January 2017

Assessment Of Climate Change And Agricultural Land Use Change On Streamflow Input To Devils Lake: A Case Study Of The Mauvais Coulee Sub-Basin

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ASSESSMENT OF CLIMATE CHANGE AND AGRICULTURAL LAND USE CHANGE ON STREAMFLOW INPUT TO DEVILS LAKE: A CASE STUDY OF THE MAUVAIS COULEE SUB-BASIN

by

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Bachelors of Science, The Pennsylvania State University, 2015

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota

May
2017

This thesis, submitted by Courtney C. Jackson in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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April 27, 2017
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Department	Geography and Geographic Information Science
Degree	Master of Science

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Courtney C. Jackson
27 April 2017

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ACKNOWLEDGMENTS

I would like to thank the North Dakota Water Resources Research Institute (NDWRRI) for the fellowship funding and support of this research. To the members of my thesis committee, I want to convey my gratitude for the guidance and support given to me over the course of this research.

ABSTRACT

Since 1993, Devils Lake in North Dakota has experienced a prolonged rise in lake level and flooding of the lake's neighboring areas within the closed basin system. Understanding the relative contribution of climate change and land use change is needed to explain the historical rise in lake level, and to evaluate the potential impact of anthropogenic climate change upon future lake conditions and management. Four methodologies were considered to examine the relative contribution of climatic and human landscape drivers to streamflow variations: statistical, ecohydrologic, physically-based modeling, and elasticity of streamflow; for this study, ecohydrologic and climate elasticity were selected. Agricultural statistics determined that Towner and Ramsey counties underwent a crop conversion from small grains to row crops within the last 30 years. Through the Topographic Wetness Index (TWI), a 10 meter resolution DEM confirmed the presence of innumerable wetland depressions within the non-contributing area of the Mauvais Coulee Sub-basin. Although the ecohydrologic and climate elasticity methodologies are the most commonly used in literature, they make assumptions that are not applicable to basin conditions. A modified and more informed approach to the use of these methods was applied to account for these unique sub-basin characteristics. Ultimately, hydroclimatic variability was determined as the largest driver to streamflow variation in Mauvais Coulee and Devils Lake.

CHAPTER I

INTRODUCTION

About five percent of the landmass of North America drains into terminal lakes, which are lakes that are located at the lowest point within a closed drainage basin (USGS, 2013b). Terminal lakes are an understudied hydrologic system. The hydrology of terminal lakes varies naturally due to precipitation (P) and streamflow (Q) inputs and evapotranspiration (ET) outputs. Terminal lakes, as unique hydrological systems, are subject to natural hydroclimatic changes in water surface elevation (WSE), and changes due to human alterations (Williams 1996). Since 1993 Devils Lake in North Dakota, the second largest inland terminal lake in the nation, has experienced prolonged rise in WSE and flooding of the lake and neighboring areas within the closed basin. The change in WSE can result from changes in the hydroclimate and/or changes in basin hydrology because of human landscape modification (Ryan and Wiche 1988; Williams 1996; Todhunter 2016). While most terminal lakes are found within arid or semi-arid climatic environments, Devils Lake experiences a sub-humid of climate. Due to this sub-humid climate, the lake receives more precipitation input into the hydrologic system, thus increasing streamflow and WSE.

Considerable research has shown that runoff volume is sensitive to both climate variability and human alteration (Ryan and Wiche 1988; Tomer and Schilling 2009; Drummond et al. 2012; Wright and Wimberly 2013; Neupane and Kumar 2015), but the relative contribution of these drivers of hydrological change has not been investigated in the Devils

Lake Basin. Understanding the relative contribution of each is critical to explaining the historical rise in the lake level/lake volume at Devils Lake, properly managing the current lake level, and evaluating the potential impact of anthropogenic climate change upon future lake conditions and management. Such a determination has not been attempted for the Devils Lake Basin, and is especially challenging because of the unique hydrology of terminal lakes, and the unusual hydrological processes present in glaciated prairie environments.

Natural hydroclimatic factors normally are the largest driver behind streamflow/lake level variation in Devils Lake (Vecchia 2008, Ryberg et al. 2014, Todhunter and Fietzek-DeVries 2016). Land use/land cover (LULC) changes possess a multitude of confounding variables influencing streamflow variation. Land use is defined as the purpose the land serves for human use; land cover change refers to the on the ground, observable surface cover. Irrigation, tile drainage, tillage practices and crop conversion are common examples of land use changes that contribute to streamflow (Wang et al. 2013b; Gupta et al. 2015; Neupane and Kumar 2015). Conversion of native prairie grasslands and wetlands to agricultural fields has been well documented land cover change for this region (Drummond et al. 2012; Wright and Wimberly 2013). LULC changes have occurred in this region throughout the study's period of record, with both contributing to streamflow variation in some capacity.

The examination of the contribution of LULC change to lake level rise in Devils Lake is a problem yet to be addressed for the basin. The purpose of this research is to investigate the relative impact of climate variation and human activities on streamflow variation in Mauvais Coulee. To achieve this purpose, the objectives of the research are to: 1) Quantify spatial and temporal change in agricultural land use over time; 2) Use appropriate wetland data to investigate spatial extent of wetland depressions within the Mauvais Coulee Sub-basin; 3)

Assemble a hydroclimatic database to establish climatic drivers to streamflow variation in the sub-basin; 4) Partition streamflow change into climatic and human components using accepted hydrological methods.

CHAPTER II

LITERATURE REVIEW

Closed Basins/Terminal Lakes

Terminal lakes result from the drainage of water within a closed basin into an inland body of water that is not connected to a larger outside body of water like a river or ocean. These lakes are typically saline in nature because of the slow accumulation of dissolved salts within the lake. Saline lakes are a product of a delicate balance between basin inputs (precipitation over the lake plus inflow from rivers) and outputs (evapotranspiration and seepage outflows) (Williams 1996). Changes within the hydrologic system of the lake only occur when there are imbalances between those four variables. Saline lakes respond quickly and sensitively to any changes in the volume of water entering them (Williams 1996). Such changes can be caused by the natural climatic variation within the basin. Historic climate change data observed in terminal lakes can be used as indicators of current or future climatic conditions of these lakes. Alternatively, human modification of the landscape can also cause increases in streamflow and lake level.

Devils Lake

Basin Description

The Devils Lake Basin in northeastern North Dakota covers 9,870 km² and is an example of a closed basin system with an inland terminal lake (Devils Lake). Figure 1 shows the spatial extent of the Devils Lake Basin at the county and state level. There are nine sub-basins that contribute to Devils Lake (Figure 2). The sub-basins draining into Devils Lake occupy about 8,600 km², whereas the Stump Lake Sub-basin covers 1,270 km² (Sethre et al. 2005). The glacial origins of these sub-basins have created numerous depressions and prairie potholes that are scattered throughout the basin. Many of these depressions are connected by poorly defined channels and swales (Ryan and Wiche 1988). Their connectivity becomes dependent on climatic conditions, and it is difficult to discern the runoff contribution of these potholes to streamflow in the basin.

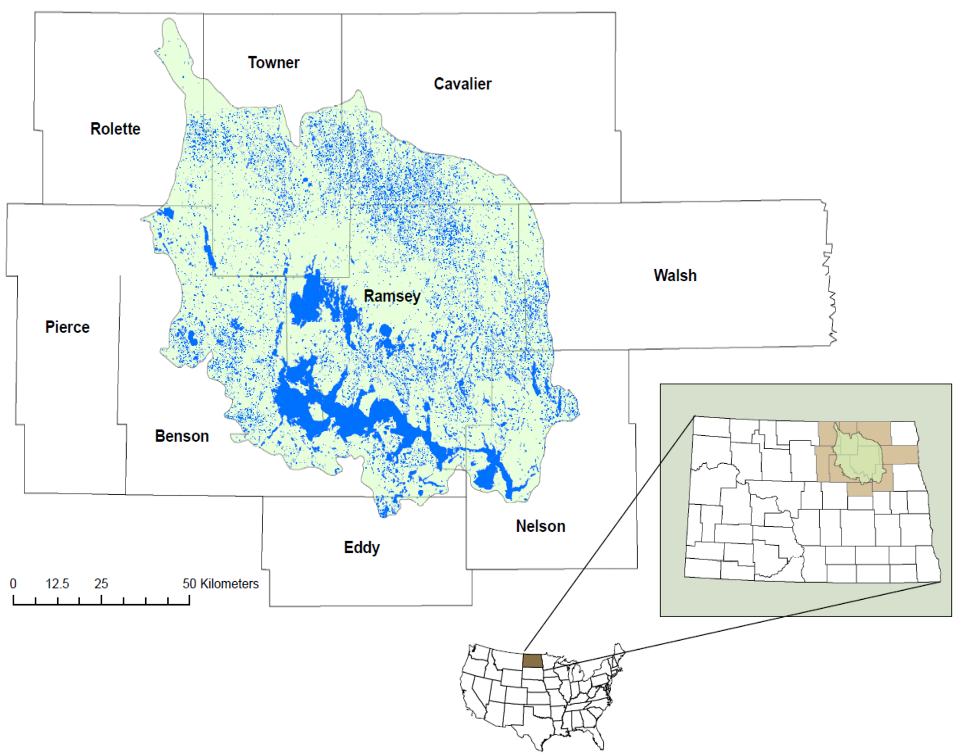

Figure 1: Location of the Devils Lake Basin (shaded area) within North Dakota. Water body extents depicted are for 1999. *Source:* Sethre et al. (2005).

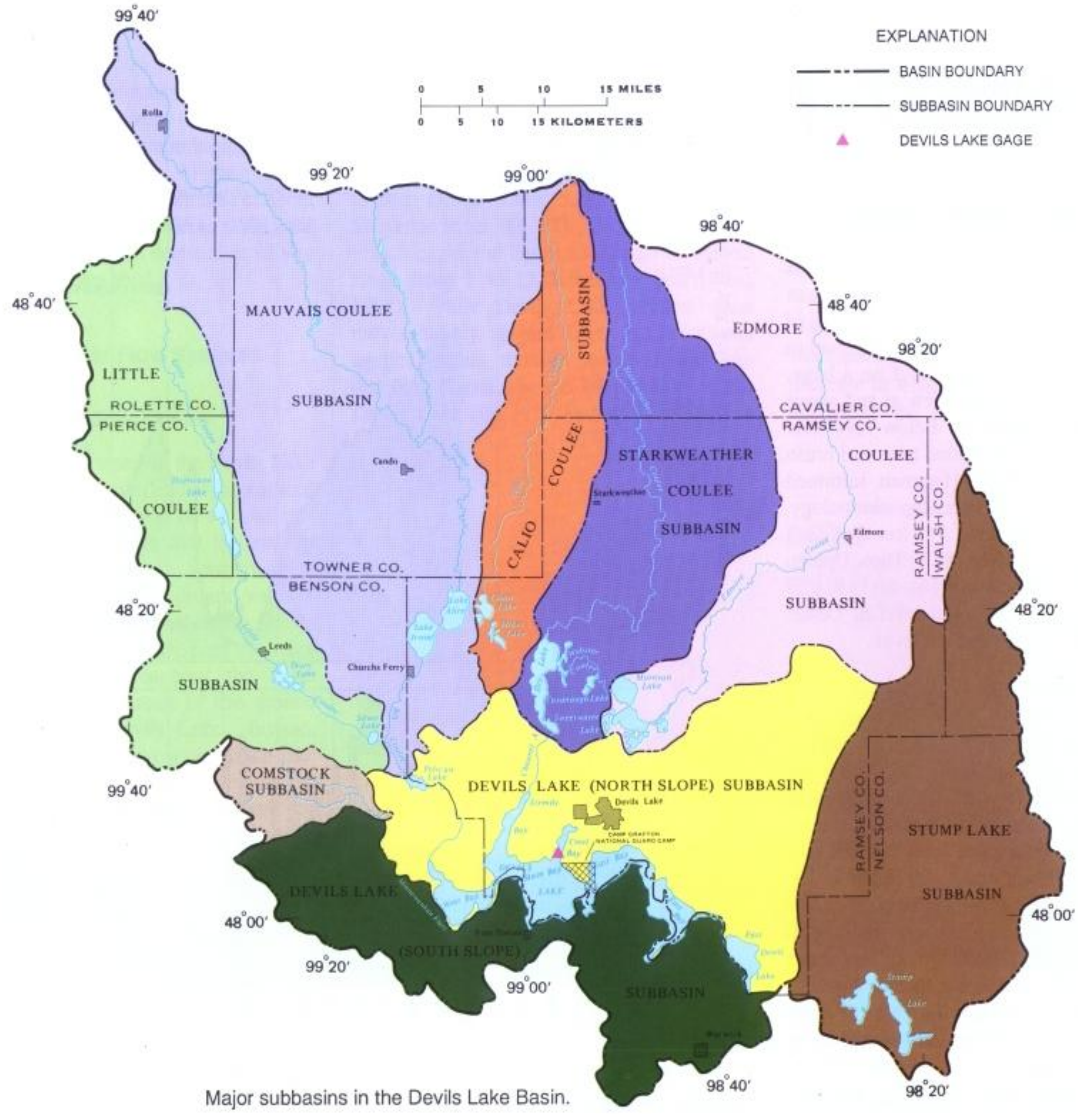

Figure 2: Map of the nine major sub-basins within the Devils Lake Basin. *Source:* USGS (2013a).

Flooding History

The weather conditions in Devils Lake over the last 25 years have resulted in wetter than normal conditions. From 1961 to 1990, the average precipitation for a weather station near Jamestown, in eastern North Dakota, for May, June, and July was 221 mm, while for the year 1993, those three months saw a total precipitation of 533 mm, marking the start of the wet cycle (Winter and Rosenberry 1998). Since 1993, the lake level in Devils Lake rose close to 9.0

meters. Beginning in 1999, Devils Lake began to overflow into Stump Lake, a smaller closed lake sub-basin located in Nelson County (Todhunter and Rundquist 2004). With the new connection to Stump Lake, continued WSE rise will result in Stump Lake reaching its elevation spill-over point where it will connect with the Sheyenne River, no longer making Devils Lake a closed basin system (Figure 3).

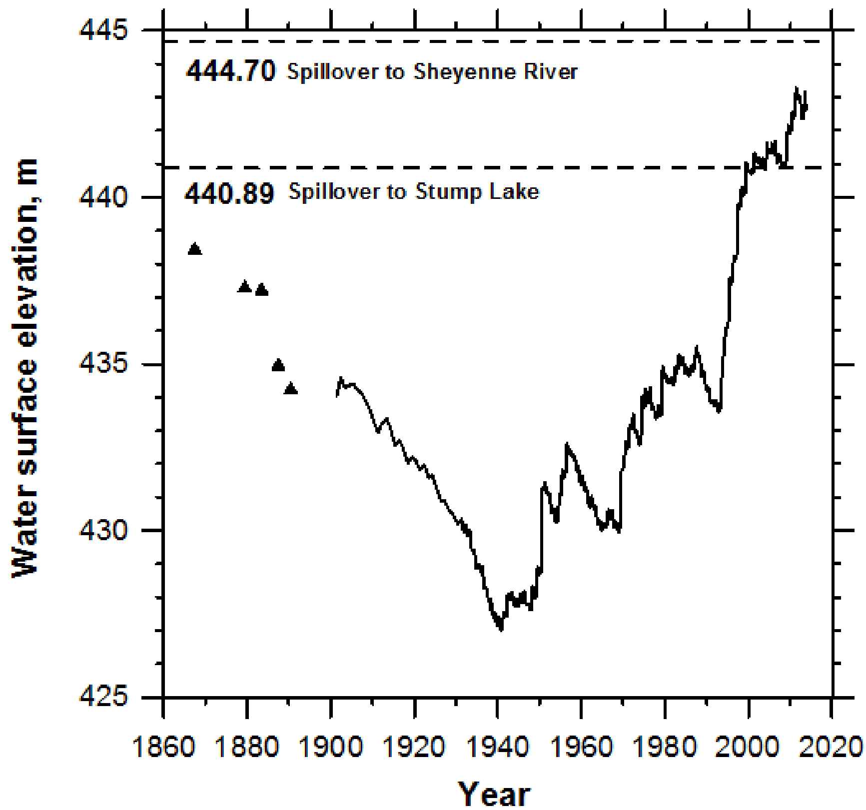

Figure 3: Water surface elevation (WSE) of Devils Lake from 1900-present, with spill-over elevations for Stump Lake and the Sheyenne River. *Source:* Todhunter and Rundquist (2004).

Lake Hydrology

The hydrologic connectivity of each major sub-basin within the Devils Lake Basin is an important aspect of lake hydrology (Figure 2). Water starts in the upper basin and flows to a lake at each sub-basin terminus. Each of these lakes may spill over into the next sub-basin and its lake. Normally the upper basin is not directly connected to Devils Lake, and only contributes to Devils Lake if its WSE is at spill level. Lake level is sensitive to any changes within the system that alter surface runoff or inflow. Changes in Devils Lake surface runoff/inflow can be attributed to climatic and anthropogenic drivers. The construction of Channel A in 1979 is an example of a human modification to the natural streamflow. The construction of Channel A and the levee on Dry Lake modified the drainage pattern in the basin. Runoff into Sweetwater, Morrison, and Dry lakes discharges through Channel A, and the remaining runoff discharges along the natural watercourse down Big Coulee into Devils Lake (Ryan and Wiche 1988).

Vecchia (2002) found a statistically significant increase in precipitation for the period of 1975–1999 over the period 1950–1974 in Devils Lake. Todhunter and Fietzek-DeVries (2016) identified two climatic modes over the 1900-2016 period of record (Figure 4). From 1900-1980 there is a dry period that is reflected in the relationship between lake level, precipitation, and soil moisture storage. From 1980-1993 there is an increase in precipitation and soil moisture storage, however the lake level does not begin to rise until 1993. After 1993 all three continue to increase. The time period of 1980-1993 is considered a lag period; groundwater and vadose storages (the unsaturated zone between the earth surface and water table) are filling until their storage capacities are met, at which point increased streamflow input to Devils Lake begins and lake level begins to rise rapidly.

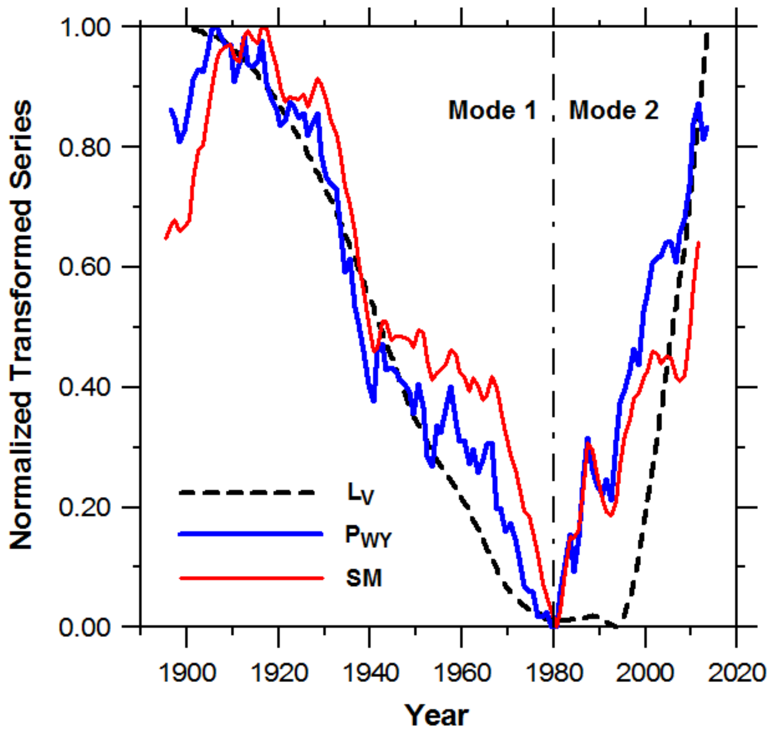

Figure 4: Climatic wet and dry modes of Devils Lake showing the changes in lake level, precipitation, and soil moisture storage from 1900-2016. *Source:* Todhunter and Fietzek-DeVries (2016).

Glaciated Plains Hydrology

The glaciated Prairie Pothole Region (PPR) can be found extending northward from central Iowa, through western Minnesota, eastern North and South Dakota, southwestern Manitoba, and southern Saskatchewan. Boundaries of the region are defined by the extent of clay-rich glacial tills deposited by the continental ice sheet during Pleistocene glaciations. The region has extensive areas of hummocky landscape containing many topographically closed drainage basins (van der Kamp and Hayashi 2009). Depressional wetlands found in this region are commonly referred to as 'prairie potholes' in the U. S. and 'sloughs' in Canada. The relative lack of naturally integrated surface drainage among depressions in the landscape is one of the reasons that runoff as spring snowmelt is retained in non-contributing areas (wetlands, ponds, and lakes) (LaBaugh et al. 1998).

During the winter months, depressions collect water in the form of snowdrifts or as runoff from snowmelt across the frozen soil (van der Kamp et al. 2003). Snow accumulation and snowmelt runoff is sensitive to land cover vegetation and the degree to which tillage disturbs soil structure. Groundwater recharge and discharge is typically centered beneath depressions where water collects from snowmelt in springtime. The very low hydraulic conductivity of clay-rich tills in most prairie depressions successfully inhibits the deep percolation of water into deep groundwater aquifers (LaBaugh et al. 1998; van der Kamp and Hayashi 2008). This causes there to be shallower, more localized groundwater systems for the PPR as the rate of groundwater flow is extremely slow. The flat topography of the PPR also restricts efficient surface runoff, but allows for the infiltration of water to be maximized and for the development of ground and surface water interaction.

Fill-Spill Hydrology

The same hydrological processes that cause water to collect in isolated depressions in the landscape also produce the runoff that contributes to streamflow. These depressions share the process of 'fill-and-spill' hydrology, where depressions continue to fill until they reach their storage capacity and then the excess drains off into the next depression until that one meets its storage capacity (Figure 5). During spring these depressions have the opportunity to fill up more rapidly, allowing for a quicker drainage into adjacent depressions. The amount of water entering a pothole through runoff, snowmelt water, or groundwater discharge in excess of direct precipitation dictates a wetland or pond's permanency (Hubbard et al. 1987).

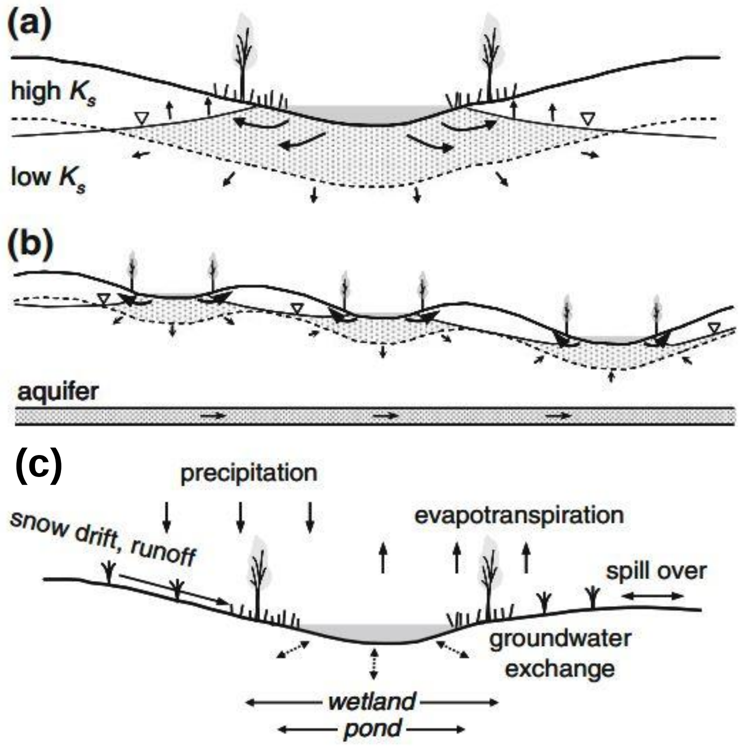

Figure 5: a) Diagram of groundwater flow under a recharge wetland; b) Diagram showing the fill–spill hydrology of water flow to wetlands; c) Water balance diagram of components in a prairie wetland. *Source:* van der Kamp and Hayashi (2009).

Drivers of Streamflow Variation

Linear Precipitation-Discharge Relationship

The relationship between precipitation and runoff is important in understanding how streamflow varies over time. Gupta et al. (2015) theorized the relationship between precipitation and runoff, under the assumption of normal basin conditions and no non-contributing area (Figure 6). There is an assumption of a linear relationship between precipitation (P) and discharge (Q), in which case any shift/change that occurs within the climate regime happens along a line (i.e. if P increases, Q increases linearly). The same climatic linear relationship holds with a landscape, resulting in an offset of the P-Q relationship (i.e. land use change produces an increase in Q for a given value of P) (Figure 6a).

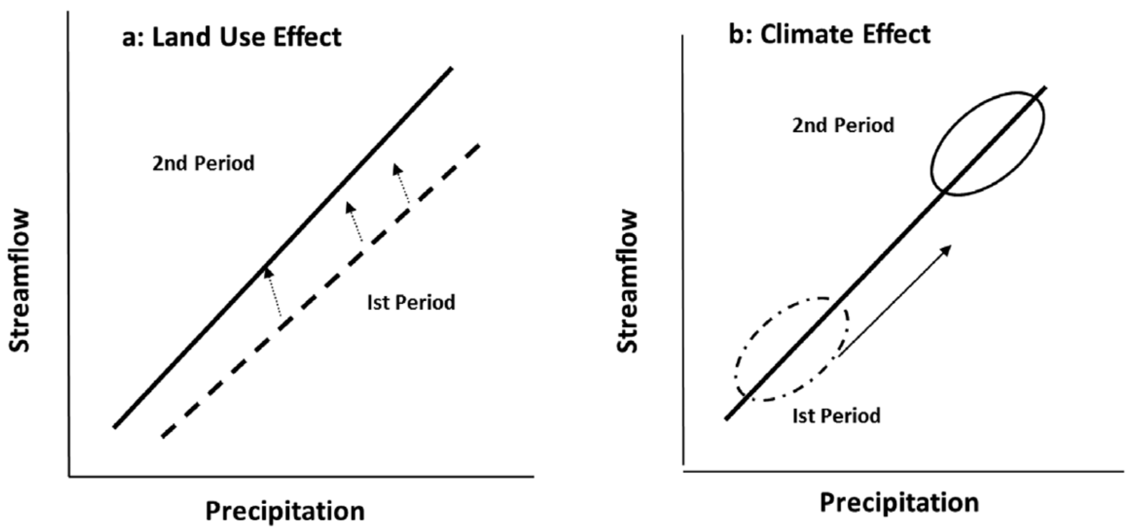

Figure 6a/b: Theorized linear P-Q relationships for normal basin conditions with no non-contributing area. *Source:* Gupta et al. (2015).

Non-Linear Precipitation-Discharge Relationship

We hypothesize that for the Mauvais Coulee and Devils Lake there is a non-linear relationship. This non-linear relationship is a result of the dynamic water storage and non-contributing area relationships, which influence the P-Q relationship. Saft et al. (2015) theorized the potential P-Q relationship with the consideration of non-contributing area influence (Figure 7). This relationship assumes that if there is an increase in P, then there will be a proportionally greater increase in percent runoff with increasing P (i.e. the percentage of runoff will vary with P).

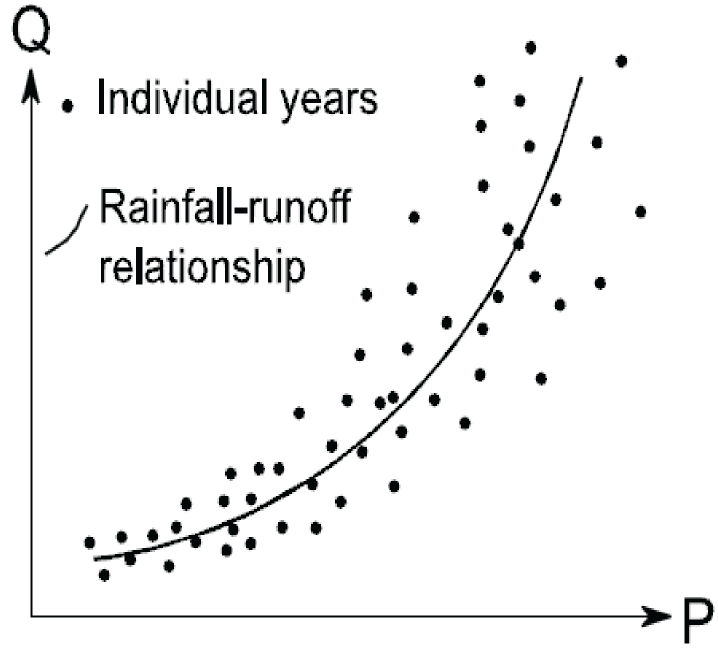

Figure 7: Theorized non-linear relationship between P-Q in a hydrological system with non-contributing area. *Source:* Saft et al. (2015).

Confounding Variables

Drivers of Hydrologic System Change

In addition to understanding the P-Q relationship, other climatic and anthropogenic variables must be considered to understand how they influence changes in a hydrologic system. Destouni (2015) produced a conceptual model identifying the various contributing factors to hydrologic system change (Figure 8). Hydrologic runoff is driven by both atmospheric and landscape change forcings. Atmospheric changes (i.e. temperature, radiation, wind, etc.) are the climatic drivers that can cause a rise in Devils Lake. Significant LULC change is another driver of streamflow change; further investigation into how LULC components are influencing the hydrologic change in Devils Lake needs to be conducted. Known changes in Mauvais Coulee are tied to changes in temperature and PET with possible human effects (i.e. irrigation, tillage practices); however, these are harder to differentiate from climatic effects.

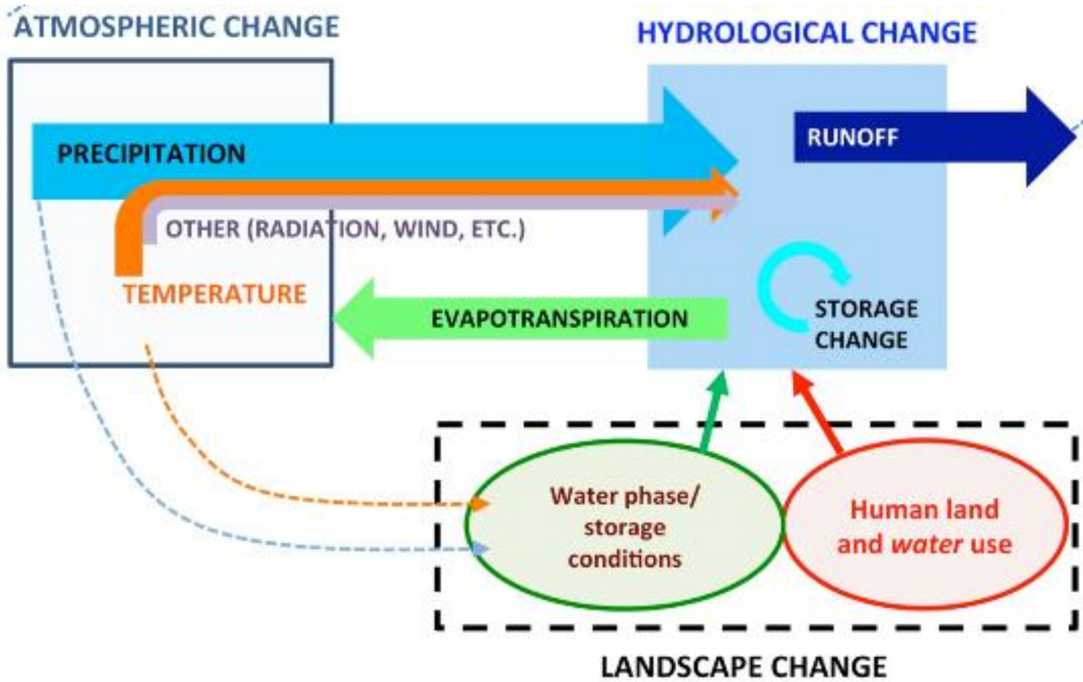

Figure 8: Drivers of hydrological system change. *Source:* Destouni (2015).

Land Use Change

Agricultural Change

One of the most important variables of LULC change is agricultural land use change. LULC change is identified as the largest contributing variable to streamflow variation (Drummond et al. 2012; Neupane and Kumar 2015; Wright and Wimberly 2013). Land cover change from natural land cover to agricultural land covers seems to have the most pronounced influence on streamflow. Neupane and Kumar (2015) found through use of the SWAT model that surface runoff increased close to four percent for corn fields in comparison to grasslands. Crop conversion is another contributor to streamflow variation. A conversion from small grains to row crops, such as has occurred in the Devils Lake Basin, produces an environment with more bare ground from which water can run off. While agricultural land cover change is the most measurable contributor to streamflow variation, the effects are typically more pronounced within the few years following the change done to the landscape.

Human Modification

Other influential variables such as wetland drainage (Johnston 2013), channel construction (Ryan and Wiche 1988), CRP enrollment (Todhunter and Rundquist 2004), agricultural drainage from irrigation (Parton, Gutmann, and Ojima 2007), and tillage practices (van Wie, Adam, and Ullman 2013) influence streamflow variation, but not as greatly in magnitude as LULC change. According to Drummond et al. (2012), the glaciated plains experience the largest amounts of LULC change fueled by economic, policy, and technological factors. The contribution of these factors is difficult to quantify because the lack of regulation throughout the various land management practices.

CHAPTER III

METHODS

Investigative Methods

It is difficult to partition the impacts of climate change and land use change on streamflow in a closed basin system. With the standard approaches, such as physically-based models and statistical methods, the assumption is made that a linear relationship exists between precipitation (P) and discharge (Q). Additionally, these methods assume that the contributing area to streamflow is constant over time with no outside contribution from non-contributing area. In the case of the Mauvais Coulee and Devils Lake, neither of these conditions is met, as seen through the hydroclimatic record and presence of innumerable, dynamic wetland depressions. Other methods such as ecohydrologic and climate elasticity methods look at the relative and quantitative relationships between climatic and hydrological variables for a region. For this study, these methodologies were surveyed and selected the most appropriate for basin conditions in the Mauvais Coulee.

Physically-Based Models/SWAT

Spatially-distributed, physically-based conceptual precipitation-runoff models can be used to quantitatively model the relationship between precipitation input and land use change, and how changes in climate and land use affect the production of surface runoff. The Cold Regions Hydrological Model (Ellis et al. 2010) has been successfully implemented in Canadian

Arctic and prairie environments, and is a possible candidate model for our study site. Tran and O'Neill (2013) produced a physical model based on climatic, geomorphologic, and LULC variables to measure streamflow variation within the Upper Mississippi River Basin. They found the model was effective in assessing and comparing the various contributing variables to streamflow at a large regional scale. In the Prairie Pothole Region of North Dakota, Liu and Schwartz (2011) developed a pothole complex hydrologic model (PCHM) to model the dynamic behavior of small water bodies and wetland complexes to climate as well to examine the role of the potholes in regional hydrology. They determined that pothole depressions of all sizes were highly sensitive to climatic variation; however the largest amount of change in surface water storage was attributed to smaller potholes (less than 250 m^2) because of their abundance and highly dynamic nature.

The Soil and Water Assessment Tool (SWAT) has also been extensively used to model the hydrologic response of streamflow in large basins to changes in precipitation input and agricultural land use change. Schilling et al. (2008) used SWAT to model potential impacts on streamflow from land cover change in west-central Iowa and found that the model supported historical observations, and that future land cover change would likely impact the water balance of agricultural watersheds. Kharel and Kirilenko (2015) used SWAT to assess the effect of climate and land use change on agricultural watersheds in the Northern Great Plains; they determined that both land use change and climate change had led to an increase in annual discharge.

Physically-based models and hydrologic models like SWAT are sophisticated and complex approaches to examining streamflow variation. While these methods may be effective for modeling the relationships between precipitation, land use change, and runoff, an extensive knowledge of regional hydrology and climate is needed to calibrate the model to basin specific parameters; these parameters add to the complexity of the model structure and ultimately make the method a time-consuming process to ensure proper calibration of the model.

Statistical

A statistical approach has commonly been used to analyze the interaction of multiple, complex set of hydroclimatic variables. Schilling et al. (2010) and Zhang and Schilling (2005) used statistical methods to examine the relationship between surface streamflow and precipitation and land-use change in the Upper Mississippi River Valley. Schilling et al. (2010) found that the historical increase in soybean row crop planting led to a direct and significant increase in the percentage of precipitation converted into surface runoff. Zhang and Schilling (2005) used statistical methods to show how agricultural changes in the basin impacted basin hydrology by changing the partitioning of precipitation into base flow and storm flow. Ehsanzadeh et al. (2012a, b) studied how the connectivity and variable water storage in local depressional features in the glaciated Canadian Prairie landscape impacted the frequency and magnitude of surface runoff input to Lake Winnipeg. The study highlighted the critical role of non-contributing areas, variable depressional storage, and the dynamic wetland connectivity that is characteristic of the Glaciated Plains.

Many studies take this approach because the structure of the methodology is simple and easy to replicate. The rationale of this method uses the idea that there is a baseline period of no streamflow change compared to an altered period of changed streamflow to find the difference in streamflow due to human drivers.

Ecohydrologic Approach

Ecohydrology refers to the long-term trends in water- and energy-use efficiencies within natural and agricultural ecosystems and watersheds. This approach qualitatively measures the relative impact of climate change and human activities on streamflow variation. Tomer and Schilling (2009) developed the conceptual framework to examine the effects of climatic and land-use factors on watershed hydrology in the Midwest U.S. for two hydrologically homogenous periods. They successfully separated climatic and land use change factors by comparing excess evaporative demand to excess water over time using the Hargreaves equation for potential evapotranspiration (ET_o) (Hargreaves and Allen 2003), showing that climate change had increased the discharge rates of Midwestern watersheds since the 1970s.

This methodology has been applied to several studies that sought to provide a relative (Peña-Arancibia et al. 2012) and quantitative (Wang et al. 2013a; Wang 2014; Ye et al. 2013) examination of streamflow variation. Peña-Arancibia et al. (2012) used this framework to identify the hydrological impacts of woodland clearing in two catchments within Queensland, Australia. The study determined that the slight increase in streamflow for the few years following the clearing was the result of the land modification. Other studies (Wang et al. 2013b; Wang 2014; Ye et al. 2013) conducted methodological reviews of the various methods, including the ecohydrologic approach, to assess contributions of climate change and human interaction to streamflow. These studies conclude that this approach is more practical and realistic in measuring the relative magnitudes of human and climate change on streamflow because the complexity of various human and climatic inputs makes quantitative measurement difficult.

The ecohydrologic approach uses long-term time series of streamflow (Q), precipitation (P), actual evapotranspiration (ET), and potential evapotranspiration (ET_o) to observe excess water and evaporative demand to better indicate drivers of LULC change and climate. The annual water balance for a catchment can be written as:

$$\Delta S = P - ET - Q \tag{1}$$

where ΔS is the change in water storage. For a longer period of record (10+ years), the assumption is made that there is no storage change for the catchment during the observed record. Actual evapotranspiration (ET) can be estimated by finding the difference between long-term mean rainfall P (mm) and Q (mm):

$$ET = P - Q \tag{2}$$

Excess evaporative demand (Eex) and excess water (Pex) are derived from calculating the relative proportions of P and ET_o to ET:

$$Eex = (ET_o - ET) / ET_o \tag{3}$$

$$Pex = (P - ET) / P \tag{4}$$

where ET_o is calculated potential evapotranspiration (Hargreaves and Allen 2003). The Hargreaves and Allen (2003) equation for evapotranspiration is written as:

$$ET_o = 0.0023 R_a (TC + 17.8) TR^{0.50} \tag{5}$$

where R_a is the extraterrestrial solar radiation, TC is the average daily temperature (ºC), and TR is the temperature range (ºC). The monthly values for R_a were obtained from the University of Oregon Solar Radiation Laboratory (http://solardat.uoregon.edu/SolarPositionCalculator.html) using the coordinates of the USGS gaging station at Devils Lake. Values were initially expressed in units of W/m^2, but were converted MJ/m^2, then finally expressed as mm/year. Annual min-max temperature values were collected from PRISM (http://www.prism.oregonstate.edu/; 2017).

Figure 9 shows the conceptual model from Tomer and Schilling (2009) illustrating the relationships of excess evapotranspiration and precipitation (Eex and Pex) to land use and climate change. Changes in land use will typically cause ecohydrologic shifts towards increased Pex and Eex, or decreased Pex and Eex; changes in climate are required to cause increased Pex and decreased Eex or decreased Pex and increased Eex (Tomer and Schilling 2009). It should be noted that the application of the conceptual model is based on the assumptions that human activities are independent of climate change, and that land use change only affects ET; however, the effects of human activities and climate are commonly interrelated with each other indirectly at broad scales (Ye et al. 2013). Overall, this conceptual model empirically differentiates the relative contributions of land use and climate change, given that the model assumptions are met.

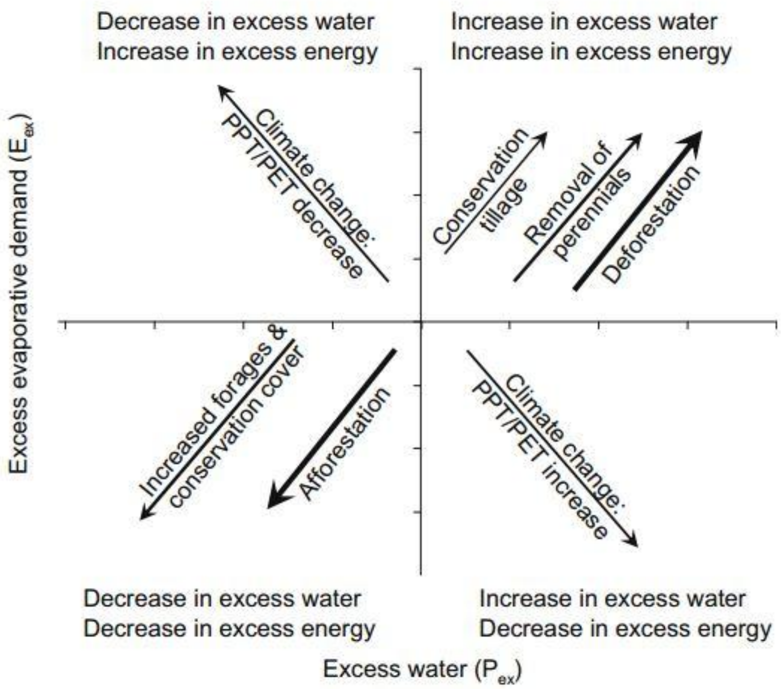

Figure 9: Conceptual model of ecohydrologic shifts associated with changes in climate and land use. Land use change directly impacts ET but not P or ET_o, therefore resulting ecohydrologic shifts in excess water and excess evaporative demand will both either increase or decrease, depending on the effect of the change on ET. On the other hand, changes in P/ ET_o ratios are needed to increase surplus water and decrease surplus evaporative demand, or vice versa. *Source*: Tomer and Schilling (2009).

Budyko Framework

The Budyko framework is an application of climate elasticity to empirically examine the co-variation and sensitivity of climate and streamflow fluctuations. Guo et al. (2015) investigated the lake level rise dynamics in Bosten Lake, China by quantitatively separating out the impact of climatic and human factors. They determined that lake level dynamics could be attributed to both human modification of the lake as well as a decrease in natural precipitation. Sun et al. (2013) determined potential drivers of streamflow variation at four hydrologic stations within the Poyang Lake Basin, China using climatic sensitivity to show the dynamic interaction of precipitation and PE that would not be picked up through other methods.

Climate sensitivity takes into consideration the unique hydrologic variables that influence a basin and does not assume that such variables are uniform across the entire basin. A major issue with the standard methods is that they assume there are no non-contributing areas that would influence the basin hydrology. This is a more informed approach because it examines the historic basin hydrology, such as the significant lag effects from groundwater and vadose storage, to understand the current streamflow conditions of the basin. It is hypothesized that by analyzing climatically uniform hydrologic periods (i.e. controlling for the climate variable) further understanding will be gained to the impacts of LULC on the basin during times of homogenous climate. This approach assumes, however, that the climate is stationary throughout the entire period of record; additionally it assumes that any human effects are only present in the post-change period.

Hydrological sensitivity can be described as the percent change in annual runoff in response to the change in annual P and ET_o (Wang et al. 2013b). For a given basin, the simplified long-term water balance equation can be written as:

$$P = ET + Q + \Delta S \tag{6}$$

where P is precipitation, ET is actual evapotranspiration, Q is streamflow, and ΔS is change in water storage. Like the ecohydrologic approach, ΔS is assumed to be zero over long periods (10+ years). Budyko (1974) introduced a dryness index (ø) for estimating actual evapotranspiration (ET) based on the idea that available average annual energy and precipitation are the principal factors in determining the rate of evapotranspiration.

Using the Budkyo (1974) framework, Zhang et al. (2001) developed a model to estimate ET through the relationship of P and ET_o:

$$\frac{ET}{P} = \frac{1+w(\frac{ET_o}{P})}{1+w(\frac{ET_o}{P})+(\frac{ET_o}{P})^{-1}} \tag{7}$$

where ET_o is the potential evapotranspiration and *w* is the plant-available water coefficient related to vegetation type with a range of 0.1 to 2.0 (Zhang et al. 2001). Wang et al. (2013b) state that it is difficult to assign a value to *w* for mixed vegetation because it is too difficult to differentiate out the separate vegetation types for a catchment. Changes in the water balance typically result from an imbalance of and ET_o. These changes in the water balance are reflected in the hydrologic sensitivity of runoff:

$$\Delta Qc = \beta\, \Delta P + y \Delta\, ET_o \tag{8}$$

where ΔQc, ΔP, and $\Delta\, ET_o$ denote changes in streamflow, precipitation, and potential evapotranspiration between the baseline and post-change periods; β and *y* are the sensitivity coefficients of runoff to precipitation and ET_o, expressed as:

$$\beta = \frac{1+2\emptyset+3w\emptyset}{(1+\emptyset+w\emptyset^2)^2} \tag{9}$$

$$y = -\frac{1+2w\emptyset}{(1+\emptyset+w\emptyset^2)^2} \tag{10}$$

where ø is the dryness index equal to ET_o / P (Li et al. 2007).

Change in streamflow (ΔQ) is then calculated by finding the difference in mean from the baseline period (Qb) and the post-change (Qpc) period (mm):

$$\Delta Q = Qpc - Qb \tag{12}$$

The differences in mean P and ET_o between the baseline and post-change period are also found. These differences in mean ΔP and $\Delta\, ET_o$, along with the sensitivity coefficients, are used to solve for ΔQc using the equation:

$$\Delta Q = \Delta Qc + \Delta Qh \tag{13}$$

where ΔQc and ΔQh represent streamflow changes because of climate factors and human factors. Since ΔQ and ΔQc are known, the equation can be rearranged to solve for the missing value (ΔQh) as a residual. The relationship between climate and human change in relation to streamflow change can be expressed in percentages. Ultimately this approach allows for a way to separate and quantify the effects of climate change from human activities upon streamflow change.

Climate Elasticity

Sankarasubramanian et al. (2001) used an empirically-based climate elasticity method to estimate the climatic elasticities of streamflow Q to P (εp) and Q to ET_o (ε_{ET0}) across the United States. The climate elasticities of Q to P and ET_o are non-parametric estimators that summarize the proportional change in streamflow because of a proportional change in P or ET_o. The climate elasticity equation of Sankarasubramanian et al. (2001) is written as:

$$\varepsilon p = \text{median}\left[\left(\frac{Q-\bar{Q}}{P-\bar{P}}\right) * \frac{\bar{P}}{\bar{Q}}\right] \tag{14}$$

where $\bar{P}$ and $\bar{Q}$ are long-term sample means (Sankarasubramanian et al. 2001). To calculate elasticity of Q to ET_o (ε_{ET0}) the same equation is used, however P is replaced by ET_o.

Agricultural LULC

ND Agricultural Statistics

North Dakota Agricultural Statistics is collected by the North Dakota Department of Agriculture in an effort to document the production of more than a dozen important commodities grown within the state. Agricultural statistics were gathered for Towner County dating from the oldest record available (1955) to the most currently available (2012) to observe the temporal variation in agricultural land use. Small grains are the predominant crop for most of the period of record, with row crops beginning to have a minor presence during the 1980s.

The last 35 years has experienced a modest conversion from small grains to row crops, as well as a gradual decrease in hay production. This information shows that agricultural land use change could potentially be a driver of streamflow variation.

USDA NASS CropScape

The U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS) produces annual statistics derived from surveys that encompass numerous aspects of the U.S. agriculture industry. One product of these statistics is the CropScape Crop Data Layer (CDL), a geospatial dataset showing the spatial distribution of agricultural across the US. Specifically, the CDL is a raster, geo-referenced, crop-specific land cover data layer created annually for the continental U.S. using moderate resolution satellite imagery and extensive agricultural ground truth (USDA NASS 2016). The use of this data, in conjunction with the ND Agriculture Statistics, provides a spatial and temporal view of LULC change within Towner County during the study period.

Wetlands

Conversion of native prairie grasslands and continuous small grain covers to row crop cultivation has been shown to increase surface runoff in the Northern Glaciated Plains (van der Kamp et al. 2003; van der Kamp and Hayashi 2009), so there has likely been an increase in runoff response to the historical agricultural land use changes in the study area. Surface water streamflow is dominated by spring snowmelt production since groundwater contributions to streamflow are minimal because of low soil hydraulic conductivity, low hydraulic gradients, and limited spring infiltration of snowmelt due to seasonally frozen soils (van der Kamp and Hayashi 2009).

The ‘Fill-Spill Hydrology’ of the glaciated plains introduces several complexities that are critical in understanding precipitation-streamflow relationships, and which must be accounted for. Field investigations, long-term water level monitoring, and high resolution analyses of glacial landscapes have shown that there is a strong dynamic and non-linear relationship between precipitation/snowmelt and streamflow (Shook and Pomeroy 2011; Shaw et al. 2012; Ehsanzadeh et al. 2012a,b; Dumanski et al. 2015). Much of the landscape consists of non-contributing area in which surface runoff flows to local depressions that must fill before overflowing to lower sub-basins. All non-contributing wetland depressions must be hydrologically connected before they begin to contribute to streamflow in larger stream reaches. The sub-basin area contributing to streamflow in the Mauvais Coulee is therefore dynamic in time, non-linear in relationship, and subject to numerous thresholds linked to the water storage content of the various depressional storages, and their degree of connectivity. These relationships have considerable influence upon the P-Q relationship.

National Wetland Inventory (NWI)

To examine the extent of wetlands within the study area of the Mauvais Coulee, the National Wetland Inventory from the U.S. Fish and Wildlife Service was used as a basis for known wetlands of the area. According to USFWS (2015) the goal of the NWI is to highlight wetlands that exhibit unique or important ecological characteristics. From 1970-1980, aerial imagery was used to produce current NWI maps; this gives a snapshot of the wetland conditions approximately 30 years ago. Johnston (2013) used NWI with aerial imagery to determine the extent of wetland loss because of agricultural expansion. There was a slight discrepancy between the aerial imagery and NWI because of the difference in time of collection, however Johnston concluded that 1,345 km² of wetlands had been converted to agriculture. Niemuth, Wangler, and Reynolds (2010) used NWI to determine how inter-annual dynamics of wetlands were related to the water regimes assigned to those wetlands by the National Wetlands Inventory. For this research, the NWI data were used as a baseline for known wetland/pothole depressions in comparison to what is identified through a Topographic Wetness Index (TWI) analysis of DEM data varying in resolution.

Digital Elevation Data

Digital Elevation Models (DEMs) are preferred to calculate terrain attributes because of the visual representation of these features and the easy computer implementation of algorithms (Rampi, Knight, and Lenhart 2014). Many of the pothole depressions found in the Prairie Pothole Region (PPR) are smaller than 0.05 ha in area (Neimuth, Wangler, and Reynolds 2010), and therefore may not be easily identified through topographic data. Additionally, because of their dynamic nature, pothole depressions vary spatially and temporally. This makes it challenging to accurately measure and quantify the full extent of pothole depressions within a given area. Standard DEM resolutions – 10 m (1/3rd arc second) and 30 m (1 arc second) – may be able to highlight wetland depressions larger than 0.05 ha, however the limited resolutions can still miss the majority of these smaller potholes.

Higher resolution data, such as LiDAR and 3 m DEMs, have finer-scale resolutions that can provide more detail per pixel than lower resolution counterparts and prove to be useful in the identification of wetland depressions (Huang et al. 2011; Rover et al. 2011; Shook and

Pomeroy 2011; Shaw et al. 2012; Serran and Creed 2016; Wu and Lane 2016). The DEMs, acquired from the National Elevation Dataset (NED), were collected for resolutions of 30 m (1 arc second), 10 m (1/3rd arc second), and 3 m (1/9th arc second); these resolutions were selected to show how finite depression identification varies with resolution.

Topographic Wetness Index (TWI)

Landscape topography is one of the largest proxy variables for studies related to the spatial distribution of water, and the variation of hydrologic conditions. The Topographic Wetness Index (TWI), also known as the Compound Topographic Index (CTI), was introduced by Beven and Kirkby (1979), and is commonly used to identify where water will collect over a given area. One of the valuable benefits of using an index such as the TWI [CTI] is the ability to represent the distribution and flow of water (saturated vs. non-saturated areas) based only on topographic data (Grabs et al. 2009). The TWI equation is:

$$\mathrm{TWI} = \ln\left(a / \tan\beta\right) \tag{14}$$

where a represents the upslope area per contour length (i.e. the flow accumulation for the catchment) and $\tan\beta$ is the local slope gradient of the ground surface. Results from the TWI calculation will determine locations of abundant wetness, which ultimately could lead to the formation of wetlands in the landscape. The application of topographic data, like DEMs and LiDAR, in conjunction with the TWI has been found to be highly useful in determining the extent and frequency of wetlands (Sørensen and Seibert 2007; Grabs et al. 2009; Rampi, Knight and Lenhart 2014).

For the Mauvais Coulee, TWI was calculated for DEM resolutions of 30 m, 10 m, and 3 m. Slope was calculated in degrees. In accordance to Rampi, Knight, and Lenhart (2014), results for slope are then modified by adding a value of 0.0001 through the raster calculator tool to avoid division by zero for the TWI calculation; the modified slope layer was then converted to radians again through the use of the raster calculator. Flow direction was analyzed through ArcGIS Hydrology toolset, and then flow accumulation was determined with results from the flow direction analysis as input. Using the raster calculator tool, the TWI equation was added into the query with the modified slope and flow accumulation result as equation inputs. A low pass 3x3 filter was applied to the output TWI layer to smooth the raster and reduce variability of cells across the image.

Hydroclimatic Database

Areal Precipitation

PRISM (Parameter-elevation Regressions on Independent Slopes Model) is a climatic dataset developed at Oregon State University (http://www.prism.oregonstate.edu/, 2017). This data set contains climatic observations from a large variety of networks that monitor climate, and produces a dataset showing the spatial and temporal patterns of climate. To select a location within the Mauvais Coulee Sub-basin for the data collection, an interpolation analysis was run through ArcGIS to determine centroid locations. Centroids were produced for each of the 10 sub-basins that make up the Mauvais Coulee as well as a centroid for the entire sub-basin. The coordinates of each centroid location were used to collect mean monthly precipitation and temperature (calculated from the monthly max/min values) for water years from 1956 to 2015.

Precipitation and temperature averages for each water year were obtained for each sub-sub-basin centroid. Areal precipitation was calculated through determining the sum of each sub-basin's annual precipitation multiplied by a weighted precipitation contribution value for each sub-basin. A time series of the areal precipitation over the period of record was produced resulting from the weighted areal precipitation calculations (see Appendix A). The calculated values of temperature and precipitation of each sub-basin were compared to the Mauvais Coulee Sub-basin centroid to determine if precipitation and temperature values were uniform across the sub-basin. Through this method, it was determined that there was no significant variation in precipitation and temperature across the basin; the data collected for the Mauvais Coulee Sub-basin was then used as the main climate dataset.

Mauvais Coulee Discharge

The U.S. Geological Survey (USGS) National Water Information System (NWIS) is a database of stored historic and current hydrologic data for more than 850,000 gaging stations across the U.S. Streamflow, surface-water quality, stream/reservoir/lake levels, and rainfall data are collected at these stations. The USGS gaging station 05056100 near Cando, ND, was used for data collection of annual streamflow discharge in the Mauvais Coulee. This station was selected because it holds the longest standing, quality hydrologic record for the basin. Backwater flooding has occurred at this station since 2009, however the USGS has noted that a very small portion of this contributes to the total volume of runoff; any backwater flooding effects that have occurred have been accounted for and corrected within the streamflow data by the USGS. Streamflow is measured in cubic feet per sec (cfs), so the data were converted to cubic meters per second (cms) (see Appendix A). A time series of annual discharge (Q) was created for the period of record (see Appendix A).

Runoff Ratio

The runoff ratio of a hydrologic system is a dimensionless unit of measure comparing the ratio of the runoff depth to the precipitation depth of a basin. This ratio is expressed as $Q / P \times 100$, where Q is the runoff depth (mm) and P is the areal precipitation (mm). The division product was multiplied by 100 to get a percentage value. Runoff depth was determined by converting the discharge from cfs to mm per year. A time series for annual runoff depth, areal precipitation, and the runoff ratio were created for the period of record (see Appendix A).

CHAPTER IV

RESULTS

Agricultural LULC

The change in agricultural land use from 1998 to 2015 for the Mauvais Coulee Sub-basin is shown in Figures 10 and 11. The NASS CropScape layer indicates that in 1998 the most common crops were sunflower, barley, other crops (classified by NASS as hay or herbs), durum wheat, and spring wheat (Figure 10). In the 2015 image, the most common crops were canola, soybeans, and spring wheat (Figure 11). A quantitative assessment would need to be performed on the data layers to give an indication of acreage that has been converted over the span of this 17-year period. From the visual spatial observation alone, however, there appears to be a significant change in agricultural land use over time. Agricultural statistics for Towner and Ramsey counties show that there has been a conversion from small grains to row crops over the last +35 years (Appendix B). This conversion from small grains to row crops would allow for more bare earth exposure, which would contribute to increased runoff from fields, ultimately contributing to increasing runoff.

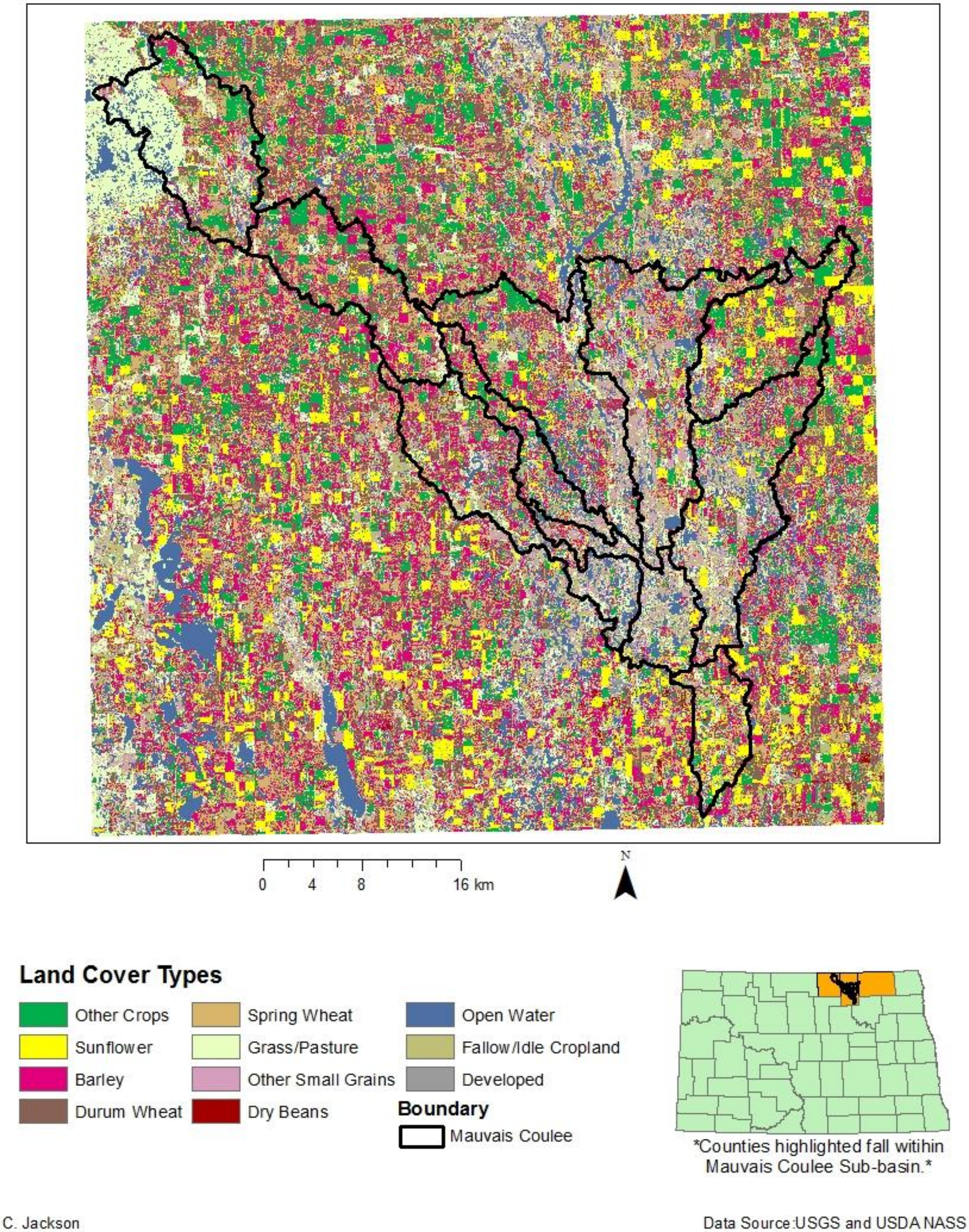

Figure 10: USDA NASS land cover types for Mauvais Coulee Sub-basin in 1998.

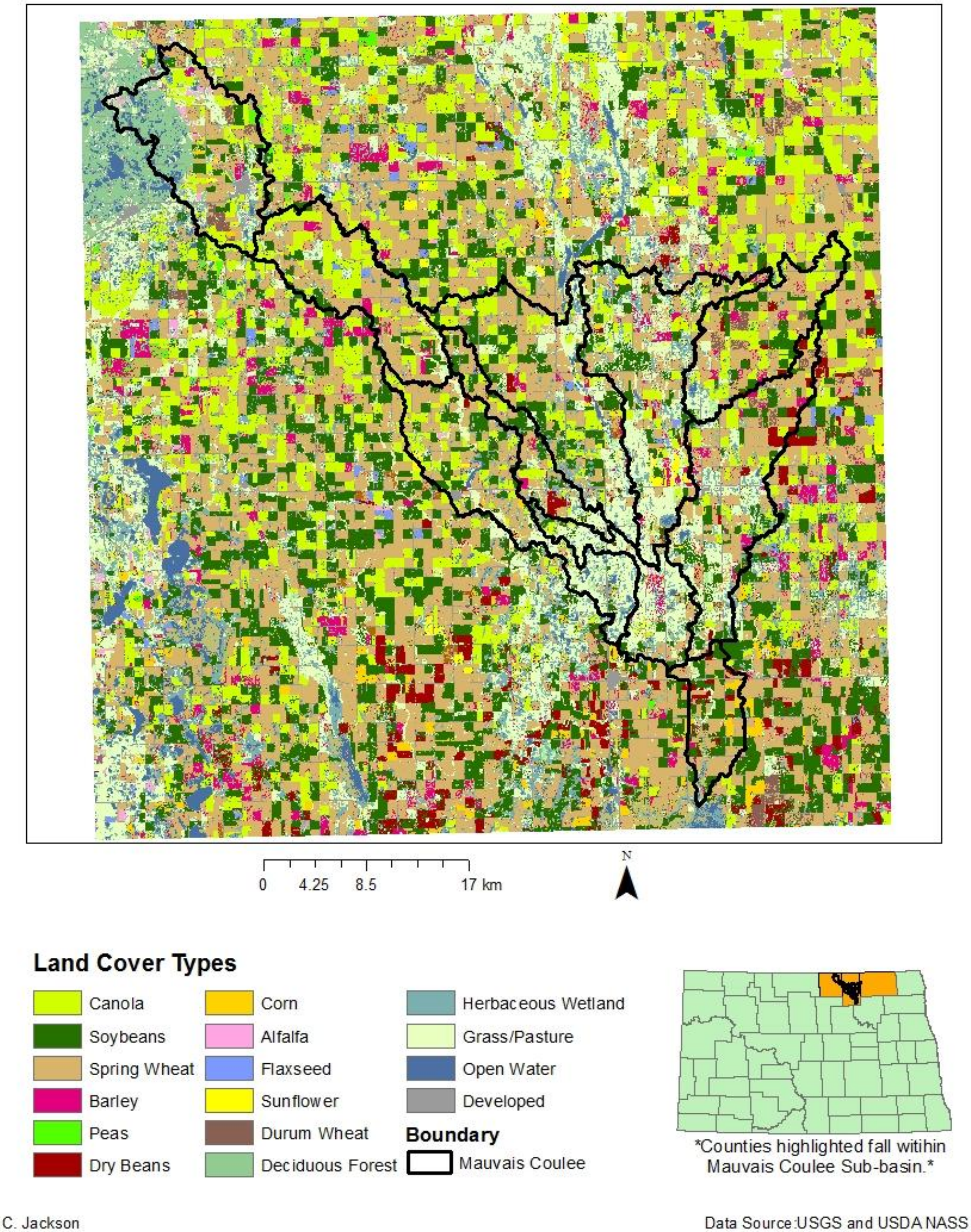

Figure 11: USDA NASS land cover types for Mauvais Coulee Sub-basin in 2015.

TWI

Figures 12-14 show the results of the TWI analysis for 30 m, 10 m, and 3 m DEM resolutions. As the resolution increased from 30 m to 10 m, more areas were identified as “wet” through the TWI; this was not the case, however when the resolution increased from 10 m to 3 m, as much of the area appeared to be overestimated for the 3 m. Both the 30 m (Figure 12) and 10m (Figure 13) TWIs shared similar results, but the 10 m appeared to identify more small wetlands and indicated more total wet areas than the 30 m. The 3 m (Figure 14) clearly identifies large water bodies, but the high resolution of the data caused output of the analysis to be ‘noisy,’ with no real indication of small wetland depressions. This could result from radiometric error in the data. Because the resolution of the data is so high, small variations within the naturally flat topography were likely over-exaggerated in the analysis, causing a blending of the TWI classes. While areas that were identified as “wet” in each of the TWI analyses did coincide with the larger NWI wetlands (Figure 15), many of the smaller wetlands and their associated hydrologically connected networks were more apparent in the NWI than in the TWIs.

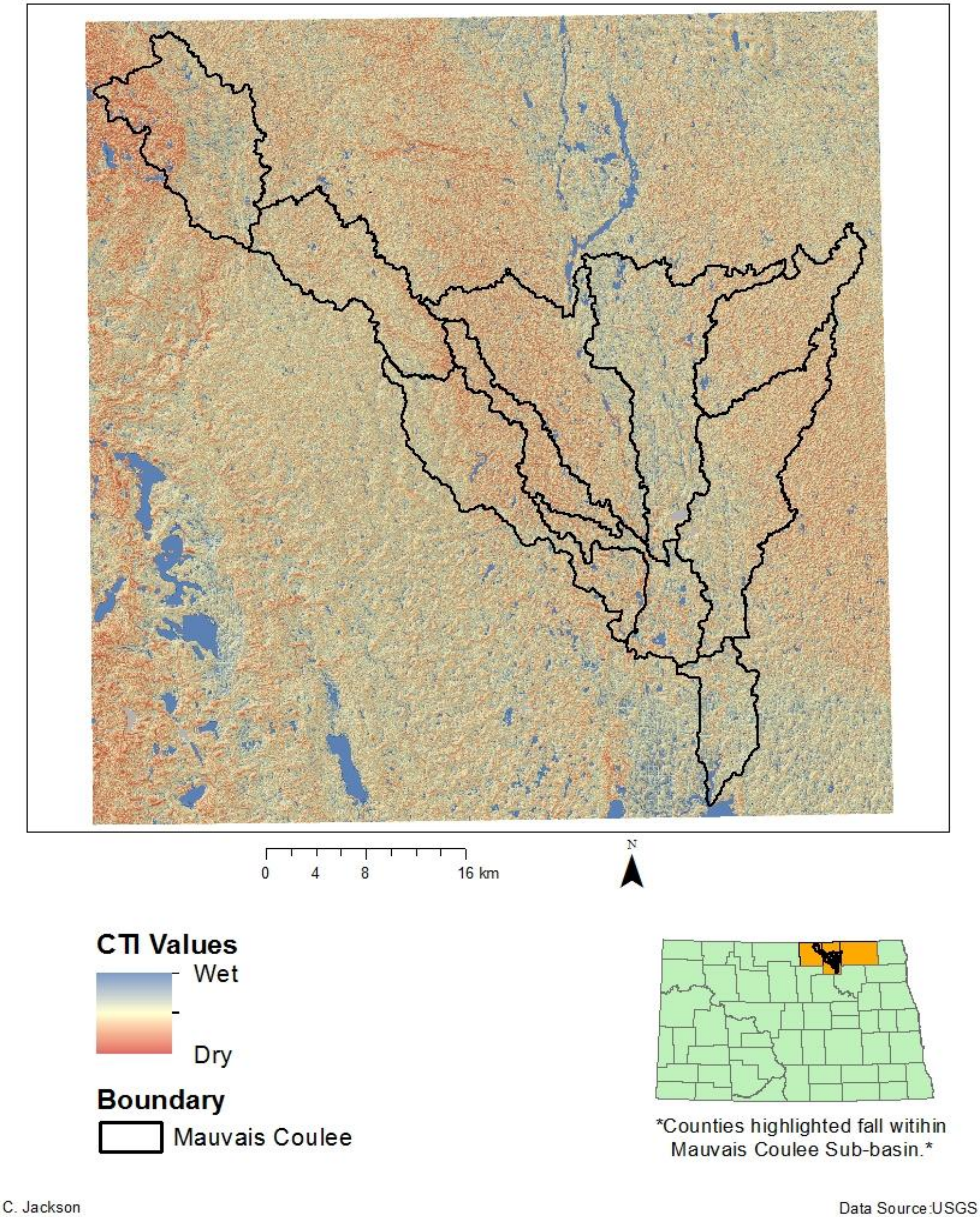

Figure 12: Results of the TWI (CTI) analysis for 30 meter DEM.

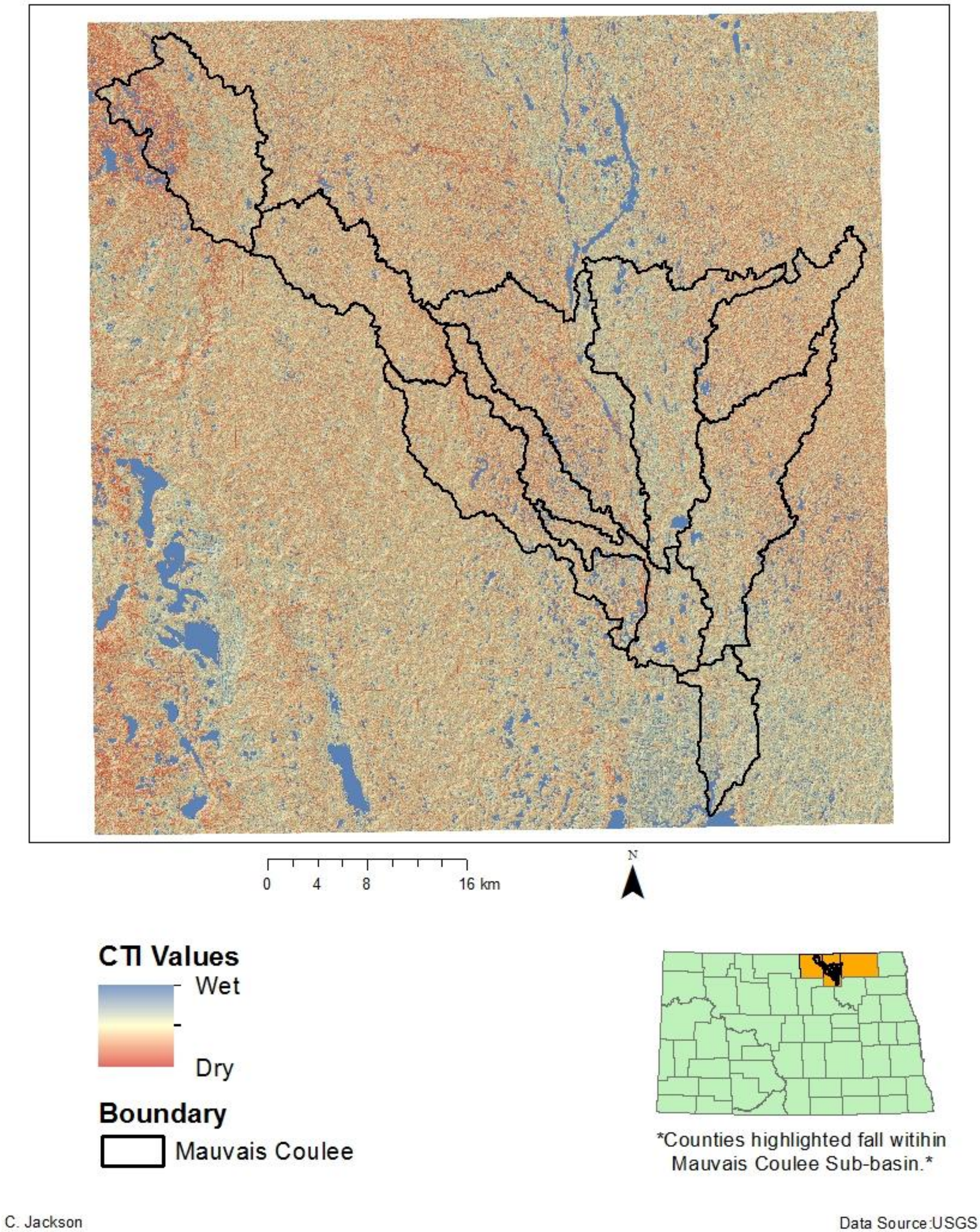

Figure 13: Results of the TWI (CTI) analysis for 10 meter DEM.

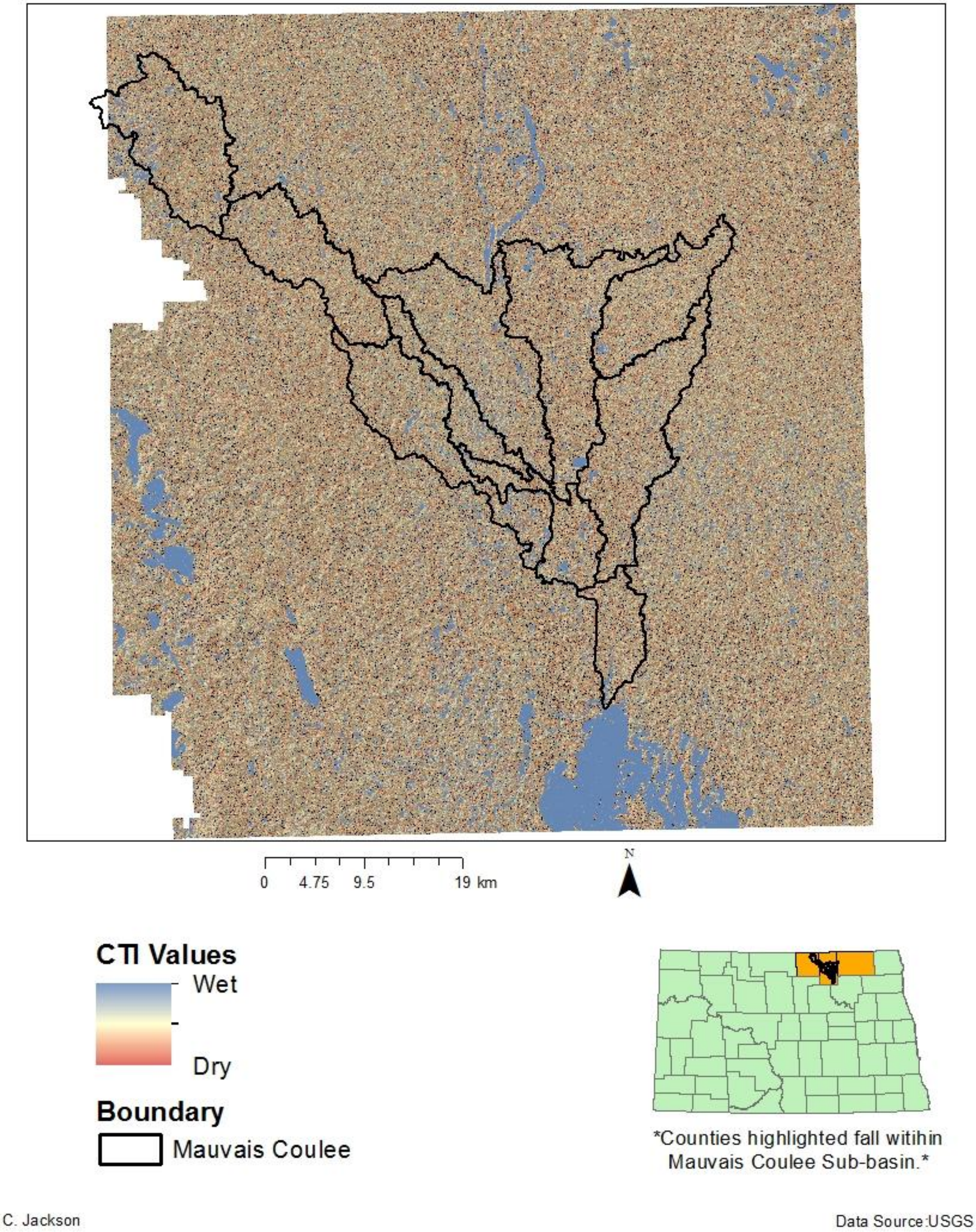

Figure 14: Results of the TWI (CTI) analysis for 3 meter DEM.

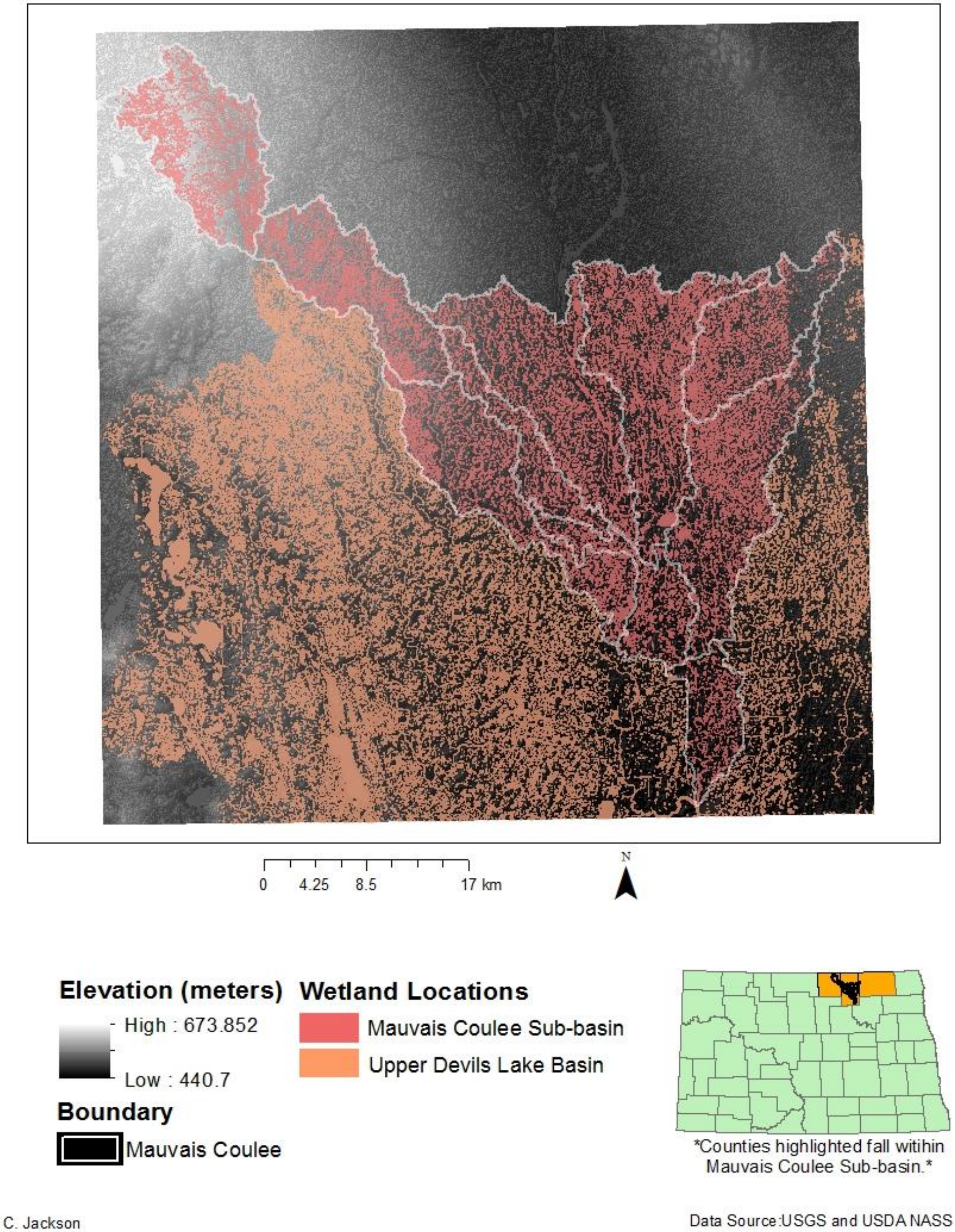

Figure 15: Locations of known wetland complexes within Mauvais Coulee Sub-basin (pink) and the Upper Devils Lake Basin (orange) in conjunction with elevation for area.

Ecohydrologic Approach

Table 1 and Figure 16 show the results for the ecohydrologic analysis based upon Tomer and Schilling (2009). The calculated excess water (Pex) and excess evaporative demand (Eex) show that Pex has increased while Eex decreased from the baseline to post-change periods. When plotted against one another (Figure 16), the data shows a trend toward the lower right corner of the figure. In the Tomer and Schilling (2009) conceptual model (Figure 9) this indicates that climate change is responsible for the increasing Pex and the decreasing Eex.

Table 1: Results of the ecohydrologic approach to determine relative contribution of climate variation and human activities to streamflow change.

Ecohydrologic Analysis			
Period		Pex	Eex
Baseline Period	1956-1992	0.037	0.452
Post-Change Period	1993-2015	0.153	0.399

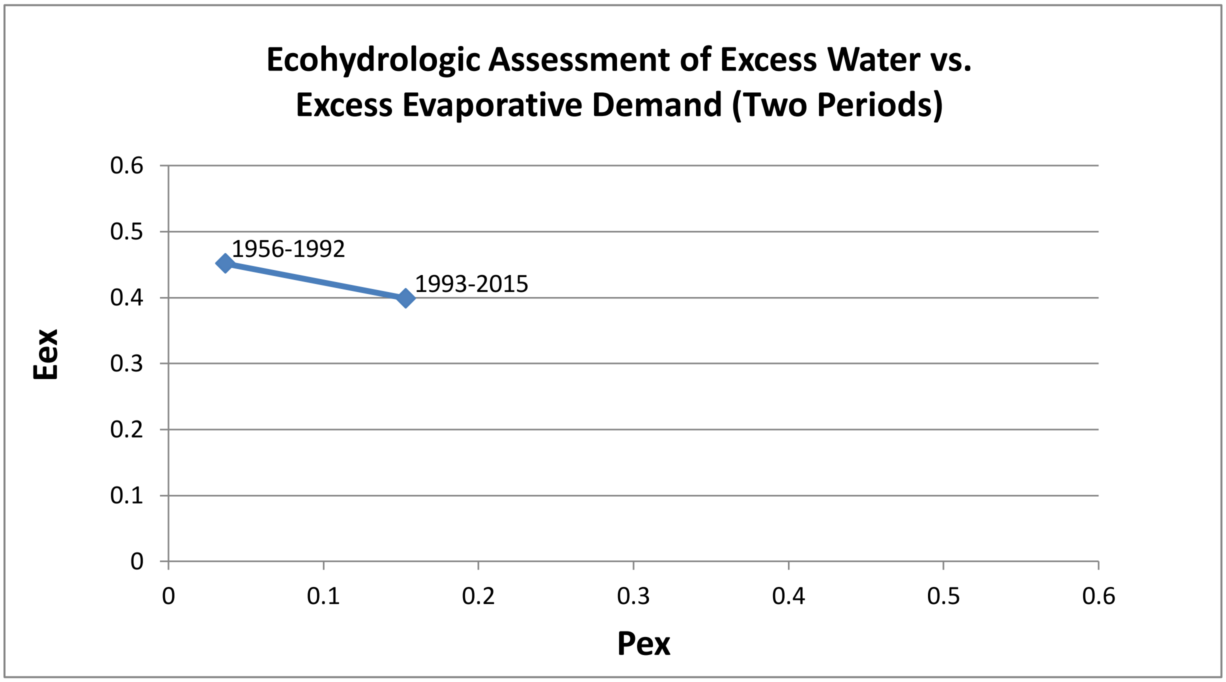

Figure 16: Plot of excess water (Pex) versus excess evaporative demand (Eex) during baseline (1956-1992) and post-change (1993-2015) periods for the ecohydrologic approach.

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Budyko Framework

Table 2 gives the results for the Zhang et al. (2001) implementation of the Budyko framework. Between the baseline and post-change period, both P (ΔP = 83.9 mm/yr) and Q (ΔQ = 71.19 mm/yr) increased from the earlier to the later period; ET_o (ΔET_o = -51.6 mm/yr) decreased over the same periods. The increased P and decreased ET_o relationship would imply a climatic driver to the hydrologic system change, however this is not the case when solving for the individual components of ΔQc and ΔQh. This analysis determined that human change contributed 90.1 percent to the streamflow variation from the baseline to post-change period, while climate change only contributed 9.9 percent. The reason for the high disparity in the percentages for ΔQc and ΔQh is due to the empirical parameter *w*. Zhang et al. (2001) state that values for *w* range typically from 0.1 to 2.0, and that the value is supposed to reflect the efficiency of the vegetation cover in using water. They cite a value of 0.5 as representative of grasslands, and a value of 2.0 as representative of forests. Using the sum of squares method, *w* was determined to be 10.0, well above any values for *w* reported in the literature. The value of *w* must get larger to remove precipitation as dictated by the assumption of water balance implied in Equation 5. The inappropriate value of *w* calls into question the appropriateness of this method for the Mauvais Coulee Sub-basin.

Table 2: Contribution of climate change and LULC changes to streamflow variation following the Zhang et al. (2001) implementation of the Budyko framework.

Period		$\overline{P}$ mm/yr	$\overline{ET_o}$ mm/yr	ø -	$\overline{Q}$ mm/yr	ΔQc	ΔQh
Baseline Period	1956-1992	480.5	849.6	1.77	17.4	-	-
Post-Change Period	1993-2015	564.4	798.0	1.47	88.6	7.03 (9.9%)	64.18 (90.1%)
		ΔP = 83.9	Δ ET_o= -51.6	-	ΔQ = 71.2		

Climate Elasticity

Table 3 gives the results of the Sankarasubramanian et al. (2001) empirical climate elasticity analysis. The elasticity of streamflow to P shows an increase, while the elasticity of streamflow to ET_o shows a decrease from the baseline to post-change periods. A larger, positive climate elasticity value indicates that the basin was producing more streamflow for a given percent change in precipitation. Wang et al. (2013b, 1168) interpret εp to mean that a 10 percent change in precipitation would cause an 18.1 percent change in runoff for an elasticity value of 1.81 from their calculation of the Luanhe River catchment. The Mauvais Coulee then, would have experienced a 29.6 percent increase in streamflow for a 10 percent increase in precipitation during the post-change period, showing a stronger sensitivity of runoff response to precipitation change.

Table 3: Climate elasticities of streamflow Q to P (ε_p) and Q to ET_o (ε_{ET0}) for Mauvais Coulee Sub-basin.

Climate Elasticities of Streamflow			
Period		ε_p mm/mm	ε_{ET0} mm/mm
Baseline Period	1956-1992	2.19	-21.36
Post-Change Period	1993-2015	2.96	-13.03

CHAPTER V

DISCUSSION

Limitations and Assumptions

While the ecohydrologic and climate elasticity approaches are considered the most appropriate choices for partitioning streamflow variation, both hold limitations because of model assumptions and uncertainties. The Tomer and Schilling (2009) ecohydrologic approach does not produce a quantitative estimation, but rather gives a relative estimation of the contribution of climate and LULC change to streamflow. The Budyko framework provides an empirically-based quantitative estimate of the contribution of climate and LULC change to streamflow; this approach is limited, however, as it relies upon an estimation of the plant water use coefficient, *w*, which may not be physically realistic. These methodologies assume that no storage change has taken place over the period of record, while employing questionable methods to identify two periods within the period of record: a baseline period and a post-change period. In the case of Mauvais Coulee, these assumptions are incorrect because both groundwater and soil moisture have experienced a significant change through the study period. This is a result of the change in the hydrologic regime of the basin from a dry to a wet climate mode during the period of record. The change in hydroclimatic modes within the basin over the period of record must be taken into consideration for both the ecohydrologic and Budyko framework approaches to be applicable to the Mauvais Coulee.

Storage Changes in the Mauvais Coulee

Groundwater Storage

Three USGS groundwater stations are located approximately 32.2 km from the Mauvais Coulee gaging station near Cando, ND. Established in the early-1970s, these wells surround the northwestern portion of Devils Lake. Figure 17 shows the change in groundwater level over time for the one of three groundwater stations located near Devils Lake (graphs for other stations found in Appendix C). Around the early-1990s there is an abrupt rise in the groundwater level, meaning a substantial increase in groundwater storage over time. This trend can be seen in all three stations. This rise is also evident in the time series of annual discharge for the Mauvais Coulee (Appendix A). The significant groundwater storage change that occurred during the period of record invalidates the assumptions required for the implementation of the ecohydrologic and Budkyo approaches.

Soil Moisture Storage

Todhunter and Fietzek-DeVries (2016) modeled the water balance for the Devils Lake basin, with soil moisture as a model output parameter. Soil moisture is a fundamental hydrological variable that regulates the conversion of moisture delivery (rain, snowmelt) into hydrological output (streamflow, lake levels) (Todhunter and Fietzek-DeVries 2016). Their study showed that for the Devils Lake area mean annual soil moisture decreased over the first half of the record, and increased over the latter half of the record (Figure 18).

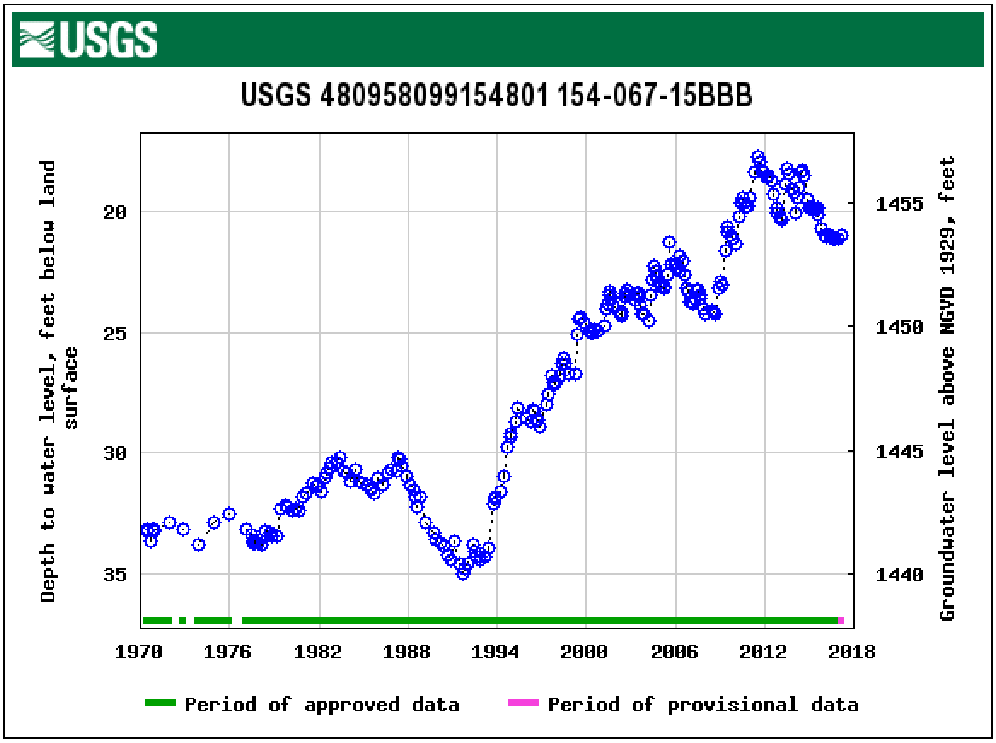


Figure 17: Groundwater table level for one of three stations surrounding Devils Lake. *Source*: USGS (2017).

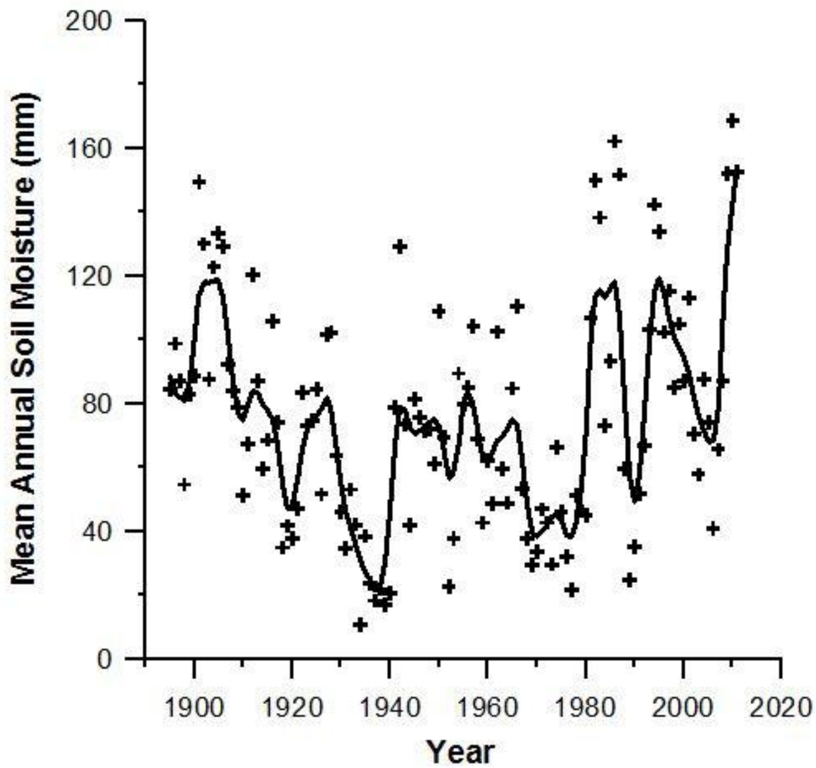


Figure 18: Mean annual soil moisture for the Devils Lake basin, ND during water years 1895-2011. *Source:* Todhunter and Fietzek-DeVries (2016).

Climatic Modes

Paleoclimatology studies of the Prairie Pothole Region have shown large climatic variability with fluctuating long, dry cycles to short, wet cycles. For Devils Lake, several studies have indicated that 1980 was a transitional year between these different climatic modes (Vecchia 2008; Todhunter and Fietzek-DeVries 2016; Todhunter 2016). Todhunter (2016) determined that hydroclimatic mode 1 is a cool, dry phase lasting from the beginning of the period of record through 1980, while hydroclimatic mode 2 is a warmer, wetter phase beginning in 1981 and continuing through the present. This was determined through the examination of normalized lake volume, annual precipitation, and mean annual temperature of Devils Lake (Figure 4). Both temperature and precipitation show a rapid increase at the 1980 transition point, but lake level does not reflect this increase until 1993. This 15-year lag between the change in the precipitation regime and the hydrologic response of the lake volume suggests that groundwater storage, soil moisture storage, and non-contributing area were lagging due to basin storage memory effects where wetlands appear to 'remember' their initial states/conditions and try to regain those forms over time (Shook and Pomeroy 2011).

Double Mass Curve Analysis

Figure 19 shows a double mass curve of cumulative streamflow and cumulative precipitation for the Mauvais Coulee Sub-basin over the period of record. The results are similar to what Todhunter (2016) obtained for the entire Devils Lake Basin. The Mauvais Coulee appears to have three distinct periods based upon P-Q relationships. The first period extends to

1977, the second from 1978 to 1991, and the third from 1992 to the present. The slope of each segment increases over time, indicating increasing Q for an increase in P.

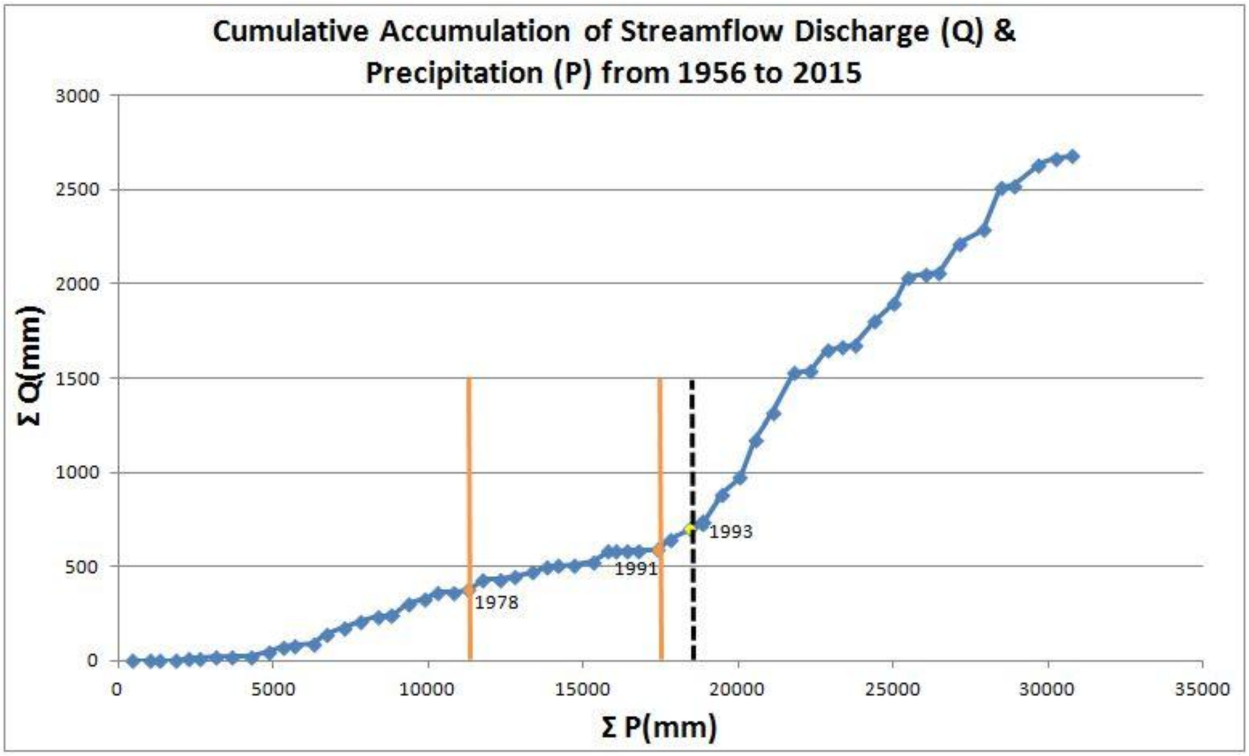


Figure 19: Cumulative streamflow and cumulative precipitation for Mauvais Coulee Sub-basin over period of record. Black dashed line indicates transitional point based upon standard hydrological approaches. Orange lines indicate three separate P-Q periods based upon double mass curve analysis.

Informed Approach

Given these observed conditions in the Mauvais Coulee Sub-basin, the application of the ecohydrologic and Budyko (1974) approaches is not feasible. These approaches assume a stationary climate, which is not the case in the Mauvais Coulee or Devils Lake Basin (Figure 4). The approaches also assume a linear P-Q relationship, while there are three identifiable P-Q relationships over the study period (Figure 19). The non-linear P-Q relationship with time for the sub-basin is because of: 1) progressive increases in antecedent soil moisture over time across the basin; 2) increased wetland complex storage with time; 3) increased wetland complex connectivity with time that leads to increasing contributing area over time; and 4) large increases in groundwater storage and vadose zone storage over time.

The Zhang et al. (2001) implementation of the Budyko framework found *w*, the empirical plant-available water coefficient, to be approximately 10.0 for the sub-basin, well beyond an acceptable range of previously reported values between 0.1 and 2.0. This is a highly quixotic value that is not reflective of actual basin conditions, but which is required for basin evapotranspiration to balance the water balance equation. The calculated results of the ecohydrologic and Budyko framework approaches contradict one another. Figure 16 (ecohydrologic) indicates that changing climate is the driver behind the change in Pex and Eex values; however Table 2 (Budyko framework) shows that the human component to change in streamflow was 90.1 percent, with 9.9 percent remaining for the climatic component.

These methods are not applicable to the partitioning of climatic and human drivers to streamflow variation because the assumptions made in the approaches are neither met nor applicable to the conditions of the Mauvais Coulee. A more rational approach for both methods would be to omit the transitional period and only perform calculations for the first and third periods identified in Figure 19. Both the first and third periods have uniform and linear P-Q relationships, and are fully within uniform hydroclimate modes. Values determined for the second period in Figure 19 encompass a period of transitional P-Q relationships, and sample two separate hydroclimatic modes.

Figure 20 is the modified ecohydrologic approach showing the relationship of Pex and Eex for the baseline to transitional and the baseline to post-change periods. From the baseline to transitional period there is a slight human influence indicated, while the baseline to post-change period relationship indicates a climate change driver. Table 4 shows the results for the climate elasticity analysis of Q-P and Q-ET_o for the two periods marked by separate but homogeneous hydroclimates, and separate but linear P-Q relationships. The elasticity of Q-P decreases between the two hydroclimatic regimes; the elasticity of Q-ET_o also decreases from the first to the last period.

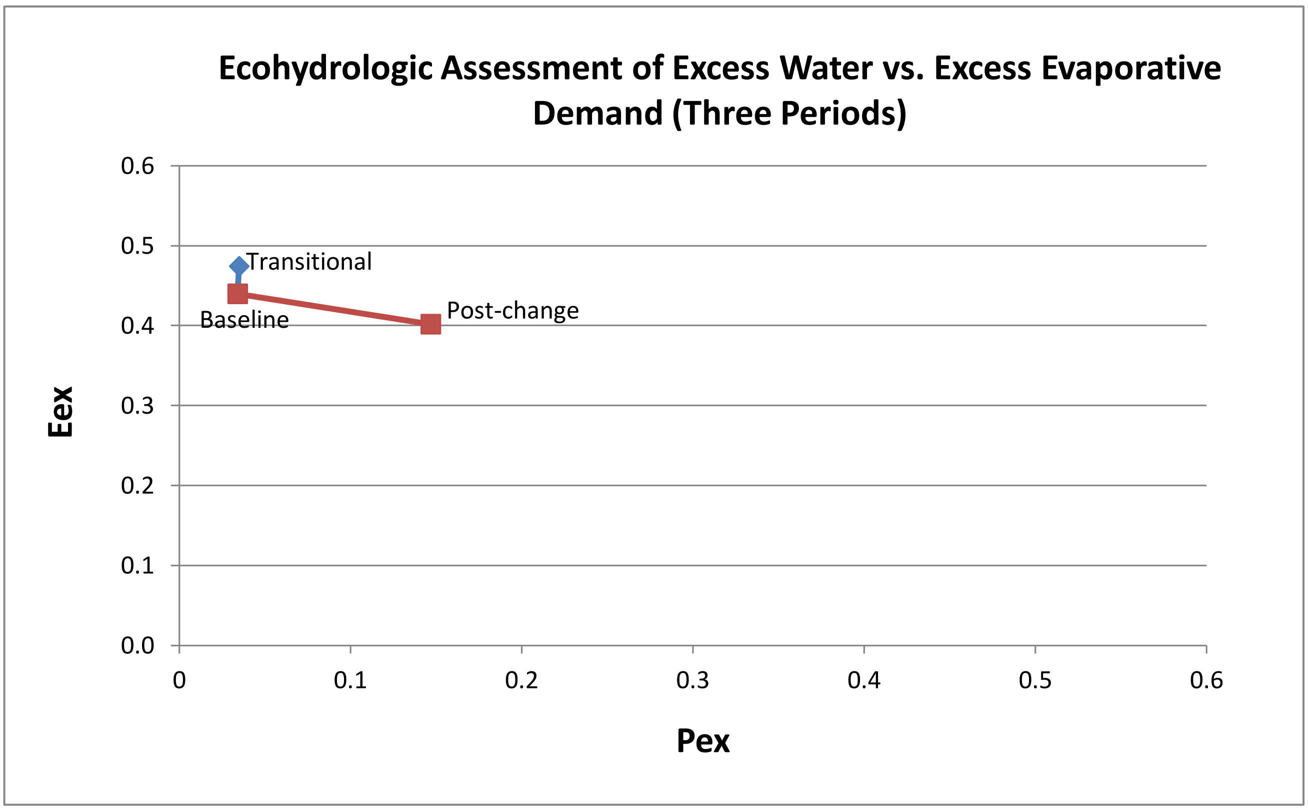


Figure 20: Plot of excess water (Pex) versus excess evaporative demand (Eex) during baseline (1956-1977), transitional (1978-1991), and post-change (1992-2015) periods for the ecohydrologic approach.

Table 4: Climate elasticities of streamflow Q to P (ε_p) and Q to ET_o (ε_{ET0}) for Mauvais Coulee Sub-basin.

Climate Elasticities of Streamflow			
Period		ε_p mm/mm	ε_{ET0} mm/mm
Baseline Period	1956-1977	3.34	-20.32
Transition Period	1978-1990	-	-
Post-Change Period	1991-2015	2.96	-13.69

CHAPTER VI

CONCLUSION

As stated in the Introduction, the purpose of this research was to investigate the relative impact of climate variation and human activities on streamflow variation in Mauvais Coulee. This purpose was achieved through: 1) Investigating the spatial extent of wetland depressions in the Mauvais Coulee Sub-basin; 2) Assembling a hydroclimatic database to establish climatic drivers to streamflow variation in the sub-basin; 3) Partitioning streamflow change into climatic and human components using accepted hydrological methods.

TWI analysis for varying DEM resolutions determined that 10 meters was the best at identifying wet areas, especially the smaller wetland depressions. The results of the 10 meter TWI corresponded with the known wetland locations shown through the National Wetland Index (NWI), giving a better perspective of the innumerable frequency of wetland depressions in this region. Agricultural statistics gathered for both Towner and Ramsey counties suggest that LULC factors are not a major contributor to changing runoff. Ramsey has experienced a large conversion from small grain to row crop agriculture over the past few decades, however any change to runoff from this would have been small in comparison to the original and more drastic LULC change from forest and grasslands to agriculture.

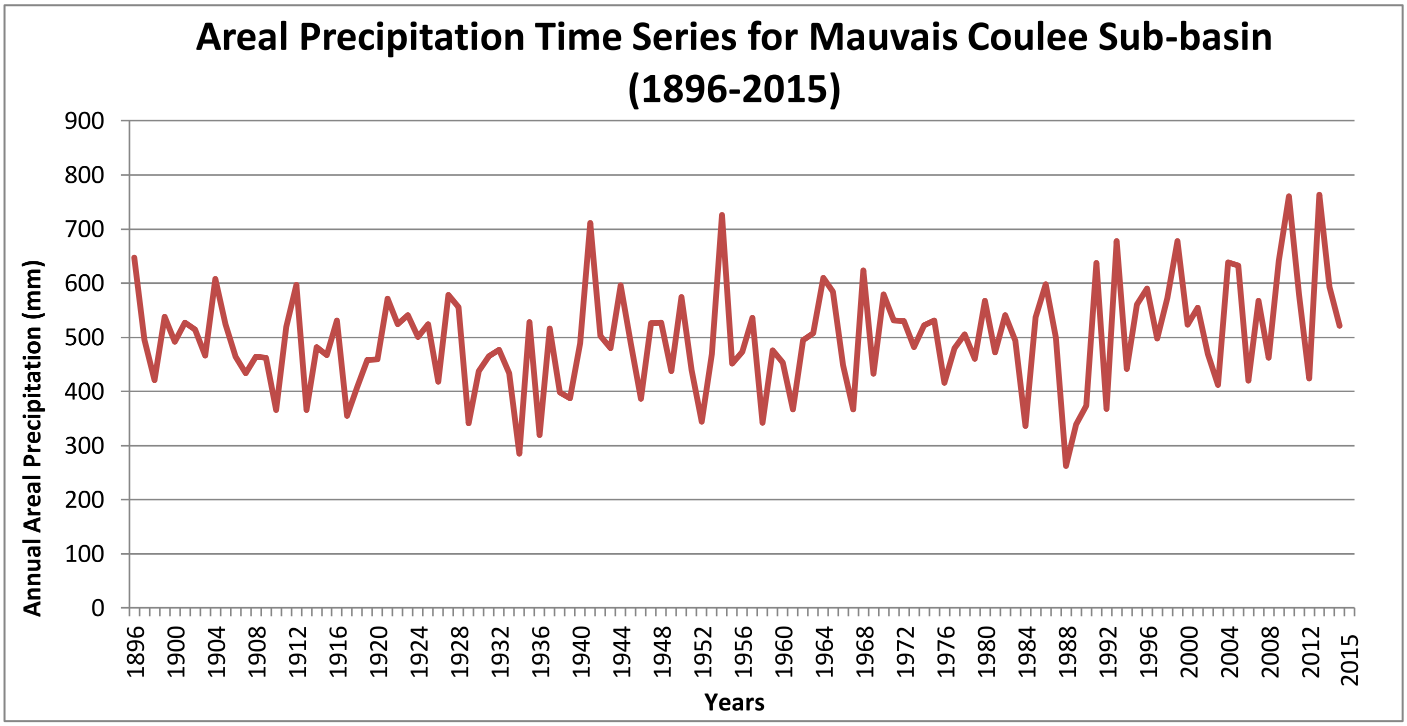
Hydroclimatic data collected from PRISM was used to establish climatic drivers to streamflow variation in the sub-basin. Four standard approaches used for the partitioning climate change and LULC change to stream flow variation were investigated. Although it was determined that the Tomer and Schilling (2009) ecohydrologic approach and the Zhang et al. (2001) implementation of the Budyko framework were the most feasible approaches, they were not applicable to the Mauvais Coulee Sub-basin. Both approaches make assumptions regarding the stationarity of climate, the linearity of P-Q relationships, and the absence of significant groundwater and vadose zone storage that are not applicable to the study period and glaciated prairie landscape.

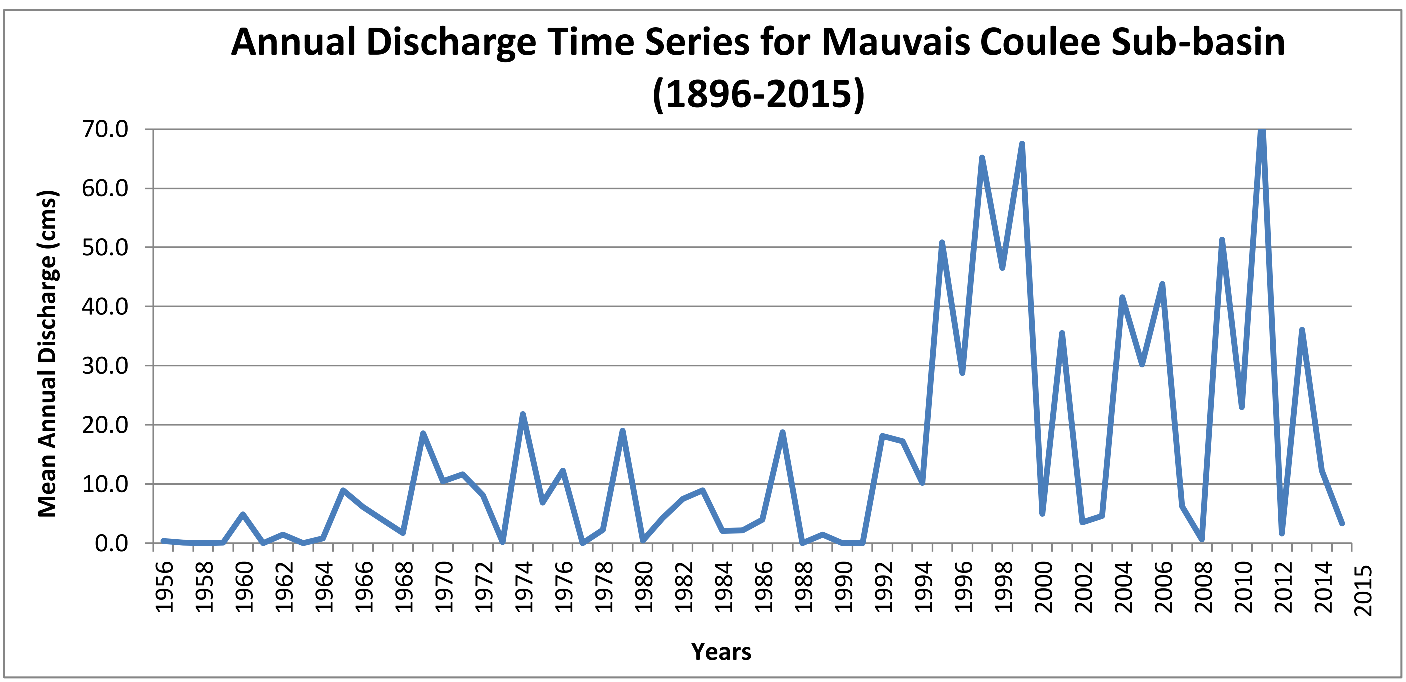
The largest driving factor to streamflow variation in the Mauvais Coulee is more likely because of the natural hydroclimatic cycles of the Devils Lake Basin, coupled with the dynamic nature of fill-spill hydrology in the glaciated plains. Dynamic hydrologic variables – such as the change in contributing area, hydrologic connectivity, groundwater storage, and soil moisture storage – attributed to the natural hydroclimatic variability of the basin makes the application of these methods unsuitable. Unique hydrologic methods that take into account the dynamic properties found at the sub-basin level are needed for future studies to fully understand changes in the basin hydrology.

APPENDICES

Appendix A

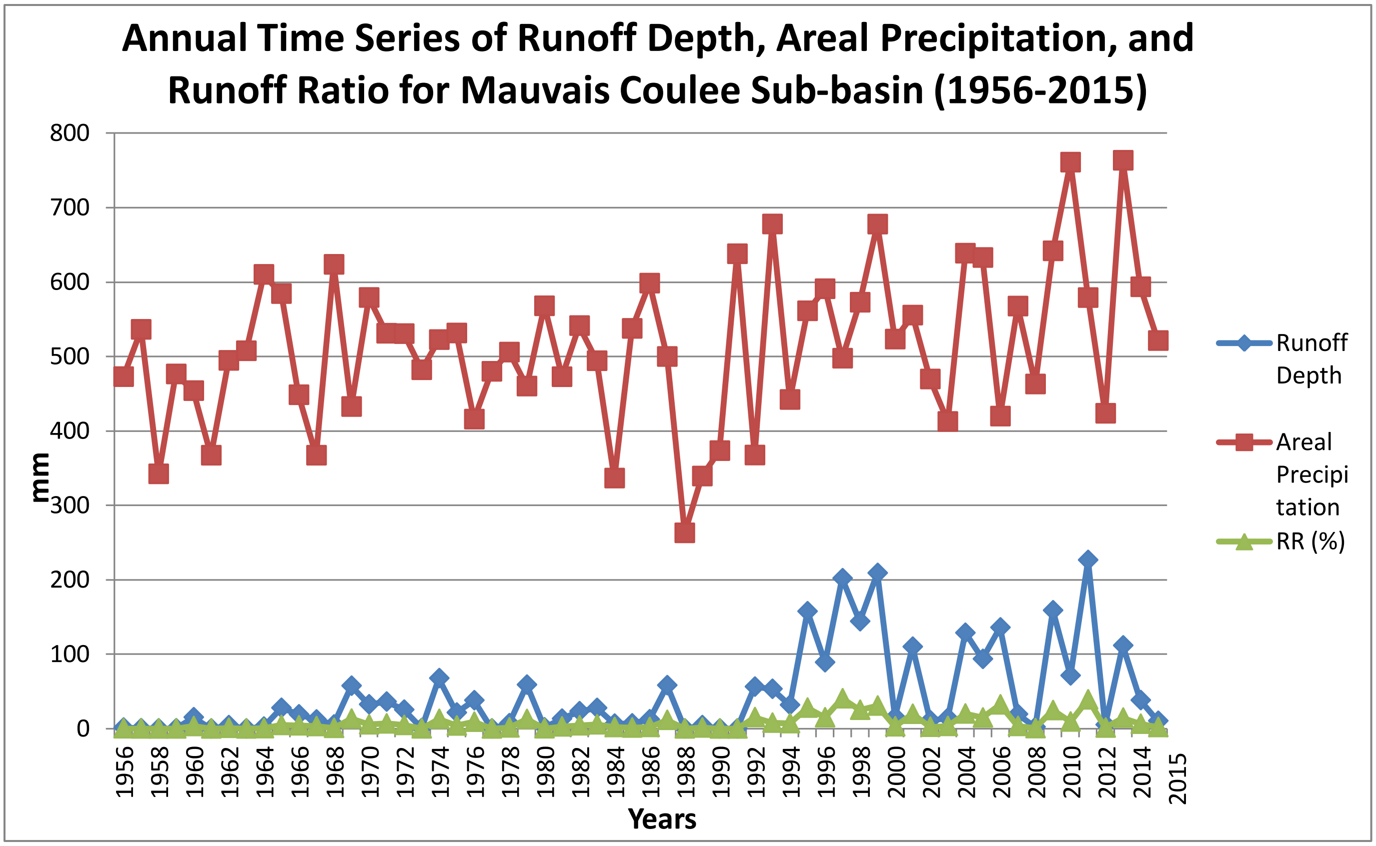
Hydrologic Data Time Series





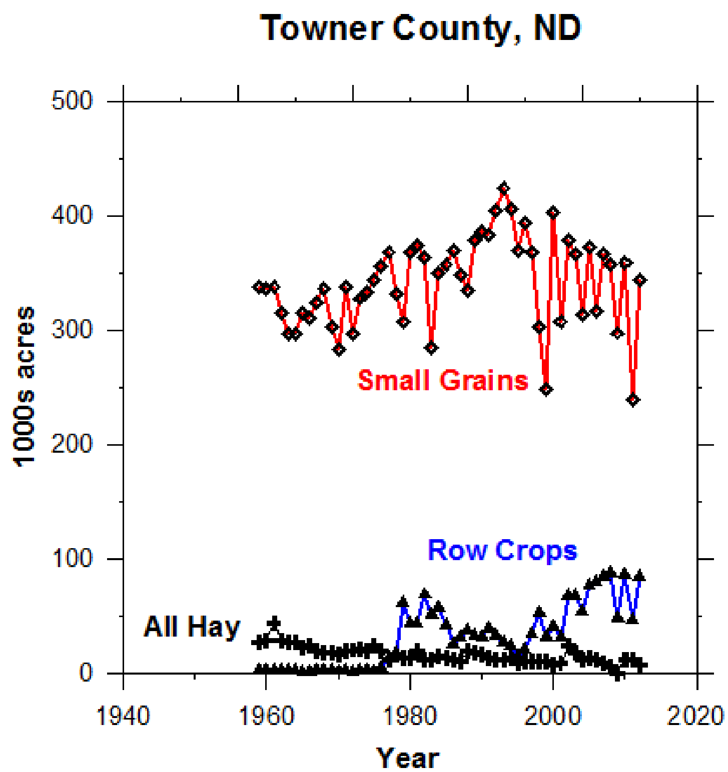
Appendix A (cont.)

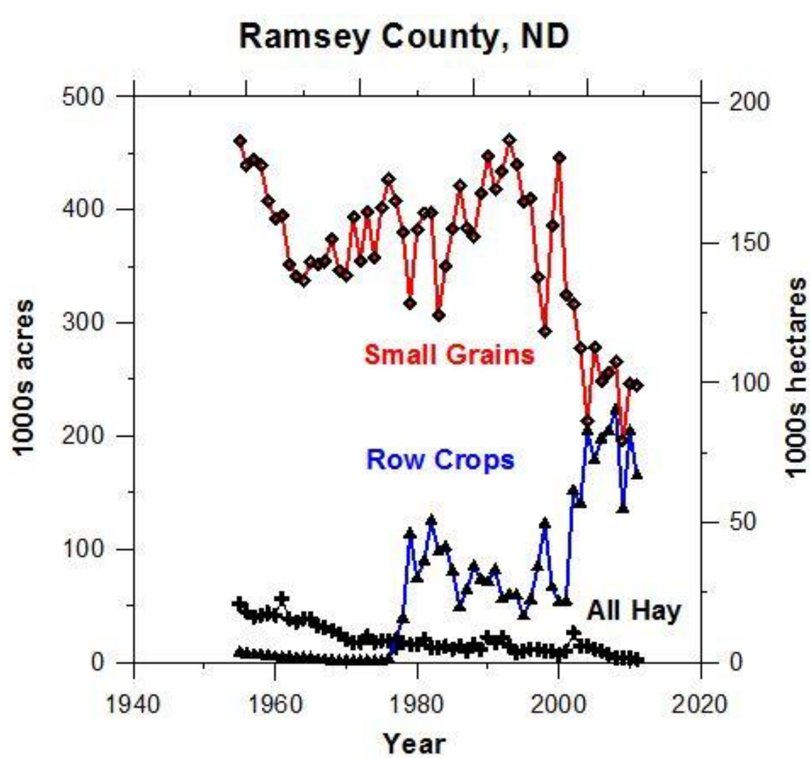
Hydrologic Data Time Series



Appendix B

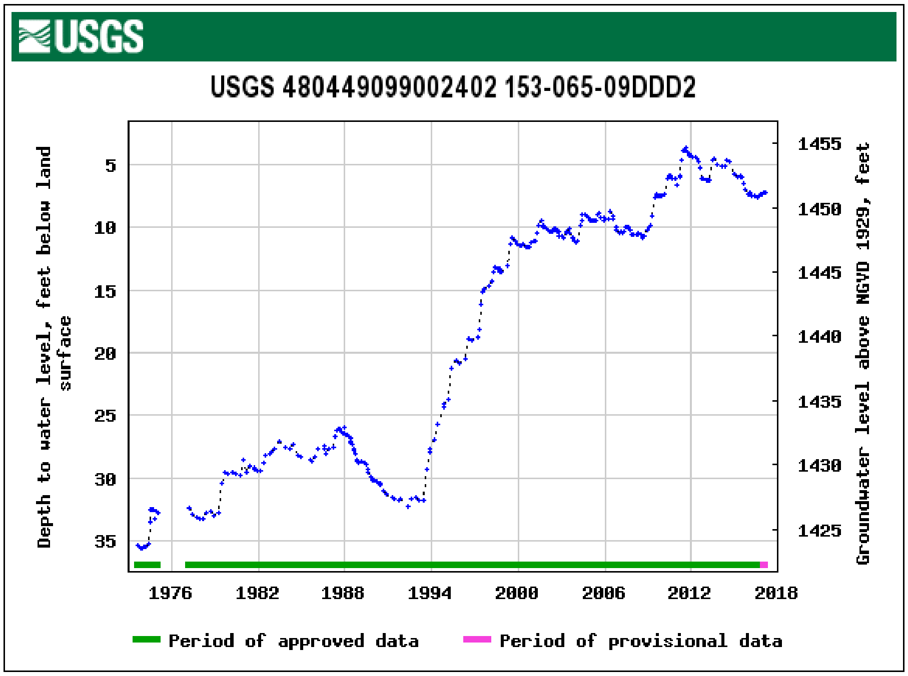
Agricultural Statistics for Towner and Ramsey Counties

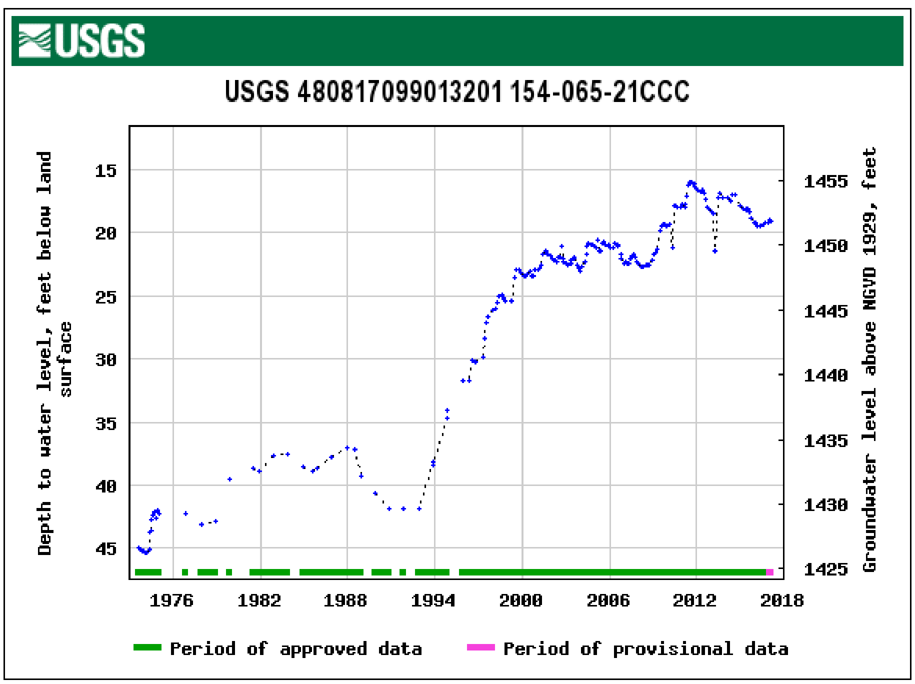




Appendix C

Additional Groundwater Station Graphs





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