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Impact Of Wetlands Loss On The Long-Term Flood Risks Of Devils Lake In A Changing Climate

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IMPACT OF WETLANDS LOSS ON THE LONG-TERM FLOOD RISKS OF DEVILS LAKE IN A CHANGING CLIMATE

by

Sergey Gulbin

Bachelor of Ecology and Environmental Management, Moscow State University, 2014

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements
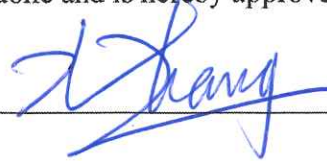
for the degree of

Master of Science

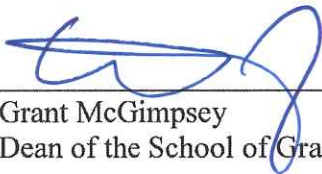Grand Forks, North Dakota

December

2017

This thesis, submitted by Sergey Gulbin 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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Rebecca Romsdahl
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This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

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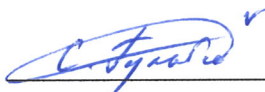
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Department   Earth System Science & Policy

Degree   Master of Science

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Sergey Gulbin

Date   December 1, 2017

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ABSTRACT

Endorheic (terminal) lakes with no water outlets are sensitive indicators of changes in climate and land cover in the watershed. Since 1990 Devils Lake watershed in North Dakota experienced a dramatic change of local climate: wet phase. This change yielded in a 10-m water level rise in just two decades. The Lake's water level increase caused flooding of adjacent areas, including towns, agriculture fields and houses of Native Americans, costing over $1 billion in mitigation.

While the climate change contribution to flooding has been established, the role of large scale land conversion to agriculture has not been researched. The purpose of this study was to assess the influence of land cover change, in particular, wetlands drainage and/or restoration on Devils Lake flooding through modeling the Devils Lake watershed. The Soil and Water Assessment Tool (SWAT) was used to simulate streamflow in all DL watershed sub-basins. The model was calibrated using the 2001-2010 USGS lake level data for the second 10 years of the study period and validated for the first 10 years (1991-2000), resulting in a satisfactory model performance compared against observed DL water level. A set of wetland loss and restoration scenarios were created based on the historical data and the Compound Topographic Index. To emulate the future climate conditions, an ensemble of CMIP5 weather integrations based on IPCC AR5 RCP scenarios was downscaled with the MarkSim weather simulator.

The results suggested that increase of wetlands area in the Devils Lake basin helps to lower lake level both under weather observed during the period 1991 – 2010 and under future climate projections up to 2040. On average, under historic climate, Lake's water level reduces by 0.47

x

meters on every 5% increase in the fractional coverage of wetlands in the basin. The lake

level descends as a result of a reduced streamflow of its two main inlets: the Big Coulee and the

Channel A. Under predicted future climate scenarios, every 5% increase in the fractional coverage

of wetlands in the basin decreases the probability of Lake's natural overspill to the Sheyenne River

by 2 – 10%, depending on the type of climate projection.

CHAPTER I

INTRODUCTION

Devils Lake History

Devils Lake (DL), located in northeastern North Dakota, is a terminal lake with a drainage area of about 9,515 km^2 (Figure 1). Since the Wisconsin glacial period, the lake has experienced multiple water level fluctuations: 6,500 years ago the lake was dominantly dry, between 6,000 and 2,500 years ago it experienced several ups and downs, and about 500 years ago, the lake was very saline at a low-level stage, and afterwards water level continually grew until the 1800s (Wiche & Vecchia, 1996). In the 20th century, the lowest Devils Lake water level was observed in the 1940s (Figure 2). After the 1940s, the lake started to rise with some periods of ups and downs, and in 1990s a period of sharp growth started. During a 20 year period from 1991 to 2010, DL water level increased by 8.5 meters, and on June 27, 2011, the highest level in recent history was recorded as 443.27 m above mean sea level. With another increase of 1.13 m, Devils Lake will overspill naturally to the Sheyenne River, a tributary of the Red River of the North. The rapid rise of Devils Lake water level since 1991 has caused inundation of adjacent agricultural fields, posed threat to surrounding communities, such as the city of Devils Lake, Minnewaukan, Church's Ferry, and influenced the whole economy and policy of the region and to some level even the state (Noone, 2012, Aakre et al., 2012, Ma et al., 2011).

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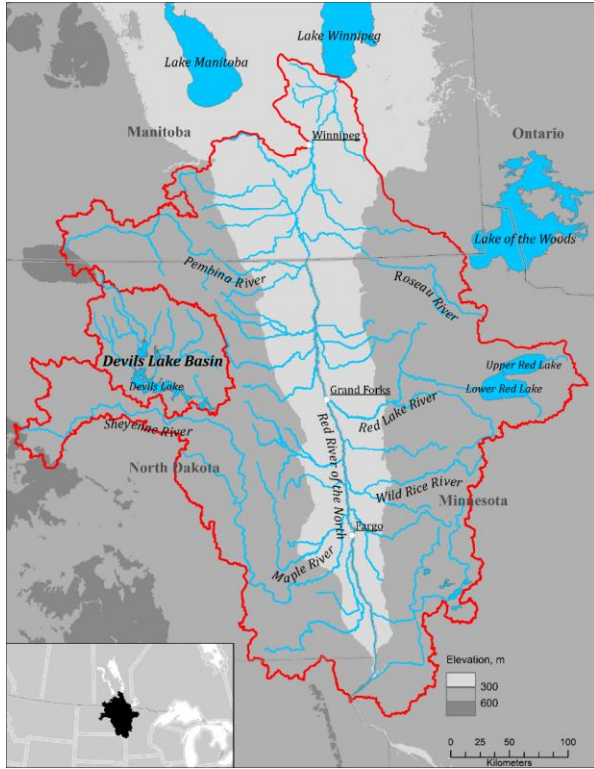
Figure 1. The Devils Lake watershed as a part of the Red River of the North basin
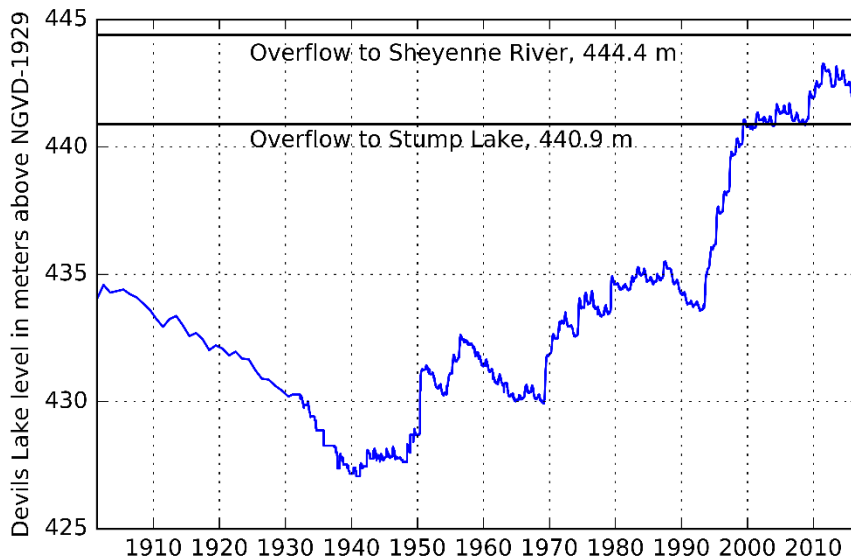
Figure 2. Observed Devils Lake water level above National Geodetic Vertical Datum of 1929

(NGVD 1929) from 1901 to 2016.

Devils Lake Flood Mitigation

In 1993, North Dakota State Water Commission initiated a research on flood mitigation. That led to development of US Army Corps study that suggested to construct an outlet diverting water to the Sheyenne River (Ma, Hipel, & De, 2011). The outlets would connect Devils Lake with the Red River of the North basin, and thus water from Devils Lake would go to the Red River of the North and eventually flows into Lake Winnipeg, located in Canada. The outlet construction, however, might cause potential water contamination of Red River of the North basin, eutrophication of Lake Winnipeg, transfer of invasive species, fishing and tourist activity reduction, but more importantly, poses a threat to the health of Red River of the North Valley residents (Ma et al., 2011). Water quality studies of Devils Lake indicate 5,000 mg/l of dissolved solids in East Bay, from where East-end outlet should connect with the Sheyenne River, and in particular, 500 mg/l of dissolved sulfates (Sether, Vecchia, & Berkas, 1999; Shabani, Zhang, & Ell, 2017; Wiche, 1997). The most recent research showed that based on hydrological modeling results, operation of two outlets increased the concentration of sulfates in the Sheyenne River during the outlet operation period, typically from April to November, to more than 500 mg/L (Shabani et al., 2017), which is higher than the ND state standard for Class IA stream (Darlymple, Dwelle, 2013). It is important to mention that North Dakota water quality standards have a site specific standard 750 mg/L of sulfates for the Sheyenne River from its headwaters to 0.1 miles downstream from Baldhill Dam, thus, technically, the concentration of sulfates in the river doesn't exceed its standard. Being concerned about possible environmental consequences of the outlet construction, Canadian representatives, in particular, Manitoba Government and US communities from the Red River of the North valley expressed protest against outlet construction. In response to multiple concerns, US Army Corps of Engineers proposed to include sand filter into the project.

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Later North Dakota received federal funding for the outlet construction, however, under pressure from the Canadian government, several conditions, such as an economic justification and compliance with the US National Environmental Policy Act were attached to the funding. Frustrated with constant delays, in 2005, the state of North Dakota decided to construct its own temporal diversion with operational pumping rate 2.8 m^3/s (Byers, 2005; Ma et al., 2011). This decision was then followed by a series of court hearings and political considerations. In 2010 the existing outlet was expanded to 7 m^3/s capacity and in 2011 construction of a new 9.9 m^3/s east end outlet with Tolna Coulee control structure began. Thus, the total pumping capacity of two outlets reached 17 m^3/s (Noone, 2012).

Total construction cost of the two outlets with operational infrastructure reached $131,000,000 (Noone, 2012). With all other expenditures, such as transportation recovery, construction of levee in the City of Devils Lake and farmers income loss, the total cost of Devils Lake rise exceeded one billion dollars (Aakre, Coon, & Hodous, 2012; Noone, 2012).

Research Objectives

In this research, we investigated the role of wetlands conversion to agriculture in Devils Lake flooding to propose an alternative solution to a common Devils Lake flooding problem. Even though the role of climate in DL rise has been thoroughly investigated and it was concluded that local climate change was the primary reason for Devils Lake rise, the role of large scale historic land conversion to agriculture has not yet been researched. The overall goal of the research was to assess the influence of land cover change, in particular, wetlands drainage and/or restoration on Devils Lake flooding. To accomplish this goal, the following specific objectives were established:

- To develop a SWAT model for the Devils Lake watershed

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- To calibrate and validate the Devils Lake basin model using the 1991-2010 history of observations

- To create four scenarios of modified wetland land cover (including wetlands area, volume, and drainage area)

- To estimate wetland conversion to agriculture effect on Devils Lake flooding by comparing simulated water level change under the historical climate using the current wetland area and four wetland area modification scenarios

- To estimate wetlands effect on Devils Lake overspill risks up to 2040s by comparing simulated water level change under the projections of the future climate using the current wetland area and four wetland area modification scenarios.

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CHAPTER II

LITERATURE REVIEW

Many studies have been conducted to examine the linkage between climate variability and the recent rise of Devils Lake water level. They concluded that fully or partially, local climate variability is the main cause of the lake level fluctuations.

The first study that analyzed connection of Devils Lake level fluctuation with local climate variability was made by G. J. Wiche (1986). Based on analysis of the available hydrological and climatological information and the regression results of the annual discharge at the Mauvais Coulee near Cando and winter precipitation (October through April), it was concluded that fluctuation of Devils Lake water level occurs largely due to local climate variability.

The study of Devils Lake climatology (Wiche, Vecchia, Osborne, & Fay, 2000) indicated that regional variation in precipitation pattern in the US Northern Great Plains played a key role in a long term flooding of Devils Lake. In the research, it is noticed that local weather, flood and drought occurrences often depend on global atmospheric circulations, the most noticeable of which is El Nino. The research indicates that low frequency of wet years over DL before the 1970s was caused by low activity of El Nino and La Nina. After 70s activity of El Nino caused more wet years over the DL basin.

Recent studies analyzed Devils Lake flooding risk under projected future climate. Vecchia (2011) developed a stochastic model for the interconnected Devils Lake and Stump Lake system and estimated the probability of natural overspill of DL to the Sheyenne River (corresponding to 444.4 meters above mean sea level) from 2011-2030. In particular, the research predicts 45% probability of spill without two outlets assuming the climate remains the same as during the period

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1981-2009. With the outlets working at full capacity, the probability of overflow decreases to 17-19%, based on the Vecchia's estimations.

Kharel and Kirilenko (2015) also analyzed the probability of Devils Lake overspill in future. Based on the model of the DL basin using the Soil and Water Assessment Tool (SWAT) and ensemble of statistically downscaled General Circulation Model (GCM) projections they find out the significant probability of overspill (7.3 - 20.0%) in the absence of outlet until 2040, but full capacity outlets almost eliminate the overall likelihood of the Lake overspill.

History of Land Cover Change in the region

Even though several studies indicate local climate variability as a major factor of Devils Lake fluctuations, some of them also note that in addition to climate, a chain of upstream lakes, potholes, wetlands and land cover modifications has some effect on Devils Lake inflow (Wiche, 1986, Swenson et al., 1955). Regarding this, we paid special attention to the history of land cover change, because Devils Lake is located in the area of an intense agricultural development and for the past 100 - 150 years, land cover of the basin has undergone significant changes.

Thomas Dahl (1990) estimated that North Dakota wetlands have lost 50% of their original acreage. When settlers first came to North Dakota, swamps covered a large portion of the territory. For the first settlers, swamps caused problems: they slowed down wagons and impeded walking; they also harbored mosquitos and malaria. Because of these obstacles, early residents drained the wetlands. Later, they were drained for the purpose of agricultural expansion. Presumably, the most famous example of such drainage is the Great Black Swamp in Ohio (Kaatz, 1955).

Despite the hardship they caused for the first settlers, nowadays wetlands are known as an important part of the hydrosphere that provide valuable benefits and services to ecosystems. One of the main ecosystem functions that wetlands provide is storage of water and thus, reducing flood

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risks with the evaporation of water from wetlands and seepage of water to the ground (Bullock & Acreman, 2003; Ogawa & Male, 1986; Voldseth, Johnson, Gilmanov, Glenn, & Millett, 2016). Wetlands provide a valuable biological function: millions of ducks and other birds choose wetlands as nesting places and use wetlands as a habitat during seasonal migration (Gibbs, 1993). Wetlands also serve as an essential buffer for sediments and nutrients which tend to concentrate in marshes and swamps before entering river streams. Consequently, wetlands contribute to improving the water quality of rivers (Johnston, Detenbeck, & Niemi, 1990; Pellerin et al., 2004).

With time, wetlands loss rate was declining: between the 1950s and 1970s, in the conterminous United States, average net wetlands loss rate was 185,350 ha/yr, in the next decade the rate reduced to 117,360 ha/yr and between 1986 and 1997 the rate was only 23,670 ha/yr (Dahl, 2000). The largest portion of wetlands was lost to agriculture (51% of all lost wetlands between 1986 and 1997) with about 400,000 ha of wetlands lost between the 1970s and 1980s, and only 80,000 ha between 1980s and 1990s (Dahl, 2000). A big role in this wetlands drainage rate reduction is given to federal policies and Acts directed to conservation and restoration of wetlands. The first measure aimed at reducing habitat loss was the Wetland Conservation Provision (also known as "Swampbuster"), part of the Food Security Act of 1985, which was included in the U.S. Farm Bill.

"Swampbuster" was focused on discouraging wetland conversion to agriculture: farmers and producers converting wetlands to cropland lost eligibility for some federal farm program benefits. Later, the Wetlands Reserve Program (WRP) was authorized in the 1990 Farm Bill. WRP is a voluntary program, incentivizing farmers and producers to restore and protect wetlands on their land. The program compensates the landowners for the land withdrawn for easement

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placement. Even though the program is voluntary, 435,040 ha wetlands were restored within seven years of working – before the 2002 Farm Bill.

In the Prairie Pothole Region (PPR) about 35,500 ha of emergent wetlands were restored from agriculture between 1997 and 2009, however, this effort was overshadowed by area of wetlands lost to agriculture: 50,770 ha (Dahl, 2014). Agriculture and expansion of deep water habitats (lakes, riverines, and reservoirs) are primary reasons of wetlands loss in the PPR during the period from 1997 to 2009, together they account for 79% of wetlands lost (Dahl, 2014). With time also mean size of wetlands in the PPR changed, if in 1983 mean area of wetland was 0.9 ha (based on the National Wetlands Inventory data), in 2009 it increased to 1.3 ha This increase happened because many more small wetlands were drained than large wetlands. Another important consequence of wetlands losses is that temporary wetlands experienced the highest rate of loss than any other types of wetlands, the area of wetlands of this type declined in almost two times. At the same time fraction of semi-permanent wetlands increased from 10% to 22% (Dahl, 2014).

Currently, Prairie Pothole Region is experiencing a new wave of wetlands drainage. Presumably, the main reason is that ethanol production has caused demand increase on corn, and the price of corn and soybeans tripled since 2002. The study, comparing wetlands cover based on the National Wetlands Inventory (NWI) data, mainly produced in the 1970s -1980s and Cropland Data Layer (CDL) of 2011 showed that in the Dakotas PPR 134,500 ha of wetlands were converted to cropland. This was 7.4 % of the wetlands acreage in the 1980s in the Dakotas PPR. Comparison of NLCD 2001 and CDL 2011 shows that between 2001 and 2011, 62,200 ha of wetlands were lost (Johnston, 2013).

The conservation provisions deterred wetlands drainage in the Dakotas, and without it, the rate of wetlands loss would be significantly higher. This is proven by studies that show that the

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rate of wetlands restoration on agricultural lands increased by 59% (U.S. Department of Agriculture, 2010). However, restored wetlands are more isolated and usually do not belong to bigger wetland complexes, which reduces their flood attenuation effect (Galatowitsch and van der Valk, 1994). Recently U.S. Fish and Wildlife Service (USFWS) set a new goal of restoring 276,110 ha of wetlands in the PPR only. Special attention to the wetlands problems is paid in Iowa and Minnesota, where state governments contribute to wetlands restoration by identifying wetland complexes for potential restoration and planning land acquisition (Dahl, 2014). Another popular mechanism of wetlands protection is easement program. USFWS practices acquisition of land under wetlands by outright purchase (fee title). Such wetlands with conservation easements remain under control of landowners, but any activities, such as draining, leveling or filling of wetlands is prohibited (Dahl, 2014).

The current interpretation of Section 404 of the Clean Water Act (CWA) indicates that the majority of wetlands in the PPR are not considered as waters of the United States and thus do not fall under the CWA. In addition, agricultural use on geographically isolated wetlands doesn't require any permit and thus drainage and filling of isolated wetlands remain unnoticed by federal agencies. Another thing that limits potential wetlands restoration is a determination of wetlands for purposes of implementing the "Swampbuster" program. So, under "Swampbuster" provision, wetlands with an established history of cropping prior to 1985 are also not considered as the waters of the United States.

Wetland role in streamflow regulation in the DL basin

One of the first studies that analyzed the effect of wetlands on flooding with the implementation of hydrologic modeling was made by Simonovic and Juliano (2001). Using HEC-HMS hydrological model, they examined wetlands effect on streamflow and flood volume by

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simulating Red River of the North flooding event in 1997. Their results indicate that a greater area of wetlands in the Red River of the North Valley would reduce the flood volume. However, they also indicate, that flood volume reduction is minimal comparing to the area of land to be restored. In addition, the simulation shows that the flood peak remains the same with the increased wetlands area, indicating that property damage would likely remain the same.

In the late 1990s and early 2000s, when the North Dakota government was striving to find the way for DL flooding mitigation, U.S. Army Corps of Engineers conducted a research, focused on the Devils Lake upper basin storage evaluation (Doeing, Forman, & Voigt Jr, 2001). This study focused on two main aspects: delineating and classifying depressions and developing a physically-based hydrological model to simulate the depressions and their hydrological functions. Using multiple sources of wetlands data, such as DEM, NWI, aerial photos and digital quad maps, they delineated and classified depressions for upper basin watershed. Upper basin was defined as a part of the Devils Lake watershed area excluding the direct drainage area of Devils Lake and Stump Lake. Depressions were classified into two main categories: possibly intact and possibly drained (since the depressions were classified without field verification, the modifier "possibly" was added). For hydrological simulation, a modified version of HEC-HMS a PRINET model (Pothole-River Networked Watershed Model) was used. After calibration, the model was run under eleven future climate scenarios (2003-2020) with various depression restoration scenarios (25, 50, 75, and 100 percent by volume of the restoration candidates). The depression restoration scenarios were compared by annual runoff reduction. The results indicate that depression restoration can reduce the volume of surface runoff entering Devils Lake and therefore level of the Lake. However, in this research, modeling of DL was not done, and thus it's hard to make any conclusions on how wetlands restoration will affect the lake level itself.

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Vining (2002) simulated streamflow and wetland storage in the Starkweather Coulee subbasin, part of the Devils Lake basin. Using DEM and topo maps, he estimated the area and storage of wetlands in the subbasin. The model simulation indicates that with increasing storage of wetlands from 20% of actual storage to 100%, the Starkweather Coulee streamflow decreases by 49% (from 45.4 to 23.1 cm) over the 18-year period.

Kharel et al. (2016) analyzed land use change in the DL basin driven by market policies under historical and changing climate. Even though the wetlands were not specifically analyzed, their results indicated that preserving grasslands acres and promoting alfalfa would reduce the risk of Devils Lake overspill under the changing climate and mitigate overflow under historic climate.

The first attempt to account for wetlands using SWAT model was made by Wang in 2008 (Wang, Yang, & Melesse, 2008). To account for limited data availability in the area of research (northwestern Minnesota) e.g. the volume and subbasin area that drains into wetlands, Wang developed a new Hydrological Equivalent Wetland (HEW) concept. The concept implies simulation of all wetlands in a subbasin as wetlands with an area equal to the summation of the wetland areas included in the subbasin. So, if HEW area parameter was estimated based on the MNDNR wetland survey (DNR - Ecological and Water Resources, 2017), other three HEW parameters fr_{imp} (fraction of a subbasin that drains into wetland), V_{nor} (volume of water stored in the HEW when filled to its normal water level) and V_{max} (volume of water stored in the HEW when filled to its maximum water level) were determined through calibration. Even though this approach is relatively simple and fast, it doesn't provide exact estimations of wetlands parameters. In addition, streamflow simulation wasn't calibrated satisfactorily for three out of five river gauges.

Later, using the same concept, Wang, assessed effects of wetland restoration in the Broughton's Creek watershed (Minnesota) (Wang et al., 2010). Their results indicated that   At

the same time, restoration of 50-80% of lost wetlands may be required to significantly reduce peak discharge and sediment loadings in the watershed.

Not all types of wetlands can be equally helpful for flood mitigation. For example, Acreman and Holden (2013) described two types of wetlands: floodplain wetlands and upland rain-fed wetlands. These two types of wetlands have the opposite effect on streamflow: upland wetlands generally contribute to flooding and floodplain wetlands tend to reduce flood potential. So, not only storage of wetlands impacts its flood mitigation capacity, but also its location relative to stream network. Another factor that plays important role in flood attenuation, is a land cover of wetlands. For example, wooded floodplain wetlands have bigger flood attenuation magnitude than grass floodplain wetlands (Acreman and Holden, 2013). Also, dry wetlands are better in flood mitigating than wet grass wetlands. Drained wetlands tend to contribute to flooding because drainage channels provide a direct route for water into a stream, this may increase total river streamflow and peak streamflow in particular (Acreman & Holden, 2013).

Golden (2016) analyzed the influence of a specific wetland category (Geographically isolated wetlands – GIWs) on streamflow. The study provides two main conclusions: average distance from GIW to stream and streamflow are positively and significantly related, and a fraction of subbasin area occupied by wetlands negatively and significantly related to subbasin flows. These results are consistent with the study by (Acreman & Holden, 2013).

CHAPTER III

METHODS AND DATA

We used Soil and Water Assessment Tool (SWAT) (Neitsch, Arnold, Kiniry, & Williams, 2011) to simulate hydrology of the Devils Lake basin. SWAT is a physically based model, which allows us to examine the relative impact of changes in input data (such as a land cover change in our case). The model is also computationally efficient, which is quite important for our large study area. SWAT requires several inputs for successful watershed simulation: Digital Elevation Model (DEM), river network, land cover, soil data, weather data, and for particular purposes of this research – lake and wetlands parameters.

Land cover and relief of the Devils Lake basin

We used 1-arc-second (approximately 30-m) resolution Digital Elevation Model (DEM) from the National Elevation Dataset (U.S. Geological Survey, 2009) in this research. Previous researches indicated that higher DEM resolution has no significant improvement of streamflow and runoff simulation (Lin et al., 2013; Tan et al., 2015). Also, using a 30-m DEM instead of 10-m the computation time was significantly reduced. DEM of the Devils Lake watershed shows that, generally, our study area is flat with absolute elevation varying from 423 to 675 meters above mean sea level. Areas with slopes steeper than 5% account for only 4.4% of the watershed area and appear mostly on the southern, western and northern boundaries of the DL watershed (Figure 3).

We used river network from National Hydrography Dataset (U.S. Geological Survey, 2013) to "burn" it into the DEM ("burn in" tool is used to force reaches to follow known pathways or streams riverbed) since current "Stream Definition" tool in SWAT does not provide required precision.

It was very important to pick the best land cover data for our research purposes. Originally, we had a choice to use either Cropland Data Layer (CDL) (USDA-NASS, 2010) provided by National Agricultural Statistics Service (NASS) or National Land Cover Dataset (NLCD) data from Multi-Resolution Land Characteristics Consortium (MRLC) (Fry et al., 2011; Homer et al., 2007), both are available at a 30-m resolution. CDL has annual data with small land cover classes, including crops data, and NLCD has datasets with broader land cover classes, updated every five years. Because our research doesn't focus on specific crops, but mostly analyzes wetlands and open water, we decided that NLCD would be a better fit for our needs. Also, a higher number of land cover classes increase computation time in SWAT, and this is an important factor for our large study area (9,515 km^2). So, we picked NLCD 2006 (Fry et al., 2011) since it's the most recent land cover dataset for our study period from the list of NLCD datasets. To reduce computation time in SWAT, original 20 land cover classes were aggregated into seven (figure 3).

The aggregated land cover map based on NLCD2006 (Fry et al., 2011) shows that the dominant land cover type in the Devils Lake basin is cropland (60.0%), and wetlands are the second dominant land cover type (10.7%). The highest concentration of wetlands is observed in the eastern part of the watershed (Figures 3, 10, 11). Open water occupies 9.9% of the area (this land cover type mostly account for lakes), hay and rangeland together cover 14.7% (hay – 8.1% and rangeland – 6.6%). Hay is mostly located on the East and South of the basin, and grasslands are mostly accumulated in a patch on the north of the region. Urban area with transportation occupy 4.1% and forest is the least dominant land cover type in the Devils Lake watershed with only 0.6% of the watershed area (almost all forests are located on the north west of the Devils Lake basin, Figure 3).

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Soil data was obtained from STATSGO database (U.S. Department of Agriculture, 1993). STATSGO provide a spatial distribution of soils with 125-m resolution. The main reason for using STATSGO was its simplicity: this soil database is integrated into SWAT, so no additional work is needed to set it up. Also, STATSGO has a fewer number of polygons for the DL basin than SSURGO and therefore is faster to run. The soils in the region are dominated by loam and clay with moderate or slow water infiltration, and this factor also contributes to high flood risks in the basin. The east of the basin is occupied by the most abundant soil type – Hamerly, it occupies 42.7% of the basin area. This soil type is poorly drained and formed in calcareous loamy till and clay in lower soil layers. On the west, Barnes soil type dominate (29.8% of the watershed area), it is also formed in loams and clay, but slightly more permeable and mostly found on till plains and moraines with slopes from 0 to 25 percent (U.S. Department of Agriculture, 2009).
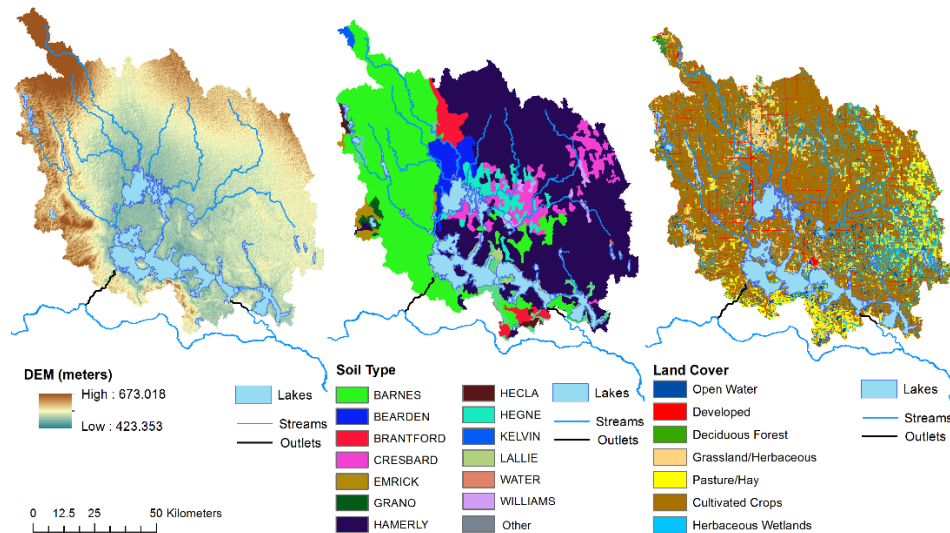
Figure 3. Topography, soil and land cover maps of the Devils Lake basin

Climate of the Devils Lake basin

The Devils Lake basin is located in the zone of influence of a set of different air masses. In winter, Arctic air masses dominate in the region, and during summer humid air from the

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Mexican Gulf comes to this area. During the whole year, Pacific air masses reach the Devils Lake basin periodically, however these air masses, when they reach Devils Lake, lose almost all their humidity while passing through the Rocky Mountains. Interaction of these air masses in this region create a continental climate with hot and short summer and cold and long winter.
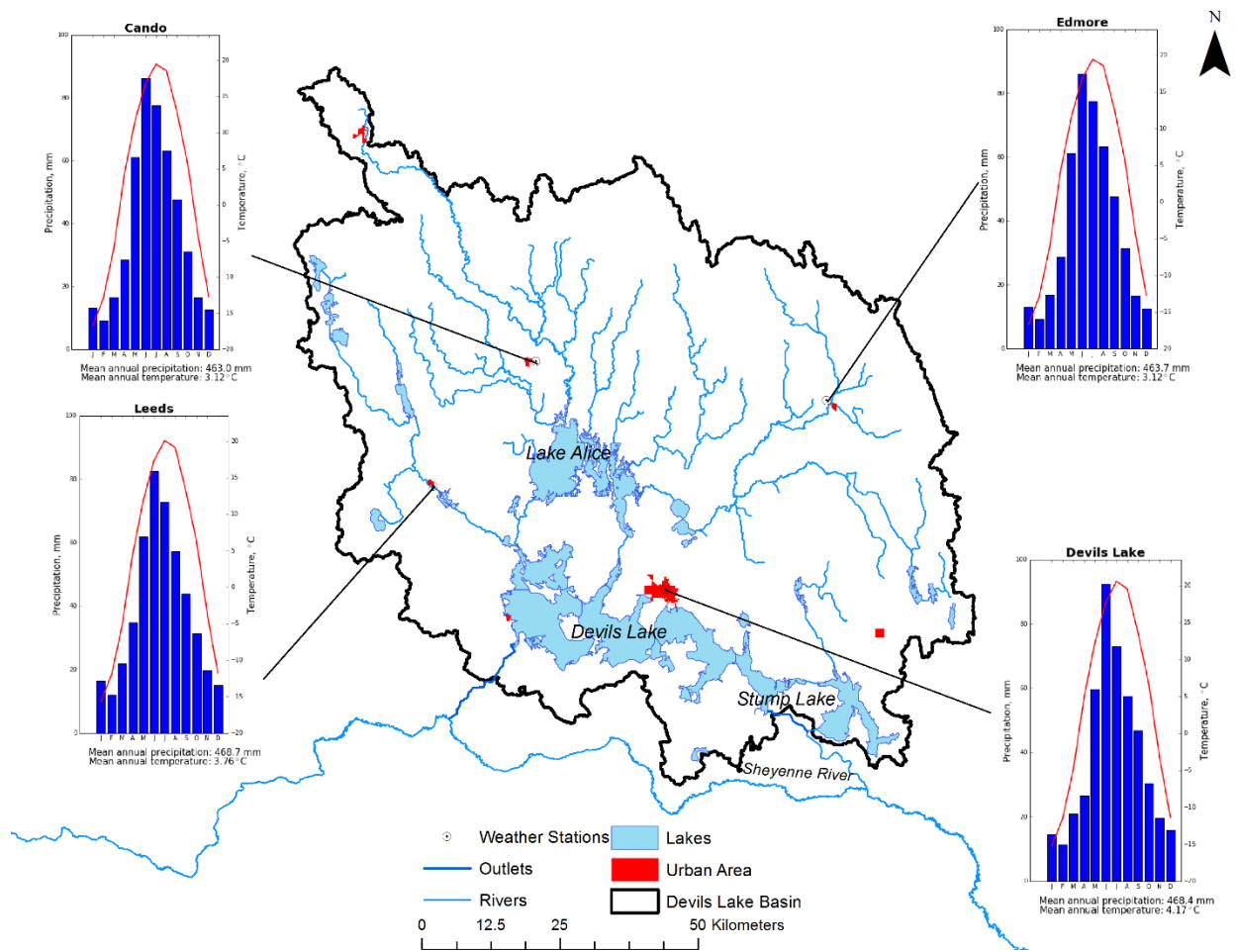
Figure 4. Monthly precipitation and temperature distribution at 4 weather stations, located in the Devils Lake basin. Estimations are based over a period of observations 1/1/1950 - 12/31/2010.

Weather data for our model was downloaded from the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) website (U.S. Department of Agriculture, 2016). From multiple weather stations located in the Devils Lake watershed, we picked four stations with consistent weather observations during our research period (Figure 4). The service provides three

valuable weather parameters, needed for SWAT simulation: minimum and maximum daily temperature and daily precipitation.

The analysis of data from four weather stations showed that mean annual precipitation in the Devils Lake basin from 1950 to 2010 is 465.9 mm with a peak during summer. Mean annual temperature in the basin is 3.2 °C with mean monthly temperature vary from -16.3 °C in January to 19 °C in July.

Figure 4 shows the variations of precipitation and temperature recorded at the four stations in the Devils Lake basin with the most consistent results. Generally, the spatial distribution of precipitation in the Devils Lake basin is uniform. The difference in the mean annual sum of precipitation between stations doesn't exceed 5.7 mm. The highest mean annual sum of precipitation was observed on the Leeds station: 468.7 mm and the lowest - in Cando: 463.0 mm. However, the annual amount of precipitation falling in the Devils Lake basin has changed significantly throughout time. Our analysis of precipitation in Devils Lake city shows that during the period 1950 – 2010, precipitation had positive linear trend 2.54 mm/year adding 155 mm over 61 years (Figure 5). A new wetter phase of climate started in the late 1980s: the mean annual precipitation is 427.7 mm during the period 1950 – 1980, and 505.5 mm during 1981 – 2010. During the 20-year period of 1991 – 2010, mean annual precipitation was even higher: 544.2 mm.

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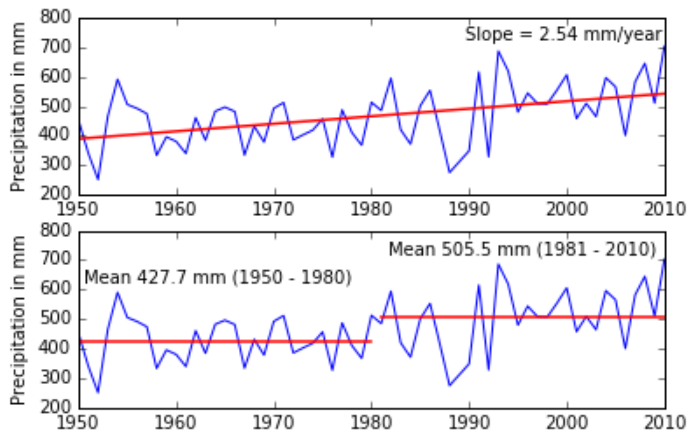
Figure 5. Annual precipitation over the Devils Lake basin from 1950 to 2010 based on the 4 weather stations observation history.

Spatial distribution of average annual temperature is more heterogeneous. The lowest mean annual temperature in the basin was observed on two stations: at Edmore and Cando, where the average annual temperature was at the level of 3.1 °C, and the highest was registered at the station, located in the City of Devils Lake: 4.2 °C, so the difference between mean annual temperatures is 1.1 °C.

Maximums and minimums of climatic parameters in the region indicate that 1988 was, probably, the driest year, in 1988 on three weather stations out of four (Edmore, Leeds, and Cando) the lowest historical annual precipitation was recorded: from 225.0 mm in Cando to 259.0 mm in Leeds (Figure 5). The year 1993 was the wettest, since on two out of 4 weather stations in the basin (Edmore and Cando) the highest historical annual sum of precipitation was recorded: 757.6 mm in Cando and 758.6 in Edmore. Regarding extreme temperature records, 1987 was the hottest year since 1950, on all 4 weather stations in this year was recorded the highest temperature: from 5.9 °C in Cando, to 6.8 °C in Devils Lake. The coldest years were 1950 and 1996: during these years mean annual temperature dropped to 0.3°C in Edmore and 1.1°C in Devils Lake (Figure 6).

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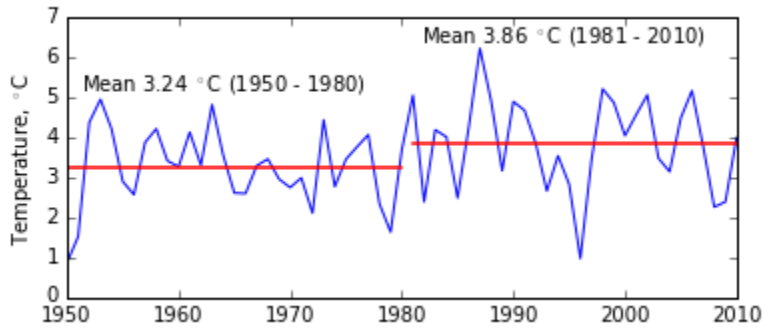
Figure 6. Mean annual temperature in the Devils Lake basin from 1950 to 2010 based on the 4 weather stations observation history.

Hydrography of the Devils Lake basin

Most of the rivers in the basin have mixed type of feeding of snowmelt, groundwater, and rain with snow thaw dominated. Thus, streamflow reaches its maximum in spring at the period of the most intense snow melting.

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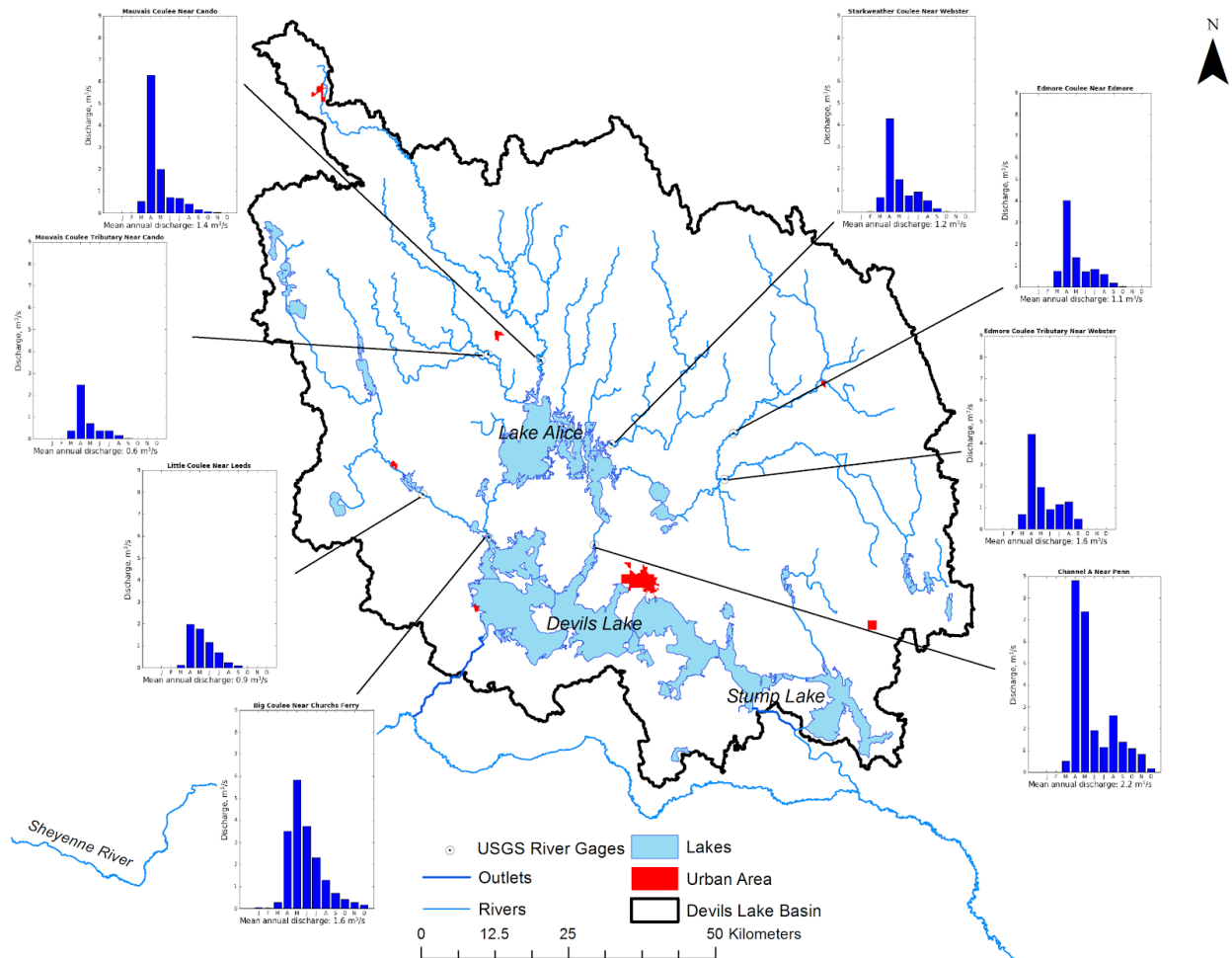
Figure 7. Average monthly discharge distribution at eight USGS river gauges in the Devils Lake basin. Mauvais Coulee tributary near Cando period of observations: 3/1986 - 9/2016; Mauvais Coulee near Cando period of observations: 1/1957 - 9/2016; Little Coulee near Leeds period of observations: 3/1998 - 9/2016; Edmore Coulee tributary near Webster period of observations: 3/1986 - 9/2016; Edmore Coulee near Edmore period of observations: 7/1957 - 9/2016; Channel A near Penn period of observations: 10/1983 - 9/1999; Big Coulee near Churchs Ferry period of observations: 10/1950 - 9/1997; Starkweather Coulee near Webster period of observations: 1/1980 - 9/2016 (U.S. Geological Survey, 2016).

Figure 7 demonstrates the spatial distribution of discharge in the Devils Lake basin, which is very heterogeneous. The highest mean annual discharge of 2.2 m^3/s was observed at the Channel A station near Penn, and the lowest - at the Mauvais Coulee tributary near Cando: 0.6 m^3/s. Obviously, downstream discharge is higher than upstream, thus Channel A and Big Coulee demonstrate the highest mean annual streamflow (since they gather water from all upstream tributaries). Annual discharge distribution reaches its peak in April when snow melting is the most intense and the lowest in winter when rivers freeze. Another distinctive feature of rivers in the basin is gradual discharge reduction after snow melting for rivers that receive water from upstream lakes, such as Big Coulee near Church's Ferry and Little Coulee near Leeds stations. Upstream Lakes smooth the discharge and prevent high flow during snow melting, and, at the same time increase flow during drier months.

Regarding the temporal distribution of discharge throughout the observation periods in the basin, it changes from year to year. The highest mean annual discharge of 15.2 m^3/s was registered on the Big Coulee near Churchs Ferry station in 1997 (Figure 8), the same year when due to the high flow of the Red River of the North, Grand Forks was flooded. Also in 1997, the second largest mean annual discharge of 7.5 m^3/s was observed on the Channel A near Penn station. Mauvais Coulee tributary and Little Coulee showed the lowest maximum of mean annual discharge during the record period: 2.0 m^3/s and 2.6 m^3/s respectively, both in 2011. The lowest historical mean annual discharge for 4 river gauges was registered in 1990 and 1991 when streams almost dried up (Figure 8).
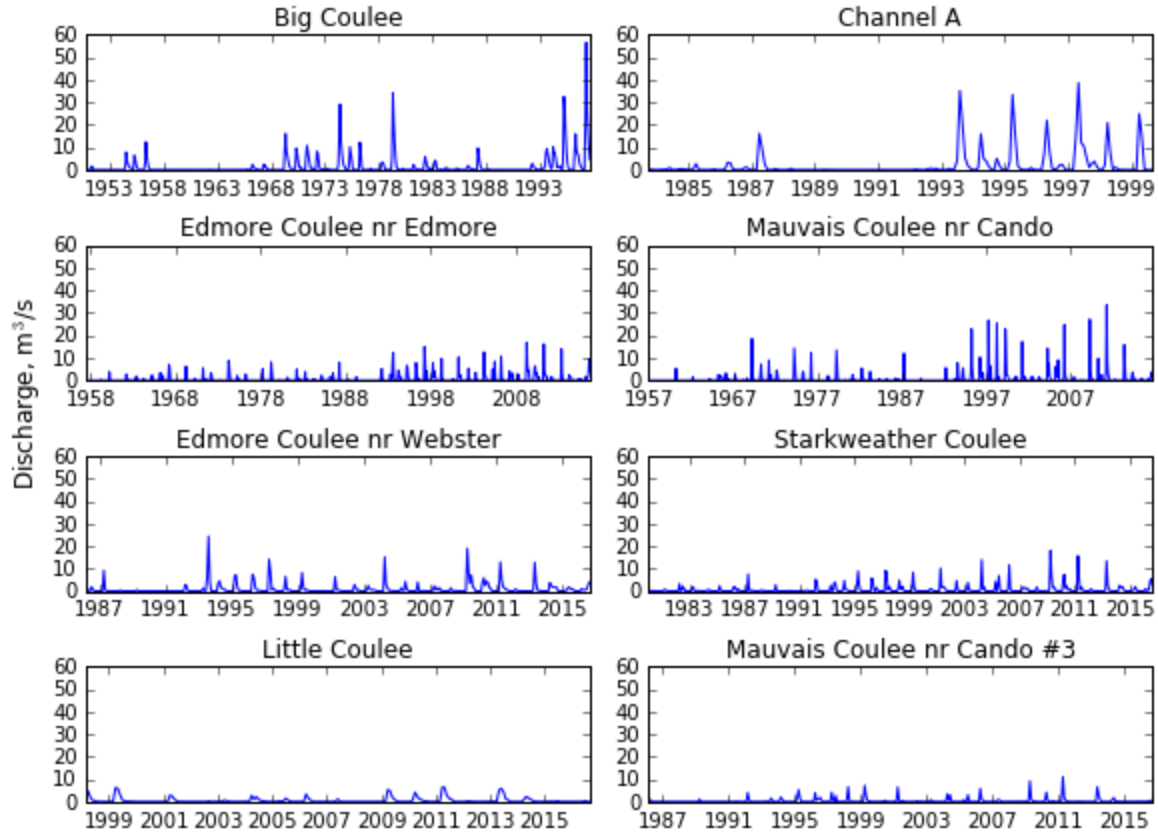
Figure 8. Observed streamflow at eight river gauges in the Devils Lake basin. Mauvais Coulee

tributary near Cando period of observations: 3/1986 - 9/2016; Mauvais Coulee near Cando

period of observations: 1/1957 - 9/2016; Little Coulee near Leeds period of observations: 3/1998

- 9/2016; Edmore Coulee tributary near Webster period of observations: 3/1986 - 9/2016;

Edmore Coulee near Edmore period of observations: 7/1957 - 9/2016; Channel A near Penn

period of observations: 10/1983 - 9/1999; Big Coulee near Churchs Ferry period of observations:

10/1950 - 9/1997; Starkweather Coulee near Webster period of observations: 1/1980 - 9/2016

(U.S. Geological Survey, 2016).

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Hypothetical Land Cover Scenarios

The objective of simulating the hypothetical scenarios is to test how modified land cover with restored/drained wetlands influence Devils Lake and its tributaries. Currently wetlands occupy around 11% of the DL basin area (based on NLCD 2006), so four hypothetical scenarios were created to test how wetlands influence on DL: two scenarios with reduced area of wetlands (absolutely no wetlands and 5% of DL watershed under wetlands), and two scenarios with wetlands coverage higher than current (50% more wetlands acreage than currently, or 16% of the watershed area and 20% of the basin occupied by wetlands). Two wetlands scenarios with 16% and 20% of the wetlands coverage fraction are intended to simulate original coverage of wetlands before active settlement in the region and the two other scenarios with wetlands coverage lower than currently are made just for comparison purposes. For hydrological simulation, the location of wetlands is as important as its number, area, and storage. To simulate the most likely location of historic wetlands in the DL basin, we used Compound Topographic Index (CTI) (Beven, K. J.; Kirkby, 1979; Moore, Grayson, & Ladson, 1991; Murphy, Ogilvie, Connor, & Arp, 2007):

$$CTI = \ln \frac{\alpha}{\tan\beta}, \qquad\qquad (1)$$

Where α represents an upland contributing area of a cell in a landscape and β the cell slope in radians

Basically, CTI shows a measure of a cell's "wetness". Studies have shown that this parameter can serve as a good determinant of surface soil water content (Moore, Burch, & Mackenzie, 1988) and wetlands locations (Murphy et al., 2007; Sayre, Comer, Cress, & Warner, 2010).

The technology of CTI computation is relatively simple and requires ArcGIS or any other raster processor. We used "Flow Direction" tool from ArcGIS to calculate flow direction from

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every cell in a raster based on their slopes and "Flow Accumulation" to determine the number of cells contributing to a source cell based on flow direction. Thus with two tools, we calculated upland contributing area by summing flow accumulation raster values. On the created raster, higher index values indicate wet areas, such as river channels, lakes, ponds and wetlands and lower values indicate ridges or steep hills (Figure 9).
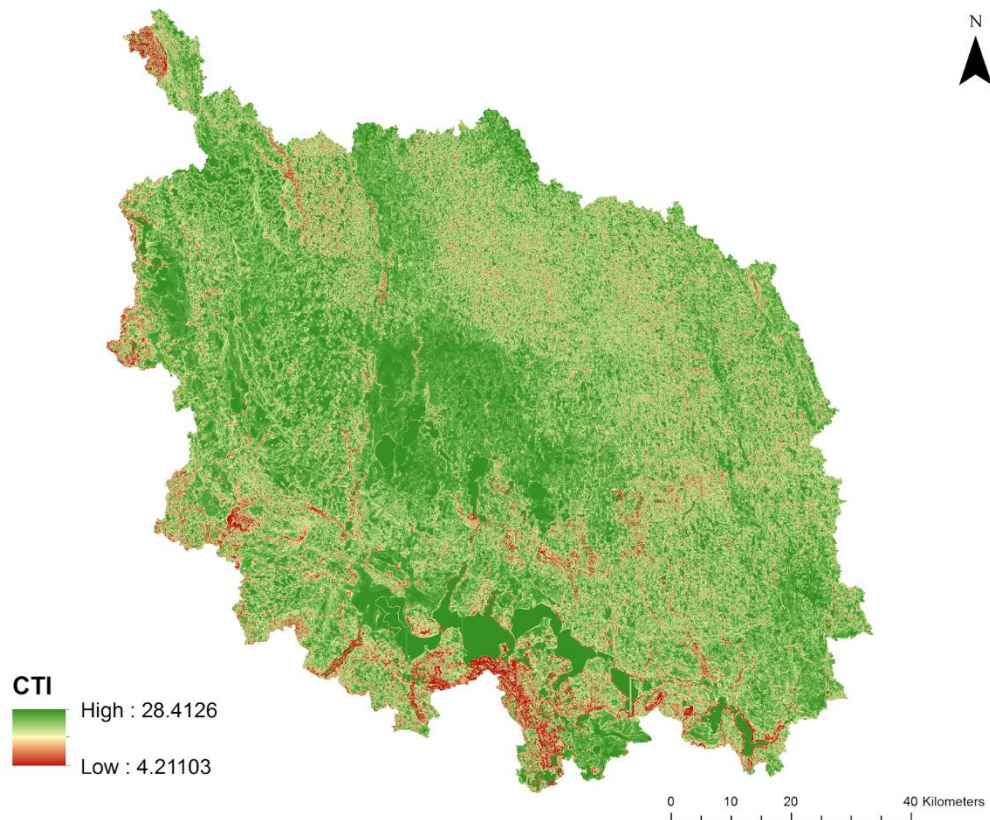
Figure 9. CTI raster of the Devils Lake basin.

For wetlands restoration scenarios (16% and 20%), CTI raster was intersected with cropland raster, since pixels of restored wetlands should be located on the farmlands. Then, knowing total area of restored wetlands, pixels with the highest CTI value were extracted from the cropland raster and replaced by wetlands. For wetlands drainage scenarios (0% and 5%), CTI raster was intersected with wetlands raster and then pixels with the highest CTI values remained and the pixels with lowest CTI values were extracted and replaced with cropland (Figure 10).

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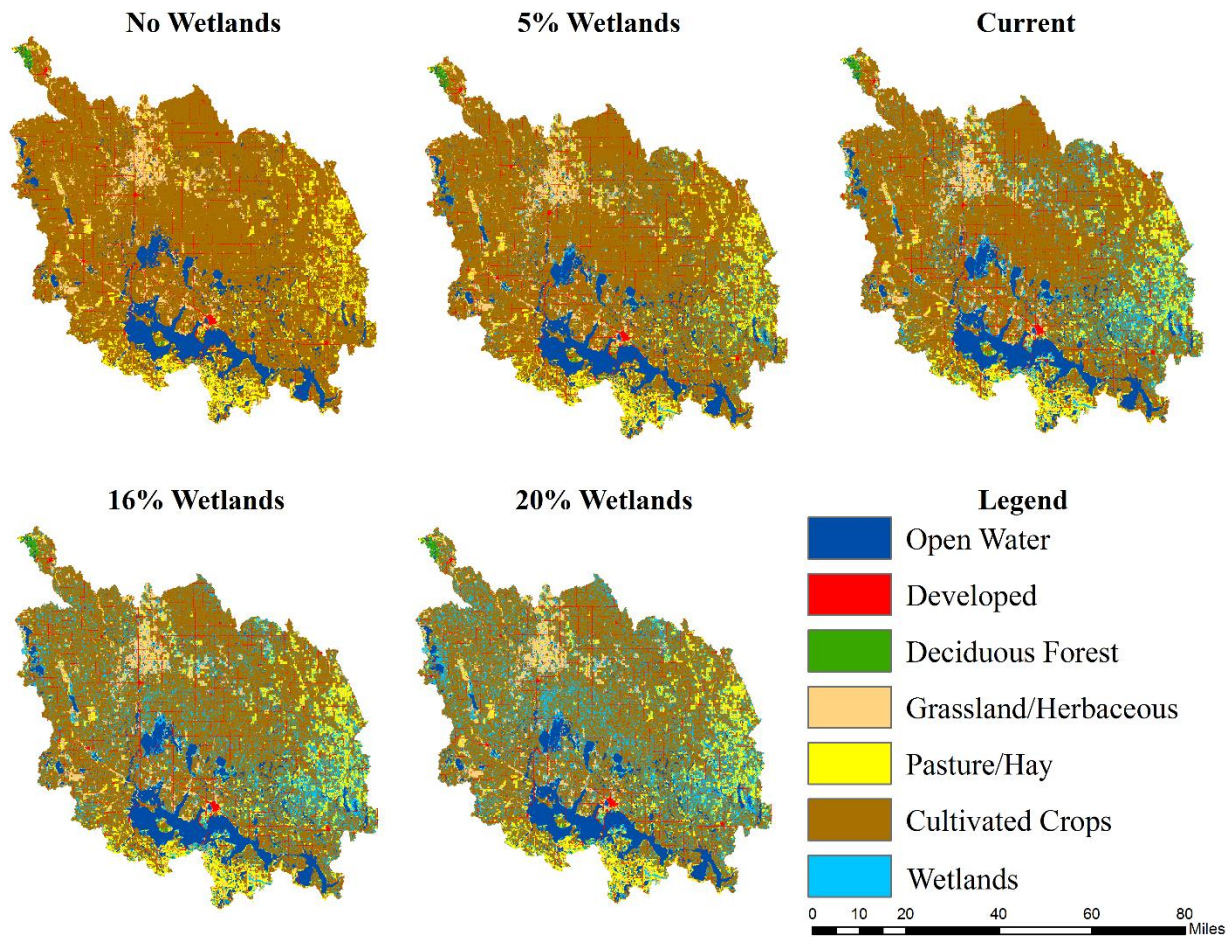
Figure 10. Four hypothetical land cover scenarios with modified wetland area and current land cover map.

Figure 11 portrays how with increased area of wetlands in the basin, a core or center of the highest wetlands density expands and shifts to the central area of the watershed and to the west. So, if in 11% wetlands scenario, the highest density of wetlands is observed on the east of the basin, in the 16% and 20% wetlands scenarios, high density of wetlands is observed also in central and western parts of the basin. These areas (central and western) provide the most favorable conditions for wetlands emergence due to its relief (Figure 9).

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5% Wetlands

11% Wetlands

16% Wetlands

20% Wetlands

Fraction of Subbasin Area Covered with Wetlands

| | < 0.1 | | 0.1 - 0.15 | | 0.15 - 0.2 | | 0.2 - 0.4 | | >0.4 |
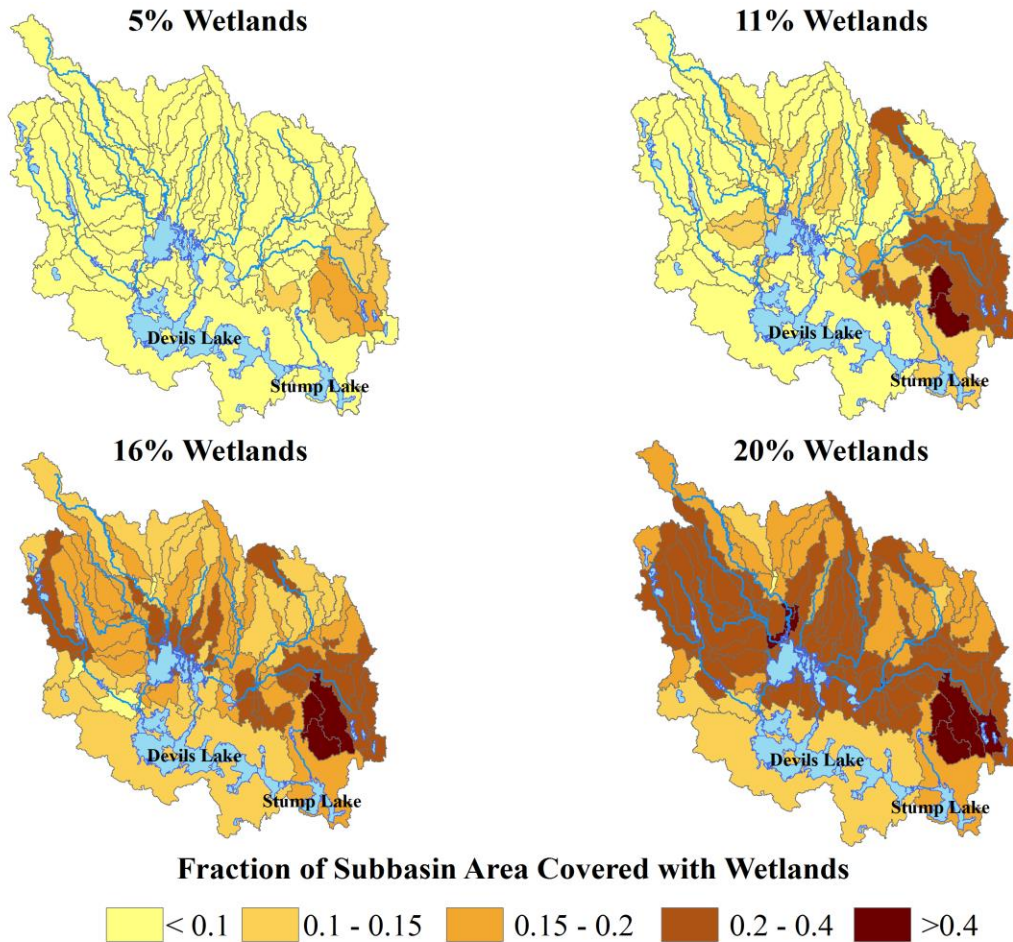
Figure 11. Fraction subbasins area occupied by wetlands in different wetland scenarios.

Wetland Parameters

To account for wetlands in our model, all wetland parameters were aggregated for each subbasin (as required by SWAT wetlands simulation process). Thus we divided our research area into as many subbasins as possible, to account for the spatial distribution of wetlands in the Devils Lake drainage basin. After the watershed delineation, the area was divided into 96 subbasins. However, the higher the number of subbasins, the higher the number of smallest spatial units, Hydrological Response Units (HRU) is required. The number of HRUs influences time for simulation and calibration, and thus we applied threshold levels to HRUs, which is frequently used in SWAT modeling. The threshold was used to specify a level of minor land use/soil/slope class.

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We used 5% threshold for land cover, 20% for soil and 15% for slope, this means that land cover, soil and slope covering less than 5%, 20%, and 15% of a subbasin area respectfully would be eliminated and dominant land cover type, soil or slope would increase its fraction in the subbasin. Threshold level used in this work was found experimentally by trying different combinations. With this threshold levels, our model accounted for 452 HRUs. To represent lakes in the model, several parameters were obtained from USGS (table 1).

Table 1. SWAT reservoir parameters for Devils Lake

Parameter	Meaning	Devils Lake
RES_VOL, 10^4 m^3	Initial volume of water in reservoir on the first day of simulation	85,000
RES_PVOL, 10^4 m^3	Volume of reservoir when filled to principal spillway	333,650
RES_PSA, ha	Surface area of reservoir when filled to principal spillway	56,092
RES_EVOL, 10^4 m^3	Volume of reservoir when filled to emergency spillway	536,600
RES_ESA, ha	Surface area of reservoir when filled to emergency spillway	97,800

(U.S. Geological Survey, 2011)

Within addition to wetlands acreage, SWAT requires also its storage and fraction of subbasin area that drains into wetlands. In the absence of such data for our study area, these parameters were estimated. For this purpose we decided to use a statistical model created for Prairie Pothole Region wetlands and described by Gleason et al. (Gleason, Laubhan, & Euliss Jr, 2008):

$$V = 0.25A^{1.4742} \qquad (2)$$

$$UA = 2.24A^{0.4647}, \qquad (3)$$

Where V represents predicted wetland volume, A wetland area, and UA upland zone area

SWAT requires the following wetland parameters: WET_MXSA, WET_MXVOL, and WET_FR (table 2). Before calculating these parameters, an assumption was made that current estimated wetlands volume and surface area correspond to wetlands filled to maximum water level.

Table 2. Mean SWAT parameters for wetlands in the Devils Lake basin

Parameter	Meaning	0% wetlands	5% wetlands	11% wetlands (current)	16% wetlands	20% wetlands
WET_MXVOL, 10^4 m^3	Volume of water stored in wetlands when filled to maximum water level	-	19,362.1	58,463.4	111,251.8	141,554.4
WET_MXSA, ha	Surface area of wetlands at maximum water level	-	47,574.7	102,201.9	152,256.4	190,298.8
WET_FR	the fraction of subbasin area that drains into wetlands	-	0.05	0.11	0.17	0.22

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Outlets

The first outlet from Devils Lake started in 2005, however, it was mostly inactive until 2011 and the total amount of water it pumped was negligible. Thus, in the historic scenarios (1991-2010) outlet in the model was neglected. However, for future climate scenarios (2011 – 2040) outlet was implemented into the model. On average, during the years when the outlets were pumping water out of the lake the most intensively (2011 - 2014), total outlets mean discharge was 11.2 m^3/s, so in future scenarios, the model was set to outflow 11.2 m^3/s during the typical operation months.

Model Calibration and Validation

Because in our research we focus mostly on Devils Lake and flood risks related with it, we calibrated model parameters based on the lake volume. The study period was divided into two 10-year parts for calibration and validation with a two-year model warm-up period prior to 1991. Devils Lake was calibrated during 2001-2010 for better calibration of the end of the study period, since it is more important for future climate scenarios simulation, and validated during 1991 - 2000. Basin parameters values (such as SFTMP.bsn, SMTMP.bsn, SMFMX.bsn, SMFMN.bsn, TIMP.bsn, SNOCOVMX.bsn, EVLAI.bsn) were used the same as in the model used by Kharel and Kirilenko (2015) (Table 3).

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Table 3. List of calibrated parameters and its fitted values.

Parameter name	Meaning	Default Value	Fitted Value
SFTMP.bsn	Snowfall temperature (°C)	1	0.58
SMTMP.bsn	Snow melt base temperature (°C)	0.5	1.28
SMFMX.bsn	Melt factor for snow on June 21 (mm H_2O/°C-day)	4.5	5.5
SMFMN.bsn	Melt factor for snow on December 21 (mm H_2O/°C-day)	4.5	2.25
TIMP.bsn	Snow pack temperature lag factor	1	0.33
SNOCOVMX.bsn	Minimum snow water content that corresponds to 100% snow cover, SNO_{100} (mm H_2O)	1	14
EVLAI.bsn	Leaf area index at which no evaporation occurs from water surface	3	3.8
GW_DELAY.gw	Groundwater delay time (days)	31	331.79
ALPHA_BF.gw	Baseflow alpha factor (1/days)	0.048	0.74
GWQMN.gw	Threshold depth of water in shallow aquifer required for return flow to occur (mm H_2O)	1000	4400.16
GW_REVAP.gw	Groundwater "revap" coefficient	0.02	0.04
REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (mm H_2O)	750	48.95
RCHRG_DP.gw	Deep aquifer percolation fraction	0.05	0.88

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OV_N.hru	Manning's "n" value for overland flow	-999	-0.08[*]
ESCO.hru	Soil evaporation compensation factor	0.95	0.30
EPCO.hru	Plant uptake compensation factor	1	0.77
CN2.mgt	Initial SCS runoff number for moisture condition II	-999	0.02[*]
CH_N(2).rte	Manning's "n" value for the main channel	0.014	0.12
ALPHA_BNK.rte	Baseflow alpha factor for bank storage (days)	0	0.40
CH_N(1).sub	Manning's "n" value for the tributary channels	0.014	8.72
EVRSV.res	Lake evaporation coefficient	0.6	0.85

*Parameters with relative change fitted value: $P = DP * (1 + RCP)$, where DP is a Default Parameter value and RCP is a calibrated Relative Change Parameter value.

The calibration process was implemented with help of SWAT-CUP software (Abbaspour, 2015a). In calibration parameters are conditioned based on the objective function. The most common objective function used for calibration performance assessment is Nash-Sutcliffe efficiency (E_{NS}) (Moriasi et al., 2007a). NSE indicates how well simulated data plot fits with the plot of observed data, it ranges from -∞ to 1.0 inclusive. Values more than 0 are generally considered acceptable, and more than 0.5 - satisfactory. However, for large quantity data calibration, such as Devils Lake volume, represented with millions of cubic meters, we find E_{NS} inefficient, because even with a large discrepancy of simulated and measured volume of Devils Lake, NSE was higher than 0.8. Thus, we used RMSE-observations standard deviation ratio (RSR) as the objective function (Abbaspour, 2015b; Moriasi et al., 2007b):

$$RSR = \frac{RMSE}{STDEVobs} = \frac{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}} \qquad (4)$$

RSR incorporates the benefits of error index statistics and accounts for normalization factor (Moriasi et al., 2007a). After 1,500 iterations, Devils Lake level was calibrated with RSR = 0.31 and RSR = 0.22 for validation (Figure 12, Table 4). Even though visually model performance during the validation period (1991-2000) look not as good as during the calibration period (2001 – 2010), RSR showed lower value during the validation because the lake experienced a greater range of changes in the water level and hence a greater value of standard deviation during the validation period from 1991 – 2000. Nevertheless, in both calibration and validation, RSR was less than 0.5, which indicates very good objective function performance (Moriasi et al., 2007a), and thus we assume that reverse calibration didn't have negative implications on the model performance.
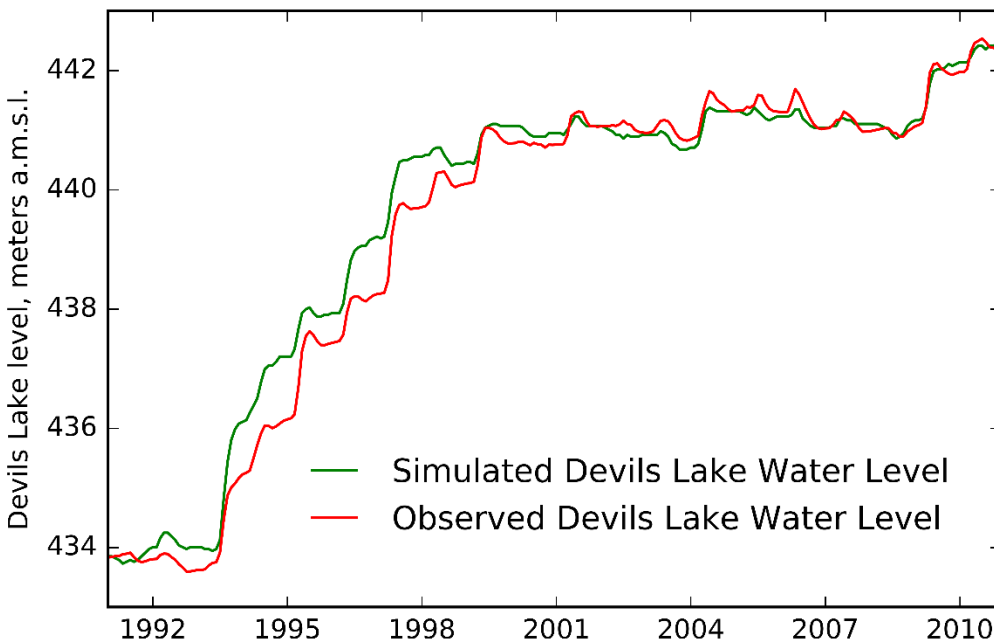
Figure 12. Observed vs. simulated Devils Lake water level.

Table 4. Devils Lake level calibration results

Period	Mean measured elevation, m	Mean simulated elevation, m	%Bias	r	E_{NS}	RMSE, m	RSR	SD, m
1991-2000	437.33	437.81	-11.0	0.99	0.95	0.59	0.22	2.7
2001-2010	441.33	441.27	1.4	0.96	0.9	0.14	0.31	0.44
1991-2010	439.33	439.54	-4.8	0.99	0.98	0.43	0.15	2.78

Future Climate Projections

Future climate scenarios were generated using the projections of 17 Global Circulation Models (GCMs) included in the Coupled Model Intercomparison Project Phase 5 (CMIP5) of the World Climate Research Programm (WCRP): BCC-CSM (v. 1.1 and 1.1m), CSIRO-Mk3.6.0, FIO-ESM, GFDL (CM3, ESM2G, and ESM2M), GISS (E2-H and E2-R), HadGEM2-ES, IPSL (CM5A-LR and CM5A-MR), MIROC (ESM, ESM-CHEM, and MIROC5), MRI-CGCM3, and NorESM1-M (Tables 5,6). 17 GCMs runs under four different radiative forcing scenarios were used to account for model uncertainty (Arnell et al., 2004) which is an accepted way of dealing with GCM biases (Faramarzi et al., 2013). Every climate scenario is represented by a one of four Representative Concentration Pathways (RCPs): RCP2.6, RCP4.5, RCP6, and RCP8.5 (Moss et al., 2010), with the numeric part of the name indicating the additional radiative forcing in 2100 relative to the base climate (W/m^2). To account for the spatial bias in the GCM climate ensemble, the projections were statistically downscaled with Marksim weather generator (Jones, Thornton, & Heinke, 2009) using the 1981–2010 and 1991-2010 weather as the base climate. Furthermore, to account for the climate variability, the weather samples were grouped into 1-year periods and

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then reshuffled 20 times. Overall, 1,360 30-year weather samples were generated for each wetland

scenario to characterize the climate of the 2011 – 2040 period (Table 5, 6).

Table 5. GCMs summary table

GCM Name	Developers	Cell size (°)	Reference
BCC-CSM 1.1	Beijing Climate Center, China Meteorological Administration	2.8125 x 2.8125	(Wu, 2002)
BCC-CSM 1.1(m)	Beijing Climate Center, China Meteorological Administration	2.8125 x 2.8125	(Wu, 2002)
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation and the Queensland Climate Change Centre of Excellence	1.875 x 1.875	(Collier et al., 2011)
FIO-ESM	The First Institute of Oceanography, SOA, China	2.812 x 2.812	(Song, Qiao, & Song, 2012)
GFDL-CM3	Geophysical Fluid Dynamics Laboratory	2.0 x 2.5	(Donner et al., 2011)
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory	2.0 x 2.5	(Dunne et al., 2012)
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory	2.0 x 2.5	(Dunne et al., 2012)
GISS-E2-H	NASA Goddard Institute for Space Studies	2.0 x 2.5	(Schmidt et al., 2006)
GISS-E2-R	NASA Goddard Institute for Space Studies	2.0 x 2.5	(Schmidt et al., 2006)
HadGEM2-ES	Met Office Hadley Centre	1.2414 x 1.875	(Collins et al., 2011)
IPSL-CM5A-LR	Institut Pierre-Simon Laplace	1.875 x 3.75	(Dufresne et al., 2013)
IPSL-CM5A-MR	Institut Pierre-Simon Laplace	1.2587 x 2.5	(Dufresne et al., 2013)
MIROC-ESM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	2.8125 x 2.8125	(S. Watanabe et al., 2011)
MIROC-ESM-CHEM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	2.8125 x 2.8125	(S. Watanabe et al., 2011)
MIROC5	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	1.4063 x 1.4063	(M. Watanabe et al., 2010)
MRI-CGCM3	Meteorological Research Institute	1.125 x 1.125	(Yukimoto et al., 2012)
NorESM1-M	Norwegian Climate Centre	1.875 x 2.5	(Kirkevåg et al., 2008)

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In general, future precipitation and temperature predicted by various GCMs are quite diverse, thus, simulating 17 different GCMs, we account for climate diversity and model uncertainty. Precipitation projection with baseline in the 1990s varies from 1.279 mm/day for RCP85 of the GFDL-ESM2G to 1.688 mm/day for the same RCP in MIROC-ESM-CHEM. Precipitation, projected with the baseline in the 1980s is lower and vary from 1.219 to 1.609 mm/day with minimum and maximum values corresponding to the same GCMs. Predicted future mean daily precipitation is higher than baseline by 3.65 – 5.1%. Temperature projection variation is even higher: from 4.061 °C (BCC_CSM 1.1(m)) to 6.577 °C (CSIRO-Mk3.6.0), and so is the difference between baseline and predicted temperature: 27.73 – 31.98% (Table 6). Main climate characteristics of climate projections up to 2040: precipitation (mm/day) and temperature (°C) are represented in the table below. Every future climate projection has "baseline" value and relative increase value (% change) that are used for future mean daily precipitation or temperature prediction. Since precipitation around the Devils Lake basin experienced significant fluctuations in the past 30 years, it was made two types of precipitation projections: based on the 1991-2010 and 1981-2010 mean precipitation values. The temperature in the region was relatively stable, so there is just one type of temperature prediction.

Table 6. Mean daily precipitation and temperature statistics on 17 different GCMs and 4 RCPs used in the research.

| | Precipitation (mm/day) | | | | | | | | Temperature (°C) | | | |
| | baseline 1991 - 2010 | | | | 1981 - 2010 | | | | 1981 - 2010 | | | |
GCM	rcp26	rcp45	rcp60	rcp85	rcp26	rcp45	rcp60	rcp85	rcp26	rcp45	rcp60	rcp85
BCC-CSM 1.1	1.420	1.477	1.474	1.445	1.354	1.408	1.405	1.378	5.574	5.574	5.099	5.669
BCC-CSM 1.1(m)	1.479	1.503	1.493	1.460	1.410	1.434	1.423	1.392	4.337	4.061	4.224	4.576
CSIRO-Mk3.6.0	1.437	1.484	1.404	1.497	1.370	1.415	1.338	1.427	6.577	6.058	5.592	6.086
FIO-ESM	1.552	1.503	1.473	1.449	1.479	1.433	1.404	1.382	6.009	5.747	5.777	6.201
GFDL-CM3	1.499	1.417	1.455	1.509	1.429	1.351	1.388	1.439	5.536	5.727	5.405	5.758
GFDL-ESM2G	1.371	1.320	1.339	1.279	1.307	1.259	1.277	1.219	5.160	5.515	5.157	5.608
GFDL-ESM2M	1.347	1.449	1.291	1.512	1.284	1.382	1.231	1.442	5.197	5.473	5.330	5.051
GISS-E2-H	1.465	1.489	1.491	1.530	1.397	1.420	1.422	1.459	5.826	5.662	5.420	5.833
GISS-E2-R	1.497	1.511	1.496	1.497	1.427	1.441	1.427	1.427	4.654	4.889	4.747	4.953
HadGEM2-ES	1.516	1.506	1.509	1.566	1.445	1.436	1.439	1.493	4.851	5.205	4.651	5.231
IPSL-CM5A-LR	1.643	1.572	1.460	1.462	1.566	1.499	1.392	1.394	4.426	4.465	4.431	4.580
IPSL-CM5A-MR	1.481	1.655	1.500	1.652	1.412	1.578	1.430	1.575	4.618	4.781	4.492	4.547
MIROC-ESM	1.600	1.551	1.610	1.688	1.525	1.479	1.535	1.609	5.589	5.774	5.338	5.682
MIROC-ESM-CHEM	1.477	1.480	1.559	1.412	1.409	1.412	1.486	1.346	4.355	4.643	4.299	4.785
MIROC5	1.447	1.525	1.482	1.478	1.379	1.454	1.413	1.409	5.207	4.978	4.633	5.093
MRI-CGCM3	1.507	1.451	1.422	1.429	1.437	1.383	1.356	1.363	4.894	4.597	5.316	4.904
NorESM1-M	1.448	1.343	1.511	1.483	1.381	1.281	1.441	1.414	5.113	5.145	4.747	5.382
Mean	1.481	1.484	1.469	1.491	1.413	1.415	1.400	1.422	5.172	5.194	4.980	5.290
Baseline	1.415				1.349				3.599			
Change	0.066	0.069	0.054	0.076	0.063	0.066	0.051	0.072	1.573	1.595	1.381	1.692
% Change	4.48%	4.67%	3.65%	5.10%	4.48%	4.67%	3.65%	5.10%				

CHAPTER IV

RESULTS

Historical Climate

First, all five wetland scenarios (one current and four hypothetical) were simulated under historical climate from 1991 to 2010 (Figure 13). Simulation results indicate that the wetlands drainage/restoration significantly impacts Devils Lake water level: the higher the area of wetlands in the basin, the lower is DL water level. On average, every 5% increase in the fraction of wetlands in the basin leads to a 0.47 meters decrease in DL water level. The differences in the lake levels simulated among various scenarios increase with time, reaching maximum values towards the end of the simulation period.
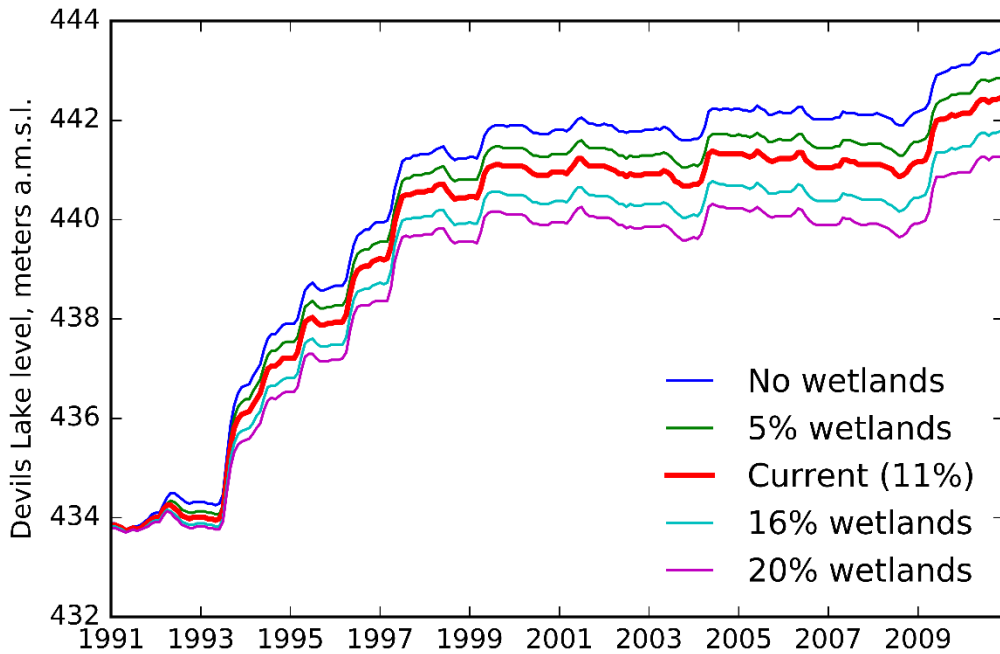
Figure 13.   Devils Lake water levels simulated for five wetlands scenarios from 1991-2010.

A detailed look at hydrological parameters of the model shows how and why Devils Lake water level varies in different scenarios. Comparison of streamflow between the wetlands scenarios with 11% wetlands (current) and 16% wetlands (hypothetical) on two USGS streamflow gauges where Big Coulee and Channel A flow into Devils Lake shows that with the restoration of wetlands, streamflow in the watershed reduces, mainly during flood peaks (Figure 14).
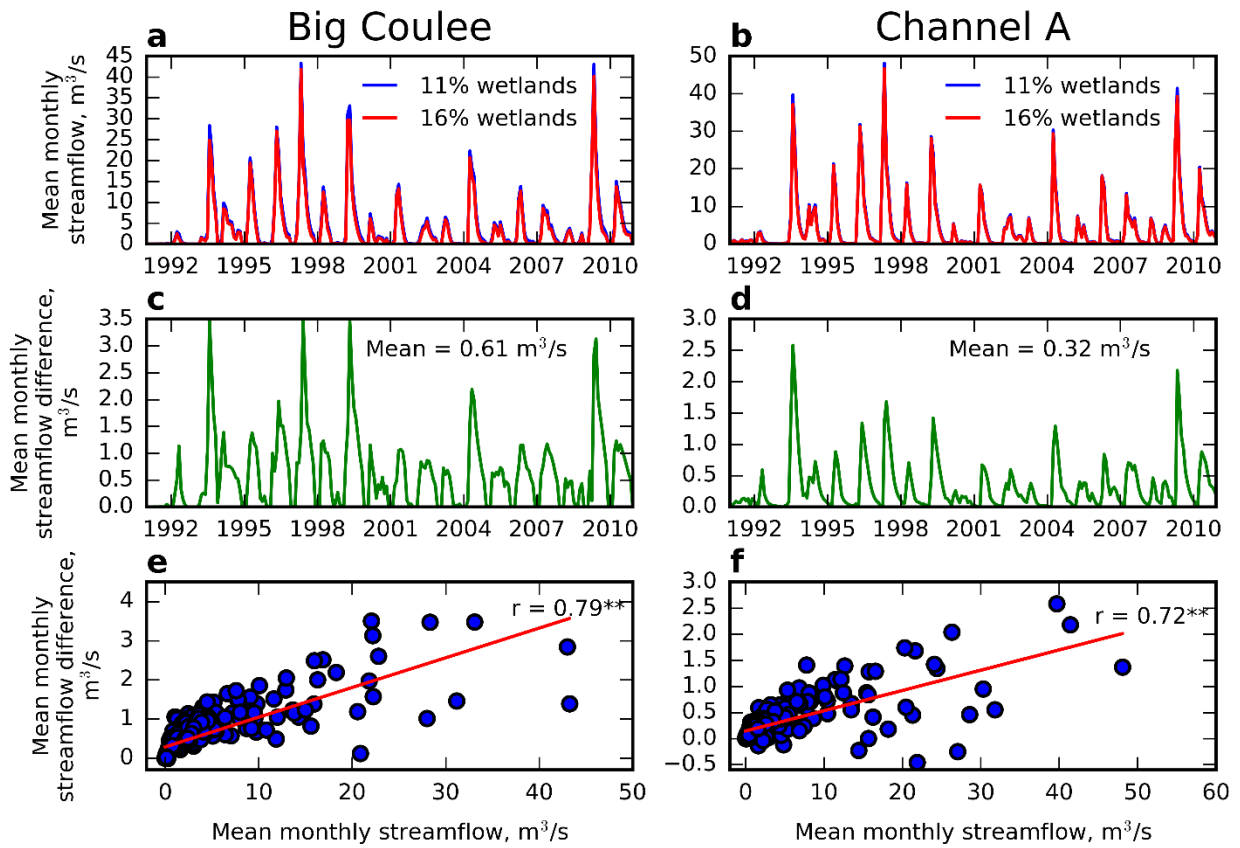
Figure 14. Comparison of simulated streamflow on the Big Coulee and Channel A for two wetlands scenarios. (a) and (b): simulated streamflow for the Big Coulee and the Channel A respectfully in 11% wetlands scenario (blue) and 16% wetlands scenario (red). (c) and (d): difference in simulated streamflow between 11% and 16% wetland scenarios for the Big Coulee

and the Channel A. (e) and (f): mean monthly streamflow vs. streamflow difference for the Big Coulee and the Channel A respectfully.

Figure 14 also demonstrates that difference in streamflow between two scenarios is higher for the Big Coulee. This is related to spatial variations in wetlands coverage between scenarios. Because the relative difference in wetlands coverage between 11% and 16% wetland scenarios in the Big Coulee basin (part of the Devils Lake basin from where water comes to the Big Coulee) is 30,945 ha, and in the Channel A basin is less than half the size: 13,283 ha, streamflow on the Big Coulee differs more between wetland scenarios (Figure 15). Figure 16 (e) and (f) show that difference between streamflow in different wetland scenarios is higher when original streamflow is high (i.e. in spring, when water is high due to snow melting).
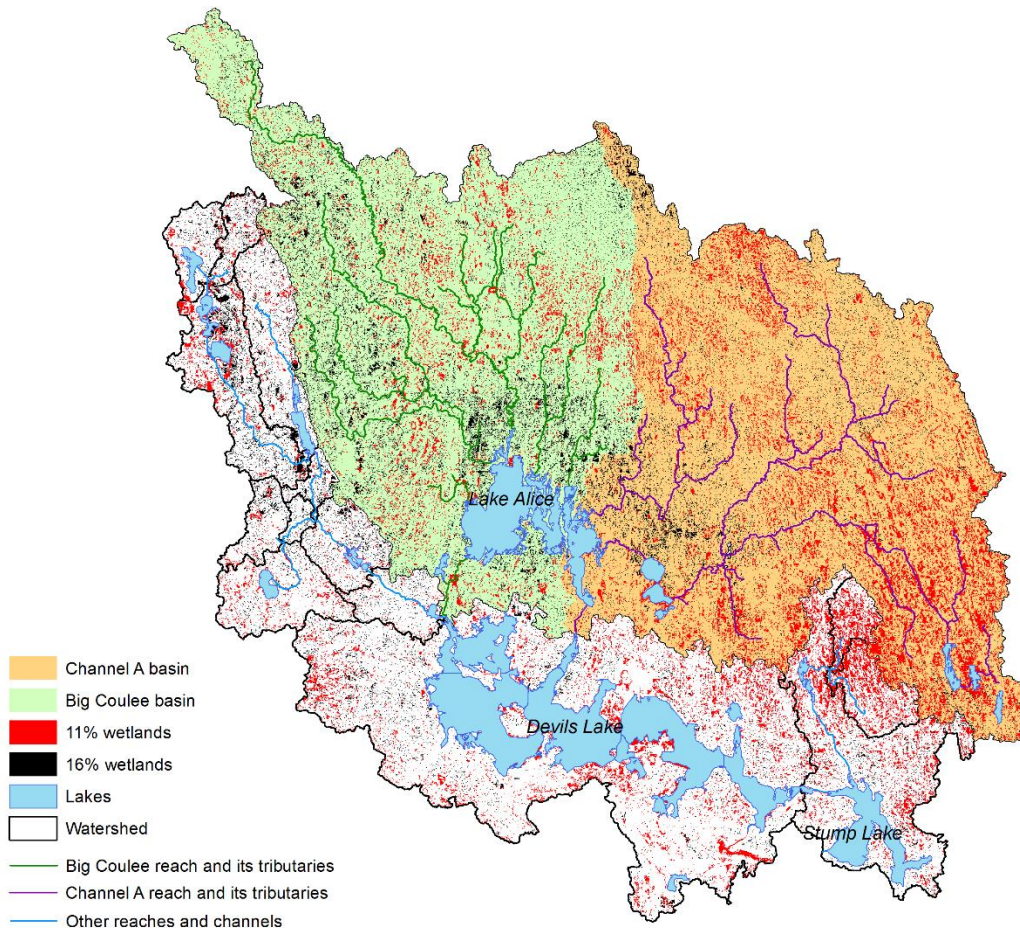
Figure 15. Wetlands area increase in the 16% scenario distribution by two basins: Channel A and Big Coulee.

If we look on how streamflow differs between scenarios on a smaller scale on the example of one year (for our research we picked the year 1999 since streamflow during that year was high and very illustrative), we'll find out that in both scenarios, streamflow reaches its peak at the same time, however in the scenario with 16% wetlands, peak value is lower on average by 1.48 m^3/s in April and 3.48 m^3/s in May (Figure 16). Also, streamflow difference between scenarios is lower at the end of the March, and higher after the peak occurs. This difference in streamflow between scenarios is a direct evidence of wetlands benefit for the Devils Lake watershed.
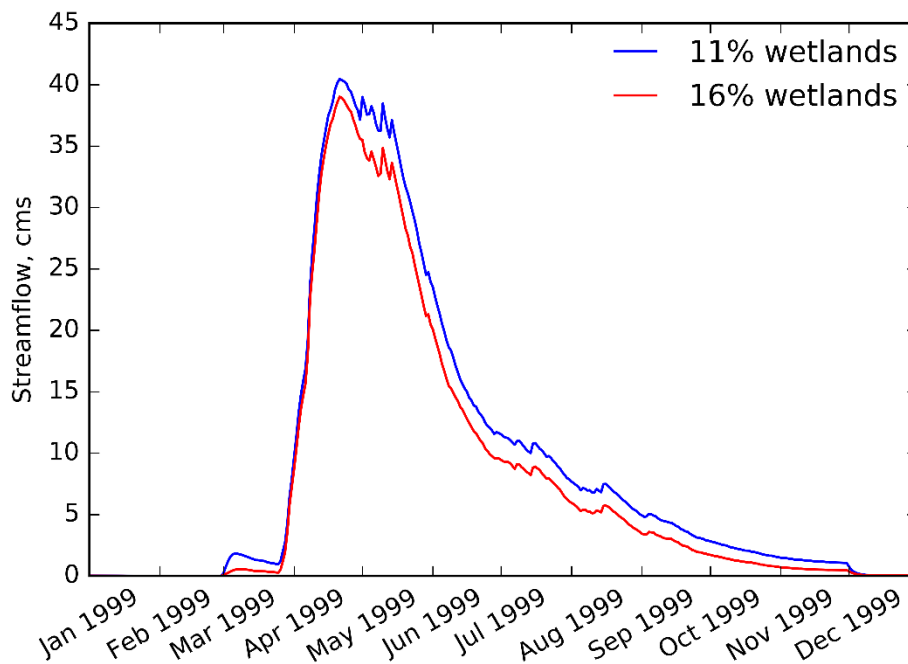
Figure 16. Streamflow on the Big Coulee USGS gauge for two wetlands scenarios in 1999.

Further analysis of streamflow difference between 11% and 16% scenarios on the Big Coulee gauge showed, that it has a positive and significant correlation with precipitation (Figure

17), i.e. the higher is precipitation, the higher will be a relative change in streamflow between scenarios.
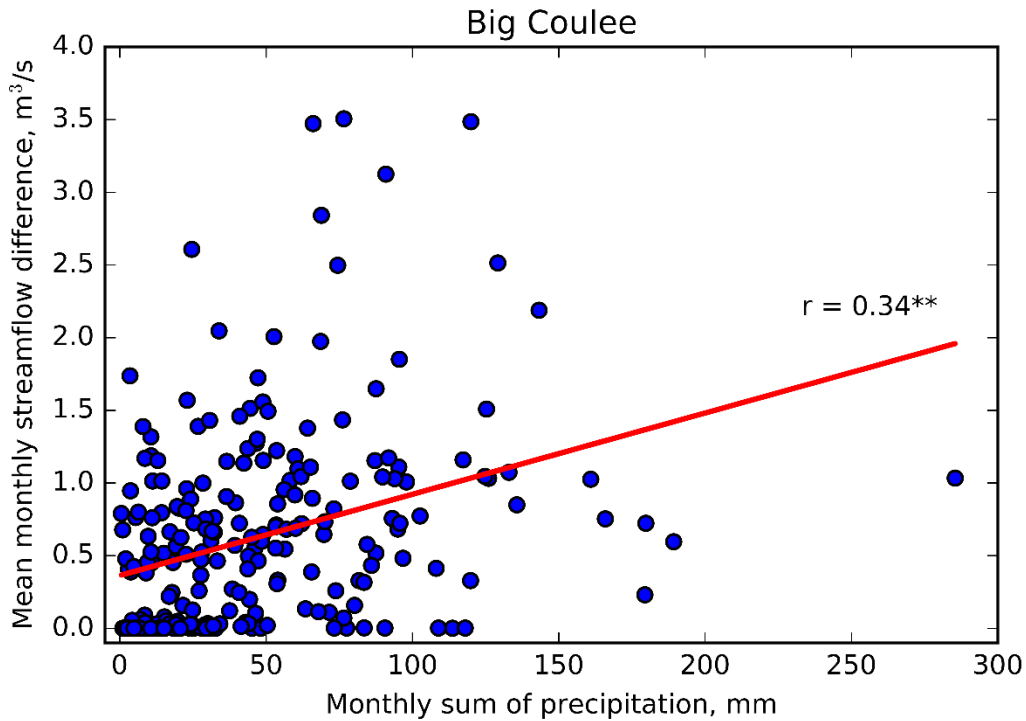
Figure 17. Variation of the mean monthly streamflow in 11% wetland scenario minus 16% wetland scenario streamflow with a monthly sum of precipitation. ** - statistically significant correlation ($p < 0.01$).

Effect of seasonal precipitation variability on streamflow was also tested. It was found that only in spring precipitation is significantly and positively correlated with the difference in streamflow between wetland scenarios (Figure 18). This indicates that spring precipitation has the highest impact on streamflow difference during this season.
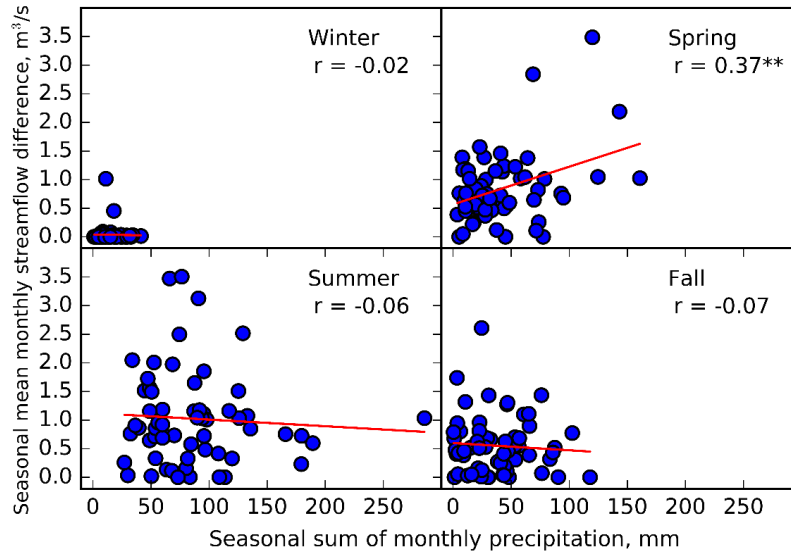
Figure 18. Seasonal variation of the Big Coulee mean monthly streamflow difference between 11% and 16% scenarios with the seasonal monthly sum of precipitation. ** - statistically significant correlation (p < 0.01).

Future climate

We showed in Figure 13 that under historical climate from 1991 to 2010, restoration of wetlands would lower the Devils Lake water level. However, the Devils Lake watershed is an area of dynamic climate change, and thus for future planning, it is very important to take into account possible future climate variations, so using our five existing wetland scenarios, we simulated the Devils Lake watershed under various future weather conditions and a baseline scenario up to 2040.

The SWAT simulations under future climate were divided into two main groups: with the outlets operating with an average rate 11.2 m^3/s during the warmer months when water is not frozen, and with not operating outlet. After simulating our models under future climate conditions, the lake output files were analyzed for water level exceedance the 444.4 m above mean sea level, at which overspill into the Sheyenne River occurs. Then, the total probability of overflow was estimated using the following equation:

$$P_c = \frac{N_{overspill}}{N}, \qquad\qquad (5)$$

where P_c is the probability of Devils Lake overspill under a climate projection c, $N_{overspill}$ is a number of simulations in which Devils Lake exceeded overspill level 444.4 meters, and N is a total number of simulated climate projections (in our case equal to the total number of shuffles: 20 for each GCM). The results are summarized in the Table 7.

Table 7. The probability of natural overspill of Devils Lake over 444.4 meters above mean sea level under various climate projections and wetland scenarios.

	SCENARIO	1980s baseline						1990s baseline					
		rcp26	rcp45	rcp60	rcp85	mean	baseline	rcp26	rcp45	rcp60	rcp85	mean	baseline
With Outlet	No wetlands	16%	16%	10%	25%	17%	1%	44%	44%	36%	52%	44%	19%
	5%	13%	10%	4%	17%	11%	0%	34%	36%	24%	36%	32%	9%
	Current (11%)	9%	7%	3%	14%	8%	0%	29%	26%	17%	32%	26%	5%
	16%	5%	2%	1%	9%	4%	0%	18%	16%	11%	21%	16%	1%
	20%	2%	0%	1%	5%	2%	0%	11%	11%	7%	16%	11%	0%
No Outlet	No wetlands	67%	71%	67%	74%	70%	80%	89%	88%	89%	93%	90%	100%
	5%	46%	54%	47%	52%	50%	37%	80%	81%	79%	82%	80%	97%
	Current (11%)	35%	44%	34%	40%	38%	17%	72%	74%	71%	74%	73%	81%
	16%	19%	22%	14%	25%	20%	4%	54%	59%	51%	56%	55%	40%
	20%	15%	11%	7%	18%	13%	2%	41%	46%	40%	41%	42%	16%
	PRECIPITATION (MM/DAY)	1.41	1.42	1.40	1.42	1.41	1.35	1.48	1.48	1.47	1.49	1.48	1.42
	TEMPERATURE C	5.17	5.19	4.98	5.29	5.16	3.60	5.17	5.19	4.98	5.29	5.16	3.60

Comparing scenarios of wetlands restoration/drainage, we can make a general conclusion that wetlands play an important role in the DL watershed, in particular, restoration of wetlands reduces future flood risks, and drainage - conversely - increases. For example, if wetlands coverage in the basin would remain the same as currently, the average risk of DL exceeding the natural overflow elevation 444.4 meters above mean sea level with an operating outlet, is 8%. Restoration of

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wetlands in an area equivalent to 50% of current wetlands acreage would reduce this risk to 4% (Table 7).

On average, GCMs project a moderate 0.06 mm/day or 22 mm/yr precipitation increase in the Devils Lake region. The future local climate is predicted to be much warmer than current: 5.16 °C average daily temperature compared to 3.6 °C observed in the past ("baseline" climate). Due to this difference in baseline and projected future climate change, our model simulation results show that average probability of Devils Lake overspill tend to be higher under conditions with climate change than under baseline scenario climate: 0 − 1% compared to 2 − 17% with operating outlet (depending on land cover scenario) and 2 − 80% vs 13 − 70% without outlet. As expected, scenarios with no outlet showed the highest risk of natural overspill: 13 − 70% compared to 2 − 17% with climate change and 2 − 80% vs 0 − 1% under baseline climate.

The results also indicate that the total range of probability of overspill between land cover scenarios is higher in the scenarios without the outlets. In other words, if a decision to turn off the pump and reverse the outlet will be taken, wetlands restoration will have a higher relative increase in flood mitigation probability. For example, our estimations show that if local climate will keep changing and outlet program will be stopped, Devils Lake will overflow to Sheyenne River before 2040 with probability 38%. Under same conditions, but if the area of wetlands in the basin will be increased by 50% and reach 16% of the watershed area, the probability of lake overspill will drop to 20%. At the same time, if outlet will keep working and acreage of wetlands in the basin will reach 16%, the probability of Devils Lake overspill will decrease by only 4%, from 8% to 4%. With all this, it can be concluded that wetlands restoration is more effective for flood mitigation in case of not working outlet.

Another conclusion that is provided by simulation results is that generally outlet is a more effective measure for flood mitigation than wetlands restoration. For example, even if acreage of wetlands in the basin will be doubled (up to 20%), without an outlet, Devils Lake will still be more likely to overspill in this scenario, than in the scenario with a working outlet and current wetlands coverage in the basin (11%). Only in a scenario when half of current wetlands area will be drained (to 5% of the Devils Lake watershed area), the probability of overspill with working outlet will be almost the same as without outlet and doubled the area of wetlands (20%). So, this means, that in the case of climate change, the amount of water that outlets pump out of the lake approximately similar to the amount of water stored in wetlands covering 15% of the basin area (1,427 km^2).

For baseline scenarios, the outlet is even more efficient: only if we double wetlands coverage in the basin, the probability of the lake overspill with no outlet will be similar to the scenario with an outlet and no wetlands.

Climate, based on the 1990s predict higher average overspill probability, so, for example, the mean range of overspill risks in different wetlands scenarios grows from 2 − 17% to 11 − 44% with an outlet and from 13 − 70% to 42 − 90% without an outlet. Future projected precipitation, based on the 1990s is so high, that even overspill likelihood in baseline scenario is higher than in a scenario with future climate, based on 1980s and no outlet. With outlet, the risk of overspill in 1990s baseline scenario is close to future climate scenario, based on the 1980s.

All other features typical for the 1980s climate based scenarios are also typical for 1990s scenarios: in the scenarios with no outlet, Devils Lake showed higher risk of overspill, range of probability of overspill between land cover scenarios is higher in case of no outlet scenarios and working outlet is a more effective measure in flood mitigation than wetlands restoration.

CHAPTER V

DISCUSSION

In this study, we analyzed influence and effectiveness of wetlands restoration in Devils Lake flood mitigation. The existing system of outlets has proven themselves to be an efficient way to reduce the risk of the lake's natural overspill: modeling of Devils Lake with coupled SWAT and CE-QUAL-W2 model showed that since August 2005, outlets have lowered the lake level by 0.7 meters (Shabani et al., 2017). At the same time, its construction was very expensive and it has some drawbacks for the local environment. For example, since the outlets started to operate, the concentration of sulfates in the Sheyenne River increased from ~100 to more than 500 mg/L, which is higher than the North Dakota state standard of 450 mg/L for stream Class IA. Other possible threats to the outlet system include the introduction of invasive species in the Red River of the North ecosystem, reduction of water quality in the Red River of the North and even in the Lake Winnipeg. Compared to outlets, wetlands restoration is a safer way for Devils Lake flood mitigation: wetlands restoration will not only reduce the lake flooding risk but also benefit the local ecosystem.

Devils Lake basin wetlands storage estimations

Previous estimations of the total area of wetlands in the Devils Lake basin vary from 817.4 km^2 (81,740 ha) of intact wetlands and 374 km^2 (37,400 ha) of possibly drained wetlands (Doeing et al., 2001) to 1,640 km^2 (164,000 ha) total area of drained and undrained wetlands (Ludden, Frink, & Johnson, 1983). Wetlands storage estimations vary from 59,405 ha*m of intact wetlands and 16,372 ha*m of possibly drained wetlands (Doeing et al., 2001) to 81,040 ha*m total capacity of drained and undrained wetlands (Ludden et al., 1983). Using the NLCD 2006 data, we estimated approximately 1,022 km^2 (102,200 ha) of undrained wetlands with the capacity of 58,463 ha*m in

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the Devils Lake watershed (volume estimation is based on the equation (2)). Thus our estimations of the wetlands area in the basin are higher than the Doeing's, but our wetlands storage estimations are similar. There are several sources of possible discrepancy between the two assessments. First of all, Doeing's estimation is based on the DEM and NWI that were created in the 1980s, whereas our estimate was based on NLCD 2006. During the 1990s, wetlands expanded in their size and volume along with the increase of water level of Devils Lake. For example, from 1992 to 2001, the size of rural wetlands in Nelson County increased by 426% (Todhunter & Rundquist, 2004), therefore it is not surprising that our estimate of the wetlands area in the basin is higher than the estimate made in the 1980s. Another reason for such discrepancy is a difference in the methods of wetlands area estimation. Doeing assessed wetlands only in the upper basin, not including the Devils Lake and the Stump Lake drainage area. The upper basin area is equivalent to 6,775.4 km^2, accounting for about two-thirds of the whole watershed area, at the same time NLCD 2006 provide classified land cover data for the whole basin (9,515 km^2) and thus in this research, we analyze wetlands from a bigger area. At the same time, wetlands storage capacity, estimated in this research by the Gleason's method (Gleason et al., 2008) almost match estimation made by Doeing. This indicates that Gleason's method probably underestimated wetlands storage in our particular case of the Devils Lake watershed wetlands. Ludden in his study (1983) combine drained and intact wetlands into one category, so, it's difficult to compare our estimations, however, our assessment of undrained wetlands area and storage are smaller than his estimation of drained and undrained wetlands combined, which means that our estimates are within the historical range of wetlands in the Devils Lake watershed.

Wetlands effect on streamflow

Our results indicate that with a higher area of wetlands in the basin, total streamflow and flooding volume, and hence the Devils Lake water volume would be reduced (Figures 13 and 14). Similarly, Simonovic and Juliano (2001) also found a lowered streamflow associated with an increase in wetlands coverage, however, their simulation showed that flood peak volume doesn't change with increased coverage of wetlands. In our model, we observed a reduction of streamflow consistently with the highest reduction during flood peaks. The difference in results is, presumably, related to two factors. First, we used different hydrologic models. Simonovic used HEC-HMS model, which uses different sub-routines than SWAT. Another reason is that in our research we compare Big Coulee streamflow after wetlands area is increased by 50% and Simonovic in his model account for much smaller wetlands restoration: from 2% to 10% of original wetlands coverage. The study of the Red River of the North flooding showed that increase of wetlands area in the basin by 10% causes reduction of flood volume by 11% (Simonovic & Juliano, 2001). Our research of the Devils Lake basin indicates that a 50% increase of wetlands would cause flow reduction in two biggest Devils Lake inlets: Big Coulee and Channel A by 27.1% and 19.4% respectively.

The study of the U.S. Army Corps of Engineers focused on the upper basin of Devils Lake (Doeing et al., 2001). Using HEC-HMS model it was found that restoration of depressions will reduce surface runoff entering Devils Lake. In particular, simulation under future climate sequences (2003 - 2020) showed that restoration of 32,279 ha of wetlands with storage 15,768 ha*m would reduce surface runoff on average by 2,960 ha*m or 19% of restored volume. Our model simulation results indicate that restoration of 50,054.5 ha of wetlands with storage 52,788.4 ha*m contributes to runoff reduction by 3,372 ha*m or 6.4% of restored volume. With the fact

that in our research we used different wetlands restoration scenarios, our studies are also different because in the report U.S. Army Corps of Engineers account only for the upper basin, which is only about two-thirds of the whole basin area, and in our study we account for wetlands from the whole watershed of Devils Lake.

Vining (2002) focused on the only one subbasin of the Devils Lake basin - Starkweather Coulee subbasin. His estimations suggest that with maximum wetlands storage increasing by 183 % streamflow reduced by 49%. Our research results show that only in the Starkweather Coulee subbasin, a wetlands area in the scenario with 16% of the basin area occupied by wetlands, was increased by 83% (comparing to 11% scenario). This land cover change contributed to streamflow reduction in the subbasin by 23.4% (almost twice as less as in the Vining's research).

There are a limited number of studies that analyzed wetlands effect on streamflow using SWAT model. Yang (2010) analyzed the influence of wetlands on the environment of the Broughton's Creek in Canada. Their results indicate that in the case of restoration of wetlands to 1968 level (increasing current wetlands acreage by 620 ha or 26% of an existing wetlands acreage), peak discharge can be reduced by 23.4%. For the Devils Lake basin, these values are lower: restoration of 50,045.5 ha (equivalent to wetlands acreage increase by 50%) leads to peak discharge reduction by 6.05% on the Big Coulee and 1.7% on the Channel A.

In general, streamflow is always correlated with precipitation, so for the Devils Lake basin, we estimated the correlation for discharge at the Mauvais Coulee and precipitation of 0.3 and p-value < 0.05, winter precipitation (December, January, and February) has an even better correlation with streamflow: 0.57 with p-value < 0.001. For the Devils Lake basin, such analysis was first conducted by Wiche (1986), where he noticed that discharge at the Mauvais Coulee gauge correlate with winter precipitation falling in Devils Lake city, and provides a coefficient of

determination of 0.2. In our research, we noticed some connection between precipitation and discharge difference between scenarios with different acreage of wetlands (11% and 16% of the watershed occupied by wetlands). So, we estimated correlation of different types of precipitation and streamflow difference for the Big Coulee and our results indicate that precipitation correlates with streamflow difference positively and significantly with a coefficient of determination 0.34 (Figure 17), also the more intense is the precipitation, the more it correlates with the difference in streamflow (Figure 18). These results suggest that with other factors that affect hydrology being equal, with higher precipitation and especially with a higher share of intense precipitation, streamflow will differ more in absolute value after wetlands restoration.

Future climate

Existing estimations of Devils Lake overspill probability under future climate are quite different: Vecchia (2011) estimated such risk under baseline climate with no outlet from 0.6% to 44.7% (depending on simulation year), and our model showed 17% risk. Considering that Vecchia used Devils Lake stochastic simulation model, and we used physically based model of the entire basin, it's hard to compare our estimations. Stochastic lake model imply absence of upper basin water flows simulation, including water percolation, surface runoff and evapotranspiration, including simulation of pothole filling process. Kharel and Kirilenko (2015) estimated overall overspill probability on the level of just 1.0% which is considerably lower than our 17%. However our probability estimations of lake water level exceeding 443.3 meters above mean sea level and mean DL level are close enough (Table 8). This indicates, that in our model after the lake exceeds 443.3 meters level, it is more likely to keep growing until 444.4 meters. When in the model by Kharel and Kirilenko, the lake has close with ours chances reaching the level 443.3 meters but at that moment it stops growing in 99% of scenarios. Under similar conditions with no outlet but under

future climate, Kharel and Kirilenko (2015) predict Devils Lake's overspill with 10.3 − 20.0% likelihood depending on the climate scenario type (varying from A1B to B1). Our model predict overspill with approximately twice as higher probability: 34.4 − 44.1% depending on the RCP. Higher projections of DL overspill in our model compared to those in Kharel and Kirilenko (2015) should be related to the different future climate scenarios used in the researches. If Kharel and Kirilenko (2015) used downscaled CMIP4 weather integrations, we used CMIP5 that predict higher precipitation and temperatures than CMIP4 (table 6). Same is observed in the scenarios with running outlet: due to wetter climate scenarios used in our research, our model predict higher probability of overspill: from 2.6% to 14.4% (depending on RCP), comparing to 0.0 − 0.6% predicted by Kharel and Kirilenko (2015) in their study.

Table 8. Main results of the baseline scenario with no outlet run from Kharel and Kirilenko (2015) and our research.

Author	Mean DL level (m)	Probability to Exceed Major Flood Level (443.3 m)	Overall Overspill Probability (444.4 m)
Kharel&Kirilenko (2015)	442.6	72.0	1.0
Our Research	442.6	83.8	16.7

Area of Devils Lake released due to wetlands restoration

Our simulation and comparison of hypothetical land cover models with current one showed that on average the lake descents by 0.47 meters on every increase in acreage of wetlands by 5% of the basin area. However, restoration of wetlands might be not in farmers' best interest, because part of their cropland will be withdrawn for wetlands. At the same time, as our simulation results showed, with the restoration of wetlands, Devils Lake recede and so it releases some land area that was previously flooded, and that means that this released land can be used again by farmers. Even

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though land released from Devils Lake will be saline and very unlikely cropped, these lands can be used as pastures, hay and for wildlife. Our estimations show that with restoring wetlands area equivalent to 500 km^2 (50,000 ha), Devils Lake area will be reduced only by 80 km^2 (8,000 ha) and doubling current wetlands acreage (from 1,022 to 2,044 km^2) will cause Devils Lake area reduction by 133 km^2 (133,000 ha). This information might be useful for a policy regarding wetlands restoration in the Devils Lake basin because it allows us to reduce the planned area of land withdrawn from farming, even though, it is not comparable to the area of restored wetlands.

The research includes the following limitations: (1) general wetlands simulation mechanism in SWAT, (2) simplified input data, (3) future climate projections uncertainties, (4) no field verifications, (5) poor SWAT modeling mechanism for frozen soil, frozen river, snowmelt and groundwater processes.

For example, SWAT wetlands modeling mechanism, generalize properties of all wetlands in a subbasin into one, however, different wetlands depending on their relative location to streamflow and type can have a different effect on river discharge (Acreman & Holden, 2013; Golden et al., 2016). To deal with such limitation, we increased a number of subbasins to maximum: 96, thus accounting for spatial diversity. Further improvement can be done by accounting for local unique topographic properties of potholes (also soil, land cover and climate) and its relationships with water, for example, by coupling SWAT model with a small scale pothole models (Tahmasebi Nasab, Zhang, & Chu, 2017). Future climate projections used in the research carry some uncertainty, probability that future climate will repeat one of the climate sequences, used in the research is less than 100%, however, to deal with such limitation, we simulated multiple shuffled versions of GCMs. At the same time, Earth' climate system is so complicated that at the moment it's impossible to predict exact future climate, so this study can provide only general

prediction pattern. Some other studies about wetlands of the Devils Lake basin rely on field verifications (Doeing et al., 2001; Gleason et al., 2008), which were not planned for this research. Consequently, to some level, this factor can affect our results, however, the wetlands parameters estimation formulas we used in the study were generated after field verification by Gleason (2008). Finally, some imperfections of SWAT model could affect our simulation (such as groundwater processes and some mechanisms related to cold temperature), but their effect assumed to be minimal. Nevertheless, with such limitations, our research results generally correspond with other similar studies and thus can be considered valid enough.

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CHAPTER VI

CONCLUSION

The study shows the importance of wetlands for flood mitigation. According to our hydrologic simulation, an increase of wetlands area in the Devils Lake basin helps to lower lake level both under weather observed during the period 1991 – 2010 and under future climate projections up to 2040.

Hypothetical wetland scenarios with an area of wetlands differ from current were compared with current wetland scenario, and consequently, it was found that Devils Lake water level would be lowered by 0.47 meters on a 5% increase in the fractional coverage of wetlands in the basin (figure 13). The lake level descends as a result of reduced streamflow of its main inlets: the Big Coulee and the Channel A.

Our study shows that as higher is the monthly sum of precipitation, the higher would be the difference between streamflow in 11% and 16% wetland scenarios (figure 17). Also, from various types of precipitation by intensity, very heavy precipitation influence the streamflow difference the most (figure 18).

If climate change would take place in the region, Devils Lake would more likely overspill than in the absence of climate change in future (tables 6, 7). Also, the range of overspill probabilities is higher in the scenarios without outlets than with outlets, so outlet disabling entails more uncertainty. Another obvious result from our model simulation suggests that with operating outlet Devils Lake will less likely overspill than in scenarios w/o outlet (tables 6, 7).

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