AER/AGS Open File Report 2014-02

Alberta Energy Regulator

Regional Hydrology of the Edmonton–Calgary Corridor, Alberta

AGS
ALBERTA GEOLOGICAL SURVEY

AER/AGS Open File Report 2014-02

Regional Hydrology of the Edmonton–Calgary Corridor, Alberta

J.T.F. Riddell[1], H. Moktan[2], and G. Jean[3]

[1] Stantec Consulting Ltd.
[2] Alberta Environment and Sustainable Resource Development
[3] Alberta Energy Regulator
Alberta Geological Survey

June 2014

ISBN 978-1-4601-0116-2

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

Riddell, J.T.F., Moktan, H. and Jean, G. (2014): Regional hydrology of the Edmonton–Calgary Corridor, Alberta; Alberta Energy Regulator, AER/AGS Open File Report 2014-02, 31 p.

Author addresses:
J.T.F. Riddell
Stantec Consulting Ltd.
10160 - 112 Street
Edmonton, AB T5K 2L6
Canada
587.756.6233
E-mail: Joseph.Riddell@santec.com

Published June 2014 by:
Alberta Energy Regulator
Alberta Geological Survey
4th Floor, Twin Atria Building
4999 – 98th Avenue
Edmonton, AB T6B 2X3
Canada

Tel: 780.422.1927
Fax: 780.422.1918
E-mail: AGS-Info@aer.ca
Website: www.ags.gov.ab.ca

Contents

Figures

Acknowledgements

We thank Alberta Environment and Sustainable Resource Development for supporting the Provincial Groundwater Inventory Program and specifically the Edmonton–Calgary Corridor study area project that facilitated the work presented in this report. We also thank all the contributors from other sections at the AGS that provided GIS, technical, and editing support towards both this report and the *Edmonton–Calgary Corridor Groundwater Atlas.*

Abstract

The Edmonton–Calgary Corridor (ECC) occupies an area of approximately 50 000 km^2 in central Alberta and was chosen as the first area to be studied in the Provincial Groundwater Inventory Program (PGIP). Successful management of freshwater resources requires an understanding of the exchanges of water between the atmospheric, surface-water, and groundwater environments. To conduct a hydrogeological characterization of the ECC, an average annual water budget was determined. Climatic and hydrometric data from Environment Canada were used to generate grids for each of the major components of a hydrological budget, including precipitation, evapotranspiration (potential and actual), maximum runoff, specific discharge, and groundwater recharge. Basic watershed analysis was performed on streamflow data to assign base-flow and runoff characteristics to a given drainage basin. Geostatistical modelling of atmospheric water fluxes was used to interpolate climate data across the province from discrete data points to determine the spatial distribution of precipitation and evapotranspiration within the ECC. Mapping results provide a simple and robust overview of the hydrology across a large region of the province. This report, and the accompanying data release, provides the hydrological component of the physical characterization in the ECC project boundary. This work is the foundation for the future development of conceptual and numerical models of sub-basins within the ECC to be completed as part of the PGIP.

1 Introduction

Hydrology is the study of the distribution, circulation, and properties of water in the hydrosphere or the combined mass of water on, under, and above the Earth's surface (Bates and Jackson, 1987). There are specific practices within hydrology—such as oceanography, hydrometeorology, surface hydrography, and hydrogeology—that quantify the natural behaviours and transfer of water between each domain of the hydrosphere. This study characterized the major exchanges between the atmosphere and the land surface and between the groundwater environment and the land surface within the Edmonton–Calgary Corridor (ECC).

The Alberta Geological Survey (AGS) and Alberta Environment and Sustainable Resource Development (ESRD) have partnered to inventory the groundwater resources in different regions of the province. The ECC (Figure 1) is the first area chosen for study as it hosts the majority of Alberta's population and continues to undergo substantial population and industrial growth, accompanied by increasing demands for water resources. The objective of the hydrological study in the ECC was to develop an average regional water budget to support a hydrogeological characterization under the Provincial Groundwater Inventory Program (PGIP). The hydrological study described in this report is intended to provide an understanding of the spatial distribution and magnitude of water budget components like precipitation, evapotranspiration, runoff, base flow, and recharge. Quantification of these parameters makes possible the development of sound conceptual models for regional-scale numerical models intended for cumulative effects management. Detailed study at a local- or site-scale of areas within the ECC may yield results differing from those in this report due to generalizations and limitations related to study at regional scales, such as data availability and averaging of hydrological phenomena. However, the large-scale study described in this report accomplishes its main goal of providing the basic hydrological framework to assist in steady-state numerical groundwater flow simulations in the ECC.

This report describes the methods used and assumptions made in computing an average annual hydrological budget for the ECC. Figure 2 shows an idealized hydrological cycle superimposed on a schematic of the ECC landscape and selected hydrological budget components, including precipitation, evapotranspiration (potential and actual), runoff, stream flow, and groundwater recharge. A variety of climate data, including hydrometric data, were used to generate geostatistical models of water fluxes. These data were also used to evaluate runoff and specific discharge values by watershed. Groundwater recharge was calculated as the residual component of the water balance after accounting for fluxes, including precipitation, evapotranspiration, sublimation, discharge of groundwater to streams, and surface water run off.

2 Study Area Description

The ECC occupies an area of approximately 50 000 km^2 and lies within portions of National Topographic Map Sheets (NTS) 83A, 83B, 83G, 83H, 82J, 82I, 82P, and 82O. The ECC is an area of very rapid urbanization and industrial growth within Canada. It is dominated by the White Zone of Alberta, consisting of agricultural and urban areas, with a small portion of the western margin designated as the Green Zone, or undeveloped natural area. The White Zone is a designation assigned by ESRD to land that is settled, populated, and generally used for agriculture. Public land in the White Zone is part of the agricultural landscape. Public land in the Green Zone is managed for timber production, watersheds, wildlife, fisheries, recreation, and other activities.

Land use in Alberta is highly influenced by physiography, soil type, vegetation, and elevation. Land use in the ECC is dominated by agriculture, grazing, and oil and gas activities. There are many sites where coal was mined at a small scale, and larger-scale active coal mining occurs in the Wabamun Lake Area (Figure 1). The undeveloped western margin of the ECC is dominantly used for forestry and recreation.

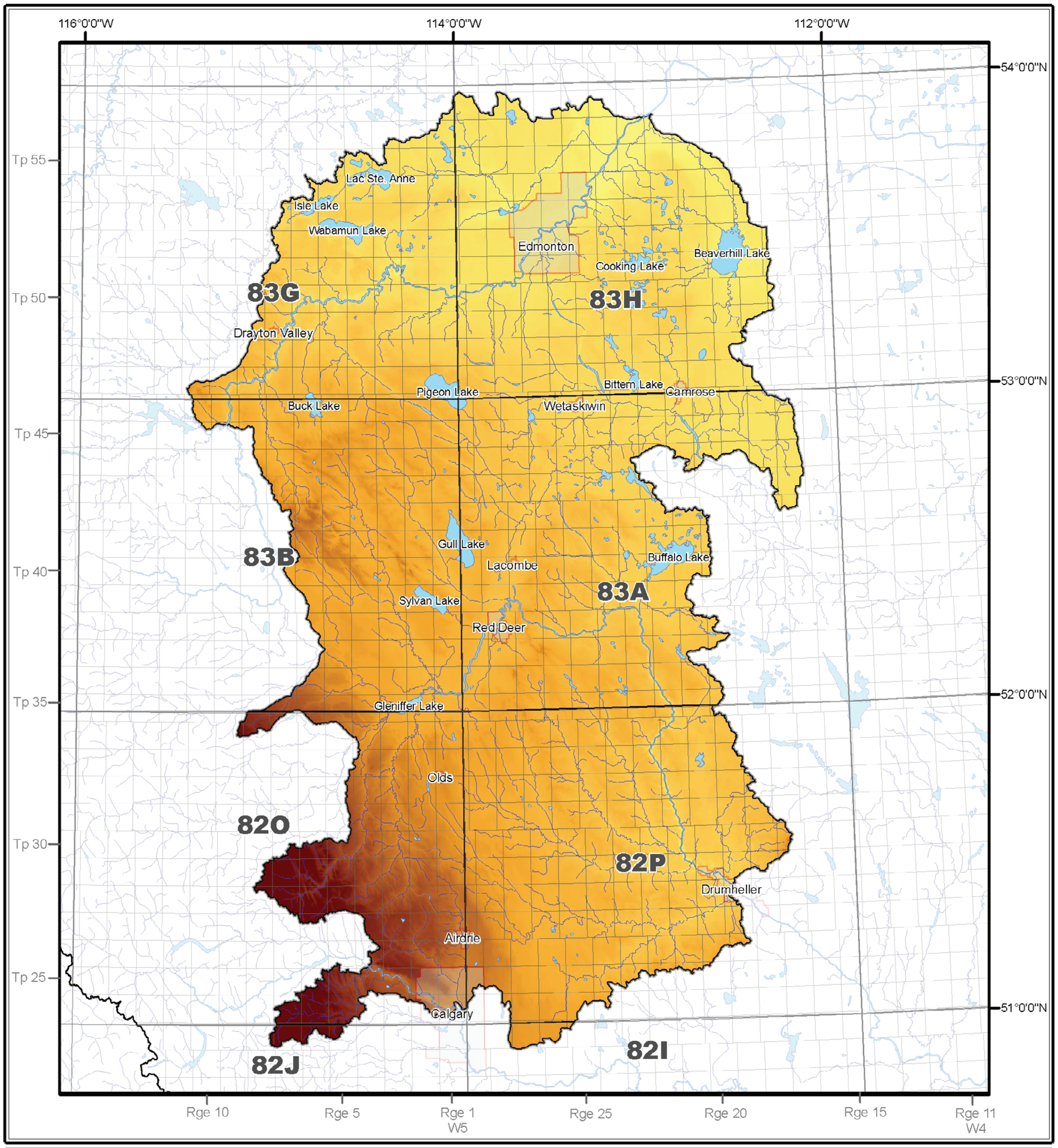


Figure 1. Study area map and land surface elevation of the ECC

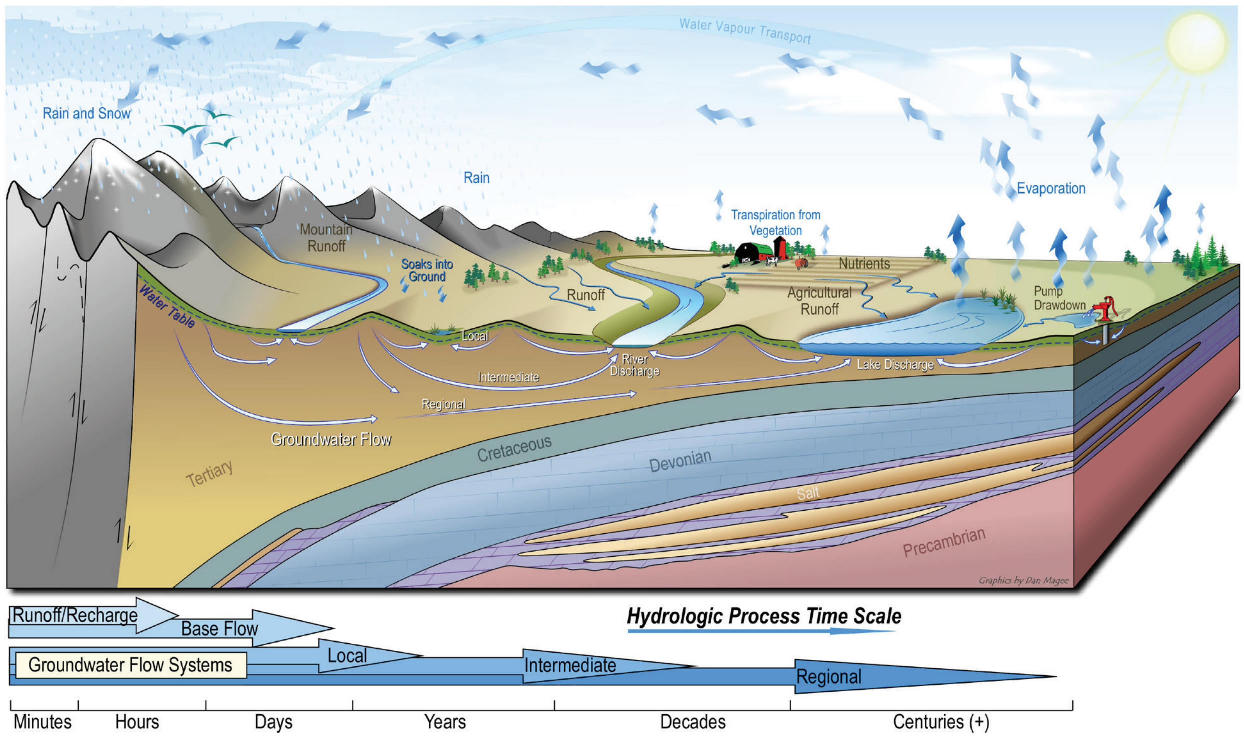


Figure 2. Idealized hydrological cycle of the Edmonton–Calgary Corridor.

The ECC includes ten contiguous sub-basin areas associated with major streams that drain surface water. Four sub-basins of the North Saskatchewan River, the headwater sub-basin of the Battle River, four sub-basins of the Red Deer River (including the Little Red Deer River), and one sub-basin of the Bow River constitute the watershed areas occupied by the ECC (Figure 3). These sub-basins were used to outline a study area that would include the densely populated portion of central Alberta while honouring physical boundaries or surface water drainage divides between basins. The resultant dimensions of the ECC are approximately 200 km wide from west to east and 300 km from north to south.

The sediment thickness above bedrock in the ECC generally thins to the west and south, corresponding to increasing land surface elevation (Figure 4; Slattery et al., 2010). There are also some moraine features within the ECC that are identified by broad areas with thicker sediment, generally composed of till in the northeast and east-central portion of the ECC. In addition, there are buried channels in the ECC which appear as linear elements with higher sediment thickness, such as the Red Deer River valley near Red Deer where the current-day Red Deer River follows the buried paleo-channel.

The footprint of the ECC encompasses the subcrop areas of several different bedrock formations, including the Paleogene Paskapoo Formation and the Cretaceous Scollard, Battle, Horseshoe Canyon, and Bearpaw formations (Figure 5). It also includes a portion of the Belly River Group subcrop area in the northeast portion of the ECC. These geological units have a broad range of lithological characteristics and resulting permeabilities.

The Paskapoo Formation was deposited in a terrestrial fluvial environment and is dominantly composed of sandstone but is highly heterolithic with muddy intervals (Lyster and Andriashek, 2012). However, in the context of this study, it is the most permeable bedrock formation. The Scollard and Horseshoe Canyon formations were deposited in a marginal marine to terrestrial fluvial setting and are generally composed of mudstone with some sand beds. The Bearpaw Formation is marine shale that regionally constitutes an important aquitard. However, the Bearpaw Formation does have localized sandy tongues that are

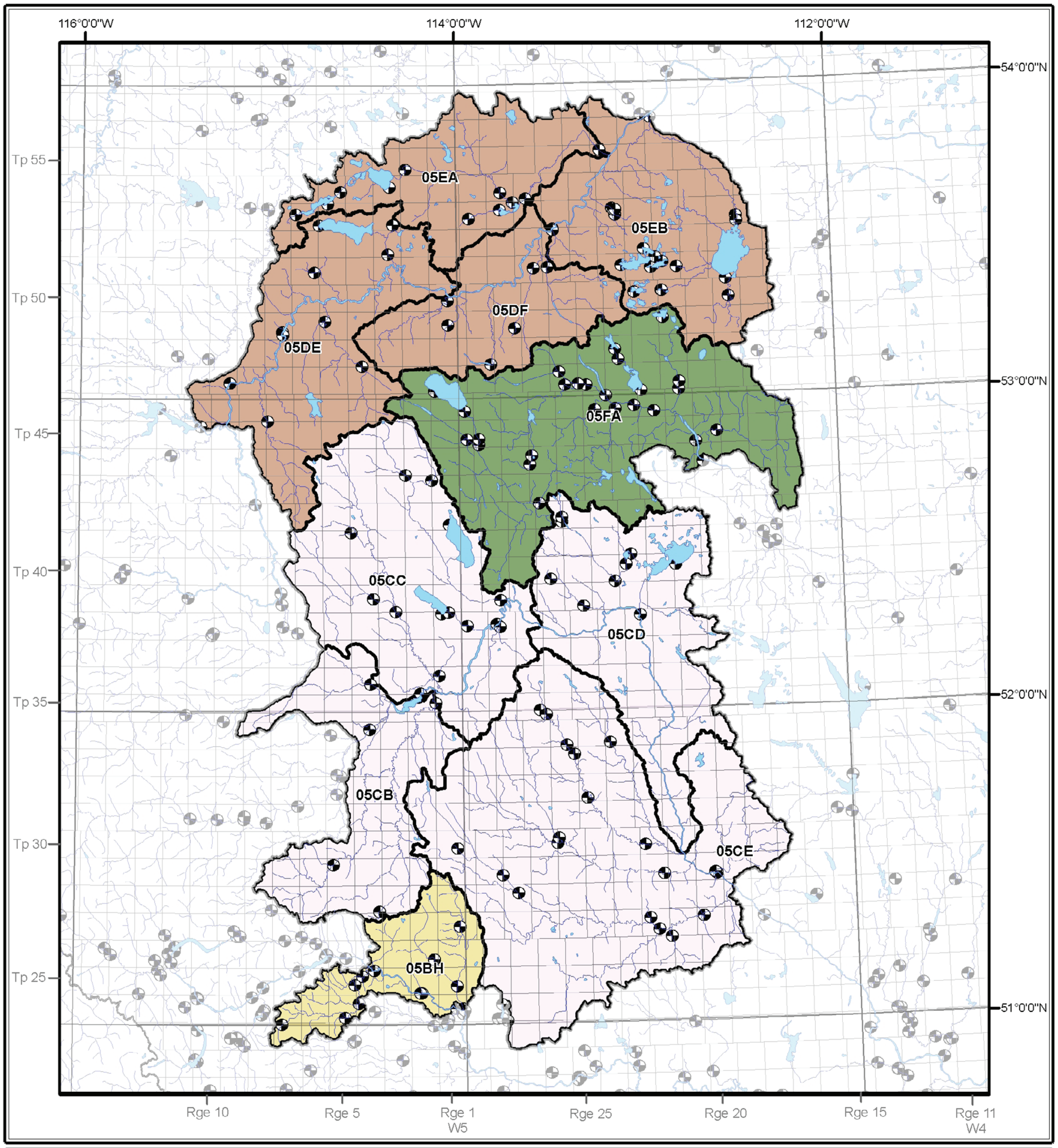


Figure 3. River basins, sub-basins, and hydrometric stations in the ECC

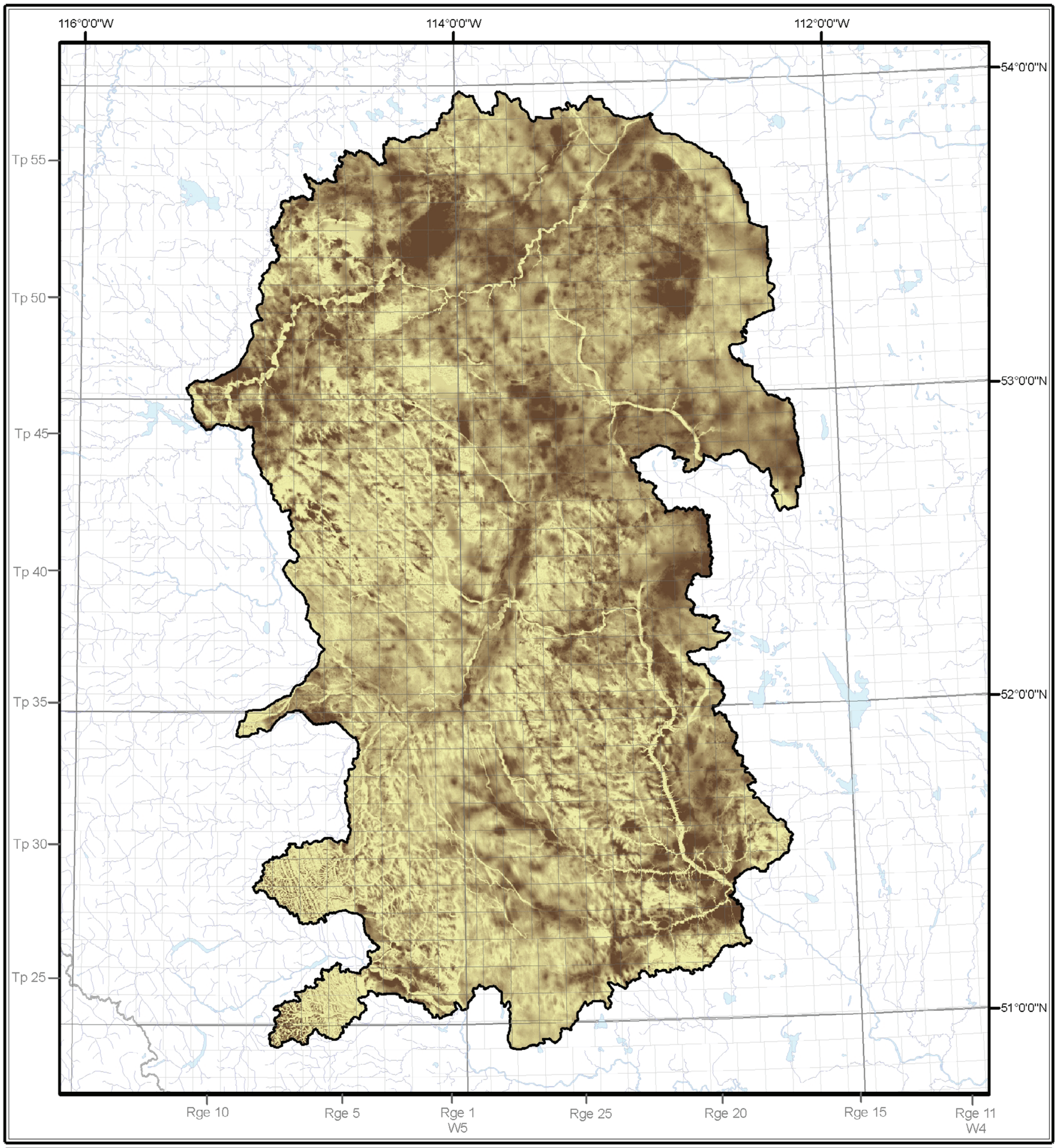


Figure 4. Map of sediment thickness above bedrock (modified from Slattery et al., 2010)

Sediment Thickness (m)

160

0

0 12.5 25 50 75 100 km

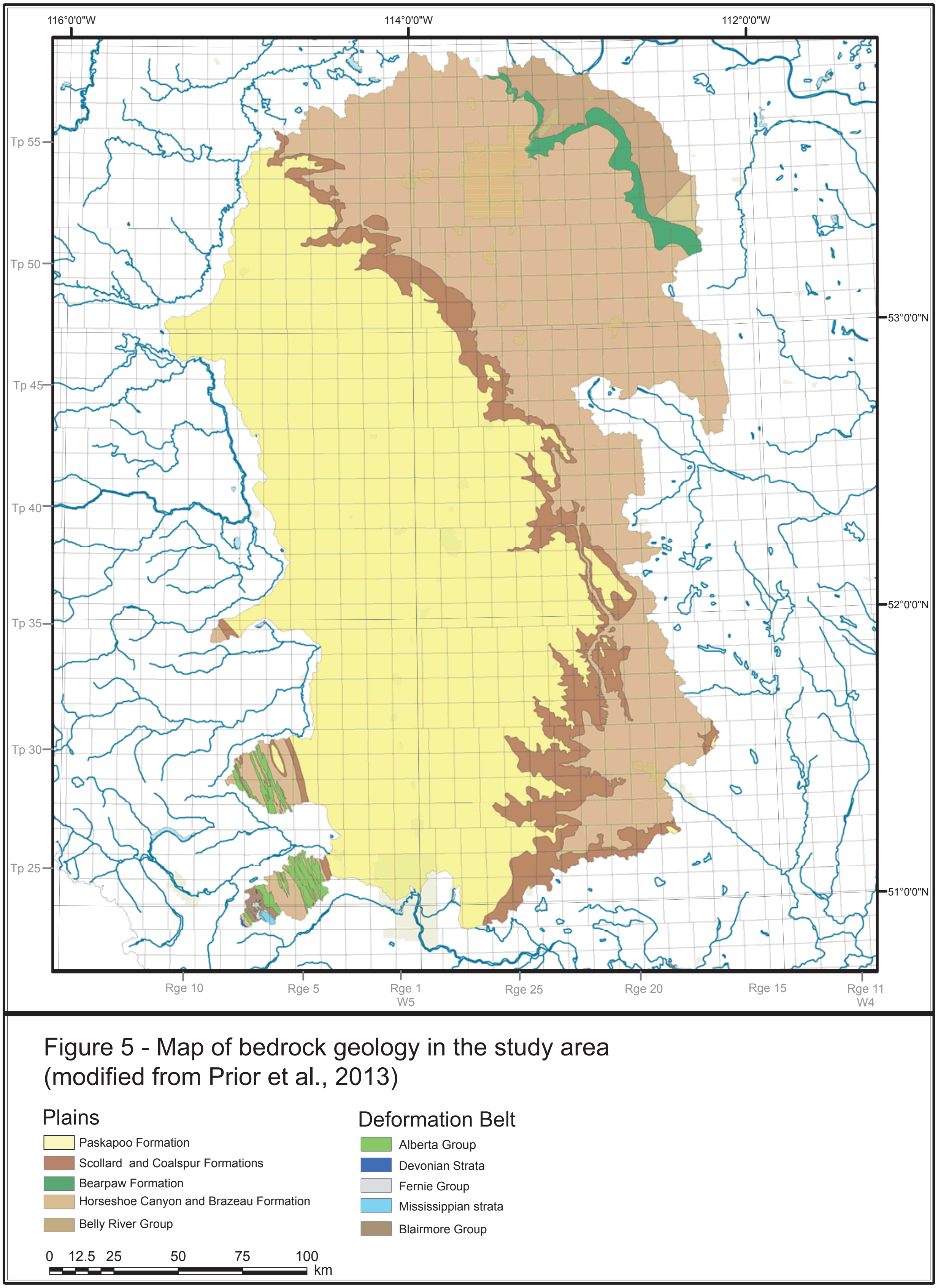


Figure 5 - Map of bedrock geology in the study area (modified from Prior et al., 2013)

locally exploited as aquifers (Hamblin, 1998). Belly River Group strata are also dominated by mudstone and sandstone units. The permeability of the bedrock and overlying sediments of a given catchment area greatly influences its hydrological response, and the resulting patterns (presented in Section 4) in hydrological mapping are highly correlated to the geological framework of the study area.

The large area covered by the ECC encompasses a wide range of hydrological conditions related to changes in climatic, topographic/physiographic, and geological conditions that exist across the project area (Riddell et al., 2009). Topography in the study area ranges from the alpine areas (southwest of the study area) that have ground elevations of < 2500 metres above mean sea level (m amsl) to approximately 550 m amsl in the northeast of the study area at the outflow of the North Saskatchewan River (Figure 1). The topographic gradient has a strong correlation to the physiography. At higher elevations, mountainous alpine and foothills physiographic elements are present. Plains physiographic elements are present at lower elevations. The sub-basin west of Calgary from the Bow River watershed alone contains mountainous alpine, foothills, and plains physiography. Further north along the western margin of the project area there are relatively undeveloped, forested foothill areas feeding the Little Red Deer River that gently transition to plains and parkland elements that dominate the ECC (Barker et al., 2011).

Changes in climate also exist across the ECC. The average annual precipitation patterns differ substantially across the ECC with the mountains just west of the study area acting as the dominant control on magnitude and spatial distribution of precipitation.

3 Water Budget Strategy and Methods

The strategy and methods to complete a regional hydrological balance for the ECC were developed with the intent to inform conceptual and numerical models. Groundwater recharge and stream flow are very important elements to effectively calibrate a groundwater model. The large regions being modelled require that boundary conditions such as recharge and stream flow are spatially distributed and not applied uniformly over large land areas. The mapping methods used are also time averaged using hydroclimatic data from 1971 to 2000; therefore, the maps represent long-term average conditions that can serve as boundary conditions for groundwater flow simulations of steady-state hydrogeological conditions.

There is no previous work quantifying regional water budgets at the scale of the ECC. There has been work done to study surface flows at a provincial scale for each major river basin by Alberta Environment (2011) as well as site-specific hydrological and hydrogeological studies, but not at a scale that is useful for integrated surface water/groundwater management and regional cumulative effects assessment. The report “North Saskatchewan River Basin: Overview of Groundwater Conditions, Issues, and Challenges” (WorleyParsons, 2009) completed for the North Saskatchewan Watershed Alliance, states that “management of the groundwater resource cannot be effective without knowledge of such key characteristics as recharge and discharge rates, cumulative drawdown, and risks to groundwater quality and quantity.” This hydrological budget model and the concurrent geological, hydrogeological, and hydrogeochemical characterization completed by the AGS are intended to determine the quantity and quality of groundwater assets within the ECC and to provide a starting point for future study.

To meet these objectives, the conceptual model for the regional annual hydrological budget needed to be simple and robust with regard to the distribution and quality of available data. The conceptual model and equation used for the water balance is shown below:

$$\Delta V_s + \Delta V_{gw} = [P - ET]A_s - Q_s - Q_{gw} \tag{1}$$

where ΔV_s is the annual change in surface water volume, ΔV_{gw} is annual change in groundwater volume, P is precipitation flux, ET is evapotranspiration flux, A_s is the surface area of the basin, Q_s is the annual volume of surface water outflow from the basin and Q_{gw} is the annual volume of groundwater outflow from the basin, including groundwater extracted from pumping wells. Given the lack of knowledge of the regional water balance, and given the time-averaged nature of the analysis, steady-state conditions ($\Delta V_s = \Delta V_{gw} = 0$) were assumed. Further, it was assumed that any cross-basin lateral flow of groundwater inflows matched the outflows from the study area.

Two approaches were used to assign spatially distributed values for each component of the water balance equation using geostatistical modelling and watershed-based analysis. The climatic components of the water balance (precipitation, potential evapotranspiration [PET], and actual evapotranspiration [AET]) were calculated with well-established empirical formulas at control points throughout the province to avoid edge-effects of interpolating only within the ECC boundary. The calculated values generated for each control point were then interpolated using the Geostatistical Analyst extension of ArcGIS. Ordinary kriging was used to generate raster grid cells with 500 m by 500 m resolution. Boundary cells were clipped at the study area boundary. Base flow and runoff were estimated from available data and assigned to topographically defined watersheds smaller than the sub-basins that constitute the ECC. This allowed runoff and base flow to be allocated to topographically controlled, local drainage networks, unlike the climatic variables, which were geostatistically modelled.

3.1 Average Annual Total Precipitation

In the annual water budget (Equation 1), precipitation is by far the dominant positive water flux given the assumption that there is no overall change in the volume of water stored in the ECC. Our study uses long-term average annual total precipitation in the ECC (Environment Canada, 2001). Data are available for 147 climate stations, which provide measurements of total annual precipitation, including rain, snow, and hail, across the province. There are 32 stations located inside the ECC boundary and 30 stations within 50 kilometres outside of the boundary (Figure 6a). Ordinary kriging was used to interpolate the entire dataset across the province, and edge effects were minimized by clipping the province-wide contours to the ECC boundary.

3.2 Average Annual Potential Evapotranspiration

Water is removed from soil by transpiring plants that draw water from the root zone, and from open water by evaporation. The combined effect of evaporation and transpiration is termed evapotranspiration (ET). Potential evapotranspiration (PET) is defined as the amount of water that would evaporate or transpire from a surface if water was available to that surface in unlimited supply (Domenico and Schwartz, 1997). Therefore, PET is useful in establishing a theoretical upper limit for ET. Potential and actual evapotranspiration can be estimated using field measurements or from empirical formulas that use basic climate data. Given the relatively dry climate of the ECC, PET is always greater than actual evapotranspiration (AET). Therefore PET is not directly used in our water budget calculations. However, understanding PET is useful to estimate the water budget for specific situations like irrigation projects and for areas that are not water limited, such as lakes and groundwater discharge areas (wetlands, riparian areas, springs, etc.).

Monthly temperature data were available for 391 stations across the province going back at least ten years (Figure 6b). Nearly all of the stations with less than ten years of data were recently added to Environment Canada's monitoring network after the year 2000. These stations were omitted to reduce noise in the dataset, as stations with short records are often skewed by unrepresentative mean monthly temperature values. Further, data collected from these stations postdate the Canadian climate normals and averages

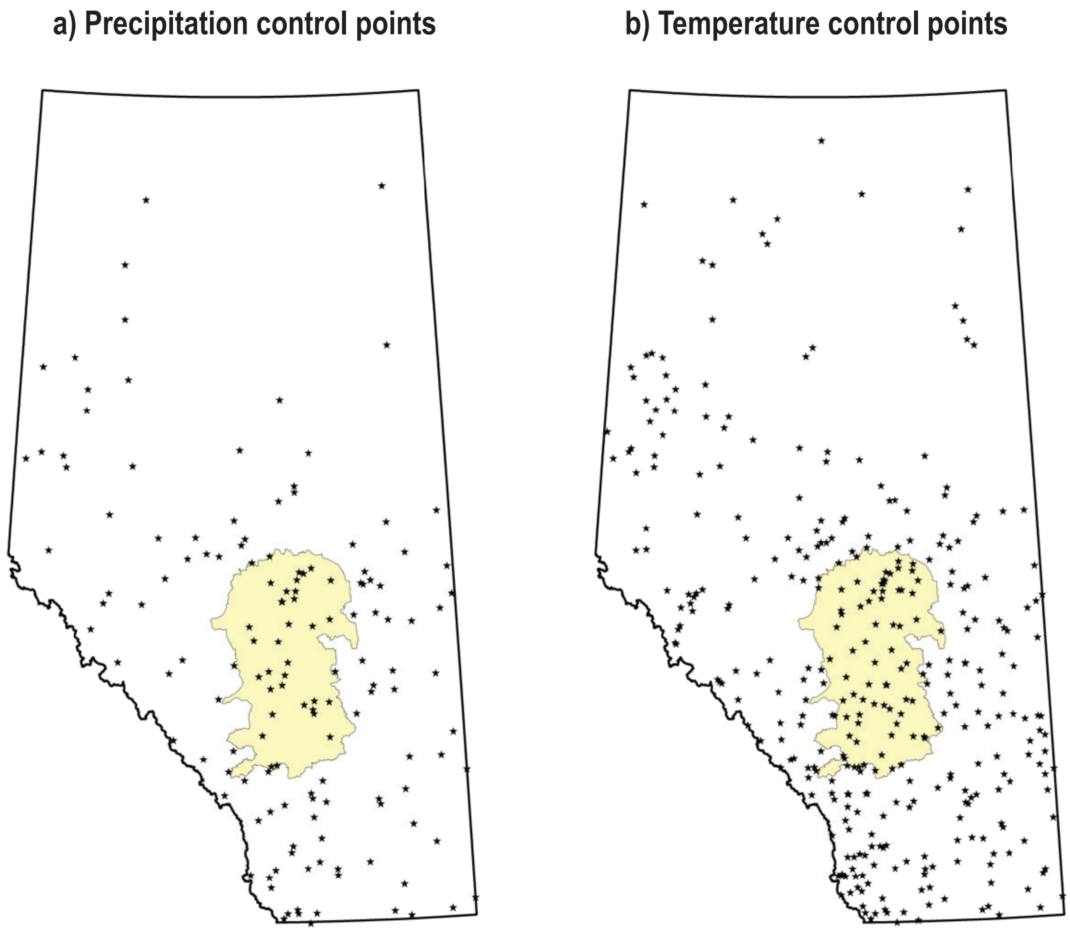


Figure 6. Distribution of control points for hydroclimatic variable mapping.

(Environment Canada, 2001) used for precipitation analysis. Similar to average annual precipitation, the calculated PET values were modelled across the province and subsequently clipped to the ECC boundary to minimize edge effects from interpolation of the data.

We chose to use Thornthwaite's formula (Thornthwaite, 1948), a simple empirical relationship, to estimate PET in millimetres (mm). Thornthwaite's formula requires commonly available climate data (average monthly temperature) and the number of daylight hours, which is a function of latitude:

$$PET_m = 16 N_m \left(\frac{10 T_m}{I} \right)^a \tag{2}$$

where m is the month (1, 2, 3…12), PET_m is monthly potential evapotranspiration (in mm), N_m is the monthly adjustment factor related to hours of daylight, T_m is the monthly temperature (°C), and I is the heat index for the year. I and the exponent a are defined as follows:

$$I = \sum_{n=1}^{12} i_m = \sum_{n=1}^{12} \left(\frac{Tm}{5} \right)^{1.5}$$ for n = 1…12, and

$$a = 6.7 \times 10^{-7} I^3 - 7.7 \times 10^{-5} I^2 + 1.8 \times 10^{-2} I + 0.49 \tag{3}$$

3.3 Average Annual Actual Evapotranspiration

Actual evapotranspiration (AET) is an estimate of the actual amount of water removed from the earth's surface by plants and evaporation. The water is removed from the soil in the root zone by plant transpiration and from open water by evaporation. Unlike PET, AET considers that, under field conditions (actual moisture conditions at the land surface), unlimited water is not available for evaporation and transpiration. As a result, in the relatively dry climate of Alberta, it is very seldom that AET approaches the calculated value for PET. By subtracting estimated AET and the runoff component of surface drainage from precipitation, the amount of groundwater recharge beneath the root zone can be determined.

Accurate measurement of AET at a regional scale is a complex problem. AET can be measured directly in several ways, including Bowen ratio systems, eddy covariance arrays, and soil-moisture-based methods. However, all of these methods have intensive data requirements and produce very site-specific AET values (Petrone et al., 2007). The regional nature of the ECC required that a simple empirical formula with minimal data requirements be used to calculate AET. Chow (1964) outlined the several empirical evapotranspiration equations used to estimate regional-scale AET, including those by Hedke, Lowry-Johnson, Penman, Blainey-Criddle, Haargreaves, and Turc. Many of these equations have several parameters that have to be estimated and require highly specific micro-meteorological data not commonly available from Environment Canada. Turc's equation (Equation 4; Turc, 1961) was used to estimate AET for the ECC as it requires only annual temperature and precipitation data. Given the greater number and widespread distribution of the temperature control points, the interpolated precipitation values were assigned to the temperature station locations for the analysis (Figure 6b). While Turc's equation is most often used to characterize the climate over very large areas, like continents, it has been shown to produce a reasonable estimate of AET at scales similar to the ECC region (Kaczmarek, 1993). This is achieved by changing the constant in the equation to minimize the residual difference in the water budget equation using base-flow and runoff data in order to better complete water budgets.

$$AET = \frac{P}{\left[K + \left(\frac{P}{I_T}\right)^2\right]^{1/2}} \tag{4}$$

where, AET is equal to annual evapotranspiration, P is equal to annual precipitation, I_T is the evaporation capacity of the air ($300 + 25T + 0.05T^3$, where T is the mean air temperature [°C]), and K is a constant which can range from 0.3 to 0.9 based on calibration with base flow data (Kaczmarek, 1993).

3.4 Average Annual Sublimation

Sublimation is the direct loss of water in the solid phase, such as snow and ice, to the atmosphere without passing through a liquid phase. Much like AET, sublimation is difficult to measure directly. Detailed snow surveying that includes snow depth, snow density, and new solid precipitation accumulation over a given time period is required to determine the snow's water equivalent lost through sublimation. Given the year-averaged nature of the water balance, a value based on the literature of a loss of 20% of winter precipitation (Pomeroy and Gray, 1995) was used for the dominantly prairie landscape of the ECC. The proportion of annual precipitation that falls as snow varies a great deal from year to year, from a recorded minimum of 13% to a maximum of 63% (Alberta Environment, 2005). However, on average, 25% of the annual precipitation in central Alberta typically falls as snow, with as much as 35% in northern regions (Alberta Environment, 2005).

3.5 Average Annual Maximum Runoff and Specific Discharge

Few studies have been completed on base-flow separation or on determining the proportion of groundwater discharge within the overall surface drainage flow volumes in the province. A book entitled *Hydraulic and Geomorphic Characteristics of Alberta Rivers* (Kellerhals et al., 1972) appears to be one of the few systematic studies of stream flows in Alberta. However, the data and analysis completed in Kellerhals et al. (1972) did not evaluate groundwater contributions and was generated with engineering applications in mind, rather than for freshwater management. Ophori and Tóth (1990) studied 32 basins in the plains region of Alberta employing numerical models to estimate base flow on drainage areas. Their study identified the interaction of streams with aquifers as a complicating factor in the analysis.

Runoff and base flow are calculated from stage data recorded at hydrometric gauging stations having established stage-discharge relationships. Annual flow volumes are then divided by the drainage basin area to arrive at an equivalent annual height of water, in millimetres, per drainage basin. The annual volume of base flow derived from a basin, when divided by the basin surface area, is called specific discharge. Stream flow or total surface drainage calculated using stage data includes both runoff and base flow. Runoff is water that travels rapidly across the land surface as overland flow and does not enter the groundwater environment. Runoff is initiated when the rate at which water is introduced at land surface exceeds the infiltration rate of a soil, or when the water table rises to meet the land surface, referred to as saturated overland flow. The timescale at the bottom of the schematic hydrological cycle in Figure 2 shows that runoff occurs over a relatively short timeframe compared to other processes in the hydrological cycle.

Water forming base flow leaves the groundwater environment through stream banks and beds and is carried out of a drainage basin as surface flow. Base flow can include groundwater contributions from local, intermediate, and regional flow systems. Base-flow separation methods are used to determine the proportion of base flow versus runoff in the total discharge of a stream. Once the runoff and base-flow components of surface drainage are determined, runoff volumes from hydrological gauging stations are then divided by the area of the surface drainage basin to express annual runoff in millimetres per unit area.

Stream discharge is plotted as hydrographs, which represent flow volume versus time. Select hydrographs from the ECC were analyzed using the Web-based Hydrograph Analysis Tool (WHAT) from the University of Purdue (http://cobweb.ecn.purdue.edu/~what/). The tool provides three different filters (local minimum, one-parameter digital, and recursive) to analyze the hydrographs. Base-flow separation analysis produced differing results depending on the filter used. The local minimum and the one-parameter digital filters greatly over-predicted base-flow volumes when compared to published minimum flow data for select streams found in Kellerhals et al. (1972). The recursive filter provided more representative results but required different maximum base flow index (BFI_{max}) parameters (maximum percentage of total flow assigned to base flow) depending on the time of year. However, there was little published information or methodologies available to guide the parameterization of the hydrograph separation tools using objective, physically based data. As such it was not feasible, nor within the scope of this project, to complete a detailed base flow separation analysis of all of the gauging stations in the ECC. Therefore, a simplified approach described below was used to determine base flow.

Average stream flow from November through February was queried, and it was assumed that 100% of flow during these months was base flow. This method provides a reasonable estimate of the minimum base flow in localities with solid precipitation through the winter months when base flow is the sole input source to streams and rivers. Total annual flow minus base flow represents an estimate of flow contributed from annual runoff. Using this simplified approach, and omitting streams with no winter flow data, base flow accounted for a minimum of approximately 30% of total stream flow across the ECC. Figure 7 illustrates the simplified approach using two different hydrographs showing the daily precipitation and stream flow volumes versus time for the North Saskatchewan River measured in Edmonton and for the outflow from the ECC on the Battle River. The time series running from 1967 to 1972 was chosen to avoid the influence of control structures like the Big Horn Dam on the North Saskatchewan River.

A total of 76 Environment Canada hydrological stations with sufficient stage data were used to evaluate runoff in the ECC. Stations with less than 3 years of data were omitted from the runoff analysis. Stations with less than 10 years of flow data were screened and omitted if data records revealed that extreme values (such as a one-in-fifty-year storm) produced unrepresentative annual average flow volumes.

This analysis was complicated given that portions of four major basins extend across the ECC boundary. Though the ECC boundary follows Environment Canada sub-basins (Figure 3), these basin boundaries were intended to monitor and manage surface flows at inter-provincial to national scale. The majority of the ECC land area is drained by first- or second-order tributaries to major streams. Many of these tributaries are gauged. To improve the representation of runoff distribution within the ECC, the ArcGIS watershed tool was applied to a 60 m resolution digital elevation model (DEM) to determine watershed areas for the named streams and creeks (Figure 8). Runoff values were then assigned to individual watersheds or groups of watersheds depending on the gauge location. Runoff was estimated for some watersheds if no stream gauge data were available. Estimates were made using precipitation data and by grouping small watersheds with similar physiography and stream morphology.

Areas that drain directly into higher-order streams (third-order and higher) were difficult to analyze. For example, it is difficult to assess the contribution of un-gauged streams that discharge directly into the North Saskatchewan River from gauge data that represents the hydrological response of the entire watershed. However, these first-order, rill-like streams have limited length and drain only a small area of table land immediately adjacent to the major streams. This small land area was therefore assigned the same runoff value as the next adjacent tributary with a gauge.

3.6 Average Annual Maximum Groundwater Recharge

Precipitation that infiltrates beneath the root zone to the saturated zone is called groundwater recharge or, simply, recharge. Recharge is difficult to evaluate, particularly at large scales across differing landforms. Understanding the magnitude and distribution of groundwater recharge is crucial to making informed decisions about how much water can be sustainably withdrawn from the natural system. Having this understanding is also critical for specified recharge boundary conditions in the numerical groundwater flow models.

Similar regional groundwater inventory studies, such as the *Hydrogeological Atlas of the Annapolis Valley* (Rivard et al., 2007), use two techniques to evaluate recharge: the stream hydrograph separation method and the water balance method (residual). Hydrograph separation is not suitable to evaluate recharge across the ECC as the area contains several un-gauged sub-basins and portions of four major streams with few gauges. In addition, control structures and reservoirs make it difficult to assess natural flows in the higher order streams such as the North Saskatchewan, Red Deer, and Bow. The steady-state water balance method to evaluate recharge was predicted to be more appropriate. This method uses the following water balance equation:

$$W = P - AET - Q_s / A_s \qquad (5)$$

where W is recharge, P is precipitation, AET is actual evapotranspiration and sublimation, Q_s is equal to total volume of annual runoff from a defined drainage basin, and A_s is the surface area of the basin.

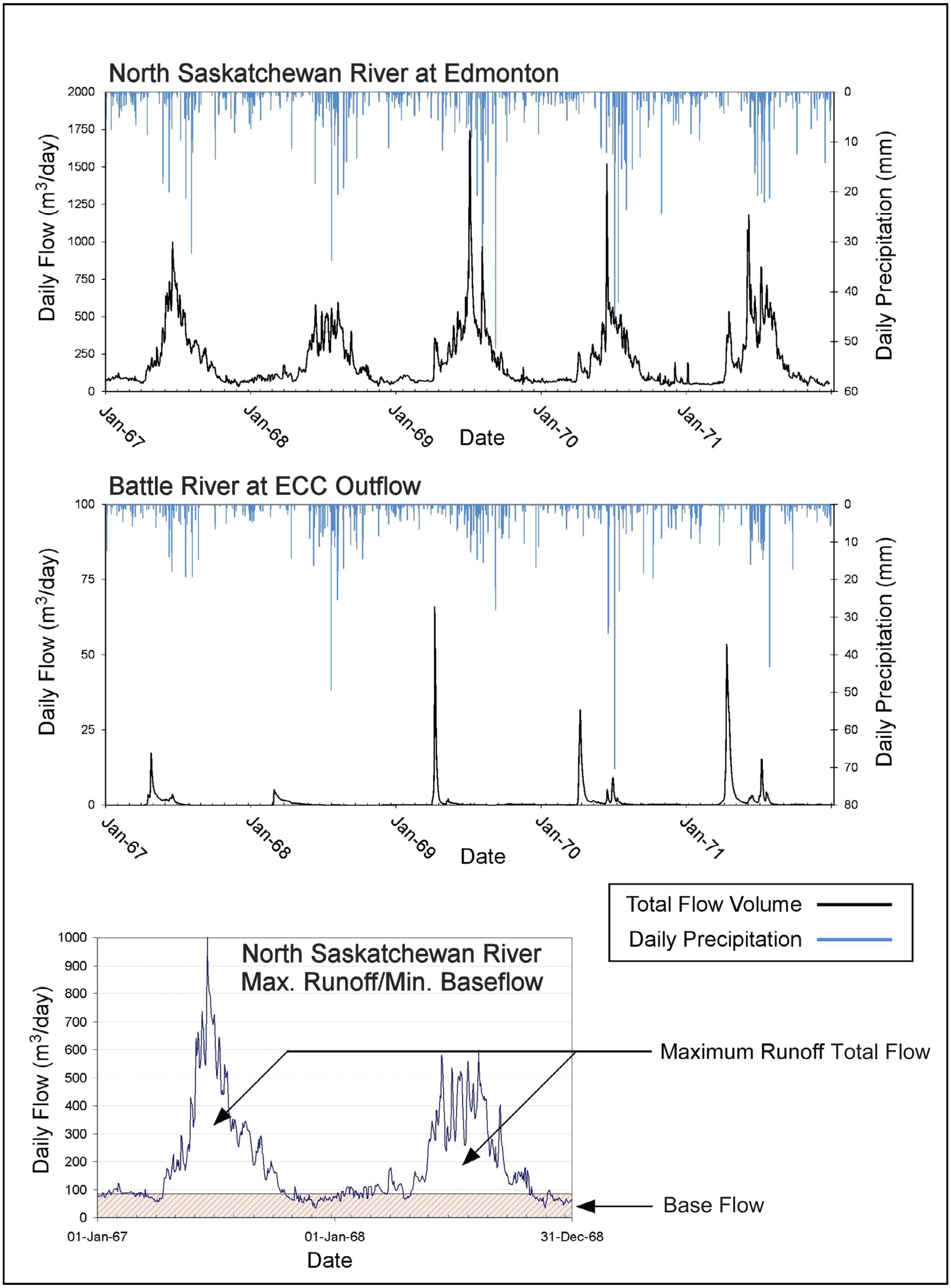


Figure 7. Hydrographs for the North Saskatchewan and Battle rivers illustrating the maximum runoff / minimum base-flow method used for hydrograph analysis.

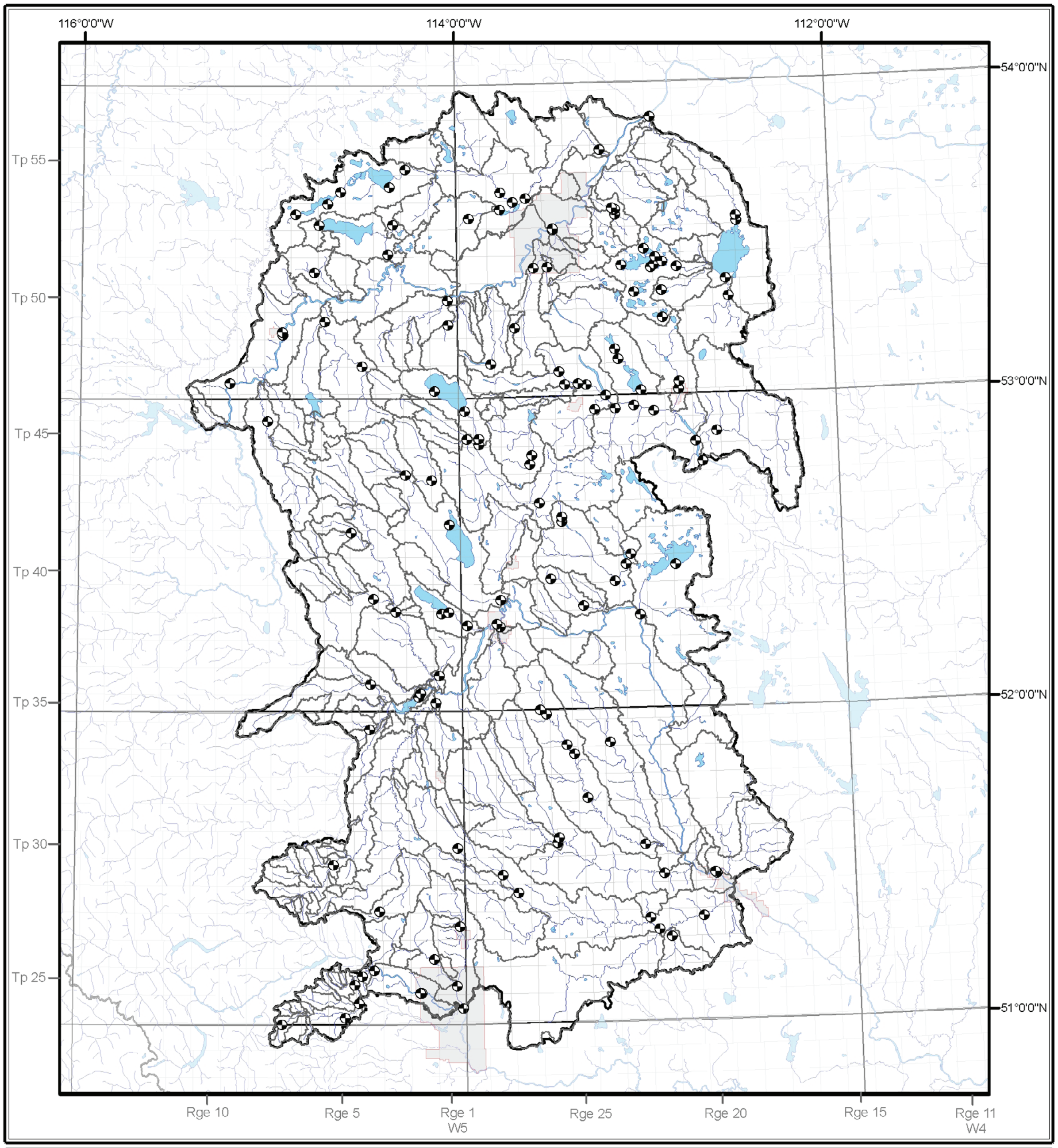


Figure 8. Topographically defined drainage basins (low-order)

Hydrometric Station

Watershed Boundary

0 12.5 25 50 75 100 km

Estimation of recharge was based on maps or gridded raster files created for the components of the water budget. The ArcGIS Spatial Analyst extension allowed for the raster values to be added and subtracted, determining the recharge term for the water-budget analysis.

4 Results

The results of the water-budget analysis are shown as a series of hydrological contour maps. The patterns and trends of each hydroclimatic variable are described below.

4.1 Annual Precipitation

Figure 9 shows the average annual precipitation across the ECC. The average annual precipitation ranges from 360 to 630 mm. It should be noted that these ranges are representative of long-term averages. Alberta has substantial natural variability in the amount and timing of precipitation on an annual basis. A trend is apparent with less precipitation in the southeast portion of the ECC area relative to the northwest. There is also a trend of decreasing precipitation from west to east. This trend is correlated to land elevation change, which decreases more sharply in the south compared to the northern portion of the ECC, which has a more gentle topographic gradient (from west to east). Cross-validation of the province-wide dataset showed an average standardized prediction error of approximately 35 mm and a standardized root mean squared error of 1.19. The average standardized prediction error is lower (approximately 15 mm) in the ECC because the data density is higher in populated areas of the province. Given the degree of natural variability on an annual basis, this prediction error is acceptable. However, it should be noted that the distribution of precipitation in Figure 9 is smoothed when compared to the measured precipitation distribution of a given year. This temporal and spatial smoothing is well suited as a recharge function for numerical groundwater flow simulations.

4.2 Annual Potential Evapotranspiration

Figure 10 shows the annual estimated PET values expressed as millimetres of water per year. The trend displayed is indicative of the microclimatic conditions, particularly the distribution of average monthly air temperature that is used as a variable in the analysis. The PET map highlights areas with high average monthly temperatures in the summer months, particularly at higher latitudes where long daylight hours allow for higher evapotranspiration rates. The results of the PET mapping are controlled by mean monthly air temperature and the number of daylight hours, which is a seasonal function of the latitude at each control point. The PET ranges from approximately 370 to 595 mm per year within the ECC. Cross-validation of the province-wide dataset showed an average standardized prediction error of approximately 20 mm and a standardized root mean squared error of 1.18. However, these errors are likely to be less than the error associated with the empirical method of calculating the PET.

4.3 Annual Actual Evapotranspiration and Sublimation

Figure 11 shows the estimated annual actual evapotranspiration and sublimation values expressed as millimetres of water per year. Turc's equation (Equation 4) was used to calculate AET at 391 temperature stations in Alberta. Unlike PET, AET considers temperature and the amount of water available for evapotranspiration through use of precipitation data. Only 147 stations had both annual temperature and precipitation data. Hence, interpolated values were used from the precipitation model (Figure 9) for the remainder of the temperature stations. The AET values were then modelled to generate Figure 11, showing AET plus sublimation in millimetres per year across the ECC. The range of values for AET range from approximately 320 to 360 mm per year but could approach PET values in areas that are not water

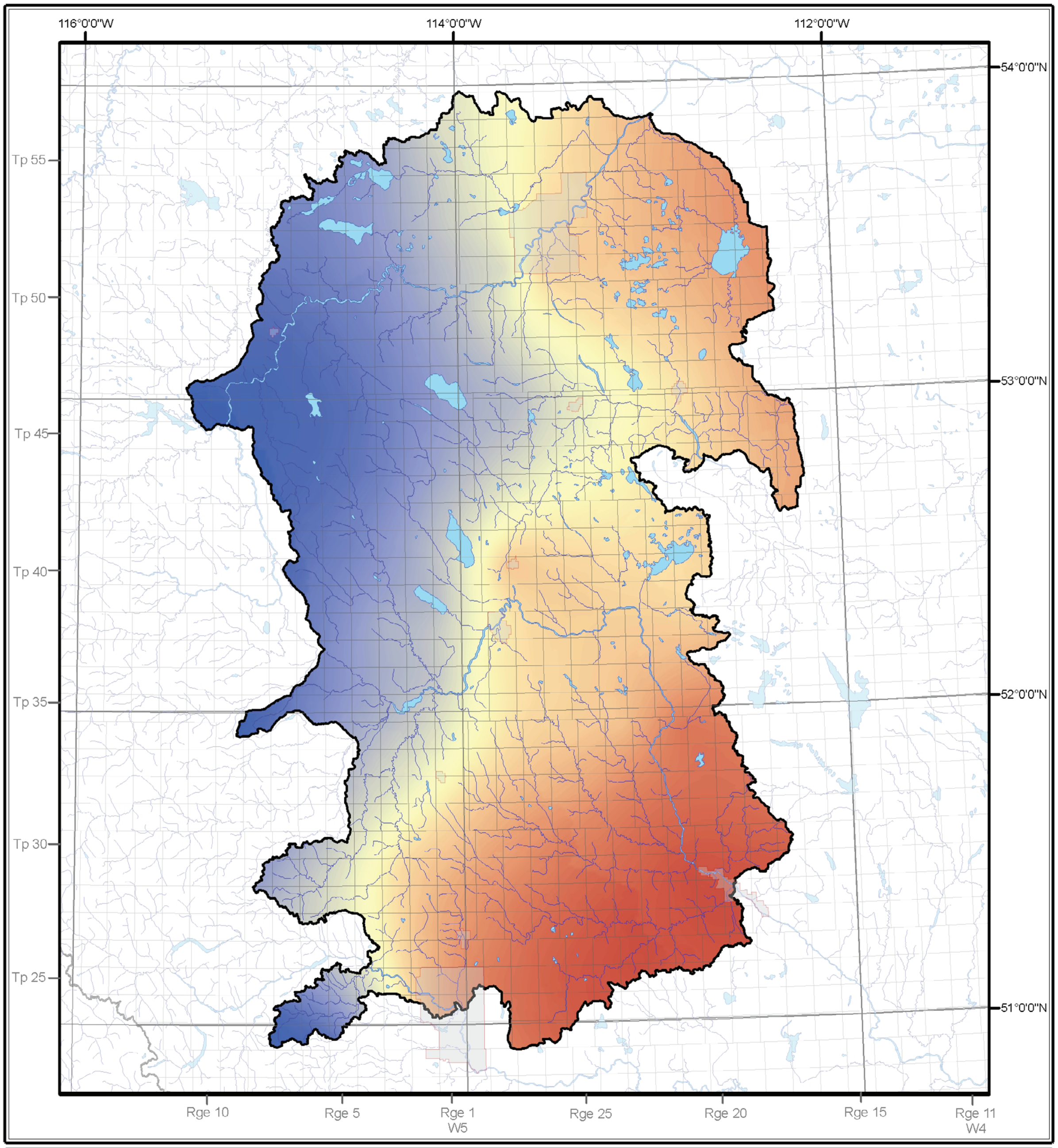
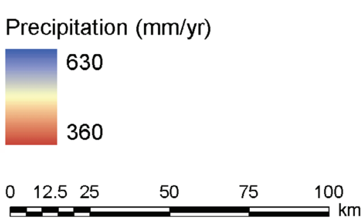


Figure 9. Average annual precipitation map



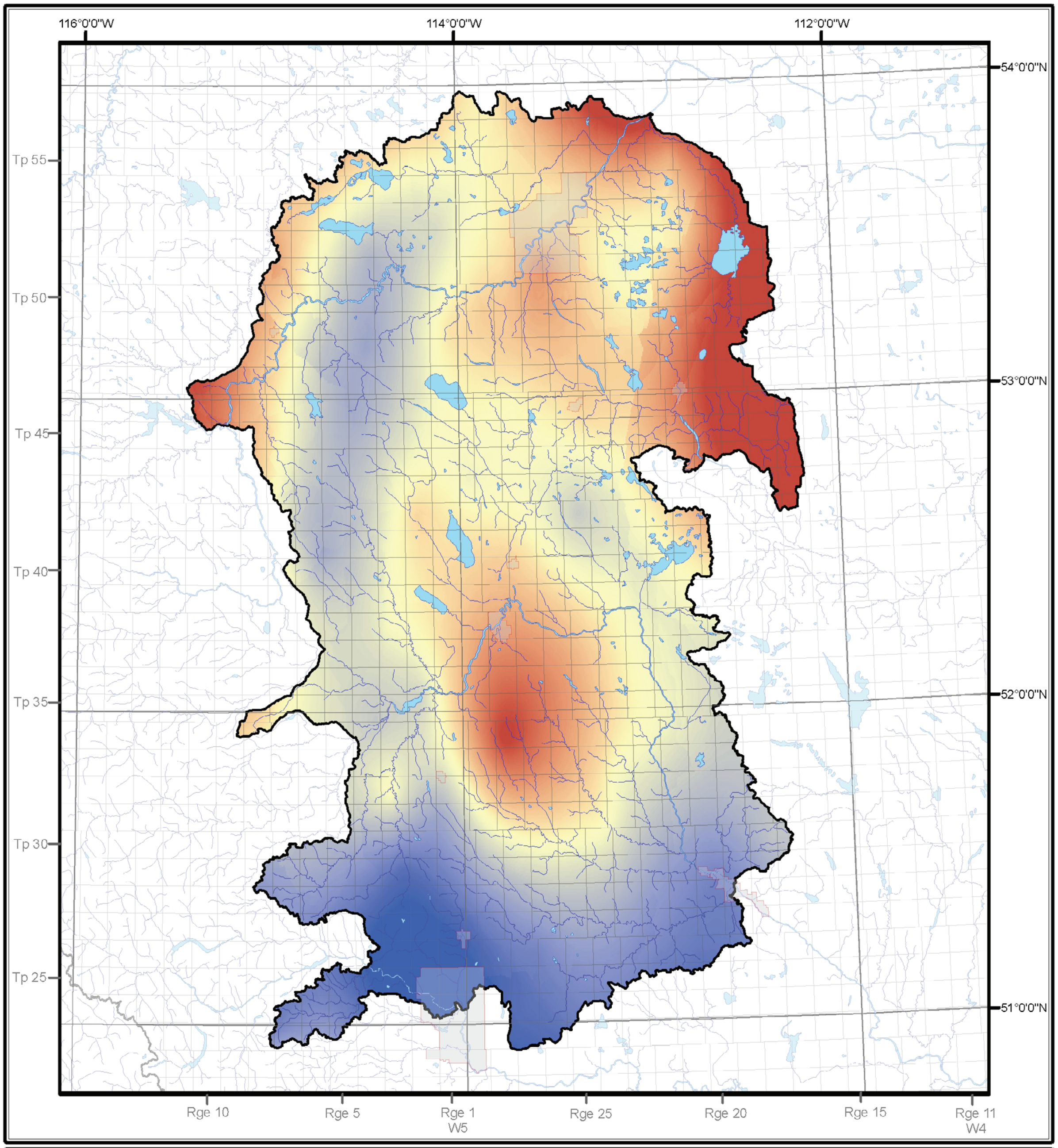


Figure 10. Average annual potential evapotranspiration map

Potential Evapotranspiration (mm/yr)

595

370

0 12.5 25 50 75 100
km

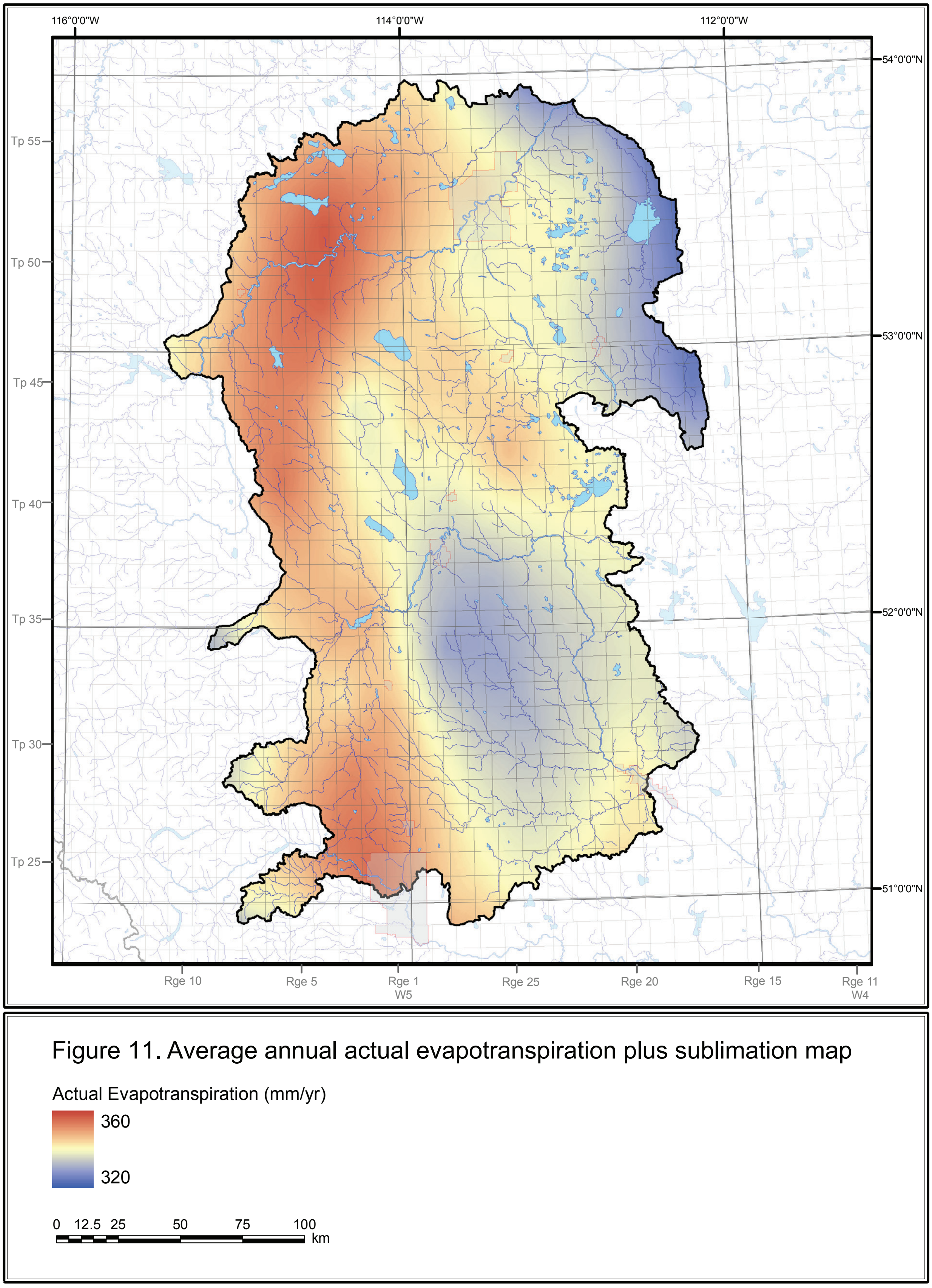


Figure 11. Average annual actual evapotranspiration plus sublimation map

limited. Cross-validation of the province-wide dataset showed an average standardized prediction error of approximately 15.2 mm and a standardized root mean squared error of 1.02. However, as in the case of PET, the geostatistical error is likely to be less than the error associated with the empirical method of calculating AET.

Patterns of AET are different from those of PET. AET is water limited over the majority of the ECC as it is, in part, based on annual precipitation. In areas that are not water limited, such as groundwater discharge features like springs, riparian wetland areas, and open water bodies, AET values could approach PET values. Literature values for the percentage of winter precipitation (20%; Pomeroy and Gray, 1995) and the percentage of annual precipitation that falls as snow (25% of annual precipitation; Alberta Environment, 2005) were used to estimate the sublimation losses based on precipitation values; thus, the pattern of sublimation across the ECC was similar to but smaller in magnitude than the precipitation patterns discussed above.

4.4 Average Maximum Annual Runoff

The runoff map (Figure 12) shows estimated runoff values for entire watersheds, which were defined using the DEM. This provided the maximum spatial resolution of runoff given the outflow-based monitoring network. The annual maximum runoff patterns in the ECC are affected by the amount of annual precipitation, the topographic gradient, and the amount of available soil moisture storage within a drainage basin as areas with thicker glacial sediments have lower run-off values (Figure 4). The maximum annual runoff values calculated at the hydrometric stations ranged from 292 mm in the headwaters of Jumping Pound Creek (southwest corner of ECC) to 0 mm in the drainage area of the Red Deer River, upstream of Drumheller. The range and spatial distribution of runoff values shown in Figure 12 highlight the spatial variability in runoff across the ECC. Figure 13 shows a histogram of maximum annual runoff values (in millimetres) for all of the stations analyzed within the ECC, indicating that the majority of the stations have low runoff values (<50 mm). It is difficult to quantify uncertainty using the watershed outflow method. However, given the long time series used for the analysis, the uncertainty is likely smallest in watersheds with long-term gauging records and highest in un-gauged basins (Figure 8).

4.5 Minimum Annual Specific Discharge

Figure 14 indicates the minimum specific discharge calculated for each of the topographically defined watersheds within the ECC. The pattern of specific discharge is comparable to that of the runoff map (Figure 12), with a general trend of reduction from west to east. As such there is significantly more specific discharge in the alpine portion of the Bow River sub-basin included in the ECC (Figure 3) and in the subcrop area of the Paskapoo Formation. Conversely, the plains portion of the ECC has limited specific discharge, as physiographically they overlie less permeable Scollard, Horseshoe Canyon, Bearpaw, and Belly River bedrock formations (Figure 5). The mapped specific-discharge patterns are somewhat similar to the runoff distribution, given that precipitation and topographic gradients also influence specific discharge. The uncertainty related to base flow is also difficult to quantify given the method used. As in the runoff analysis, the un-gauged basins (Figure 8) would have a higher degree of uncertainty.

4.6 Minimum Annual Recharge

The distribution of mean annual recharge (Figure 15) represents the residual term in the water balance equation discussed in Section 3. Estimated recharge values range from 235 mm to negative recharge values ranging in magnitude from 0 to −10 mm in some cases. These slightly negative values (i.e., 0 to −10 mm) are isolated to the southeast of the ECC, near Drumheller. These negative recharge values are

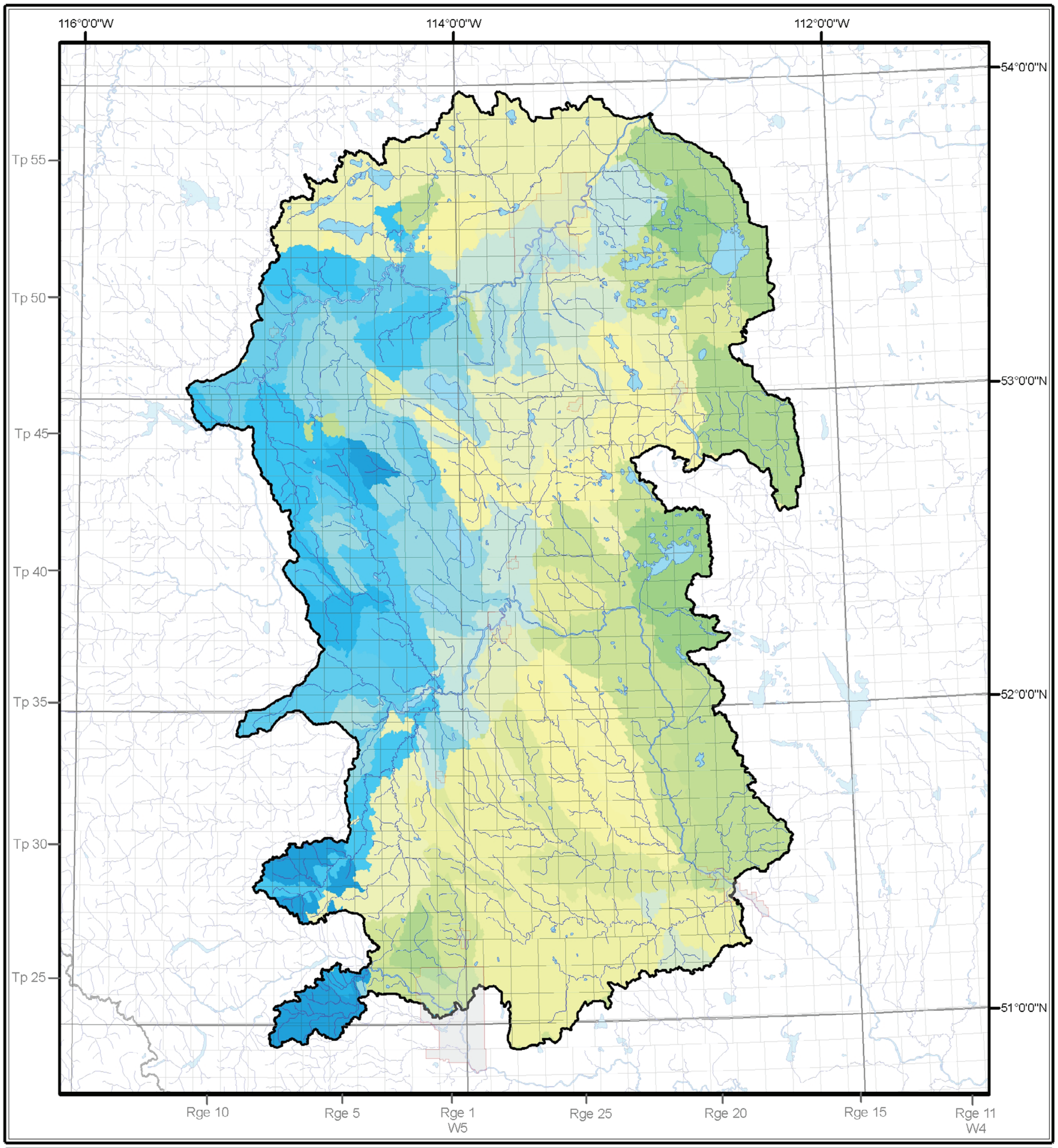


Figure 12. Average annual maximum runoff map

Annual Runoff (mm/yr)

300

0

0 12.5 25 50 75 100 km

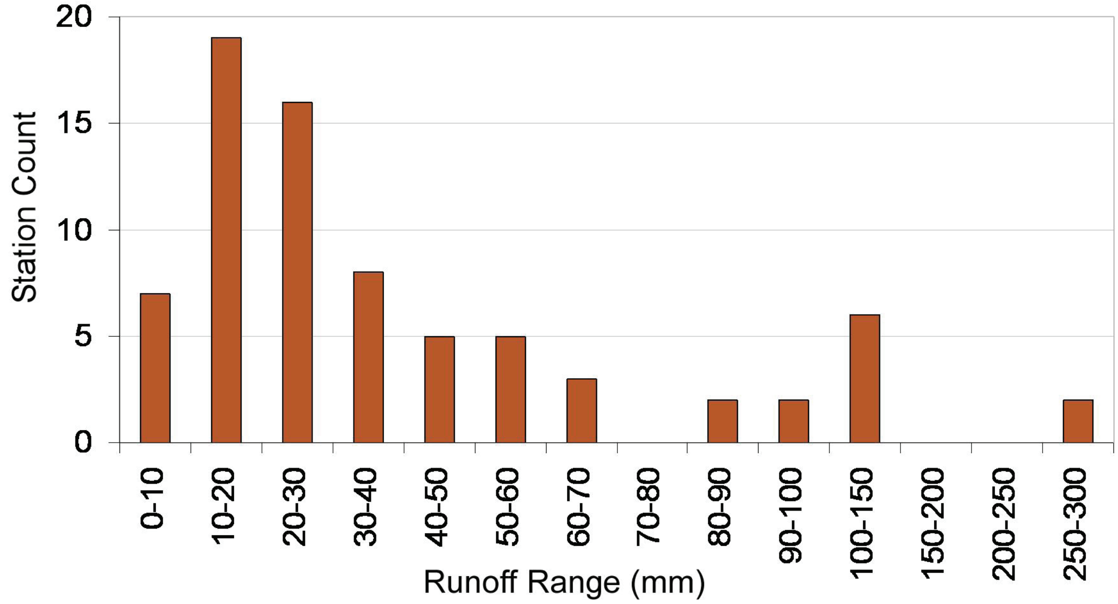


Figure 13. Histogram of average annual maximum runoff.

due to the semi-arid conditions seen in most average years. However, infrequent recharge events have been shown to occur in these areas. Minimum potential recharge in the areas near Drumheller, as shown in Figure 15, represent positive numbers.

5 Discussion

The overarching goal of this water budget analysis is not only to provide input (boundary conditions) for a numerical groundwater flow model and to assist in policy development and the regulation of the resource, but to provide a first-order understanding of the regional water budget within the ECC. As such, it should be noted that the information and data presented in this report are useful as a starting point for addressing studies of local-scale water budgets.

This study quantifies the relative trends across the ECC for each of the water balance components. It is believed that knowledge of the trends and average conditions are important for studying and managing freshwater resources over the long term. Further, given the high degree of natural climatic variability, it is more useful to assess the average conditions rather than the annual extremes such as drought or surplus conditions.

5.1 Uncertainty in Interpolated Hydroclimatic Variables

There are additional elements of uncertainty with all of the water balance components beyond the challenge of regional-scale determination for each of the water budget terms. There is uncertainty in the spatial allocation of average monthly air temperature, precipitation, and evapotranspiration (PET and AET) that is related to interpolation. Interpolation of these data provides a reasonable estimate of each hydrological budget component over most of the ECC. However, data bias introduces error when interpolated from the original dataset. For example, mountain precipitation stations being located in valley bottoms collect representative data on the precipitation where they are located, but likely

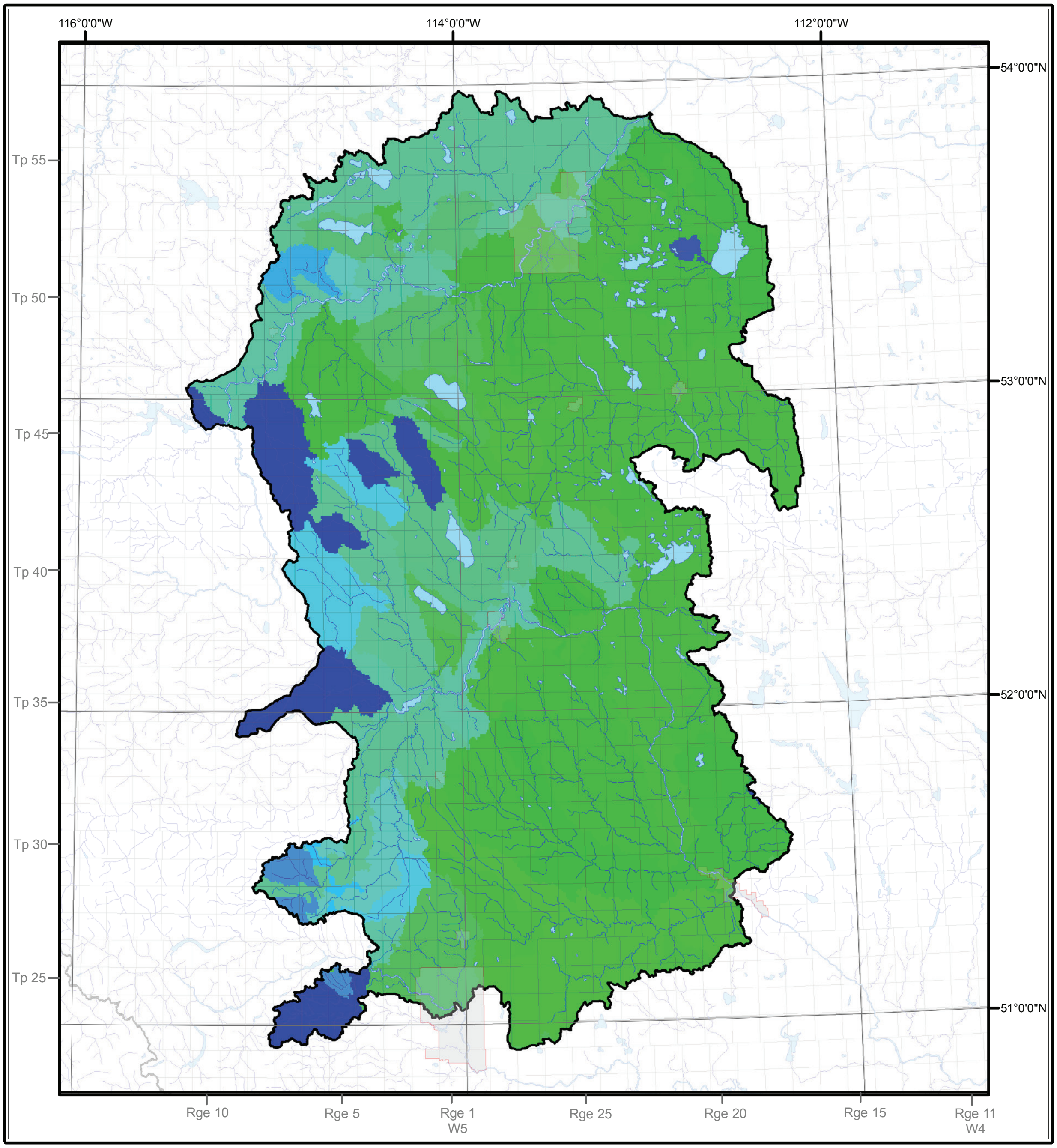
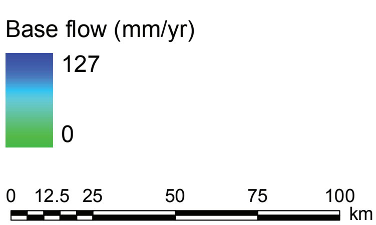


Figure 14. Average annual specific discharge map



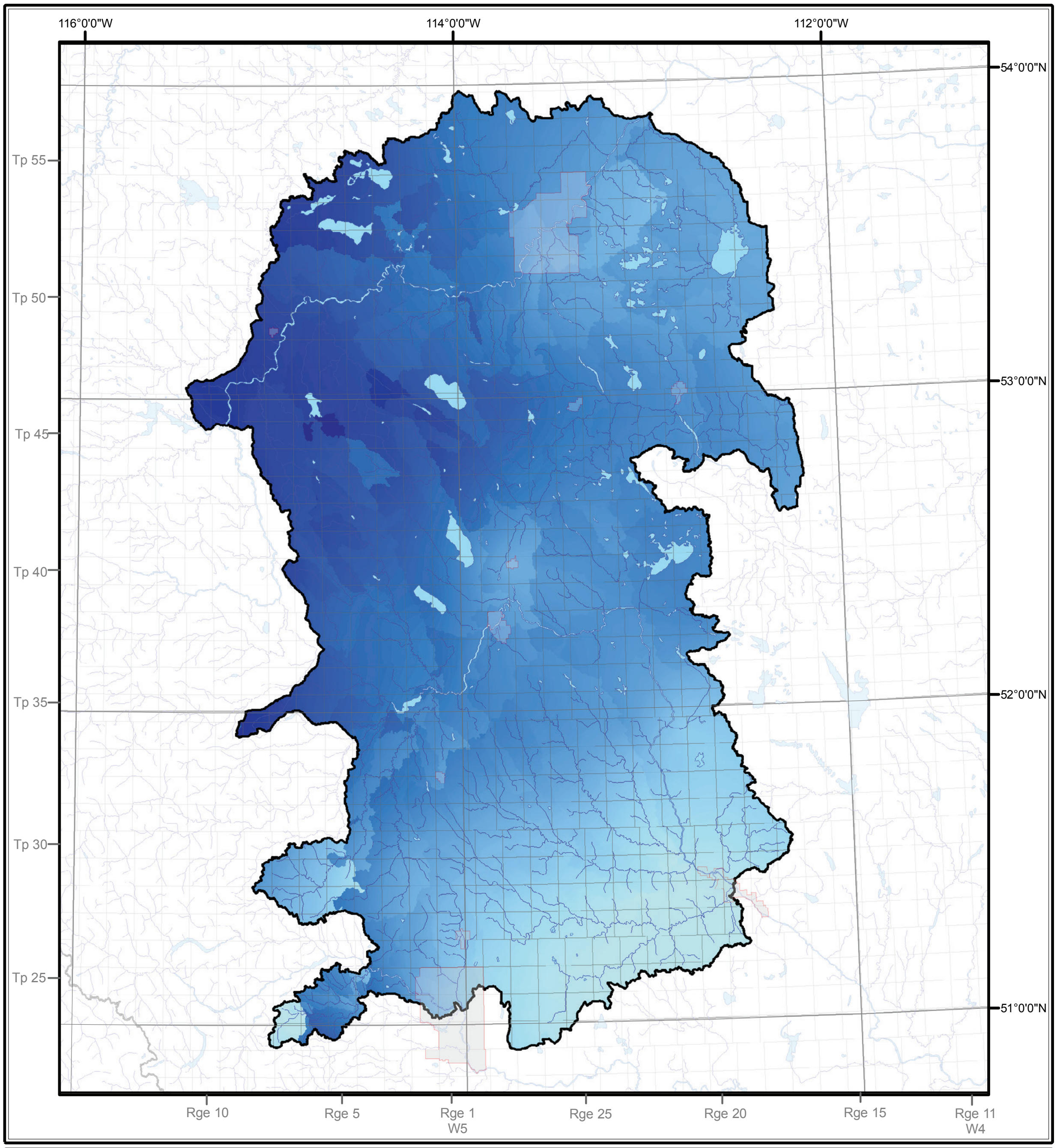


Figure 15. Average annual minimum recharge map

Recharge (mm/yr)

235

0

0 12.5 25 50 75 100 km

underestimate the precipitation amounts at high elevations, which dominate the southwestern portion of the province. Values are interpolated without consideration of land surface elevation changes or other micro-meteorological factors that may affect the hydroclimatic variables at a given location. However, this was deemed acceptable for the intended application of the water budget analysis.

Further, the empirical relationships used to determine PET and AET produce estimated values that are highly dependent on micro-meteorological variables not considered in the simple methods used to produce our results. However, to complete a water balance with minimal meteorological data over the large land area covered by the ECC, and relatively small percentage of the study area considered mountainous, the interpolation errors and uncertainty related to Thornthwaite's and Turc's formulas is acceptable and generate best estimates for the average annual water balance (Lu et al., 2005).

The uncertainty related to sublimation can also be combined with interpolated hydroclimatic variables, as it is primarily a function of the amount of winter (solid) precipitation. Given the variability and uncertainty related to precipitation, a value of 20% of winter precipitation for sublimation in prairie and plains areas (Pomeroy and Gray, 1995) was deemed sufficient. The error introduced by using this generalization is considered minimal given the long-term averaging of the water budget components. Sublimation is an important flux to consider as it accounts for 17.5 mm to 32.5 mm across the ECC annually.

5.2 Uncertainty in Watershed-Based Hydrological Variables

The methods used to compute runoff and specific discharge were intended to provide coarse estimates of annual values at a regional scale. The high spatial variability of the results is due to diverse physiography, geological framework, and climate. The purpose of the regional water balance, the nature and characteristics of the watersheds within the ECC, as well as the data density and types did not support the use of detailed base-flow separation methods.

The uncertainty related to recharge is the cumulative errors from all of the input variables. The general patterns of recharge across the study area are likely more reflective of the relative recharge patterns in the ECC rather than the absolute values for recharge. Further, despite using a watershed-based approach to assign runoff and specific discharge, these variables are not independent of the regional groundwater flow system. As specific groundwater flow systems are characterized, the recharge estimated in Figure 15 likely occurs at higher rates over less land area in delineated recharge zones.

5.3 ECC Water Budget Summary

Dramatically different hydrological regimes are present in the ECC. This analysis has identified groups of watersheds that have similar values of hydrological budget components based on common patterns in their physiography, geology, and climate.

There are some discernible patterns in the runoff distribution across the ECC. The western margin of the ECC, especially the mountainous portion of the Bow River sub-basin in the southwest, generates substantial runoff (Figure 12). This area can be considered alpine and has significantly higher precipitation, high topographic gradients, and little to no soil moisture storage capacity. Therefore, higher runoff values are expected in alpine drainage basins in comparison to the plains region. Land use may also be a factor, as the western portion of the ECC is forested and largely undeveloped, whereas the plains region is predominantly agricultural.

The calculated maximum annual runoff reflects the transitions in topography, geology, and physiography from the foothills in the west to the plains in the east. Several lowland areas and broad valley bottoms that are well connected to groundwater flow systems receive groundwater discharge and support extensive wetlands that have lower runoff than the surrounding basins. The headwaters of the Battle River, near Battle Lake, occupy a large, broad valley with wetlands at the bottom that buffer runoff response through riparian zone evapotranspiration. A large area of ice-contact lacustrine and fluvial deposits between Edmonton and Wabamun Lake (Shetsen, 1990) has lower runoff than the surrounding basins due to thick glacial sediments with hummocky, undulating topography and high potential for soil moisture storage, resulting in a poorly defined drainage network.

Stagnation moraines found in the Cooking Lake and Buffalo Lake areas have poorly developed drainage networks and generate little runoff. Much of the precipitation is impounded in closed drainage basins and accounts for the numerous small lakes, ponds, and wetlands in these areas. Throughout most of the Red Deer River Basin, aside from the upper reaches of the Little Red Deer River in the foothills, the maximum annual runoff is less than 20 mm. This is due to the relatively dry climate, agricultural land use, and relatively flat topography (other than the incised drainage valleys). Similarly, the Battle River Basin also has low (<20 mm) maximum annual runoff.

The specific-discharge pattern appears to be strongly controlled by the permeability of both surface materials (Shetsen, 1990), where present, and the underlying bedrock that make up the geological framework of a given basin. Drainage basins with significant recharge and permeable porous media enhance localized groundwater flow and consequently permit high base-flow volumes to the streams.

This type of geological control on specific discharge is apparent in drainage basins on the western margin of the ECC. The Paskapoo Formation is known to be very sand rich and coarse grained in many areas, composed of highly permeable sandstone (Lyster and Andriashek, 2012), and is often fractured within the vicinity of the deformation belt. This results in high-permeability bedrock that can be incised and drained by streams, promoting specific discharge. Similarly, specific discharge appears higher in the Red Deer River Valley near the City of Red Deer due to the subcrop area of the Haynes Member of the Paskapoo Formation, which is known to have higher permeability than the overlying Lacombe Member. The buried valley in the Red Deer River Valley is also filled with coarse-grained preglacial sand and gravel sediments (Barker et al., 2011), which promote discharge of base flow from the groundwater flow system into the Red Deer River where hydraulic communication between sediments and stream exists.

The entire study area also exhibits high natural variability in recharge, and though the long-term average recharge is low or even negative, areas can be recharged by a single precipitation event or wet year which can replenish stored soil moisture such that drought conditions can be buffered (Toop, 2010). The western margin of the ECC, as well as the stagnation moraine areas, have significantly higher recharge than surrounding areas, largely controlled by the surface drainage characteristics (i.e., runoff and base flow) of the land forms. The recharge estimated for the areas west of the deformation belt appear to be too low given the amount of precipitation and water chemistry patterns that would indicate freshwater recharge into the Paskapoo Formation (Grasby et al., 2008). This is supported by a large degree of uncertainty in many of the water balance variables along the mountain front, especially precipitation (given the complex seasonal snow pack dynamics) and relatively sparse surface flow gauging and precipitation stations in these undeveloped areas.

Eight areas or hydrological regions have been identified and are shown in Figure 16 to summarize areas with common hydrological characteristics. These hydrological regions encompass the ten Environment Canada sub-basins (Figure 3). The discussion below is confined to within the ECC project boundary, but characteristics of these hydrological regions likely extend beyond the project area. The wide range in recharge is related to the precipitation and evapotranspiration patterns that vary across the entire study area. A brief description of each of the regions is also provided with some interpretation of the hydrological characteristics of each region.

The area defined as the North Saskatchewan Boreal Plain hydrological region covers most of the drainage area of the North Saskatchewan River within the ECC, except for the Cooking Lake Moraine area (Figure 16). The North Saskatchewan Boreal Plain represents the southern extreme of the Western Boreal Plain. Land use is mixed, with significantly more forested area than in the plains to the south. This area overlies the Paskapoo, Scollard, Horseshoe Canyon, and Belly River bedrock formations. The bedrock underlying this region is dominantly fine grained, with the exception of the small portion of the Paskapoo subcrop area in the western portion of the North Saskatchewan Boreal Plain, resulting in a large range of groundwater recharge rates. The relatively low permeability of deposits underlying the majority of this hydrological region is the dominant control on hydrological processes, which is supported by the entire region having similar runoff and specific-discharge patterns.

The stagnation moraines in the Cooking Lake and Buffalo Lake areas have extensive stagnation or dead-ice moraine deposits. Though these areas make up a relatively small proportion of the ECC, they have distinct hydrological characteristics relative to the surrounding landscape. The poorly developed drainage network and undulating dimpled land surface, combined with regionally elevated topographic position in this hydrological region, account for the high recharge values relative to the adjacent land areas. The moraine areas are shown on Figure 14 as two distinct areas, including the Cooking Lake Uplands and the Buffalo Lake Plain physiographic regions, where stagnation moraine deposits are common (Gravenor and Ellwood, 1957; Pettapiece, 1986).

Like most of the North Saskatchewan Boreal Plain hydrological region, the Battle River Plain hydrological region is situated above largely fine-grained bedrock formations. This region is dominated by agricultural land use. Runoff is limited to spring melt and large storm events. Base flow appears to maintain discharge in most of the streams in the region, though it contributes only 2 to 10 mm of water annually. Recharge ranges significantly across the hydrological region, driven by a substantial precipitation gradient, with more precipitation in the west relative to the outflow area (Driedmeat Lake) than at the eastern margin of the ECC. Much of the recharge in this hydrological region is likely discharged from groundwater flow systems into the wide riparian area along the Battle River.

The Red Deer River Plain hydrological region occupies a large portion of the Red Deer River Basin within the ECC. This area is dominated by water-intensive agricultural activities and land uses and is subject to regular seasonal drought conditions, accounting for an apparent net negative recharge value in some years. This region does not include the north-northwest-draining portion of the Red Deer River upstream of the City of Red Deer or the Little Red Deer River watershed area, as they have significantly higher runoff ranges and steeper topographic gradients generated by the bedrock topography in the Paskapoo Formation subcrop area. The Red Deer River Plain, including the Red Deer River downstream of Red Deer and its southeast-draining tributaries, overlie the muddy Lacombe Member of the Paskapoo Formation (Lyster and Andriashek, 2012) as well as parts of the Scollard and Horseshoe Canyon formations. The area has a well-developed drainage network with steeply incised drainage courses as seen in the badlands and as coulees further west. These features were created at a time when there was more water available on the landscape given that modern-day drainages often occupy the same features as the paleo-drainage network. Steep incision into the muddy bedrock creates relatively large hydraulic head gradients, focusing groundwater flow to discharge into the surface-water drainages. Low runoff and base-flow volumes are characteristic throughout the region due to the combination of soil moisture storage potential buffering runoff and low-permeability bedrock limiting base-flow volumes.

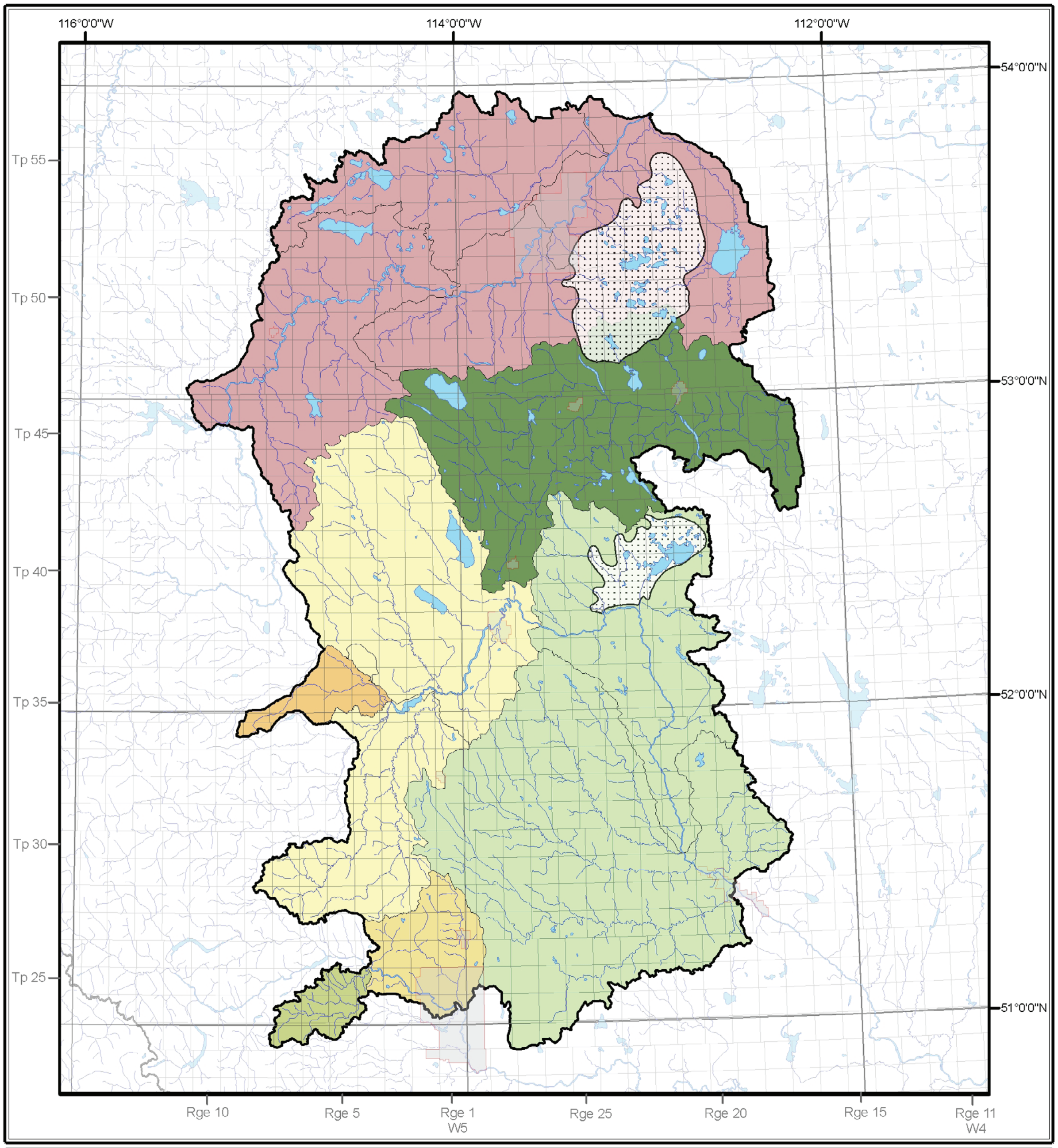
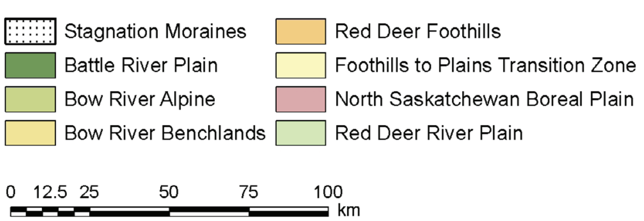


Figure 16. Hydrological regions in the Edmonton-Calgary Corridor



The Foothills to Plains Transition Zone hydrological region includes the western portion of the Red Deer River drainage basin, including the Little Red Deer River and the Red Deer River drainage area upstream of the City of Red Deer. This area generally corresponds to the Buck Lake Upland physiographic region described by Pettapiece (1986). The hydrological region is entirely underlain by the Paskapoo Formation, including the fine-grained Lacombe Member and the coarse-grained Haynes Member. This area has a substantial precipitation gradient, with greater precipitation in the west relative to the east that also corresponds to the change in elevation. Specific-discharge patterns are variable and are strongly influenced by the permeability of the underlying bedrock. Runoff is generally higher in the west relative to the east owing to higher annual precipitation and steeper topographic gradients.

The Red Deer Foothills hydrological region is composed of the headwater drainage basins of both the Red Deer and Little Red Deer rivers. This region represents an area where topographic gradients and annual precipitation are high, resulting in higher annual runoff and substantially more base flow in comparison to the plains. The proximity to the deformation belt results in fractured bedrock enabling high base-flow volumes and possibly a strongly developed local groundwater flow system.

The Bow River Benchlands drain the portion of the Environment Canada Bow River sub-basin included in the ECC, north and northwest of Calgary. This area is similar to the Red Deer River Plain but with slightly higher values of specific discharge, which are likely attributed to the relatively high permeability of the Cordilleran till cover inferred based on lithological descriptions and grain-size analysis (Boydell, 1978). The Bow River Alpine hydrological region has the highest annual precipitation, the most complex snow pack melt dynamics, and the greatest topographic gradients resulting in the greatest values of runoff and specific discharge in the ECC. The greater specific discharge is likely due to a high degree of hydraulic communication between the deformed and fractured bedrock forming the substrate of the Bow River.

5.4 Challenges and Limitations of Regional-Scale Assessment

There were several challenges in determining the annual water budget for the study area due to the large land area occupied by the ECC. The primary complication in assessing the surface-water hydrology of the ECC is that the stream-gauging network was designed to initially inventory surface flows at a national scale and was later supplemented to assist in managing water resources at a provincial scale. At the scale of the ECC, the hydrometric monitoring network is sparse with no instrumentation measuring outflow from a number of small watershed areas drained by first-order streams. Many gauging stations used in our study measure stage data on the North Saskatchewan, Red Deer, and Bow rivers at locations outside of our study area. The separation between gauging stations within the ECC leaves substantial portions of the landscape un-gauged. There are also several control structures that alter the timing and magnitude of surface flows on the North Saskatchewan, Red Deer, and Bow rivers within the ECC. Control structures make it difficult to assess the natural surface-water flow regime and complicate hydrological assessments like stream-flow separation or base-flow analysis on controlled streams, especially when there is little or no monitoring data prior to the installation of control structures.

Most of Alberta, particularly the ECC, has a relatively dry climate, making evapotranspiration (ET) a very substantial component of the hydrological budget. Errors in determining ET can have a meaningful effect on determining a water budget. Even at a local scale, ET is difficult to measure without intensive instrumentation. Applying local results at a regional scale requires careful consideration (Maulé et al., 2006). The network of equipment to measure ET in the ECC is limited, and therefore upscaling ET fluxes from local measurements yields uncertain results.

There is substantial annual variability in the timing and quantity of precipitation, as well as the air temperature. These variations affect components of the water budget including precipitation and evapotranspiration. Soil moisture varies significantly in relation to the water deficit or surplus created by the precipitation to evapotranspiration ratio in each year. Soil moisture plays an important role in storing water during prolonged dry periods and can therefore provide a buffer against drought. Given the hydrological variability of the ECC, long-term data records are required to assess long-term average or mean conditions for precipitation and air temperature. These records are available and have been used, though any given year can show substantial deviation from the long-term average.

5.5 Future Hydrological Study in ECC

Only recently have watershed alliances and stewardship groups in the province begun studying individual basins in greater detail. These studies often focus on the surface hydrology, land use patterns, and threats to water quality within the watershed. However, evaluation of groundwater interaction with surface water has not been studied in great detail. This knowledge gap associated with groundwater has been identified as important by watershed groups.

Watershed alliances are currently established for the major stream basins, such as the North Saskatchewan, Battle River, and Red Deer and Bow River. Each of these groups faces different challenges, knowledge gaps, and drivers for future study based on water and land use in addition to socioeconomic factors. For example, surface-water demand for irrigation is common in the Bow River Basin and the southern portion of the Red Deer Basin, whereas this is not a driver within the North Saskatchewan Basin.

6 Summary

There are several conclusions to draw from the hydrological characterization and regional water balance this report presents. First, the ECC contains several fundamentally different hydrological regimes, ranging from alpine catchments with little soil storage, strongly developed drainage networks that rapidly respond to atmospheric inputs, to plains watersheds with tens of metres of unsaturated media creating massive soil moisture storage potential with poorly developed drainage networks that buffer the hydrological response to atmospheric inputs.

This study also concludes that there is a continuing need to evaluate recharge through different methods with field verification to achieve a better understanding of where and when recharge occurs. The uncertainty regarding the evapotranspiration estimates as mapped in this study translates directly to uncertainty in actual recharge. However, in this study the absolute values of AET and recharge are perhaps less important than understanding the spatial patterns of magnitude and temporal variability of recharge. Given that this study is averaged over time, it does not address the temporal variability of recharge, but it does conclude that recharge in the ECC ranges from net water deficit (representing a loss of stored water over a given year) to upwards of 200 mm of recharge annually. Natural variability within the ECC climate makes the average annual recharge difficult to evaluate (e.g., infrequent storm events can account for a year's worth of recharge in one event).

Supplemental surface-water monitoring stations installed at the outflow points from each Environment Canada sub-basin would greatly enhance our understanding of the proportional contribution of surface water (runoff) and groundwater (base flow) to overall surface water drainage. Additional monitoring stations would also allow for enhanced calibration and more accurate parameterization of numerical models.

7 References

Alberta Environment (2011): Water allocations compared to average natural flow; URL <http://environment.alberta.ca/01722.html> [September 2013].

Barker, A.A., Riddell, J.T.F., Slattery, S.R., Andriashek, L.D., Moktan, H., Wallace, S., Lyster, S., Jean, G., Huff, G.F., Stewart, S.A. and Lemay, T.G. (2011): Edmonton–Calgary Corridor groundwater atlas; Energy Resources Conservation Board, ERCB/AGS Information Series 140, 90 p., URL <http://www.ags.gov.ab.ca/publications/abstracts/INF_140.html> [August 2013].

Bates, R. and Jackson, J. (1987): Glossary of geology (3rd edition); American Geological Institute, Alexandria, Virginia.

Boydell, A.N. (1978): Multiple glaciations in the Foothills, Rocky Mountain House area, Alberta; Alberta Research Council, Bulletin 36, 35 p.

Chow, V. T. (1964): Handbook of applied hydrology: a compendium of water-resources technology; McGraw-Hill, New York, New York.

Domenico, P. and Schwartz, F. (1997): Physical and chemical hydrogeology; John Wiley and Sons, Ney York, New York..

Environment Canada (2001): Canadian climate normals and averages (1971–2000); URL <http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html> [August 2013].

Grasby, S., Chen, Z., Hamblin, A., Wozniak, P. and Sweet, A. (2008): Regional characterization of the Paskapoo bedrock aquifer system, southern Alberta; Canadian Journal of Earth Sciences, v. 45, no. 12, p. 1501–1516.

Gravenor, C.P. and Ellwood, R.B. (1957): Glacial geology of the Sedgewick District, Alberta; Earth Science Report, ESR 1957-01, 45 p.

Hamblin, A.P. (1998): Edmonton Group/St. Mary River Formation: summary of literature and concepts; Geological Survey of Canada, Open File Report 3578.58 p.

Kaczmarek, Z. (1993): Water balance model for climate impact analysis; ACTA Geophysica Polonica, v. 41, no. 4, p. 1–16.

Kellerhals, R., Neill, C.R. and Bray, D.I. (1972): Hydraulic and geomorphic characteristics of rivers in Alberta; Research Council of Alberta, River Engineering and Surface Hydrology Report 72-1. 52 p.

Lu, J., Sun, G., McNulty, S. and Amatya, D. (2005): A comparison of six potential evapotranspiration methods for regional use in the southeastern United States; Journal of the American Water Resources Association, June, p. 621–633.

Lyster, S. and Andriashek, L.D. (2012): Geostatistical rendering of the architecture of hydrostratigraphic units within the Paskapoo Formation, central Alberta; Energy Resources Conservation Board, ERCB/AGS Bulletin 66, 103 p., URL <http://www.ags.gov.ab.ca/publications/abstracts/BUL_066.html> [August 2013].

Maulé, C., Helgason, W., McGinn, S. and Cutforth, H. (2006): Estimation of standardized reference evapotranspiration on the Canadian Prairies using simple models with limited weather data; Canadian Biosystems Engineering, v. 48, Abstract 1.1–1.11.

Ophori, D. and Toth, J. (1990): Relationships in regional groundwater discharge to streams: an analysis by numerical simulation; Journal of Hydrology, v. 119, p. 215–244.

Pettapiece, W.W. (1986): Physiographic subdivisions of Alberta; Land Resource Research Centre, Agriculture Canada, scale 1:1 500 000.

Petrone, R. M., Silins, U. and Devito, K.J. (2007): Dynamics of evapotranspiration from a riparian pond complex in the Western Boreal Forest, Alberta, Canada; Hydrological Processes, v. 21, p. 1391–1401, doi:10.1002/hyp.6298.

Pomeroy, J.W. and Gray, D.M. (1995): Snowcover accumulation, relocation and management; National Hydrology Research Institute, Science Report No.7, 144 p.

Prior, G.J., Hathway, B., Glombick, P.M., Pană, D.I., Banks, C.J., Hay, D.C., Schneider, C.L., Grobe, M., Elgr, R. and Weiss, J.A. (2013): Bedrock geology of Alberta; Alberta Energy Regulator, AER/AGS Map 600, scale 1:1 000 000, URL <http://ags.gov.ab.ca/publications/abstracts/MAP_600.html> [June 2014].

Rivard, C., Deblonde, C., Boivin, R., Bolduc, A., Paradis, S.J., Paradis, D., Liao, S., Gauthier, M.J., Blackmore, A., Trepanier, S., Castonguay, S., Drage, J. and Michaud, Y. (2007): Canadian groundwater inventory: hydrogeological atlas of the Annapolis Valley, Nova Scotia; Geological Survey of Canada, Open File 5541, URL <http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/3fd29ecc-485b-501d-ae80-78e9b5cbb031.html> [September 2013].

Riddell, J.T.F., Andriashek, L.D., Jean, G. and Slattery, S.R. (2009): Preliminary results of sediment coring in the Edmonton–Calgary Corridor, central Alberta; Energy Resources Conservation Board, ERCB/AGS Open File Report 2009-17, 81 p., URL <http://www.ags.gov.ab.ca/publications/abstracts/OFR_2009_17.html> [August 2013].

Slattery, S.R., Barker, A.A., Andriashek, L.D., Jean, G., Stewart, S.A., Moktan, H. and Lemay, T.G. (2010): Bedrock topography and sediment thickness mapping in the Edmonton–Calgary Corridor, central Alberta: an overview of protocols and methodologies; Energy Resources Conservation Board, ERCB/AGS Open File Report 2010-12, 16 p., URL <http://www.ags.gov.ab.ca/publications/abstracts/OFR_2010_12.html> [August 2013].

Shetsen, I. (1990): Quaternary Geology of Central Alberta; Alberta Research Council, Map 213. Scale 1:500 000. URL <http://www.ags.gov.ab.ca/publications/abstracts/MAP_213.html> [September 2013]

Thornthwaite, C. W. (1948): An approach toward a rational classification of climate; Geographic Review, v. 38, p. 55–94.

Toop, D. (2010): Impact of the June 2005 storm groundwater levels in the Bow River Basin, Alberta; GeoCanada Conference, Calgary, Alberta, May 10, 2010.

Turc, L. (1961): Evaluation des besoins en eau d'irrigation, evapotranspiration potentielle, formulation simplifie et mise à jour; Annales Agronomiques, v. 12, p. 13–49.

WorleyParsons Resources and Energy (2009): North Saskatchewan River Basin: overview of groundwater conditions, issues, and challenges; Report issued to North Saskatchewan Watershed Alliance, URL <http://www.nswa.ab.ca/content/north-saskatchewan-river-basin-overview-groundwater-conditions-issues-and-challenges> [September 2013].