Theses and Dissertations

Theses, Dissertations, and Senior Projects

January 2018

Mitigating Environmental Impacts Of Terminal Lake Flooding: A Case Study Of Devils Lake, North Dakota

Afshin Shabani

Follow this and additional works at: https://commons.und.edu/theses

Recommended Citation

MITIGATING ENVIRONMENTAL IMPACTS OF TERMINAL LAKE

FLOODING: A CASE STUDY OF DEVILS LAKE, NORTH DAKOTA

by

Afshin Shabani

Bachelor of Science, Gonbad Kavoss University, 2008

Master of Science, University of Tehran, 2011

A Dissertation

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for degree of

Doctor of Philosophy

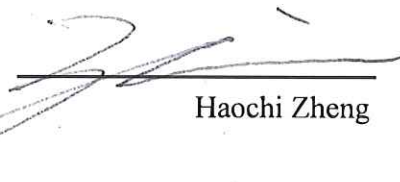Grand Forks, North Dakota

December

2018

This dissertation, submitted by Afshin Shabani in partial fulfillment of the requirements for the Degree of Doctor Philosophy from the University of North Dakota, has been read by Faculty Advisory Committee under whom the work has been done and is hereby approved.

_____
Xiaodong Zhang (Chair)

_____
Xuefeng Chu
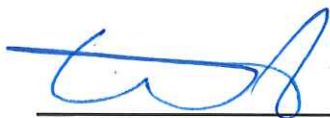
_____
Haochi Zheng

_____
Jeffrey VanLooy

_____
Jianglong Zhang
(Member at large)

This dissertation is being submitted by the appointed advisory committee as having met all of the requirements of the school of Graduate Studies at University of North Dakota and is hereby approved.

_____
Grant MCGimpsey
Dean of the Graduate School

December 6, 2018
Date

iii

PERMISSION

Title   Mitigating Environmental Impacts of Terminal Lake Flooding: A Case Study of

               Devils Lake, North Dakota

Department   Earth System Science and Policy

Degree   Doctor of Philosophy

In presenting this dissertation in partial fulfillment of the requirement for a graduate degree from the University of North Dakota. I agree that the library of this university shall make it freely available for inspection. I further agree that permission for extensive copying for scholarly purposes may be granted by the professor who supervised my dissertation work or, in this absence, by the Chairperson the department of the dean of the School of Graduate Studies. It is understood that any copying or publication or other use of this dissertation or part thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of North Dakota in any Scholarly use Which may be made of any material in my dissertation.

Signature   Afshin Shabani

Date   12/03/2018

iii

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENT

ABSTRACT

Devils Lake is an endorheic lake in the Red River of the North basin in northeastern North Dakota. During the last two decades, the lake water level has risen by nearly 10 m, causing floods that have cost more than 1 billion USD in mitigation measures. Another increase of approximately 3.0 m in the lake water level would cause spillage into the Sheyenne River. To alleviate this potentially catastrophic spillage, two artificial outlets were constructed. However, the artificial drainage of water into the Sheyenne River raises water quality concerns because the Devils Lake water contains significantly higher concentrations of dissolved solids, particularly sulfates. In this study three important concerns related to the Devils Lake flooding are being addressed: (1) How has the current wet climate cycle impacted water level and distribution of sulfate concentrations in Devils Lake? (2) Does the current outlet management increase the risk of flood and/or water quality degradation in the Sheyenne River? (4) What is the optimal outlets strategy to control Devils Lake flooding and minimize the impact on discharge and sulfate concentration in the Sheyenne River? It was found the Devils Lake water level without the operating the outlet would be 1.1 meters above its actual level in June 2018. The sulfate concentrations of Devils Lake showed a general increase from west to east, with the east end concentration being ~ 3 times greater than the west side. Since 2008, inflowing the fresh water to the lake has also decreased the Devils Lake sulfate concentration by 6%. It was found operating the outlets has increased the Sheyenne River discharge and sulfate concentration to 40 $m^3\,s^{-1}$ and 800 $mg\,l^{-1}$, respectively. The current outlets operation has limited the Sheyenne River discharge to less than two-year flood, however, it has violated the 750 $mg\,l^{-1}$ North Dakota sulfate concentration standard for Stream Class I A. Based on the optimization method, an alternative management strategy was identified to control the Devils Lake water levels and preserve water quantity and quality of the Sheyenne River. Our

optimization approach offered a "win-win" management strategy that maintains the efficiency of the outlets and conserves both river sulfate concentration ≤ 650 mg l^{-1} and discharge ≤ 26 m^3 s^{-1}. Using National Oceanic and Atmosphere Administration (NOAA) Climate Forecast System version 2 (CFSv2) data we predicted that following the alternative management will reduce the lake water levels by 0.16 m from July to October 2018.

CHAPTER I

INTRODUCTION

Problem statement

Devils Lake is an endorheic lake in the Red River of the North basin in northeastern North Dakota. Its proximity to the 100th meridian – a theoretical line that divides the North American continent into a generally wet region to the east and a dry region to the west – might be the reason for its significant water level fluctuation over time (Ma et al. 2011). In the last century, Devils Lake water levels have changed by 16 meters, fallen to 427 m in 1941 and risen to 443.3 m in 2011. The current wet climate cycle started from 1993 has nearly increased the lake elevation by 10 m and flooded the Devils Lake City and the adjacent communities built within the historical confines of the lake, inundated farmland and caused significant damage to both infrastructure and the community. Over one billion USD has been spent on mitigation measures (Zheng et al. 2014), including upper basin management to reduce runoff, continuing infrastructure protection, and developing emergency outlets (Kharel et al. 2016). Currently, operating two outlets is the main management strategy for controlling Devils Lake water levels by discharging 1.33 km^3 of the lake water into the Sheyenne River (Kharel and Kirilenko 2015).

To mitigate the Devils Lake flooding two emergency outlets were constructed at the west and east sides of the lake to drain the lake water to the Sheyenne River in a controlled fashion. The west outlet was completed in August 2005 with an initial release capacity of ~ 3 m^3 s^{-1}. In 2010, the west outlet was expanded to 7 m^3 s^{-1} and in 2012 an east outlet with a capacity of 10 m^3 s^{-1} was completed. However, releasing water through the Devils Lake outlets is controversial because the lake water contains a significantly higher concentration of dissolved solids, particularly sulfate, than the surrounding water bodies. To control the Devils Lake flooding and prevent its

1

uncontrolled spillage to the Sheyenne River at elevation of 444.4 m, which if happen could potentially lead to catastrophic flooding and water quality disaster to downstream communities (Ma et al. 2011) the North Dakota Department of Health has increased the Sheyenne River sulfate concentration from 300 mg l^{-1} to 450 mg l^{-1} in 2006 to match the State-wide sulfate standard for the stream Class I A, and to an emergency level of 750 mg l^{-1} in 2009 to allow more water to be diverted from Devils Lake to the Sheyenne River. Since 2012, the west and east outlets have operated with an average discharge of 5.9 and 6.6 $m^3 s^{-1}$, respectively, from April to October and lowered the lake water level to 441.8 m. However, the Sheyenne River sulfate concentration has also increased (Figure 1).
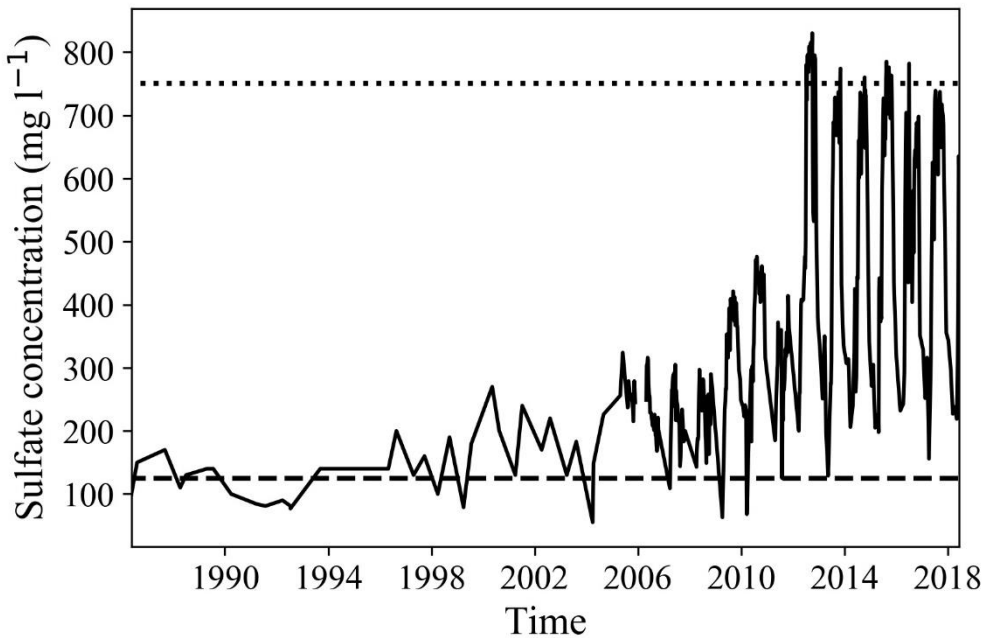
Figure 1. Sheyenne River sulfate concentration measured at Cooperstown gauging station for the time period from 1986 to 2018. The black dot line is representing the 750 mg l^{-1} ND sulfate standard implemented in the Sheyenne River. Black dash line is the 125 mg l^{-1} historical average sulfate concentration for the time period from 1951 to 2004.

2

<center>**Literature Review and Justification of Study**</center>

Several studies in the past have focused on Devils Lake flooding. Wich et al. (1986) simulated Devils Lake water levels from 1985 to 1990 for two different high and low runoff scenarios. They predicted the lake water levels would reach a minimum elevation of 443.1 m during low discharge and exceed a maximum 436.3 m for the high discharge for their study time period. The impact of rising water level was also predicted to be severe at the west part of the lake compared to the south part. They estimated 0.09 km^3 inflow into Devils Lake at an elevation of 434.67 m which would expand south and west shorelines by 12 and 48 m. Schuh (1999) correlated eastern North Dakota flooding events, particularly the Devils Lake flooding, with rising ground water level as result of current wet climate cycle and occurrence of the large weather events that have started since 1941. Within the Devils Lake watershed, he estimated that during wet climate conditions ground water table has increased by 0.3 m for each 25 mm of water added to the system. Large precipitation events such as those that occurred in 1993 and 1998 were estimated to have a strong influence on the water table in Devils Lake watershed (Schuh 1999). However, he also concluded that the long-term rising trend is likely due to a combination of sustained events that created minor, yet positive relative changes in the balance of ground water recharge to discharge.

Recent studies on Devils Lake flooding have provided valuable insight into the future water levels of the lake. Vecchia (2002) used a multiple linear regression model to simulate Devils Lake water level by fitting the observed lake water level to the surface water inflow, precipitation, and evaporation. He later coupled his model with a stochastic method to simulate future climate and natural overspill from 2008 to 2040 (Vecchia 2008). The result of his study indicated the likelihood of overflow is 72% and 37% if the current wet period was sustained for another 10 and 30 years, respectively. Kharel and Kirilenko (2015) considered regional climate variability in their study to

<center>3</center>

project Devils Lake water level. They downscaled climate data from 15 General Circulation Model (GCM) for Devils Lake and estimated an increase in the average total precipitation for the entire watershed by 2.7% for the 2020s and 3.4 % for the 2050s compared to 1980-2010. They developed a Soil and Water Assessment Tool (SWAT) to simulate the lake water level and integrated the result of their downscaled climate data into their model to examine the probability of natural spillage. They calculated the probability for (1) the outlets were considered non-operational for the past climate (1981-2010) and future climate scenarios, and (2) the outlets operated with full capacities under climate change scenario. Considering the past scenario from 1981-2010, they estimated that without operating the outlets the probability of the lake overspill would have been near 1%. For the moderate climate change scenario, their estimated probability range increased to 8.6-20%. And under the extreme climate change scenario, estimates increased further to 85% and 95% for the 2020s and 2050s, respectively. However, they concluded operating the outlets with full capacity would completely eliminate the chance of spillage.

Because of their location within closed basins, terminal lakes are very sensitive to land use change (Williams-Sether et al. 1996). To evaluate the possibility of land use management as an alternative for the Devils Lake outlets Kharel et al. (2016) coupled their SWAT model with a simple economic model to assess the impacts of land use change scenarios. They considered Devils Lake 2006-2010 land use as a baseline and created four different scenarios based on increasing price of dominant crops (corn, soybean, and wheat) and cash incentives for rangeland and alfalfa. The results showed under current climate and baseline scenario the probability of overspill without operating the outlets is 2% by 2020, and increasing the area of rangeland and alfalfa by 343% and 124% would also completely eliminate the probability of overspill. However, the higher overspill

4

probabilities were observed using projected climate data, a maximum 17% for the baseline scenario and a minimum 7.4% for increasing area of rangeland and alfalfa.

Gulbin (2017) developed a SWAT model to evaluate the impact of wetlands restoration on Devils Lake water level for historical (1991-2010) and future (2010-2040) climate scenarios. He used Compound Topographic Index, Digital Elevation Model (DEM) and land use data to create a set of wetland loss and restoration scenarios. The result of his study indicated that an increase in wetland area decreases Devils Lake water level for both historical and future climate scenarios. This relief occurs since wetlands act as a sponge and store surface runoff which increases evapotranspiration. The result of increasing 5% of wetland area showed a 0.47 m reduction in the historical lake water level and 2 -10% postponing of the probability of future natural spillage.

The rising water level in Devils Lake has raised concerns regarding both water quantity and quality; however, most of the previous studies on the Devils Lake flooding have focused on its water balance (Vecchia 2002, Vecchia 2008, Kharel and Kirilenko 2015, Kharel et al. 2016, Gulbin 2017, Wich et al. 1986). Several studies projected the lake water level and calculated the chance of natural spillage, but ignored the impacts of the current outlets operation on the flood risk and water quality of the Sheyenne River (Vecchia 2002, Vecchia 2008, Kharel and Kirilenko 2015, Kharel et al. 2016). This additional concern is of great importance because the outlets operation can impact the Sheyenne River by increasing the risk of flood, increasing the river's sulfate concentration, causing channel erosion and sedimentation, and introducing invasive species (US Army Corps of Engineers 2003).

Damages and losses that have resulted from Devils Lake are extensive and have affected the regional economy (Zheng et al. 2014). Devils Lake flooding represents a very complex hydrological and water quality problem which engages multiple stakeholders from both the Devils

5

Lake and Sheyenne River watersheds. Comparing these two communities (Larson 2012) noted that Devils Lake stakeholder tend to be more concerned with flood mitigation while those work and live downstream are interested in potential water quality issues. However, in the past the priority has been given to the lake water level which potentially led to water quality degradation in the Sheyenne River as sulfate levels increased (Figure 1). Unfortunately, the environmental impacts of the current outlets management on the downstream river is still unknown. In recent times, individuals affected by the lake flooding particularly within Sheyenne River communities are eager to find a management strategy that considers the water quality along with the lake water level control.

Research Objectives

The major objectives of proposed research are: (1) investigate the impact of the current wet climate cycle on Devils Lake water level and sulfate concentration, (2) evaluate the impacts of Devils Lake outlets on water quantity and quality of the Sheyenne River, (3) propose an optimal outlets management strategy to control Devils Lake flooding and minimize the impact on discharge and sulfate concentration in the Sheyenne River.

Research Questions

The following important concerns related to Devils Lake flooding and the outlets operation are answered in this research:

1. How has the current wet climate cycle impacted water level and distribution of sulfate concentrations in Devils Lake?

2. Does the current outlet management increase the risk of flood and/or water quality degradation in the Sheyenne River?

6

3. What is the optimal outlets management strategy to control Devils Lake flooding and minimize the impact on discharge and sulfate concentration in the Sheyenne River?

Research Methods

The research objectives and questions are accomplished and answered respectively through the following tasks:

(1). Soil and Water Assessment Tool (SWAT) and CE-QUAL-W2 models are coupled to simulate the Devils Lake water levels and sulfate concentrations.

(2). A SWAT model is developed to generate the Sheyenne River native discharge and connected to coupled SWAT and CE-QUAL model for Devils Lake to calculate the impacts of the outlets on the river water quantity and quality.

(3). An optimization method is conducted to introduce an optimal outlet management strategy for controlling Devils Lake water levels and conserving the Sheyenne River discharge and sulfate concentration.

Layout of Dissertation

This dissertation is designed in a three paper format in which each paper form a chapter and accomplish part of research objectives by answering the research questions stated above. In total, this dissertation composes of 5 chapters, with chapters 2, 3, and 4 representing each manuscript. The references used in all chapters also are listed together at the end of the dissertation to fulfil the University of North Dakota required dissertation format.

Chapter 2 accomplish the first objective function by answering the first research question: How has the current wet climate cycle impacted water level and distribution of sulfate concentrations

in Devils Lake? It provides details on developing a coupled hydrology and water quality model for Devils Lake. It shows the result of the Devils Lake water level and sulfate concentration simulations. In overall, this chapter summarizes the efficiency of the outlets in controlling Devils Lake water level, roughly estimates the impact of the outlets on the Sheyenne River water quality, and proposes a water quality mitigation strategy for the Sheyenne River based on findings in this chapter.

Chapter 3 tackles difficulties in calibration of the CE-QUAL-W2 model. CE-QUAL-W2 is widely used for simulating hydrodynamic and water quality of aquatic environments. Currently, the model calibration is mainly based on trial and error and therefore is subject to the knowledge and experience of users. This chapter overcomes these issues by implementing the Improved Global Harmony Search (IGHS) algorithm for automatically calibrating CE-QUAL-W2.

Chapter 4 accomplishes objectives 2 and 3 by answering questions number 2 and 3: Does the current outlet management increase the risk of flood and/or water quality degradation in the Sheyenne River? what is the optimal outlet management strategy to control Devils Lake flooding and minimize the impact on discharge and sulfate concentration in the Sheyenne River? It explains how the native discharge and sulfate concentration is calculated for the Sheyenne River. It describes the impacts of current outlets management on the Sheyenne River water quantity and quality. This chapter uses the findings from the previous chapters to propose an optimal outlet management strategy to control Devils Lake water level and conserve Sheyenne River water quantity and quality.

Chapter 5 summarizes this Ph.D. research by briefly explaining the outcomes of each research question. It describes limitations of the current research and outlines suggestion and recommendation for a future research direction.

List of Publications

1. **Shabani, A.**, Zhang, X. and Ell, M. 2017. Modeling Water Quantity and Sulfate Concentration in the Devils Lake Watershed Using Coupled SWAT and CE-QUAL-W2. Journal of American Water Resources Assessment. 53 (4), 748-760.
2. **Shabani, A.** Xiaodong Zhang, Xuefeng Chu, Timothy P. Dodd, and Haochi Zheng, 2018. Water Quality Conservation in mitigating Devils Lake Flooding. Journal of American Water Resource Association, under review.
3. **Shabani, A.** Xiaodong Zhang, Xuefeng Chu, Haochi Zheng, Jeffery Vanlooy, 2018. Automatic calibration of CE-QUAL-W2 Model using Improved Global Harmony Search Algorithm. In preparation to submit to the Water Journal.
4.

List of Professional Presentations

1. **Shabani, A,** Zhang, X., Mike Ell. And Timothy P. Dood. 2018**.** Examining the impact of Devils Lake outlets on flood risk of the Sheyenne River. Bismarck, North Dakota, March 6-8.
2. **Shabani, A.,** Zhang X. 2017. Examining the impact of Devils Lake outlet on the flood risk of the Sheyenne River. American Geophysical Union conference, New Orleans, Louisiana, 11-15 December.
3. **Shabani, A.,** Zhang X., Ell, M. 2016. Modeling Water Quantity and Sulfate Concentration in Devils Lake Watershed Using Coupled SWAT and CE-QUAL-W2. American Geophysical Union conference, San Francisco, California, 12-16 December.
4. **Shabani, A.,** Zhang X., Ell, M. 2016. Modeling Water quantity and quality in Devils Lake Watershed Using Coupled SWAT and CE-QUAL-W2. South Dakota Water Quality conference, South Dakota State University, Brooking. 27 October.
5. **Shabani, A.,** Zhang, X., and El, M. 2016. Modeling water quantity and quality in Devils Lake Watershed Using SWAT. North Dakota Water Quality Conference, Bismarck. 2-4 March.
6. **Shabani, A.,** Zhang, X. and Ell, M. 2015. Modeling water quantity and quality in Devils Lake watershed using SWAT Model. SWAT conference, Purdue University, Lafayette, Indiana, 14-16 October.

Poster:

1. **Shabani, A.**, Zhang, X. 2017. Modeling water quantity and sulfate concentration in the Devils Lake using coupled SWAT and CE-QUAL-W2 models. ND EPSCoR state conference, Fargo, North Dakota, 12 April.
2. **Shabani, A.**, Zhang, X. 2016. Modeling water quantity and quality in the Devils Lake watershed using SWAT. ND EPSCoR state conference Grand Forks, North Dakota. 19 April.

CHAPTER II

MODELING WATER QUANTITY AND SULFATE CONCENTRATION IN DEVILS LAKE WATERSHED USING COUPLED SWAT AND CE-QUAL-W2

Introduction

Devils Lake is an endorheic lake in the Red River of the North basin in northeastern North Dakota (Figure 2). Its proximity to the 100th meridian – a theoretical line that divides the North American continent into a generally wet region to the east and a dry region to the west – might be the reason for its significant precipitation fluctuation over time (Ma et al. 2011). Since the end of the last glaciation about 10,000 years ago, the alternating dry and wet cycles in the region dramatically changed the water level several times, varying from low to overflowing (Larry Leistritz et al. 2002). The recent wet cycle that started in 1993 (Figure 3) has raised the water level by nearly 10 m, reaching a record high of 443.3 meters above sea level on June 27, 2011. At a level of 444.7 meters above sea level, it would spill naturally and catastrophically into the Sheyenne River, which flows via the Red River into Lake Winnipeg, Manitoba, Canada (Figure 2). Because Devils Lake city and the adjacent communities are built within the historical confines of the lake, the rising lake level has inundated farm lands and caused significant damage to both infrastructure and the community. Over one billion USD have been spent in mitigation measures (Zheng et al. 2014), including upper basin water management to reduce runoff, continuing infrastructure protection, and developing emergency outlets (Kharel and Kirilenko 2015).

However, releasing water through the Devils Lake outlets is controversial because the water contains a significantly higher concentration of dissolved solids, particularly sulfate, than the surrounding water bodies. The impaired water quality is largely due to the fact that Devils Lake is a terminal lake, so it accumulates nutrients, sediment, and other dissolved solids entering from the watershed that has been primarily used for agricultural production. Because of its high salt

10

concentration, the water is not suitable for irrigation (Ma et al. 2011). The concerns about artificially pumping water from Devils Lake to the Sheyenne River (Figure 2) have led the Government of Manitoba to file a lawsuit in the United States court and the International Joint Commission to address a potentially detrimental impact on the water quality of Lake Winnipeg, which supports the largest freshwater commercial fishery in Western Canada and a thriving tourism industry for Manitoba.
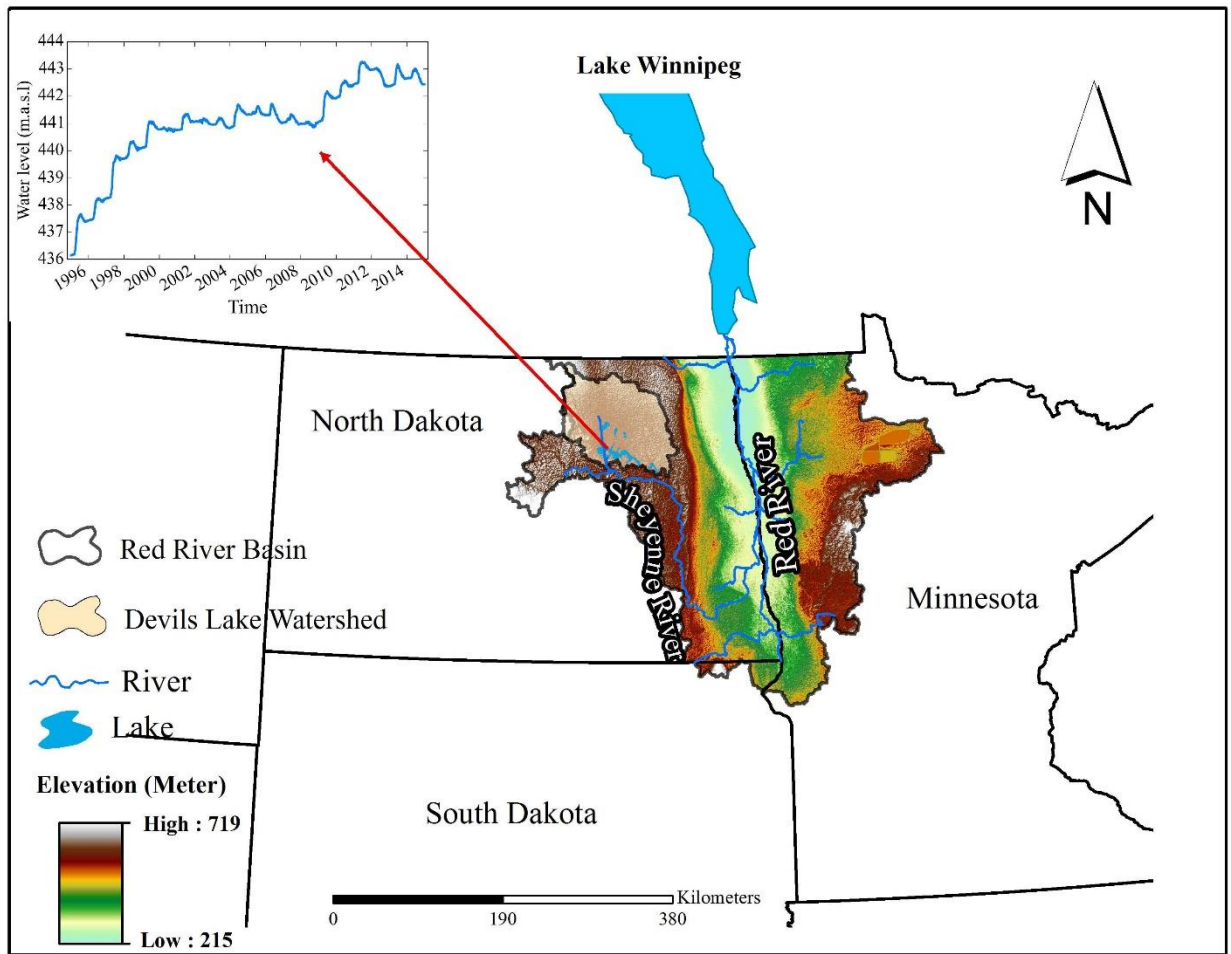
Figure 2. The Digital Elevation Model (DEM) showing the U.S. portion of the Red River of the North basin and the Devils Lake watershed. The insert depicts monthly water levels of Devils Lake from 1995 to 2014.
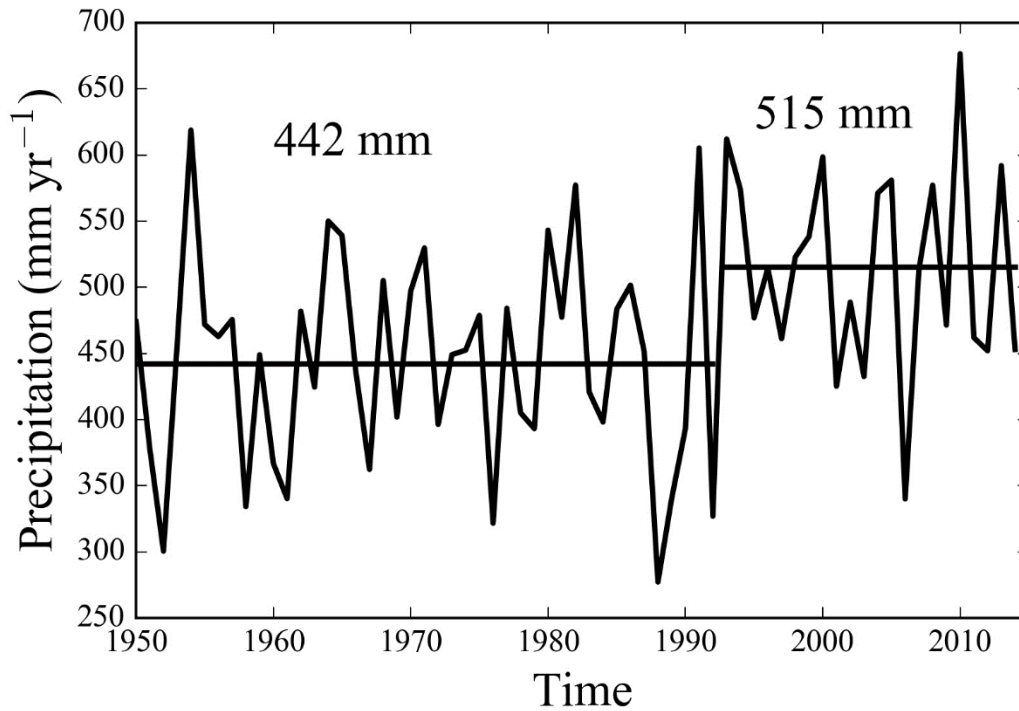
Figure 3. Annual precipitation over the Devils Lake watershed from 1950 to 2014. The two horizontal bars indicate the average annual precipitations before and after 1993, when the recent shift from a dry to a wet cycle occurred. The two horizontal bars indicate the average annual precipitations before and after 1993, when the recent shift from a dry to a wet cycle occurred.

The rising water level in Devils Lake has raised concerns regarding both water quantity and quality; however, most of the previous studies on the Devils Lake flooding have been focused on its water balance. Wich et al. (1986) simulated lake levels from 1985 to 1990 for two different high and low runoff scenarios. A remote sensing imagery analysis showed that the wetland size in the Devils Lake watershed had quadrupled from 1992 to 2001(Todhunter 2001).Doeing and Forman (2001) developed a physical hydrologic model to evaluate the impact of wetland restoration on inflow to Devils Lake. Vecchia (2008) used a stochastic method to simulate future climate and flooding risks from 2008 to 2040 and found that the chances are 72% and 37% if the current wet condition would last for another 10 and 30 years, respectively. Vecchia (2011) later

12

combined this stochastic model with a downstream routing model to examine the impact of outlet discharge and potential natural spilling of Devils Lake. He found that the emergency outlet operation would significantly decrease, but not completely eliminate, the chance of natural spilling. Using the Soil and Water Assessment Tool (SWAT) with an ensemble of projections from 15 General Circulation Models (GCM), Kharel and Kirilenko (2015) found a significant probability (7.3 to 20.0%) of overspill in the next few decades in the absence of outlets.

None of these studies, however, have tried to examine water quality. The goal of this study is to better understand how the water quality of the lake, particularly its sulfate concentration, changes with a rising water level by simulating both water quantity and quality. We will further discuss our findings in relation to the water quality of the Sheyenne River. The SWAT and CE-QUAL-W2 models were selected for this simulation because of their proven capacity in simulating hydrology (SWAT) and water quality (CE-QUAL-W2) in tributaries and lakes (Arnold et al. 1998, Cole and Wells 2003). To the best of our knowledge, the spatial distribution and temporal changes of the sulfate concentration in Devils Lake have never been simulated before. The results of this study will aid in water management and decision making to mitigate Devils Lake flooding and the impact on downstream rivers.

Methodology

Study Area

The Devils Lake watershed encompasses an area of 10,187 km^2. The terrain in the watershed is generally flat (Figure 2), with slopes typically < 2%. Approximately 73% of the land is used for agricultural production (Figure 4), with spring wheat, soybeans, canola, and corn being the main crops. The rest of the land comprises grassland (10%), Conservative Reserve Program (CRP) land (4%), waterbodies (6%), forest (1%) and developed area (5%). Two sub-watersheds,

13

Mauvais Coulee Tributary Number 3 and Little Coulee have soils of the Harmely series $(0 - 3\%$ slopes with low to moderate permeability) and the remaining sub-watersheds have soils of the Svea series $(0 - 25\%$ slopes with moderate to well drained permeability) (Figure 4).

At 440.7 meters above sea level, Devils Lake water spills into Stump Lake, which spills naturally into the Sheyenne River at 444.7 meters above sea level (Figure 2). Water enters the lake mainly by direct precipitation and surface runoff with little contribution from ground water (Williams-Sether et al. 1996). Below the spillage level, water is only removed from the lake by evaporation. Since 1993, the lake water level has increased by ~10 meters because of an increase in precipitation (Figure 3).
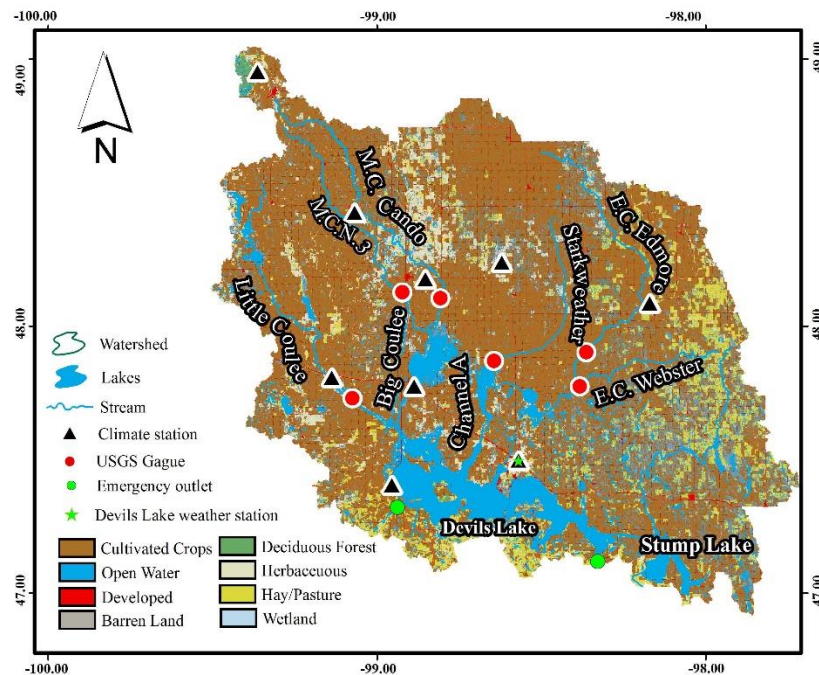
Figure 4. The Devils Lake watershed is delineated into 11 sub-watersheds; those sub-watersheds that have USGS gauging stations (red circle) are labeled with their names. Further shown are 9 USDA climate stations (black triangles), the Devils Lake airport weather station (green star), the ND Department of Health water sampling stations (black circles), and locations of the two emergency outlets (green circles) built to release water from Devils Lake to the Sheyenne River.

14

SWAT Model and Data

SWAT is a physically-based hydrological model that has been used frequently to evaluate the impact of climate, land use and management activities on hydrology and water quality(Saleh et al. 2000, Gassman et al. 2007, Krysanova and Arnold 2008). SWAT accounts for snow accumulation and melting (Ahl et al. 2008), which is important because in the study area approximately 50% of stream flow in March and April originates from snowmelt. Data needed to run the model were acquired from various sources (Table 1). The time-series data, such as flow rates and water temperature, were visually inspected and apparent outliers were excluded.

The 10 meter USGS Digital Elevation Model (DEM) was used to set up the model and delineate the watershed into eleven sub-watersheds. The delineating errors such as shape discrepancy were corrected in reference to the USGS 10-digit hydrologic units. The terrain slope was estimated from the DEM, the land use was acquired from the USDA National Agriculture Statistic Service (NASS), and the soil types were extracted from the STATSGO dataset. The entire watershed was divided into 233 hydrological response units (HRUs), using commonly adopted thresholds, 5% for land use and 10% for soil and no threshold for slope (Her et al. 2015). The daily precipitation, minimum and maximum temperatures were acquired from nine USDA weather stations in the area (shown as black triangles in Figure 4).

Since the study area is mainly used for agricultural production, it is important to consider crop rotations and fertilizer applications. The most common crop rotations were estimated using 17 NASS land use maps from 1997 to 2014. Following USDA (2005), a 50 kg ha^{-1} nitrogen rate typically applied for corn and wheat was assumed for non-legume croplands, and a 30 kg ha^{-1} phosphorus rate typically applied for corn, wheat, soybean, and alfalfa was assumed for all croplands.

15

Devils Lake was defined in SWAT as a daily managed reservoir, for which the relationships among lake elevation, surface area, and volume were derived from the USGS survey data (Table 1). Daily outputs for the west and east outlets (green dots in Figure 4) started in August 2005 and July 2012, respectively.

Table 1. Sources of input data for the Devils Lake Watershed.

Data type	Sources
Digital Elevation Model (DEM)	https://gdg.sc.egov.usda.gov/ (10 m resolution)
Land use/land cover	https://www.nass.usda.gov/Data_and_Statistics/ (NASS- 30 m horizontal grid)
Soil	http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/ngce/ (STATSGO)
Weather data	http://www.ars.usda.gov/Research/docs.htm?docid=19435 http://www.prism.oregonstate.edu/ (Daily data) https://mesonet.agron.iastate.edu/request/download.phtml?network=ND_ASOS (Hourly data)
Fertilizer	www.usda.gov/nass/
Stream flow and sulfate concentration	http://maps.waterdata.usgs.gov/mapper/index.html
Lake temperature and sulfate concentration	https://www.ndhealth.gov/WQ/sw/Z8_SWData/viewer.html
Lake volume and area	(http://nd.water.usgs.gov/devilslake/data) (USGS survey data)
Lake bathymetry	https://www.nd.gov/itd/statewide-alliances/gis
Outlet discharge	http://www.swc.nd.gov/basins/devils_lake/outlets/discharge_monitoring/

SWAT Calibration and Validation

The SWAT model was run with a daily time-step, starting with a five-year warmup period, followed by a calibration period from 1995 to 2003 and a validation period from 2004 to 2014. This time span was chosen because of the availability of data needed to drive the model. Since

16

snow is important in this study area, the snow fall and snowmelt parameter values were calibrated first following Kharel et al. (2016). Among the eleven sub-watersheds, only the following six have USGS gauging stations for daily stream flow (red dots in Figure 4): Mauvais Coulee Tributary Number 3 (M.C. N.3), Mauvais Coulee Cando (M.C. Cando), Edmore Coulee Edmore (E.C. Edmore), Starkweather, Edmore Coulee Webster (E.C. Webster), and Little Coulee. For each sub-watershed with a gauging station a baseflow recession constant value was calculated after separating stream baseflow from measured daily stream flow using the automated web GIS based hydrograph analysis tool - WHAT (Lim et al. 2007). For those sub-watersheds without gauging stations this parameter was assigned from the calculated values of nearby sub-watersheds. For the remaining SWAT parameters, a sensitivity analysis was conducted using the Latin hypercube parameter sampling method implemented in SWAT-CUP (Abbaspour 2014). The simulated stream flows were found to be most sensitive to the following six parameters (Table 2): moisture condition II curve number, ground water revap coefficient, surface runoff lag coefficient, plant uptake compensation factor, soil evaporation compensation coefficient, and soil available water capacity. These six parameters were calibrated automatically using the SUFI 2 algorithm with the Nash-Sutcliffe coefficient (E_{NS}) as the objective function (Abbaspour 2014). For the sub-watersheds with gauging stations (Figure 4), the Nash-Sutcliffe coefficient was computed using measured stream flows; however, for the rest of sub-watersheds without gauging stations, the observed lake water levels were used. The two parameters of lake evaporation coefficient and hydraulic conductivity were also calibrated automatically based on the observed lake water levels. The key SWAT parameters and their calibrated values are listed in Table 2.

Three statistic parameters, coefficient of determination (R^2), Nash-Sutcliffe coefficient (E_{NS}), and Percent Bias (PBIAS) were used to evaluate simulated flow (Moriasi et al. 2007,

17

Moriasi et al. 2015). Additionally, the root mean square error (RMSE) was used to evaluate the

water level simulation.

Table 2. Values of SWAT parameters calibrated for the Devils Lake Watershed.

Parameters and units	Description	Acceptable range	Calibrated values/ranges
SFTMT $_{(basin)}$[a]	Snowfall temperature (C)	-5–5	0.58
SMTMP $_{(basin)}$[a]	Threshold temperature for snowmelt (C)	-5 – 5	1.28
SMFMX $_{(basin)}$ [a]	Melt factor on June 21 (mm H$_2$O day^{-1} C^{-1})	0–10	5.5
SMFMN $_{(basin)}$ [a]	Snowmelt factor on December (mm H$_2$O °C-day)	0–10	2.25
TIMP $_{(basin)}$ [a]	Snow temperature lag factor	0–1	0.33
ALPHA_BF$_{(groundwater)}$[b]	Baseflow recession constant	0–1	0.1-0.3
CN$_2$ $_{(management)}$[c, d]	Moisture condition II curve number	±25% of default value	-0.12% / 0.15% of default value
GW_REVAP$_{(groundwater)}$[c, d]	Revap coefficient (Revap: water in shallow aquifer returning to root zone (mm H$_2$O))	0.02–0.2	0.04-0.15
SURLAG $_{(HRU)}$[c, d]	Surface runoff lag coefficient	0–24	2.0
EPCO $_{(HRU)}$[c,d]	Plant uptake compensation factor	0–1	0.4-0.8
ESCO $_{(HRU)}$[c,d]	Soil evaporation compensation coefficient	0–1	0.23-0.44
SOL_AWC $_{(soil)}$[c,d]	Available water capacity	±25% of default value	-0.20% / 0.15% of default value
EVRSV $_{(reservoir)}$[d]	Lake evaporation coefficient	0–1	0.5
RES_K $_{(reservoir)}$[d]	Hydraulic conductivity (mm hr^{-1})	0–1	0.05

[a] parameters whose values are taken from Kharel et al. (2016)

[b] calculated from stream baseflow

[c] parameters to which the simulated stream flows are most sensitive

[d] parameters are calibrated automatically using the SUFI 2 algorithm (see text for details)

CE-QUAL-W2 Model

CE-QUAL-W2 is a two dimensional (longitudinal-vertical) laterally-averaged

hydrodynamic and water quality model for rivers, estuaries, and reservoirs (Cole and Wells 2003).

The CE-QUAL-W2 model was chosen for two reasons. First, the shape of Devils Lake is narrow

and long (Figure 4), and the CE-QUAL-W2 model is designed to simulate this type of waterbody.

Second, in terms of water quality in Devils Lake, the sulfate concentration is of major concern and

18

CE-QUAL-W2 has been shown to successfully simulate the dynamics of water constituents in reservoirs (Flowers et al. 2001, Debele et al. 2008).

Both the hydrodynamic and water quality simulations in CE-QUAL-W2 depend on accurate representation of the bathymetry (Debele et al. 2008). Therefore a toolbox was developed in ArcGIS to divide the lake into 96 longitudinal segments, each of which is 1 km wide (Figure 5). A segment width of 1 km was used because that is the typical pixel size of satellite sensors, which were intended for use in future studies. Depending on their total depth, the segments were divided into up to 17 layers. Each layer is 1.5 meters deep, because Devils Lake bathymetry data were derived from a 1.5-meter contour map. The lake has four tributaries (labeled as inflows 1-4 in Figure 5). While the SWAT model was run from 1995 to 2014, we only ran CE-QUAL-W2 from 2008 to 2014 because of (1) the significant computation time required to run CE-QUAL-W2 at an hourly time-step, (2) the connection of Devils Lake and Stump Lake after 2007, which allows them to be treated as one, and (3) the development of the water quality degradation, which became apparent after 2009 when the west outlet started to operate at full capacity. Hourly meteorological data of temperature, dew point, wind speed and direction, cloud cover and precipitation were downloaded from the Automated Surface Observation System (ASOS) Network's Devils Lake station (green star in Figure 5). The model automatically filled missing data by linear interpolation and calculated the solar radiation.

SWAT-simulated flow was provided to CE-QUAL-W2 as input. Water temperature for the inflow tributaries was estimated following Neitsch et al. (2009). Since SWAT does not simulate sulfate in tributaries measured data were used as input for the CE-QUAL-W2 model. The six gauging stations (red dots in Figure 5) have seasonal measurements of sulfate concentrations; however, none of these are located in those tributaries that directly flow into the lake. The Load

Estimator (LOADEST) software (Runkel et al. 2004) was used to estimate daily values from the seasonal measurements of sulfate concentrations at each station and their average was applied as daily sulfate concentrations in the tributaries that directly flow into the lake. The initial vertical distribution of sulfate at each segment was assumed to be uniform, with an initial value interpolated from the field measurements (black dots in Figure 5) taken at a depth of one meter in May 2008.

CE-QUAL-W2 has the ability to treat different types of artificial outflows such as pumps, withdrawals, spillways, etc. The two emergency outlets in Devils Lake (identified as blue rectangles in Figure 5) were defined as withdrawals in this model.
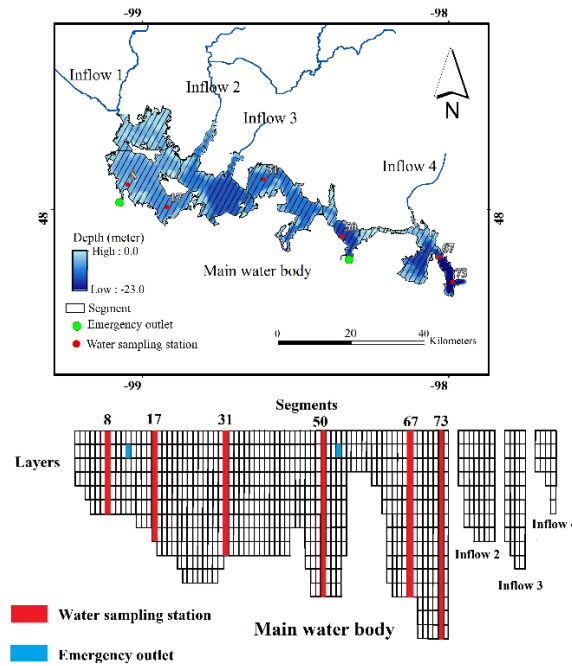
Figure 5. Segmentation and computational grids created for the CE-QUAL-W2 model. The lake is divided into 96 segments along approximately west to east direction and 17 vertical layers. Each segment is 1 km long in longitudinal (approximately west to east) direction; each layer is 1.5 m deep.

The CE-QUAL-W2 model was manually calibrated with regard to the lake water level and temperature for 2008-2009 and validated for 2010-2014. Table 3 lists the CE-QUAL-W2 parameters that were adjusted during the calibration. Three statistic parameters: PBIAS, mean

absolute error (Abs Error) and coefficient of determination (R^2), were used to evaluate the model performance (Cole and Wells 2003).

Table 3. Values of CE-QUAL-W2 parameters calibrated for Devils Lake.

Parameters	Description	Calibrated value
CHEZY	Bottom frictional resistance (m^2 s^{-1})	70
WSC	Wind sheltering coefficient	2.0
BETA	Fractional solar radiation absorbed at water surface	0.7

RESULTS

Stream Flows and Lake Water Levels

The simulated daily stream flows were compared with the observations in Figure 6 and Table 4 for the six sub-watersheds with gauging stations. While the maximum flow rates varied among different sub-watersheds, the discharges in each sub-watershed followed a similar pattern: reducing to the minimum levels in late fall and winter due to snow accumulation and reaching maximum levels during the spring as a result of snowmelt and spring precipitation. Overall, the SWAT model was able to simulate the stream flows well with $E_{NS} > 0.5$ and $|PBIAS| < 25\%$ (Table 4) for all but the M.C. N.3 and M.C. Cando tributaries, for which the model significantly underestimates the peak flows ($E_{NS} < 0.5$) in both the calibration and validation periods.

Figure 7 compares the simulated water level of Devils Lake with the observation. SWAT was able to capture the changes of water level very well, with a root mean square error of 0.35 m. The simulation showed that without the operation of the outlets, the water level would have been 0.70 m higher at the end of the simulation period (Figure 7). Note that both SWAT and CE-QUAL-W2 can simulate lake water levels. In this study, the SWAT simulation was used for predicting

21

water levels because the CE-QUAL-W2 model mainly uses water level as a constraint for mass

conservation (Debele et al. 2008).
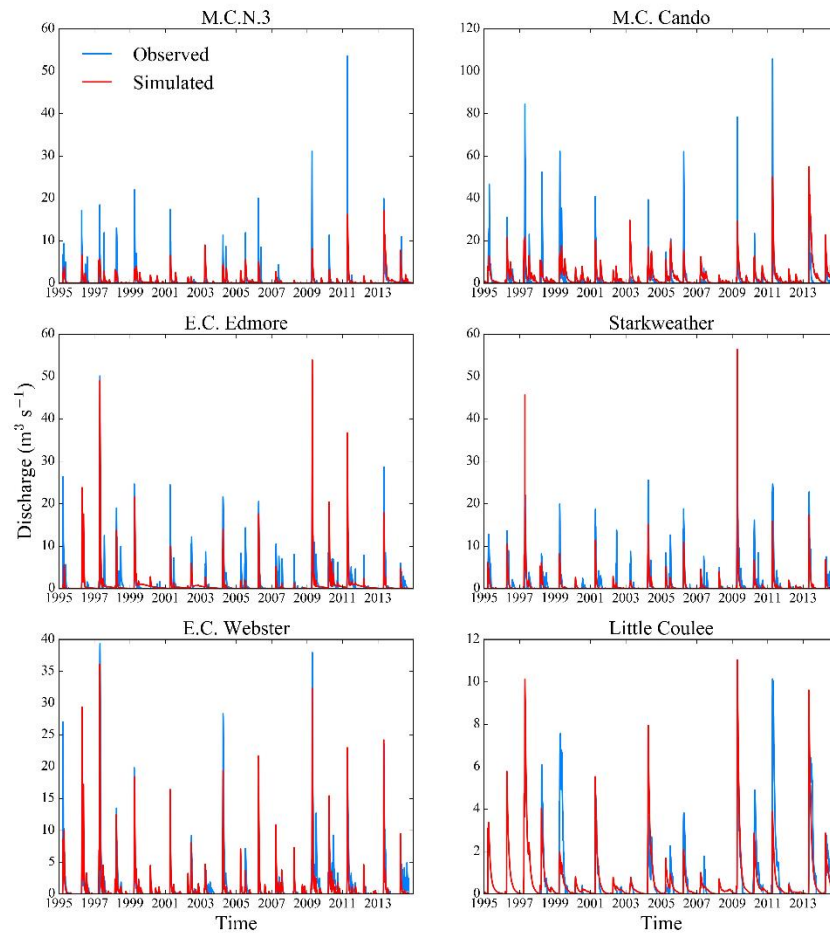
Figure 6. Simulated and observed flow rates for the 6 gauged tributaries from 1995 to 2014. For Little Coulee, the observations started in 1998.

Table 4. Statistical evaluation of the SWAT model for simulating flow rates at 6 sub-watersheds.

Sub-watershed	Number of observation (1995-2014)	Calibration period			Validation period		
		R^2	E_{NS}	PBIAS (%)	R^2	E_{NS}	PBIAS (%)
M.C. N.3	7305	0.35	0.35	-30	0.45	0.44	-25
M.C. Cando	7305	0.34	0.33	-36	0.47	0.37	-40
E.C. Edmore	7305	0.68	0.68[**]	11.8[**]	0.64	0.64[*]	23[*]
Starkweather	7305	0.60	0.58[*]	22[*]	0.70	0.62[*]	20[*]
E.C. Webster	7305	0.74	0.74[**]	-2.8[***]	0.64	0.62[*]	15[*]
Little Coulee	6149	0.52	0.51[*]	17.3[*]	0.6	0.59[*]	9.3[**]

[***] Very good simulation: $0.75 < E_{NS} \leq 1.0$, |PBIAS| < 10%

[**] Good simulation: $0.65 < E_{NS} \leq 0.75$, $10\% \leq$ |PBIAS| < 15%

[*] Satisfactory simulation: $0.50 < E_{NS} \leq 0.65$, $15\% \leq$ |PBIAS| < 25%

Unsatisfactory simulation: $E_{NS} \leq 0.50$, |PBIAS| > 25% (Moriasi et al., 2007, 2015)
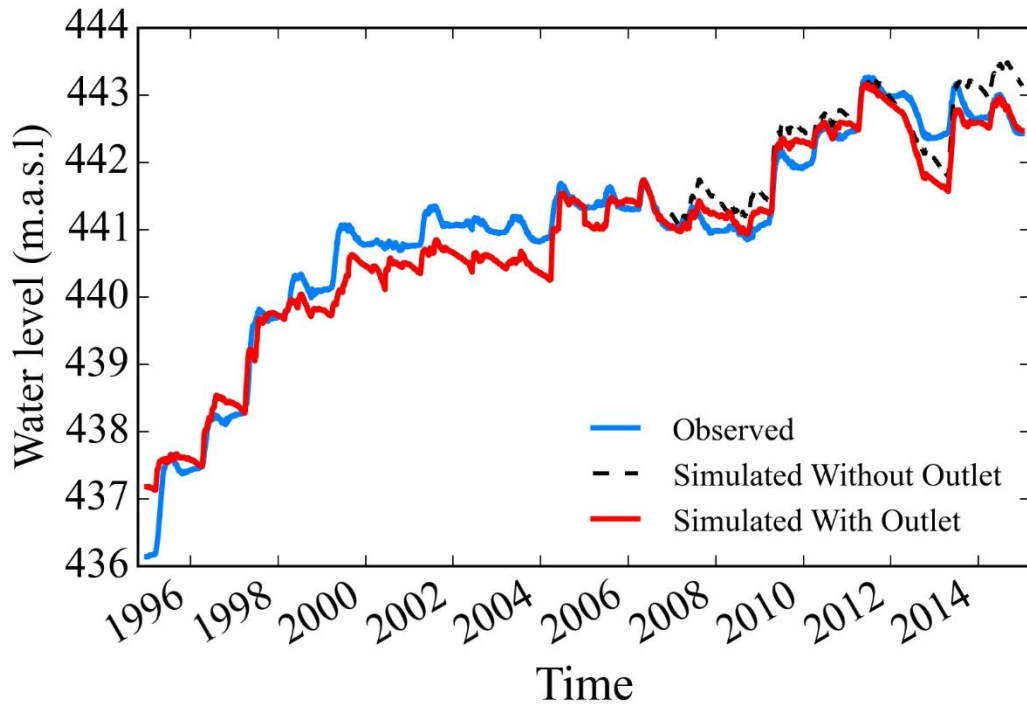
Figure 7. Comparison of SWAT-simulated and observed Devils Lake water levels from 1995 to 2014.

23

Lake Temperature and Sulfate Distributions

The calibrated CE-QUAL-W2 model is able to simulate the lake water levels with $R^2 = 0.8$ and RMSE = 0.5 meters. The water levels predicted by the two models were very similar to each other (RMSE = 0.35 and 0.5 meters for SWAT and CE-QUAL-W2, respectively), indicating the general agreement in mass balance simulated by the two models. Simulated water temperature profiles were in general agreement with the field measurements, which have been conducted seasonally at segments 8, 17, 31, and 50 (locations shown as red dots and rectangles in Figure 5). As an example, the comparison for segment 31 is shown in Figure 8. The lake temperature changed significantly, from ~ 2-3 °C during winter (Figure 8 a and e) to ~ 22-23 °C during late summer and early fall (Figure 8 d and f). The simulated water temperature profiles indicate that water is well mixed during spring, summer and fall seasons (Figure 8 b, c, d, f, and h), which is also consistent with the observations. Strong winds during these seasons and the relatively shallow depth of the lake prevented the water from stratification (Afshar et al. 2011). However, the model could not reproduce the winter stratification due to the lake freezing (Figure 8 e and g), but this did not affect the performance of the model in the other seasons. In general, the simulated temperature agreed with the observation with a mean absolute error of < 0.85 °C.

24
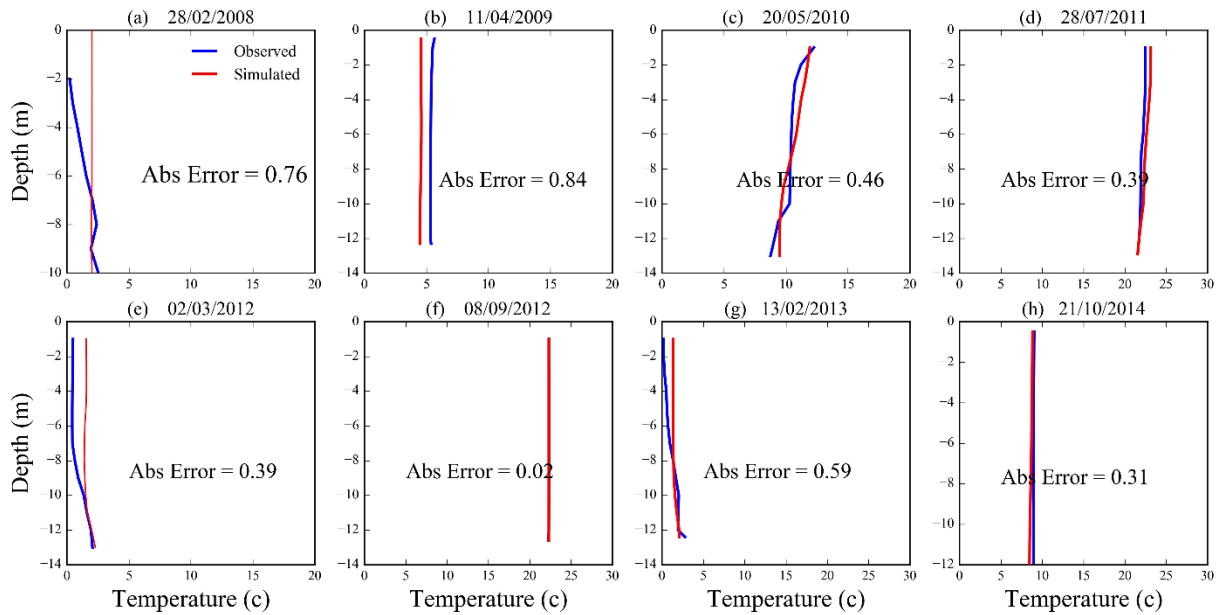
Figure 8. Comparison of CE-QUAL-W2 simulated and observed lake water temperature at segment 31.

The comparison between observed and simulated sulfate concentrations at segments 8, 17, 31, 50, 67, and 73 from 2008 to 2014 (Figure 9) indicates that CE-QUAL-W2 performed well in simulating sulfate dynamics ($r^2 = 0.85$). The model tended to overestimate sulfate at lower concentrations but underestimate it at higher concentrations (Figure 9). This bias, however, is limited (|PBIAS| = 11%). From 2008 to 2014, the sulfate concentration in Devils Lake has decreased by ~ 6% (comparing dots in Figure 9 of lighter shades with those of darker shades) due to continuous dilution with water from the basin. Figure 10 shows the distribution of sulfate concentrations simulated for Devils Lake on July 1, 2012. There is a general increase from west to east, with the east end concentrations (~ 1700 mg l^{-1}) being ~3 times greater than at the west side (~600 mg l^{-1}). This west-east gradient is caused by the remaining historically high concentration of sulfate in the eastern part of the lake and the strong dilution in the western side by water with lower sulfate concentration flowing into the lake from the Big Coulee and Channel

25

A tributaries (Figure 3). The vertical distribution of sulfate–similar to temperature–is well mixed (Figure 8).
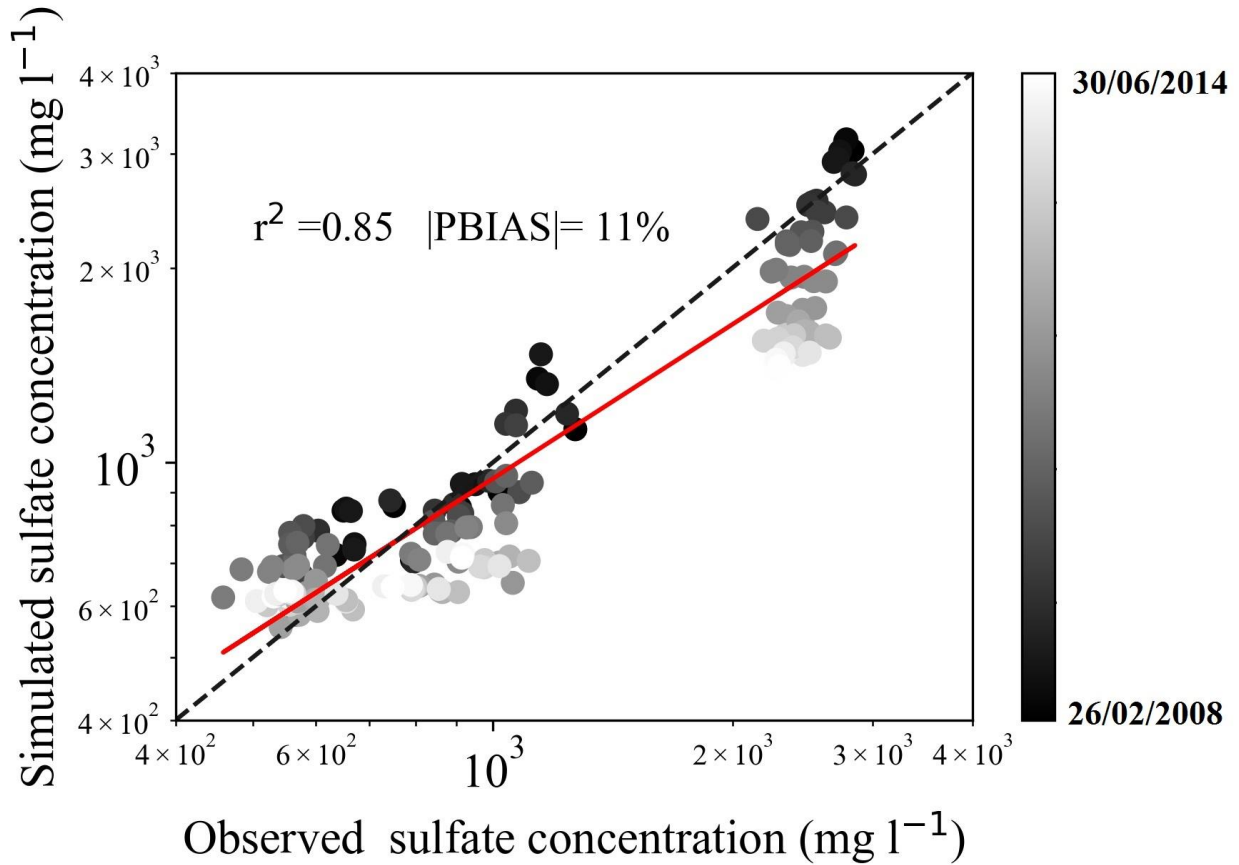
Figure 9. Comparison of CE-QUAL-W2 simulated and observed sulfate concentration (mg l⁻¹) at segments 8, 17, 31, 50, 67, and 71 from 2008 to 2014. The earlier data are represented by darker shades and the newer by lighter shades. The dashed line represents 1:1 relationship and the red line the linear regression of the simulated vs. observed data.
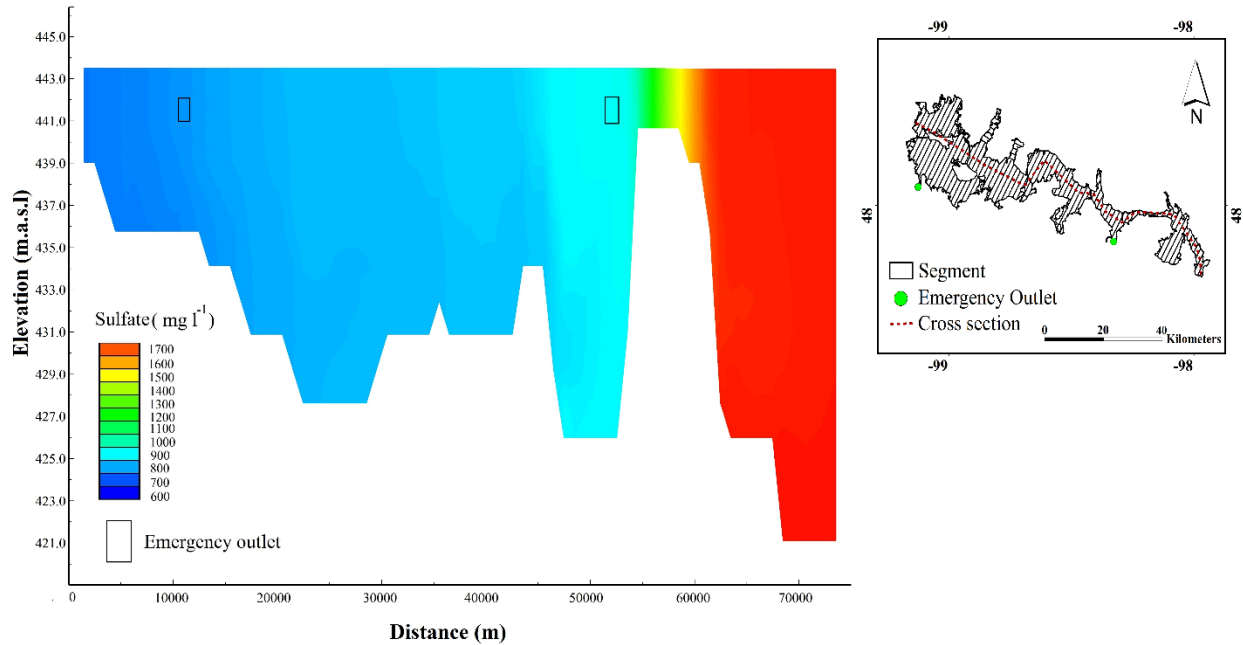
Figure 10. Sulfate concentrations simulated along the cross section (red dashed line in the insert) on July 1, 2012. The x-axis represents the distance from the west end of the lake. The two rectangles indicate the approximate locations of the west and east outlets.

DISCUSSION

With only a zero-dimension mass-balance component for waterbodies, the SWAT model cannot simulate the physical and chemical dynamics of lakes, which the CE-QUAL-W2 model is capable of doing. The successful application of the CE-QUAL-W2 model, however, relies on accurate input data such as weather parameters and stream flows (Gao and Li 2014). For the weather data, real-time measurements from the weather station near the city of Devils Lake were used (Figure 4). Unfortunately, there are no gauging stations measuring flow rates in the four tributaries that directly flow into the lake (inflows 1-4 in Figure 5). Therefore, the performance of the CE-QUAL-W2 model in this case relied on how well the SWAT model can simulate the stream flow at the four inflow tributaries. The water levels simulated by the CE-QUAL-W2 model agree with the measurement with an RMSE = 0.5 m (for comparison, RMSE = 0.35 m for SWAT, Figure

27

7) suggesting that SWAT can indeed provide reasonably accurate estimation of stream flows into the lake.

Snowmelt during early spring plays a major part in peak stream flows and the rising of the water level of Devils Lake. As constrained by the SWAT model, one snowmelt temperature, which was estimated to be 1.28 °C via calibration, is applied for the entire watershed. Analysis of simulated stream flows showed that for the M.C. N.3 and M.C. Cando sub-watersheds the model overestimated the flow on average by 114% and 430% respectively in March and underestimated the flow by 25% and 23% respectively in April. As shown in Figure 4, these two sub-watersheds are located in the northern part of the Devils Lake watershed, where snowmelt might happen at a higher temperature, and hence at a later time, than in the other sub-watersheds (Clow 2010). With a lower snowmelt temperature, the SWAT model predicted earlier melting for these two sub-watersheds and hence increased surface runoff during early spring and decreased it in the remaining seasons (Ahl et al. 2008). A higher snowmelt temperature (5° C) was tested, which showed improved flow simulation for these two tributaries but resulted in a poorer performance for the other tributaries. For the simulation, it was decided to further apply the snowmelt temperature of 1.28 °C because a physical explanation was not found for changing values in the two worse performing sub-watersheds. More importantly, this error in surface runoff distribution had limited impact on the prediction of the lake water levels, which is most critical for ensuring a correct water balance.

The results showed that operating two emergency outlets in the past few years has lowered the lake water level by ~0.7 m, but not sufficiently to prevent the lake water level from rising (Figure 7). Similar results have been reported in the past (Vecchia 2011, Kharel and Kirilenko 2015). Since there is a ~37% chance for the current wet condition to continue until 2040 (Vecchia

2008), these results indicate that Devils Lake will likely reach the natural spill elevation by that time. One of the solutions to avoid this natural, but potentially disastrous, spill would be to increase the pumping of water from Devils Lake to the Sheyenne River.

The west outlet constructed in August 2005 had a maximum release capacity of ~ 3 $m^3 s^{-1}$, which was later upgraded to 7 $m^3 s^{-1}$ in June 2010. The east outlet started to operate in July 2012 with a maximum capacity of 10 $m^3 s^{-1}$. In total, two pumps can discharge water with a maximum capacity of 17 $m^3 s^{-1}$. The operation of the two outlets has been guided by two requirements: total stream flow of the Sheyenne River at the outlets' insertion points should be < 17 $m^3 s^{-1}$ to prevent the river from overbank flooding (US Army Corps of Engineers 2003); and the total sulfate concentration in the river should be < 450 mg l^{-1} to meet the North Dakota Department of Health standard for stream Class IA. After an initial intermittent operation from its completion in 2005 until 2009, the west outlet operates almost continuously during the non-freezing seasons with an average discharge rate of ~ 5 $m^3 s^{-1}$ (Figure 11-b). Still the lake water level reached the record high in June 2011 (Figure 7). The east outlet started to operate immediately after its completion in July 2012 with an average discharge rate of 7.6 m^3 s^{-1} (Figure 11-b). As shown in Figure 11-a, the operation of the two outlets often elevated the total stream flow of the Sheyenne River slightly above the 17 $m^3 s^{-1}$ limit.

The operation of the outlets, while releasing the pressure of the rising water level in Devils Lake, has also led to significant degradation of water quality in the Sheyenne River (Figure 11-c). Pumping water from the east outlet causes more serious degradation of the water quality in the Sheyenne River since the water at the east outlet was discharged at a higher rate (Figure 11-b) and contains higher concentration of sulfate (Figure 10) than at the west outlet. With an average sulfate concentration of 105 mg l^{-1} in the Sheyenne River upstream of the outlets, it was estimated that

29

during the outlet operation period, typically from April to November, pumping water from the west outlet alone would raise the average sulfate concentration to 404 mg l^{-1}, from the east outlet alone to 536 mg l^{-1}, and from both to 585mg l^{-1}. Therefore, operating the east outlet violates the ND state standard of 450 mg l^{-1} for stream Class IA. Apparently, the current operation of the outlets is a "wicked problem" (Rittel and Webber 1973, Stahl 2014): solving the Devils Lake flooding issue leads to another issue of degrading the water quality in the Sheyenne River. The results suggest that one possible compromise is to increase the discharge rate at the west outlet where the sulfate concentration is much lower than at the east side (Figure 10). For example, the 450 mg l^{-1} requirement for sulfate concentration in the Sheyenne River would be met if the maximum discharge from the east outlet was reduced to 8 m^3 s^{-1} while proportionally increasing the discharge from the west outlet to maintain the same amount of total discharge. If the same amount of total discharged water from the two outlets were to be released from the west outlet alone, the sulfate concentration could be further lowered to ~410 mg l^{-1}. Either of these outlet operation scenarios would meet the ND state standard of 450 mg l^{-1} for stream Class IA. However, both scenarios would require further upgrading of the pump capacity of the west outlet by at least 2 m^3 s^{-1}.
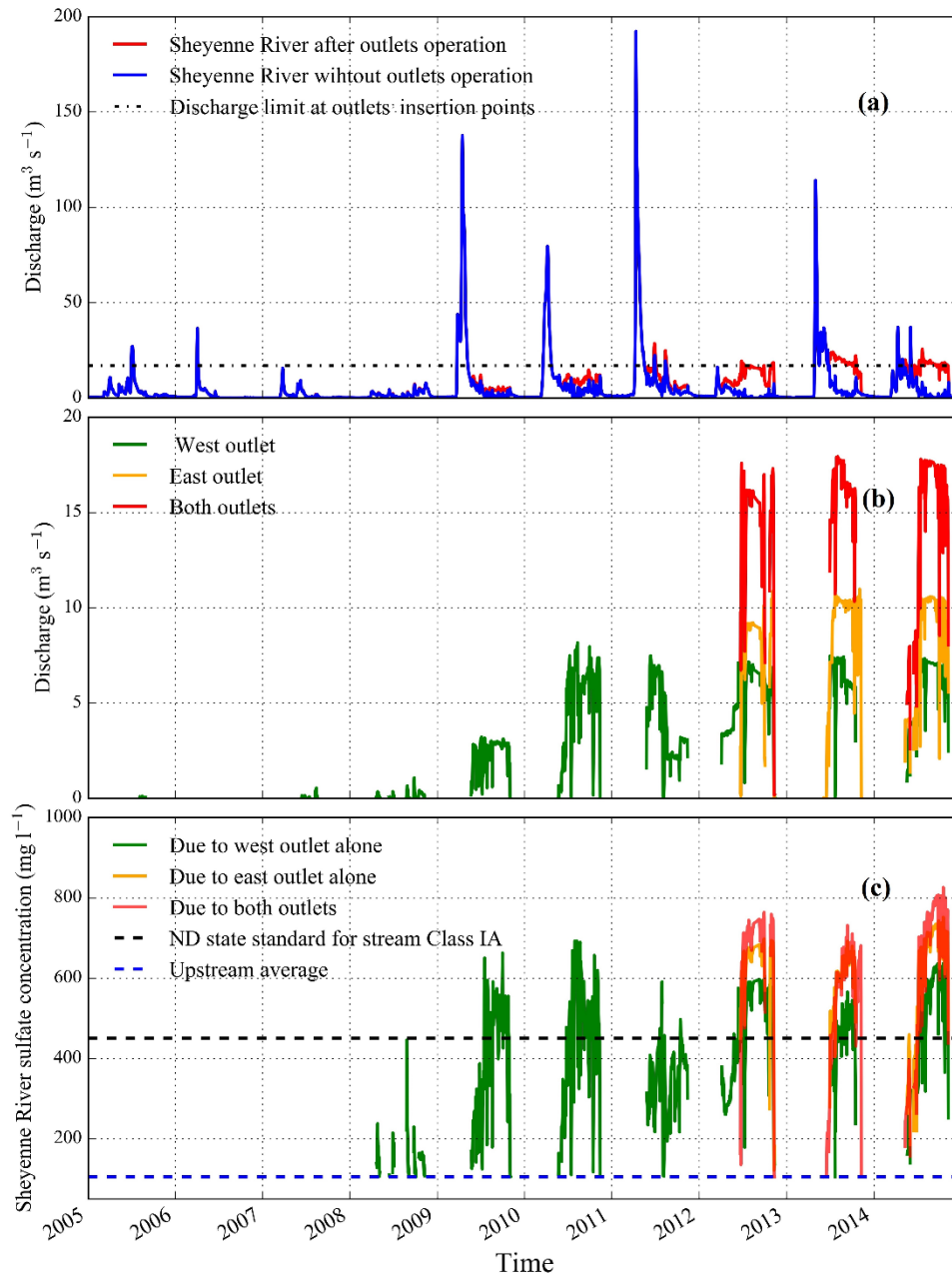
 Figure 11. Temporal variations of (a) Sheyenne River discharge rate; (b) outlet discharge rates; and (c) estimated Sheyenne River sulfate concentration.

CONCLUSION

The SWAT and CE-QUAL-W2 models were successfully coupled to study the changes in both water quantity and quality associated with the rising water levels in Devils Lake caused by a prolonged wet cycle since 1993. The SWAT model performed well in simulating both stream flow

31

and lake water levels. Indeed, the SWAT simulation is able to reproduce the water levels with a root mean square error of 0.35 m and shows that the operation of the two outlets since August 2005 has lowered the lake level by 0.70 m (Figure 7). With SWAT-simulated daily outflow at the four tributaries (inflow 1 - 4 in Figure 5) as the input, the CE-QUAL-W2 model is able to simulate the temperature and sulfate concentration in Devils Lake in good agreement with the field observations (Figures 8 and 9). The coupled SWAT and CE-QUAL-W2 simulation shows that sulfate concentrations in Devils Lake increase from west to east (Figure 10), which makes operation of the east outlet more of a concern for degrading the water quality in the Sheyenne River. One possible solution proposed by this study to mitigate Devils Lake water level and Sheyenne River water quality degradation is to reduce the east outlet operation to < 8 m^3 s^{-1} and upgrade the west outlet capacity by at least 2 m^3 s^{-1}.

The results of this study demonstrate the potential of coupling the SWAT and CE-QUAL-W2 models for evaluating watershed and reservoir management practices. Currently, we have deployed a buoy monitoring water quality in Devils Lake, and are incorporating these near-real time data into our coupled model to further enhance its performance in simulating both water quantity and quality in the Devils Lake watershed. We are also planning to look further into possible outlet management scenarios and to analyze their effects on flooding potential and sulfate concentrations in the Sheyenne River.

AUTOMATIC CALIBRATION OF CE-QUAL-W2 MODEL USING IMPROVED GLOBAL HARMONY SEARCH ALGORITHM

Introduction

CE-QUAL-W2 is a well-known water quality model that has been widely used to simulate physical and biochemical processes in lakes, rivers, estuaries, and reservoirs (Afshar et al. 2011, Flowers et al. 2001). The model, composing of one hydrodynamic and one water quality component, requires calibration with field observation. Currently, this process is based on trial and error along with visual inspection, during which the model variables are manually adjusted until a desirable comparison is achieved between prediction and observation for one or a set of calibration variables. The manual calibration, which has shown limited success(Afshar et al. 2011, Shabani et al. 2017, Flowers et al. 2001, Smith 2014, Galloway 2011), is time-consuming and could be subjective and/or inefficient depending on the knowledge and experience of the modeler (Afshar et al. 2011).

Heuristic algorithms take advantage of speed and power of a computer to find the optimal solution through optimization. These algorithms use exhaustive search and an empirical guideline to search for the optimal solution (Zhara et al. 2013). Although heuristic algorithms have shown good performance in many optimization problems, they are not efficient for large-scale combinational and highly non-linear optimization problems (Zhara et al. 2013). Inspired by natural phenomena, meta-heuristic optimization techniques are developed to find optimal or near-optimal global solution (Maier et al. 2014) in the complex model parameter space (Yoo and Kim 2014). In the last two decades, meta-heuristic algorithms have received considerable attention as a reliable method for automatic calibration of hydrological, ecological and water quality models. Chen et al. (2016) applied the Particle Swarm Optimization (PSO) technique to calibrate Liuxihe model (a

catchment flood forecasting model) by finding the optimal set of values for the model variables that best reproduces the river hydrograph shape and peak discharge. Tashkova et al. (2012) tested five meta-heuristic algorithms including Particle Swarm Optimization, differential ant-stigmergy algorithm (DASA), continuous DASA, differential evolution, and algorithm 717 for automatic calibration of their food web model for Lake Bled in Slovenia. The outcome of the study demonstrated the superiority of meta-heuristic algorithms over the manual method, even though they did not observe a significant difference in the performance among different meta-heuristic algorithms.

Meta-heuristic algorithms such as Genetic Algorithm (GA) and PSO have been used for automatic calibration of CE-QUAL-W2 model. Ostfeld and Salomons (2005) applied a combination of 'hurdle-race' and a hybrid GA-K-Nearest Neighbor algorithm (GA-KNN) for calibration of CE-QUAL-W2 model in simulating temperature and dissolved oxygen for Lower Columbia Slough in Oregon, USA. They found the hybrid method reliable and robust with significantly decreased computational time as compared to the GA method. Kazemi (2010) applied PSO and GA algorithms for calibration of CE-QUAL-W2 model and found PSO performed better and faster than GA in finding the optimal solution. Afshar et al. (2011) applied the PSO algorithm for calibration of CE-QUAL-W2 model in simulating water budget and temperature of Karkheh Reservoir in Iran. Their calibrated model produced results in agreement with the field data.

Even though PSO has been successfully tested for solving numerous optimization problems (Aote 2013), in particular, for calibration of CE-QUAL-W2 model (Kazemi 2010, Afshar et al. 2011), the algorithm has a couple of drawbacks: 1) PSO can often easily fall into a local optimal, to which solutions prematurely converge (Aote 2013), 2) the performance of the

PSO is highly dependent on the number of initial solutions used by the algorithm to detect the optimal solution (Evers and Ghalia 2009).

Harmony Search (HS) is a meta-heuristic algorithm inspired by musical performance process (Geem 2009). HS has a simple structure and only requires a few control parameters for its operation which makes it adaptive to different types of optimization problems (Geem 2009). HS has shown the ability to overcome the PSO drawbacks by using its control parameter efficiently(Ülker 2017). Several studies have verified the strength of the HS for detecting optimal solution in a non-linear and complex solution space (Evers and Ghalia 2009, Zong Woo et al. 2001). In a previous study (Shabani et al. 2017), we developed a CE-QUAL-W2 model for Devils Lake in Nort Dakota, USA, and manually calibrated it for simulation of water temperature. The calibration process was tedious and highly time-consuming even though we only calibrated two model variables. The objective of this study is to implement and test HS algorithm for automatic calibration of CE-QUAL-W2. Specifically, we will implement the latest version of HS algorithm, Improve Global Harmony Search (IGHS(Xiang et al. 2014)), and test it on CE-QUAL-W2 model that we have developed for Devils Lake. For comparison, we will also implement PSO algorithm, which has been used for calibration of CE-QUAL-W2 (Kazemi 2010, Afshar et al. 2011). The performance of the two calibration algorithms will be evaluated by comparing the final simulated water temperature with their corresponding field measurements.

Methodology

CE-QUAL-W2 Model

CE-QUAL-W2 is a two dimensional (longitudinal-vertical) hydrodynamic and water quality model for the lakes, rivers, estuaries, and reservoirs (Cole and Wells 2003). The model assumes lateral homogeneity in velocities, temperature, and constituents of a water body, and

35

therefore is best suited for simulating large and narrow waterbodies such as Devils Lake (Figure 1). The model also includes an ice cover algorithm, which is important for studying Devils Lake in wintertime with frozen surface water. For this study, our focus is to simulate water temperature and from literature review (Ostfeld and Salomons 2005, Afshar et al. 2011, Cole and Wells 2003) we found six variables are important for temperature simulation. Among these six variables (Table 1), the fraction of solar radiation absorbed within 0.6 m depth of water (BETA) is needed for correcting attenuation of solar radiation in the lake; the wind sheltering coefficient (WSC) is used for calculation of heat loss, and the rest of the parameters are needed to calculate heat balance under the ice condition. We checked the sensitivity of these variables for our model using SALib 1.1.2 sensitivity analysis library in Python. Our analysis showed all the selected parameters are highly sensitive at the 95 % level of significance test ($P < 0.05$).
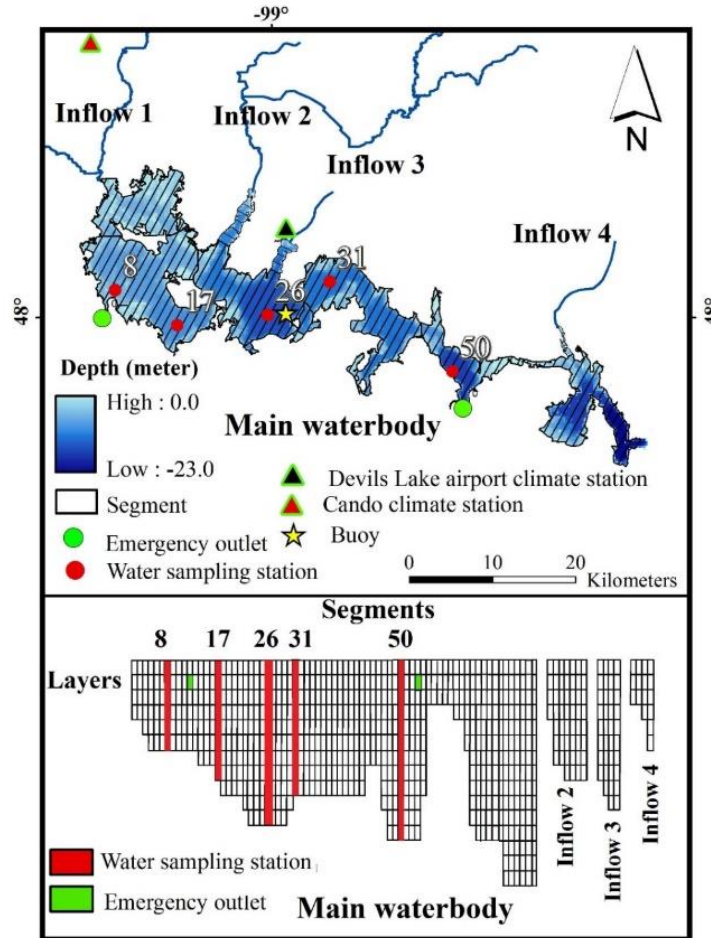
Figure 12. Segmentation and computational grids created for the CE-QUAL-W2 model to simulate the water temperature of Devils Lake. The lake is divided into 96 segments along approximately west to east direction and 17 vertical layers. Each segment is 1 km long in longitudinal (approximately west to east) direction; each layer is 1.5 m deep. The five red points and rectangles represent the seasonal water temperature sampling locations. Two green circles and rectangles are representing two emergency outlets. Black and red triangles represent weather stations located in the Devils Lake city airport and Cando. The yellow star represents the location of the buoy that we deployed in 2015.

37

Table 5. The calibration variables and their expected ranges of values used in the CE-QUAL-W2 model for simulating Devils Lake water temperature.

Model variables	Name	Default value	Range of possible values
Fraction of solar radiation absorbed within 0.6m from the water surface	BETA	0.45	0.30 - 0.8
Wind sheltering coefficient	WSC	1.0	0.5 – 2.0
Solar radiation extinction coefficient (m^{-1})	GICE	0.07	0.01 – 0.14
Coefficient of water-ice heat exchange through the melt layer (W m^{-2} °C)	HWICE	10.0	5.0 – 15.0
Fraction of solar radiation reflected by the ice surface	ALBEDO	0.25	0.20 – 0.30
Temperature above which ice formation is not allowed (°C)	ICET	3.0	2.0 – 4.0

Objective Function

Temperature profiles are measured seasonally at five stations in Devils Lake (red circles and rectangles in Figure 1). We used data collected from 2008 to 2011 to automatically calibrate CE-QUAL-W2 model. The model ran in an hourly time step for two periods; 2008-2011 for calibration and 2012-2016 for validation. To validate our model, we compared hourly temperature simulated by the CE-QUAL-W2 model with temperature measurements gathered by a buoy (yellow star in Figure 1) from 2012 to 2016. We calculated the Root Mean Square Error (RMSE) in water temperature between simulation and observation. We used the temperature RMSE as the objective function and tried to minimize (Eq. 1) it by seeking an optimal combination of values of the calibration parameters within their respective bounds listed in Table 1 (Eq. 2):

38

$$\text{Min} \left(RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \right) \qquad (1)$$

subject to

$$X_{jL} \leq X_j \leq X_{jU} \qquad j=\text{BETA, WSC, ..., ICET} \qquad (2)$$

where P_i *and* O_i are simulated and observed water temperature and N is the number of observations; X_j is a calibration variable listed in Table 5 and its value is bounded between X_{jL} and X_{jU}.

To further evaluate the performance of the calibrated CE-QUAL-W2 in simulating temporal variation of lake temperature, we compared the temperature simulated in an hourly time step with temperature measurements gathered by a buoy (yellow star in Figure 12) from 2011 to 2016.

Improved Global Harmony Search Algorithm (IGHS)

In music, harmony is the sound effect caused by more than one musical instrument that plays at once (Theodossiou and Kougias 2012). A group of musicians can create a harmony by playing within their possible pitches. If the musicians generate a good harmony, they save their pitches in a memory in order to create a better harmony next time. The musicians can improvise their harmony by 1) playing pitches similar to those stored in the memory, 2) enriching the new harmony with new pitches that have not been played before, or 3) randomly play within their possible pitches. In the HS algorithm, the harmony is an analogy to the model output in term of objective function, each musician to a decision variable, and a group of musicians represents a solution. Similar to the harmony improvisation process, the HS modifies and improvises initial solutions toward an optimal solution. In calibration, a set of values assigned to the calibration

39

variables determines the RMSE value of the model output just as the pitches of musical instrument that determines the aesthetic quality.

HS uses control parameters to guide its search within a solution space. To enhance the convergence rate of the algorithm, several studies have modified the HS algorithm (Mahdavi et al. 2007, Omran and Mahdavi 2008). Recently, Xiang et al. (2014) proposed Improved Global-best Harmony Search (IGHS) that performs better than the HS and other modified versions in solving optimization problems (for more details see (Xiang et al. 2014)). We used IGHS to calibrate CE-QUAL-W2 model. The general procedures of implementing IGHS are as follows,

(1) *Initialize the optimization problem and algorithm parameters*. We specified the optimization problem using equations 1 and 2. IGHS algorithm parameters such as memory size, Memory Consideration Rate (MCR) and Variable/Pitch Adjustment Rate (VAR), and termination criteria were defined. MCR is a probability of creating a new solution from the solutions in the memory and VAR is a probability of modifying the new solution. We considered a memory with size of 10, and a range of values from 0.7 to 0.9 for MCR, and 0.25 to 0.5 for VAR (Ayvaz 2007). The termination criteria was set to 50 iterations because of length of simulation time, approximately half an hour per iteration, and this number of iteration is common (Ostfeld and Salomons 2005, Afshar et al. 2011).

(2) *Initialize a set of solutions.* We created a group of 10 solutions using the opposite-based learning approach,

For i=1 to 10 do (3)

For j in [BETA, WSC,....., ICET] do

$$x_{ij} = x_{lj} + r \times (x_{uj} - x_{lj})$$

$$ox_{ij} = (x_{uj} + x_{lj}) - x_{ij}$$

40

end for

end for

where, r is a uniformly distributed random number between 0 and 1; $X=\{x_{BETA}.......x_{ICET}\}$ is a solution and $OX=\{ox_{BETA}........ox_{ICET}\}$ is a solution at the opposite location of X in the solution space. We selected the solution with the smaller RMSE from a set of $X \cup OX$ and saved it in the memory (Figure 13). The advantage of this method is that the opposite position of the generated solution is also evaluated for choosing a better solution (Tizhoosh 2005). The RMSE value of each solution was calculated by running CE-QUAL-W2 model and the results were saved in the last column of the memory (Figure 13). We sorted the solutions based on their RMSE values in which the first and last rows of memory represented the best and worst solutions.

$$\begin{bmatrix} BETA_1 & WSC_1 & GICE_1 & .... & ICET_1 & RMSE_1 \\ BETA_2 & WSC_2 & GICE_2 & .... & ICET_2 & RMSE_2 \\ BETA_3 & WSC_3 & GICE_3 & .... & ICET_3 & RMSE_3 \\ & ....&...............&...............&...............& \\ BETA_9 & WSC_9 & GICE_9 & .... & ICET_9 & RMSE_9 \\ BETA_{10} & WSC_{10} & GICE_{10} & .... & ICET_{10} & RMSE_{10} \end{bmatrix}$$

Figure13. Scheme of memory generated in this study.

(3) *Improvise the memory*. In each iteration we improvised and updated memory as follows, (for details see (Xiang et al. 2014)),

While Iter ≤ max Iter (50) do   (4)

41

calculate the value of MCR and PAR value (Eqs.5, 6)

if r (0, 1) ≤ MCR

create a solution by randomly selecting its variables from the memory

if (0, 1) ≤ VAR

slightly modified the value of the selected variables

else:

create a random solution (Eq.7)

update the memory

where, Iter is the current iteration and max Iter is 50. The value of MCR and VAR were dynamically adjusted using following equations:

$$MCR_{Iter} = (MCR_{min} + \frac{MCR_{max} - MCR_{min}}{max\ Iter} \times Iter) \times max(0, sgn(sin(Iter))) \qquad (5)$$

$$VAR_{Iter} = (VAR_{min} + \frac{VAR_{max} - VAR_{min}}{VARIter} \times Iter) \times max(0, sgn(sin(Iter))) \qquad (6)$$

MCR_{min}, MCR_{max}, VAR_{min}, and VAR_{max} represent the lower and upper bounds of the MCR and VAR parameters, and their values were set in step 1; sgn and sin are sign and sin functions, respectively.

A random solution was created,

$$x_{j}^{'} = x_{cj} + \phi \times (x_{cj} - x_{dj}) \qquad for \qquad j=\text{BETA, WSC,}….., \text{ICET} \qquad (7)$$

$X^{'} = \{x_{BETA}^{'}....x_{ICET}^{'}\}$ is a new solution created using a random method; c and d are unequal random numbers between 1 and size of memory (10), and ϕ is a uniformly random number distributed between (-1,1). At the end of each iteration we updated the memory if the RMSE of new solution was better than the RMSE of the worst solution in the memory.

42

PSO Algorithm

PSO is a population-based evolutionary algorithm derived from animal social behaviors. While traveling, a group of animals like birds, fishes, etc. individually adjust their position and velocity using their own information and the information from the group to minimize the effort of searching for food and shelter (Khare and Rangnekar 2013). For example, among a group of birds that search for the hidden food over an area, there is always a bird that is closer than the others to the source of food. Noticing the bird approaching the food, the other birds become attracted and fly the same direction. And the birds that are farther from the food are willing to fly faster. During the searching, if any other bird comes closer to the target than the first, the birds will change their direction and follow the new bird. This process repeats until the group of birds eventually flock to the place of food. PSO mimics this phenomenon for solving an optimization problem. In this method, each solution is like a bird that can fly in multi-dimensional solution space by adjusting its position using its own and the group information. In PSO, the food is an analogy to optimal solution and the adjustment of birds' position is equal to the development of the solutions. The procedure of PSO are as follows: 1) initialize the problem and algorithm parameters, 2) initialize a group of solutions, 3) calculate the new velocity for the solutions, 4) update the position of solutions in the solution space using calculated velocity, and 5) check the stopping criterion. The steps 3 and 4 repeats until termination criteria satisfied. We implemented a PSO algorithm for calibration of CE-QUAL-W2 model following Afshar et al. (2011) and the algorithm was ran for the same termination criteria with IGHS algorithm, 50 iterations. The procedure of implementing PSO is as follows,

(1) The PSO parameters were set and a group of 10 solutions was randomly created

$$x_j = x_{lj} + r \times (x_{uj} - x_{lj}) \qquad \text{for} \qquad j = \text{BETA, WSC, ..., ICET} \qquad (8)$$

43

where, $X=\{x_{BETA}\ldots\ldots x_{ICET}\}$ is a solution. The solutions were stored in a memory similar to Figure 13. The corresponding vector velocity of each solution was created by combining the speed of the solution variables (v_{ij}, Eq. 10),

$$v_j = 0.1 \times (x_{uj} - x_{lj}) \qquad \text{for} \qquad j=\text{BETA, WSC, \ldots.,ICET} \qquad (9)$$

where, $v=\{v_{BETA}\ldots.v_{ICET}\}$ is the solution speed and was stored in a parallel memory. The RMSE value of each solution was calculated by running CE-QUAL-W2 model and the results were saved in the memory similar to Figure 13.

(2) In each iteration the position of the solutions toward the optimal solution was updated,

$$v' = w \times v + c_1 \times r \times (Pbest\ X - X) + c_2 \times r \times (Gbest\ X - X) \qquad (10)$$

$$w = w_2 + (w_1 - w_2) \times \frac{\max iter - iter}{\max iter} \qquad (11)$$

$$X' = X + v' \qquad (12)$$

where v' is the new velocity of a solution; w is the inertia weight; w_1 and w_2 are the maximum and minimum value of inertia weight and were set to 0.9 and 0.4 respectively; c_1 and c_2 are acceleration constant equal to 0.5 (Afshar et al. 2011); *Pbest X* and *Gbest X* are the best positions in term of the RMSE value that have been achieved by each solution and group of solutions so far; X' and X are the new and previous solutions, respectively. Throughout the PSO iteration, if a new solution was found better than the previous one, we replaced the old solution with the new solution. Otherwise, the solution remained unchanged.

(3) We repeated step 2 for 50 iterations similar to IGHS.

44

Results

IGHS Algorithm

The convergence of the IGHS algorithm is presented in Figure 14. The RMSEs for the 10 IGHS initial solutions varied between 1.40 and 1.80 °C (Figure 14a), where the minimum and maximum RMSE belong to solutions 1 and 10, respectively. In primary stage of the algorithm or the first 20 iterations, the diversity between initial solutions (Figure 14a) in memory helped the IGHS to create different solutions, or carry out a global search within the solution space (large peaks in Figure 14b), and find a new best solution with RMSE of 1.24 °C in iteration 18. Since the algorithm consistently updated the memory with good solutions, by approaching the termination criteria the diversity between solutions became smaller which allowed the algorithm to search in the neighborhood of the solutions for the better solution (small peaks in Figure 14b). This smooth transition from a global to a local search helped the IGHS to detect an optimal solution with RMSE = 1.23 °C in iteration 39.

45
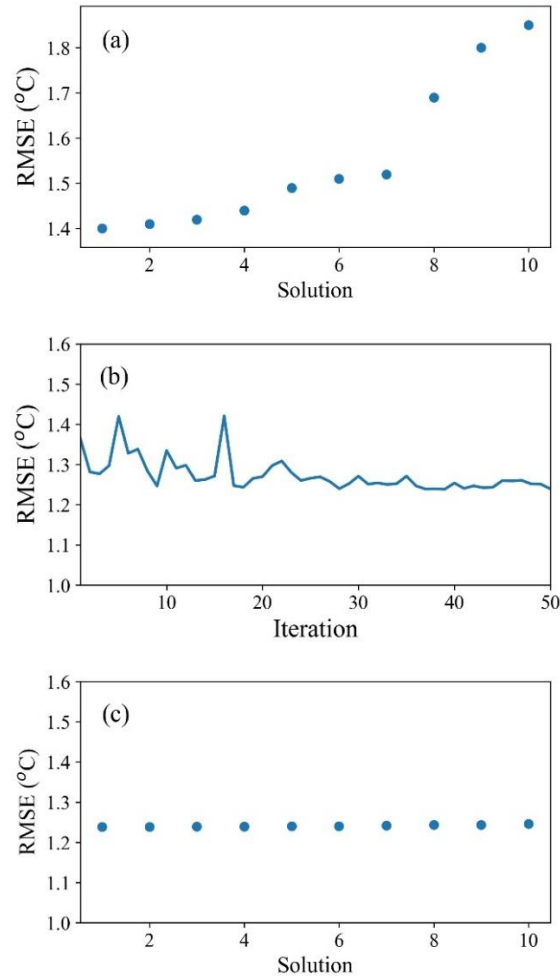
Figure 14. a) IGHS memory composing of 10 initial solutions used for thermal calibration of CE-QUAL-W2 model, b) RMSE of the new solutions calculated through the memory improvisation process, c) improvised memory after 50 iterations.

PSO Algorithm

The convergence of the PSO algorithm is illustrated in Figure 15. The RMSEs calculated for the initial 10 PSO initial solutions varied between 1.33 and 3.21 °C, where the minimum (the best solution so far) and maximum (the worst solution so far) RMSE values belong to solutions 10 and 2, respectively (Figure 15a). Throughout the first group movement or the first 10 iterations, the rest of solutions (the other birds) adjusted their position toward the best solution/number 10 (the source of food) (Figure 15b). The distances of the movement were longer (or the speeds of movements were faster) for those solutions (such as numbers 2 and 6) that had larger distance

46

toward the best solution, which shows a more significant decrease of their RMSE values. For example, the RMSE values decreased by 1.85 and 1.0 °C for solutions 2 and 6, respectively (Figures 15b). This process was repeated for the next group movements (Figures 15c, d, and e) until it reaches the stop criteria, which was 50 iteration (Figure 15f). Figure 15 also highlights one of the drawbacks of the PSO algorithm. The PSO algorithm, in this case, was not able to find an answer better than solution 10, which in fact was randomly created during the initialization of solutions. The PSO converged by gathering the other solutions around this solution.
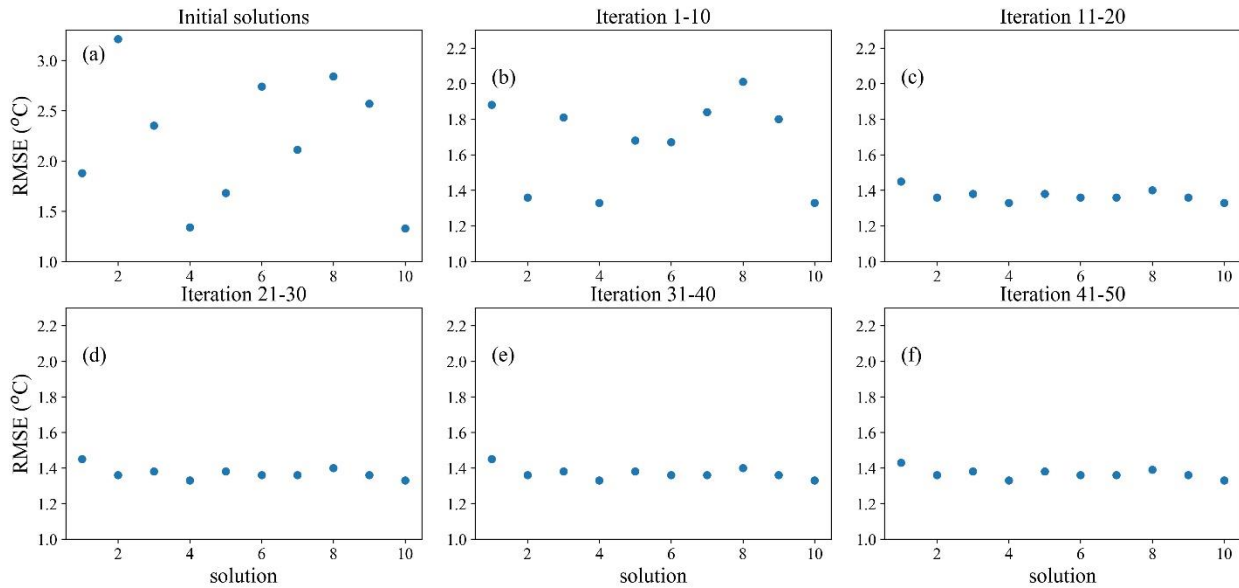
Figure 15. a) PSO 10 initial solution applied for thermal calibration of the CE-QUAL-W2 model, b-f) the minimum RMSE achieved by solutions through each set of iterations.

Devils Lake water temperature

The RMSE of final solutions calculated by IGHS and PSO algorithms for calibration of the CE-QUAL-W2 model are shown in Figure 16. The IGHS performed better than PSO by finding a better solution with RMSE of 1.23 °C vs. 1.33 °C. We used the calibrated variables achieved by IGHS and PSO (Table 2) to calculate the water temperature in Devils Lake. Figure 17 shows the result of IGHS, PSO, and manual calibration methods in capturing the temporal variation of water

temperature in Devils Lake. All calibrated models simulated trend of water temperature in the lake with R^2 =0.98, however, the IGHS calibration (Figure 17c) performed better than PSO with RMSE of 0.77 vs. 0.91 °C, respectively (Figure 17b). Our IGHS calibration method also improved the result of the simulated water temperature by 0.2 °C compared to the manual calibration (Figure 17a vs. 17c).
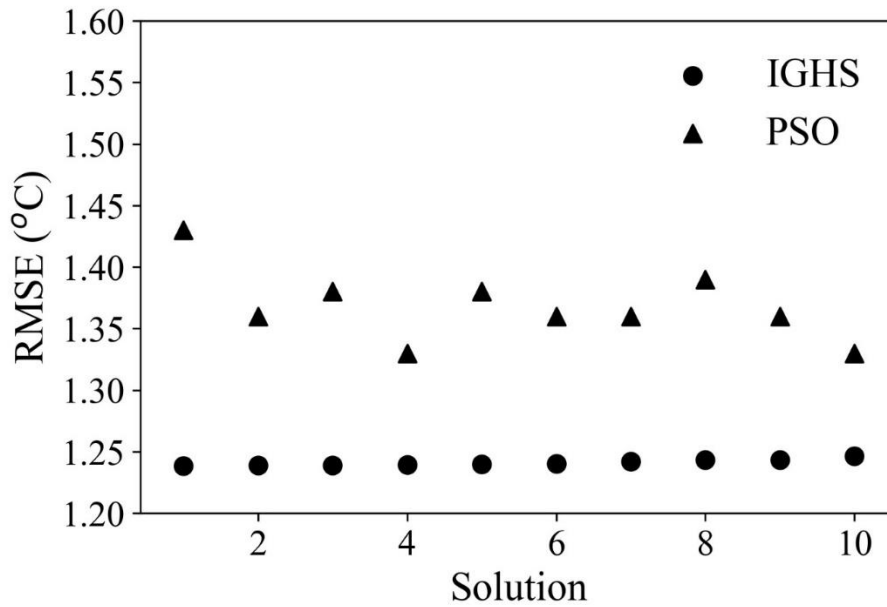
Figure 16. The RMSE of final solutions created by PSO (black triangles) and IGHS (black circles) algorithms for calibration of the CE-QAUL-W2 model.

Table 6. The RMSE and calibrated values for CE-QUAL-W2 parameters achieved by IGHS, PSO and manual methods.

Calibration	RMSE (°C)		Variable					
	Calibration	Validation	BETA	WSC	GICE	HWICE	ALBEDO	ICET
Default	------	------	0.45	1.0	0.07	10.0	0.25	3.0
IGHS	1.23	0.77	0.41	1.62	0.14	7.79	0.29	3.15
PSO	1.33	0.91	0.44	1.80	0.09	15.0	0.28	4.0
Manual	1.49	0.98	0.70	2.0	------	------	------	------

48
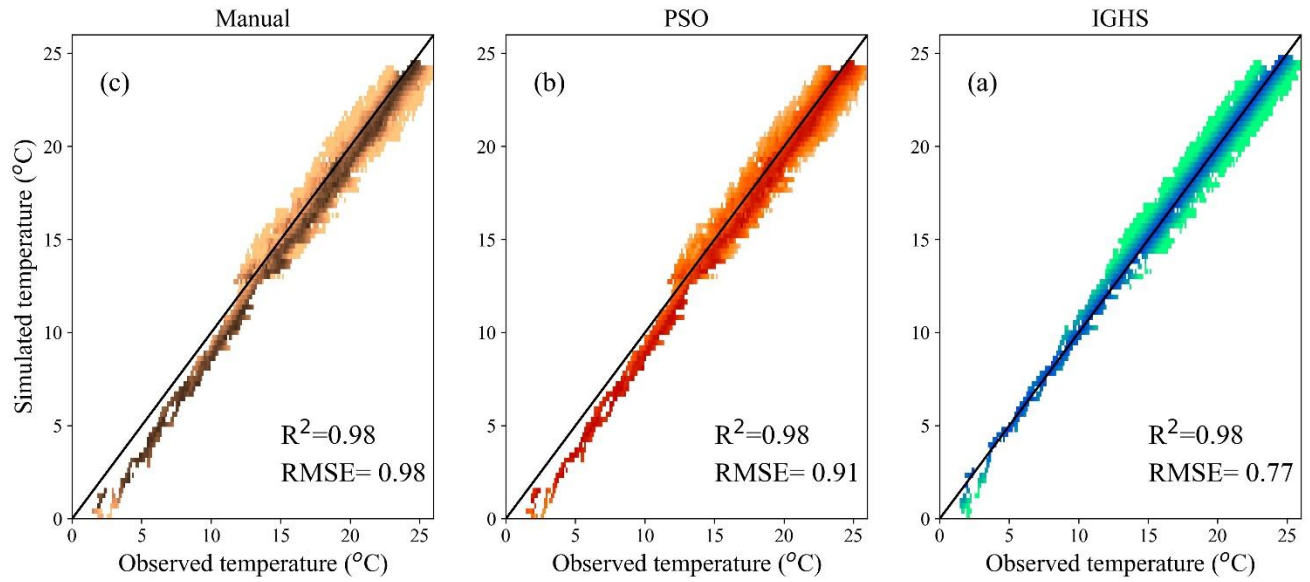
Figure 17. Temporal variation of Devils Lake water temperature simulated by (a) IGHS, (b) PSO, and (c) manual calibrated CE-QUAL-W2 model. The black dash line shows 1:1 relationship. All three methods simulated the temporal variation of water temperature with $R^2 = 0.98$.

Discussion

In this study, an automatic calibration of CE-QUAL-W2 model was presented using two meta-heuristic algorithms IGHS and PSO for calculating Devils Lake water temperature. The model was automatically calibrated by adjusting six decision variables. The result of our study indicated the superiority of the IGHS algorithm over the PSO in calibration of CE-QUAL-W2 model (Figures 16 and 17). Our automatic calibrated model also performed better than manual calibration in simulating the lake water temperature (Figure 17).

The PSO in this study was subjected to a premature convergence in which the algorithm trapped in local optima (solution 10) that was created during the initialization of solutions (Figure 15). PSO converges by linearly decreasing the velocity of solutions and gathering around an optimum solution. Because of this, the converged solutions may not have sufficient speed to escape from the local optima after they are gathered to the convergence point (Bahareh Nakisa 2014).

49

This process was observed in figure 15 where the early stages of the PSO the solutions tended to quickly converge toward the best local solution (Figures 15b,c, d) because they converged to this point they did not have enough velocity to escape (Figure 15e and f). One possible approach to solve this problem would be increasing the number of algorithm iterations which allows the solution to carry a better search in their neighborhood before converging to the optimum point. However, this was not the case for this study because of the high computational cost of the CE-QUAL-W2 model. Unlike the PSO, IGHS performed a smooth transition from global to local search to find the optimum solution (Xiang et al. 2014). The IGHS benefits from a random search subordinate method that allows the algorithm to escape from the local optima during each iteration.

The main step before accepting the result of an automatic calibration process is that the calibrated values attached to the variables should be physically sound. The solar radiation absorbed in the water provides heat and energy to the aquatic life. BETA shows the fraction of solar radiation absorbed within 0.6 m depth of water and it can be calculated from an empirical equation using Secchi disk depth (Pathmathevan et al. 2001). We calculated the value of this parameter using Secchi disk measurements for the Devils Lake for the time period of study. The BETA ranged between 0.21 and 0.73 for the lake and had an average value of 0.50 (Figure 18). The calculated the value of this parameters by our automatic calibration was 0.41 (Table 6) which is within the range of observation for Devils Lake and close to the average value of the measurements.

50
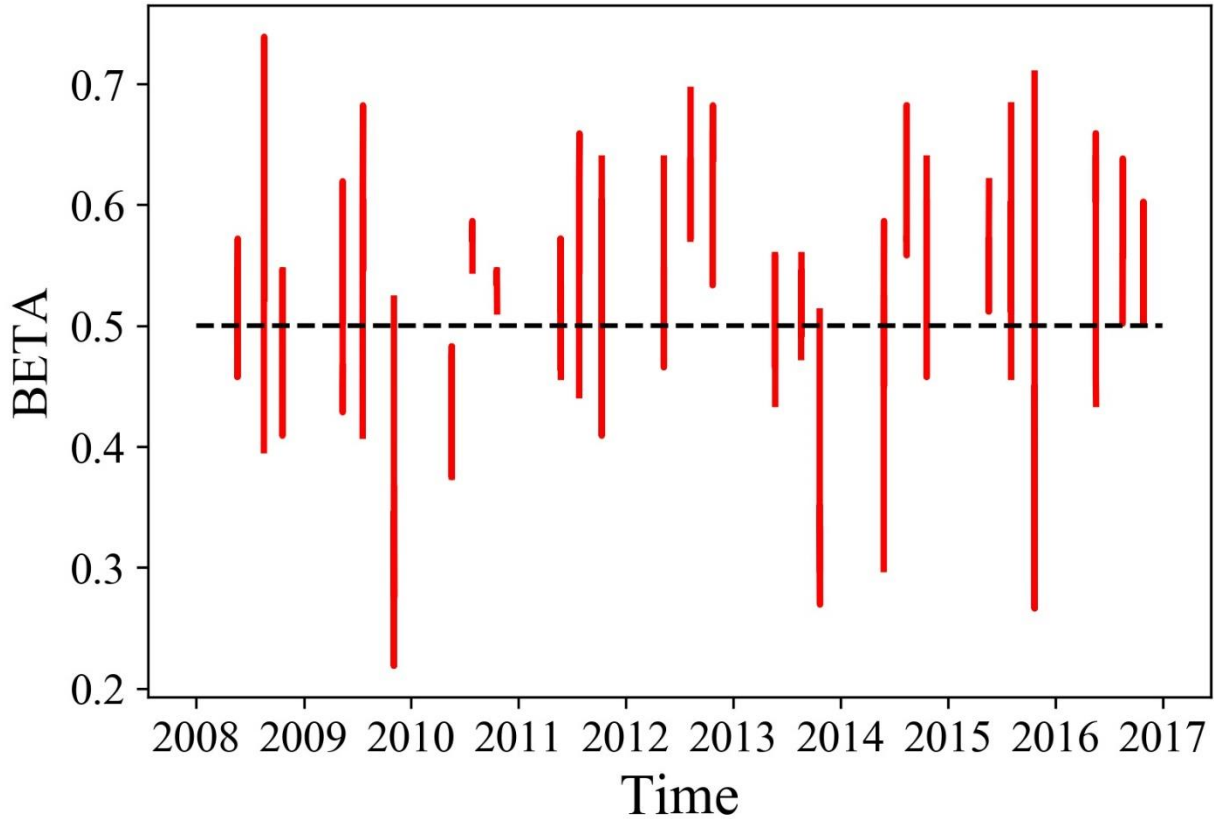
Figure 18. The fraction of solar radiation (BETA) absorbed within 0.6 m depth of Devils Lake water calculated from Secchi disk measurements. The black dash line shows the average value.

Wind is in direct connection with the lake water temperature through influencing the heat flux of water – air interface that affects the evaporation, and shear stress force which generates water current and mixes the lakes water columns. However, complex surroundings around the lake like tree canopy reduces the wind velocity over a lake and affects the result of simulated water temperature (Markfort et al. 2010). Because the wind speed records from the nearby climate station often use to determine the wind stress over the lake, the WSC is defined to adjust the recorded wind to the condition expected over the lake surface (Markfort et al. 2010). In this study, we used wind records at the Devils Lake airport climate station (black triangle in Figure 12) for our model. The calculated value for WSC shows that the wind speed over the lake is 1.61 times stronger than

51

measurements in the climate station. We further investigated our calculated value for WSC by comparing the wind speed data measured by climate station and buoy. The result of this comparison for a time period from May to October 2015 is shown in Figure 19. The graph confirms that the wind speed over the lake (blue line) is greater than measurements in climate station (red line) by a factor 1.30, which agrees better with IGHS-calibrated value of 1.61 (Table 6). The difference in wind speeds measured by buoy and climate station is likely due to the location of the climate station which is placed on the north side of the lake (black triangle in Figure 12) whereas winds were blowing predominantly from the south during the comparison period. The surrounding structures around the climate station acts as a shelter by reducing the wind speed.
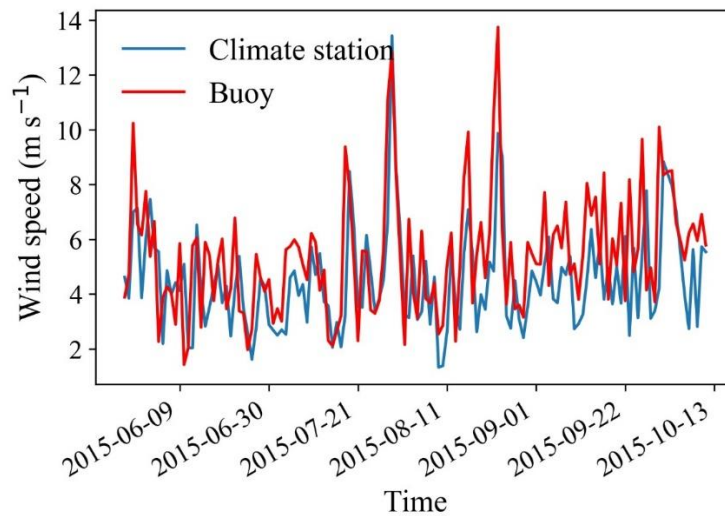
Figure 19. Blue and red graphs show the average daily wind speed measured respectively by Devils Lake airport climate station and buoy for the time period from May to October 2015.

Conclusion

Current calibration of the CE-QUAL-W2 is based on the trial and error, which is time-consuming and subjective to knowledge and experiment of the modeler. In this study, we proposed an automatic calibration method for simulating the Devils Lake water temperature using the IGHS algorithm. The IGHS was used to finely tune the model variables for calculating the water

temperature. The automatic calibrated model simulated the profile depth and temporal variation of the lake water temperature with RMSE of 1.33°C and 0.77°C, respectively. The proposed method superior to the primary method (PSO) applied for the calibration of the CE-QUAL-W2 model and created 0.20 °C improvement over the manual calibration for the simulation time period from 2011 to 2016.

We found that the application of PSO for optimization of a non-linear and highly complex problem such as calibration of the CE-QUAL-W2 may lead to algorithm premature convergence (Figure 15). In contrast, the IGHS successfully detected the near optimal solution within the model variables space and offered a reliable calibration in which the calibrated value of the variables were physically sounds compared to their measured values. The method developed in this study is also applicable to calibrate the model for simulating the other water quality constituents.

WATER QUALITY CONSERVATION IN MITIGATING DEVILS LAKE FLOODING

Introduction

Terminal lakes drain approximately 27% of the land surface area on earth (Todhunter 2001). Lacking outlets, terminal lakes maintain the balance of water supply from direct precipitation, surface runoff, and groundwater seepage through evaporation. Though these lakes have their own physical and chemical characteristics, a feature most common among all of them is vulnerability to climate change (Van Der Kamp et al. 2008). Water levels in a terminal lake change in response to the shift between wet and dry climate cycles. During a wet cycle, the water levels increase because the amount of precipitation surpasses evaporation and other losses; in contrast, a dry cycle results in an intensive evaporation and water level reduction. In North America, altering wet and dry climate cycles in the past has dramatically changed water levels of terminal lakes varying from low to overflowing (Van Der Kamp et al. 2008). Due to their unique drainage systems, terminal lakes tend to increase rapidly during wet climate cycles, frequently causing damages by flooding their adjacent land and communities. Precipitation over Great Salt Lake in Utah, USA, had increased 134% between 1982 and 1986, raising the lake water level by 3.66 m to a historical level of 1283.77 m and causing more than $300 million flood damages. Malheur Lake in Southeastern Oregon started to rise in 1982 and quickly reached its natural spillage at an elevation of 1247.5 m into the adjacent Mud and Harney Lakes. In 1986, the lake reached an elevation of 1250.4 m and inundated 40,470 ha of the surrounding lands. The cost of Malheur Lake flooding from 1982 to 1986 was estimated to be more than $20 million (Wahab 1987). Quill Lake, located in Saskatchewan, Canada, consists of three small lakes: Big Quill Lake, Mud Lake, and Little Quill Lake that together form a unified lake at an elevation of 518.2 m. Since 2004, the Quill Lake water level has risen by nearly 7 m from 513 m to 520.64 m in 2016. High

water levels have caused damages to nearby transportation networks and flooded more than 30,000 ha of public and private lands (KGS Group Consulting Engineers 2016). The water level of Devils Lake, North Dakota, has risen by nearly 10 m since 1993 (Figure 20). The rising water has flooded portions of the City of Devils Lake and adjacent communities, inundated farmlands, and caused significant damage to infrastructures in the area. Over $1 billion has been spent in mitigating the flooding (Zheng et al. 2014).

As a common approach to control a lake flooding, construction of outlets which diverts water from the terminal lake into the nearby waterbodies is considered as a timely and effective mitigation measure (Morrisette 1988). However, this type of diversion typically has negative impacts on downstream waterbodies, for example, by changing natural flow regime, degrading water quality, and/or introducing invasive species (Kharel and Kirilenko 2015). To mitigate Great Salt Lake flooding, a $60 million pumping system was constructed in 1986 to remove water from the lake to Great Salt Lake Desert (Morrisette 1988). Since the pump only operated for a short period before the lake started to recede in 1987 as a dry cycle came, the environmental impacts of the outlet have never become a concern. However, very often the environmental consequences passed on the downstream communities could render the diversion strategy politically controversial. To mitigate the Malheur Lake flooding several short- and long-term solutions were proposed. One of the long-term solutions was to drain water from the lake into the nearby Malheur River through a drainage canal (Virginia canal). While the plan was supported by farmers and ranchers in the Malheur County, the neighboring counties opposed it because pumping water from the lake into the river could cause river bank erosion and sedimentation, damage fisheries, and lower the quality of water being withdrawn from the river for irrigation (Wahab 1987). Failure of reaching a consensus, the proposed plans were never implemented. Fortunately, the Malheur Lake

55

water level started to recede in 1987. To mitigate Quill Lake flooding several options including tributary diversions, outlet construction, and decommission of agricultural drainage networks were considered. While agricultural drainage is not a significant cause of the lake water level rise, neither of the two other solutions has been implemented because their environmental impacts have yet to be studied (KGS Group Consulting Engineers 2016).

Devils Lake has experienced a prolonged wet climate cycle starting in 1993 (Schuh 1999) which elevated the water level to a historical record of 443.3 m in 2011. At 444.4 m, Devils Lake would naturally spill into the Sheyenne River. To prevent uncontrolled spillage, which could potentially lead to catastrophic flooding and water quality disaster to the downstream communities (Ma et al. 2011) since spillage occurs at the lowest quality water out of Stump Lake (east end of Devils Lake), a control structure was constructed in 2012 at Tolna Coulee (Figure 22) where the natural spill could be limited to a maximum of 85 m^3 s^{-1} if the lake reaches the maximum elevation of 444.4 m. To further control the Devils Lake flooding and to avoid its natural spillage, two emergency outlets were constructed at the west and east parts of the lake to drain the lake water to the Sheyenne River in a controlled fashion. While the main purpose of the outlets is to prevent the Devils Lake water level from continuously rising to its spillage level (444.4 m), their operation is further guided by two requirements: (1) Sheyenne River at the outlet insertion points should not be overbanked (US Army Corps of Engineers 2003); and (2) water quality standards should be maintained to meet beneficial use for aquatic life in the Sheyenne River as determined by the North Dakota Department of Health (NDDOH) and codified in North Dakota Administrative Code (NDAC) 33-16-02.1.

The west outlet was completed in August 2005 with a maximum release capacity of 3 m^3 s^{-1}. The west side of Devils Lake has a sulfate concentration of ~600 mg l^{-1}, about 5 times higher

than the average historical sulfate concentration of 125 mg l^{-1} for the Sheyenne River, estimated from the measured sulfate data at gauging stations 3 and 4 (Figure 21). Between 2005 and 2008, the west outlet operated sporadically to follow the downstream water quality regulation. The sulfate concentration level of the Sheyenne River was initially limited at 300 mg l^{-1}. As a result, the west outlet only diverted 46,872 m^3 in 2005 and did not operate at all in 2006, due to the fact that the background sulfate concentration in the Sheyenne River was already high. Later, the NDDOH modified the Sheyenne River sulfate concentration limit to 450 mg l^{-1} to match the state-wide Stream Class IA standards. In 2009, with the Devils Lake water level continuing to rise, the NDDOH adopted an emergency rule to allow sulfate concentration up to 750 mg l^{-1} from the headwaters of the Sheyenne River to 0.16 km downstream from the Baldhill Dam (NDAC 33-16-02.1-09). The Baldhill Dam and its reservoir (Lake Ashtabula) separate the upstream of the Sheyenne River from the downstream (Figure 22).

As the lake level continued to rise to an eventual peak of 1.1 m from overflowing, it became clear that a greater outlet capacity would be urgently needed to reduce the probability of an uncontrolled overflow into the Sheyenne River. In response, the State of North Dakota made the decision to invest further in outlet infrastructure. In 2010, the west outlet was expanded to 7 m^3 s^{-1} and in 2012 an east outlet with a capacity of 10 m^3 s^{-1} was completed.

In a recent study, we found that operating the two outlets from 2005 to 2014 had lowered the Devils Lake water levels by 0.7 m (Shabani et al. 2017). We also found that the sulfate concentration generally increases from the west end of the lake, where relative fresher water from the basin flows in, to the east end of the lake, where the natural spillage would occur (Figure 20).

Discharge water from the Devils Lake outlets is in direct connection with the lake water levels and the Sheyenne River water quantity and quality. Since 2012, the west and east outlets

have operated with an average discharge of 5.9 and 6.6 $m^3 s^{-1}$, respectively, from April to October and lowered the lake water level to 441.8 m (Figure 20). However, discharging the low quality lake water particularly from the east outlet has violated the 750 mg l^{-1} ND sulfate standard for the Sheyenne River upstream. The goal of this study is to identify an alternative mitigation strategy that lowers the lake water levels and prevent the risk of flooding in the downstream river, and at the same time preserve the water quality of the Sheyenne River. To achieve this goal, we developed a SWAT model for the Sheyenne River to simulate the daily discharge and connect it to our previously coupled SWAT and CE-QUAL-W2 model developed for Devils Lake to calculate the sulfate concentrations in the river. The coupled system is capable to provide the whole profile of water level in the lake and the corresponding sulfate concentration in the river for identifying the desired outcomes as an optimal solution.
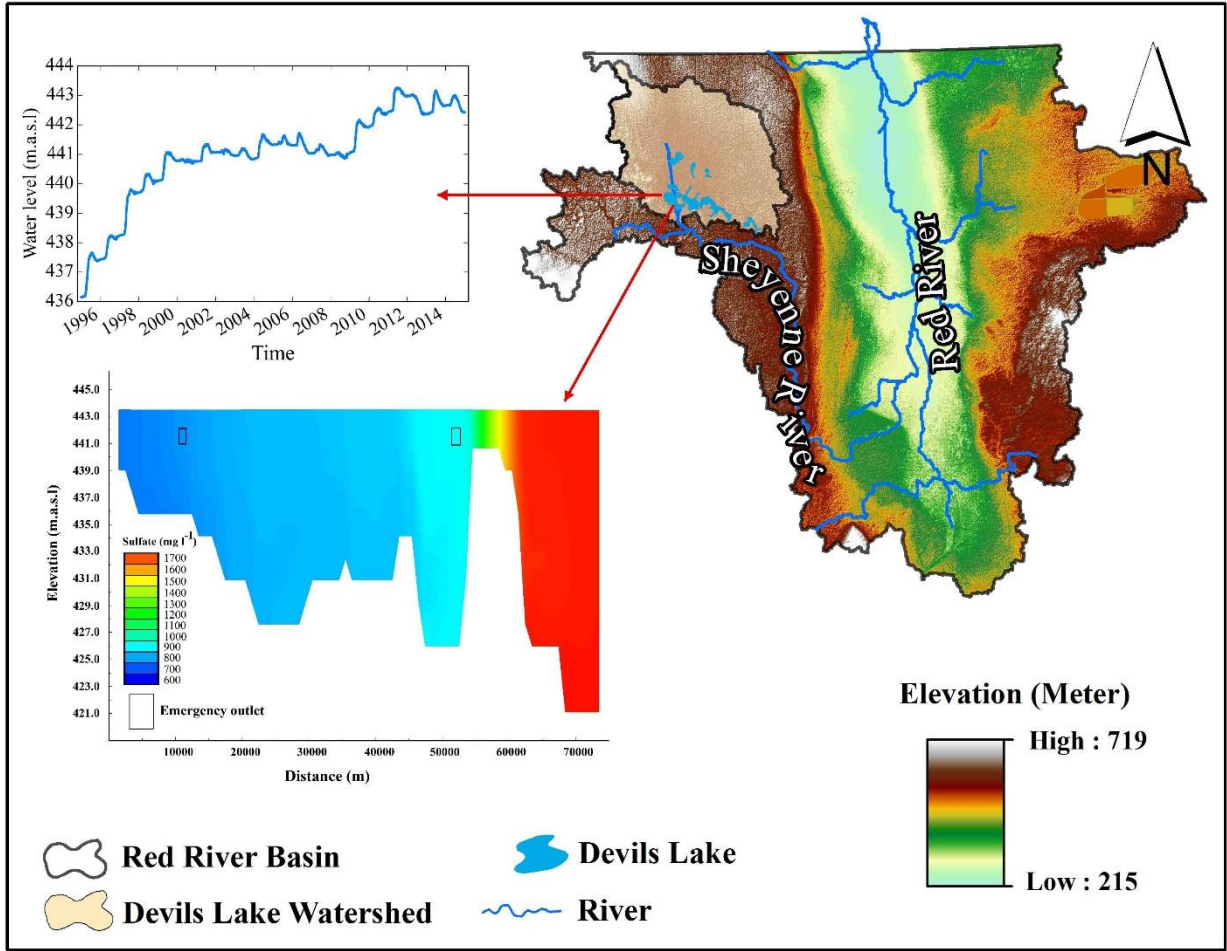
Figure 20. The Digital Elevation Model showing the U.S. portion of the Red River of the North basin and the Devils Lake watershed. The two inserts depict observed daily water levels of Devils Lake from 1993 to 2018 and simulated sulfate concentrations from the west end to the east end on July 1, 2012 (Shabani et al. 2017).
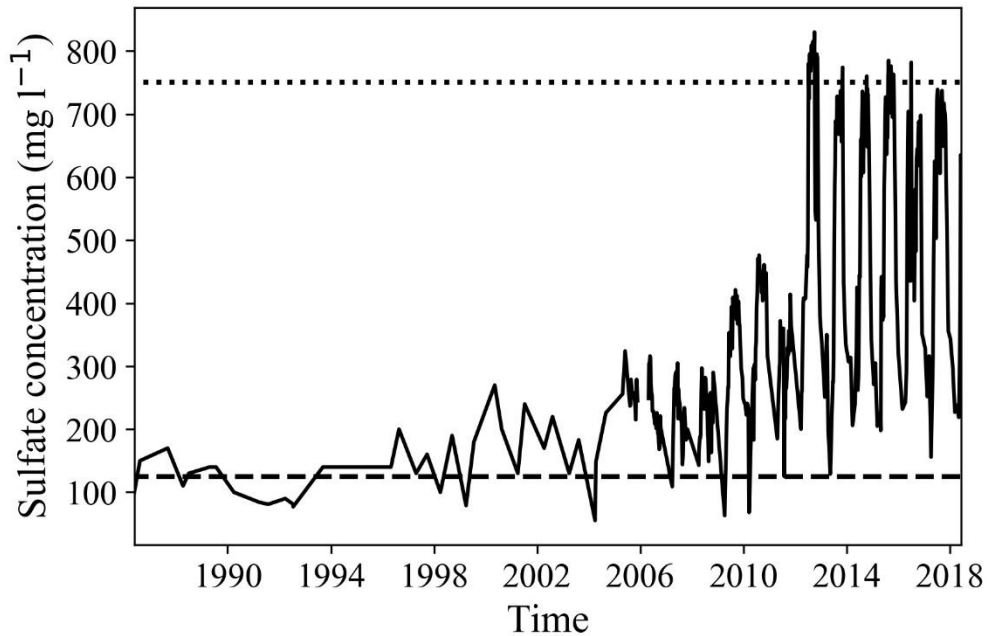
Figure 21. Sheyenne River sulfate concentration measured at gauging station 4 for the time period from 1986 to 2018. The black dot line is representing the 750 mg l^{-1} ND sulfate standard implemented in the Sheyenne River. Black dash line is the 125 mg l^{-1} historical average sulfate concentration, which is calculated from measured sulfate data at gauging stations 3 and 4 for the time period from 1951 to 2004.

Methodology

Study Area

Devils Lake and the Sheyenne River are within the Red River of the North drainage system. The rapid rising of Devils Lake water level since 1993 (Figure 20) has prompted the construction of two outlets to discharge water from Devils Lake to the Sheyenne River (Figure 22). The water discharged from the outlets mixes with the river water and flows into Lake Ashtabula before reaching the downstream Sheyenne River. Since Lake Ashtabula is a controlled reservoir with different hydrological features from the Sheyenne River, we focused our study area on the upstream of the Sheyenne River, i.e., from its headwater to just before its entrance to Lake Ashtabula (Figure 22).

60
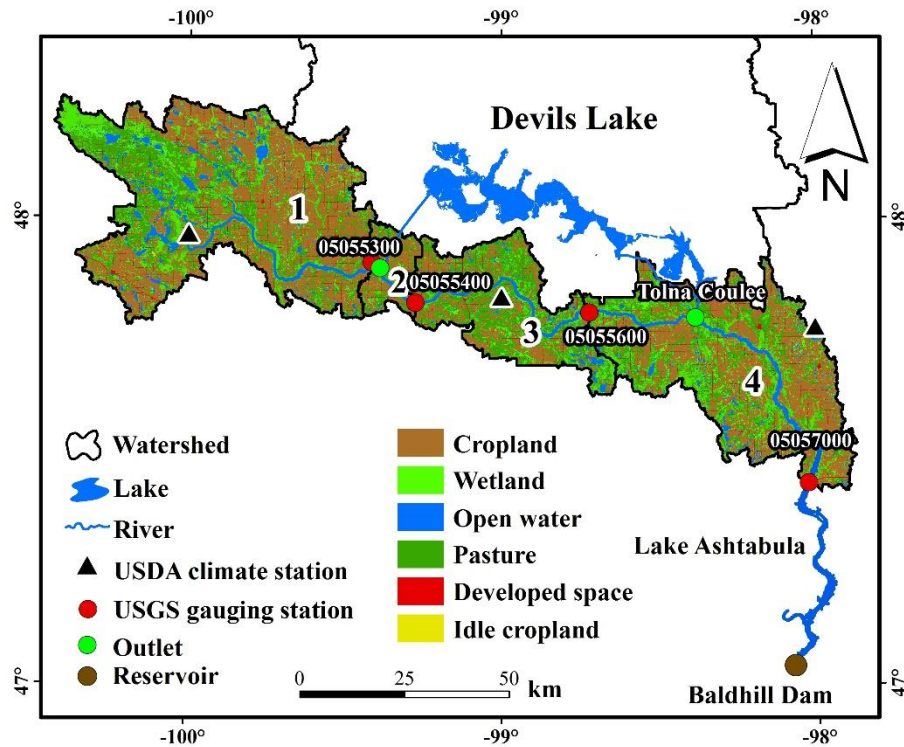
Figure 22. The upstream of the Sheyenne River watershed is delineated into 4 sub-watersheds, overlaid with the land use map. Also shown are three USDA climate stations (black triangles), four USGS gauging stations (red circles), and the insertion points (green circles) of the two outlets. The four USGS gauging stations are: 05055300, 05055400, 05055600, and 05057000, which will be referred to hereafter as 1 to 4, respectively.

Within the study area, the Sheyenne River meanders 302 km, encompassing a drainage area of 5,610 km^2. Except during the early spring when snow melts, discharge is typically low. For example, the discharge measured at gauging station 4 during the spring and summer seasons from 1950 to 2004 has a median value of 0.9 m^3 s^{-1} and a 95 percentile value < 17 m^3 s^{-1} (Figure 23). The Sheyenne River watershed is mostly flat, with slopes typically < 3%. About 59% of the area is comprised of croplands, mainly planting spring wheat, soybeans, dry beans, corn, and sunflowers. Pasture and grassland cover 38% of the watershed, and the remaining 3% includes water bodies, wetlands, idle cropland, and developed area (Figure 22). Soils in the watershed are mainly EMRICK, SVEA, and HEIMDAL, and they are deep with well or moderately well draining capacity.

61
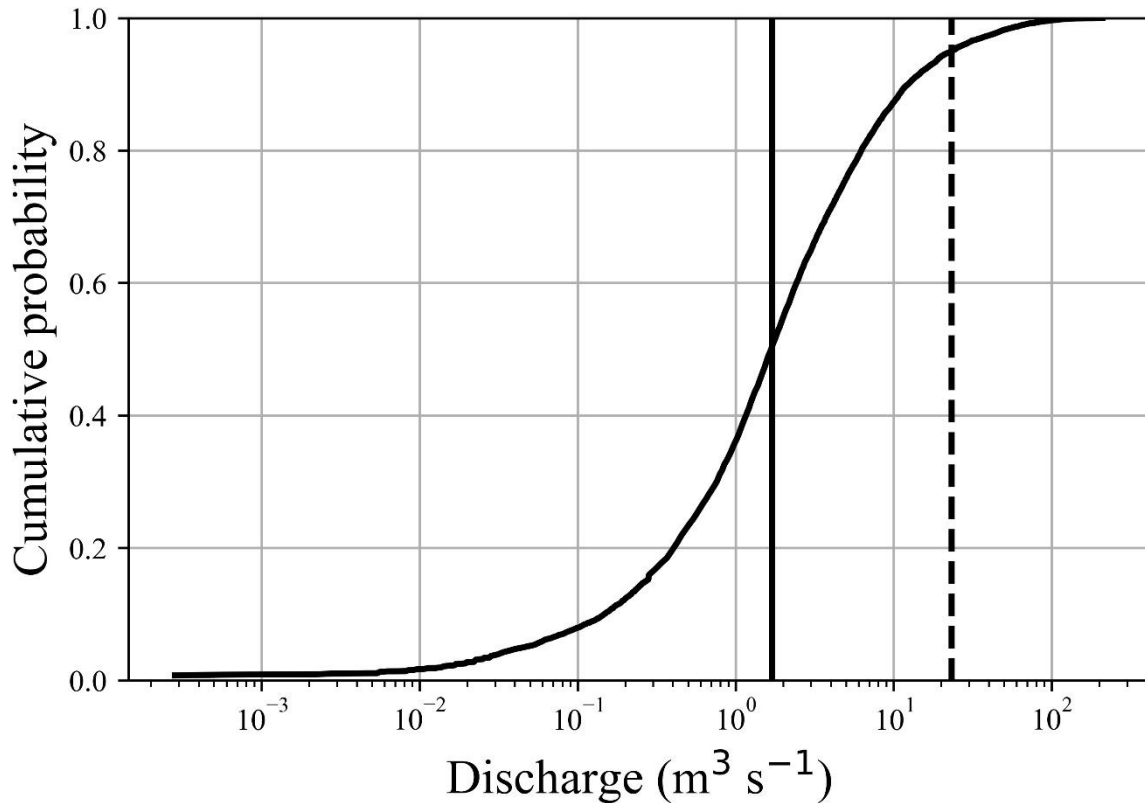
Figure 23. Cumulative distribution of the Sheyenne River discharge estimated using data collected at gauging station 4 between April and October from 1950 to 2004. The median discharge rate is 0.9 m^3 s^{-1} (vertical solid line) and 95th percentile is at 17 m^3 s^{-1} (vertical dashed line).

SWAT model

SWAT has been widely used for watershed-scale hydrology and water quality modeling (Saleh et al. 2000, Gassman et al. 2007, Krysanova and Arnold 2008, Qiu and Wang 2014, Tahmasebi Nasab et al. 2017, Kharel et al. 2016). A 10-m Digital Elevation Model (DEM) was used to delineate the upstream Sheyenne River watershed into 4 sub-watersheds, bordered by four USGS gauging stations (Figure 22). The land use map from the USDA National Agricultural Statistics Service (NASS), the soil type map from the USDA STATSGO dataset, and the slope distribution estimated from the DEM were used to divide the watershed into 69 hydrologic response units (HRUs), using commonly used thresholds for land use, 5%, soil, 10%, and slope, no threshold (Her et al. 2015). Climate data including daily precipitation, maximum and minimum

المنارة للاستشارات

www.manaraa.com

temperatures were acquired from three USDA weather stations (black triangles in Figure 22). The two outlets were defined as point sources in the SWAT model (green circles in Figure 22), and their daily discharge values were obtained from the North Dakota State Water Commission. Table-1 lists the data used in this study and their sources.

We ran the SWAT model with a daily time step for three time periods: 1995 – 1999 for warm-up to properly establish the initial values of its parameters, 2000 – 2007 for calibration and from beginning of 2008 to June 2018 for validation. Among the four USGS gauging stations (red circles in Figure 22), stations 1 and 2 started operating in 2004 and 2005, respectively, while stations 3 and 4 have been operating since 1950. SWAT simulated daily discharge at the four gauging stations was used to conduct a sensitivity analysis using the Latin hypercube parameter sampling method implemented in SWAT-CUP (Abbaspour 2014). The simulated discharge was found most sensitive to the following nine parameters (Table 8): threshold temperature for snowmelt, snowmelt factors, moisture condition II curve number, groundwater revap coefficient, surface runoff lag coefficient, plant uptake compensation factor, soil evaporation compensation coefficient, and soil available water capacity. These nine parameters were calibrated automatically using the SUFI 2 algorithm with the Nash-Sutcliffe model efficiency coefficient (E_{NS}) as the objective function (Abbaspour 2014).

63

Table 7. Sources of input data for this study.

Data type	Sources
10-m Digital Elevation Model	https://gdg.sc.egov.usda.gov/
30-m Land use/land cover	https://www.nass.usda.gov/Data_and_Statistics/
STATSGO Soil	http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/ngce/
Weather data	http://www.ars.usda.gov/Research/docs.htm?docid=19435 http://www.prism.oregonstate.edu/
Discharge	http://maps.waterdata.usgs.gov/mapper/index.html
Outlets discharge	http://www.swc.nd.gov/basins/devils_lake/outlets/discharge_monitoring/
Sheyenne River sulfate concentration	http://maps.waterdata.usgs.gov/mapper/index.html https://www.ndhealth.gov/WQ/sw/Z8_SWData/viewer.html
NOAA Climate Forecast System version 2 (CFSv2)	ftp://ftpprd.ncep.noaa.gov/pub/data/nccf/com/cfs/prod/cfs

64

Table 8. Values of SWAT parameters calibrated for the Sheyenne River watershed.

Parameters and units	Description	Acceptable range	Calibrated values/ranges
SMTMP (basin)	Threshold temperature for snowmelt (°C)	-5.0 – 5.0	2.0
SMFMX (basin)	Snowmelt factor on June 21 (mm H_2O °C^{-1}d^{-1})	0.0–10.0	4.50
SMFMN (basin)	Snowmelt factor on December 21 (mm H_2O °C^{-1}d^{-1})	0.0–10.0	1.17
CN$_2$ (management)	Curve number (AMC II)	±25.0% of default value	-0.11% of default value
GW_REVAP(groundwater)	Revap coefficient (Revap: water in shallow aquifer returning to root zone (mm H_2O))	0.02–0.20	0.10
SURLAG (HRU)	Surface runoff lag coefficient	0.0–24.0	4.60
EPCO (HRU)	Plant uptake compensation factor	0.0–1.0	0.23
ESCO (HRU)	Soil evaporation compensation coefficient	0.0–1.0	0.47
SOL_AWC (soil)	Available water capacity	±25.0% of default value	-0.07% of default value

Two statistical parameters, coefficient of determination (R^2) and E$_{NS}$, were used to evaluate the performance of the SWAT model in terms of comparison between the simulated and measured river discharges (Moriasi et al. 2007).

Flood frequency analysis

The knowledge of frequency and magnitude of flood peak is important to assess the flood risk. Flood frequency analysis is an approach to calculate the magnitude of flood-peak discharge and the associated exceedance probability (Gotvald et al. 2012). The log-Pearson Type III method,

65

as recommended by Bulletin 17B of Interagency Advisory Committee on Water Data (1982), is commonly used for flood frequency analysis by USGS (Gotvald et al. 2012). We calculated the magnitude of flood for 5 recurrence intervals (2, 5, 10, 25, and 50 years) by applying the log-Pearson Type III distribution to the dataset of annual maximum instantaneous discharges measured for more than 60 years at gauging stations 3 and 4 (Table 9).

TABLE 9. The Sheyenne River flood frequency calculations using log-Pearson Analysis III for the period of record from 1950 to 2014.

Return Period	Gauging station 3	Gauging station 4
(years)	Discharge ($m^3 s^{-1}$)	Discharge ($m^3 s^{-1}$)
2.0	28.0	39.0
5.0	67.0	87.0
10.0	100.0	128.0
25.0	149.0	187.0
50.0	190.0	236.0

Sheyenne River Sulfate Concentration

In a previous study, we coupled SWAT and CE-QUAL-W2 models to simulate the water level and sulfate concentration of Devils Lake (Shabani et al. 2017). Using the same model development, we extended our simulation to 2018 to match the time period of our present study. The Sheyenne River sulfate concentrations at the outlet insertion points ($S_i(t)$, mg l^{-1}) is calculated by:

$$S_i(t) = \frac{(Q_R(t) \times S_R(t) + (Q_W(t) \times S_W(t)) + (Q_E(t) \times S_E(t))}{Q_R(t) + Q_W(t) + Q_E(t)} \tag{13.0}$$

where $Q_R(t)$ (m^3 s^{-1}) is the Sheyenne River natural discharge at time (t) which was calculated by turning off the outlets in our SWAT model; $Q_W(t)$ and $Q_E(t)$ (m^3 s^{-1}) are the measured discharge at the west and east outlets, respectively ; $S_W(t)$ and $S_E(t)$ (mg l^{-1}) are the sulfate concentration at the

66

west and east outlets simulated by using the coupled SWAT and CE-QUAL-W2 model developed in Shabani et al. (2017); $S_R(t)$ is the Sheyenne River sulfate concentration and was set to 125 mg l^{-1} representing the average sulfate concentration at gauging stations 3 and 4 (Figure 22) before the construction of the outlets. Gauging station 3 has 292 seasonal sulfate concentration records for the time period from 1951 to 2004, and gauging station 4 has 36 seasonal sulfate measurements for the time period from 1984 to 2004. The average sulfate concentration for the Sheyenne River was calculated using these seasonal measurements. Daily native sulfate concentrations in the river should be used to calculate change in the river sulfate concentration at the time of the outlets operation. One straightforward method to estimate daily sulfate concentration in the river is to apply a regression model which uses correlation between measured sulfate and river discharge at the time of sampling for its estimation (Burke et al. 2018). We tested this method but unfortunately did not find a strong correlation between measured sulfate concentrations and river discharge at the time of sampling for both gauging stations 3 and 4, $R^2 \leq 0.02$. The calculated Sheyenne River sulfate concentrations from Equation 1 were validated against measurements at gauging stations 3 and 4 using two statistical parameters, coefficient of determination (R^2) and percentage of bias (PBIAS) (Moriasi et al. 2007).

Optimization of Devils Lake Outlets Management

We applied an optimization method to test if the current outlets management strategy can be improved with less environmental impact on the Sheyenne River. The main objective function is to minimize the river sulfate concentration (Equation 14.0) by adjusting the volume of water released from the outlets when both outlets were operational from April 2012 to June 2018. The discharge of west and east outlets are two variables that will be adjusted within their maximum capacity (Equations 14.1 and 14.2). Since, the west side of Devils Lake has lower sulfate

67

concentrations (Figure 20) compared to the east side we prioritized the operation of the west outlet above the east outlet, which will start only after the west outlet reaches its full capacity (Equation 14.3). Note that the current outlets operations do not have this feature, even though the operation of the east outlet has a higher impact on water quality in the Sheyenne River (Shabani et al., 2017). In order to maintain the efficiency of the outlets in controlling Devils Lake water level, we constrain the total volume of discharged water from the outlets in our model to be equal to the total amount of water that has been released from the outlets during this test time period (1.16 km^3, Equation 14.4). In addition, to control risk of flood in the Sheyenne River during the outlet operation we constraint the total discharge in the Sheyenne River below a constant value (Q, Equation 14.5) which were to be determined later in this study. Conceptually, the optimization model for the Devils Lake outlets management can be expressed as:

$$\text{Minimize } (S_i(t)) \tag{14.0}$$

$$0 \le Q_W(t) \le 7 \tag{14.1}$$

$$0 \le Q_E(t) \le 10 \tag{14.2}$$

$$\textit{If } Q_W(t) < 7 \textit{ then } Q_E(t) = 0 \tag{14.3}$$

$$\int_{2012}^{2018}[Q_W(t) + Q_E(t)]dt = 1.16 km^3 \tag{14.4}$$

$$Q_R(t) + Q_W(t) + Q_E(t) \le Q \tag{14.5}$$

where, Q_W and Q_E are discharge from the west and east outlet within their maximum capacity of 7 and 10 m^3 s^{-1}, respectively; Q_R is the Sheyenne River natural discharge; Q is the maximum discharge (m^3 s^{-1}) in the Sheyenne River during the outlet operation and its value will

68

be determined after evaluating the impact of the current outlet management on the Sheyenne River discharge. We numerically simulated the dynamic system for the time period from beginning of 2012 to June 2018 to test if the proposed operation scheme can further reduce the environmental impact on the downstream Sheyenne River. We then incorporate the National Oceanic and Atmosphere Administration (NOAA) near-term Climate Forecast System version 2 (CFSv2) data (Table 7) in our models, combined with the optimized outlet operation schedule, for future prediction.

RESULTS

SWAT Modeling and Impact of Outlets on Discharge

The simulated daily discharges at the four gauging stations are compared with the observations in Table 10 and Figure 24. The performance of the SWAT model ranged from satisfactory to very good for the calibration period and was satisfactory for the validation period (Table 10). The model underestimated the spring peak flows for both calibration and validation periods in all sub-watersheds (Figure 24). Also, the underestimation was greater for the validation period, during which higher discharge was observed than during the calibration period. The Sheyenne River experienced three major floods in 2009, 2011, and 2013, respectively. The flood frequency analysis using the data collected since 1950 at gauging stations 3 and 4 (Table 9) indicated that the 2009, 2011 and 2013 floods had 20-, 50- and 10-year recurrences, respectively. For the 2011 flood, the maximum daily peak flows reached 192 and 228 $m^3\ s^{-1}$ at gauging stations 3 and 4, respectively, both being historically high (Figure 24). It also caused the Sheyenne River to reach its second highest crest on record in Valley City (located downstream of Baldhill Dam, Figure 22). For the 2009 and 2013 floods, no major flooding damage was reported.

69

Table 10. Statistical evaluation of the SWAT model for simulating discharge at 4 gauging stations.

Gauge	Number of observation (2000-2016)	Calibration period		Validation period	
		R^2	E_{NS}	R^2	E_{NS}
1	5381.0	0.85	0.78***	0.60	0.57*
2	4839.0	0.81	0.67**	0.57	0.55*
3	6756.0	0.66	0.52*	0.62	0.53*
4	6756.0	0.74	0.62*	0.63	0.59*

*** Very good simulation: $0.75 < E_{NS} \leq 1.0$

** Good simulation: $0.65 < E_{NS} \leq 0.75$

* Satisfactory simulation: $0.50 < E_{NS} \leq 0.65$

Unsatisfactory simulation: $E_{NS} \leq 0.50$ (Moriasi et al. 2007)
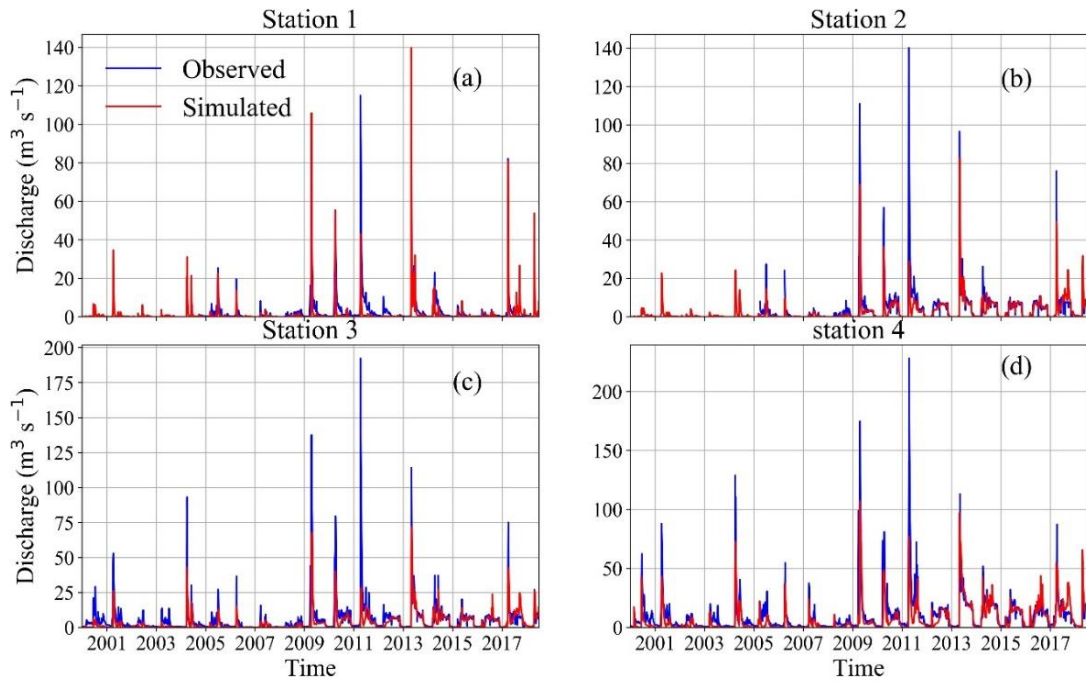
Figure 24. Simulated and observed discharge from 2000 to 2018 at 4 gauging stations. For gauging stations 1 and 2, the observation started in 2004 and 2005, respectively; and for gauging stations 3 and 4, the observation started in 2000.

70

Since one of the guidelines for operating the outlets is to avoid the Sheyenne River overbank flooding, the general operation of the outlets follows the following criteria: (1) no operation during the winter frozen time, (2) minimum or no operation during early spring when flash floods tend to occur, and (3) maximum discharge during the summer and fall seasons when the base river discharge is typically low. In general, outlet operations have been managed to keep the river discharge to a maximum of ~ 26 $m^3 s^{-1}$ at gauging station 4 (Figure 25-d) which allows low lying fields along the riverbank to be farmed. Occasionally, river discharge exceeded this target when major precipitation events occurred while the outlets were operating. For example, one of the largest increases in the Sheyenne River discharge occurred on August 25, 2014, when both outlets were operating at their full capacities and 63 - 100 mm of rain fell in the area increasing the river discharge from 19 to ~ 40 $m^3 s^{-1}$ at gauging station 4 (green star in Figure 25-d). Since 2012, the two outlets have operated at their respective maximum capacities for 152 days, during which it occurred only in 6 days that the Sheyenne River discharge reached above 26 $m^3 s^{-1}$ at gauging station 4 (Figure 25-d). In other words, the most severe impacts on discharge, such as the one occurred on August 25, 2014, have only happened 20% of the time when the two outlets operated at their maximum capacities and 2.6 % of the time over their entire operation period. With the operation schedule of the two outlets (Figure 25-a), we simulated the discharge with and without the outlets. On average, pumping water from the west outlet increased discharge at gauging stations 2 and 3 from ~2 $m^3 s^{-1}$ to ~10 $m^3 s^{-1}$ (Figure 25-b and c), and pumping from both outlets increased discharge at gauging station 4 from 8 to ~26 $m^3 s^{-1}$ (Figure 25-d). So far, the largest impact on the Sheyenne River discharge when both outlets operate approached the two-year flood (black dash lines in Figure 25).

71
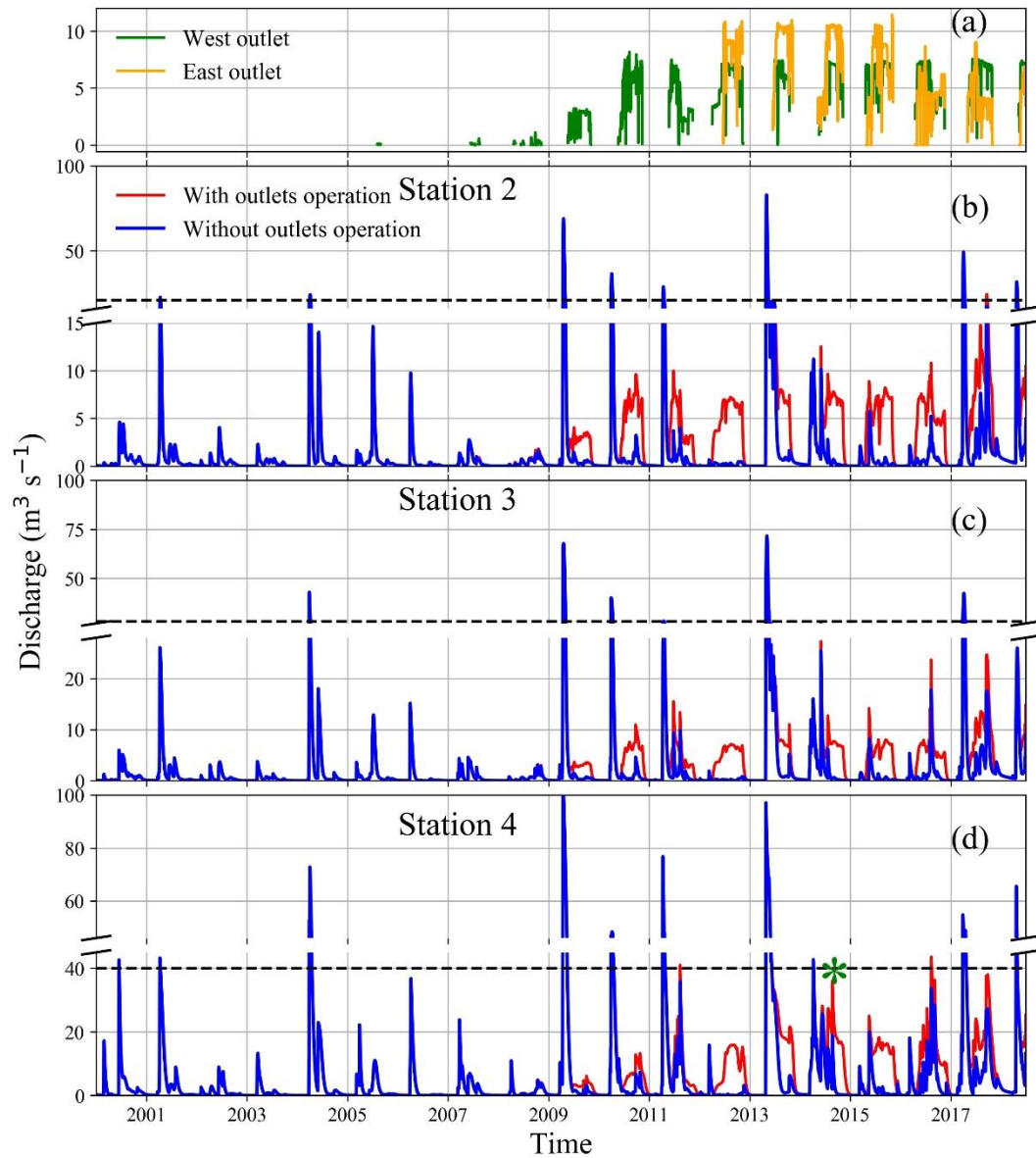
Figure 25. (a) The discharges of two outlets; (b, c, and d) the Sheyenne River discharge simulated at gauging stations 2, 3, and 4 with and without the operation of the outlets. The west and east outlets started their operation in August 2005 and July 2012, respectively. Black dash lines indicate the discharge rates corresponding to the two-year flood at the three gauging stations. The green star denotes the occurrence on August 25, 2014, of one of the largest impacts of the outlets on the Sheyenne River discharge.

Impact on Sulfate Concentration of the Sheyenne River

The sulfate concentrations simulated from the beginning of 2012 to June 2018 are compared with the observations at gauging station 3 and 4 in Figure 26, showing a good agreement

72

with $R^2 = 0.46$ and PBIAS = 5.0% for gauging station 3 (Figure 26-a), and $R^2 = 0.58$ and PBIAS = -4.0% for gauging station 4 (Figure 26-b). Note that the sulfate concentrations measured at gauging station 3 are mainly affected by the west outlet discharge and sulfate measurements at gauging station 4 are affected by discharge from both outlets. The comparisons shown in Figure 26 suggest that we simulated the sulfate concentration in the river reasonably well. Figure 27 shows the sulfate concentrations simulated at the gauging stations 3 and 4 from the beginning of 2012 to June 2018 when both outlets operated. Operating the west and east outlets has increased the river sulfate concentration from 125 mg l^{-1} to 600 mg l^{-1} (black line Figure 27), and 800 mg l^{-1} (grey line in Figure 27), respectively. The Sheyenne River sulfate concentrations at the gauging stations 3 and 4 are low during spring seasons when the streamflow of the river is greater and becomes higher toward summer and fall seasons when the streamflow of the river is low and relatively a greater amount of water is pumped from Devils Lake (Figure 25).
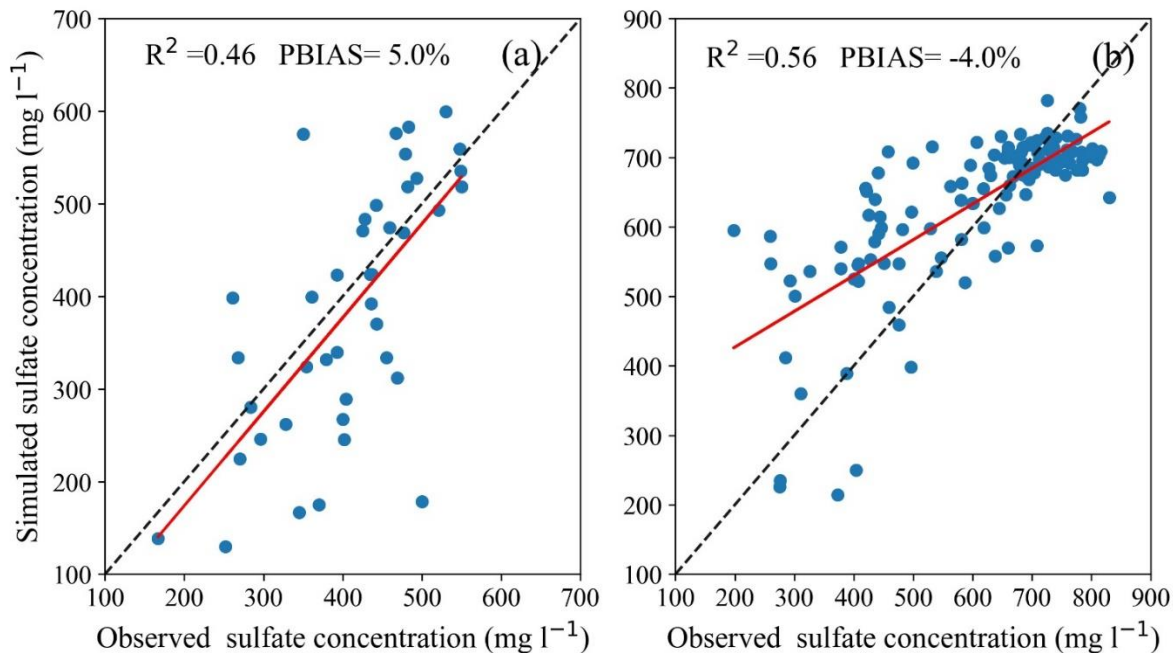
Figure 26. Comparison of the Sheyenne River simulated and observed sulfate concentrations at gauging stations 3 (a) and 4 (b). The dashed line represents 1:1 relationship and the red line the linear regression of the simulated vs observed data.
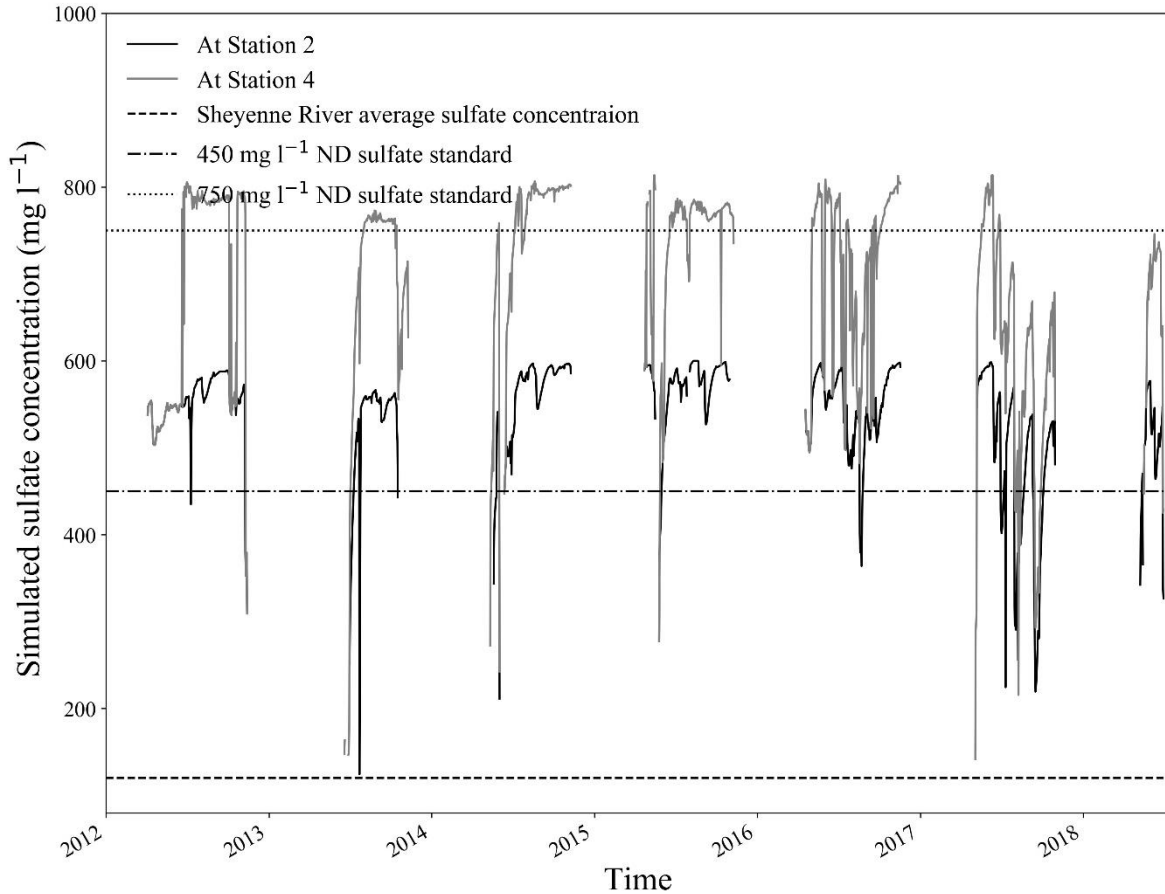
Figure 27. Temporal variation in the Sheyenne River sulfate concentration simulated at gauging stations 3 (black line) and 4 (grey line). Black dash line, dash-dot line, and dot line respectively show the Sheyenne River average sulfate concentration of 125 mg l^{-1}, ND state-wide sulfate standard of 450 mg l^{-1} for Stream Class I A, and 750 mg l^{-1} sulfate standard for the upstream of the Sheyenne River.

Optimization of Devils Lake Outlet Management

We ran the optimization model (Equation 14) by varying the values of the outlets discharge. The optimization generated operation schedules of two outlets. We then used the outlet schedules to estimate the amount of water were to be withdrawn. The results for the time period from the beginning of 2012 to June 2018 are shown in Figure 28. Apparently, the more relaxed the river constraints of sulfate and total discharge are, the more water can be withdrawn from Devils Lake. For example, with $S = 450$ mg l^{-1} and $Q(t) = 7$ m^3 s^{-1}, the lake water can only be reduced by 4 cm per year; in contrast, the lake level can be lowered by 24 cm with $S = 750$ mg l^{-1} and $Q(t) = 30$ m^3

74

s^{-1}. Interestingly, the amount of the lake level that can be reduced vary little for S > 600 mg l^{-1} as long as the two outlets operate in an order from the west outlet to the east outlet (Equation 2.5). The optimized and current management schedule are compared in Figure 29 for the west (a) and east (b) outlets from beginning of 2012 to June 2018. In both cases, a total of 1.16 km^3 water is removed from Devils Lake. For the current management, 49% was removed from the west outlet and 51% from the east outlet. For the optimized schedule, 61% is removed from the west outlet and 39% from the east outlet. The river discharge under the optimized management is ≤ 26 m^3 s^{-1}, but it occasionally reached > 40 m^3 s^{-1} under the current management (Figure 29-c). Most importantly, the sulfate concentration is limited to ≤ 650 mg l^{-1} with the optimized management whereas under the current management the concentration frequently reached 750 mg l^{-1}.

Predicted schedules for the west and east outlets using our alternative management strategy for the rest of the operation time in 2018, July to October, are showing in Figure 30. Applying our optimized management plan, we projected that the two outlets can discharge an additional 0.11 km^3 of lake water (Figure 30a and b) by the end of October, which will result in a further 0.16 m reduction in Devils Lake water levels (Figure 30-e). Under the predicted schedule, the west outlet will operate with its full capacity of 7 m^3 s^{-1} for the first days of July and then its discharge decreases to half capacity through the middle of the month (Figure 30-a) to prevent the risk of flood in the Sheyenne River (Figure 30-c). The east outlet will be shut down for almost first half of July (Figure 30-b). For the rest of the year, we predicted that the west outlets will operate at its full capacity and the discharge from the east outlets (Figure 30-b) varies from 10 to 4 m^3 s^{-1}. Over this time period, the total Sheyenne River discharge is < 26 m^3 s^{-1} (Figure 30-c) and the total sulfate concentration is ≤ 650 mg l^{-1} (Figure 30-d), both at station 4.
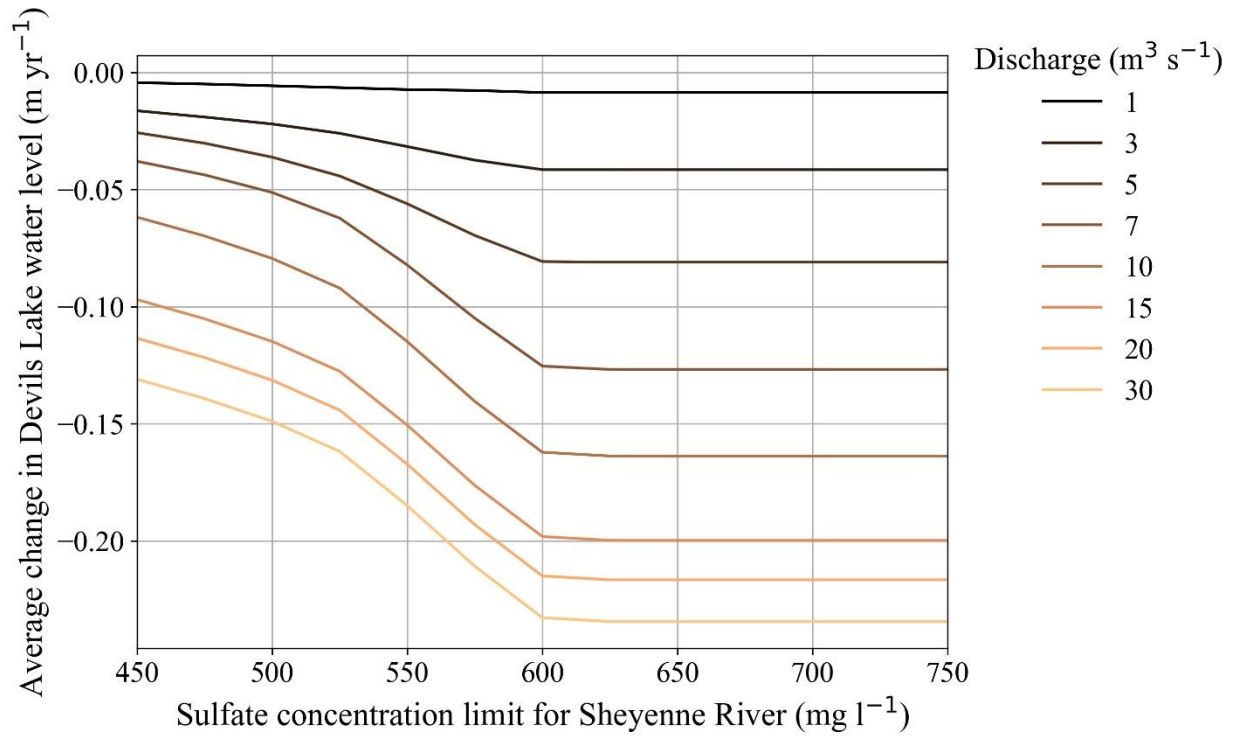
Figure 28. Average annual change in the Devils Lake water level with respect to its impact on sulfate concentration and discharge in the Sheyenne River calculated using equation 2 for the time period from beginning of 2012 to June 2018. Note that, the outlets were operated in an order from the west outlet to the east outlet.
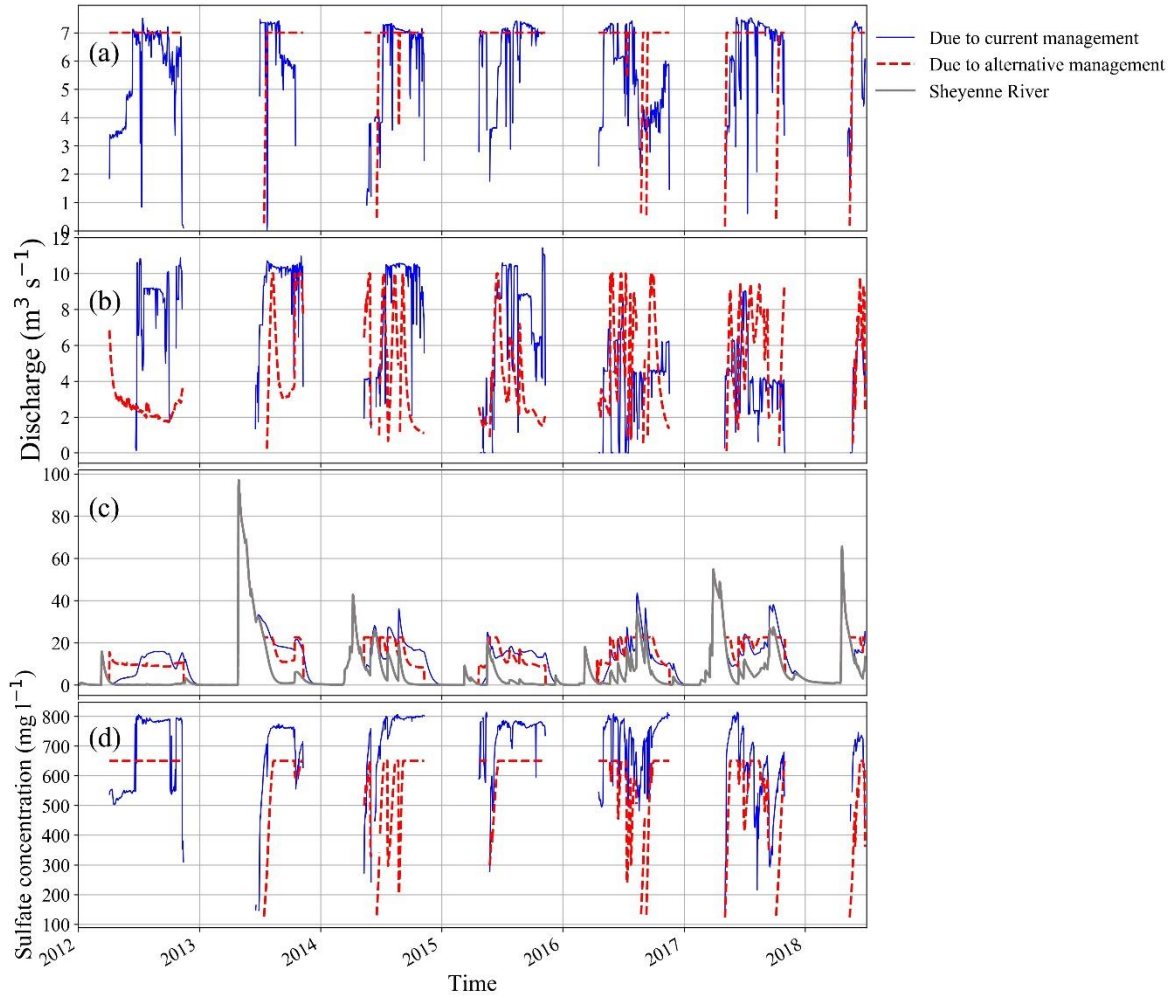
Figure 29. a) volume of discharge water from the west outlet, b) volume of discharge water from the east outlet, c) Sheyenne River discharge after the outlets operation at gauging station 4, d) Sheyenne River sulfate concentrations after the outlets operation for both current (blue) and alternative (red dashed line) management at gauging station 4.
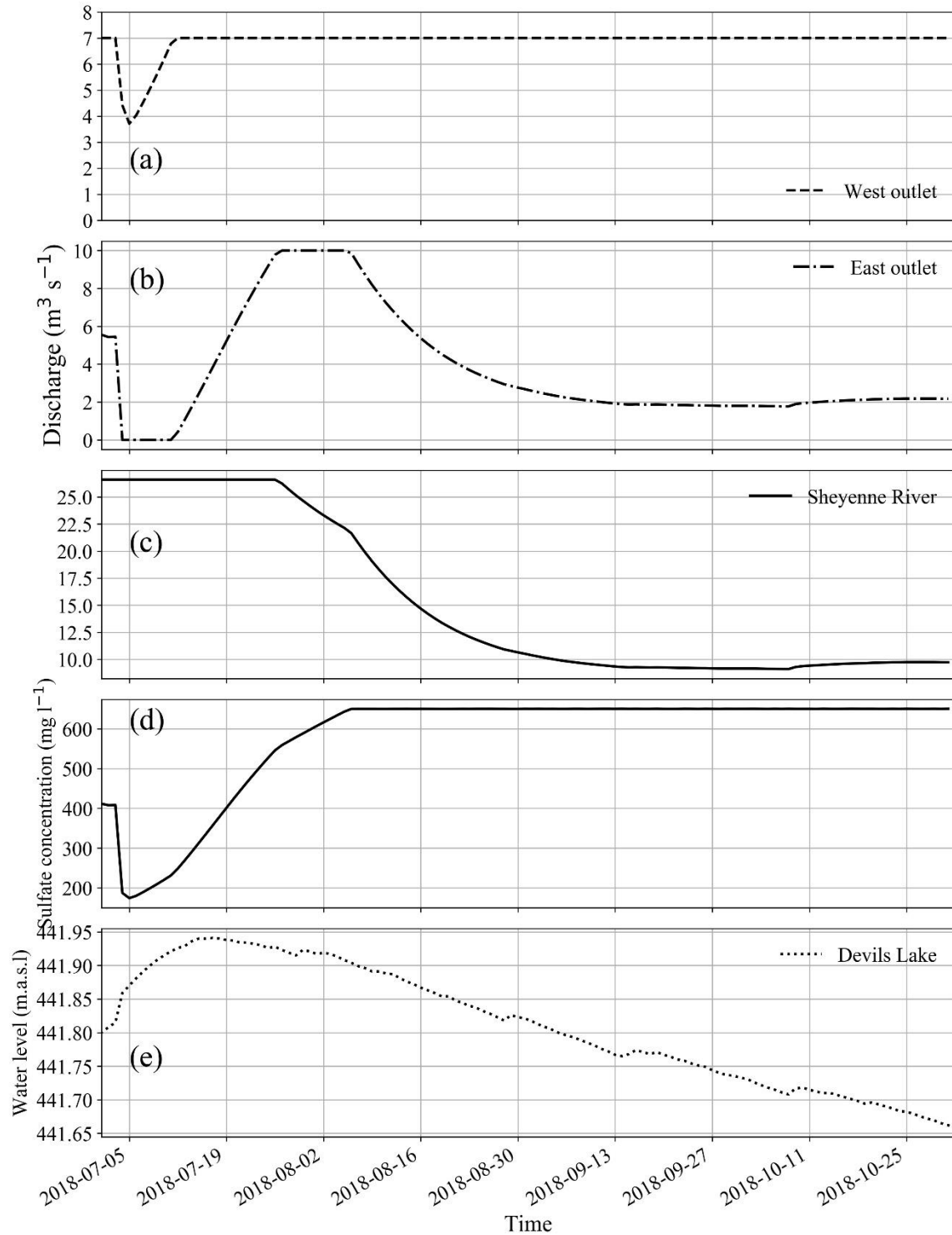
Figure 30. a) predicted volume of discharge water from the west outlet, b) predicted volume of discharge water from the east outlet, c) predicted discharge at gauging station 4 in the Sheyenne River after the outlets operation, d) predicted Sheyenne River sulfate concentrations at gauging station 4 after the outlets operation, e) predicted Devils Lake water level.

78

DISCUSSION

Two outlets were built to divert water from rising Devils Lake to the Sheyenne River. We evaluated the impacts of the diverted water on the Sheyenne River by developing a SWAT model for simulating daily discharge of the river and connected the model with the coupled SWAT and CE-QUAL-W2 model (Shabani et al. 2017) which was used to simulate water balance and sulfate distribution in Devils Lake. The simulated Sheyenne River daily discharge and sulfate concentrations agreed well with the observations (Figure 24 and 28). By turning the outlets on and off in the model, we found that the maximum impact on the river discharge is less than a two-year flood (Figure 25) based on the flood analysis using the data collected before the operation of the outlets. Since Devils Lake contains much higher concentrations of sulfate than the Sheyenne River, diverting the lake water has elevated the sulfate concentration in the river from a historical average of 125 mg l^{-1} to as high as 800 mg l$^{-1}$ (Figure 27). Using the optimization method we proposed an alternative management that can simultaneously mitigate the impacts of the outlets on the Sheyenne River by controlling sulfate concentrations and discharge to $\leq$ 650 mg l^{-1} and $\leq$ 26 m^3 s^{-1}, respectively (Figure 29). We incorporated NOAA CVFv2 data in our model and applied the outlets schedule for the rest of outlet operation time in 2018. Our prediction showed two outlets under alternative management can lower the lake water levels by 0.16 from July to October (Figure 30- e).

We used SWAT model to simulate the Sheyenne River discharge for evaluating the impact of the outlets (Figure 25) and providing forecast discharge for the river which was then applied to predict volume of discharge water for the outlets (Figures 30-a and b). Although the SWAT model was able to simulate discharge for the Sheyenne River satisfactorily (Table 10), it underestimated the daily peak flows in early spring, which was particularly significant during large spring flooding events, such as those that occurred in 2009, 2011, and 2013 (Figure 24). Previous studies in the

79

Red River of the North basin have also reported the underestimation of peaks simulated by SWAT (Wang and Melesse 2005, Wang et al. 2008, Kharel and Kirilenko 2015). Spring floods in the Red River basin are typically associated with cold climate conditions in winter and early spring, such as harsh blizzards, early snow melting events, and/or ice jam process in the rivers (Todhunter 2001). Though SWAT is an applicable tool for simulating and predicting discharge it is not yet able to accurately capture snowmelt and backwater effects of ice jam process in a cold region (Wang and Melesse 2005, Wang et al. 2008, Kharel and Kirilenko 2015, Shabani et al. 2017). By excluding the early spring (March and April) dataset, we found improvement in SWAT simulated discharges at all stations (Figure 31), except station 1 where the model nearly performed the same. However, these underestimations in the Sheyenne River flood peaks did not affect our results because the outlets did not operate during the flooding events.
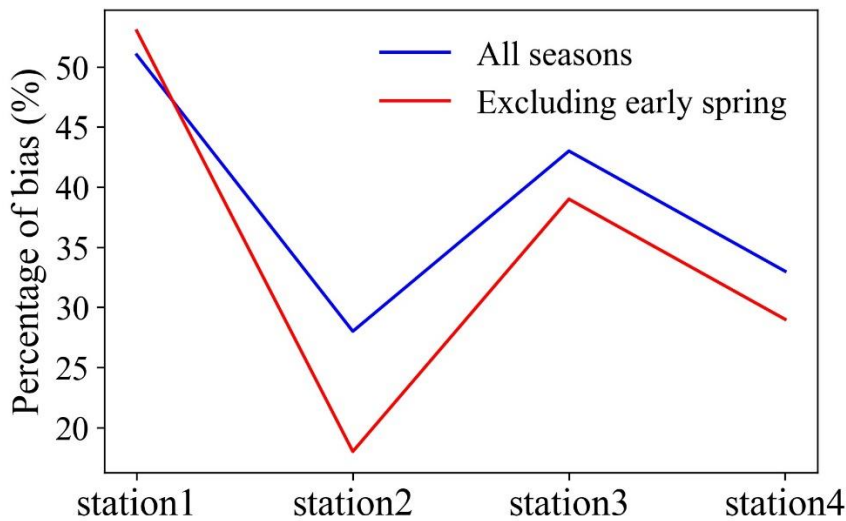
Figure 31. Percentage bias of the SWAT simulated Sheyenne River discharge for all seasons (blue line) and all seasons excluding early spring (March and April, red line) for the time period from 2000 to 2016.

The west and east outlets will not operate when the lake water level elevations are below 440.45 and 440.75 m, respectively (North Dakota State Water Commission 2012). The lake water

elevation has been consistently above 441 m since 2010 (Figure 20), and hence the two outlets have been operating regularly since 2012 after their constructions were completed. When the outlets operate, the discharge is normally low during the early spring when the river flow is typically at the highest due to snow melting, and reaches the maximum capacities during the summer time when the river typically has the lowest discharge (Figure 24). Our study showed that the maximum impact of the current operating schedule on the Sheyenne River is within the historical confines of the two-year flood (black dashed line in Figure 25).

Another impact of diverting the Devils Lake water, which has much higher sulfate concentration than the Sheyenne River, is the water quality degradation (Figure 27). From 2005 to 2018, the operations of the outlets have drawn down 1.1 m of water. Since the current wet cycle is predicted to continue for the next 20 years (Vecchia 2008, Kharel et al. 2016), we assume that on average 0.15 m year^{-1} of water from Devils Lake will need to be diverted annually. This would elevate the sulfate concentration in the Sheyenne River to a minimum of ~500 mg l^{-1} (Figure 28). This also explained why the sulfate standard for the Sheyenne River has been increased twice before, from 300 to 450 mg l^{-1} and finally to 750 mg l^{-1} to allow an effective control of the rising Devils Lake, which indicates a higher risk. Over the years of operations of the two outlets, the sulfate concentrations in the Sheyenne River have been frequently near or over the limit of 750 mg l^{-1}. We showed that the impact on sulfate concentration in the river can be lowered without compromising the current goal of controlling the Devils Lake water level if the outlets can be optimally operated. Shabani et al. (2017) showed that sulfate concentration in Devils Lake increases from west to east; the sulfate concentration is 600 mg l^{-1} at the west outlet and 950 mg l^{-1} at the east outlet. Therefore, the principle is to prioritize the operation of the west outlet and to use the east outlet as a backup when additional water needs to be withdrawn from the lake. In

81

addition, we limit the maximum total discharge at gauging station 4 to be ≤ 26 m^3 s^{-1} when both outlets operate to control the risk of the flood in the river.

In theory, the proposed strategic outlet management offers potential in further reducing the impacts on both water quantity and quality in the Sheyenne River by prioritizing the west outlet discharge. However, in practice there are several limitations, such as weed growth clogging the intakes, temporary power outages, and regular shutdowns for maintenance, which could make continuous full capacity discharge of the west outlet difficult to achieve. In the future, if these challenges can be overcome, this optimized outlets management strategy can support policymaking in reducing flood risk in Devils Lake watershed while preserving water quality in the Sheyenne River.

CONCLUSIONS

In this study, an optimal management strategy was identified by using the optimization method to mitigate the impacts of the Devils Lake outlets on the Sheyenne River water quantity and quality. The results of our developed SWAT model, flood analysis, and field measurements showed that the current outlet management has increased the Sheyenne River discharge and sulfate concentration to 40 m^3 s^{-1} and >750 mg l^{-1}, respectively (Figures 25 and 27), which raise concern of both water quality and quantity in the Sheyenne River. Prioritizing the operation of the west outlet above the east and implementing the alternative management strategy help to preserve the efficiency of the outlets in lowering the Devils Lake water level (Figures29 and 30), and in the meantime mitigate the impacts of the outlets by controlling the sulfate concentration and discharge to ≤ 650 mg l^{-1} and ≤ 26 m^3 s^{-1}, respectively in the downstream river (Figures 29 and 30).

Using the optimization approach, we provided the decision makers with an alternative outlet management, which is efficient in terms of Devils Lake flooding control and its downstream

impacts (Figures 29 and 30). The alternative management, which can be predicted up to 9 months into the future using NOAA's forecast weather data, can be easily implemented while having the least environmental impacts.

The methodology developed in this study demonstrates a novel approach for solving a complex hydrology and water quality problem. The designed coupled system consists of hydrology and water quality models integrated with an optimization method is also applicable to similar cases like Quill Lake in Saskatchewan, Canada.

Chapter V

SUMMARY and RECOMMENDATIONS

Summary

Since 1993, the Devils Lake water level has risen by nearly 10 m causing flood for the Devils Lake City and inundated surrounding farmlands. In the past, more than one billion dollars has been spent on the lake flooding mitigation. To elevate the lake flooding two outlets are constructed at the west and east side of Devils Lake with a capacity of 7 and 10 $m^3\,s^{-1}$, respectively, to divert the lake water to the Sheyenne River in a control fashion. Since 2012, two outlets have been operating with an average capacity of 5.9 and 6.6 $m^3\,s^{-1}$, respectively, from April to October, and in total diverted 1.33 km^3 of the lake water to the river by June 2018. However, the diversion of the poor lake water quality could potentially causes water quality degradation in the Sheyenne River. The rising water level in Devils Lake has raised concerns regarding both water quantity and quality; however, most of the previous studies on the Devils Lake flooding have focused on its water balance (Vecchia 2002, Vecchia 2008, Kharel and Kirilenko 2015, Kharel et al. 2016, Gulbin 2017, Wich et al. 1986). Devils Lake flooding represents a very complex hydrological and water quality problem which engages multiple stakeholders with different water quantity and quality interest from both the Devils Lake and Sheyenne River watersheds. A successful mitigation plan for the lake flooding requires a study for both hydrology and water quality of Devils Lake and the Sheyenne River.

The major objectives of this study were: (1) investigate the impact of the current wet climate cycle on Devils Lake water level and sulfate concentration, (2) evaluate the impacts of Devils Lake outlets on water quantity and quality of the Sheyenne River, (3) propose an optimal outlets management strategy to control Devils Lake flooding and minimize the impact on discharge

84

and sulfate concentration in the Sheyenne River. Each objective of this study was addressed through their corresponding questions and result are summarized below:

Objective 1 Question. *How has the current wet climate cycle impacted water level and distribution of sulfate concentrations in Devils Lake?*

In this study, a coupled SWAT and CE-QUAL-W2 model for Devils Lake was developed to simulate the lake water level and sulfate concentration. The result of coupled model showed the lake water level without operation of the outlets would be 1.1 m higher than its actual level in June, 2018. The simulated sulfate concentration in Devils Lake showed a general increase from west to east, with the east end concentration (1700 mg l^{-1}) being ~ 3 times greater than west side (~600 mg l^{-1}). Since 2008, inflowing the fresh water to the lake has decreased the Devils Lake sulfate concentration by 6%.

Objective 2 Question. *Does the current outlet management increase the risk of flood and/or water quality degradation in the Sheyenne River?*

To address these questions a SWAT model was developed for the Sheyenne River and connected to the previous coupled SWAT and CE-QUAL-W2 model for Devils Lake. The result of coupled system showed the outlets has been managed to keep the river discharge to a maximum of 26 m^3 s^{-1} in downstream of the outlets. However, the river discharge occasionally reached 40 m^3 s^{-1} during the time that both outlets were operational with their full capacities. Operating the west and east outlets has increased the river sulfate concentration from 125 mg l^{-1} to 600 mg l^{-1}, and 800 mg l^{-1}, respectively. The Sheyenne River flood analysis results indicated that the current increase in the river streamflow is limited to two-year flood, however, the new ND sulfate concentration standard of 750 mg l^{-1} has been frequently violated.

85

Objective 3 Question. *What is the optimal outlets strategy that controls Devils Lake water level and Sheyenne River water quantity and quality?*

Operation of the Devils Lake outlets has increased the Sheyenne River discharge and sulfate concentration to ~ 40 m^3 s^{-1} and >750 mg l^{-1}, respectively. In this study, an optimal strategy for the outlet was identified using the coupled system and an optimization method to control Devils Lake water level and preserve the Sheyenne River water quantity and quality. Our optimization approach offered a "win-win" management strategy that maintains the efficiency of the outlets and preserved both the Sheyenne River sulfate concentrations ≤ 650 mg l^{-1} and discharge ≤ 26 m^3 s^{-1}.. Using National Oceanic and Atmosphere Administration (NOAA) Climate Forecast System version 2 (CFSv2) data it was predicted that following the alternative management will reduce the lake water levels by 0.16 m from July to October 2018

In addition to achievements for Devils Lake flooding issue, this study also facilitated the calibration process of the CE-QUAL-W2 by providing an automatic calibration. The proposed method overcomes the high computational effort by the manual calibration and improved the quality of the final calibration result.

Limitations

The study has some limitations related to modeling and water management scenario. SWAT model is limited to use one snowmelt temperature for entire watershed which caused a deficiency in simulating the early spring peak flow in Devils Lake and Sheyenne River watershed. The SWAT model does not account for the sulfate, which limited its utility for simulation of Devils Lake sulfate concentraion. The model also precludes the potholes and wetlands from simulation by filling depression through watershed delineation which can oversimplify the hydrology of the region.

CE-QUAL-W2 model requires bathymetry of the waterbody for its calculation, the lack of bathymetry data for the Sheyenne River prevented us to apply of this model for the river. This study also proposed the strategic outlet management by assuming that the west outlet can operate with full capacity for entire outlet operation time, however, in practice there are several limitations due to weed growth clogging the intakes, temporary power outages, and regular shutdowns for the maintenance.

Recommendations

✓ This study demonstrated that the Sheyenne River discharge and sulfate concentration has increased as result of the outlet operation. However, it did not consider the consequence of these changes on the Sheyenne River human communities and aquatic life. A further study is required to investigate the potential risk of this artificial change in the river discharge and sulfate concentration.

✓ Our developed hydrology and water quality system has an ability to simulate several water quality constituents such as total suspended solids (TSS) and nutrients concentrations in Devils Lake and Sheyenne River. A new study can take advantage of the developed system and calculate the impacts of the outlets on others river water quality constituents.

✓ The proposed outlet management strategy in this study reduced both water quantity and quality impact of the outlets on the Sheyenne River which potentially is beneficial through decreasing the risk of the flood and providing clean water for the downstream communities. However, an economic analysis for our proposed strategy would further help policy-makers in their decision to implement the new plan.

REFERENCES

Abbaspour, K. C., 2014. SWAT-CUP 2012: SWAT Calibration and Uncertainty Programs - a User Manual. Switzerland: Swiss Federal Institute of Aquatic Science and Technology, 106.

Afshar, A., Kazemi, H. and Saadatpour, M. 2011. Particle Swarm Optimization for Automatic Calibration of Large Scale Water Quality Model (CE-QUAL-W2): Application to Karkheh Reservoir, Iran. *Water Resources Management,* 25(10), 2613-2632.

Ahl, R. S., Woods, S. W. and Zuuring, H. R. 2008. Hydrologic Calibration and Validation of SWAT in a Snow-Dominated Rocky Mountain Watershed, Montana, U.S.A. [1]. *Journal of the American Water Resources Association,* 44(6), 1411-1430.

Aote, S. S. 2013. A Brief Review on Particle Swarm Optimization : Limitations & Future Directions. *Interanational Journal of Computer Science Engineering,* 2(5), 196-200.

Arnold, J. G.*, et al.* 1998. Large Area Hydrologic Modeling and Assessment Part I: Model Development 1. *Journal of the American Water Resources Association,* 34(1), 73-89.

Ayvaz, M. T. 2007. Simultaneous determination of aquifer parameters and zone structures with fuzzy c-means clustering and meta-heuristic harmony search algorithm. *Adv Water Resour,* 30.

Bahareh Nakisa, M. Z. A. N., Mohamad Naim Rastgoo, Salwani Abdullah 2014. A Survey: Paricle Swarm Optimization Based Algorithm to Solve Premature Convergence Problem. *Journal of computer science,* 10(9), 1758-1765.

Burke, M.*, et al.* 2018. Identifying the Driving Factors of Water Quality in a Sub-Watershed of the Republican River Basin, Kansas USA. *International Journal of Environmental Research and Public Health,* 15(5), 1041.

Chen, Y., Li, J. and Xu, H. 2016. Improving flood forecasting capability of physically based distributed hydrological models by parameter optimization. *Hydrol. Earth Syst. Sci.,* 20(1), 375-392.

Clow, D. W. 2010. Changes in the Timing of Snowmelt and Streamflow in Colorado: A Response to Recent Warming. *Journal of Climate,* 23, 2993-2306.

Cole, T. M. and Wells, S. A., 2003. *CE-QUAL-W2: A Two-dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.1.* Vicksburg, MS.

Debele, B., Srinivasan, R. and Parlange, J.-Y. 2008. Coupling upland watershed and downstream waterbody hydrodynamic and water quality models (SWAT and CE-QUAL-W2) for better water resources management in complex river basins. *Environmental Modeling & Assessment,* 13(1), 135-153.

Doeing, B. J. and Forman, S. M., 2001. *Final Report: Devils Lake Upper Basin Storage Evaluation.*

Evers, G. I. and Ghalia, M. B., Regrouping particle swarm optimization: A new global optimization algorithm with improved performance consistency across benchmarks. ed. *2009 IEEE International Conference on Systems, Man and Cybernetics*, 11-14 Oct. 2009 2009, 3901-3908.

Flowers, J. D., Hauck, L. M. and Kiesling, R. L. 2001. USDA: Lake Waco-Bosque River Initiative Water Quality Modeling of Lake Waco Using CE-QUAL-W2 for Assessment of Phosphorus Control Strategies.

Galloway, J. M., 2011. *Simulaiton of the Effect of the Devils Lake State Outlet on Hydrodynaimcs and Water Quality in Lake Ashtabula.* U.S. Geological Survey Scientific Investigation Report.

Gao, L. and Li, D. 2014. A review of hydrological / water - quality models. *Frontier Agriculutre Science Enginnering,* 1(4), 267-276.

Gassman, P. W.*, et al.* 2007. The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions. *Transactions of the ASABE,* 50(4), 1211-1250.

Geem, Z. W. 2009. Particle-swarm harmony search for water network design. *Eng Optimiz,* 41.

Gotvald, A. J.*, et al.*, 2012. *Methods for Determining Magnitude and Frequency of Floods in California, Based on Data Through the Water Year 2006.* Reston, VA, 2012-5113.

Gulbin, S., 2017. *Impact of Wetlands Loss on the Long-Term Flood Risks of Devils Lake in a Changing Climate* (Master of Science). University of North Dakota.

Her, Y.*, et al.* 2015. Threshold Effects in HRU Definition of the Soil and Water Assessment Tool. *Transactions of the ASABE,* 58(2), 367.

Kazemi, H., 2010. *Calibration of large scale water quality model (CE-QUAL-W2) by hybrid algorithm. M.Sc. thesis, Iran University of Science and Technology.*

KGS Group Consulting Engineers, 2016. *Quill Lakes Flood Mitigation Study Concept Design Report.* Saskatchewan, Canda.

Khare, A. and Rangnekar, S. 2013. A review of particle swarm optimization and its applications in Solar Photovoltaic system. *Applied Soft Computing,* 13(5), 2997-3006.

Kharel, G. and Kirilenko, A. 2015. Considering Climate Change in the Estimation of Long-Term Flood Risks of Devils Lake in North Dakota. *Journal of the American Water Resources Association,* 51(5), 1221-1234.

Kharel, G., Zheng, H. and Kirilenko, A. 2016. Can Land-Use Change Mitigate Long-Term Flood Risks in the Prairie Pothole Region? The Case of Devils Lake, North Dakota, USA. *Regional Environmental Change,* 16(8), 2443-2456.

Krysanova, V. and Arnold, J. G. 2008. Advances in Ecohydrological Modeling with SWAT—a Review. *Hydrological Sciences Journal,* 53(5), 939-947.

Larry Leistritz, F., Leitch, J. and Bangsund, D. 2002. Regional Economic Impacts of Water Management Alternatives: the Case of Devils Lake, North Dakota, USA. *Journal of Environmental Management,* 66(4), 465-473.

Larson, D. 2012. Runaway Devils Lake: In the Wake of Climate Change, a North Dakota Lake Swells Without Rage People of Property and with No Easy Fix in Sight. *American Scientist,* 100(1), 46.

Lim, K. J.*, et al.* 2007. AUTOMATED WEB GIS BASED HYDROGRAPH ANALYSIS TOOL, WHAT1. *JAWRA Journal of the American Water Resources Association,* 41(6), 1407-1416.

Ma, J., Hipel, K. W. and De, M. 2011. Devils Lake Emergency Outlet Diversion Conflict. *Journal of Environmental Management,* 92(3), 437-447.

Mahdavi, M., Fesanghary, M. and Damangir, E. 2007. An improved harmony search algorithm for solving optimization problems. *Applied Mathematics and Computation,* 188(2), 1567-1579.

Maier, H. R.*, et al.* 2014. Evolutionary algorithms and other metaheuristics in water resources: Current status, research challenges and future directions. *Environmental Modelling & Software,* 62, 271-299.

Markfort, C. D.*, et al.* 2010. Wind sheltering of a lake by a tree canopy or bluff topography. *Water Resources Research,* 46(3).

Moriasi, D. N*., et al.* 2007. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the ASABE,* 50(3), 885-900.

Moriasi, D. N*., et al.* 2015. HYDROLOGIC AND WATER QUALITY MODELS: KEY CALIBRATION AND VALIDATION TOPICS. *Transactions of the ASABE,* 58(6), 1609-1618.

Morrisette, P. M. 1988. The Rising Level of the Great Slat Lake: Impacts and Adjustment. *American Meteorological Society,* 69(9), 1034-1040.

Neitsch, S. L., Arnold, J. G. and Williams, J. R., 2009. Soil and Water Assessment Tool Theorethical Documentation Version 2009. Texas: Texas Water Resource Institute, 647.

North Dakota State Water Commission, 2012. *Devils Lake Outlets Operations Plan.*

Omran, M. G. H. and Mahdavi, M. 2008. Global-best harmony search. *Applied Mathematics and Computation,* 198(2), 643-656.

Ostfeld, A. and Salomons, S. 2005. A hybrid genetic—instance based learning algorithm for CE-QUAL-W2 calibration. *Journal of Hydrology,* 310(1), 122-142.

Pathmathevan, M., Huang, G. and Tamai, N. 2001. REFINED TEMPERATURE MODELING IN LAKE YANAKA BY USE OF SECCHI DEPTH AND A PHYSICALLY-BASED EDDY DIFFUSIVITY. *Doboku Gakkai Ronbunshu,* 2001(677), 215-219.

Qiu, Z. and Wang, L. 2014. Hydrological and Water Quality Assessment in a Suburban Watershed with Mixed Land Uses using the SWAT Model. *Journal of Hydrologic Engineering,* 19(4), 816-827.

Rittel, H. W. J. and Webber, M. M. 1973. Dilemmas in a General theory of Planning. *Policy Sciences,* 4(2), 155-169.

Runkel, R. L., Crawford, C. G. and Cohn, T. A. 2004. Load Estimator (LOADEST): A FORTRAN Program for Estimating Constituent Loads in Stream and Rivers: U.S. Geological Survey Techniques and Methods Book4, Chapter A5. 1-69.

Saleh, A*., et al.* 2000. Application of SWAT for the Upper North Bosque River Watershed. *Transactions of the ASABE,* 43(5), 1077-1088.

Schuh, W. M. 1999. Climate Effects on Groundwater in Eastern North Dakota. *Proceeding of the North Dakota Academy of Science,* 53, 53-57.

Shabani, A., Zhang, X. and Ell, M. 2017. Modeling Water Quantity and Sulfate Concentrations in the Devils Lake Watershed Using Coupled SWAT and CE-QUAL-W2. *Journal of the American Water Resources Association,* 53(4), 748-760.

Smith, E. A., Kiesling, R.L., Galloway, J.M., and Ziegewied, J.R., 2014. *Water Quality and Algal Community Dynamics of Three deepwater Lakes in Mineasota Utlilizing CE-QUAL-W2 model.*: U.S. Geological Survey Scientific Investigation Report.

Stahl, C. H. 2014. Out of the Land of Oz: the Importance of Tackling Wicked Environmental Problems Without Taming Them. *Environment Systems and Decisions,* 34(4), 473-477.

Tahmasebi Nasab, M., Singh, V. and Chu, X. 2017. SWAT Modeling for Depression-Dominated Areas: How do Depressions Manipulate Hydrologic Modeling? *Water,* 9(1), 58.

Tashkova, K*., et al.* 2012. Parameter estimation in a nonlinear dynamic model of an aquatic ecosystem with meta-heuristic optimization. *Ecological Modelling,* 226, 36-61.

Theodossiou, N. P. and Kougias, I. P., 2012. Harmony Search Algorithm. *WIT Transaction on State of the Art in Science and Enginnering.*

Tizhoosh, H. R., Opposition-Based Learning: A New Scheme for Machine Intelligence. ed. *International Conference on Computational Intelligence for Modelling, Control and*

Automation and International Conference on Intelligent Agents, Web Technologies and Internet Commerce (CIMCA-IAWTIC'06), 28-30 Nov. 2005 2005, 695-701.

Todhunter, P. E. 2001. A Hydroclimatological Analysis of the Red River of the North Snowmelt Flood Catastrophe of 1997. *Journal of the American Water Resources Association,* 37(5), 1263-1278.

Ülker, E. D., A PSO/HS based algorithm for optimization tasks. ed. *2017 Computing Conference*, 18-20 July 2017 2017, 117-120.

US Army Corps of Engineers, 2003. *Devils Lake, North Dakota, Final Integrated Planning Report and Environmental Impact Statement, Hydrology, Hydraulics, and Water quality.*

Van Der Kamp, G., Keir, D. and Evans, M. S. 2008. Long-term Water Level Changes in Slosed-Basin Lakes of the Canadian Prairies. *Canadian Water Resources Journal,* 33(1), 23-38.

Vecchia, A. V., 2002. *Simulation of a Proposed Emergency Outlet from Devils Lake, Noth Dakota. U.S. Geological Survey Water Resources Investigation Report 02-4042.*

Vecchia, A. V., 2008. *Climate Simulation and Flood Risk Analysis for 2008-40 for Devils Lake, North Dakota.* 2008-5011.

Vecchia, A. V., 2011. *Simulation of the Effects of Devils Lake Outlet Alternatives on Future Lake Levels and Water Quality in the Sheyenne River and Red River of the North.* 2011-5050.

Wahab, A., 1987. *The Problems of Implementing Flood Damage Reduction Measures in the Vicinity of Malheur/Harney Lakes, Oregon.* (Master). Oregon State University.

Wang, X. and Melesse, A. M. 2005. Evaluation of the SWAT Model's Snowmelt Hydrology in a Northwestern Minnesota Watershed. *Transactions of the ASABE,* 48(4), 1359-1376.

Wang, X., Yang, W. and Melesse, A. M. 2008. Using Hydrologic Equivalent Wetland Concept Within SWAT to Estimate Streamflow in Watersheds with Numerous Wetlands. *Transactions of the ASABE,* 51(1), 55-72.

Wich, G. J., Hoetzar, S. M. and Rankl, J. G., 1986. *Hydrology of the Devils Lake Basin, Northeastern North Dakota.*

Williams-Sether, B., Lent, R. M. and Wiche, G. J. 1996. Variations in Surface-Water Quantity and Quality as a Result of the 1993 Summer Flood in Devils Lake Basin, North Dakota

Xiang, W.-l.*, et al.* 2014. An improved global-best harmony search algorithm for faster optimization. *Expert Systems with Applications,* 41(13), 5788-5803.

Yoo, D. G. and Kim, J. H. 2014. Meta-heuristic algorithms as tools for hydrological science. *Geoscience Letters,* 1(1), 4.

Zhara, B., Siti, M. and Hj, S. 2013. A Reviw of Population-based Meta-Heuristic Algorithm. *International Journal of Advances in Soft Computing and Its Application,* 5, 2074-8523.

Zheng, H., Barta, D. and Zhang, X. 2014. Lesson Learned from Adaptation Response to Devils Lake Flooding in North Dakota, USA. *Regional Environmental Change,* 14(1), 185-194.

Zong Woo, G., Joong Hoon, K. and Loganathan, G. V. 2001. A New Heuristic Optimization Algorithm: Harmony Search. *SIMULATION,* 76(2), 60-68.