Groundwater Recharge Estimates for the Lower Tertiary and Upper Cretaceous Aquifers in the Williston and Powder River Structural Basins

by

Katherine Aurand

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Prepared by:

Degree Candidate

Approved by:

Major Professor - Arden Davis, Ph.D.

Graduate Division Representative – Thomas Fontaine, Ph.D., Civil Engineering Dept.

Committee Member – J. Foster Sawyer, Ph.D.

Committee Member – Andrew Long, Ph.D., U.S. Geological Survey

Head of the Geology and Geological Engineering Department - Laurie Anderson, Ph.D

Dean of Graduate Education - Doug Wells, Ph.D.

Abstract

A numerical soil-water-balance (SWB) model was used to estimate groundwater recharge in the Williston and Powder River structural basins in the Northern Great Plains. The SWB model consisted of 1 km^2 grid cells across the entire study area. Recharge was estimated for glacial deposits and exposed areas of the Lower Tertiary and Upper Cretaceous aquifer systems in the Dakotas, Montana, Wyoming, Saskatchewan, and Manitoba. The water-table fluctuation (WTF) and chloride mass-balance (CMB) methods were applied to local areas with available groundwater-level and chloride data. SWB model results were compared to the WTF and CMB results, potentiometric surfaces, and previous investigations. A sensitivity analysis was conducted for the SWB model input parameters.

The annual SWB model recharge rates were averaged from 1981 to 2011. Average calculated recharge in the Williston basin was 0.190 in/yr (1,281 ft^3/sec) and ranged from no recharge to 4.71 in/yr. Calculated recharge decreased to the west and was greatest in the northeastern part of the basin where glaciofluvial deposits are present. Recharge was calculated to be about 1.1 percent of precipitation in the Williston basin. Average recharge in the Powder River basin was 0.136 in/yr (248 ft^3/sec) and ranged from no recharge to 4.46 in/yr. Calculated recharge rates are greatest during the late spring and early summer for both basins. Recharge was about 0.8 percent of precipitation in the Powder River basin. The SWB models did not activate the surface-water flow routing algorithm; therefore, recharge is probably underestimated and a scale factor could be used to account for the additional recharge to downslope cells from surface-water runoff.

Diffuse recharge estimates from the SWB models are reasonable and compare reasonably well with local recharge estimation results, potentiometric surfaces, and previous investigations. However, the SWB model results should be used cautiously, keeping in mind the assumptions of the model and the input data.

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Introduction

This project describes methods and estimates of groundwater recharge from precipitation to the Quaternary glacial aquifers and the Lower Tertiary and Upper Cretaceous aquifers in the Williston and Powder River structural basins. This project was completed as part of a U.S. Geological Survey groundwater availability study for the basins. The numerical soil-water-balance (SWB) model (Dipps and Bradbury, 2007; Westenbroek and others, 2010) was used to estimate diffuse recharge in both basins. The SWB model results were compared to local recharge estimation results, potentiometric surface maps, and previous groundwater studies. The water-table fluctuation method and chloride mass balance method were used to estimate local recharge rates where data were available. Recharge in the Powder River basin also was compared to potentiometric surface maps from Hotchkiss and Levings (1986). Recharge in the Williston basin was compared to preliminary potentiometric surface maps generated as part of the U.S. Geological Survey's Lower Tertiary and Upper Cretaceous groundwater availability study (Thamke and others, 2013). The thesis project was completed in conjunction with the South Dakota School of Mines and Technology and the U.S. Geological Survey.

Previous Studies

The difference between precipitation and potential evapotranspiration, or how much water is available for recharge to the groundwater system or as runoff to streams, was previously determined to be 0 to 5 in/yr for the study area, based on a national study (Roy and others, 2005). Estimated average annual groundwater recharge was previously determined to be primarily 0 to 0.5 in/yr in the study area based on a national study (Wolock, 2003).

Previous studies have estimated recharge in the Williston and Powder River basins, but there has not been a regional analysis explicitly investigating recharge for the basins. Previous recharge estimates in the Williston basin have all been conducted at a local scale. Chloride and nitrate deposition methods and the peak-displacement method were used to estimate recharge rates of 0.03 to 2.31 in/yr at the East Poplar oil field in northeastern Montana in 2006 (Healy, *in preparation*). The chloride deposition method, a water balance, and the water-table fluctuation method were used in the Cherry Creek drainage in Prairie County, Montana, to estimate recharge in the mid-1990s. The best estimate in that study was a recharge rate of 0.11 to 0.13 in/yr (Rose, 1996). Steady-state drainage equations were used to estimate a mean recharge of 0.08 in/yr in the upper Arm River Valley in southeastern Saskatchewan (Meyboom, 1967). Rehm and others (1982) used water-table hydrographs to estimate recharge rates of 0.67 in/yr to 3.15 in/yr in sandy material and 0.07 in/yr in fine-grained material in the Falkirk study area in central North Dakota.

Hotchkiss and Levings (1986) used a digital groundwater model to determine average annual recharge for the Powder River basin as 0.0245 in/yr. The Bureau of Land Management (2002) estimated an average recharge of 0.03 in/yr in the Powder River basin from a calibrated, steady-state simulation of a numerical groundwater model.

The SWB model has been used to estimate recharge at the regional scale in the Lake Michigan basin (Westenbroek and others, 2010) and the High Plains (Stanton and others, 2011). Flow routing to simulate recharge from runoff was not activated in the Lake Michigan basin SWB model because the large cell size (500 km x 500 km) would cause the recharge from runoff to be greatly overestimated (Feinstein and others, 2010).

Description of Study Area

The study area (Figure 1) is the extent of the Fox Hills Sandstone or its Canadian equivalents in the Williston and Powder River structural basins. Reference to the Williston and Powder River basins hereafter encompasses that extent. The basins are separated by the Miles City arch. The Williston basin covers approximately 91,300 mi^2 in North Dakota, South Dakota, and Montana in the United States and Saskatchewan and Manitoba in Canada. The Powder River basin covers approximately 24,800 mi^2 in Wyoming and Montana.

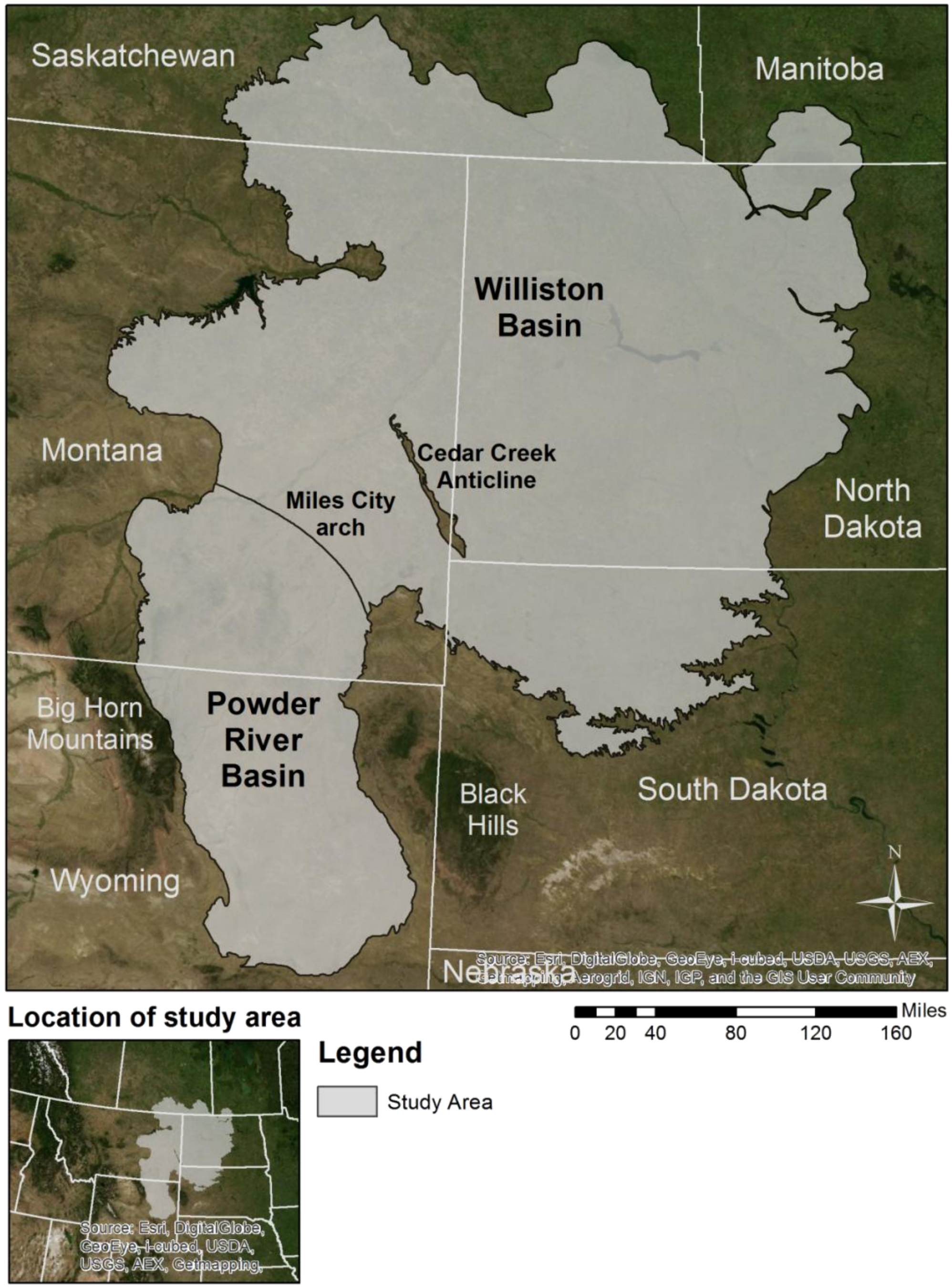

Figure 1. Location of study area.

Geology

The surficial geology of the Williston and Powder River basins is composed of Lower Tertiary and Upper Cretaceous sedimentary units and Pleistocene glacial deposits. The Upper Cretaceous units are the Fox Hills Sandstone and the Hell Creek Formation and their equivalents. The Lower Tertiary unit is the Fort Union Formation and its equivalents. Pleistocene glacial deposits are present in the Williston basin and are primarily clayey till with scattered glaciofluvial and glaciolacustrine deposits. The glacial deposits in the Williston basin are mostly continuous north of the Missouri River; the primary exception is the Peerless Plateau in the northwestern area of the basin.

The Fox Hills Sandstone is present in Wyoming, Montana, and North and South Dakota. Its Canadian equivalents are the Eastend Formation in Saskatchewan and the lower Boissevain Formation/Coulter Member of the Pierre Shale in Manitoba (Thamke and others, *in review*). The Fox Hills Sandstone is a late Cretaceous fine- to medium-grained marine sandstone with thin beds of sandy shale, mudstone, and siltstone representing shore and nearshore deposits. It conformably overlies the Pierre/Bearpaw Shale, and deposition is from the final stage of the late Cretaceous inland sea (Murphy, 2001).

The Hell Creek Formation is present in Montana and North and South Dakota. It is equivalent to the lower part of the Lance Formation in northeastern Wyoming (Balster and Ballard, 1971). Its Canadian equivalents are the Frenchman Formation in Saskatchewan and the Boissevain Formation in Manitoba (Thamke and others, *in review*). The Hell Creek Formation is a late Cretaceous, heterogeneous, continental clastic deposit composed of nonmarine sandstone, siltstone, shale, and discontinuous coal beds (Hotchkiss and Levings, 1986). It was likely deposited in swamps and floodplains adjacent to the late Cretaceous inland sea. The Hell Creek Formation is commonly divided into an upper and lower unit based on a moderately persistent coal seam (Rigby and others, 1990) or based on the relative percentage of sandstone (Hotchkiss and Levings, 1986). It overlies the Fox Hills Sandstone and its equivalents.

The early Tertiary (Paleocene) Fort Union Formation is commonly divided into two or three members and is present in Wyoming, Montana, and North and South Dakota. Depending on the geographical location, the members have different names. The lowest (oldest) members of the Fort Union Formation are the Tullock Member in Wyoming, the Ludlow and Tullock Members in Montana, and the Ludlow and Cannonball Members in North and South Dakota (Thamke and others, *in review*). This lowermost group of members is composed of interbedded sandstone, siltstone, shale, and thin coal beds (Hotchkiss and Levings, 1986). The members were deposited in flood basins and swamps of a large alluvial plain draining from the newly formed Rocky Mountain uplift. The members directly overlying the lowermost members are the Lebo Shale Member in Wyoming and Montana and the Slope Formation in North and South Dakota (Thamke and others, *in review*). The Lebo Shale is mostly dark shale with interbedded carbonaceous shale, siltstone, and sparse, thin coal beds (Hotchkiss and Levings, 1986). It locally contains a basal channel sandstone (Lewis and Hotchkiss, 1981). It was likely formed in a freshwater lacustrine environment (McLellan, 1992). The Slope Formation consists of interbedded sandstone, siltstone, mudstone, claystone, and lignite (Murphy, 2001). Its depositional environment was the same as the lowermost Fort Union Formation members. The uppermost (youngest) Fort Union Formation members include the Tongue River Member in Wyoming, the Tongue River and Sentinel Butte Members in Montana, and the Sentinel Butte Member in North Dakota (Thamke and others, *in review*). The Bullion Creek Formation in North Dakota is equivalent to Montana's Tongue River Member. The Tongue River Member is a fine-to medium-grained massive fluvial sandstone and siltstone. Thick coal beds are common, and clinker and baked-shale outcrops are prolific at the land surface in the Powder River basin and to a lesser extent in the Williston basin. The Bullion Creek Formation is composed of alternating beds of yellow sandstone, siltstone, mudstone, claystone, and lignite (Murphy, 2001). The Sentinel Butte Member contains blue and gray sandstones, siltstones, mudstones, and claystones (Murphy, 2001). The depositional environment of these uppermost members is similar to the rest of the Fort Union Formation members: continental deposits primarily from drainage responses to the Rocky Mountain Uplift. The Canadian equivalents to the Fort Union Formation are the Ravenscrag Formation in Saskatchewan and the Turtle Mountain Formation in Manitoba (Thamke and others, *in review*). The Fort Union Formation and its equivalents conformably overlie the Hell Creek Formation and its equivalents (Hotchkiss and Levings, 1986).

Hydrogeologic Setting

The Lower Tertiary and Upper Cretaceous (LTUC) aquifer system is composed of six hydrogeologic units (Figure 2) corresponding to the lithostratigraphic units mentioned in the previous section. Hydrogeologic units defined by Lewis and Hotchkiss (1981) and Hotchkiss and Levings (1986) for the Powder River basin were redefined so that the units could be consistent throughout both basins. The six hydrogeologic units overlie a thick shale unit (Pierre/Bearpaw Shales), and it is assumed that there is little or no hydraulic connection between the LTUC aquifer system and the aquifers underlying the shale. This basal confining unit encircles the LTUC aquifer system at the land surface in the study area with the exception being where the Bull Mountain structural basin and the Bighorn Mountains are adjacent to the Powder River structural basin.

The Lower Tertiary and Upper Cretaceous aquifer systems range from 0 to 2,246 ft and 0 to 1,047 ft thick, respectively, within the Williston basin and from 0 to 7,180 ft and 0 to 5,070 ft thick in the Powder River basin (Thamke and others, *in review*). In ascending lithostratigraphic order, the hydrogeologic units are the Fox Hills aquifer system, the Lower Hell Creek confining unit, the Upper Hell Creek aquifer system, the Lower Fort Union aquifer system, the Middle Fort Union confining unit, and the Upper Fort Union aquifer system.

Glacial deposits ranging in thickness from 0 to 756 ft overlie the LTUC aquifer system in the northeastern part of the Williston structural basin. The glacial deposits primarily consist of clayey, compacted till, fine-grained glaciolacustrine deposits, and glaciofluvial sand and gravel deposits. Even though till can contain sand, gravel, and boulders, the matrix is typically clay, resulting in very low permeability. Till acts as a confining unit where it overlies the LTUC aquifer system. The upper layer of till is typically weathered and fractures are present, which control subsurface flow. This active zone is typically less than 10 m deep and contains prairie potholes. The glaciofluvial sand and gravel aquifers are highly productive in the study area and exist at the land surface or are contained within the till.

One of the key differences between the glacial system in the Williston basin and the glacial system in the Upper Midwest is the stream density, which is a function of climate. The Upper Midwest, which has a humid climate, has a large stream network with water in the upper till zone discharging to streams. There are fewer streams in the Williston basin because the climate is semi-arid, and many streams are ephemeral. In the Williston basin, it would be difficult for water to move far enough laterally through the till to discharge to streams (as can occur in the Upper Midwest) because of the longer distances between streams and the lack of substantial precipitation. Therefore, the vertical flow component is likely more important in the till. Lateral flow will be important in the sand and gravel deposits.

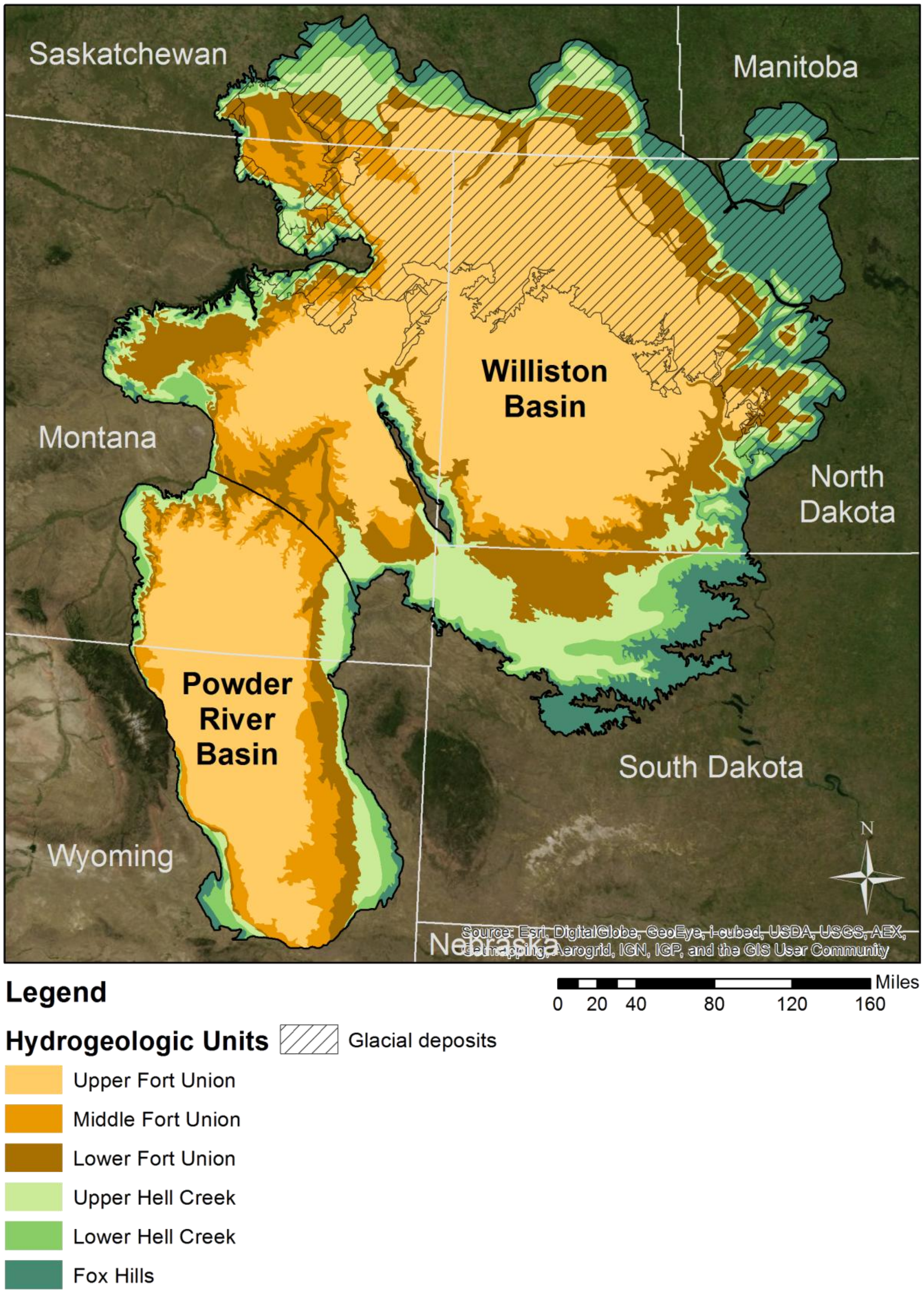

Figure 2. Hydrogeologic units present in the study area (data from Thamke and others, *in review*).

Physiography and Land Use

The study area is primarily composed of gently rolling hills. The terrain is typically hummocky where glacial deposits are present. Streams and rivers easily erode the sedimentary rocks, producing areas of relatively high topographic relief. The Yellowstone, Powder River, and Missouri rivers are the main surface-water features in the study area. Clinker often acts as a resistant cap in the Powder River basin, resulting in buttes.

Six main physiographic regions are present in and around the study area (Figure 3). The Peerless Plateau is an area of exposed bedrock surrounded by glacial deposits. The Missouri Coteau is a topographically high area created by glacial debris. It divides rivers that drain to the Gulf of Mexico from rivers that drain to the Hudson Bay. The Prairie Pothole Region is composed of numerous kettle lakes formed by glaciotectonic features and melting ice blocks during the last glacial period. The depressions typically fill with water from rainfall and snowmelt, and some are connected to the groundwater system. The Black Hills, Laramie Mountains, and Bighorn Mountains are topographically high areas that receive greater amounts of precipitation and recharge than the Williston and Powder River basins.

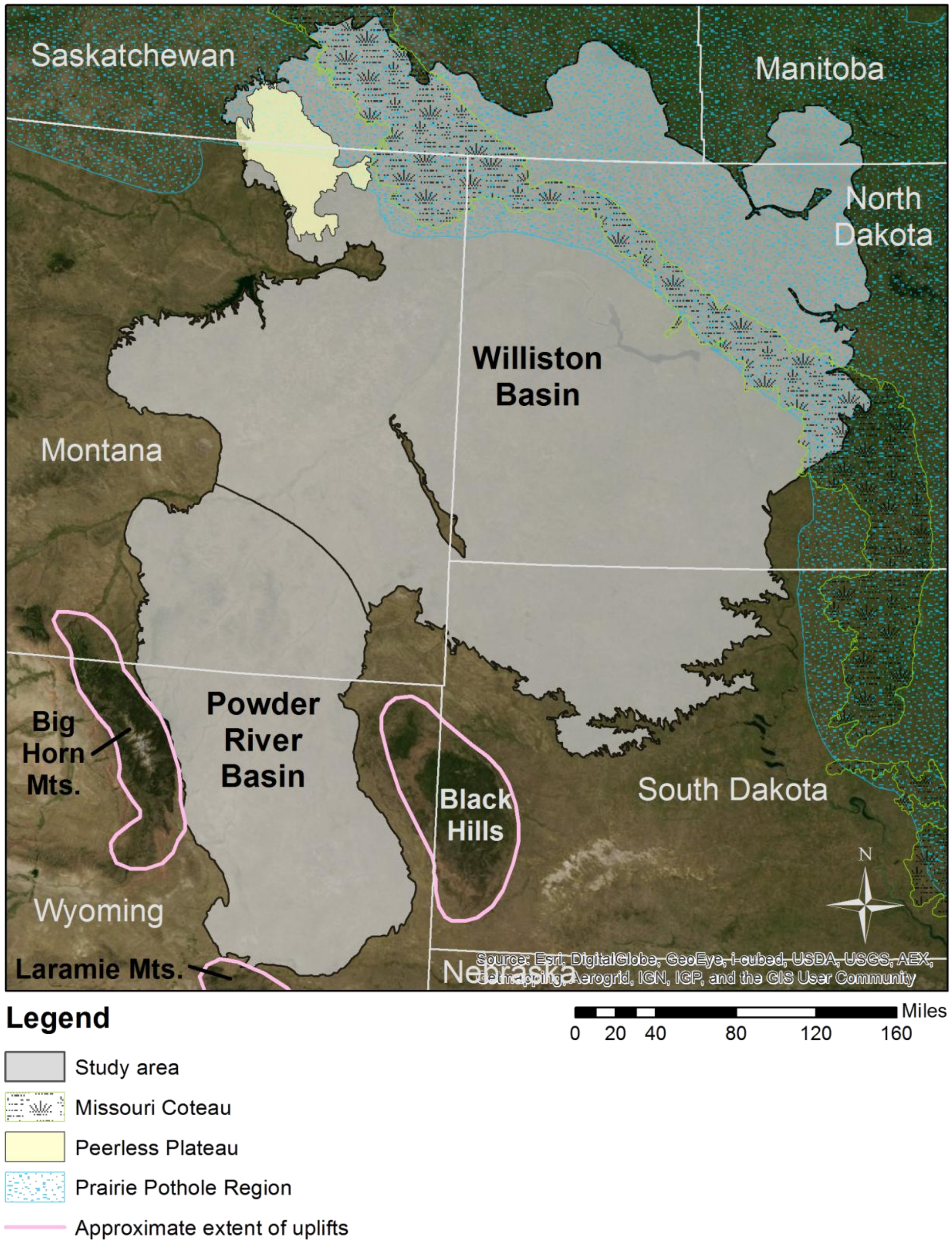

Figure 3. Locations of physiographic regions in and around the study area.

Land cover in the study area is dominated by grasslands, cultivated crops, evergreen forest, and pastures (Tables 1 and 2).

Table 1. Table of land cover types present in the Williston basin. Data based on the 2006 National Land Cover Dataset (Fry and others, 2011).

Land Use Code	Description	Amount of Coverage
71	Grassland/Herbaceous	47.88%
82	Cultivated Crops	33.14%
81	Pasture/Hay	5.62%
52	Shrub/Scrub	4.21%
11	Open Water	2.19%
21	Developed, Open Space	1.99%
95	Emergent Herbaceous Wetlands	1.52%
41	Deciduous Forest	1.38%
90	Woody Wetlands	0.74%
42	Evergreen Forest	0.63%
31	Barren Land	0.33%
22	Developed, Low Intensity	0.20%
23	Developed, Medium Intensity	0.10%
43	Mixed Forest	0.05%
24	Developed, High Intensity	0.004%

Table 2. Table of land cover types present in the Powder River basin. Data based on the 2006 National Land Cover Dataset (Fry and others, 2011).

Land Use Code	Description	Amount of Coverage
71	Grassland/Herbaceous	55.39%
52	Shrub/Scrub	33.66%
42	Evergreen Forest	6.78%
82	Cultivated Crops	1.06%
90	Woody Wetlands	0.96%
31	Barren Land	0.57%
81	Pasture/Hay	0.54%
21	Developed, Open Space	0.44%
95	Emergent Herbaceous Wetlands	0.26%
11	Open Water	0.12%
22	Developed, Low Intensity	0.10%
41	Deciduous Forest	0.07%
23	Developed, Medium Intensity	0.03%
24	Developed, High Intensity	0.01%

Climate

The study area is semi-arid, receiving 11.10 to 24.67 in/yr of precipitation in the Williston basin and 11.44 to 20.80 in/yr in the Powder River basin (Figure 4). Average annual precipitation for each basin and average annual actual evapotranspiration (AET) calculated from the SWB models are summarized in Appendix A.

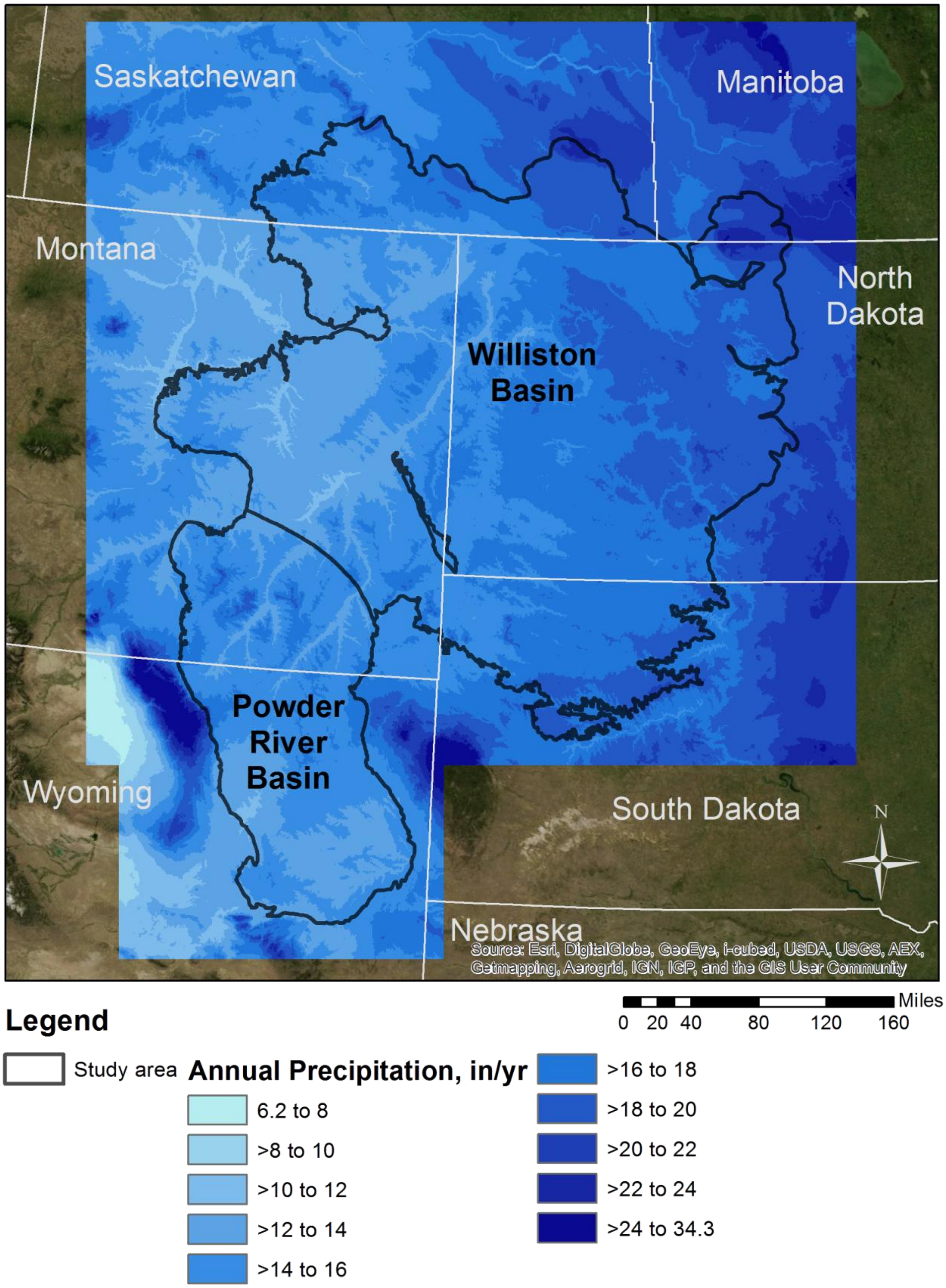

Figure 4**.** Average annual precipitation in the model area from 1981 to 2011, based on Daymet climate data (Thornton and others, 2012; Thornton and others, 1997).

Methods

SWB Model Theory

The SWB model is a two-dimensional, gridded code that estimates recharge based on the soil-water-balance methodology (Figure 5). The inputs for the SWB model include daily precipitation and temperature data, land-use classification, soil type, and surface-water flow direction. Recharge is based on a modified Thornthwaite-Mather soil-water accounting method (Thornthwaite and Mather, 1957), where recharge is calculated as the difference between the change in soil moisture and the flow rates of sources and sinks (equation 1).

$$R = (p + s + f_{in}) - (c + ET + f_{out}) - \Delta m \qquad (1)$$

where all equation terms are expressed as the height of water for each model cell, and

R	is the daily recharge in inches,
p	is precipitation in inches,
s	is snowmelt in inches of equivalent water,
f_{in}	is surface-water inflow,
c	is interception,
ET	is evapotranspiration,
f_{out}	is surface-water outflow, and
Δm	is the change in soil moisture (positive when increasing).

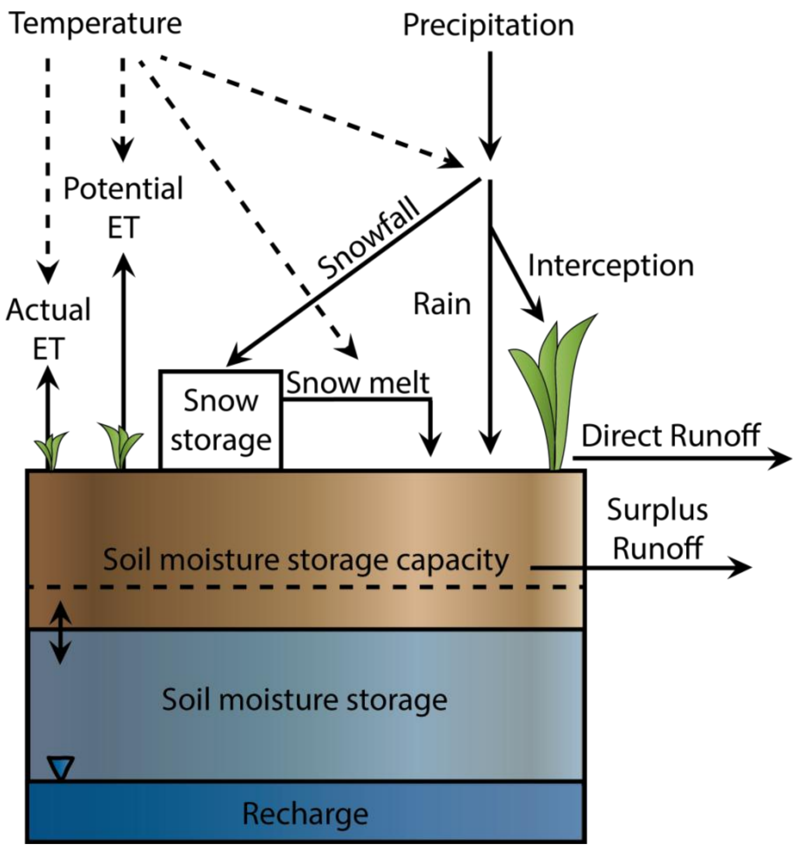

Figure 5. Schematic diagram of soil-water-balance methods.

Sources

The three recharge sources are precipitation, snowmelt, and inflow. Precipitation includes both rainfall and snowfall, and the model includes a temperature-index algorithm to determine when precipitation is rainfall and when it is snowfall (equation 2).

$$T_{prcp} = T_{avg} - \frac{1}{3} * (T_{max} - T_{min}) \tag{2}$$

where precipitation is snowfall when T_{prcp} is less than or equal to the freezing point of water. T_{max} and T_{min} are the daily maximum and minimum air temperatures and T_{avg} is the average of T_{max} and T_{min}. Snow and snowmelt are expressed as snow water equivalent, and the code assumes that 1.5 mm (0.059 in) of snow melts per day per average degree Celsius that the daily maximum temperature is above the freezing point (Dripps and Bradbury, 2005; Westenbroek and others, 2010).

Inflow is the daily surface runoff from an adjoining, upslope cell based on an eight-point flow-direction grid derived from a digital elevation model. Inflow is zero when flow routing is not used.

Sinks

The three sinks are interception, outflow, and evapotranspiration. Interception is precipitation that does not reach the land surface because it is intercepted by the leaves and branches of plants and trees. An interception value for each land cover can be specified and for two seasons: growing and dormant.

Outflow is synonymous with surface runoff. It is calculated by using the curve number (CN) method of the Natural Resources Conservation Service (NRCS; formerly Soil Conservation Service). This method calculates the precipitation loss for each time interval and then subtracts that from the maximum accumulated precipitation depth for that interval. When the precipitation rate exceeds the infiltration rate, runoff occurs. Therefore, no runoff occurs until the accumulated precipitation on the pervious area is greater than the initial loss amount. The CN method does not take into account temperature of the soil, which can have an effect on the infiltration rate. The CN method calculates precipitation excess, or runoff, as a function of cumulative precipitation, soil cover, land use, and antecedent moisture (Cronshey and others, 1986). Runoff is calculated by equation 3 when precipitation is greater than initial abstraction.

$$Ro = \frac{(P - I_a)^2}{(P - I_a + S_{max})} \qquad (3)$$

where all terms are expressed as inches of water, and

Ro	is the direct runoff,
P	is the rainfall depth,
I_a	is the initial abstraction,
S_{max}	is the maximum storage term as described in equation 6, and
$P\text{-}I_a$	is also called effective rainfall, or P_e

The runoff (precipitation excess) is zero until the accumulated rainfall exceeds the initial abstraction. The initial abstraction term represents interception and depression storage, which are losses that occur before runoff initiation. An empirical relationship of initial abstraction and potential losses was determined by the NRCS (equation 4).

$$I_a = 0.2\ S_{max} \qquad (4)$$

The SWB model allows an alternative initial abstraction term to be 0.05 S_{max} instead, which increases runoff for smaller precipitation events and has been suggested to be more appropriate for long-term simulations (Woodward and others, 2003).

The relationship between initial abstraction and the maximum storage term can substitute into equation 3 to produce another way to show the cumulative excess precipitation at time t (equation 5).

$$P_e = \frac{(P - 0.2S_{max})^2}{P + 0.8\ S_{max}} \qquad (5)$$

The potential losses and watershed characteristics (soil type, land use, and percent impervious area) are related through the curve number (equation 6).

$$S_{max} = \frac{1{,}000}{CN} - 10 \quad (6)$$

where CN is the curve number and is dimensionless. Equation 6 is valid only if the maximum storage term is expressed in inches. Metric units require different constants.

The curve number is a term used to define the difference between precipitation and initial abstraction, which is a summation of processes that reduce runoff such as interception, depression storage, and infiltration (Woodward and others, 2003). The curve number is based on land use, hydrologic condition, average percent impervious area, and hydrologic soil group. The curve number is unique for each land cover and soil type combination. Curve numbers can range from 0 to 100 (Mockus, 1964), but typical values are from 30 to 98 (Woodward and others, 2003). Higher curve numbers result in lower rates of infiltration and vice versa.

The advantage of using the NRCS CN is that the method is simple, predictable, and stable. It also relies on only one parameter which is a function of the soil group, land use, surface condition, and antecedent moisture condition. The method is well established in the United States and abroad (Ponce and Hawkins, 1996).

Curve numbers are increased or decreased depending on the amount of precipitation within the previous five days. The antecedent runoff conditions are defined in Table 3.

Table 3. Antecedent runoff conditions used in the SWB code, where the precipitation amount is a summation of the previous five days' precipitation in inches (reproduced from Westenbroek and others, 2010).

Condition	Soil Wetness	Dormant Season	Growing Season
I	Dry	< 0.05	<1.4
II	Average	0.5-1.1	1.4-2.1
III	Near saturation	>1.1	>2.1

Curve numbers are typically described for antecedent runoff condition II. When soil is either dry or near saturation, the curve numbers are adjusted according to equations 7 and 8 (Mishra and Singh, 2003).

$$CN_{ARC\ (III)} = \frac{CN_{ARC(II)}}{0.427+0.00573*CN_{ARC\ (II)}} \quad (7)$$

$$CN_{ARC\ (I)} = \frac{CN_{ARC(II)}}{2.281-0.01281*CN_{ARC\ (II)}} \quad (8)$$

When soil is frozen, infiltration rates are decreased and runoff from precipitation is increased. The SWB model tracks frozen ground by using the continuous frozen ground index (CFGI), which is described in equation 9 (Molnau and Bissel,1983).

$$CFGI_i = A * CFGI_{i-1} - T * e^{(-0.4K*D)} \geq 0 \quad (9)$$

where

$CFGI_i$ is continuous frozen ground index on day i (°C-days),
$CFGI_{i-1}$ is continuous frozen ground index on day i-1(°C-days),
T is daily mean air temperature (°C),
A is daily decay coefficient (unitless),
K is snow reduction coefficient (cm^{-1}), and
D is the depth of snow on ground (cm).

T, the daily mean air temperature, is calculated by the model as the average of the daily maximum and daily minimum air temperatures. The daily decay coefficient, A, is 0.97 (Molnau and Bissel, 1983). The snow reduction coefficient, K, is 0.5 cm^{-1} for temperatures above 32°F (0°C) and 0.08 cm^{-1} for temperatures below 32°F (0°C) (Molnau and Bissel, 1983). When no snow is present, the CFGI simply tracks how the temperature deviates from the freezing point of water. The CFGI allows for a transition range through which runoff is enhanced and is defined by the probability of runoff enhancement factor, P_f (equation 10) (Molnau and Bissel, 1983).

$$P_f = \frac{CFGI - LL}{UL - LL} \tag{10}$$

where

P_f is the daily probability that runoff will be increased by frozen ground conditions (dimensionless),
UL is the upper limit of CFGI (°C-days), and
LL is the lower limit of CFGI (°C-days).

The ground is considered to be completely frozen above the CFGI upper limit and completely thawed below the CFGI lower limit. Molnau and Bissel (1983) recommended that the upper limit be defined as 83°C-days and the lower limit be defined as 56°C-days. P_f is used to linearly interpolate between average soil conditions and saturated soil conditions (Westenbroek and others, 2010). Saturated soil conditions are used to simulate frozen ground conditions because little to no infiltration is allowed for either case.

Evapotranspiration (ET) is precipitation loss from the following: evaporation from the soil, evaporation of intercepted water, evaporation from depression storage, and transpiration of water by trees and plants (Gupta, 2008). Potential ET (PET) is the amount of ET that would occur if a sufficient amount of water were available. Actual ET (AET) is equal to the PET when precipitation minus PET is positive because there is enough water available for the total amount of PET to occur. When precipitation minus PET is negative, the AET is only equal to the amount of water that can be extracted from the soil. The SWB model assumes the water table is below the root zone and water from the aquifer itself does not contribute additional moisture to increase AET. AET is calculated based on the amount of moisture available in the soil column.

Five methods are available to calculate PET in the SWB model code. The code is constructed such that all methods except the Hargreaves and Samani (1985) method produce an estimate of PET that is uniform across the model grid. The Hargreaves and Samani method can produce a spatially variable estimate of PET because it only requires daily maximum and minimum air temperatures. Hargreaves and Samani (1985) estimated daily PET according to equation 11.

$$ET_o = 0.0023 * R_a * (TC + 17.8) * TR^{0.50} \quad (11)$$

where

R_a is incoming solar energy, based on Earth's distance from the sun (Langley/day),

TC is daily average temperature (°C) (the mean of the daily T_{max} and T_{min}), and

TR is daily T_{max} minus daily T_{min}(°C).

Soil Moisture

The Thornthwaite and Mather (1957) soil-water balance method was used to calculate soil moisture on a daily time step. The first step of the method is to subtract PET from precipitation (P-PET). If the result is positive, there is a potential surplus of water. If the result is negative, there is a potential deficiency of water. The second step of the method is to calculate an accumulated potential water loss (APWL) that is a continuous sum of daily P-PET results for periods when the results are consecutively negative. Soils give up water more readily during the first days when P-PET is zero, and the water yield is decreased as the APWL increases. A nonlinear relationship exists between soil moisture and the APWL, which was described in a series of tables produced in Thornthwaite and Mather (1957) and incorporated into the SWB code. Finally, the change in soil moisture is calculated as the difference between the amount of moisture in the soil for the previous day and the current day for a given grid cell (Westenbroek and others, 2010). The soil moisture term is bounded by the soil's maximum water-holding capacity and the soil's wilting capacity. The soil moisture is increased when P-PET is positive, and the Thornthwaite-Mather soil tables are used to calculate a new, reduced APWL. If the new soil moisture is greater than the soil's maximum holding capacity, the excess moisture is converted to recharge and the APWL is reset to zero. The soil moisture term is determined by the current APWL if P-PET is negative for the day.

Model Limitations

Hydrologic computer models are powerful tools that, when used correctly, can provide accurate insight into physical processes and responses. The SWB model is a simplification of reality, and its accuracy is a function of its assumptions, the quality of the input data, and the knowledge and capability of the modeler.

Curve Number Method

The curve number method was developed from small agricultural watersheds in the midwestern United States, so applicability elsewhere and for regional-scale applications is uncertain. Other limitations are that rainfall intensity is not considered, default initial abstraction (0.2 S_{max} or 0.05 S_{max}) is not dependent on storm characteristics, and the predicted values are not in accordance with classical unsaturated flow theory (it does not physically represent the process). The curve number method was designed to evaluate flood stages and was not intended for everyday magnitudes (Garen and Moore, 2005). However, the method is well established in the United States and abroad (Ponce and Hawkins, 1996).

Infiltration Rates

When flow routing is activated in the model, surface runoff cascades downgradient until it reaches a cell that can accept the water as recharge or until it reaches a surface-water feature. If localized depressions exist, the surface runoff pools in those cells and produces unrealistically high recharge values. A maximum infiltration value for each land use and soil type combination can be specified in the lookup table to decrease this effect. The maximum infiltration value is still applied when flow routing is not activated, but it has a proportionally smaller impact on the recharge rates. The maximum infiltration rate in the lookup table can be set to equal the saturated vertical hydraulic conductivity of the underlying hydrogeologic unit.

Evapotranspiration Algorithms

The Hargreaves and Samani (1985) ET method is the only applicable method available in the SWB code for a regional scale model because it is the only method in the SWB code to provide spatially variable ET. However, the Hargreaves and Samani ET method only takes into account maximum and minimum air temperature and solar radiation. It does not take into account vegetation type and density, active and dormant seasons, cloud cover, wind speed, or humidity.

Climate Data

Gridded climate data sets are generated by interpolating point observation stations. The actual precipitation and maximum and minimum air temperatures throughout the entire study area are estimated by these interpolation methods and not specifically known.

SWB Model Input

Two SWB models were constructed and executed (model control files are shown in Appendix B). The SWB method requires a rectangular grid, and the model boundaries were extended at least 15 miles from the basin boundaries (Figure 6). Model cell size was 1 km x 1 km to match the gridded climate data. The Williston basin SWB model was 710 km x 735 km and had 521,850 cells. The Powder River basin SWB model was 475 km x 310 km and had 147,250 cells.

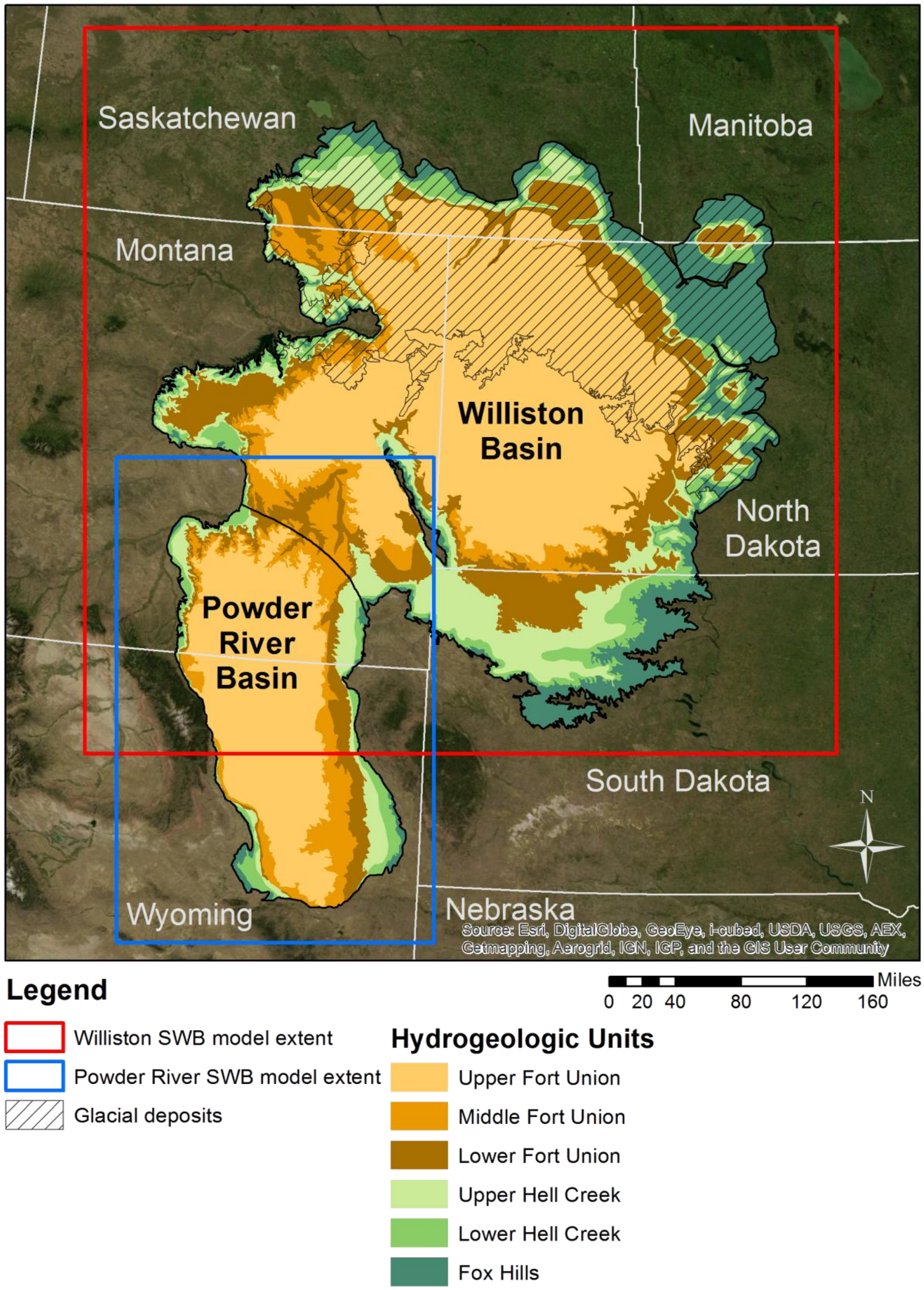

Figure 6. SWB model boundaries.

Assumptions

Maximum Infiltration Rates

The maximum infiltration rates for the NRCS hydrologic soil groups A, B, C, and D were similar to rates used in other SWB regional models (Stanton and others, 2011; Westenbroek and others, 2010). The glacial deposit maximum infiltration rates were set to equal the maximum infiltration values determined for glacial deposits in the Lake Michigan Basin (Westenbroek and others, 2010).

Initialization Period

Initial conditions, such as initial soil moisture, snow cover, and initial frozen ground index, were estimated at the start of the model. A model was run for 1980 as a ramp-up year. The results from the end of the 1980 calculations then were used as the initial values for the 1981 to 2011 simulation.

Input Data

Climate

SWB requires data for precipitation and minimum and maximum temperature on a daily basis. The Daymet data set (Thornton and others, 2012; Thornton and others, 1997) includes gridded daily precipitation and daily minimum and maximum air temperature at 1 km^2 resolution. The Daymet data set is produced by interpolating available ground observation data based on a spatial convolution of a truncated Gaussian weighting filter with the available set of station locations. The ground observation data for the United States is from the Cooperative Summary of the Day network of weather stations archived and distributed by the National Climate Data Center (NCDC) and from the SNOwpack and TELemetry (SNOTEL) dataset managed and distributed by the

Natural Resources Conservation Service (NRCS). Canadian ground observation data used in the Daymet method is from the Government of Canada (Environment Canada). The quantity and location of observation stations varies throughout time. The Daymet method uses all available observation stations for each time step. The spatial distribution of observation stations used for 2005 climate data is shown in Figure 7.

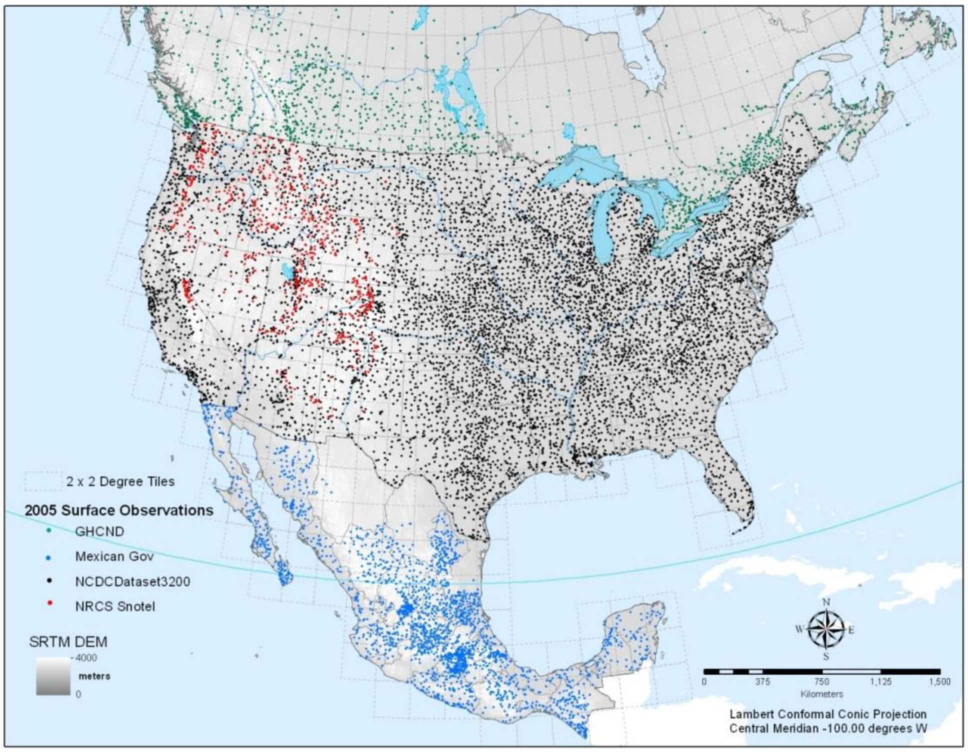

Figure 7. Spatial distribution of climate observation stations used in the Daymet method for the year 2005 (copied from http://daymet.ornl.gov; accessed April 1, 2013).

SWB model projection and cell size were set to match the Daymet data because precipitation is the primary factor influencing groundwater recharge and is the only water source in the SWB model. The Geo Data Portal (Blodgett and others, 2011) was used to extract the required Daymet values. Daymet does not have data for December 31 on leap years, but it has data for February 29. The SWB model requires all 366 days during leap years, so the Daymet input for December 30 of leap years was also used for December 31.

Land Use

The land use data, also known as the land cover data, were obtained from the Multi-Resolution Land Characteristics Consortium's (MRLC) 2006 National Land Cover Dataset (NLCD) (Fry and others, 2011). Canadian land cover data were synchronized with the American land cover data according to the procedure described in Appendix C. The land cover types were based on vegetation and level of development and used to determine the curve number (Cronshey and others, 1986). Each model cell was assigned a land cover type from the land cover that occupied the majority of the cell (Figure 8).

Available Soil-Water Capacity

The available soil-water capacity values (in inches of water per foot of soil) were obtained from NRCS soil surveys. A weighted average of the available water capacity throughout the soil depth was calculated, and the major soil type within the model cell was used to assign the value to the cell (Figure 9). The available soil-water capacity for the glacial deposits was determined by soil texture according to Westenbroek and others (2010).

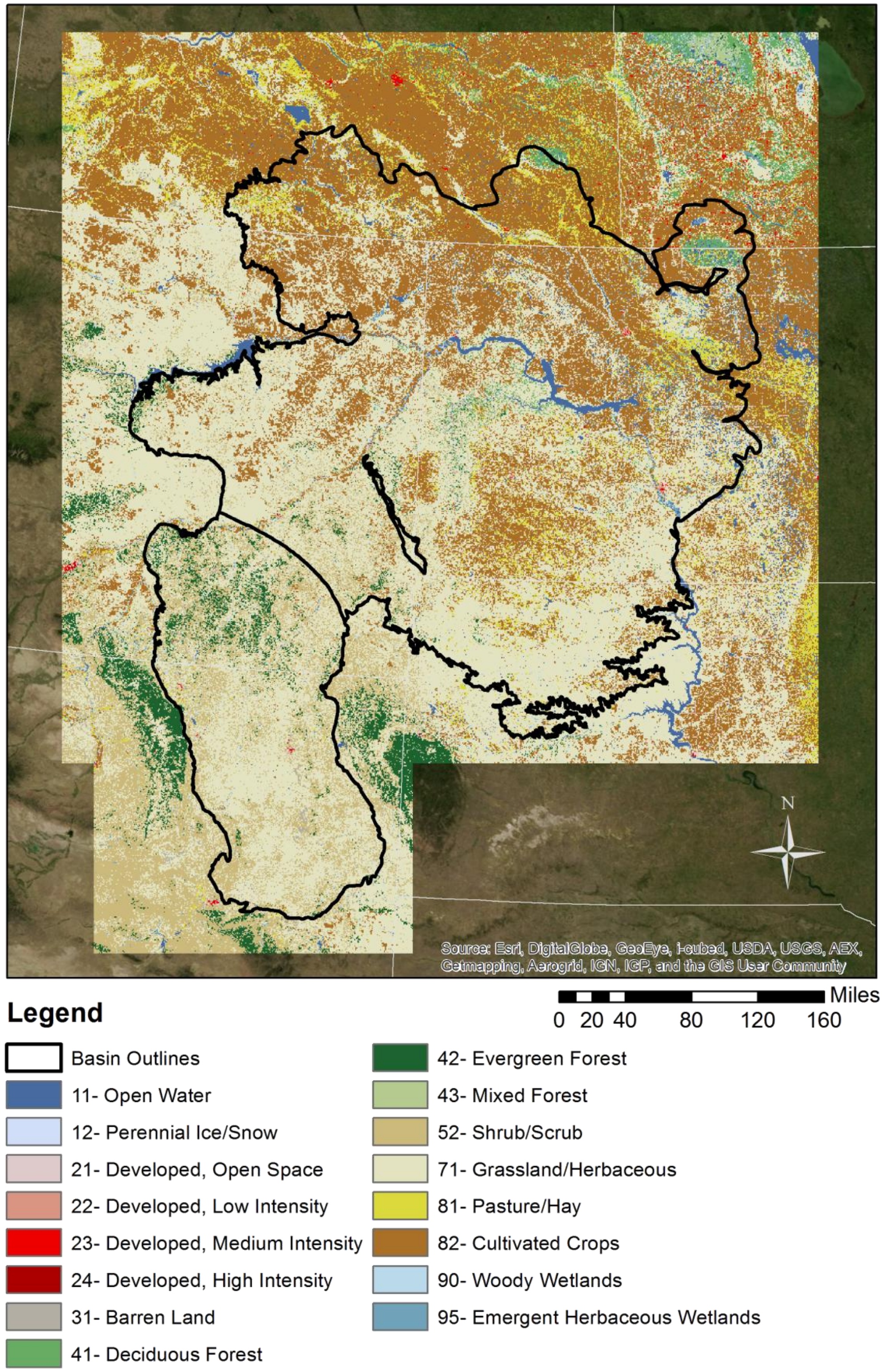

Figure 8. Land cover upscaled from a 30 m x 30 m cell size to a 1 km x 1 km cell size. Grassland and crops are the dominant land covers.

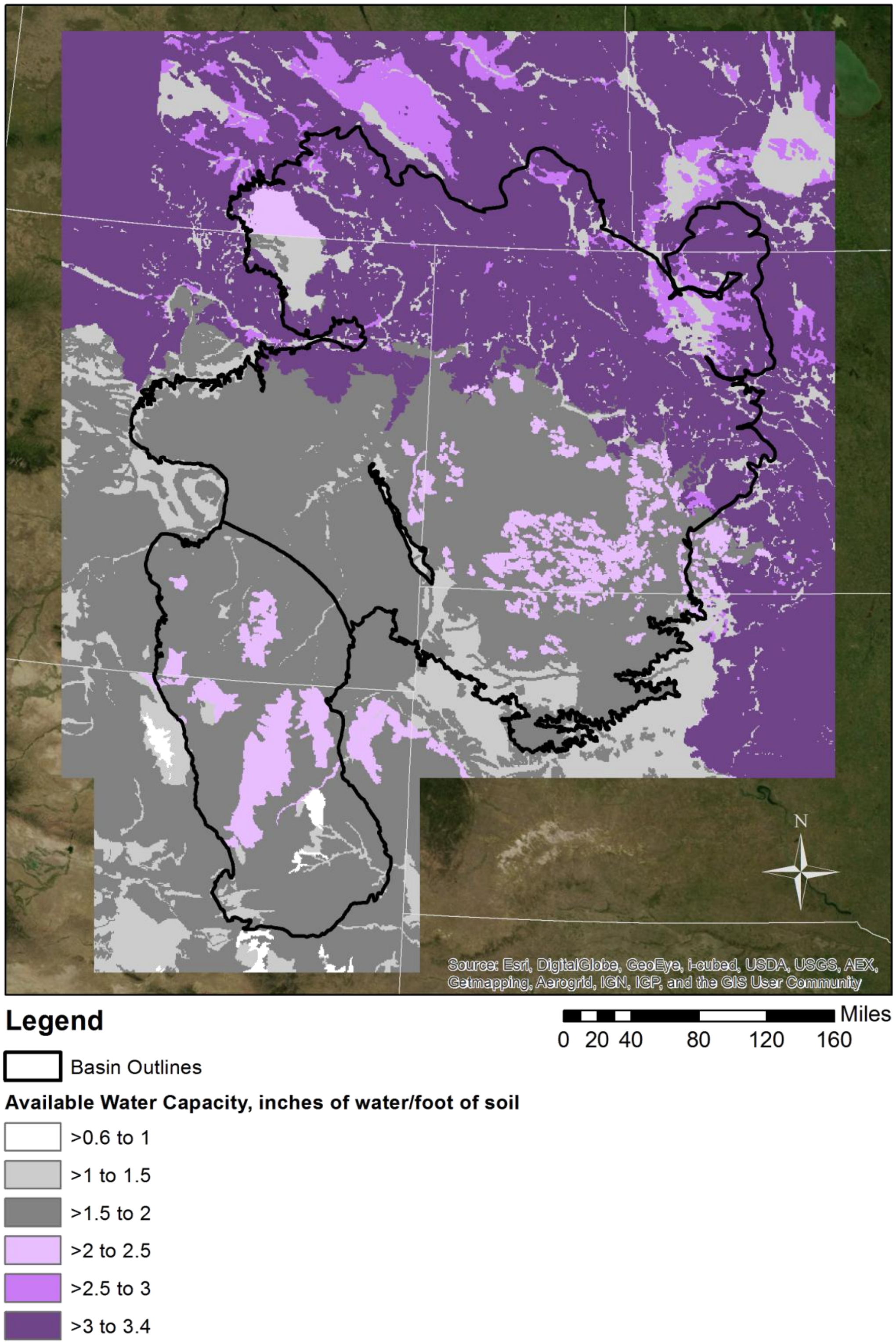

Figure 9. Available soil-water capacity in inches of water per foot of soil.

Hydrologic Soil Groups

The hydrologic soil groups are necessary to assign a curve number in the lookup table (Appendix D). They are also used to assign a maximum infiltration rate and root zone depth. The NRCS has grouped soils into four hydrologic groups based on the infiltration rate of the least permeable layer in the soil column (NRCS, 2007) (Table 4).

Table 4. NRCS hydrologic soil groups.

Hydrologic Soil Group	**Minimum Infiltration Rate (in/hour)**	**Texture**
A	0.3-0.45	Sand, loamy sand, or sandy loam
B	0.15-0.30	Silt loam or loam
C	0.05-0.15	Sandy clay loam
D	0-0.05	Clay loam, silty clay loam, sandy clay, silty clay, or clay

Where glacial deposits are present at the land surface, additional hydrologic soils groups were created to better account for the spatial variability of recharge with regard to the permeability of the glacial deposits. This method is consistent with Westenbroek and others (2010) and Feinstein and others (2010), where they used Quaternary geologic maps to assign hydrologic soil groups and available water capacities based on glacial deposit lithology. In this study, Quaternary geologic and sediment maps (Fullerton and others, 1995; 2000; 2007) were used to define the hydrologic soil groups. Where these maps did not cover parts of the glacial deposits, a Quaternary sediments map (Soller and others, 2012) was used. Surficial-geology maps were not available for the far northwestern part of the SWB model, and therefore it was assumed to be entirely clayey till, which is the dominant glacial deposit in the model extent. This area is outside of the study area (basin extent). The additional hydrologic soil groups were 1) till, 2) glaciolacustrine deposits, 3) glaciofluvial deposits, 4) loess and eolian deposits, and 5) glaciotectonic deposits. The Quaternary geologic and sediment maps also included an open water category that did not have geologic or sediment data associated with it. The parameters in the lookup table for the open water hydrologic soil group were coded such that it would be treated the same as the open water land cover group. Recharge in open water cells is not calculated in the SWB code because open water cells are assumed to drain through surface-water features, which are not explicitly considered in the SWB code (Westenbroek and others, 2010).

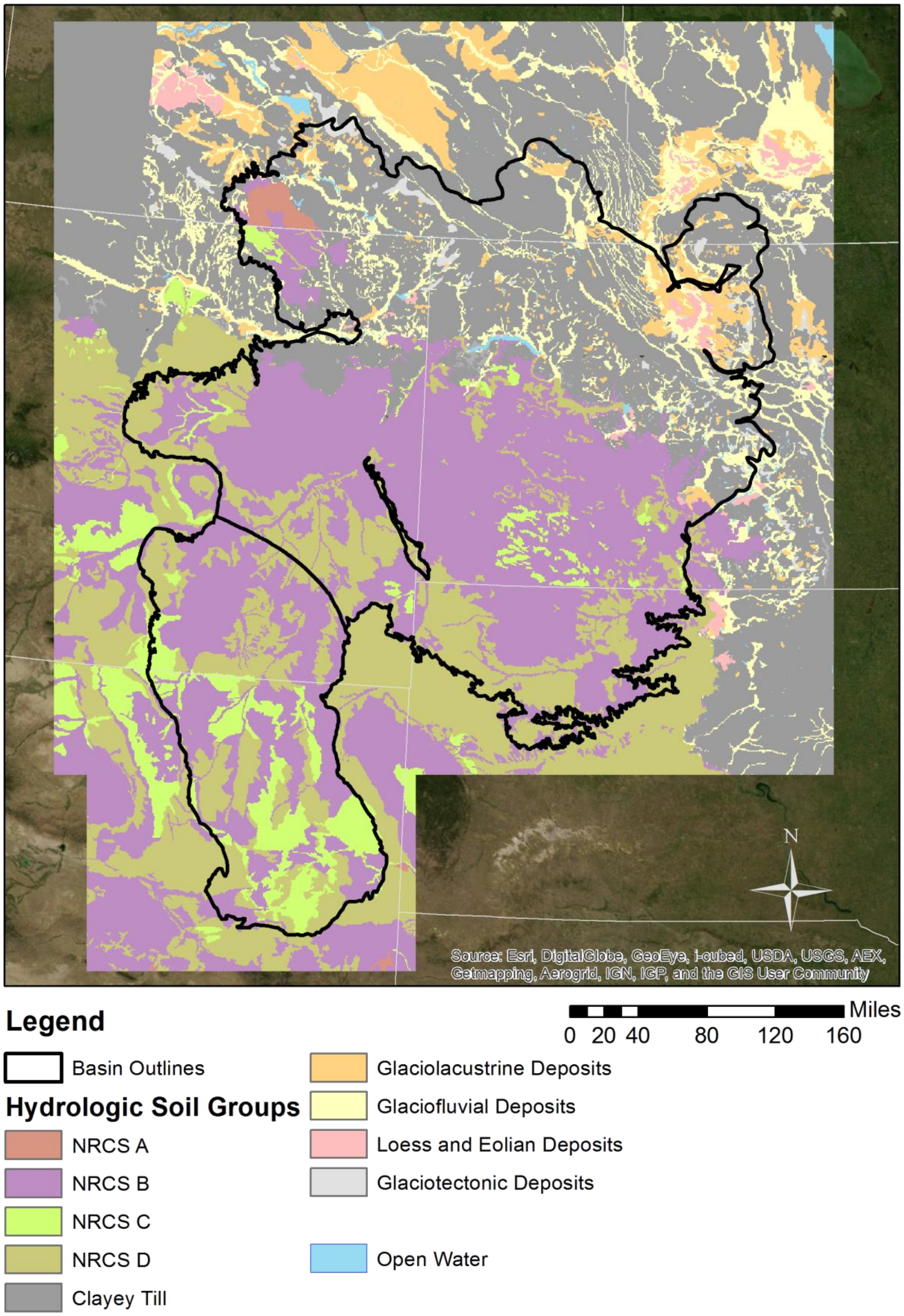

Figure 10. Hydrologic soil groups used for the SWB models.

Land Use Lookup Table

The land use lookup table is a matrix that specifies a curve number, maximum infiltration, interception amount, and root zone depth for each land cover and hydrologic soil group combination. Lookup tables used for the SWB model simulations are shown in Appendix D. These glacial deposit hydrologic soil groups were condensed to three hydrologic soil groups to assign the available water capacity and root zone depths in the lookup table. The groupings were as follows and correspond to glacial deposit classes used by Westenbroek and others (2010) and Feinstein and others (2010): till (composed of the till and glaciotectonic deposits), fine-grained (glaciolacustrine deposits), and coarse-grained (glaciofluvial deposits, loess, and eolian deposits).

The curve numbers were assigned from Cronshey and others (1986). Some land cover types have good, fair, and poor curve numbers conditions for each hydrologic soil group. The good condition curve number is used when better than average infiltration occurs and runoff is decreased. The poor condition curve number is used when infiltration is impaired and runoff is increased. Fair conditions reflect average infiltration and runoff. Where good, fair, and poor conditions were available for assigning a curve number for a specific land cover / hydrologic soil group combination, fair condition curve numbers were used because they best reflect the average of the spatial variability of infiltration and runoff.

The curve numbers for the glacial deposit hydrologic soil groups were assigned on the basis of grain size. The curve numbers for till were assigned the same values as NRCS hydrologic soil group D. The glaciolacustrine curve numbers were an average of NRCS hydrologic soil groups B and C. The glaciofluvial and loess and eolian deposits were assigned curve numbers from NRCS hydrologic soil group A. The glaciotectonic features were assigned curve numbers that were the average of the till and glaciolacustrine curve numbers.

Maximum infiltration values were determined by the method described in the SWB Model Input – Assumptions section above.

Precipitation interception fractions, which are a function of land cover, were set to equal the values recommended by Westenbroek and others (2010) and used in other SWB models (Feinstein and others, 2010; Stanton and others, 2011).

Root zone depths were assigned based on common vegetation types for each land cover. The common vegetation types for the Northern Great Plains were described in Barker and Whitman (1988). Root zone depths were based on data from Canadell and others (1996).

Surface-Water Flow Direction

A flow direction grid of the model area can be used if surface runoff routing is turned on. This allows the runoff to be moved to the nearest downgradient cell instead of simply being removed from the system. The SWB overland flow routing option was not used for the basin SWB models because the large cell size greatly overestimated the amount of excess water routed downslope. This practice of disabling flow routing for models with large grid cells is consistent with Feinstein and others (2010) and Westenbroek and others (2010). Two simulations of the Powder River model were run with flow routing turned on and off, and the average annual recharge rate with the flow routing option was almost 200 percent more than without the flow routing option.

However, running a model without the flow routing option underestimates recharge because it does not capture recharge from runoff.

Water-Table Fluctuation Method

The water-table fluctuation (WTF) method uses easily accessible groundwater level data to estimate recharge and might be one of the most commonly used recharge estimation techniques (Healy and Cook, 2002). The WTF method assumes that rises in groundwater levels are a result of recharge from precipitation arriving at the water table (Healy, 2010), relating water-table elevation changes and storage changes in the aquifer. For this assumption to be valid, only recharge to unconfined aquifers can be estimated by this method (Healy and Cook, 2002). Recharge is calculated by multiplying the specific yield of the aquifer by the change in water height as shown in Equation 12 (Healy, 2010) and as demonstrated in Figure 11. The change in water height (ΔH) is the difference between the extrapolated antecedent recession curve and the peak of the rise from the recharge event (Healy, 2010). The extrapolated antecedent recession curve is the path the well hydrograph would have followed if the recharge event had not occurred (Healy, 2010).

$$R(t_j) = Sy * \Delta H(t_j) \quad (12)$$

where

$R(t_j)$ is recharge (in) occurring between times t_0 and t_j,
Sy is specific yield (dimensionless), and
$\Delta H(t_j)$ is peak water-table rise (in) attributed to the recharge period.

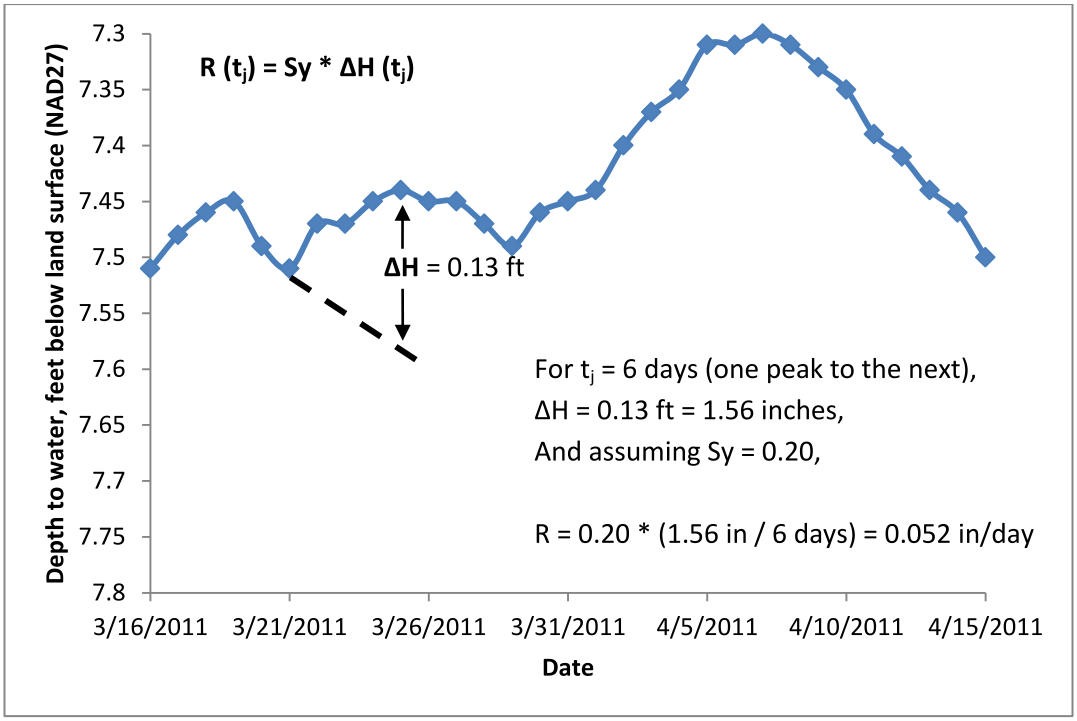

Figure 11. Graph of depth to the water table describing the steps to calculate recharge over a time step.

Specific yield is the ratio of (1) the volume of water which the rock, after being saturated, will yield to gravity to (2) its own volume (Meinzer, 1923). For the water-table fluctuation method to be applied, it is assumed that the amount of available water in a unit surface area is equivalent to the height of the water column (Healy, 2010).

There are three primary approaches for calculating ΔH: graphical, simple water-table level analysis program application, and application of programs automating generation of recession curves.

The traditional graphical approach is performed by manually drawing the antecedent recession curves on a well hydrograph. The curves are based on the scientist's best guess as to how the recession curve would behave in the absence of recharge events. This approach is very time-consuming and subjective. It is not easily repeatable because scientists will calculate slightly different results depending on their unique interpretations of the hydrographs.

The approach that applies a simple water-table level analysis program to calculate changes in water levels is easy to use and, unlike the graphical method, is fast and repeatable. It is also the least subjective approach (Delin and others, 2007). One program used to calculate changes in water level is RISE, which was developed in 2003 by Al Rutledge of the U.S. Geological Survey (Geoff Delin, U.S. Geological Survey, written comm., 2012). RISE is a simple program that reads a daily-values file of groundwater elevation or depth to groundwater and calculates the daily rise. The daily rise is calculated as the amount by which the water level is higher than the previous day (Geoff Delin, U.S. Geological Survey, written comm., 2012). If the resulting number is negative, it is re-set to zero. The output contains daily, monthly, and quarterly time periods over which the groundwater level rise is summed. The main disadvantage with RISE is it does not take into account the antecedent recession curve, and therefore the resulting recharge calculations could be slightly less than actual recharge.

Programs automating generation of recession curves typically use regression equations to predict the antecedent recession curve after a defined period of groundwater level recession. The programs can be time-consuming to apply, but they are repeatable and less subjective than the graphical approach. Three programs exist to automatically generate recession curves and calculate the resulting ΔH: a master recession curve (MRC) approach as described by Delin and others (2007), a time series approach as described by Crosbie and others (2005), and a master recession curve approach as described by

Heppner and Nimmo (2005). The reader is directed to the above references for detailed discussion.

Advantages of the WTF method include the availability of continuous groundwater level data required to perform the analysis. It is also unnecessary to determine and analyze the mechanisms by which water moves through the unsaturated zone (Healy and Cook, 2002). The WTF method is simple and easy to apply. It is representative of several to perhaps thousands of square meters (Healy, 2010), making it a better method for estimating local recharge (versus point recharge) values.

Disadvantages of the WTF method are associated with the estimates of specific yield used in the calculations and the applicability of assumptions inherent in the method (Healy, 2010).

A major assumption with the WTF method is that the observed well hydrograph only reflects natural water-table fluctuations caused by groundwater recharge and discharge and is not influenced by other effects such as groundwater pumping and nearby stream levels (Healy and Cook, 2002). Other mechanisms affecting the groundwater level data include evapotranspiration if the water table is in close proximity to the land surface, atmospheric pressure, entrapped air between the water table and the advancing wetting front, and tidal effects (Healy, 2010). Another important assumption is that specific yield is known and constant over the time period, which typically is not true (Healy and Cook, 2002; Healy, 2010). The pre-recharge water-level recession path is assumed to be accurately extrapolated in order to precisely determine ΔH (Healy and Cook, 2002; Healy, 2010). The final primary assumption is that recharge occurs as a result of discrete events in time, such as precipitation from a rainstorm (Healy and Cook, 2002; Healy, 2010). Steady, diffuse recharge such as slow snowmelt cannot be accounted for with the WTF method.

The RISE program was used to calculate ΔH because of its ease of use and repeatability. Eleven U.S. Geological Survey water wells from the National Water Information System (NWIS) met the shallow well criterion and had daily groundwater level data (Figure 12). After the groundwater level data were prepared for RISE input and the program calculated the daily groundwater level rise, which was compiled into monthly time periods (∑ΔH), the yearly ∑ΔH then was determined. The yearly ∑ΔH was multiplied by an arbitrarily determined specific yield of 0.20, a value which is a rough average of specific yield values determined for sand and gravel facies such as in an alluvial aquifer (Healy, 2010).

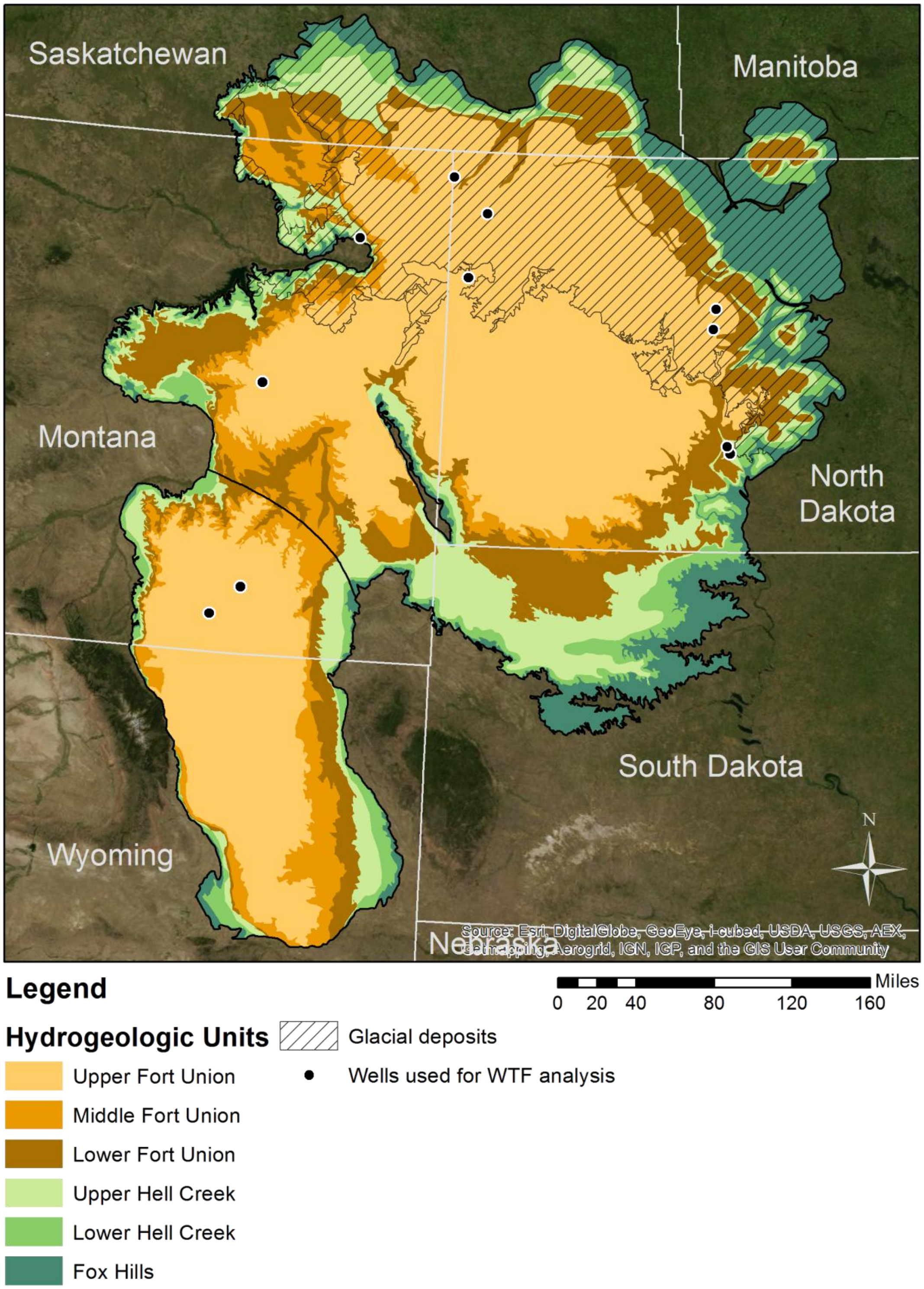

Figure 12. Location of data points used in the WTF analysis.

Chloride Mass Balance Method

The chloride mass balance (CMB) method determines the rate of recharge to an aquifer based on the chloride concentration in the groundwater and the rate of atmospheric chloride deposition. Meteoric chloride is a good groundwater tracer because 1) it does not adsorb onto silicates because it is anionic, 2) it is very soluble in water, and 3) it typically does not participate in geochemical or biochemical reactions (Healy, 2010). The CMB method is based on Gardner's (1967) conceptual model, where chloride concentrations are uniform underneath the zero-flux plane and steady-state conditions are present within the unsaturated zone. Fast infiltration rates flush chloride through the system quickly, resulting in low chloride concentrations. Conversely, slow infiltration rates flush chloride through the system slowly, resulting in high chloride concentrations (Healy, 2010). The CMB method is derived from using the water-budget equation to estimate infiltration through a column extending to the water table by associating a chloride concentration with each component of the water-budget (Healy, 2010). It is typically applied in arid and semiarid climates where irrigation, runon, and runoff are negligible (Healy, 2010). Recharge is then calculated according to equation 13.

$$R = \frac{PC_p^*}{C_{gw}} \qquad (13)$$

where

R is recharge in in/yr,
P is precipitation in in/yr,
C_p^* is effective chloride concentration, and
C_{gw} is the concentration of chloride in groundwater.

The effective chloride concentration is the sum of the total wet and dry deposition rate divided by precipitation (Healy, 2010). The National Atmospheric Deposition Program (https://nadp.isws.illinois.edu; accessed March 15, 2013) has isopleth maps of annual average chloride deposition and concentration in precipitation throughout the United States from 1985 to present. Historical dry deposition data are not available at the national scale. However, it is commonly assumed that dry deposition is equal to wet deposition (Dettinger, 1989; Nolan and others, 2007; Gates and others, 2008; Healy and others, 2008)

An assumption with this method is that all chloride in the aquifer is derived from atmospheric deposition, although other sources of chloride can be accounted for if known. The CMB method is simple to apply and inherently takes into account mechanisms of flow through the unsaturated zone. Chloride concentrations in groundwater are readily available throughout the United States.

For this study, chloride concentrations from groundwater were collected from the U.S. Geological Survey (http://waterdata.usgs.gov/nwis/qw; accessed January 15, 2013). The deposition rates for chloride were obtained from the National Atmospheric Deposition Program (https://nadp.isws.illinois.edu; accessed March 15, 2013), and it was assumed that dry deposition was equal to wet deposition. Figure 13 shows the distribution of the data points used in the CMB analysis.

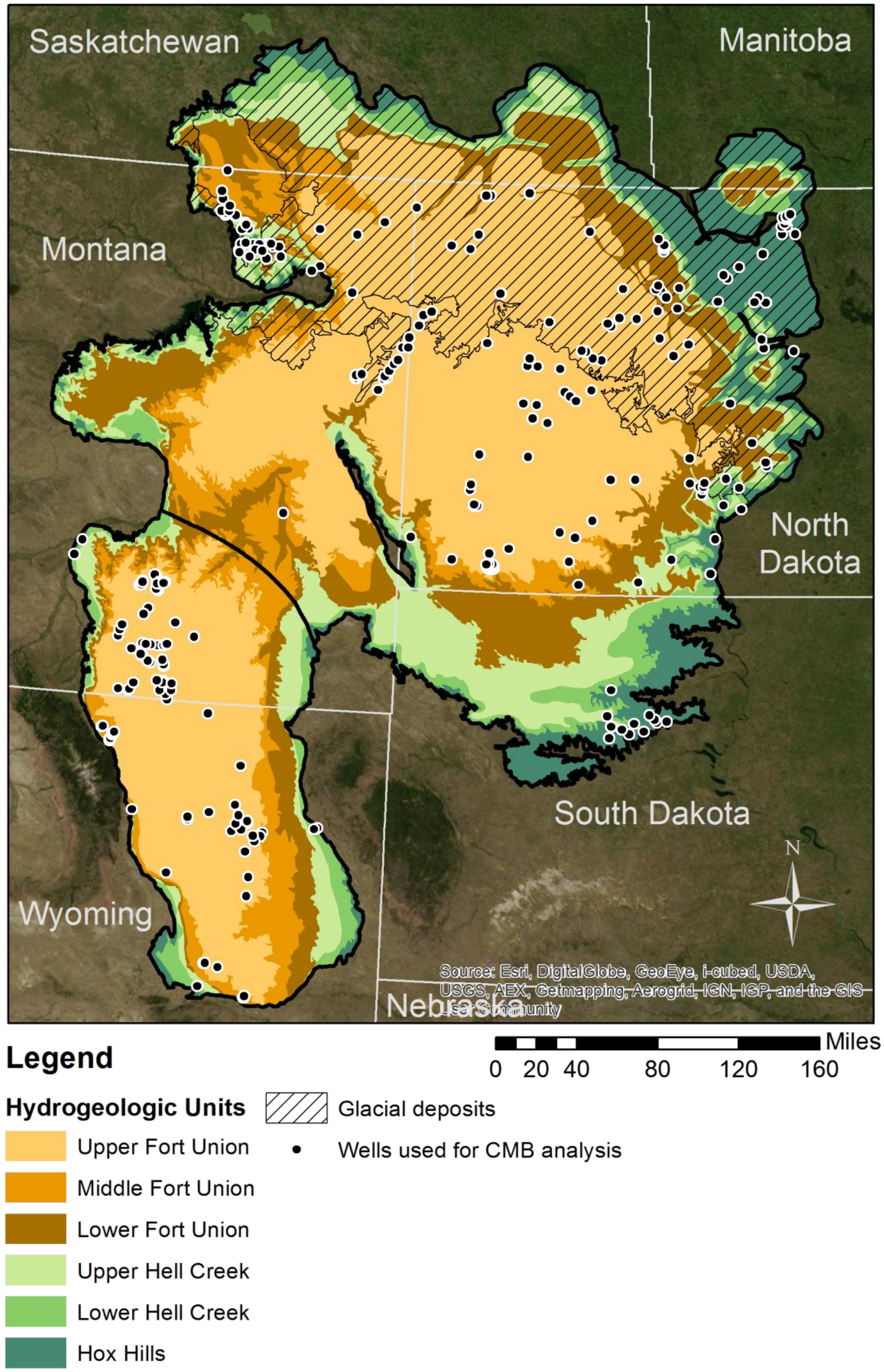

Figure 13. Location of data points used in the CMB analysis.

Results

Diffuse Recharge

Data from 1980 were used by the SWB model to simulate initial conditions. The models were run for a 31-year period from 1981 to 2011, and the annual results for recharge, precipitation, and actual evapotranspiration are shown in Appendix A. The average annual recharge results described below (Figure 14) were summarized from this 31-year simulation period. Calculated recharge rates for both basins fell within the range described by Roy and others (2005) for the study area, where the difference between monthly precipitation and potential evapotranspiration ranges from 0 to 5 in/yr. Average annual recharge from 1981 to 2005 (Figure 15) also was determined because that is the time length used for the predevelopment period of the U.S. Geological Survey groundwater availability study. Calculated recharge rates were greatest during the late spring and early summer for both basins.

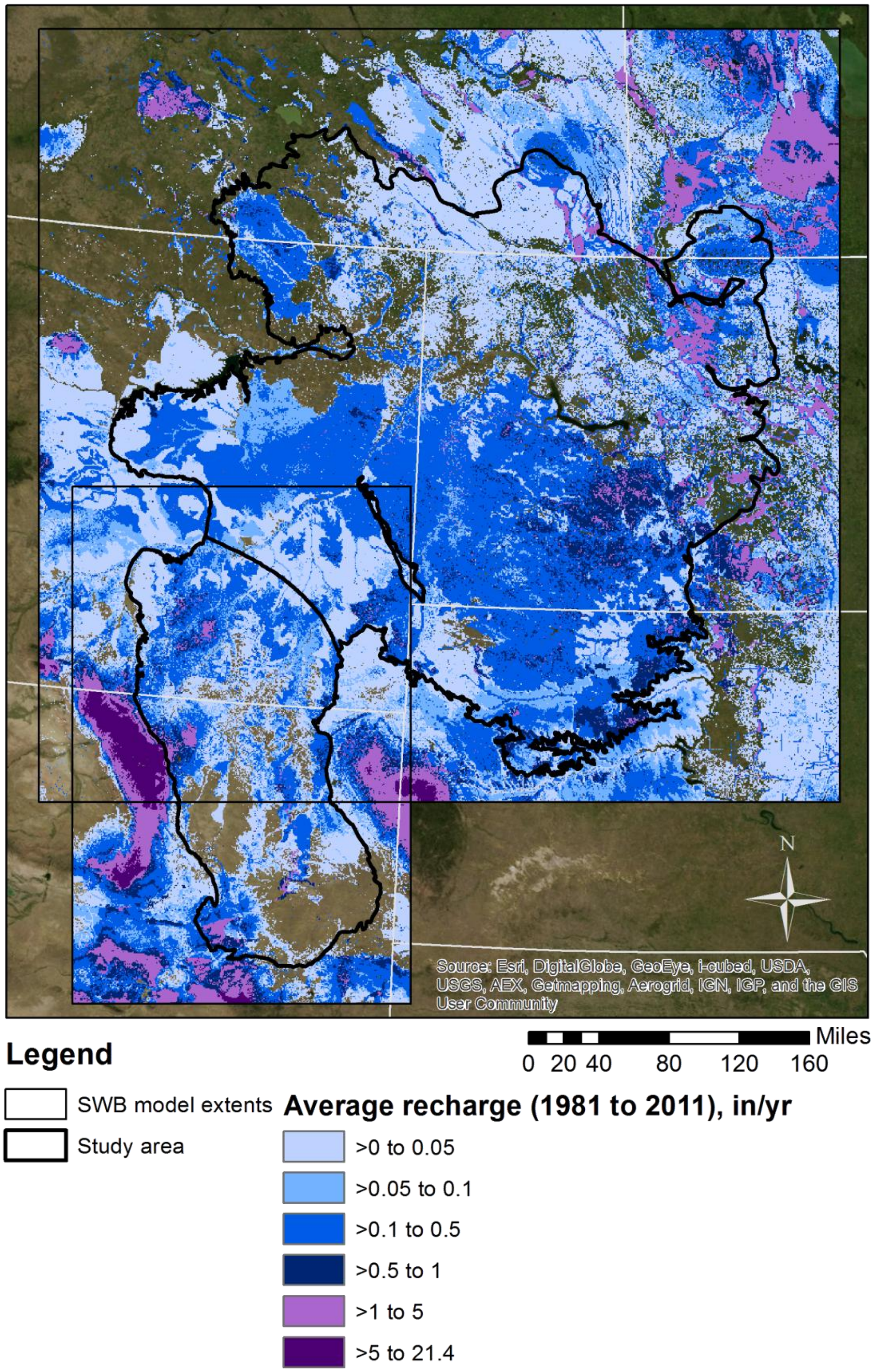

Figure 14. Calculated average annual recharge for the Williston and the Powder River basins from the SWB model (1981 to 2011). The olive green within the model boundaries represents areas with a calculated average annual recharge of 0 in/yr.

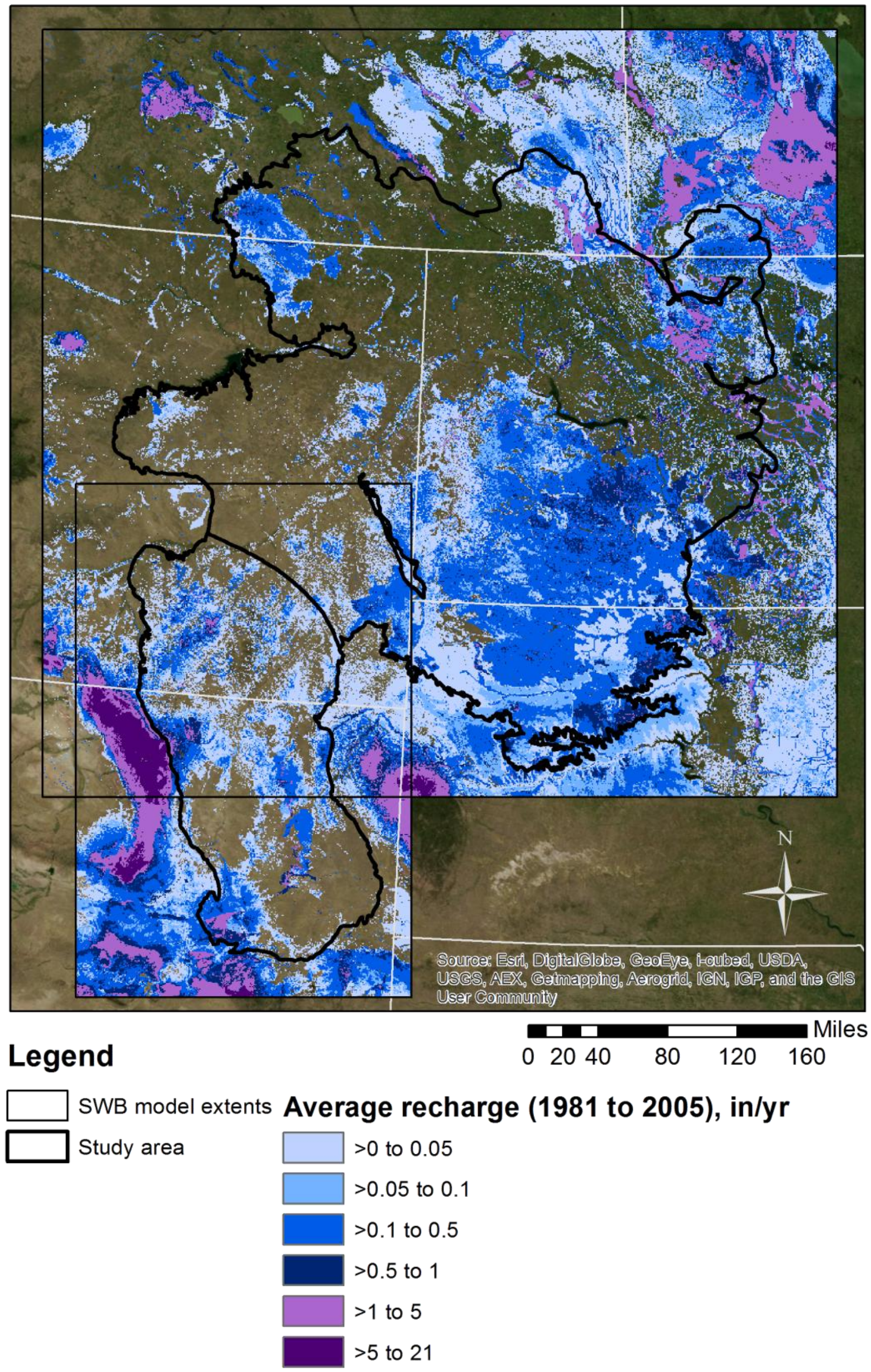

Figure 15. Calculated average annual recharge for the Williston and the Powder River basins from the SWB model (1981 to 2005). The olive green within the model boundaries represents areas with a calculated average annual recharge of 0 in/yr.

Williston Basin

The calculated average recharge in the Williston structural basin was 0.190 in/yr (1,281 ft^3/sec, or cfs). This is about 1.10 percent of precipitation. Calculated recharge rates varied from no recharge to 4.71 in/yr. About 30.5 percent of the basin did not receive any recharge from precipitation according to the SWB model. The first quartile of the recharge rates was 0.012 in/yr, the median was 0.087 in/yr, and the third quartile was 0.240 in/yr. A histogram of the average recharge values (Figure 16) with bins of 0.25 in/yr shows that the calculated recharge values were positively skewed and that very few were greater than 1 in/yr. The highest calculated recharge values were where glaciofluvial and loess deposits are present (Figure 17). The Peerless Plateau and the southeastern area of the Williston basin were the primary areas where recharge occurs in areas not overlain by glacial deposits. Recharge in the area overlain by glacial deposits was controlled by sand and gravel (typically in the form of glaciofluvial deposits) and loess. Hardly any recharge was calculated for areas overlain by clayey till.

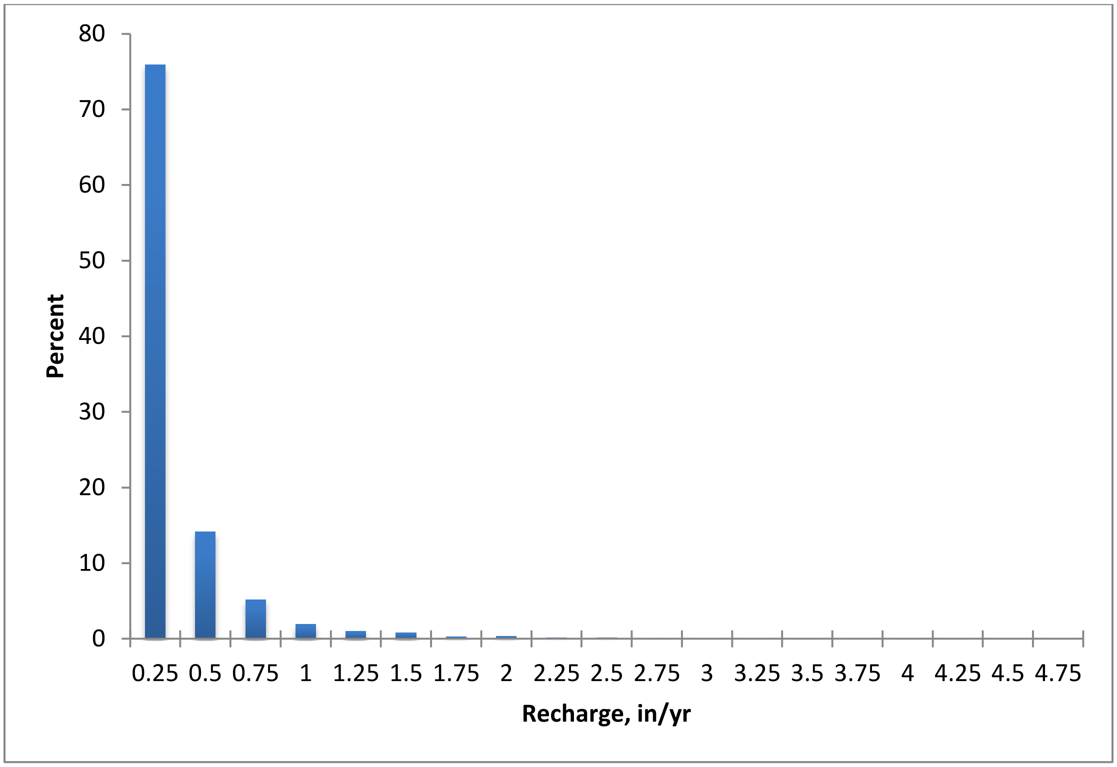

Figure 16. Histogram of calculated SWB recharge values for the Williston basin.

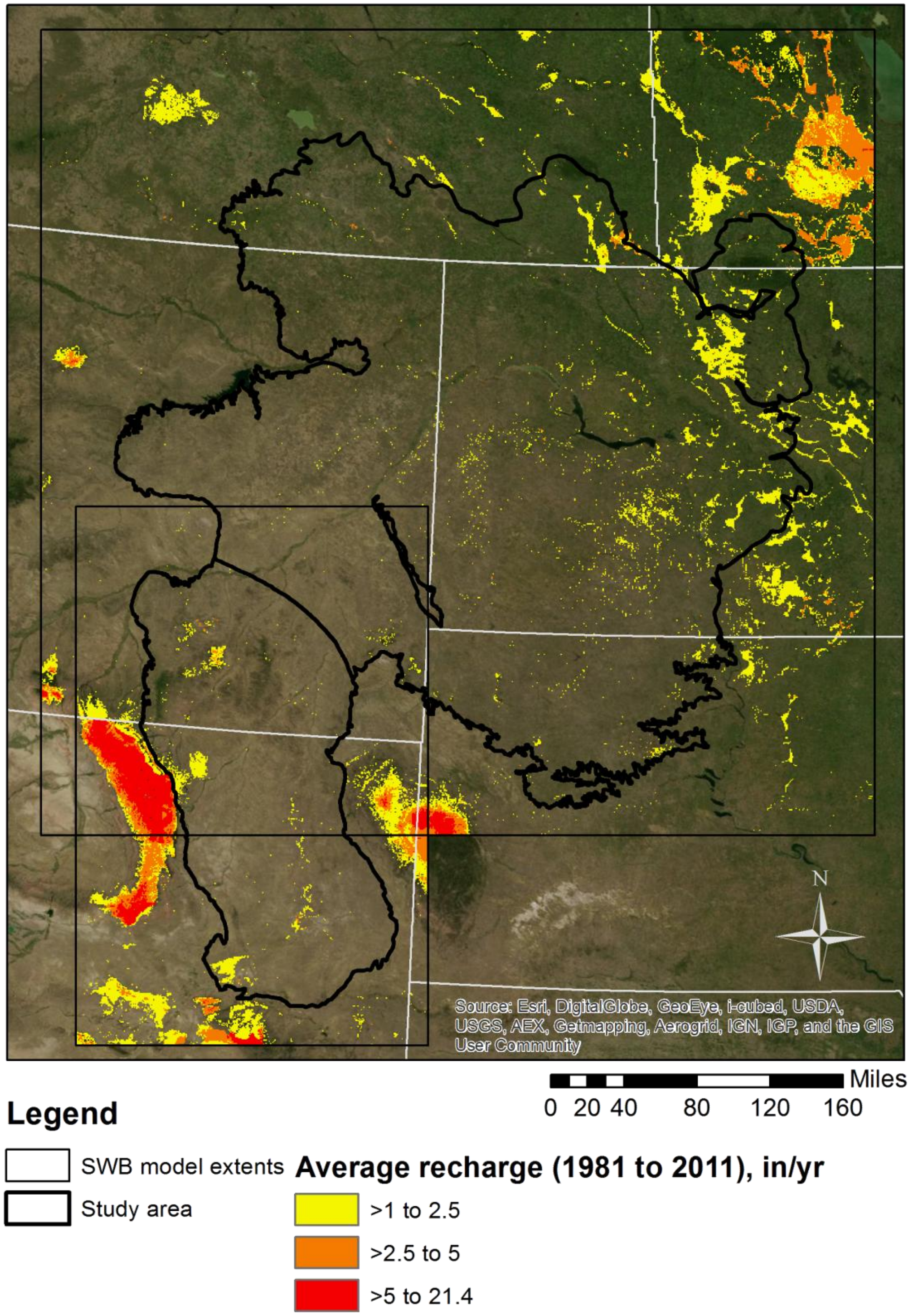

Figure 17. Distribution of calculated SWB recharge values that are greater than 1 in/yr.

Powder River Basin

The calculated average recharge for the SWB model in the Powder River structural basin was 0.136 in/yr (248 cfs). This was about 0.82 percent of precipitation. Recharge rates varied from no recharge to 4.46 in/yr. About 40.6 percent of the basin does not receive any recharge from precipitation, according to the SWB model. The first quartile of the recharge rates was 0 in/yr, the median was 0.037 in/yr, and the third quartile was 0.135 in/yr. A histogram of the average recharge values (Figure 18) with bins of 0.25 in/yr shows that the calculated recharge values were positively skewed and that very few were greater than 1 in/yr.

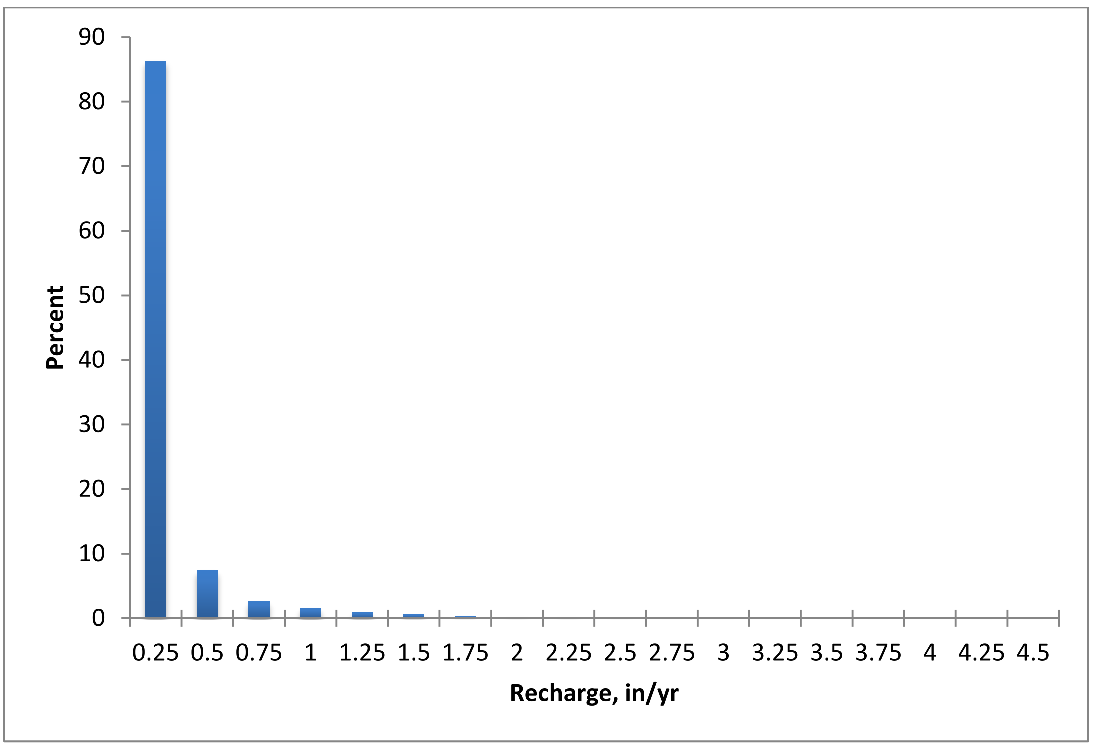

Figure 18. Histogram of calculated SWB recharge values for the Powder River basin.

The highest calculated recharge values were at the foothills of the Bighorn Mountains between Sheridan and Buffalo, Wyoming, and at the foothills of the Laramie Mountains east of Casper, Wyoming (Figure 17). Comparatively high recharge rates also were calculated northwest of the Tongue River Syncline in the northern part of the basin and in the south-central part of the basin. The Upper Fort Union aquifer, which underlies most of the Powder River basin, receives the majority of the recharge from precipitation in the basin.

Sensitivity Analysis

In order to determine which parameters have the greatest effect on the output, a sensitivity analysis was conducted. Sensitivity can be tested by increasing or decreasing a parameter by a specified percentage and evaluating the change in the modeling results with respect to the change in the model parameter (Equation 14).

$$Relative\ Percent\ Sensitivity = \frac{\%\ Change\ in\ model\ result}{\%\ Change\ in\ parameter} \times 100 \qquad (14)$$

The sensitivity analysis was conducted for the Powder River basin for the curve number, maximum infiltration, and root zone depth values in the land use lookup table by manually increasing each value by 10 percent. Where this would result in an unreasonable input value for the lookup table, the “initial” model’s value was altered. Temperature data was also increased by 10 percent to determine the sensitivity of the ET method of Hargreaves and Samani (1985), which is a sub-routine of the model and is primarily dependent upon the temperature input data. The precipitation data were also increased by 10 percent. The relative percent difference between the original and new parameters and the percent difference between the original and new average annual recharge values were calculated with Equation 14 and are given in Appendix E. If the relative percent sensitivity was greater than +/- 10 percent, the model was considered to be sensitive to that parameter.

The model was considered to be sensitive to 16 parameters tested in the sensitivity analysis (relative percent sensitivity +/- 10 percent). The precipitation data were the most sensitive parameter with a relative sensitivity of 821 percent. All of the sensitive parameters are highlighted in Appendix E and are listed in order of descending sensitivity in Table 5.

Table 5. Sensitive parameters for the Powder River SWB model in descending order.

Parameter			
Section	**Hydrologic Soil Group**	**Land Cover Code**	**Relative Percent Sensitivity**
Precipitation	---	---	821.3
Temperature	---	---	-590.8
Root Zone	B	52	-103.5
Root Zone	B	71	-73.8
Curve Number	B	71	-42.4
Curve Number	B	52	-35.9
Curve Number	D	52	-29.5
Curve Number	B	31	-19.7
Curve Number	C	52	-17.3
Curve Number	C	71	-14.54
Curve Number	D	71	-14.51
Root Zone	C	52	-14.1
Root Zone	D	52	-14.0
Curve Number	C	31	-12.6
Root Zone	C	71	-10.6
Root Zone	B	42	-10.2

Precipitation is positively correlated with recharge. Recharge is increased when precipitation is increased because there is more water available for recharge. Temperature is negatively correlated with recharge. Recharge is decreased when temperature is increased because more water becomes evapotranspiration with the increase in temperature according to the Hargreaves and Samani (1985) method.

The effect of a lookup table parameter on the model results was a function of the soil group area and land cover area occupied in the basin. The greater the land cover and/or soil group area, the greater the parameter sensitivity. The grassland and shrub land cover classifications cover the majority of the study area, and the lookup table parameters associated with those two land covers are consistently the most sensitive within each hydrologic soil group. Conversely, hydrologic soil group NRCS A is not present within the Powder River basin, and the relative percent sensitivity of the associated lookup table parameters is zero as a result.

Curve numbers are negatively correlated with recharge. An increase in the curve number results in an increase in runoff and therefore a decrease in recharge. The maximum infiltration rate is positively correlated with recharge. An increase in the maximum infiltration rate allows more water to become recharge. The maximum infiltration also has the smallest effect on recharge out of the parameters tested in the sensitivity analysis. If the Powder River model was run with the overland flow routing scenario activated, the relative percent sensitivity of the maximum infiltration would increase. The root zone depths are negatively correlated with recharge. An increase in the root zone depth creates a taller column through which water can more easily be drawn back into the atmosphere via ET. Also, an increase in the root zone creates a longer path along which precipitation must follow before it can infiltrate to the bottom of the root zone and be converted to recharge in the SWB code.

Local Recharge

It is beneficial to use multiple methods in this type of investigation to check for consistency between methods, even though, as Healy and Cook (2002) have pointed out, consistency between methods is not necessarily an indication of accuracy. The SWB model results were compared to the water-table fluctuation and chloride mass balance local recharge estimates. The model results also were compared with potentiometric surface maps.

Water-Table Fluctuation

In the Williston basin, nine wells had at least one year of continuous groundwater level data to use for the WTF analysis. The recharge rates ranged from 0.339 to 2.59 in/yr, with an average of 1.38 in/yr (Figure 19 and Table 6). In the Powder River basin, two wells in alluvial aquifers had at least one year of continuous groundwater level data to use for the WTF analysis. The recharge rates were 1.49 and 0.556 in/yr. WTF recharge rates were compared to the average annual recharge values (from 1981 to 2011) produced from the SWB models corresponding to each well's location (Table 7 and Figure 20). The recharge calculated from the WTF method is consistently greater than the recharge calculated by the SWB method.

Table 6. Recharge estimates for the Williston basin using the WTF method. Nine wells were used in the analysis.

Aquifer	Alluvial	Glacial	Tongue River
# of observations	1	7	1
Range of recharge rates, in/yr	---	0.339 to 2.59	---
Mean recharge, in/yr	0.628	1.54	1.01

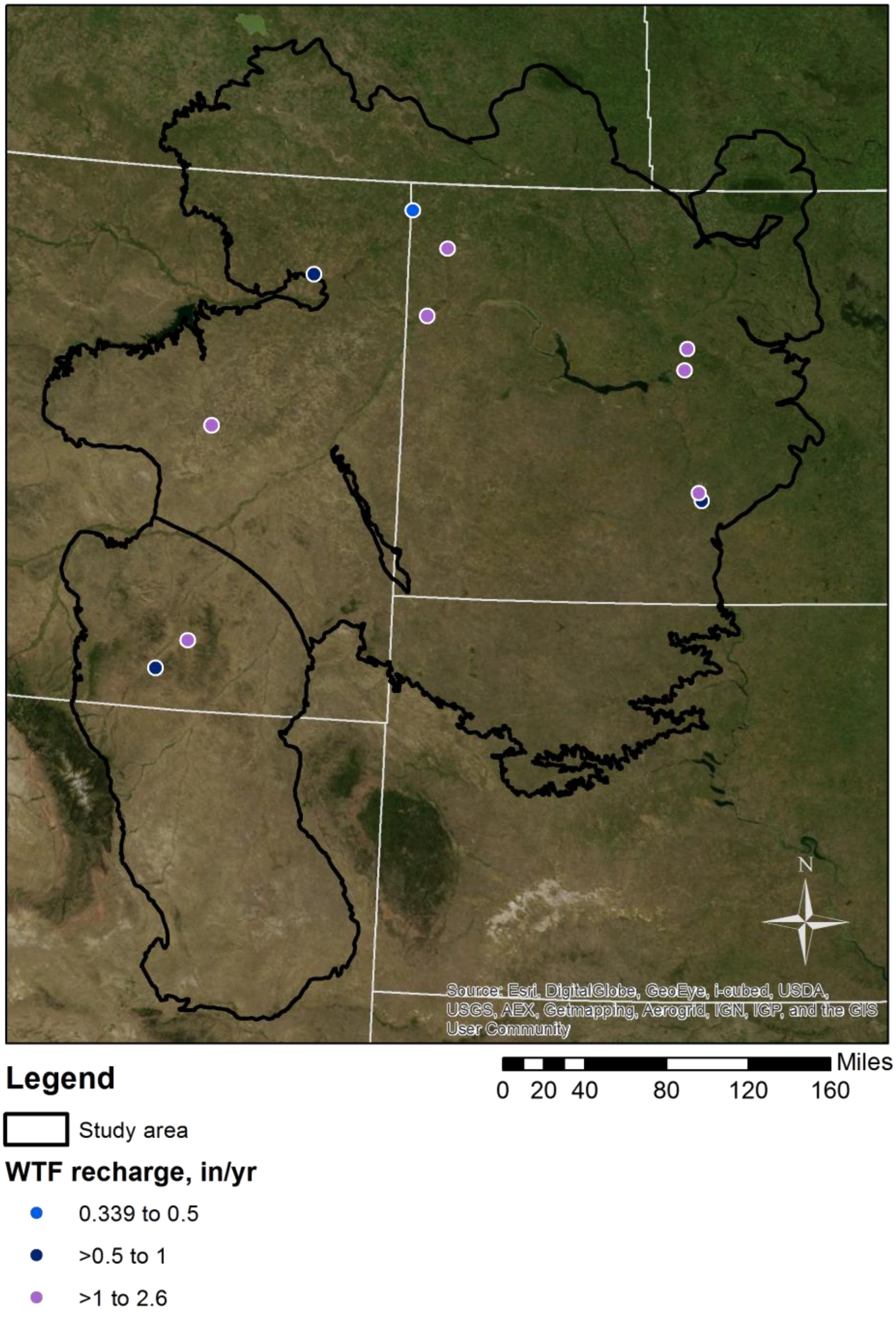

Figure 19. Recharge rates calculated by the WTF method.

Table 7. Comparison of WTF recharge results to SWB results.

Basin	Aquifer	WTF recharge rate, in/yr	SWB recharge rate, in/yr	WTF recharge - SWB recharge
Williston	Alluvial	0.628	0.051	0.577
Williston	Tongue River	1.01	0.103	0.909
Williston	Glacial	1.16	0.560	0.603
Williston	Glacial	1.96	1.39	0.576
Williston	Glacial	2.59	0.049	2.54
Williston	Glacial	0.339	0.034	0.305
Williston	Glacial	2.00	0.143	1.86
Williston	Glacial	0.786	0.223	0.563
Williston	Glacial	1.94	0.707	1.23
Powder River	Alluvial	1.49	0.111	1.38
Powder River	Alluvial	0.556	0.071	0.485

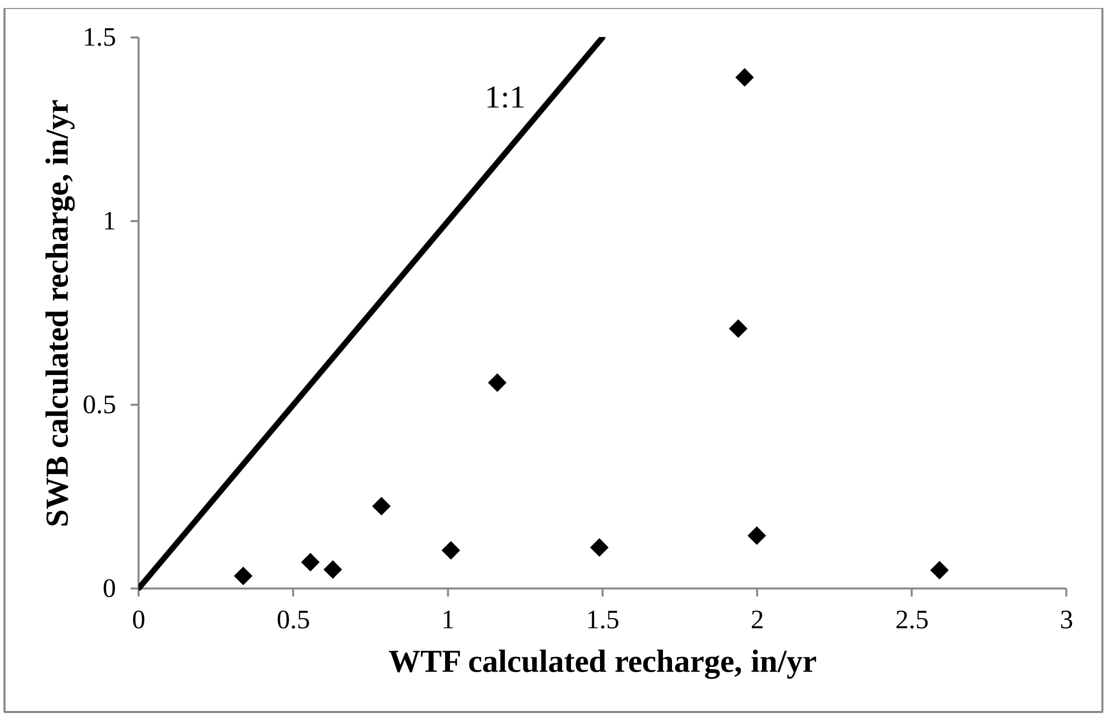

Figure 20. Comparison of WTF recharge results to SWB recharge results.

Chloride Mass Balance

More than 300 chloride concentration data were used to determine recharge rates in the basins. Recharge rates calculated by the CMB method are summarized in Tables 8 and 9 and shown in Figure 21. CMB recharge rates were compared to the average annual recharge values (from 1981 to 2011) produced from the SWB models corresponding to each well's location (Figure 22). The majority of the CMB recharge values compare well with the SWB recharge values.

Table 8. Recharge estimates for the Williston basin using the CMB method.

Aquifer	Alluvium	Glacial	Fort Union	Hell Creek	Fox Hills / Hell Creek	Fox Hills
# of observations	17	121	97	19	17	20
Range of recharge rates, in/yr	0.008 to 1.19	0.006 to 6.72	0.005 to 3.58	0.003 to 2.15	0.011 to 0.916	0.0004 to 0.207
Median recharge, in/yr	0.095	0.198	0.321	0.160	0.188	0.052

Table 9. Recharge estimates for the Powder River basin using the CMB method.

Aquifer	Alluvium	Fort Union	Fox Hills / Hell Creek	Fox Hills
# of observations	39	83	2	2
Range of recharge rates, in/yr	0.008 to 0.616	0.022 to 1.212	0.582 to 0.719	0.084 to 0.786
Median recharge, in/yr	0.196	0.196	0.651	0.435

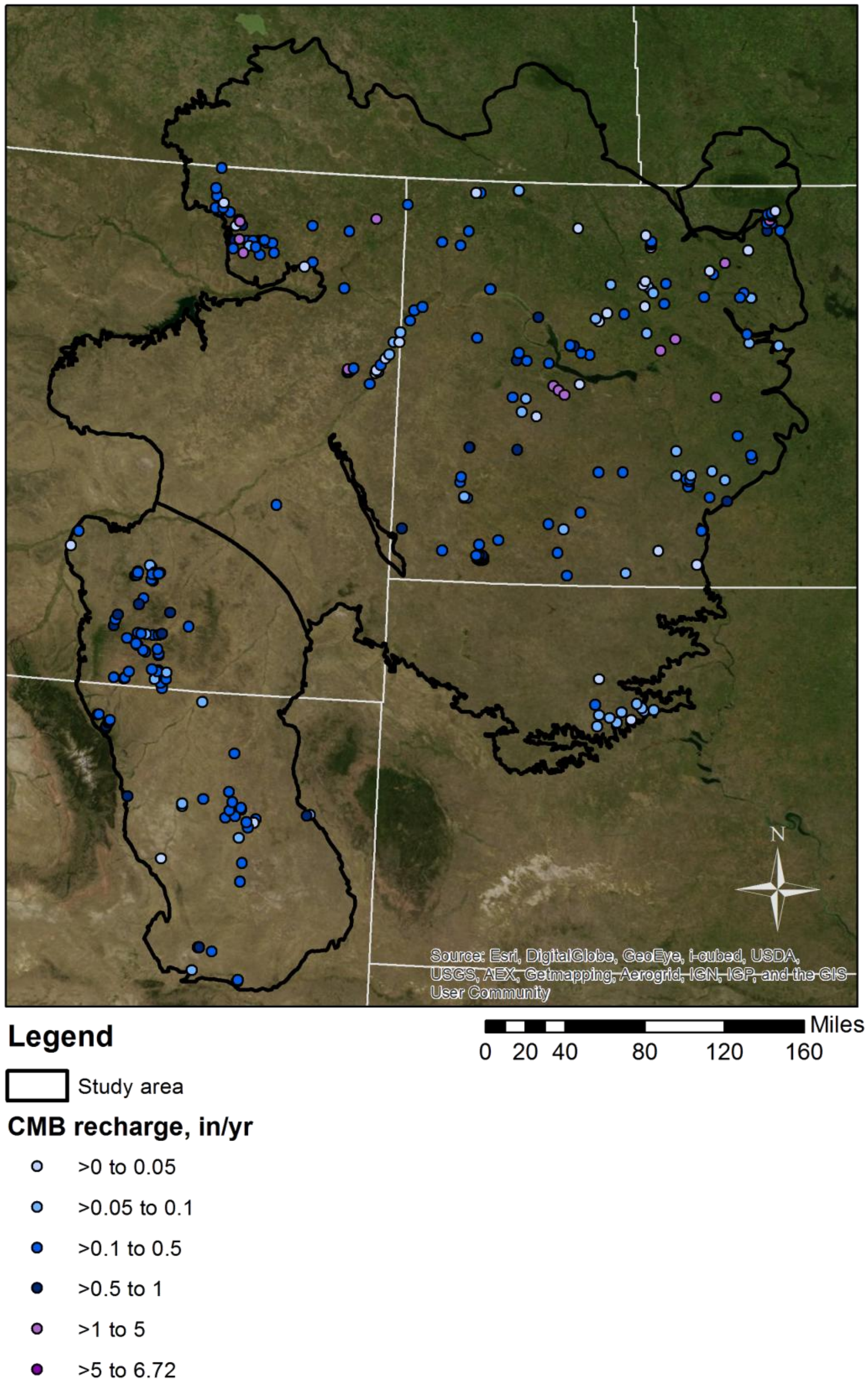

Figure 21. Recharge rates calculated by the CMB method.

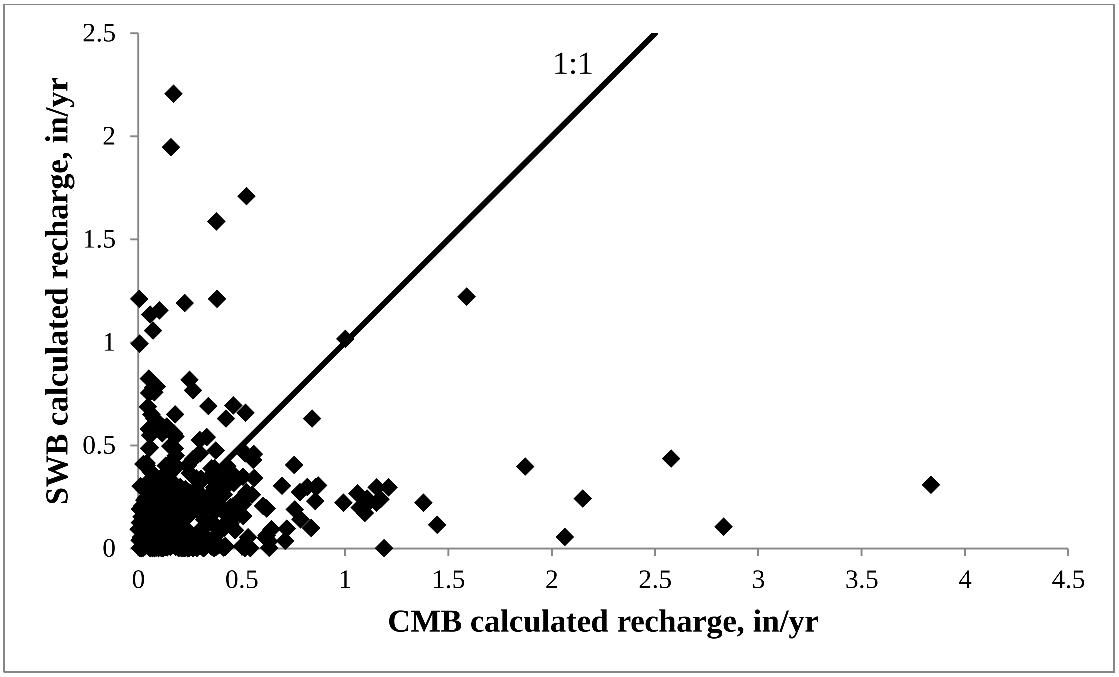

Figure 22. Comparison of CMB recharge results to SWB recharge results.

Potentiometric Surfaces

The Powder River SWB model results were compared to the potentiometric maps from Hotchkiss and Levings (1986). The Tongue River Member of the Upper Fort Union Formation is present at the land surface in the majority of the Powder River basin, and the potentiometric surface of the Tongue River aquifer was compared with the SWB recharge values (Figure 23). The Williston SWB model results were compared to the preliminary potentiometric maps from Thamke and others (*in review*). The potentiometric surface of the Lower Fort Union hydrogeologic unit was compared with the SWB recharge values (Figure 24).

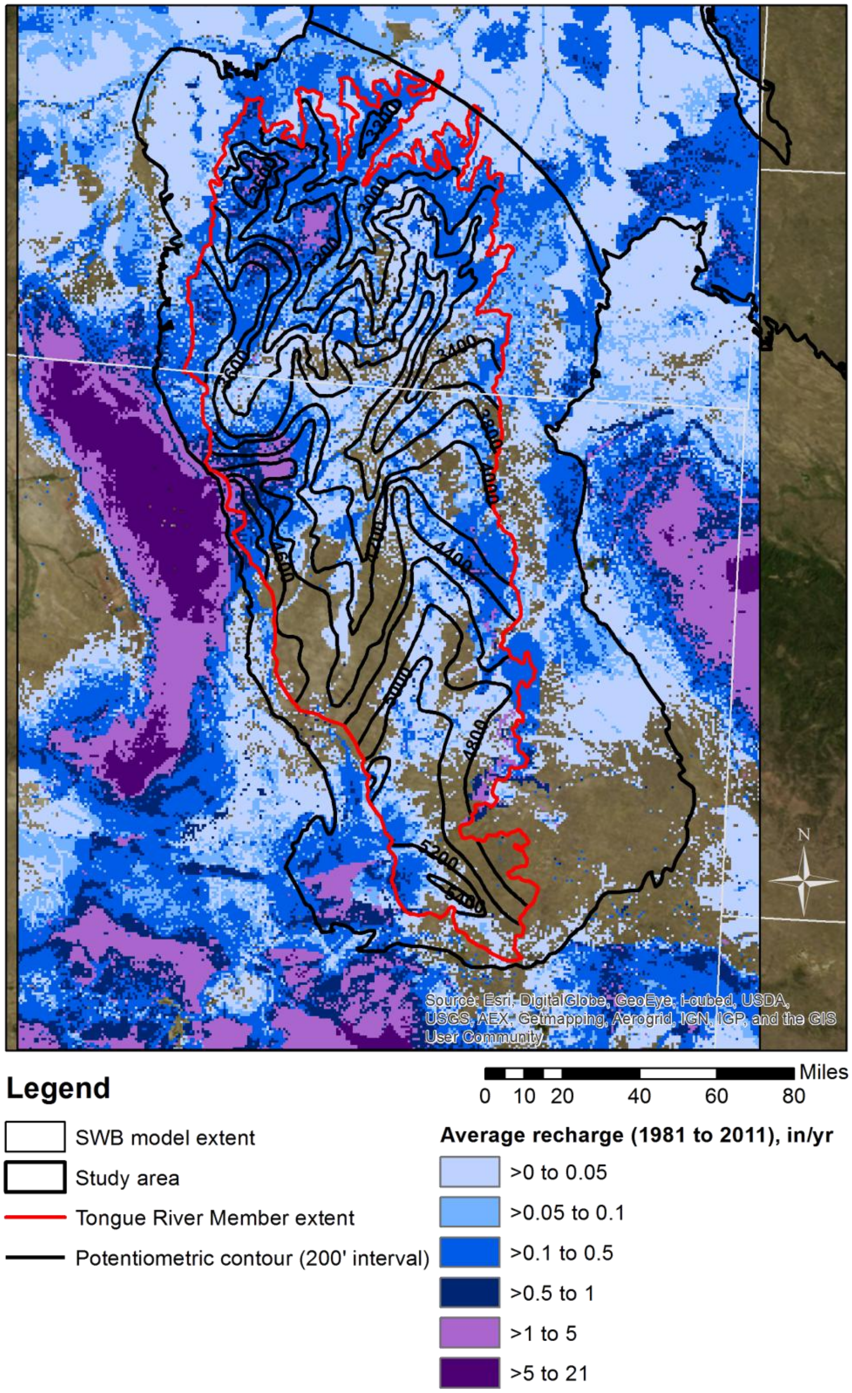

Figure 23. Comparison of Powder River basin SWB model results to the potentiometric surface of the Tongue River Member of the Fort Union Formation from Hotchkiss and Levings (1986). The olive green within the model boundaries represents areas with a calculated average annual recharge of 0 in/yr.

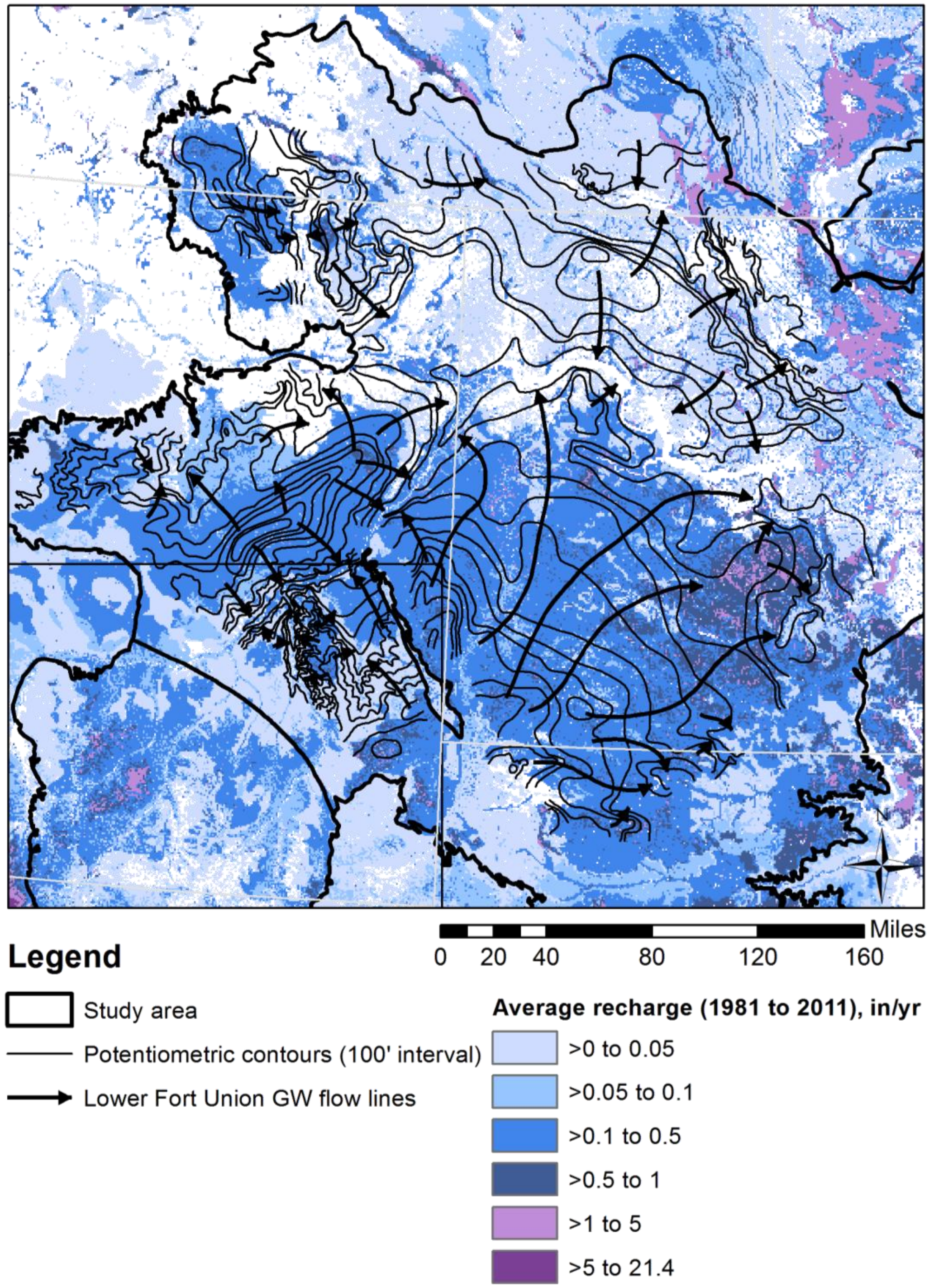

Figure 24. Comparison of the Williston SWB model results to the preliminary potentiometric surface of the Lower Fort Union hydrogeologic unit from Thamke and others (*in review*). The white areas within the model boundaries represents areas with a calculated average annual recharge of 0 in/yr.

Discussion

The SWB model results should be used cautiously, keeping in mind the assumptions of the model and the input data. The calculated SWB recharge rates are estimates and can be scaled when coupled with a groundwater model. The power of the SWB method is that it provides a gridded coverage of recharge estimates, and it is more robust than simply interpolating a few scattered local recharge estimates. The SWB models are non-unique because parameters in the lookup table can be adjusted in various combinations to arrive at the same end result. The SWB models did not activate the surface-water flow routing algorithm; therefore, recharge is probably underestimated and a scale factor could be used to account for the additional recharge to downslope cells from surface-water runoff.

The main reason why the average annual recharge rates that were calculated for the 1981 to 2005 time period were less than the 1981 to 2011 average annual recharge rates is because 2011 was a very wet year that resulted in record flooding along the Missouri River system. The average annual recharge calculated for 2011 is shown in Figure 25.

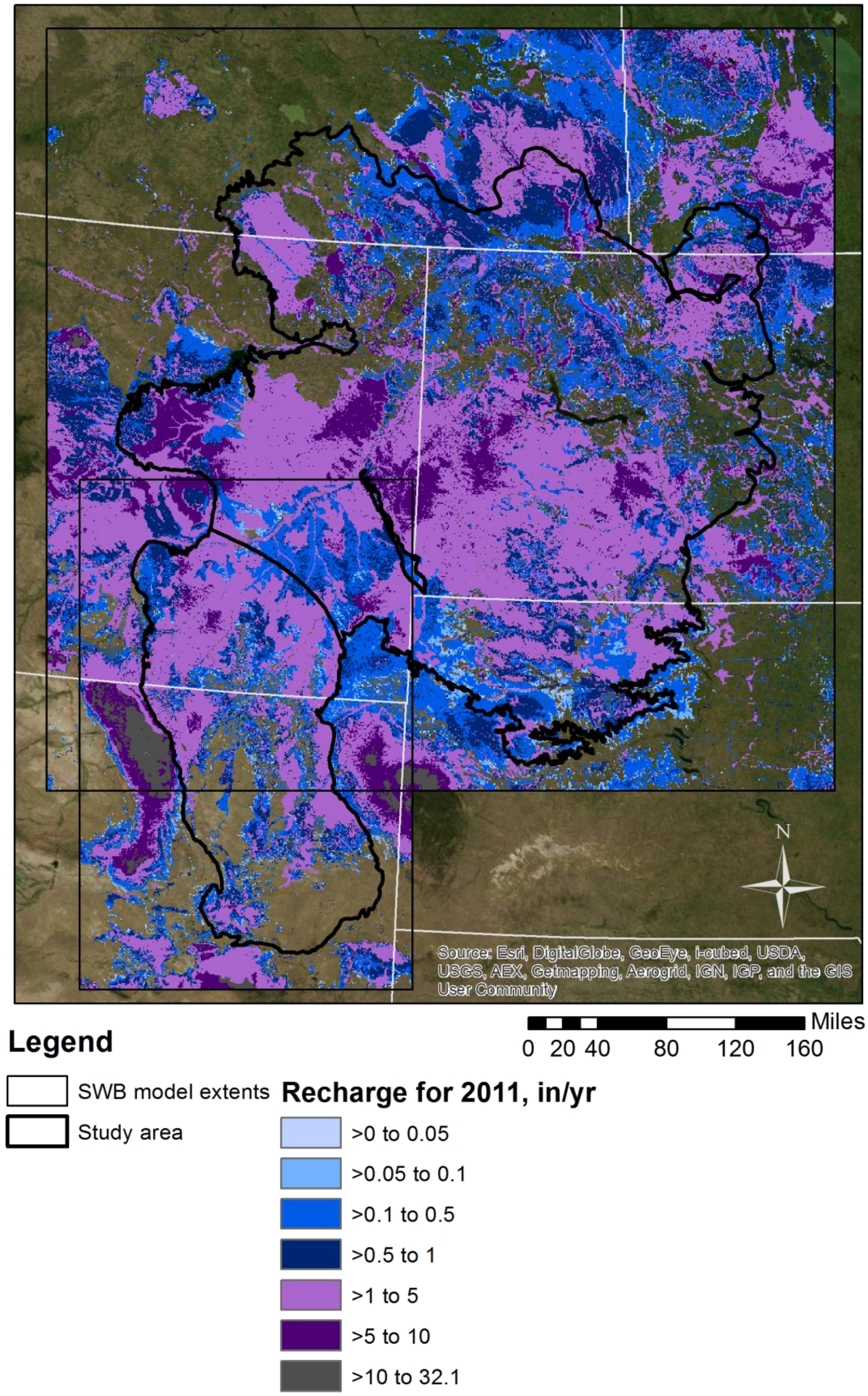

Figure 25. Average annual recharge for the Williston and the Powder River basins from the SWB model for 2011. The olive green within the model boundaries represents areas with a calculated average annual recharge of 0 in/yr.

It is useful to have values from previous investigations in the study area to compare with the final values from the SWB models. The overall range of calculated recharge rates in both basins from the SWB models fell within the range of potential recharge to the groundwater system (0 to 5 in/yr) as previously determined by Roy and others (2005). Also, the majority of the recharge rates were between 0 and 0.5 in/yr, which was consistent with results of Wolock (2003).

The local recharge estimates from the WTF analysis all fell within the recharge range from the SWB models, but the WTF recharge rates were consistently higher than the SWB recharge rates when the data were compared spatially. The average WTF recharge rates were greater than the SWB average recharge rates. This could be because wells in unconfined aquifers are more likely to be located where groundwater is more readily available, which would be in areas of greater recharge. Therefore, this is likely to have positively skewed the WTF recharge rates.

The local recharge estimates from the CMB analysis also all fell within the range of the calculated SWB recharge rates. The majority of the CMB recharge values compare well with the SWB recharge values when compared spatially, but there is no consistent trend between the two methods. About half the CMB recharge rates were greater than the SWB recharge rates when comparing well locations with model cells, and the other half of the CMB recharge estimates were less than the SWB recharge estimates.

The SWB results in the Williston basin compared reasonably well with the preliminary potentiometric surface of the Lower Fort Union hydrogeologic unit from Thamke and others (*in review*). Both the model and the potentiometric surface showed groundwater recharge occurring in the Peerless Plateau. The southern area of the basin matched well with the potentiometric surface, but the northern part of the basin had a few areas where recharge should be occurring, according to the potentiometric surface, but calculated values were greater in the SWB model. The SWB results in the Powder River basin matched very well with the potentiometric surface from Hotchkiss and Levings (1986).

The SWB models were not calibrated to baseflow in the study area because of the great number of sinking streams in the study area. More than 70 percent of the total recharge in each basin is from sinking streams (Bednar, *in review*). As aridity increases, focused recharge from features such as sinking streams becomes the dominant recharge mechanism and diffuse recharge becomes less important (Lerner and others, 1990). This appears to be the case in the semi-arid study area, and the diffuse recharge (SWB model calculated recharge) in the Williston basin decreases toward the less humid west. The average recharge rate in the Powder River basin is less than the average recharge rate of the Williston basin. The Powder River basin is situated in an area of greater average aridity than the Williston basin, so the statement by Lerner and others (1990) appears to apply.

Evapotranspiration in the SWB model simulations was calculated by the method of Hargreaves and Samani (1985), which only considers daily air temperature values and solar radiation. ET is calculated by a sub-process of the model, and values from another ET dataset cannot be used for the model. The AET from the SWB models (Appendix A) was compared to the national estimates of AET produced by Sanford and Selnick (2013), who combined a water-balance approach with a regression equation based on climate and land-cover factors to determine average annual AET using data from 1971 to 2000.

Average annual AET ranged from 12.20 to 15.75 in/yr in the Powder River basin and from 12.20 to 19.69 in/yr in the Williston basin (Sanford and Selnick, 2013). The AET from the SWB models was, on average, less than the estimates of Sanford and Selnick (2013). Future work could include comparing the PET output from the SWB models to other PET datasets that use more robust algorithms such as the Penman-Montieth method (Montieth, 1965).

Conclusions

The annual SWB model recharge rates were averaged from 1981 to 2011. Average calculated recharge in the Williston basin was 0.190 in/yr (1,281 cfs) and ranged from no recharge to 4.71 in/yr. Calculated recharge decreased to the west and was greatest in the northeastern part of the basin where glaciofluvial deposits are present. Recharge was calculated to be about 1.1 percent of precipitation in the Williston basin. Average recharge in the Powder River basin was 0.136 in/yr (248 cfs) and ranged from no recharge to 4.46 in/yr. Calculated recharge rates are greatest during the late spring and early summer for both basins. Recharge was about 0.8 percent of precipitation in the Powder River basin. The SWB models did not activate the surface-water flow routing algorithm; therefore, recharge is probably underestimated and a scale factor could be used to account for the additional recharge to downslope cells from surface-water runoff.

Diffuse recharge to groundwater in the Williston and Powder River basins is very small (< 1 percent of precipitation). Typically, focused recharge becomes more important than diffuse recharge for aquifer replenishment as the degree of aridity increases (Lerner and others, 1990); this is seen in the recharge estimation results presented. Diffuse recharge estimates from the SWB models are reasonable and compare reasonably well with local recharge estimation results, potentiometric surfaces, and previous investigations. It is helpful to compare multiple recharge estimation methods to check the validity of models. The SWB results will be useful input for a numerical groundwater model. However, the SWB model results should be used cautiously, keeping in mind the assumptions of the model and the input data.

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List of Appendices

Appendix A: Average annual recharge, precipitation, and actual evapotranspiration

Year	Williston structural basin				
	Recharge, in in/yr	Recharge fraction[a]	Recharge, in ft^3/s	Precipitation, in in/yr	Actual ET, in in/yr
1981	0.021	0.0014	139	14.30	12.33
1982	0.272	0.0132	1,826	20.52	14.11
1983	0.291	0.0229	1,959	12.70	12.54
1984	0.051	0.0039	345	13.12	10.34
1985	0.033	0.0021	221	15.41	11.35
1986	0.181	0.0092	1,218	19.62	15.59
1987	0.089	0.0059	598	14.95	14.28
1988	0.000	0.00002	1	9.84	7.80
1989	0.033	0.0024	223	14.10	10.95
1990	0.006	0.0005	41	12.45	10.94
1991	0.006	0.0003	42	18.24	13.58
1992	0.037	0.0027	249	13.76	11.36
1993	0.114	0.0055	765	20.77	15.14
1994	0.036	0.0022	241	16.26	12.54
1995	0.543	0.0312	3,651	17.40	14.40
1996	0.162	0.0096	1,093	16.86	12.64
1997	0.559	0.0399	3,762	14.03	13.09
1998	0.034	0.0018	230	19.29	12.72
1999	0.409	0.0230	2,752	17.78	16.80
2000	0.006	0.0003	38	18.54	12.94
2001	0.137	0.0096	918	14.24	13.99
2002	0.009	0.0006	60	13.91	10.41
2003	0.027	0.0018	184	14.83	11.89
2004	0.050	0.0032	336	15.63	12.17
2005	0.043	0.0023	286	18.65	15.14
2006	0.064	0.00	433	12.99	11.43
2007	0.113	0.01	760	16.87	14.37
2008	0.026	0.00	172	18.78	11.60
2009	0.684	0.04	4,598	17.14	14.26
2010	0.118	0.01	793	21.32	17.03
2011	1.752	0.08	11,784	22.09	17.96
Average (1981-2005)	0.126	0.008	847	15.89	12.76
Average (1981-2011)	0.190	0.011	1,281	16.33	13.09

[a] Recharge as a percent of precipitation

Year	Powder River structural basin				
	Recharge, in in/yr	**Recharge fraction[a]**	**Recharge, in ft^3/s**	**Precipitation, in in/yr**	**Actual ET, in in/yr**
1981	0.0005	0.00003	0.82	13.46	10.20
1982	0.0506	0.0026	92	19.77	14.34
1983	0.1239	0.0106	226	11.70	11.00
1984	0.1102	0.0083	201	13.20	11.76
1985	0.0072	0.0006	13	11.91	9.55
1986	0.0223	0.0014	41	16.46	13.03
1987	0.1420	0.0102	259	13.90	13.75
1988	0.0036	0.0004	7	8.50	7.34
1989	0.0269	0.0019	49	14.46	11.20
1990	0.0447	0.0036	82	12.42	12.42
1991	0.0466	0.0031	85	15.24	12.65
1992	0.0023	0.0002	4	13.91	11.54
1993	0.0488	0.0026	89	18.42	15.18
1994	0.0404	0.0029	74	13.88	11.05
1995	0.3676	0.0207	672	17.79	15.93
1996	0.1430	0.0095	261	15.04	12.25
1997	0.2942	0.0191	538	15.40	14.44
1998	0.0996	0.0054	182	18.40	13.36
1999	0.2402	0.0163	439	14.71	15.36
2000	0.0106	0.0008	19	12.53	10.32
2001	0.0254	0.0021	46	11.81	10.71
2002	0.0100	0.0009	18	10.82	8.79
2003	0.0917	0.0061	168	15.03	12.13
2004	0.0117	0.0011	21	10.67	9.46
2005	0.1797	0.0102	328	17.69	14.37
2006	0.0660	0.0055	121	12.00	10.87
2007	0.3318	0.0200	606	16.60	14.64
2008	0.1794	0.0100	328	17.91	13.96
2009	0.2237	0.0153	409	14.63	12.69
2010	0.0542	0.0033	99	16.31	13.87
2011	1.2024	0.0599	2,197	20.09	15.49
Average (1981-2005)	0.086	0.006	157	14.28	12.09
Average (1981-2011)	0.136	0.008	248	14.67	12.38

[a] Recharge as a percent of precipitation

Appendix B: SWB model control files

Williston basin control file

```
#MODEL DOMAIN DEFINATION (REQUIRED)
GRID 735 710 0 0 735000 710000 1000
#
#UNITS OF LENGTH
GRID_LENGTH_UNITS METERS
#
#OUTPUT SUPRESSION
SUPPRESS_SCREEN_OUTPUT
#
#GROWING SEASON (REQUIRED)
GROWING_SEASON 160 271 TRUE
#
#Precipitation (REQUIRED)
Precipitation arc_grid climate\precip\PRCP
#
#Temperature (REQUIRED)
Temperature ARC_GRID climate\temp\tmax climate\temp\tmin
#
#Soil Group (REQUIRED)
Soil_Group arc_grid input\soils_hyd_grp.ASC
#
#Land Use (REQUIRED)
Land_Use ARC_GRID input\land_cover.ASC
#
#AVAILABLE soil water Capacity (REQUIRED)
Water_Capacity ARC_GRID input\soils_awc.asc
#
#Soil Moisture Accounting Method (REQUIRED)
SM T-M std_input\SOIL-MOISTURE-RETENTION-EXTENDED.grd
#
#Open water land use
Open_water_land_use 11
#
#Land Use Lookup (REQUIRED)
Land_Use_lookup_table std_input\LU_LOOKUP.txt
#
#inital soil moisture (REQUIRED)
INITIAL_SOIL_MOISTURE CONSTANT 50
#
#INITIAL SNOW COVER (REQUIRED)
INITIAL_SNOW_COVER CONSTANT 0
#
```

```
#runoff SOLUTION METHOD (REQUIRED)
RUNOFF C-N NO_ROUTING
#
#EVAPOTRANSPIRATION METHOD (REQUIRED)
ET HARGREAVES 43.990 50.961
#
#CONTINUOUS FROZEN GROUND THRESHOLD VALUES
UPPER_LIMIT_CFGI 83
LOWER_LIMIT_CFGI 56
#
#INITIAL FROZEN GROUND INDEX
INITIAL_FROZEN_GROUND_INDEX CONSTANT 100
#
#INITIAL ABSTRATCTION METHOD (OPTIONAL)
#INITIAL_ABSTRACTION_METHOD HAWKINS
#
#OUTPUT SUPPRESSION (OPTIONAL)
SUPPRESS_DISLIN_MESSAGES
#
#START YEAR (OPTIONAL)
STATS_START_YEAR 1981
#
#OUTPUT OPTIONS
OUTPUT_OPTIONS RECHARGE NONE GRID GRID
OUTPUT_OPTIONS SM_APWL NONE NONE NONE
OUTPUT_OPTIONS SNOWCOVER NONE NONE NONE
OUTPUT_OPTIONS RUNOFF_OUTSIDE NONE NONE GRID
OUTPUT_OPTIONS ACT_ET NONE NONE GRID
OUTPUT_OPTIONS POT_ET NONE GRID GRID
OUTPUT_OPTIONS REJECTED_RECHARGE NONE NONE GRID
OUTPUT_OPTIONS INTERCEPTION NONE NONE GRID
OUTPUT_OPTIONS GROSS_PRECIP NONE NONE GRID
OUTPUT_OPTIONS SNOWFALL NONE NONE NONE
OUTPUT_OPTIONS MAX_TEMP NONE NONE NONE
OUTPUT_OPTIONS MIN_TEMP NONE NONE NONE
OUTPUT_OPTIONS CFGI NONE NONE NONE
OUTPUT_OPTIONS NET_PRECIP NONE NONE GRID
OUTPUT_OPTIONS SOIL_MOISTURE NONE NONE NONE
#
#BEGIN SOLUTION (REQUIRED)
SOLVE_NO_TS_DATA 1980 2011
#
EOJ
```
#

Powder River basin control file

```
#MODEL DOMAIN DEFINATION (REQUIRED)
GRID 310 475 0 0 310000 475000 1000
#
#UNITS OF LENGTH
GRID_LENGTH_UNITS METERS
#
#OUTPUT SUPRESSION
SUPPRESS_SCREEN_OUTPUT
#
#GROWING SEASON (REQUIRED)
GROWING_SEASON 153 280 TRUE
#
#Precipitation (REQUIRED)
Precipitation arc_grid climate\precip\PRCP
#
#Temperature (REQUIRED)
Temperature ARC_GRID climate\temp\tmax climate\temp\tmin
#
#Soil Group (REQUIRED)
Soil_Group arc_grid input\soils_hyd_grp.ASC
#
#Land Use (REQUIRED)
Land_Use ARC_GRID input\land_cover.ASC
#
#AVAILABLE soil water Capacity (REQUIRED)
Water_Capacity ARC_GRID input\soils_awc.asc
#
#Soil Moisture Accounting Method (REQUIRED)
SM T-M std_input\SOIL-MOISTURE-RETENTION-EXTENDED.grd
#
#Open water land use
Open_water_land_use 11
#
#Land Use Lookup (REQUIRED)
Land_Use_lookup_table std_input\LU_LOOKUP.txt
#
#inital soil moisture (REQUIRED)
INITIAL_SOIL_MOISTURE CONSTANT 0
#
#INITIAL SNOW COVER (REQUIRED)
INITIAL_SNOW_COVER CONSTANT 0
#
#runoff sOLUTION METHOD (REQUIRED)
RUNOFF C-N NO_ROUTING
```

```
#
#EVAPOTRANSPIRATION METHOD (REQUIRED)
ET HARGREAVES 42.428 46.860
#
#CONTINUOUS FROZEN GROUND THRESHOLD VALUES
UPPER_LIMIT_CFGI 83
LOWER_LIMIT_CFGI 56
#
#INITIAL FROZEN GROUND INDEX
INITIAL_FROZEN_GROUND_INDEX CONSTANT 100
#
#INITIAL ABSTRATCTION METHOD (OPTIONAL)
#INITIAL_ABSTRACTION_METHOD HAWKINS
#
#OUTPUT SUPPRESSION (OPTIONAL)
SUPPRESS_DISLIN_MESSAGES
#
#START YEAR (OPTIONAL)
STATS_START_YEAR 1981
#
#OUTPUT OPTIONS
OUTPUT_OPTIONS RECHARGE NONE GRID GRID
OUTPUT_OPTIONS SM_APWL NONE NONE NONE
OUTPUT_OPTIONS SNOWCOVER NONE NONE NONE
OUTPUT_OPTIONS RUNOFF_OUTSIDE NONE NONE GRID
OUTPUT_OPTIONS ACT_ET NONE NONE GRID
OUTPUT_OPTIONS POT_ET NONE GRID GRID
OUTPUT_OPTIONS REJECTED_RECHARGE NONE NONE GRID
OUTPUT_OPTIONS INTERCEPTION NONE NONE GRID
OUTPUT_OPTIONS GROSS_PRECIP NONE NONE GRID
OUTPUT_OPTIONS SNOWFALL NONE NONE NONE
OUTPUT_OPTIONS MAX_TEMP NONE NONE NONE
OUTPUT_OPTIONS MIN_TEMP NONE NONE NONE
OUTPUT_OPTIONS CFGI NONE NONE NONE
OUTPUT_OPTIONS NET_PRECIP NONE NONE GRID
OUTPUT_OPTIONS SOIL_MOISTURE NONE NONE NONE
#
#BEGIN SOLUTION (REQUIRED)
SOLVE_NO_TS_DATA 1980 2011
#
EOJ
```

#

Appendix C: Land cover correlation for American and Canadian data

USA legend: http://www.mrlc.gov/nlcd06_leg.php; Canadian legend: http://www.geobase.ca/geobase/en/data/landcover/csc2000v/description.html

Canada			USA		
Code	**Label**	**Description**	**Code**	**Label**	**Description**
0	No data	No Data.	**---**	**---**	**---**
11	Cloud	Cloud.	**---**	**---**	**---**
12	Shadow	Shadow.	**---**	**---**	**---**
20	Water	Lakes, reservoirs, rivers, streams, or salt water.	**11**	Open Water	areas of open water, generally with less than 25% cover of vegetation or soil.
30	Barren/ Non-vegetated	Predominately non-vegetated and non-developed. Includes: exposed lands, snow, glacier, rock, sediments, burned areas, rubble, mines, other naturally occurring non-vegetated surfaces. Comments: Mines or similar human activity may be mapped by this class, or may be mapped by the developed class. Excludes fallow agriculture.	**31**	Barren Land (Rock/Sand/Clay)	areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.
33	Exposed land	River sediments, exposed soils, pond or lake sediments, reservoir margins, beaches, landings, burned areas, road surfaces, mudflat sediments, cutbanks, moraines, gravel pits, tailings, railway surfaces, buildings and parking, or other non-vegetated surfaces.	**31**	Barren Land (Rock/Sand/Clay)	areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.

34	Developed	Land that predominantly built-up or developed and vegetation associated with these land covers. This includes road surfaces, railway surfaces, buildings and paved surfaces, urban areas, industrial sites, mine structures and farmsteads.	**23**	Developed, Medium Intensity	areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.
50	Shrubland	Predominantly woody vegetation of relatively low height (generally ±2 meters). Comments: May include grass or grassland wetlands with woody vegetation, regenerating forest.	**52**	Shrub/Scrub	areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.
51	Shrub tall	At least 20% ground cover which is at least one-third shrub; average shrub height greater than or equal to 2 m. In the North, moist to wet erect tall shrub > 40 cm forming more than 25% of the vegetated cover, consisting mainly of dwarf birch (Betula), willow (Salix) and / or alder (Alnus). Remaining cover consists of graminoids, lichen and may contain < 10% prostrate dwarf shrubs and bare soil.	**52**	Shrub/Scrub	areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.
52	Shrub low	At least 20% ground cover which is at least one-third shrub; average shrub height less than 2 m. In the North, Moist erect low shrub < 40 cm forming more than 25% of the vegetated cover, consisting mainly of dwarf birch (Betula) and/or willow (Salix). Remaining cover consists of graminoids, lichen and may contain prostrate dwarf shrubs and bare soil.	**52**	Shrub/Scrub	areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.

80	Wetland	Land with a water table near/at/above soil surface for enough time to promote wetland or aquatic processes (semi-permanent or permanent wetland vegetation, including fens, bogs, swamps, sloughs, marshes, etc.). Comments: This class is mapped based on cover properties corresponding with image date(s) conditions.	**95**	Emergent Herbaceous Wetlands	Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
81	Wetland – Treed	Land with a water table near/at/above soil surface for enough time to promote wetland or aquatic processes; the majority of vegetation is coniferous, broadleaf, or mixed wood.	**90**	Woody Wetlands	areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
82	Wetland – Shrub	Land with a water table near/at/above soil surface for enough time to promote wetland or aquatic processes; the majority of vegetation is tall, low, or a mixture of tall and low shrub.	**90**	Woody Wetlands	areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
83	Wetland – Herb	Land with a water table near/at/above soil surface for enough time to promote wetland or aquatic processes; the majority of vegetation is herb.	**95**	Emergent Herbaceous Wetlands	Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
100	Herb	Vascular plant without woody stem (grasses, crops, forbs, graminoids); minimum of 20% ground cover or one-third of total vegetation must be herb.	**71**	Grassland/ Herbaceous	areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.
110	Grassland	Native Grass: Predominantly native grasses and other herbaceous vegetation may include some shrubland cover. Land used for range or native unimproved pasture may appear in this class. Comments: Alpine meadows fall into this class.	**71**	Grassland/ Herbaceous	areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.

120	Cultivated Agricultural Land	Agricultural land, including annual and perennial crops; and would exclude grassland. Comments: This class is mapped when the distinction of sub-agricultural covers (classes 121-122) is not possible.	**82**	Cultivated Crops	areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.
121	Annual Cropland	Annually cultivated cropland and woody perennial crops. Includes annual field crops, vegetables, summer fallow, orchards and vineyards. Comments: Classification process primarily detects and delineates lands that change from bare cover to green/vegetated cover during the growing season.	**82**	Cultivated Crops	areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.
122	Perennial Cropland and Pasture	Periodically cultivated cropland. Includes tame grasses and other perennial crops such as alfalfa and clover grown alone or as mixtures for hay, pasture or seed. Comments: Fall seeded crops such as winter wheat may be erroneously identified in this class. Grassland and shrubland may be delineated within in this class.	**81**	Pasture/Hay	areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.
210	Coniferous Forest	Predominantly coniferous forests or treed areas. May include mixed forests and shrubland areas.	**42**	Evergreen Forest	areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.
211	Coniferous Dense	Greater than 60% crown closure; coniferous trees are 75% or more of total basal area.	**42**	Evergreen Forest	areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.

212	Coniferous Open	26-60% crown closure; coniferous trees are 75% or more of total basal area.	**42**	Evergreen Forest	areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.
213	Coniferous Sparse	10-25% crown closure; coniferous trees are 75% or more of total basal area.	**42**	Evergreen Forest	areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.
220	Deciduous Forest	Predominantly broadleaf/deciduous forests or treed areas. May include mixed forests and shrubland areas.	**41**	Deciduous Forest	areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
221	Broadleaf Dense	Greater than 60% crown closure; broadleaf trees are 75% or more of total basal area.	**41**	Deciduous Forest	areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
222	Broadleaf Open	26-60% crown closure; broadleaf trees are 75% or more of total basal area.	**41**	Deciduous Forest	areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
223	Broadleaf Sparse	10-25% crown closure; broadleaf trees are 75% or more of total basal area.	**41**	Deciduous Forest	areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
230	Mixed Forest	Mixed coniferous and broadleaf/deciduous forests or treed areas.	**43**	Mixed Forest	areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.

231	Mixed wood Dense	Greater than 60% crown closure; neither coniferous nor broadleaf tree account for 75% or more of total basal area.	**43**	Mixed Forest	areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.
232	Mixed wood Open	26-60% crown closure; neither coniferous nor broadleaf tree account for 75% or more of total basal area.	**43**	Mixed Forest	areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.
233	Mixed wood Sparse	10-25% crown closure; neither coniferous nor broadleaf tree account for 75% or more of total basal area.	**43**	Mixed Forest	areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.

Appendix D: Lookup table used for the Williston and Powder River SWB models

The Powder River SWB model only used the NRCS hydrologic soil groups (A, B, C, and D).

		Curve Number									
Land Cover Code	Land Cover Description	A	B	C	D	Till	Glacio-lacustrine	Glacio-fluvial	Loess and Eolian Deposits	Glacio-tectonic Deposits	Open Water
11	Open Water	100	100	100	100	100	100	100	100	100	100
12	Perennial Ice/Snow	40	40	40	40	40	40	40	40	40	100
21	Developed, Open Space	49	69	79	84	84	74	49	49	79	100
22	Developed, Low Intensity	72	82	87	89	89	84.5	72	72	86.75	100
23	Developed, Medium Intensity	77	86	91	94	94	88.5	77	77	91.25	100
24	Developed, High Intensity	89	92	94	95	95	93	89	89	94	100
31	Barren Land	77	86	91	90	90	88.5	77	77	89.25	100
41	Deciduous Forest	43	48	57	63	63	52.5	43	43	57.75	100
42	Evergreen Forest	37	41	61	71	71	51	37	37	61	100
43	Mixed Forest	40	44	59	67	67	51.5	40	40	59.25	100
52	Shrub/Scrub	49	68	79	84	84	73.5	49	49	78.75	100
71	Grassland/ Herbaceous	56	71	81	89	89	76	56	56	82.5	100
81	Pasture/Hay	49	69	79	84	84	74	49	49	79	100
82	Cultivated Crops	71	80	87	90	90	83.5	71	71	86.75	100
90	Woody Wetlands	88	89	90	91	91	89.5	88	88	90.25	100
95	Emergent Herbaceous Wetlands	89	90	91	92	92	90.5	89	89	91.25	100

		Maximum infiltration rates (in/day)									
Land Cover Code	Land Cover Description	A	B	C	D	Till	Glacio-lacustrine	Glacio-fluvial	Loess and Eolian Deposits	Glacio-tectonic Deposits	Open Water
11	Open Water	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0
12	Perennial Ice/Snow	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0
21	Developed, Open Space	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0
22	Developed, Low Intensity	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0
23	Developed, Medium Intensity	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0
24	Developed, High Intensity	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0
31	Barren Land	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0
41	Deciduous Forest	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0
42	Evergreen Forest	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0
43	Mixed Forest	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0
52	Shrub/ Scrub	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0
71	Grassland/ Herbaceous	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0
81	Pasture/ Hay	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0
82	Cultivated Crops	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0
90	Woody Wetlands	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0
95	Emergent Herbaceous Wetlands	1.125	0.675	0.3	0.075	0.12	0.24	2	2	0.12	0

		Interception	
Land Cover Code	Land Cover Description	Growing	Dorment
11	Open Water	0	0
12	Perennial Ice/Snow	0	0
21	Developed, Open Space	0.0835	0
22	Developed, Low Intensity	0.0835	0
23	Developed, Medium Intensity	0.0835	0
24	Developed, High Intensity	0.0835	0
31	Barren Land	0	0
41	Deciduous Forest	0.09	0
42	Evergreen Forest	0.11	0
43	Mixed Forest	0.05	0
52	Shrub/Scrub	0.0625	0
71	Grassland/Herbaceous	0.09	0
81	Pasture/Hay	0.09	0
82	Cultivated Crops	0.09	0
90	Woody Wetlands	0.05	0
95	Emergent Herbaceous Wetlands	0	0

Depth of root zone (ft)											
Land Cover Code	Land Cover Description	A	B	C	D	Till	Glacio-lacustrine	Glacio-fluvial	Loess and Eolian Deposits	Glacio-tectonic Deposits	Open Water
11	Open Water	0	0	0	0	0	0	0	0	0	0
12	Perennial Ice/Snow	0	0	0	0	0	0	0	0	0	0
21	Developed, Open Space	2.5	2.5	2	2	2	2	2.5	2.5	2	0
22	Developed, Low Intensity	2.5	2.5	2	2	2	2	2.5	2.5	2	0
23	Developed, Medium Intensity	2.5	2.5	2	2	2	2	2.5	2.5	2	0
24	Developed, High Intensity	2.5	2.5	2	2	2	2	2.5	2.5	2	0
31	Barren Land	1	1	1	1	1	1	1	1	1	0
41	Deciduous Forest	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	0
42	Evergreen Forest	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	0
43	Mixed Forest	5	5	5	5	5	5	5	5	5	0
52	Shrub/Scrub	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	0
71	Grassland/ Herbaceous	4	4	4	4	4	4	4	4	4	0
81	Pasture/Hay	4	4	4	4	4	4	4	4	4	0
82	Cultivated Crops	3	3	3	3	3	3	3	3	3	0
90	Woody Wetlands	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	0
95	Emergent Herbaceous Wetlands	2	2	2	2	2	2	2	2	2	0

Appendix E: Sensitivity analysis

Original average annual recharge (in/yr): 0.136347

Note: this base value is different than the value presented in the results section because a few curve numbers had to be decreased so that the 10% increase in the parameter would not create an unrealistic value.

Sensitive model parameters (relative percent sensitivity +/- 10%) are highlighted.

Section	Hydrologic Soil Group	Land Cover Code	Actual Value	10%	Average annual recharge (in/yr) 10%	Relative percent sensitivity 10%
Curve Number (unitless)	A	12	40	44	0.136347067	0
		21	49	53.9	0.136347067	0
		22	72	79.2	0.136347067	0
		23	72	79.2	0.136347067	0
		24	84	92.4	0.136347067	0
		31	77	84.7	0.136347067	0
		41	43	47.3	0.136347067	0
		42	37	40.7	0.136347067	0
		43	40	44	0.136347067	0
		52	49	53.9	0.136347067	0
		71	56	61.6	0.136347067	0
		81	49	53.9	0.136347067	0
		82	71	78.1	0.136347067	0
		90	83	91.3	0.136347067	0
		95	84	92.4	0.136347067	0
	B	12	40	44	0.136347067	0
		21	69	75.9	0.136198993	-1.09
		22	82	90.2	0.136179062	-1.23
		23	81	89.1	0.136256728	-0.663
		24	87	95.7	0.136320199	-0.197
		31	86	94.6	0.133667275	-19.7
		41	48	52.8	0.136345996	-0.008
		42	41	45.1	0.136332669	-0.106
		43	44	48.4	0.136347067	0
		52	68	74.8	0.131451177	-35.9
		71	71	78.1	0.130565853	-42.4
		81	69	75.9	0.136231928	-0.844
		82	80	88	0.135344018	-7.4
		90	84	92.4	0.136064229	-2.1
		95	85	93.5	0.135648298	-5.1

Section	Hydrologic Soil Group	Land Cover Code	Actual Value	10%	Average annual recharge (in/yr) 10%	Relative percent sensitivity 10%
Curve Number (unitless)	**C**	12	40	44	0.136347	0
		21	79	86.9	0.13621	-1.01
		22	87	95.7	0.136298	-0.361
		23	86	94.6	0.136347	0
		24	89	97.9	0.136347	0
		31	91	100.1	0.134625	-12.6
		41	57	62.7	0.136346	-0.004
		42	61	67.1	0.13634	-0.053
		43	59	64.9	0.136347	0
		52	79	86.9	0.133993	-17.3
		71	81	89.1	0.134364	-14.5
		81	79	86.9	0.136309	-0.282
		82	87	95.7	0.136179	-1.23
		90	85	93.5	0.136276	-0.518
		95	86	94.6	0.136133	-1.57
	D	12	40	44	0.136347	0
		21	84	92.4	0.136268	-0.581
		22	89	97.9	0.136311	-0.261
		23	89	97.9	0.136342	-0.036
		24	90	99	0.136347	0
		31	90	99	0.135375	-7.1
		41	63	69.3	0.136347	0
		42	71	78.1	0.136262	-0.626
		43	67	73.7	0.136347	0
		52	84	92.4	0.132325	-29.5
		71	89	97.9	0.134369	-14.5
		81	84	92.4	0.136337	-0.071
		82	90	99	0.136313	-0.249
		90	86	94.6	0.136336	-0.078
		95	87	95.7	0.136277	-0.513

Section	Hydrologic Soil Group	Land Cover Code	Actual Value	10%	Average annual recharge (in/yr) 10%	Relative percent sensitivity 10%
Maximum Infiltration (in/day)	**A**	12	1.125	1.2375	0.136347	0
		21	1.125	1.2375	0.136347	0
		22	1.125	1.2375	0.136347	0
		23	1.125	1.2375	0.136347	0
		24	1.125	1.2375	0.136347	0
		31	1.125	1.2375	0.136347	0
		41	1.125	1.2375	0.136347	0
		42	1.125	1.2375	0.136347	0
		43	1.125	1.2375	0.136347	0
		52	1.125	1.2375	0.136347	0
		71	1.125	1.2375	0.136347	0
		81	1.125	1.2375	0.136347	0
		82	1.125	1.2375	0.136347	0
		90	1.125	1.2375	0.136347	0
		95	1.125	1.2375	0.136347	0
	B	12	0.675	0.7425	0.136347	0
		21	0.675	0.7425	0.136372	0.182
		22	0.675	0.7425	0.136348	0.009
		23	0.675	0.7425	0.136347	0.002
		24	0.675	0.7425	0.136347	0
		31	0.675	0.7425	0.136362	0.106
		41	0.675	0.7425	0.136352	0.038
		42	0.675	0.7425	0.136576	1.68
		43	0.675	0.7425	0.136347	0
		52	0.675	0.7425	0.137394	7.7
		71	0.675	0.7425	0.137052	5.2
		81	0.675	0.7425	0.136365	0.129
		82	0.675	0.7425	0.136372	0.185
		90	0.675	0.7425	0.136349	0.012
		95	0.675	0.7425	0.13635	0.023

Section	Hydrologic Soil Group	Land Cover Code	Actual Value	10%	Average annual recharge (in/yr) 10%	Relative percent sensitivity 10%
Maximum Infiltration (in/day)	**C**	12	0.3	0.33	0.136347	0
		21	0.3	0.33	0.136373	0.187
		22	0.3	0.33	0.136349	0.014
		23	0.3	0.33	0.136347	0
		24	0.3	0.33	0.136347	0
		31	0.3	0.33	0.136388	0.303
		41	0.3	0.33	0.13635	0.025
		42	0.3	0.33	0.136356	0.066
		43	0.3	0.33	0.136347	0
		52	0.3	0.33	0.136602	1.87
		71	0.3	0.33	0.136488	1.03
		81	0.3	0.33	0.136351	0.029
		82	0.3	0.33	0.136354	0.050
		90	0.3	0.33	0.136351	0.029
		95	0.3	0.33	0.136359	0.088
	D	12	0.075	0.0825	0.136347	0
		21	0.075	0.0825	0.136362	0.111
		22	0.075	0.0825	0.136351	0.025
		23	0.075	0.0825	0.136347	0.003
		24	0.075	0.0825	0.136347	0
		31	0.075	0.0825	0.136434	0.639
		41	0.075	0.0825	0.136347	0
		42	0.075	0.0825	0.136388	0.297
		43	0.075	0.0825	0.136347	0
		52	0.075	0.0825	0.136961	4.5
		71	0.075	0.0825	0.136517	1.24
		81	0.075	0.0825	0.136349	0.013
		82	0.075	0.0825	0.13635	0.021
		90	0.075	0.0825	0.136348	0.007
		95	0.075	0.0825	0.136354	0.049

Section	Hydrologic Soil Group	Land Cover Code	Actual Value	10%	Average annual recharge (in/yr) 10%	Relative percent sensitivity 10%
Root Zone Depth (ft)	**A**	21	2.5	2.75	0.136347	0
		22	2.5	2.75	0.136347	0
		23	2.5	2.75	0.136347	0
		24	2.5	2.75	0.136347	0
		31	1	1.1	0.136347	0
		41	4.5	4.95	0.136347	0
		42	5.5	6.05	0.136347	0
		43	5	5.5	0.136347	0
		52	3.5	3.85	0.136347	0
		71	4	4.4	0.136347	0
		81	4	4.4	0.136347	0
		82	3	3.3	0.136347	0
		90	4.5	4.95	0.136347	0
		95	2	2.2	0.136347	0
	B	21	2.5	2.75	0.135934	-3.0
		22	2.5	2.75	0.136267	-0.589
		23	2.5	2.75	0.1363	-0.347
		24	2.5	2.75	0.136339	-0.061
		31	1	1.1	0.135878	-3.4
		41	4.5	4.95	0.136288	-0.433
		42	5.5	6.05	0.134951	-10.2
		43	5	5.5	0.136347	0
		52	3.5	3.85	0.122232	-103.5
		71	4	4.4	0.12628	-73.8
		81	4	4.4	0.136076	-1.99
		82	3	3.3	0.135755	-4.3
		90	4.5	4.95	0.136223	-0.910
		95	2	2.2	0.136127	-1.61

Section	Hydrologic Soil Group	Land Cover Code	Actual Value	10%	Average annual recharge (in/yr) 10%	Relative percent sensitivity 10%
Root Zone Depth (ft)	C	21	2	2.2	0.136221	-0.926
		22	2	2.2	0.136333	-0.103
		23	2	2.2	0.136347	0
		24	2	2.2	0.136347	0
		31	1	1.1	0.136148	-1.46
		41	4.5	4.95	0.136332	-0.111
		42	5.5	6.05	0.136308	-0.287
		43	5	5.5	0.136347	0
		52	3.5	3.85	0.13442	-14.1
		71	4	4.4	0.134905	-10.6
		81	4	4.4	0.136317	-0.219
		82	3	3.3	0.136278	-0.509
		90	4.5	4.95	0.136316	-0.231
		95	2	2.2	0.136282	-0.479
	D	21	2	2.2	0.136311	-0.267
		22	2	2.2	0.136338	-0.063
		23	2	2.2	0.136346	-0.008
		24	2	2.2	0.136347	0
		31	1	1.1	0.136264	-0.607
		41	4.5	4.95	0.136347	0
		42	5.5	6.05	0.136221	-0.927
		43	5	5.5	0.136347	0
		52	3.5	3.85	0.134445	-14.0
		71	4	4.4	0.135681	-4.9
		81	4	4.4	0.136343	-0.033
		82	3	3.3	0.136335	-0.088
		90	4.5	4.95	0.136344	-0.025
		95	2	2.2	0.136331	-0.119
Precipitation	---	---	---	---	0.248329	821.3
Temperature	---	---	---	---	0.055792	-590.8

Vita

Katherine (Katie) Aurand was born in Rapid City, South Dakota, in 1989. She graduated from Stevens High School in 2007. That same year, Katie was selected as the female South Dakota Presidential Scholar. Katie graduated from the South Dakota School of Mines and Technology (SDSM&T) in 2011 with a B.S. in environmental engineering and a minor in geology.

Katie has worked as a student hydrologist at the U.S. Geological Survey since May 2011. During her time as a master's student, she also worked as a research assistant and teaching assistant at SDSM&T. In 2012, Katie was selected as the SDSM&T outstanding master's student. Katie was also the recipient of the Mickelson Fellowship, Gries Fellowship, and the Ivanhoe Excellence Award. She married Ivar Melby in 2012.

Katie is a student member of the Association of Environmental and Engineering Geologists (AEG), American Institute of Professional Geologists (AIPG), Geological Society of America (GSA), Society of Women Engineers (SWE), and the Society of Petroleum Engineers (SPE). She is also a member of Tau Beta Pi, the engineering honor society, and serves as the newsletter chair for the Unsaturated Zone Interest Group (UZIG).

Katie received first place for her master's thesis project at the graduate student poster competition at the AIPG national conference in September, 2012. She also received first place at the Rocky Mountain Section AEG student night in March, 2013, and first place at the Western South Dakota Hydrology Conference in April, 2013.