canada) - Weather Spark.” <https://weatherspark.com/y/3393/Average-Weather-in-Dalmeny-Canada-Year-Round> (August 2, 2023).

WSA. 2021. “Observation Well Network - Water Security Agency.” <https://www.wsask.ca/water-info/ground-water/observation-well-network/>, <https://www.wsask.ca/water-info/ground-water/observation-well-network/> (May 26, 2023).

WSL. 2024. “Fire Weather Indices Wiki | Potential Evapotranspiration.” <https://wikifire.wsl.ch/tiki-indexf125.html?page=Potential+evapotranspiration> (June 2, 2023).

# Appendix A

East-West cross-section of the area surrounding the Dalmeny aquifer in Saskatchewan.



- Lithology**
- Topography
  - Clay or Shale
  - SE
  - Sand
  - Ground
  - Outlined Tilt
  - Unexcavated Tilt

PERIOD	TIME	SAKATON AREA		SYMBOL
		STRATIGRAPHY	LITHOLOGY	
QUATERNARY	Holocene	Alluvial	10000	10000
			10000	10000
	Pleistocene	Recent	10000	10000
			10000	10000
			10000	10000
			10000	10000
		Older	10000	10000
			10000	10000
			10000	10000
			10000	10000
CRETACEOUS	Cretaceous	10000	10000	
		10000	10000	
		10000	10000	
		10000	10000	
		10000	10000	
		10000	10000	
		10000	10000	
		10000	10000	
		10000	10000	
		10000	10000	

- LIMITATIONS**
- 1) ONLY A PORTION OF THE DALMENY AQUIFER IS SHOWN. THE ENTIRE AQUIFER IS NOT SHOWN.
  - 2) THE DALMENY AQUIFER IS NOT SHOWN IN THIS SECTION. THE DALMENY AQUIFER IS NOT SHOWN IN THIS SECTION.
  - 3) THE DALMENY AQUIFER IS NOT SHOWN IN THIS SECTION. THE DALMENY AQUIFER IS NOT SHOWN IN THIS SECTION.
  - 4) NO INTERPRETATIONS OR CORRECTIONS ARE MADE TO THE DATA PROVIDED. THE DATA IS AS SHOWN.