The effects of climate change on nutrient loading and river discharge

By

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ABSTRACT

This study was conducted to identify temporal changes in nutrient and sediment concentrations and loads (total phosphorus, particulate phosphorus, total dissolved phosphorus, total nitrogen, and total suspended solids) in Swan River and Woody River of the Swan Lake watershed, Manitoba. Temporal changes in physical hydrology (river discharge and precipitation) were also investigated to determine if these parameters influenced the changes in water quality concentrations and loads across the Swan Lake watershed. Annual and seasonal totals of water quality variables, river discharge, and average watershed total precipitation were examined for change over 30 years. The results showed a statistically significant increase in nutrients and total suspended solids (TSS), and river discharge, particularly in Swan River. Both rivers experienced statistically significant increases during the spring season with changes in median values as high as 450% in TSS between 1989 – 2000 and 2010 – 2018. Annual river discharge in Swan River and Woody River increased by 182% and 103%, respectively, with Swan River experiencing a statistically significant increase over the 30-year period. Seasonally, both rivers increased statistically significantly in the spring season with an 80% increase. Total precipitation across the watershed increased 3% annually, including a 6% increase in the spring, and summer and fall seasons, and 8% decrease in the winter season between 1995 – 2001 and 2009 – 2015. There were correlations between water quality variables and river discharge, and between river discharge and precipitation. Precipitation in this area influences river discharge and since nutrients and sediments are strongly correlated with river discharge, precipitation indirectly influences nutrient and sediment exports.

ACKNOWLEDGEMENTS

I cannot express my gratitude towards all the individuals who have helped me through these last couple of years. It's been a journey!

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1 INTRODUCTION

Increases in nutrient loading to some Canadian lakes has caused severe eutrophication and algal bloom development (McCullough et al., 2012; Schindler et al., 2012; Michalak et al., 2013; Dumanski et al., 2015). The primary mechanisms of delivery of nutrients and suspended sediment to a lake are via runoff and river discharge. Runoff is an important factor in transporting nutrients and suspended sediments from the watershed into a stream or river, while rivers and streams are an important component in linking the watershed landscape to downstream waterbodies (Dodds et al., 2004; Nielsen et al., 2012). The presence of excessive nutrients, particularly nitrogen and phosphorus, in waterways may lead to eutrophication and the presence of algal blooms. Nuisance algal blooms can lead to ecological, aesthetic, and human health impacts on lakes and streams, such as fish kills, odour and taste problems, degradation of drinking water, and unsafe swimming areas (Ellison and Brett, 2006; Strickland et al., 2010).

The primary driving force in transporting nutrients and suspended sediment from a catchment area to rivers and streams in the semi-arid prairie region of Canada is through snowmelt runoff (Van Der Kamp et al., 1999; Salvano et al., 2009; Rattan et al., 2017). The primary snowmelt period typically occurs for 12 – 18 days in the spring (Rattan et al., 2017). More than 80% of annual surface runoff occurs during the snowmelt period (Granger et al., 1984; Little et al., 2007; Tiessen et al., 2010; Shrestha et al., 2012; Rattan et al., 2017) and accounts for 65 – 95% of annual river discharge (Corriveau et al., 2013) in Southern Manitoba, despite only one-third of annual precipitation being received as snow (Gray and Landine, 1988). Snowmelt throughout the Canadian prairies may transport up to 80% of annual total phosphorus (TP) and total nitrogen (TN) loads (Glozier et al., 2006; Corriveau et al., 2011). More specifically, the Red River watershed in Manitoba exported over 60% of the annual TP and TN loads during the 12 – 18-day primary snowmelt period (Rattan et al., 2017). Snowmelt runoff occurs when melting snow is moving across soils that are often frozen with restricted infiltration ability (Granger et al., 1984; Cade-Menun et al., 2013; Liu et al., 2013). Freezing and thawing of unharvested vegetation residue is susceptible to lysing (i.e., breakage of cells) and releases nutrients increasing nutrients concentrations in snowmelt runoff (Tiessen et al., 2010; Cade-Menun et al., 2013; Liu et al., 2013). On the other hand, during the summer season when soils are not frozen and infiltration and biological activity (nutrient uptake and cycling in soils) are more favourable (Cade-Menun et al., 2013), less runoff and nutrients move to the waterways. The snowmelt period typically produces the highest flow (Novotny and Stefan, 2007) and nutrient concentrations (Shrestha et al., 2012; Rattan et al., 2017), making this period the main discharge and nutrient loading event of each year in the Prairie Provinces.

Changes in nutrient loading in rivers and lakes surrounded by agricultural areas are associated with anthropogenic impacts on nutrient inputs and the timing and quantity of runoff moving over the landscape. Massive land cover conversion for agricultural use has allowed snowmelt runoff to move across the landscape at faster rates. Changes in agricultural practices have increased nutrients in the soils and allowed for quicker drainage of runoff off the land (Tiessen et al., 2010; Rattan et al., 2017). Drainage (e.g., removal of wetlands and construction of drainage channels) has increased the rate and total volume of water flow into rivers and lakes (Schindler et al., 2012; Dumanski et al., 2015) and reduced nutrients retention on the land (Van Der Kamp et al., 1999; Dumanski et al., 2015). The transition to conservation tillage has increased the availability of bioavailable dissolved phosphorus for export in snowmelt events (Tiessen et al., 2010; Schindler et al., 2012; Cade-Menun et al., 2013). Furthermore, the increased use of synthetic and manure fertilizers, along with the expansion of livestock production (Strickland et al., 2010), particularly in the mid-1990s (Schindler et al., 2012), increased the amount of nitrogen and phosphorus stored in soil surfaces (Han et al., 2012) and runoff (Salvano et al., 2009; Strickland et al., 2010; Schindler et al., 2012; Michalak et al., 2013). These changes play a vital role in changes in concentrations and runoff; however, climate change is causing further changes to runoff and river discharge and affecting nutrient loading to rivers and lakes. Climate change has altered and intensified nutrient and suspended sediment loads (Chen et al., 2015; McCullough et al., 2012; Rattan et al., 2017) to nearby rivers and downstream lakes.

Although it is imperative to consider anthropogenic loading with nutrient increases in rivers and lakes, climate and hydrology need consideration regarding changes in nutrient exports. Climate-related factors, such as temperature and precipitation, further exacerbate nutrient loads by influencing hydrological events (Liu et al., 2013; Rattan et al., 2017). Temperature changes in the Prairie Provinces of Canada (Alberta, Saskatchewan, and Manitoba) were notably occurring before the 1990s. January, March, April, and June all experienced significant warming, with over 60% of stations experiencing this warning in March and June over 4 – 5 decades (Gan, 1998). Across the Lake Winnipeg watershed from 1961 – 2003, annual maximum and minimum temperatures increased by 0.32°C and 0.39°C per decade, respectively (Dibike et al., 2012). Over a similar period in the Lake Winnipeg watershed, there were no significant trends in annual precipitation (Burn et al., 2008; Dibike et al., 2012; Dumanski et al., 2015); however, there were significant seasonal changes, which have varied across the Lake Winnipeg watershed. The Saskatchewan River watershed experienced a significant decline in winter precipitation by 30%, while the Upper Assiniboine and Red River watersheds experienced a significant increase in summer precipitation by 20% from 1961 – 2003 (Dibike et al., 2012). Similar trends in precipitation were also seen in the Smith Creek Research Basin in Saskatchewan, where snowfall based on annual snow depth declined and summer rainfall increased from 1975 – 2014 (Dumanski et al., 2015). Although annual precipitation did not change, the form of precipitation has shifted. Changes to seasonal precipitation in this watershed resulted in the ratio of snowmelt runoff to snowfall declining to 47% of annual discharge since the 1970s, and the ratio of runoff to rainfall increased to 34% which may be attributed by the increase in multi-day rainfall events (Dumanski et al., 2015).

Warmer temperatures in the winter and spring seasons resulted in earlier spring snowmelt across the Prairie Provinces (Gan, 1998; Burn et al., 2008) and northern USA (Novotny and Stefan, 2007), as much as two weeks earlier than historically recorded (Dumanski et al., 2015). An earlier snowmelt period is also occurring in the Yellow River watershed in China; even though snowmelt runoff is not the primary runoff, it is still the predominant form of runoff during the spring season (Zhang et al., 2022). In addition, regions with warmer temperatures in the Prairie Provinces experienced decreased snowfall and snowpack in winter and increased rainfall events in the late winter and early spring (Burn et al., 2008; Dumanski et al., 2015). These changes likely promoted earlier snowmelt and more frequent snowmelt events (Novotny and Stefan, 2007). Although spring snowmelt runoff volume and peak flow decreased with earlier and quicker warming during the snowmelt period, nutrient loading increased due to flooding associated with rapid and flashier runoff generation when frozen soils are still present (McCullough et al., 2012; Cade-Menun et al., 2013; Liu et al., 2013).

In the prairie region of Canada, rainfall events have increased in intensity and frequency. Novotny and Stefan (2007) and Dumanski et al. (2015) found an increase in rainfall amounts and the number of days each rainfall event occurs (i.e., more multiple-day rainfall events) during the summer months. These changes led to higher runoff rates and peak flows, more peaks days of flow in the summer (Novotny and Stefan, 2007; Burn et al., 2008), and more frequent flooding due to more intense rainfall events during the summer and fall months (Novotny and Stefan, 2007; McCullough et al., 2012). More multiple-day rainfall and flooding events increase the amount of runoff over the land, attributed to the increased nutrient loading in rivers and lakes (McCullough et al., 2012; Dumanski et al., 2015) and discharge (Rattan et al., 2017).

Intense storms have a strong impact on erosion and intensify loading of particulate nutrients and sediment. During a storm event in northwest Washington, USA, Ellison and Brett (2006) found TP to increase by 200% while particulate phosphorus (PP) increased by 614%. Bioavailable phosphorus also increased by 72% during a storm event even though bioavailable PP decreased (down to 19% from 73% during baseflow). Total suspended solids (TSS) and total dissolved phosphorus (TDP) also increased during a storm event regardless of landcover type. In fact, Ellison and Brett (2006) determined flow state had a larger influence on TSS (42%), TP (36%) and PP (51%) concentrations whereas TDP was more influenced by landcover state (44%). Total phosphorus however can be influenced by both flow and landcover state (21% landcover) because TDP and PP are influenced by different conditions. Nutrients and suspended sediment even behave differently during the rising and falling stages of discharge from rainstorm events based on the rainfall intensity and soil conditions (see Guo et al., 2022); however, in general, nutrients and suspended sediment increased due to soil erosion. Typically, the highest load of nutrients and suspended sediment occur during the early to peak phase of a storm event, and more intense storms export more nutrients than less intense ones (Chen et al., 2015).

Changes in landscape and anthropogenic factors have a stronger influence on concentrations, whereas climate-related factors have a stronger influence on hydrological events, which carry over to nutrient loads. Discharge has a positive relationship with nutrient loads, and increases in runoff and river discharge, particularly in major agricultural areas, are associated with higher precipitation and flooding rates (McCullough et al., 2012). Small changes in precipitation can dramatically influence river discharge. Zhang et al. (2022) reported that a -20% to 20% change in precipitation led to a -33% to 47% change in total runoff. Furthermore, Ehsanzadeh et al. (2012) reported that a change in precipitation of 20% in the Lake Winnipeg watershed led to an increase of 300% in river discharge through the 20th century. River discharge is highly sensitive to precipitation, and since nutrients are strongly correlated with river discharge, changes in river discharge can strongly affect nutrient and sediment loads in rivers.

1.1 Lake Winnipegosis and Lake Manitoba watershed (Upper MBGL)

Manitoba is home to three large lakes, Lake Winnipeg, Lake Winnipegosis, and Lake Manitoba (Figure 1.1), and collectively they are called the Manitoba Great Lakes (MBGL). Lake Winnipeg is the largest of the MBGL and the third largest lake in Canada. This lake is experiencing increased nutrient loading and development of massive cyanobacteria algal blooms since the 1990s, which is attributed with the extensive changes in land use and climate change (McCullough et al., 2012; Schindler et al., 2012). However, Lake Winnipegosis and Lake Manitoba, the other two MBGL and the 12th and 14th largest lakes, respectively, in Canada, have received very little attention and remain rather a large mystery in comparison to Lake Winnipeg. The MBGL have important ecological and economical benefits to the province of Manitoba, such as fisheries, hydrology, wildlife, and recreation (Bortaluzzi, 2003); however, they are experiencing many environmental pressures, including regulation of water level, increase in nutrients, changes in surrounding land use, and climate change.

Collectively, Lake Winnipegosis and Lake Manitoba have a watershed that covers approximately 134,700 km^2, spanning across most of west-central Manitoba and part of east-central Saskatchewan (Figure 1.1). Much of the northern portion of this watershed is within the Boreal Plains containing many natural wetlands and forested areas with a few agricultural, mining, and forestry practices (LMRRAC, 2003). The southern portion of this watershed is found within the Prairie Plains which is heavily dominated by agricultural use for pasture and cropland (LMRRAC, 2003; Page, 2011; Stanley, 2017).

Based on a literature search, Lake Winnipegosis has received little scientific attention except for biological (fisheries and wildfowl) surveys in the mid-1900s. In comparison, Lake Manitoba has received more attention, particularly on its general hydrology and fisheries since the late 1870s (Bortaluzzi, 2003). Recent studies conducted on Lake Manitoba focussed on its large southern marsh, Delta Marsh. The two most recent in-depth overview studies on Lake Manitoba's water quality focussed on its south basin (Hughes and Williamson, 2002; Page, 2011). Based on total phosphorus (TP) and chlorophyll-a (chla) concentrations, Hughes and Williamson (2002) indicated the south basin of Lake Manitoba was mesotrophic during the 1960s and 1970s. In later years (2005 and 2006), Lake Manitoba was considered eutrophic based on mean chla concentrations for both basins with phosphorus being the limiting nutrient (Page, 2011).

The north basin of Lake Manitoba was found to have higher nitrogen concentrations than the south basin, while the south basin had higher phosphorus (Hughes and Williamson, 2002; Page, 2011). The differences between the two basins are due to differences in nutrient loading from the three major inflowing tributaries entering Lake Manitoba: Assiniboine River Diversion, Whitemud River, and Waterhen River. From 1981 – 1984 and 1988 – 2001, the average TP and

TN concentrations in the Assiniboine River Diversion were higher than in the other two tributaries (Hughes and Williamson, 2002) due to extensive agricultural land use surrounding this tributary. However, when river discharge was considered, Waterhen River became the major contributor to both TP and TN loading, contributing an average of 58.5% and 77.3%, respectively, for all years, whereas Assiniboine River Diversion only contributed 30.2% and 15.4%, respectively. In the later study conducted by Page (2011), TN concentrations between Waterhen River and Assiniboine River Diversion were quite similar (3.89 mg/L and 3.52 mg/L, respectively) but when including river discharge, Waterhen River was still the major contributor to TN loads, contributing 48% and 77% of TN in 2005 and 2006, respectively. For these two years, Assiniboine River Diversion contributed 75% and 67%, respectively, of TP, making it the major contributor to TP to the lake. Thus, high diversion flows of comparatively phosphorus-rich Assiniboine River water may contributed to the higher trophic status in Lake Manitoba in 2005 and 2006.

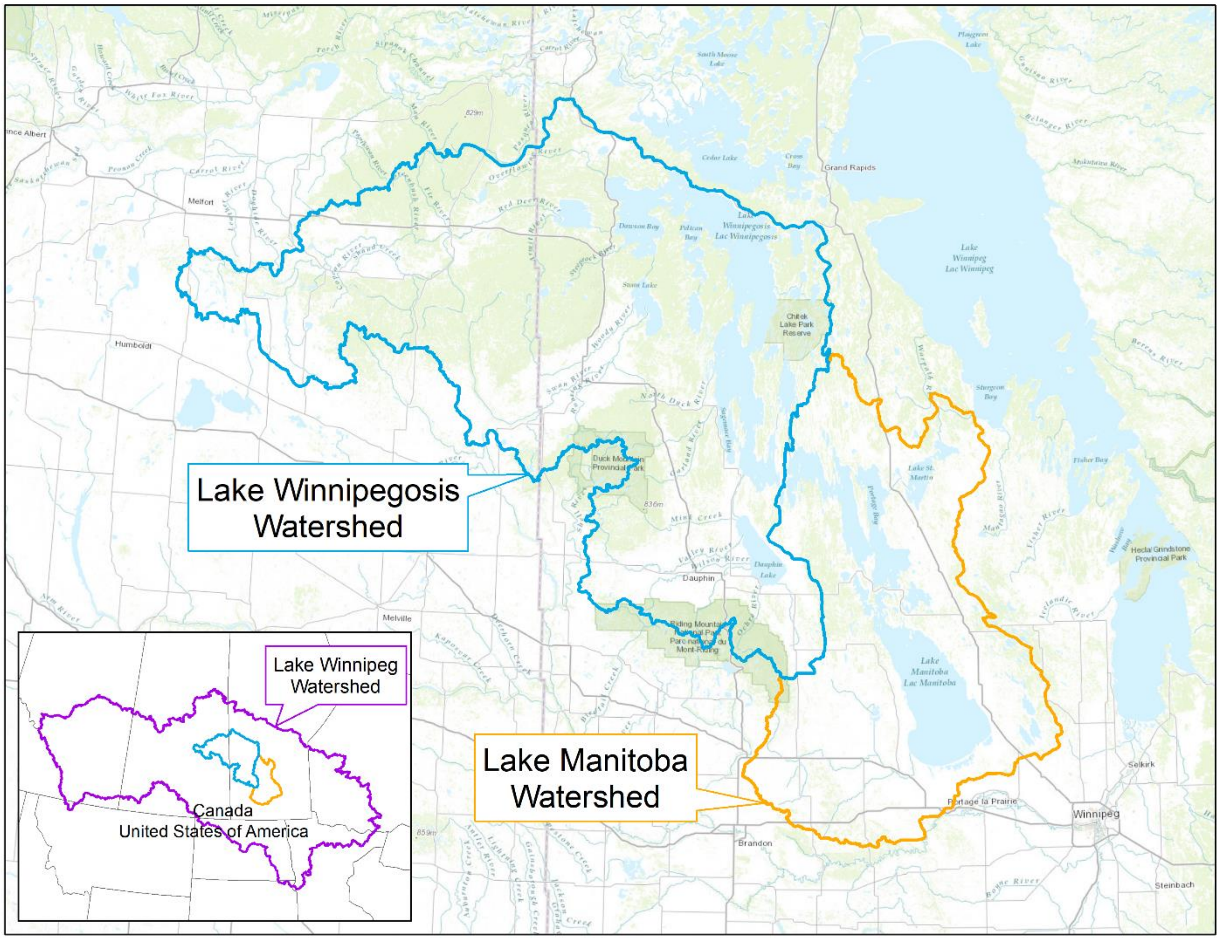

Figure 1.1. A schematic diagram of Lake Winnipegosis and Lake Manitoba Watersheds.

1.2 Project Motivation

Several large rivers flowing into Lake Winnipegosis (e.g., the Mossy, Shoal and Red Deer Rivers) contribute most of the water inflow to this lake. However, the nutrient loads from most of these rivers are reduced by sequestration in large lakes (Donald et al., 2015) hence obscuring the effects of the surrounding land use. To better understand nutrient loading within the Lake Winnipegosis watershed attributed to heavily developed land used for agriculture, two tributary rivers are examined, Swan River and Woody River, which flow into Swan Lake, upstream from Lake Winnipegosis. Communities in this area have growing concerns related to water quality. To gain more knowledge on nutrient loading impacts in this area and within the Upper MBGL region, this study will perform a long-term analysis of nutrient loading and physical hydrology (i.e., river discharge and precipitation). There has been little or no investigation of the climate-related impact on changes in nutrients in this region. This study will use publicly available data to obtain a better understanding of changes in nutrient export from this area and how climate change may have impacted these changes in nutrient exports.

1.3 Project Objective

The overarching objective of this study is to quantify nutrient changes in two neighbouring river watersheds in western Manitoba over time and determine their relationship, if any, with discharge and precipitation. The method is to examine temporal changes in nutrient concentrations and loads, including total phosphorus, nitrogen and suspended solids, and physical hydrology, including river discharge and precipitation, over a 30-year period, and to explore the relationships between these concentrations and physical hydrology.

Therefore, the three sub-objectives of this project are:

a) To identify any temporal changes in nutrient exports of in the Swan and Woody Rivers from 1989 – 2018; and

b) To identify any temporal changes in physical hydrology, specifically river discharge and precipitation from 1989 – 2018; and

c) To examine the relationship between nutrient concentrations, river discharge, and precipitation.

2 CHANGES IN NUTRIENT LOADING AND THE POTENTIAL INFLUENCES FROM RIVER DISCHARGE AND PRECIPITATION IN TWO MANITOBA NEIGHBOURING RIVERS

2.1 Introduction

Water quality is a concern for many lakes in Canada. Nutrient inputs, particularly phosphorus have increased over the last century, with a significant change occurring in the mid-1990s, leading to more frequent and larger algal blooms (Strickland et al., 2010; McCullough et al., 2012; Dumanski et al., 2015). In recent years, land use and climate changes have significantly affected nutrient concentrations and loads. The changes in land use and agricultural practices (Tiessen et al., 2010; Dumanski et al., 2015; Rattan et al., 2017) increased nutrient inputs in soils and have caused nutrients to move off the land at quicker rates. Climate change is also affecting the timing and quantity of precipitation across Canada (Akinremi et al., 1999; Zhang et al., 2007; Millett et al., 2009; Dibike et al., 2012) that in turn are affecting river discharge rates and nutrient loading with consequences on runoff quantity, timing of delivery and water residence time in a watershed (Rattan et al., 2017). The combination of anthropogenic and climate-related changes in runoff and discharge have resulted in increased nutrient loading in many Canadian rivers and lakes (Chang et al., 2001; McCullough et al., 2012; Schindler et al., 2012; Shrestha et al., 2012; Michalak et al., 2013; Dumanski et al., 2015).

Rivers and streams are an important component in the transportation of nutrients in addition to other dissolved substances and suspended sediments from land to waterbodies throughout the watershed (Nielsen et al., 2012). Runoff is the predominant driver in the nutrient transport process to our rivers (Salvano et al., 2009). Across the Lake Winnipeg watershed , approximately 80% of the total annual surface runoff is accounted by spring snowmelt runoff (Glozier et al., 2006) despite only one-third of annual precipitation being received as snow (Gray and Landine, 1988). Within the Red River watershed of the Lake Winnipeg watershed, snowmelt contributes over 40% of discharge and over 60% of nutrient export during the ice-free periods (Rattan et al., 2017).

Rainfall runoff contributes a smaller portion to river discharge even though most annual precipitation occurs in this form. In recent years, there has been a shift in seasonal precipitation across the Canadian Prairies; however, little to no change in annual precipitation has been observed (Dibike et al., 2012; Dumanski et al., 2015). In a 43-year study (1961–2003), Dibike et al. (2012) found the Upper Assiniboine and Red River watershed experienced a significant 20% increase in rainfall (summer precipitation) and a significant 30% decline in snowfall (winter precipitation) in the Saskatchewan River watershed. The sensitivity of runoff to changes in precipitation can vary from -33% to 47% with a -20% to 20% change in precipitation (Zhang et al., 2022).

Nutrient and sediment transport is highly dependent on discharge rates, and both are highly correlated with precipitation variability (Wilby, 1993; Kleinman et al., 2006). In the Smith Creek Research watershed in Saskatchewan, Canada, spring discharge from the decline of snowmelt runoff decreased by 47% while the rise in rainfall has caused an increase of 34% in summer discharge since the 1970s (Dumanski et al., 2015). These changes imply the importance of seasonal precipitation and its factor in runoff mechanism, discharge rate, and nutrient loads.

The Lake Winnipeg watershed is large, and nutrient delivery, let alone changes in nutrient delivery associated with changes in precipitation, and runoff in many of its sub-watersheds associated with shifts in climate and land-use remain unstudied. This study examined two understudied local rivers in the Swan Lake watershed, Swan River and Woody River. These rivers are upstream from the second largest lake in Manitoba, Lake Winnipegosis, prior to reaching Lake Winnipeg. This area provides many ecological and economical services to the province of Manitoba, such as fisheries, agriculture, wildlife, and recreation (Bortaluzzi, 2003). There are growing water quality concerns from the communities in the Swan Lake Watershed District, including Wuskwi Sipihk First Nation on the shore of Swan Lake at the mouth of the Woody River (G. McCullough, pers. comm. 2022). This study focused on the changes in precipitation, river discharge, and nutrient and sediment concentrations and loads in this understudied area over a 30-year period.

2.2 Swan and Woody Rivers Study Area

2.2.1 Location

Swan River and Woody River are roughly parallel and drain into Swan Lake (Figure 2.1). Swan Lake is a shallow (<3m) lake located on the west side of Manitoba. It connects to Dawson Bay of Lake Winnipegosis via the Shoal River. The Swan Lake watershed is part of the larger Upper Manitoba Great Lakes (MBGL) watershed, which includes Lake Winnipegosis, Lake Manitoba, and Lake Waterhen, all of which are upstream of Lake Winnipeg.

The watersheds of both rivers are situated within the Swan Lake watershed that bounds the Manitoba-Saskatchewan border. These watersheds drain from the Manitoba Escarpment through terrain formerly covered by glacial Lake Agassiz. Swan River Valley is U-shaped and contains two plains, Swan River Plain (i.e., the east portion of the valley) and Kenville Plain (i.e., the south portion of the valley, near the Town of Kenville). To the north of the valley are the Porcupine Hills and to the south are the Duck Mountains uplands.

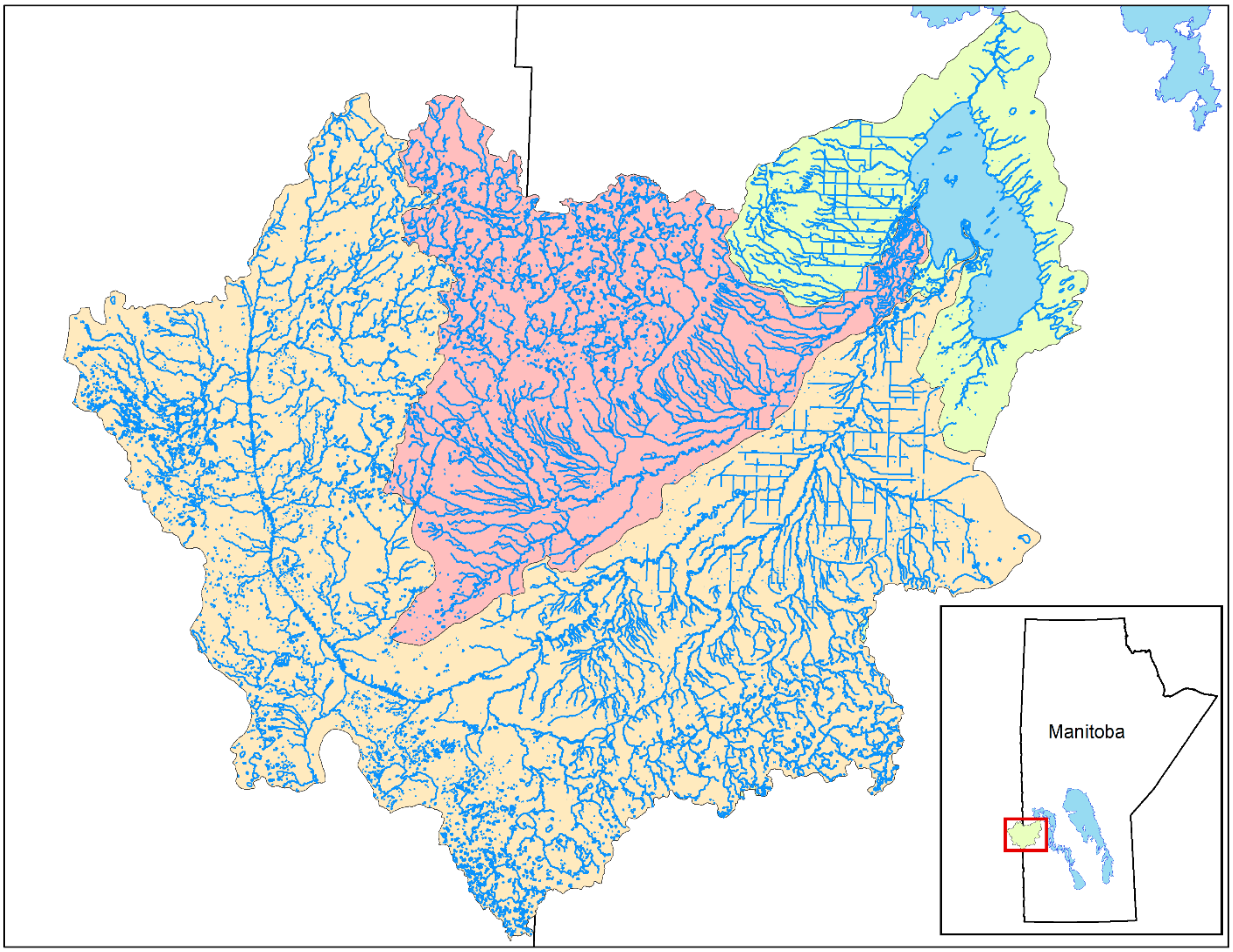

Figure 2.1. Swan and Woody Rivers and their watersheds (beige and rose, respectively) within the remaining Swan Lake watershed (olive) showing the extent of its water system.

2.2.2 Geology

The Swan River Valley is bounded to the north by the Porcupine Hills upland and to the south by the Duck Mountains upland. The Swan River Valley separates the two uplands and contains both Swan and Woody Rivers. It is approximately 45 km wide and 70 km long (Nielson, 1988). Porcupine Hills and Duck Mountains reach a land elevation of 730 and 700 metres above sea level (masl), respectively. The Escarpment slopes down to 580 and 520 masl throughout the Swan River Plain to 260 masl at Swan Lake.

Devonian carbonate rocks underlying bedrock are prevalent on the far eastern part of the watershed surrounding Swan Lake and are comprised of limestone, dolomites, and calcareous shales (Ehrlich et al., 1962; Nielson, 1988). Cretaceous sandstone and shale deposits are prevalent throughout the central and western portions of the watershed. Lacustrine soils formed by glacial lake deposits are prevalent in the watershed and consist mainly of gravel, clay, silt, and sand layers. Unconsolidated alluvial and organic material deposits in the western portion of the watershed cover the glacial and lacustrine sediment layers (SLWD, n.d.). The soils in the Swan River Plain comprise imperfectly drained soils, such as Gleyed Rego Black, Meadow, and Peaty soils. The Kenville Plains are comprised of well-drained soils, mostly of Orthic Dark Grey and Orthic Black soils. The uplands mainly comprise of soils in the Grey Wooded great group (Ehrlich et al., 1962).

2.2.3 Land Use and Vegetation

The primary economic activities within the Swan Lake Watershed are agriculture, forestry, manufacturing, hunting, tourism, and outdoor recreation (Bortaluzzi, 2003). Most tourism and recreational activities occur in the Porcupine Hills and Duck Mountains, in addition to forestry, hunting, and commercial and recreational fishing (SLBMP, 2004).

The highest population density in the Swan Lake watershed is in the Town of Swan River, with a population of 4049 in 2021. In total, approximately 12,000 people live within this watershed (Statistics Canada, 2022). The Swan Lake Basin Management Plan (SLBMP, 2004) reported 11 water treatment facilities throughout the Swan Lake watershed. Some of the larger towns, including Swan River, Benito, and Minitonas, use the Swan River system to discharge treated effluent wastewater from their wastewater treatment lagoons.

Agriculture is the dominant land use in the Swan River Valley, covering approximately 90% of this area (Ehrlich et al., 1962) and 42% across the entire watershed (SLWD, n.d.). The land is mostly used for annual crops, such as grain or cereal production, with some livestock production, primarily for beef production (AAFC-AESB and MAFRI, 2011).

Forest vegetation covers 37% of the watershed (SLWD, n.d.). Most of the forested areas in the Swan River Valley have been removed for agricultural purposes. Forested areas are the dominant vegetation in the Porcupine Hills and Duck Mountains. The uplands have a mix of aspen (*Populus tremuloides*), balsam poplar (*Populus balsamifera*), white birch (*Betula papyrifera*), white spruce (*Picea glauca*) and balsam fir (*Abies balsamea*) (Ehrlich et al., 1962). In the lowlands section, a mix of aspen (*Populus tremuloides*), balsam poplar (*Populus balsamifera*), white spruce (*Picea glauca*), white birch (*Betula papyrifera*). Jack pine (*Pinus banksiana*) are found throughout sandy and gravelly areas. Poorly drained areas, such as bogs, contain black spruce (*Picea mariana*) and tamarack (*Larix laricina*). Many small lakes and wetlands reside in the Porcupine Hills and Duck Mountains.

2.2.4 Climatology

The climate in this watershed is categorized as sub-humid, with extreme seasonal variation. Average temperatures at two Environment Climate Change Canada weather stations in the region, Swan River and Pelly (Figure 2.2), were 1.8°C and 0.7°C, respectively, based on the 1981 – 2010 climate normals (Government of Canada, 2022). Both stations commonly experienced temperatures above 30°C in summer months and below -30°C in winter months. The Swan River Valley region experiences warmer temperatures earlier than the mountainous regions (Porcupine Hills and Duck Mountains) due to lower elevation. The mountainous region of the watershed experiences a later snowmelt period than the Swan River Valley region (SLWD, n.d.).

Swan River received an average of 547 mm of precipitation throughout 1981 – 2010, with approximately 76% falling as rain and 24% as snow. Pelly received an average of 573 mm of precipitation throughout those years, with approximately 71% falling as rain and 29% as snow. On average, there were approximately 155 days per year of precipitation with totals between 0.2 mm and 10 mm, and approximately 18 days per year with precipitation falling greater than 10 mm in the Swan River and Pelly area (Government of Canada, 2022).

2.2.5 Hydrology and Drainage

Swan Lake is the largest lake in the watershed at 308 km^2. Its watershed is approximately 10,000 km^2 and is dominated by two major river watersheds, the Swan River and the Woody River watersheds. Swan and Woody Rivers are major rivers flowing into Swan Lake and have many smaller tributaries and lakes within their watersheds (Figure 2.1). Swan River and Woody

River run nearly parallel to each other, and both curve up from the north portion of the watershed, west of the Porcupine Hills.

Swan River is approximately 250 km long, and its watershed covers approximately 6200 km^2. Both the river and watershed are split almost evenly between the provinces of Manitoba and Saskatchewan. Swan River flows south from the northwest corner of the watershed in Saskatchewan, then turns northeast towards Swan Lake. Water is captured on the north and northwest sides of the Duck Mountains and the southern portion of the Swan Lake watershed. The major tributaries flowing into Swan River are the Sinclair River, East and West Favel River, Ruby River, and Roaring River.

Woody River is approximately 150 km long, and its watershed covers approximately 2600 km^2. Woody River flows south towards the central portion of Swan Lake watershed in Saskatchewan, then turns northeast towards Swan Lake. Water is captured from the west and south sides of the Porcupine Hills. The major tributaries flowing into Woody River are Bowsman River and Birch River.

Water flows continuously throughout the year in both Swan and Woody Rivers. Peak flow typically occurs in April and May. Tributaries typically flow during the spring melt period and high rainfall events. The tributaries can become dry in the fall. Major flooding events in this area occurred in 1988, 1995, 2006, and 2012 (SLWD, n.d.).

2.2.6 Summary of Water Quality Surveys Pre-2011

The Water Quality Branch operated by the Province of Manitoba began water quality sampling for Swan and Woody Rivers in 1975 and 1974, respectively, once per year until 1977.

Sampling was reinstated in July 1988, after which the sampling frequency increased to three to four times per year. Jones and Armstrong (2001) examined trends in total phosphorus (TP) and total nitrogen (TN) concentrations from 1988 – 1999 in various rivers across Manitoba. Both Swan and Woody Rivers experienced a decline in nutrient residual scores of concentrations over the years. While the concentrations of TP and TN in Swan River declined significantly over this period, the decline in Woody River was statistically insignificant. Absolute concentrations were not provided in this study for these rivers. On the other hand, Bourne et al. (2002) examined nutrient loads for these rivers over a shorter period (1994 – 2001) and reported annual averages for both TP and TN loads. The annual mean of TP and TN over the 8-year period for Swan River was 53 tonnes/y and 373 tonnes/y, respectively. Woody River had an annual mean of 20 tonnes/y and 173 tonnes/y, respectively. Total nitrogen loads in Woody River experienced no change from 1988 – 1999, whereas changes in TP and TN loads for Swan River and TP load for Woody River were not reported.

Manitoba Water Stewardship (2011) provided a water quality report of the Swan Lake watershed, including a Water Quality Index (WQI) for the Swan and Woody Rivers. The WQI for Swan and Woody Rivers are categorized between ‘Fair’ and ‘Good’ throughout 1974 and 2010, with the exception in 1996 with Woody River being ‘Poor’ based on guidelines provided by Williamson (2002). Total phosphorus in both rivers was typically above the guideline of 0.05 mg/L. No guidelines were reported for TN. A steady increase was observed in TP and TN over the period between 1974 and 2010.

2.3 Methods

2.3.1 Data Sources and Cleaning

All data was sourced from government available data. Locations of the water quality, hydrometric flow (river discharge), and weather stations are displayed in Figure 2.2.

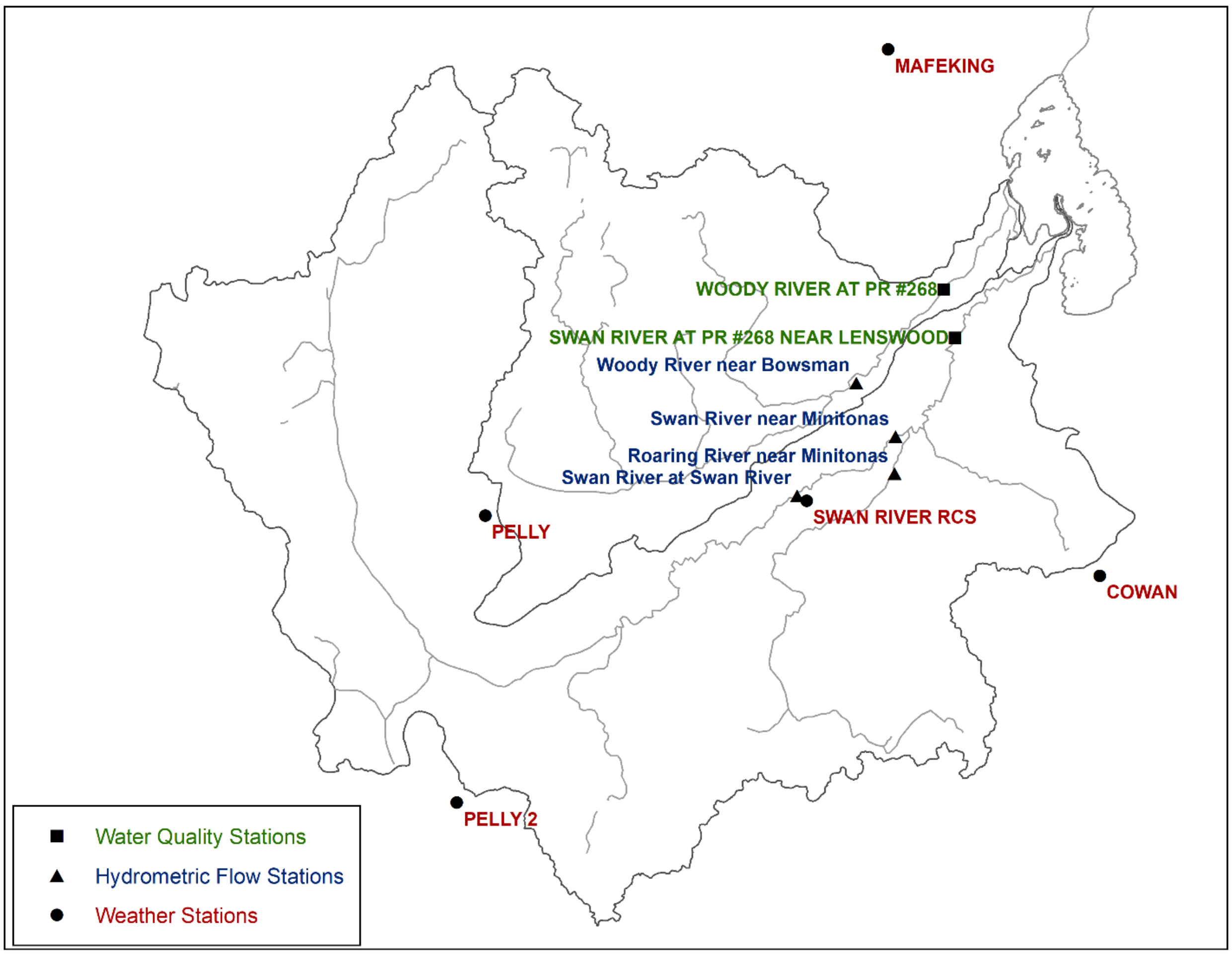

Figure 2.2. Locations of the water quality (green), hydrometric (blue), and weather stations (red) used in this study.

2.3.1.1 Precipitation

Daily precipitation data were obtained from the Adjusted and Homogenized Canadian Climate Data (AHCCD; https://open.canada.ca/data/en/dataset/d6813de6-b20a-46cc-8990-01862ae15c5f) for Swan River and Pelly (data available until 2007 and 2016, respectively). Additionally, daily precipitation for Swan River RCS and three other stations (Pelly 2, Mafeking, and Cowan), just outside of the Swan Lake watershed, were obtained from Environment and Climate Change Canada (ECCC) Historical Climate data (HCD; https://climate.weather.gc.ca/index_e.html). Historical Climate Data extended the AHCCD for Swan River to 2018. Stations ranged from 44 – 118 km from each other (see Figure 2.2).

Precipitation data used in this study required extensive data screening and gap-filling. Initially, precipitation data from Swan River, Pelly, Pelly 2, Cowan, and Mafeking were examined graphically to identify gaps. For this process, data was stratified into warm and cold seasons based on months (May to October as the warm season and the remaining months as the cold season). A non-parametric Kruskal-Wallis rank sum test and pairwise Wilcoxon test were used to determine differences between precipitation among the stations between 1995 – 2001. This period had the least number of gaps. Since there were many data gaps in Swan River from 2002 – 2008 and other stations had complete months missing throughout the 30-year period, the precipitation datasets were divided into two separate seven-year periods. The periods under examination are 1995 – 2001 and 2009 – 2015 for Swan River, Pelly, Pelly 2, and Mafeking. The removal of the Cowan station from the analysis was due to many data gaps in the second period. Inverse distance weighting (IDW) filled any remaining daily precipitation gaps in the four weather stations (Tabios and Salas, 1985; F.-W. Chen and Liu, 2012). Although, there are statistical differences between some stations, all stations, including Cowan, were used to fill gaps.

Data from the AHCCD corrected any known errors or discrepancies in daily temperature and precipitation measurements of the HCD. For the precipitation data in Pelly 2 and Mafeking, and Swan River from 2007 to 2018, data from the HCD was converted to match the AHCCD adjusted precipitation dataset. This conversion process began with determining a snow-rain threshold using the temperature data from the HCD. Temperature data gaps were filled using IDW. Similar to the technique used for determining a snow-rain threshold by Dai (2008), counts of temperatures on days with rain and snow (Swan River AHCCD adjusted precipitation) were separated into 1°C bins between -8°C and +8°C. These counts were converted to frequency by dividing each count by the total count of precipitation values. The rain and snow frequencies can be interpreted as the probability rain or snow will occur at temperatures less than or equal to, or greater than or equal to, respectively. Cumulative counts were performed with all values from all seasons. Temperatures that observed an occurrence of less than 5% rain or snow event were averaged to determine the snow-rain threshold. Total precipitation values were categorized as daily rain and snow values based on the snow-rain threshold of +1°C. This follows the predicted snow-rain threshold found by Jennings et al. (2018), where southern Manitoba has a threshold between +1 and +3°C. For consistency across the four weather stations, the +1°C snow-rain threshold was used on all four stations to categorize daily total precipitation values into daily rain and snow values. The resulting rain and snow totals were converted to follow AHCCD adjusted precipitation dataset using Mekis and Vincent (2011) adjusted equation, which for rain accounts for measured daily rainfall, funnel wetting correction, evaporation, retention correction, and wind correction factor. For snowfall, a snow equivalent adjustment factor was multiplied to the daily snow value. The adjusted rain and snow values were added together to obtain an adjusted total precipitation value. After the conversion of rain and snow values, post-2007 Swan River precipitation data from the HCD was added to the AHCCD to have a complete time series.

2.3.1.2 River Discharge

Hydrometric flow data were obtained from Environment Climate Change Canada's historical hydrometric online database, Water Survey of Canada (WSC; https://wateroffice.ec.gc.ca/). Daily river discharge data for Woody River (near Bowsman; 05LE004), Roaring River (near Minitonas; 05LE005) and Swan River (near Minitonas; 05LE006) were available from WSC dating back to 1954, 1959, and 1960, respectively. These WSC gauging stations are typically operational from March to October and not operational from November to February due to ice cover and negligible flow during winter.

Data gaps during the open-water season in Swan River, Roaring River, and Woody River were estimated using regression analysis. The missing daily discharge were estimated by comparing the daily discharge values from one neighbouring river. Three linear regression equations between daily discharges at pairs of rivers were examined based on a date range where most data gaps occurred for each season (spring, summer, and fall) between 2000 and 2018. These range of dates differed between each river. Woody River did not contain any data gaps during the open-water period. Swan River used Woody River, and Roaring River used Swan River to estimate missing daily values (small gaps). Swan River was more strongly correlated with Woody River (coefficient of determination; $R^2 > 0.79$) relative to the relationship observed between Roaring and Swan Rivers ($R^2 > 0.33$). Swan River discharge for 2014 contained the largest gap of two months and was estimated using an older upstream automated gauge (Swan

River near Swan River; 05LE001). Linear regression analysis between the measured daily water levels from both Swan River hydrometric stations were used to estimate missing 2014 water levels in station 05LE006. Stage-discharge curves from the non-missing 2014 values examined the spring (March to May) and the combined summer and fall (June to October) seasons ($R^2 > 0.99$). The stage-discharge curve equation was used to calculate the missing daily discharge rates. Daily discharge during the ice-cover period (November to February) was filled using a modified interpolation method to obtain declining discharge rates during these months of the year (Rattan et al., 2017). The Swan River hydrometric station used in this study, recorded winter discharge until February 1997. For each year through this period, monthly mean discharge from November to February was expressed as the fraction of the discharge on the antecedent October 31. The averages of these fractions estimated discharge on the 15th day of each missing winter month by multiplying the average fraction by the discharge on the antecedent October 31. These monthly average were treated as mid-month values to interpolate daily mean discharge through the missing winter months using the package 'Zoo' (Zeileis et al., 2021) in R. Woody River had no years with discharge recordings from November to February. Therefore, daily discharge through the missing ice-covered periods from November to February was initially estimated by linear interpolation in R using the 'Zoo' package. The interpolated daily discharge was used to calculate the fraction of discharge to determine the estimated discharge on the 15th day of each missing winter month, and then interpolated in R between each estimated 15th day to estimate daily mean discharge during the ice-cover periods with declining rates, similar to the method used on Swan River.

River discharge for Swan River was calculated by the addition of discharge values from the Swan River hydrometric stations (05LE006) and the Roaring River hydrometric stations

(05LE005). New watershed areas were calculated to determine the extent of the watershed upstream from the water quality stations. The new watershed area downstream from the water quality stations for Swan River is 6020 km^2 and 2330 km^2 for Woody River. An area ratio was used to prorate the watershed area from the hydrometric stations to the water quality stations (difference in area of 950 km^2 for Swan River and 220 km^2 for Woody River watersheds). This multiplier was applied to daily discharge, and these prorated values were used to examine annual and seasonal changes in river discharge. The term 'Swan River' for river discharge will be the summed, prorated discharge for both Swan River (05LE006) and Roaring River (05LE005). Hereafter, analyses on river discharge will use these prorated discharge values for both Swan River and Woody River discharge analysis.

In this study, continuous records of river discharge are examined from 1989 – 2018, in water years (November 1 to October 31). It is also examined in two periods, 1989 – 2000 and 2010 – 2018, to match periods with water quality data suitable for comparative analysis. When examining runoff, the years used are 1995 – 2001 and 2009 – 2015 to match precipitation analysis. Annual analyses for river discharge includes all seasons (spring, summer, fall, and winter). Seasonal analyses, however, only includes spring, summer, and fall, with summer and fall seasons merged into one season. The decision to merge summer and fall resulted from discharge data ending on October 31st, leaving only two months for the fall season with recorded values. Interpolated winter discharge values (November to February) left some uncertainty in this seasonal analysis. In addition, annual water yields (i.e., runoff) were calculated by dividing the annual total discharges by the prorated watershed areas.

2.3.1.3 Water Quality

Water chemistry data between 1988 and 2018 were obtained from the Province of Manitoba's Water Quality Management Section in support of this study. Water samples were collected by staff three to four times per year since 1988. Most years contain three water samples during the open water period, typically in the spring, summer, and fall season. Under-ice sampling began in 2006. Water samples were analyzed for various water quality variables by the ALS Environmental Laboratory (ALS; Winnipeg) from 1988 to March 2001 (hereafter ALS1), then Cantest Ltd (CNT; Winnipeg) until March 2009, and then back to ALS to the present (hereafter ALS2). The CNT period was removed from this study due to differences in laboratory techniques, which resulted in higher concentrations than obtained in ALS1 and ALS2 for equivalent samples (Appendix A; also see McCullough, 2015). The water quality variables examined in this study include total phosphorus (TP), particulate phosphorus (PP), total dissolved phosphorus (TDP), total nitrogen (TN), and total suspended solids (TSS) in the Swan River (at PR #268 near Lenswood; MB05LE011) and Woody River (at PR #268; MB05LE015) stations. Total nitrogen is the sum of nitrate-nitrite and total Kjeldahl nitrogen (ammonia plus organic nitrogen). Concentrations indicated as below detection limits are expressed as half the reported values, and concentrations above the detection limit retained the reported value (Government of Canada, 2020).

Daily concentrations of nutrients and TSS were estimated using linear regression analysis (Dolan et al., 1981; Quilbé et al., 2006; Johnes, 2007; Moatar et al., 2017) between the measured water chemistry concentrations and daily WSC discharge rates during the open-water periods. All regressions were considered significant at an alpha level of 0.05 (95% confidence level). Prior to regression analysis, concentration and discharge data were stratified into high and low flow (7 cu m/s threshold for Swan River and 5 cu m/s threshold for Woody River). The flow thresholds presented a visual break in a scatter plot between discharge rates and TP concentrations (Figure 2.3), and each flow class had roughly the same number of data points from the whole dataset. However, over 80% of total discharge is accounted for by daily discharges above the threshold for both rivers. To assess any influences on elemental concentrations from current stream conditions or prior conditions, that day and the prior consecutive two-, three-, four-, five-, and six-day maximum discharge was determined for each day in the concentrations dataset. This may account for any changes in concentrations from the response to changes in water discharge from direct precipitation or runoff into the rivers (G. McCullough, pers. comm., 2020). Discharge and concentration data were log-transformed to make the data more normally distributed. Days with zero value discharge were replaced with 0.001 m^3/s. Differences between regression coefficients were assessed using an analysis of covariance for ALS1 and ALS2. The coefficients were not statistically different (Table A.1 in Appendix A). From this, a single power regression equation for both ALS periods was used to calculate daily concentrations during high flow days. See Appendix A for explanation of merging ALS periods for determining daily concentration. Concentrations during low flow days used the median value of concentration at low flows for both ALS periods. Regressions and regression statistics for each parameter with stratification of flow are found in Figure 2.4 and Table 2.1, respectively. Total dissolved phosphorus had a weak correlation with the flow in both rivers; therefore, TDP at high flow is the difference between TP and PP rather than calculated by a regression, as demonstrated in Figure 2.4.

Nutrient and TSS loads, in tonnes per year (tonnes/y), were determined by multiplying the estimated daily nutrient concentrations by the daily prorated discharge, then summed over a period (annually or seasonal) to determine annual and seasonal total loads. Flow-weighted mean concentrations (FWMCs), in milligrams per litre (mg/L), were calculated by dividing the sum of daily nutrient loads over a specified period (annually or seasonally) by the sum of daily prorated discharge over that same period. Winter values for discharge were interpolated. However, winter loads in both rivers comprised a small portion of annual loads (1 – 5% in Swan River and 2 – 6% in Woody River across all water quality variables), so that they have little influence on trends or changes in annual loads. Nonetheless, the uncertainty due to the need to estimate winter discharge supports the decision to exclude the winter period from the seasonal analysis of this study. Nutrient and TSS yields were calculated by dividing annual loads by the watershed area upstream to the water quality stations (6020 km^2 for Swan River and 2330 km^2 for Woody River).

Annual analyses for FWMCs, loads, and yields includes all seasons (spring, summer, fall, and winter). Seasonal analyses, however, only include spring, summer, and fall, with summer and fall seasons merged into one season. Combining summer and fall seasons resulted from discharge data ending on October 31st, leaving only two months for the fall season with recorded values.

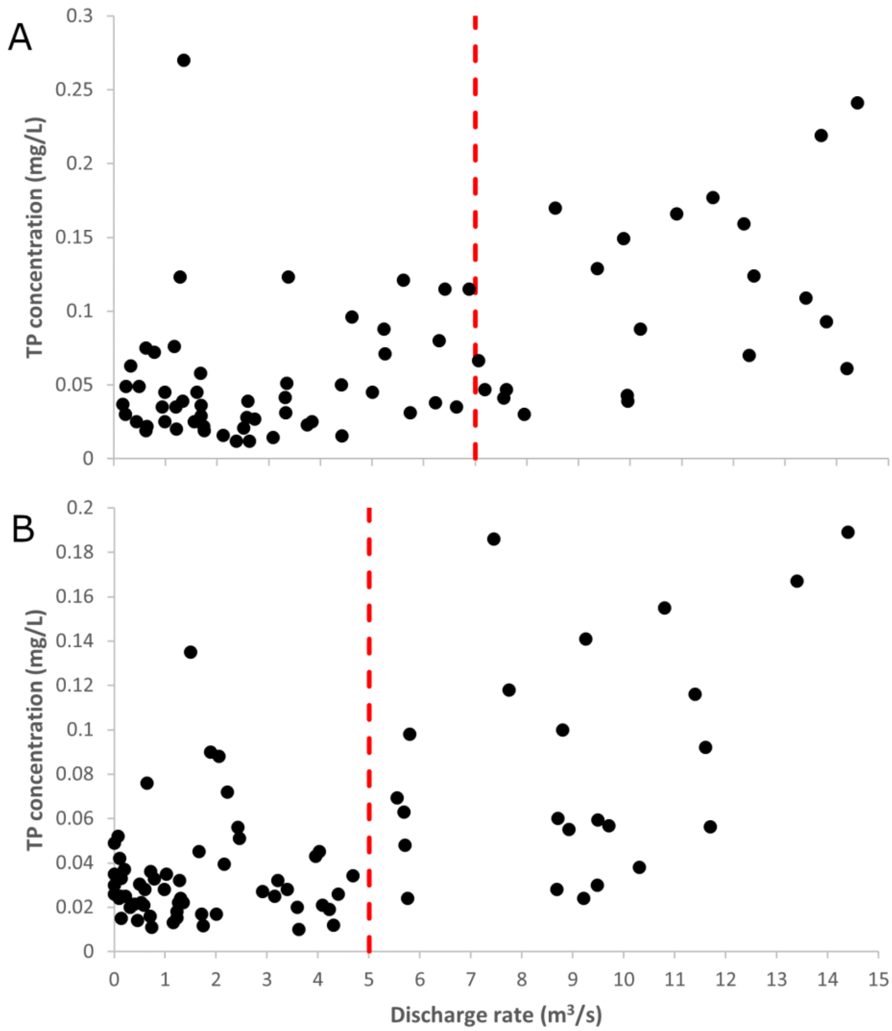

Figure 2.3. Measured total phosphorus concentrations versus that day discharge to assist in determining the high and low flow threshold for Swan River (A) and Woody River (B). Dashed red line indicates high and low flow threshold. Axes on both plots are scaled finer for better observation of threshold. Thresholds were based on visual break in the scatterplot and each flow class having roughly the same number of data points from 1988 – 2018.

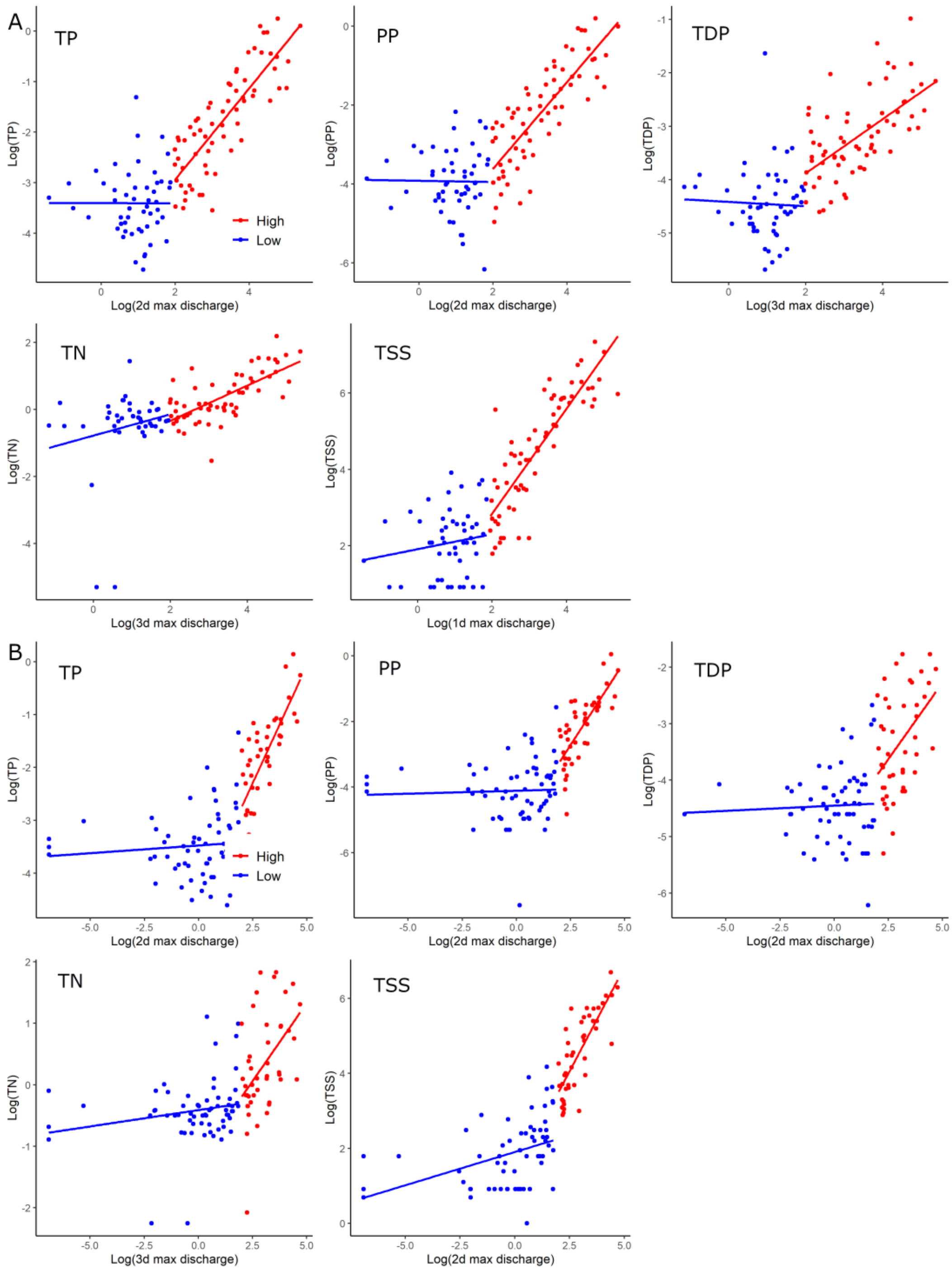

Figure 2.4. Regression plots of nutrient and TSS concentrations versus discharge. These regressions were used for calculating daily concentrations in Swan (A) and Woody (B) Rivers for ALS1 and ALS2 period. Discharge axis is the max discharge over that day and consecutive days of the observed water quality used to calculate concentrations. Both ALS concentration points were combined to determine one regression equation for daily calculations. Regressions are stratified in high (red) and low (blue) flow. Only high flows used a regression equation to calculate daily concentrations. Concentrations at low flow used the median of all concentrations at low flow.

Table 2.1. Regression statistics of nutrient and TSS concentrations versus river discharge used to calculate daily concentrations in Swan and Woody Rivers for ALS1 and ALS2 periods during high and low flow. Low flows produced poor correlation of determination (R^2) values and these regressions were not used for calculating daily concentrations, therefore, showing regression statistics for regression using 2-day max discharge. Significance of 5% indicated in bold.

	Max Day Discharge	R	R-squared	Std. Error	t-value	p-value
			Swan River – High flow			
TP	2-day	0.82	0.67	0.09	10	**<0.01**
PP	2-day	0.82	0.68	0.11	10	**<0.01**
TDP	3-day	0.57	0.33	0.09	4.9	**<0.01**
TN	3-day	0.68	0.47	0.08	6.2	**<0.01**
TSS	1-day	0.82	0.74	0.12	12	**<0.01**
			Swan River – Low flow			
TP	2-day	0.01	<0.01	0.22	0.04	0.97
PP	2-day	0.01	<0.01	0.25	0.04	0.97
TDP	2-day	-0.05	<0.01	0.23	-0.29	0.78
TN	2-day	-0.04	<0.01	0.13	-0.23	0.82
TSS	2-day	0.22	0.05	0.27	1.4	0.18
			Woody River – High flow			
TP	2-day	0.80	0.64	0.12	7.6	**<0.01**
PP	2-day	0.80	0.64	0.14	7.6	**<0.01**
TDP	2-day	0.51	0.26	0.18	3.4	**<0.01**
TN	3-day	0.58	0.32	0.14	3.9	**<0.01**
TSS	2-day	0.80	0.64	0.15	7.5	**<0.01**
			Woody River – Low flow			
TP	2-day	0.09	<0.01	0.06	0.60	0.56
PP	2-day	0.02	<0.01	0.07	0.15	0.86
TDP	2-day	0.15	0.02	0.05	1.0	0.31
TN	2-day	0.25	0.06	0.03	1.8	0.09
TSS	2-day	0.31	0.10	0.07	2.3	**0.03**

2.3.2 Trend and Correlation Analysis

The calculated parameters used in this study are annual and seasonal FWMCs, loads, annual yields, and total annual and total seasonal discharge and precipitation. Concentrations, loads, and precipitation data had a large gap between the two periods. Normal distributions between periods with continuous data were compared using the Shapiro-Wilk test, quantile-quantile plots, and density plots. River discharge data were not normally distributed, and at least one period from the water quality and precipitation datasets exhibited a non-normal distribution. The non-parametric Mann-Whitney test (e.g. Mann and Whitney, 1947; also referred as the Wilcoxon Rank sum test) was used to test the differences between the two periods in a two-sided and one-sided tests; i.e., Ho: the two random samples are drawn from the same population, for two-sided test, HA: the two random samples are drawn from different populations, and for a one-sided test, HA: the two random samples are drawn either greater than or less than the population, but not both.

The non-parametric Mann-Kendall test was used to determine the significance of continuous trends (Mann, 1945; Kendall, 1975) in discharge data. First, the Durbin-Watson (D-W; Durbin and Watson, 1950, 1951) test checked for the degree of lag-1 serial correlation (AR(1)). Since serial correlation was present in the data, a modified Mann-Kendall test, Trend Free Pre-Whitening (TFPW) procedure (Yue et al., 2002a,b), was used to test for trends with serial correlation removed in Swan River and Woody River datasets. Generally, the TFPW procedure first removes the linear component from the data, then pre-whitens using the AR(1) coefficient. This pre-whitened data is then tested using the Mann-Kendall trend test. For a more complete and detailed description of the methodology, see Yue et al. (2002a,b). The TFPW procedure was performed in R using the package ‘modifiedmk’ (Patakamuri, 2021).

Correlation between daily water quality concentrations and discharge was examined using the coefficient of determination (R^2), the square of the Pearson correlation coefficient (R). Correlation between annual and seasonal prorated discharge and precipitation data were examined using the non-parametric, Spearman's rho correlation test.

These analyses were conducted in RStudio using R Stats (R Core Team, 2021), unless otherwise stated. Differences and trend analyses are statistically significant at a 95% confidence level (i.e., $p\text{-value} < 0.05$). A hydrological (water) year is from November 1 to October 31.

2.4 Results

2.4.1 Precipitation

Precipitation analyses were restricted to two seven-year periods, 1995-2001 (P1) and 2009-2015 (P2), due to large gaps in the intervening precipitation data at some weather stations. Precipitation at the four weather stations (Swan River, Pelly, Pelly 2, and Mafeking) was averaged to obtain average annual and seasonal precipitation across the watershed. Annual and seasonal total precipitation amounts for each weather station and watershed average are reported in Appendix B. Percent change of median annual precipitation at the four weather stations are displayed in Figure 2.5. The changes in precipitation at the four weather stations between the two seven-year periods are small and insignificant (p-value >0.05 for all individual stations). The median annual precipitation across the watershed in P1 is 592 mm, and in P2 is 611 mm. The summer and fall combined season accounts for 60% of seasonal precipitation in both periods, and 21% of seasonal precipitation occurs in the spring season. Annual and seasonal changes across the watershed are also small (Figure 2.6) and insignificant (p-value > 0.05; Table 2.2).

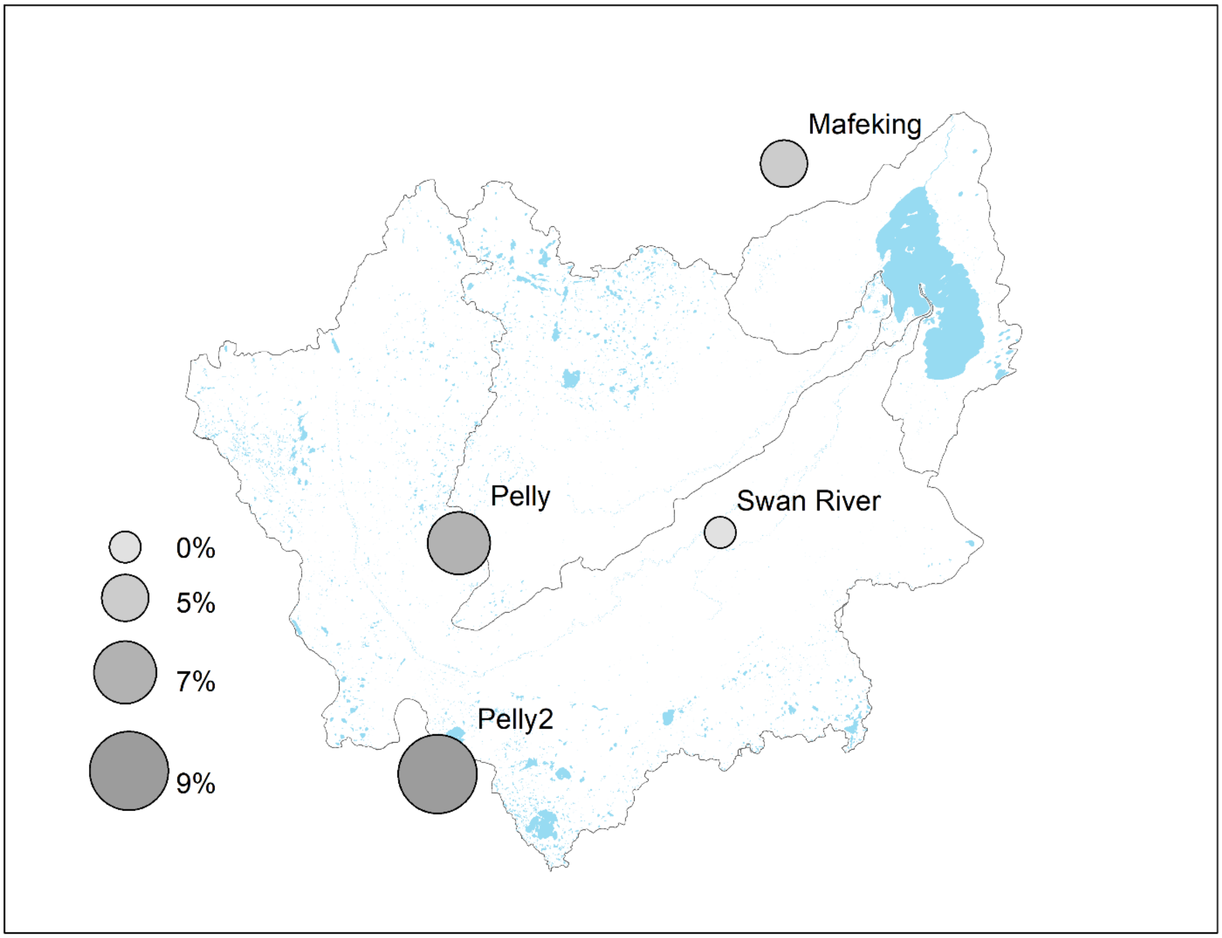

Figure 2.5. Percent changes in annual precipitation between 1995 – 2001 (P1) and 2009 – 2015 (P2) of four weather stations within and near the Swan Lake watershed. Circle diameters illustrate the percent change at the weather station e.g., [median (1995 – 2001) – median (2009 – 2015)] / median (2009 – 2015)].

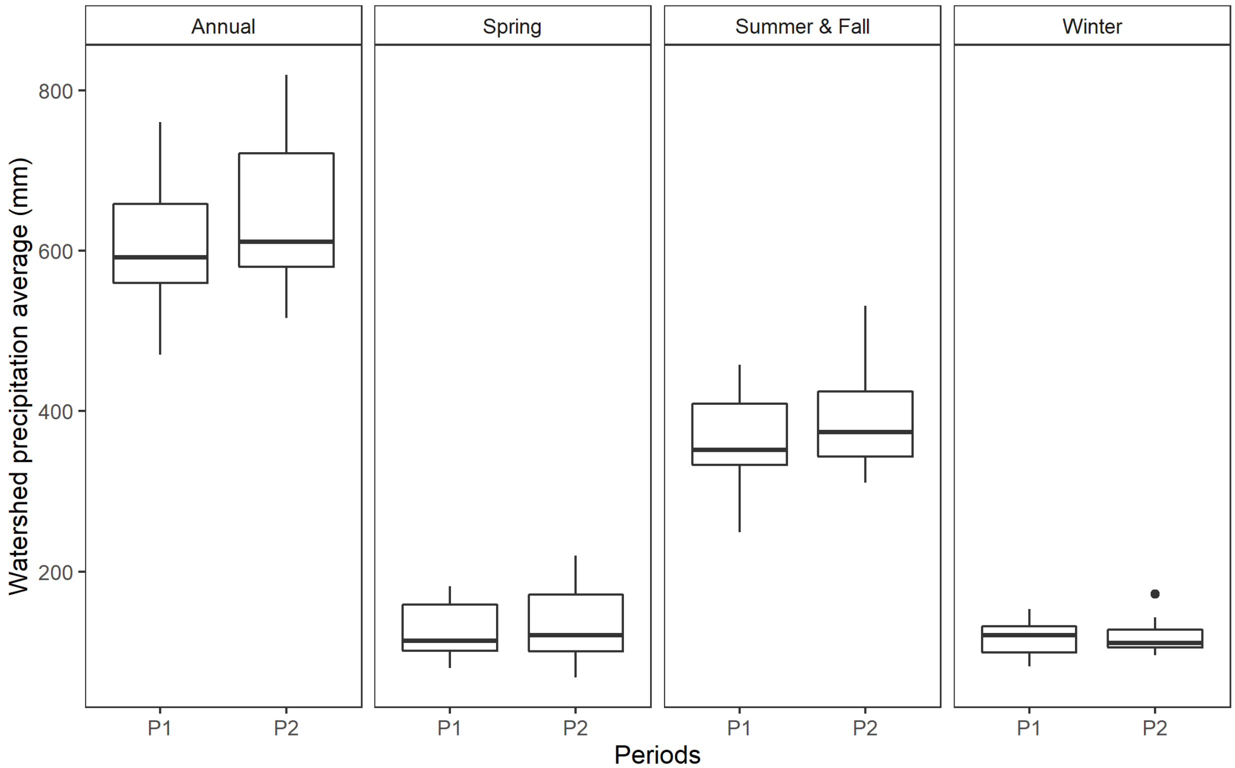

Figure 2.6. Boxplot of the average watershed annual and seasonal precipitation (mean total precipitation from Swan River, Pelly, Pelly 2, and Mafeking weather stations) in 1995 – 2001 (P1) and 2009 – 2015 (P2). These boxplots present the median, lower and upper quartile, and any outliers.

Table 2.2. Absolute median precipitation in 1995 – 2001 (P1) and 2009 – 2015 (P2), Mann-Whitney statistics, and p-value (two-sided test) for the changes in median annual and seasonal precipitation for the watershed average (mean of all weather stations). Significance of 5% indicated in bold.

	P1 (mm)	P2 (mm)	Change	W-stat	p-value
Annual	592	611	3%	18	0.46
Spring	114	121	6%	23	0.90
Summer and Fall	352	374	6%	21	0.71
Winter	121	111	-8%	26	0.90

2.4.2 River Discharge

Daily discharge over the 30-year period is shown in Figure 2.7. November to February daily discharge values was estimated through interpolation to examine annual total discharge rates. Both rivers showed typical discharge characteristics, with peak discharge occurring in the spring freshet period. Peak discharge occurred in April in 19 out of the 30 years in Swan River and 17 times in Woody River (Table 2.3). The peak flow between 1989 and 2018 averaged 147 m^3/s in Swan River and 83 m^3/s in Woody River; medians were 145 m^3/s and 70 m^3/s, respectively. The date of peak in Swan River advanced by 9.5 days/year (statistically insignificant; Tau = -0.08, p-value = 0.54), whereas Woody River advanced by 32 days/year (statistically significant; Tau = -0.29, p-value = 0.03) through the period. A second smaller peak often occurred during June and July, particularly in Swan River (Figure 2.7). In both rivers, the discharge in the late fall and winter was low and showed little variation. In other months, discharge showed pronounced inter-annual variability.

Annual and seasonal discharge data are reported in Appendix C, while the mean and median of total discharges for the 30 years are provided in Table 2.4. Swan River produced higher discharge rates than Woody River. Figure 2.8 visually displays the thirty-year annual discharge time series, with linear trend lines for Swan River and Woody River. The linear increase in annual discharge for Swan River and Woody River was 182% and 103%, respectively, over the 30 years. Both hydrometric stations presented AR(1) serial correlation in annual totals, with a D-W statistic of 0.20 and 0.27, respectively. Seasonal totals (spring, and summer and fall) had a D-W statistic ranging from 0.43 to 0.71. Although both streams showed a positive increase in discharge, Swan River was the only river with a statistically significant trend (p-value < 0.05; Table 2.5).

Seasonal discharge analyses only examined spring and the combined summer and fall seasons (Figure 2.9). Of these two seasons and because of the freshet, the spring had the highest mean and median annual discharge rate (Table 2.4). Both seasons in Swan River experienced a linear increase in discharge across the 30-year time series. While the increasing trend of 146% for the spring season was statistically significant (Table 2.5), the 174% trend increase in the summer and fall season was not statistically significant (significance at p-value ≤ 0.05). In contrast, in Woody River, both seasons experienced a statistically insignificant increase over the 30 years (85% and 82%, respectively).

The change in river discharge between the two water quality periods, ALS1 and ALS2, was also examined. Prorated mean and median daily river discharge for ALS1 and ALS2 periods in Swan and Woody Rivers are found in Table 2.8 and Table 2.10, respectively. The distributions of annual and seasonal total discharge of ALS1 and ALS2 for the Swan and Woody Rivers appears in Figure 2.10 and Figure 2.11, respectively. Annual discharge, and discharge during both the spring and summer and fall seasons, is higher in ALS2 relative to ALS1. These increases are statistically significant (p-value ≤ 0.05) for each period (with annual and the two seasonal categories; Table 2.6) in Swan River and Woody River, except during the summer and fall seasons (p-value > 0.05) in Woody River.

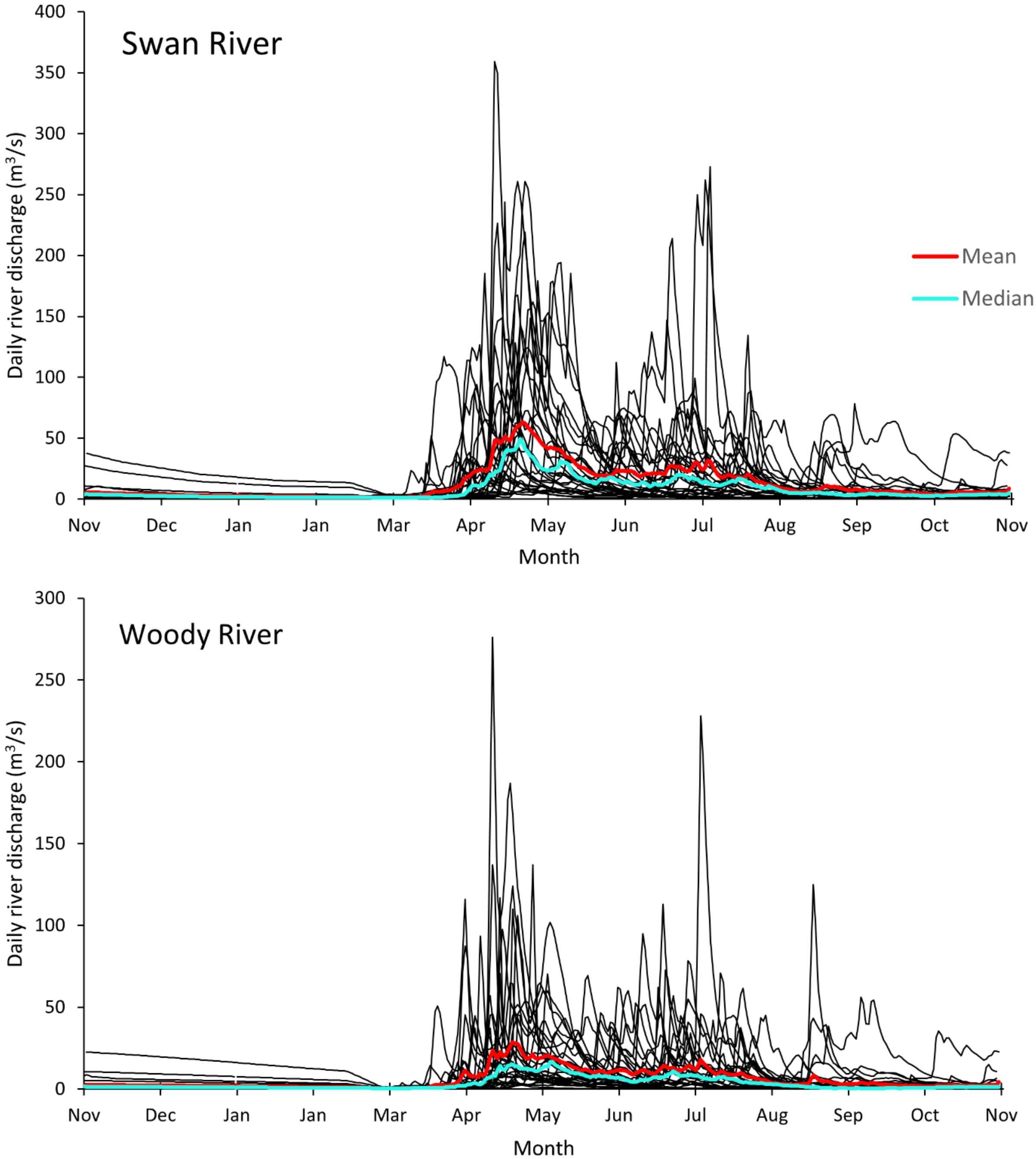

Figure 2.7. Daily discharge for each date of each year for a water year (1989 – 2018) in Swan River (top) and Woody River (bottom). Black lines are daily flow for each year; the red line is the mean discharge and the teal line is the median discharge of all years.

Table 2.3. Annual peak discharge and peak date in Swan and Woody Rivers.

	Swan River		Woody River	
Water year	Peak (m^3/s)	Peak day	Peak (m^3/s)	Peak day
1989	15.29	April 22	8.6	April 22
1990	94.2	April 05	53.7	April 26
1990	13.22	April 11	6.98	May 17
1991	44.35	April 20	19.3	May 05
1992	273	July 06	228	July 05
1993	89	July 22	55	June 30
1994	260.8	April 24	125	August 19
1995	149.1	May 01	69.4	May 20
1996	219.3	April 24	110	April 21
1997	99.3	June 30	70.9	July 13
1998	76.8	May 07	44.3	May 21
1999	87.76	June 28	57.2	June 23
2000	128.3	April 20	25.8	April 20
2001	23.17	April 16	6.32	April 22
2002	95.2	April 13	37.3	April 12
2003	185.4	April 07	93.5	April 07
2004	89.4	June 06	60.1	June 06
2005	359.2	April 12	276	April 13
2006	167.6	April 21	97.8	April 17
2007	243.7	April 15	117	April 15
2008	149.2	April 15	57.1	April 12
2009	146.9	June 19	56.2	September 07
2010	226.5	April 13	137	April 13
2011	213.9	June 20	113	June 19
2012	194.3	May 08	137	April 29
2013	261.9	July 04	106	April 23
2014	113.9	April 01	87.4	April 02
2015	142.9	April 21	70.6	April 15
2016	126.9	April 06	116	April 02
2017	148.5	April 26	50.2	June 10
2018	15.29	April 22	8.6	April 22

Table 2.4. Thirty-year (1989 – 2018) annual and seasonal arithmetic mean and median of discharge in Swan River and Woody River discharge. Standard deviation (SD) in parentheses. Discharge values have been prorated to the water quality stations.

		Annual (10^6 m^3/y)	Spring (10^6 m^3/season)	Summer and fall (10^6 m^3/season)
Swan River	Mean (SD)	472 (256)	241 (157)	194 (142)
	Median	403	191	184
Woody River	Mean (SD)	206 (111)	97.0 (66.8)	88.1 (65.9)
	Median	213	89.4	69.9

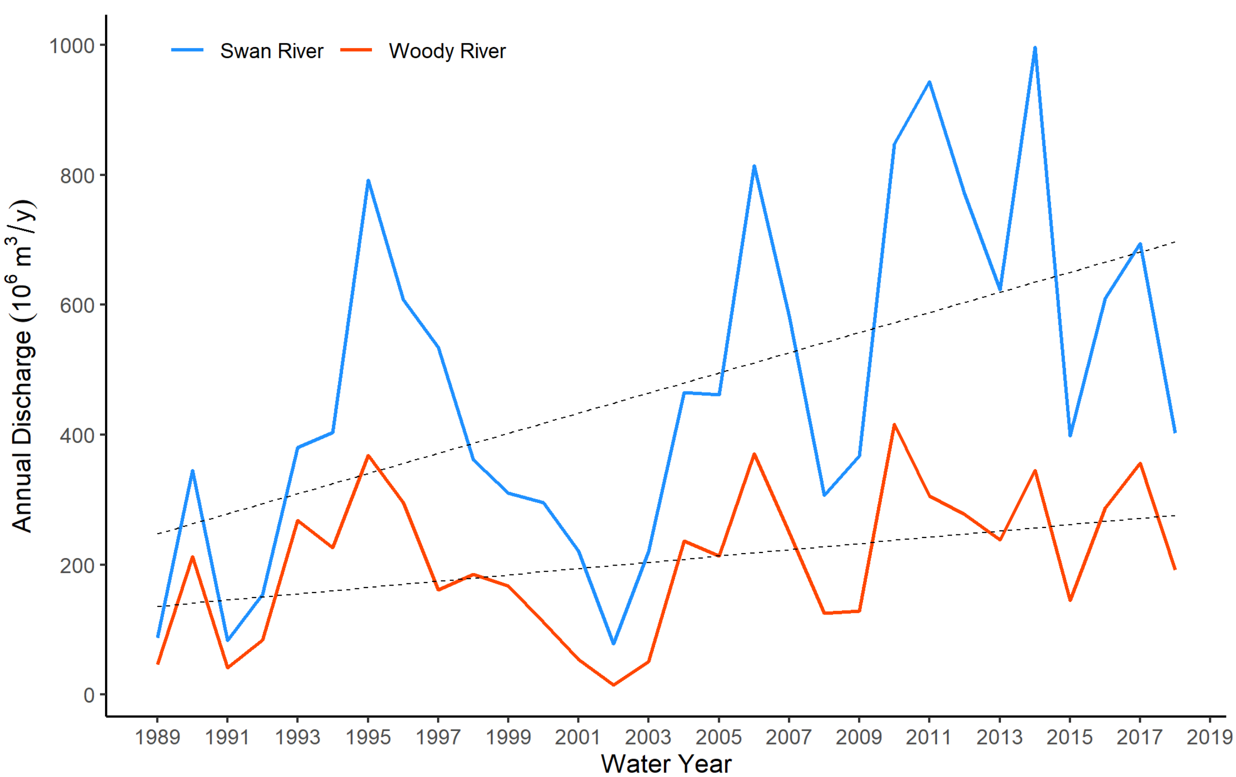

Figure 2.8. Total annual discharge in Swan and Woody Rivers from 1989 – 2018. Dash lines represent linear trends.

Table 2.5. Descriptive statistics of Trend Free Pre-Whitening Mann-Kendall test for annual and seasonal discharge long-term changes in Swan River and Woody River from 1989 – 2018. Significance of 5% indicated in bold.

		Trend	Tau	p-value
Swan River	Annual	Increasing	0.33	**0.01**
	Spring	Increasing	0.31	**0.02**
	Summer/fall	Increasing	0.16	0.24
Woody River	Annual	Increasing	0.21	0.12
	Spring	Increasing	0.22	0.10
	Summer/fall	Increasing	0.10	0.45

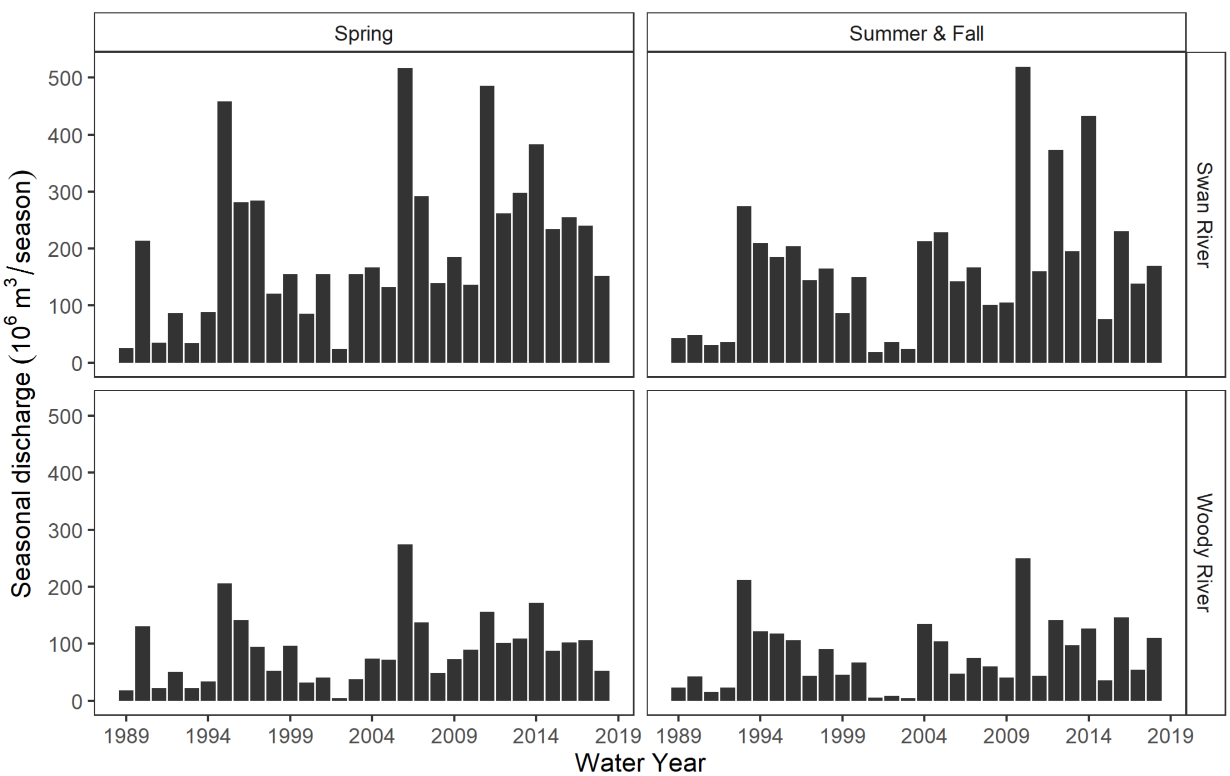

Figure 2.9. Total seasonal discharge in Swan and Woody Rivers from 1989 – 2018.

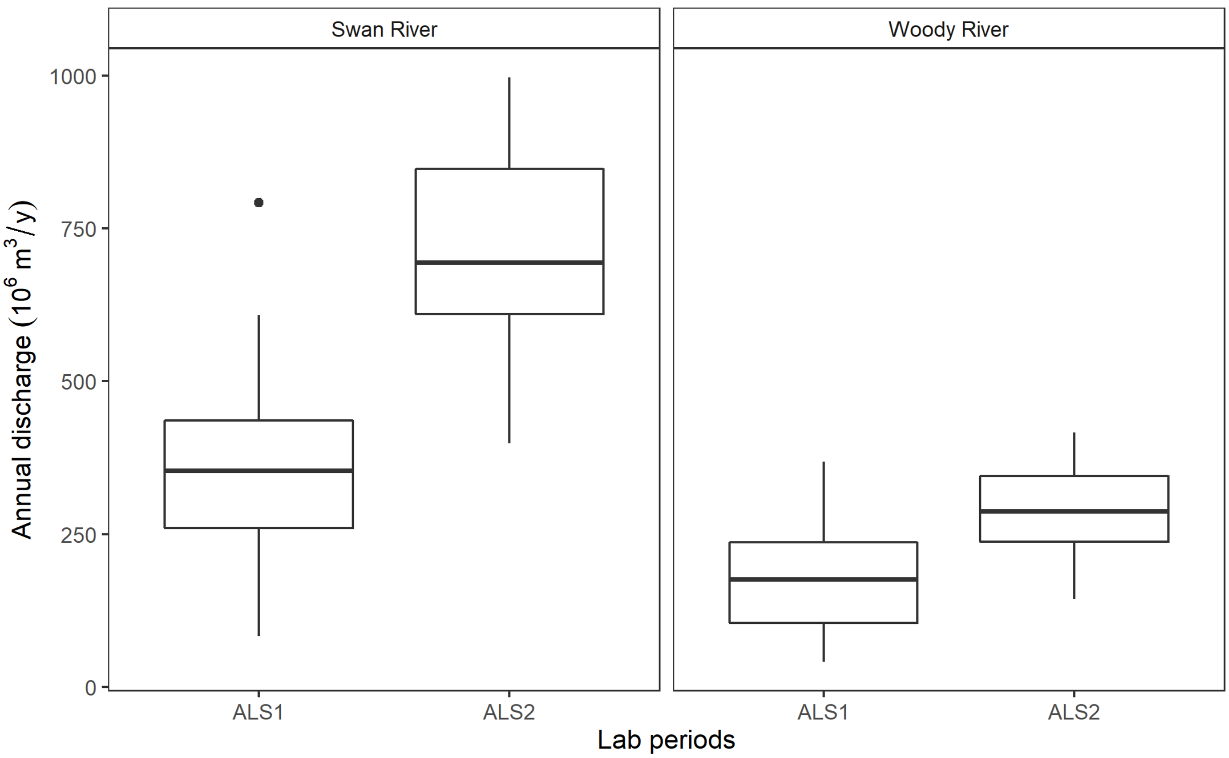

Figure 2.10. Total annual river discharge in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers.

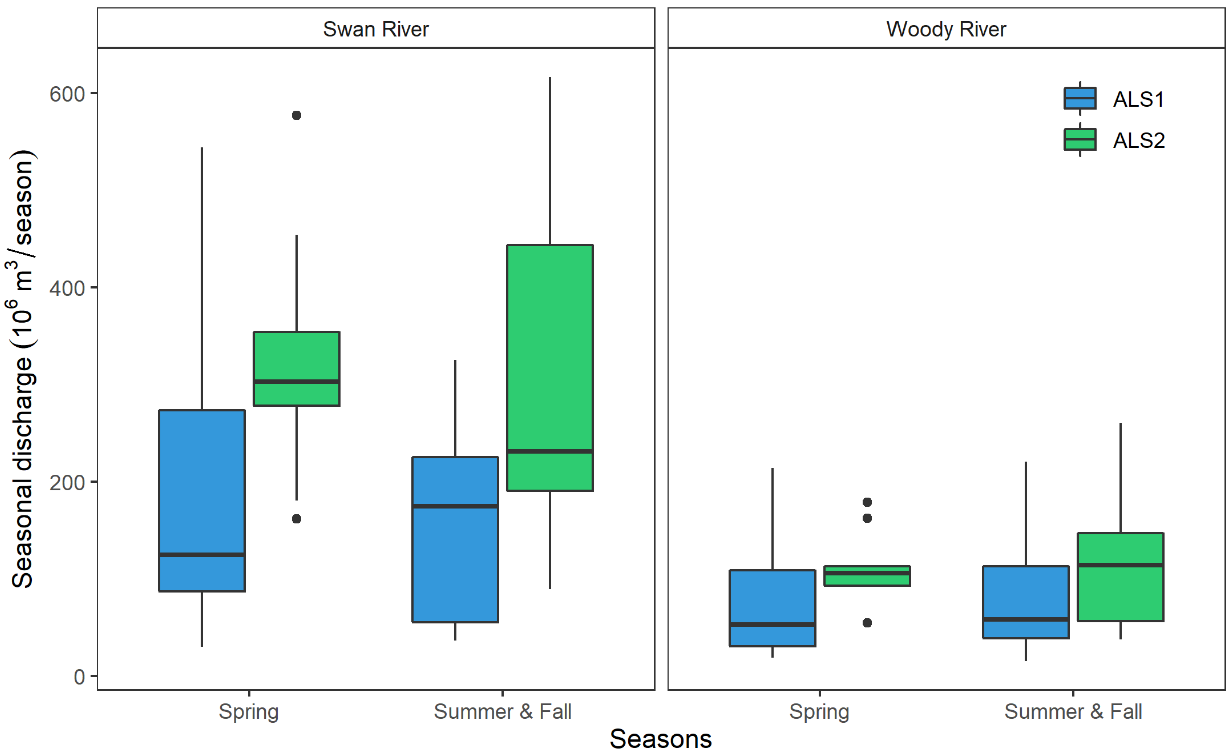

Figure 2.11. Total seasonal discharge (spring, and summer and fall) in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers.

Table 2.6. Statistical results showing the percent change of medians from ALS1 (1989 – 2000) and ALS2 (2010 – 2018), and p-values of Mann-Whitney test using a two-sided and one-sided test for annual and seasonal flow in Swan River and Woody River. Significance of 5% indicated in bold.

	Swan River			Woody River		
	Change	Two-sided	One-sided	Change	Two-sided	One-sided
Annual	96%	**<0.01**	**<0.01**	63%	**0.03**	**0.01**
Spring	143%	**0.03**	**0.02**	99%	0.08	**0.04**
Summer and Fall	32%	0.07	**0.03**	96%	0.13	0.06

2.4.3 Water Quality

Total phosphorus (TP), particulate phosphorus (PP), total dissolved phosphorus (TDP), total nitrogen (TN), and total suspended solids (TSS) flow-weighted mean concentrations (FWMCs) and loads are examined in this study. Annual and seasonal FWMCs and load values are reported in Appendix D.

Mean annual and seasonal FWMCs and loads are presented in Table 2.7 and Table 2.8, respectively, for Swan and Woody Rivers. Standard deviations are in parentheses, and percent changes of means between ALS1 and ALS2 are included. At least one period (ALS1 or ALS2) for each parameter displayed a non-normal distribution even with outliers removed; therefore, the following results discuss the differences in medians of FWMCs and loads between the two periods (Table 2.9 and Table 2.10, respectively). A non-parametric Mann-Whitney (M-W) test was used to determine whether the two independent samples (ALS1 and ALS2) are drawn from the same population (i.e., statistically different) and whether a sample population is statistically larger. Statistical results for FWMCs and loads for the water quality variables are tabulated in Table 2.11 but discussed in separate sections.

Table 2.7. Comparison of annual and seasonal arithmetic mean of flow-weighted mean concentrations (mg/L) and percentage of change of annual and seasonal total phosphorus (TP), particulate phosphorus (PP), total dissolved phosphorus (TDP), total nitrogen (TN) and total suspended solids (TSS) for 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2) in Swan River and Woody River. Standard deviation in parentheses.

		ALS1	ALS2	Change
		Swan River		
Annual	TP (mg/L)	0.223 (0.145)	0.329 (0.105)	48%
	PP (mg/L)	0.182 (0.145)	0.278 (0.112)	53%
	TDP (mg/L)	0.041 (0.016)	0.051 (0.008)	24%
	TN (mg/L)	1.56 (0.542)	2.00 (0.353)	28%
	TSS (mg/L)	263 (270)	416 (214)	58%
Spring	TP (mg/L)	0.235 (0.205)	0.391 (0.141)	66%
	PP (mg/L)	0.191 (0.204)	0.333 (0.147)	74%
	TDP (mg/L)	0.044 (0.019)	0.057 (0.009)	30%
	TN (mg/L)	1.61 (0.77)	2.24 (0.484)	39%
	TSS (mg/L)	279 (382)	503 (274)	80%
Summer and Fall	TP (mg/L)	0.154 (0.118)	0.252 (0.164)	64%
	PP (mg/L)	0.116 (0.11)	0.205 (0.171)	77%
	TDP (mg/L)	0.038 (0.018)	0.047 (0.0161)	24%
	TN (mg/L)	1.29 (0.484)	1.7 (0.582)	32%
	TSS (mg/L)	147 (182)	294 (321)	100%
		Woody River		
Annual	TP (mg/L)	0.170 (0.124)	0.196 (0.046)	15%
	PP (mg/L)	0.139 (0.123)	0.155 (0.043)	12%
	TDP (mg/L)	0.031 (0.014)	0.041 (0.005)	32%
	TN (mg/L)	1.21 (0.418)	1.36 (0.161)	12%
	TSS (mg/L)	148 (152)	160 (51.1)	8%
Spring	TP (mg/L)	0.150 (0.132)	0.235 (0.075)	57%
	PP (mg/L)	0.116 (0.119)	0.189 (0.072)	63%
	TDP (mg/L)	0.033 (0.017)	0.045 (0.004)	36%
	TN (mg/L)	1.15 (0.506)	1.51 (0.248)	31%
	TSS (mg/L)	118 (137)	200 (87.5)	69%
Summer and Fall	TP (mg/L)	0.149 (0.136)	0.153 (0.094)	3%
	PP (mg/L)	0.121 (0.135)	0.116 (0.084)	-4%
	TDP (mg/L)	0.028 (0.016)	0.037 (0.012)	32%
	TN (mg/L)	1.13 (0.476)	1.2 (0.377)	6%
	TSS (mg/L)	128 (167)	115 (95.7)	-10%

Table 2.8. Comparison annual and seasonal arithmetic mean of loads (tonnes/y), prorated mean daily discharge (Q; m^3/s), and percentage of change of annual and seasonal total phosphorus (TP), particulate phosphorus (PP), total dissolved phosphorus (TDP), total nitrogen (TN) and total suspended solids (TSS) for 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2) in Swan River and Woody River. Standard deviation in parentheses.

		ALS1	ALS2	Change
		Swan River		
Annual	TP (mg/L)	107 (118)	244 (143)	128%
	PP (mg/L)	90.7 (112)	209 (139)	130%
	TDP (mg/L)	15.8 (10.3)	34.7 (9.5)	120%
	TN (mg/L)	665 (567)	1440 (654)	117%
	TSS (mg/L)	140000 (205000)	320000 (246000)	129%
	Q (m^3/s)	11.5 (25.1)	22.1 (35.5)	92%
Spring	TP (mg/L)	72.1 (112)	139 (101)	93%
	PP (mg/L)	63.6 (109)	122 (96.9)	92%
	TDP (mg/L)	8.56 (7.21)	17.9 (5.70)	109%
	TN (mg/L)	406 (508)	770 (456)	90%
	TSS (mg/L)	103000 (202000)	188000 (168000)	83%
	Q (m^3/s)	23.3 (39.6)	40.6 (48.9)	74%
Summer and Fall	TP (mg/L)	33.7 (38.9)	98.1 (104)	191%
	PP (mg/L)	26.7 (35.8)	83.9 (99.8)	214%
	TDP (mg/L)	6.94 (5.36)	14.1 (10.7)	103%
	TN (mg/L)	242 (211)	596 (504)	146%
	TSS (mg/L)	36200 (58700)	128000 (176000)	254%
	Q (m^3/s)	11.8 (20.1)	22.9 (33.8)	94%
		Woody River		
Annual	TP (mg/L)	40.5 (44)	56.3 (21.6)	39%
	PP (mg/L)	34.3 (41.2)	44.3 (18.1)	29%
	TDP (mg/L)	6.25 (5.07)	11.9 (4.21)	90%
	TN (mg/L)	254 (205)	390 (128)	54%
	TSS (mg/L)	37500 (49200)	45700 (19900)	22%
	Q (m^3/s)	5.73 (13.6)	9.03 (14.5)	58%
Spring	TP (mg/L)	20 (29.5)	30.1 (17.7)	51%
	PP (mg/L)	16.4 (26.1)	24.5 (15.5)	49%
	TDP (mg/L)	3.59 (3.72)	5.55 (2.39)	55%
	TN (mg/L)	124 (143)	188 (87.5)	52%
	TSS (mg/L)	17500 (29600)	26200 (17600)	50%
	Q (m^3/s)	10.4 (18.0)	15.1 (20.0)	45%
Summer and Fall	TP (mg/L)	20.1 (31.7)	22.9 (20.3)	14%
	PP (mg/L)	17.6 (31.4)	17.7 (16.6)	1%
	TDP (mg/L)	2.49 (2.27)	5.21 (4.06)	109%
	TN (mg/L)	121 (136)	165 (123)	36%
	TSS (mg/L)	19900 (38800)	17900 (17700)	-10%
	Q (m^3/s)	6.32 (14.7)	9.33 (13.9)	48%

Table 2.9. Comparison of annual and seasonal median of flow-weighted mean concentrations (mg/L) and percentage of change of annual and seasonal total phosphorus (TP), particulate phosphorus (PP), total dissolved phosphorus (TDP), total nitrogen (TN) and total suspended solids (TSS) for 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2) in Swan River and Woody River. Standard deviation in parentheses. Percentages in bold are significantly greater at 5% (one-sided test). P-values for differences between ALS1 and ALS2 are found in Table 2.11.

		ALS1	ALS2	Change
		Swan River		
Annual	TP (mg/L)	0.202	0.273	**35%**
	PP (mg/L)	0.148	0.214	**45%**
	TDP (mg/L)	0.045	0.053	18%
	TN (mg/L)	1.54	1.83	**18%**
	TSS (mg/L)	179	285	**60%**
Spring	TP (mg/L)	0.177	0.354	**100%**
	PP (mg/L)	0.122	0.291	**140%**
	TDP (mg/L)	0.046	0.059	28%
	TN (mg/L)	1.47	2.14	**46%**
	TSS (mg/L)	129	416	**223%**
Summer and Fall	TP (mg/L)	0.145	0.181	25%
	PP (mg/L)	0.099	0.125	26%
	TDP (mg/L)	0.035	0.053	51%
	TN (mg/L)	1.29	1.49	15%
	TSS (mg/L)	105	136	29%
		Woody River		
Annual	TP (mg/L)	0.144	0.181	26%
	PP (mg/L)	0.107	0.144	35%
	TDP (mg/L)	0.036	0.041	**14%**
	TN (mg/L)	1.18	1.30	10%
	TSS (mg/L)	103	148	44%
Spring	TP (mg/L)	0.107	0.239	**123%**
	PP (mg/L)	0.072	0.195	**173%**
	TDP (mg/L)	0.035	0.044	26%
	TN (mg/L)	1.04	1.51	**45%**
	TSS (mg/L)	63.6	206	**224%**
Summer and Fall	TP (mg/L)	0.128	0.156	22%
	PP (mg/L)	0.092	0.113	23%
	TDP (mg/L)	0.027	0.042	56%
	TN (mg/L)	1.12	1.25	11%
	TSS (mg/L)	85.7	107	25%

Table 2.10. Comparison of annual and seasonal median of loads (tonnes/y), prorated median daily discharge (Q; m^3/s), and percentage of change of annual and seasonal total phosphorus (TP), particulate phosphorus (PP), total dissolved phosphorus (TDP), total nitrogen (TN) and total suspended solids (TSS) for 1989–2000 (ALS1) and 2010–2018 (ALS2) in Swan River and Woody River. Standard deviation in parentheses. Percentages in bold are significantly larger at 5% (one-sided test). P-values for differences between ALS1 and ALS2 are found in Table 2.11.

		ALS1	ALS2	Change
		Swan River		
Annual	TP (mg/L)	74	231	**213%**
	PP (mg/L)	53.9	181	**237%**
	TDP (mg/L)	17.2	35.1	**104%**
	TN (mg/L)	570	1360	**139%**
	TSS (mg/L)	63200	242000	**283%**
	Q (m^3/s)	3.39	7.04	**108%**
Spring	TP (mg/L)	25.1	98.6	**292%**
	PP (mg/L)	18.4	78.6	**328%**
	TDP (mg/L)	6.73	18.4	**174%**
	TN (mg/L)	193	618	**221%**
	TSS (mg/L)	19600	101000	**459%**
	Q (m^3/s)	7.46	21	**181%**
Summer and Fall	TP (mg/L)	28.9	38.9	35%
	PP (mg/L)	19.7	28.0	42%
	TDP (mg/L)	7.77	11.252	45%
	TN (mg/L)	255	331	30%
	TSS (mg/L)	21200	31800	50%
	Q (m^3/s)	5.24	9.56	**83%**
		Woody River		
Annual	TP (mg/L)	29.5	53.8	83%
	PP (mg/L)	21.8	44.1	102%
	TDP (mg/L)	5.88	12.1	**106%**
	TN (mg/L)	219	409	**87%**
	TSS (mg/L)	20900	47300	**126%**
	Q (m^3/s)	1.50	2.79	**86%**
Spring	TP (mg/L)	6.03	23.2	**285%**
	PP (mg/L)	4.05	18.9	**368%**
	TDP (mg/L)	1.99	4.96	149%
	TN (mg/L)	58.8	157	**168%**
	TSS (mg/L)	3600	20100	**457%**
	Q (m^3/s)	3.69	8.47	**130%**
Summer and Fall	TP (mg/L)	8.29	19	129%
	PP (mg/L)	6.04	13.9	130%
	TDP (mg/L)	1.28	5.1	**299%**
	TN (mg/L)	70.1	151	116%
	TSS (mg/L)	5720	13300	132%
	Q (m^3/s)	2.05	3.83	**87%**

Table 2.11. Statistical results of differences in medians from ALS1 (1989 – 2000) and ALS2 (2010 – 2018) using Mann-Whitney test U test (two-sided and one-sided test) for annual and seasonal flow-weighted mean concentrations (FWMC) and loads in Swan River and Woody River. Significance of 5% indicated in bold.

		FWMC						Loads					
		Swan River			Woody River			Swan River			Woody River		
		U-stat	Two-sided	One-sided	U-stat	Two-sided	One-sided	U-stat	Two-sided	One-sided	U-stat	Two-sided	One-sided
Annual	TP	26	**0.05**	**0.02**	33	0.15	0.07	18	**0.01**	**<0.01**	32	0.13	0.06
	PP	26	0.06	**0.03**	33	0.15	0.07	20	**0.01**	**0.01**	32	0.13	0.06
	TDP	32	0.13	0.06	25	**0.04**	**0.02**	8	**<0.01**	**<0.01**	21	**0.02**	**0.01**
	TN	25	**0.04**	**0.02**	34	0.17	0.08	17	**0.01**	**<0.01**	29	0.08	**0.04**
	TSS	27	0.06	**0.03**	32	0.13	0.06	21	**0.02**	**0.01**	30	0.10	**0.05**
Spring	TP	24	**0.03**	**0.02**	27	0.06	**0.03**	25	**0.04**	**0.02**	30	0.10	**0.05**
	PP	24	**0.03**	**0.02**	26	**0.05**	**0.03**	24	**0.03**	**0.02**	29	0.08	**0.04**
	TDP	32.5	0.13	0.07	35.5	0.20	0.10	17	**0.01**	**<0.01**	31	0.11	0.06
	TN	25	**0.04**	**0.02**	28	0.07	**0.03**	25	**0.04**	**0.02**	29	0.08	**0.04**
	TSS	24	**0.03**	**0.02**	26	**0.05**	**0.02**	24	**0.03**	**0.02**	28	0.07	**0.03**
Summer/fall	TP	36	0.22	0.11	48	0.70	0.35	33	0.15	0.07	41	0.38	0.19
	PP	36	0.21	0.11	48	0.15	0.07	34	0.17	0.08	42	0.42	0.21
	TDP	44.5	0.52	0.26	35	0.19	0.09	28	0.07	0.03	28	0.07	**0.03**
	TN	33	0.15	0.07	48	0.70	0.35	31	0.11	0.06	38	0.28	0.14
	TSS	37	0.25	0.12	48	0.70	0.35	36	0.22	0.11	42	0.42	0.21

2.4.3.1 Total Phosphorus

Swan River annual TP FWMCs (Figure 2.12) in ALS1 and ALS2 increased by 35% in ALS2 relative to ALS1. The increase is statistically significant at 95% confidence (p-values ≤ 0.05). Seasonally, TP FWMCs (Figure 2.13) significantly increased by 100% in the spring between periods (p-value ≤ 0.05). The median TP during the summer and fall seasons increased by 25% in ALS2 relative to ALS1; however, the increase is insignificant (p-value > 0.05). The median annual TP loads (Figure 2.14) in Swan River experienced a 213% increase in loads in ALS2 relative to ALS1 (differences are significant at p-value ≤ 0.05). Seasonal TP loads (Figure 2.15) in the spring in ALS1 and ALS2 experienced an increase of 292% in ALS2 relative to ALS1 (p-value ≤0.05), while the summer and fall experienced a non-significant increase of 35% from ALS1 relative to ALS2 (p-value >0.05).

In comparison to Swan River, annual TP FWMCs (Figure 2.12) in Woody River increased 26% from ALS1 to ALS2 (differences are not statistically greater at p-value > 0.05). The medians of spring TP FWMCs (Figure 2.13) had a statistically significant increase of 123% (p-value ≤ 0.05). The summer and fall season increased by 22% in ALS2 relative to ALS1 (differences are not statistically greater at p-value > 0.05). Annual TP loads in ALS1 and ALS2 (Figure 2.14) in Woody River increased by 83% (difference are not statistically greater at p-value > 0.05). Medians TP loads in the spring season (Figure 2.15) experienced a 285% significant increase (p-value ≤ 0.05) while summer and fall experienced a non-significant increase of 129% (p-value > 0.05).

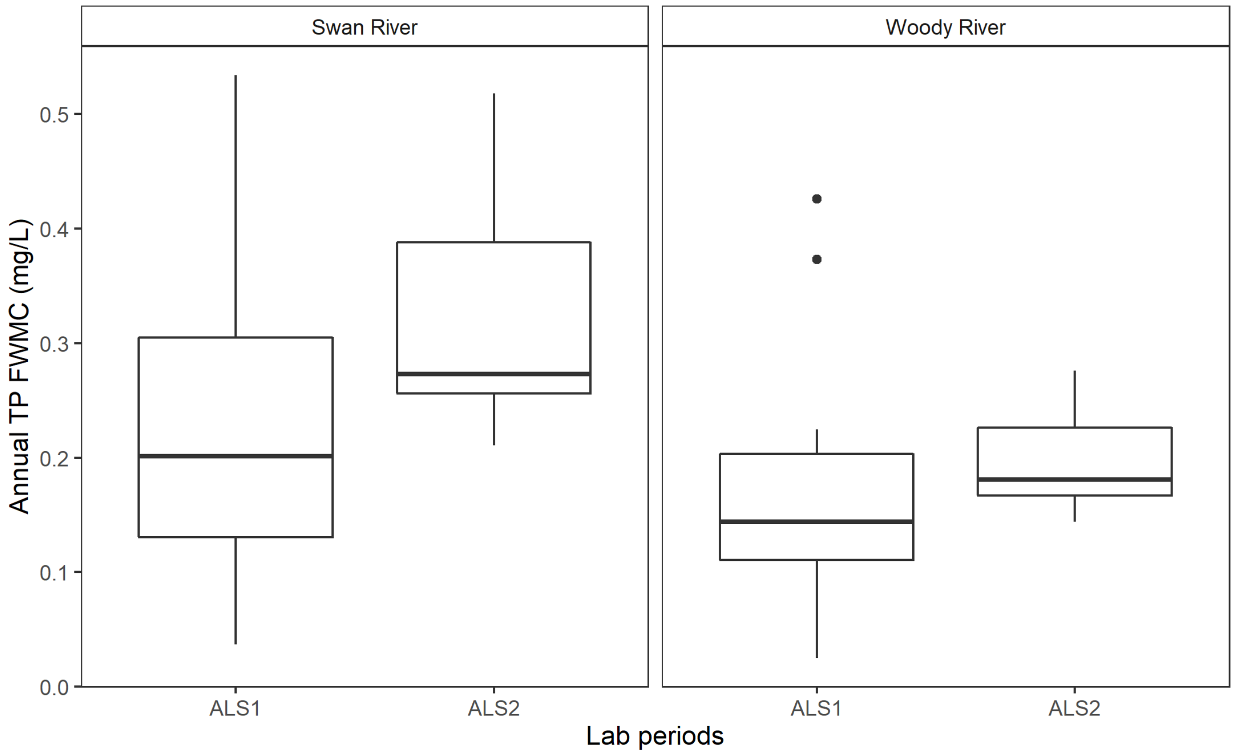

Figure 2.12. Total phosphorus (TP) annual flow-weighted mean concentrations (FWMC) in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Annual values are reported in Appendix D.

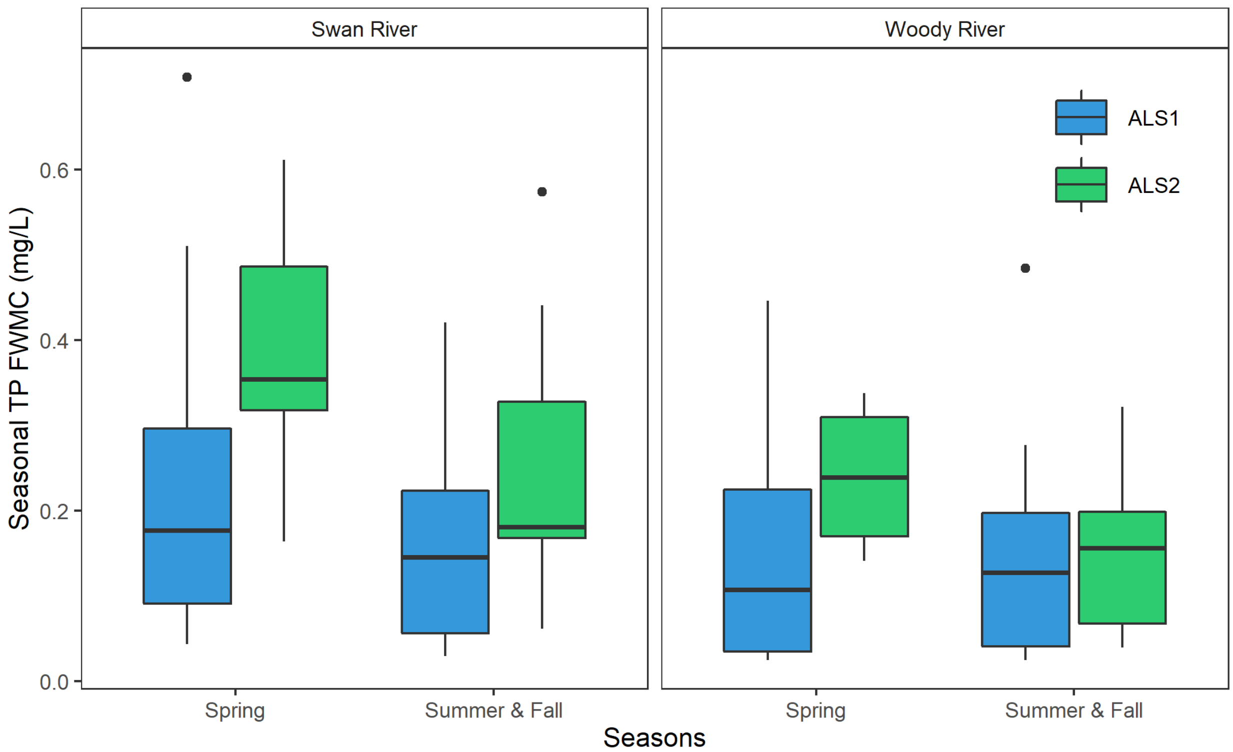

Figure 2.13. Total phosphorus (TP) seasonal flow-weighted mean concentrations (FWMC) in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Seasonal values are reported in Appendix D.

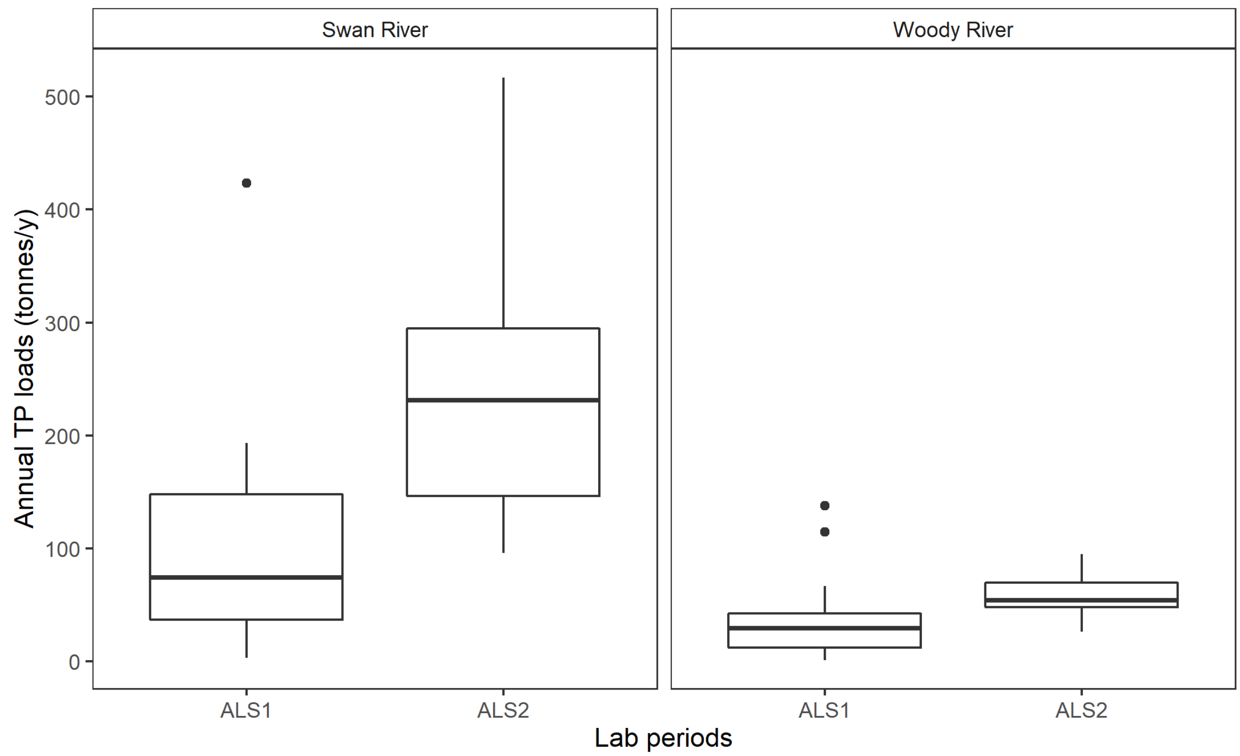

Figure 2.14. Total phosphorus (TP) annual loads in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Annual values are reported in Appendix D.

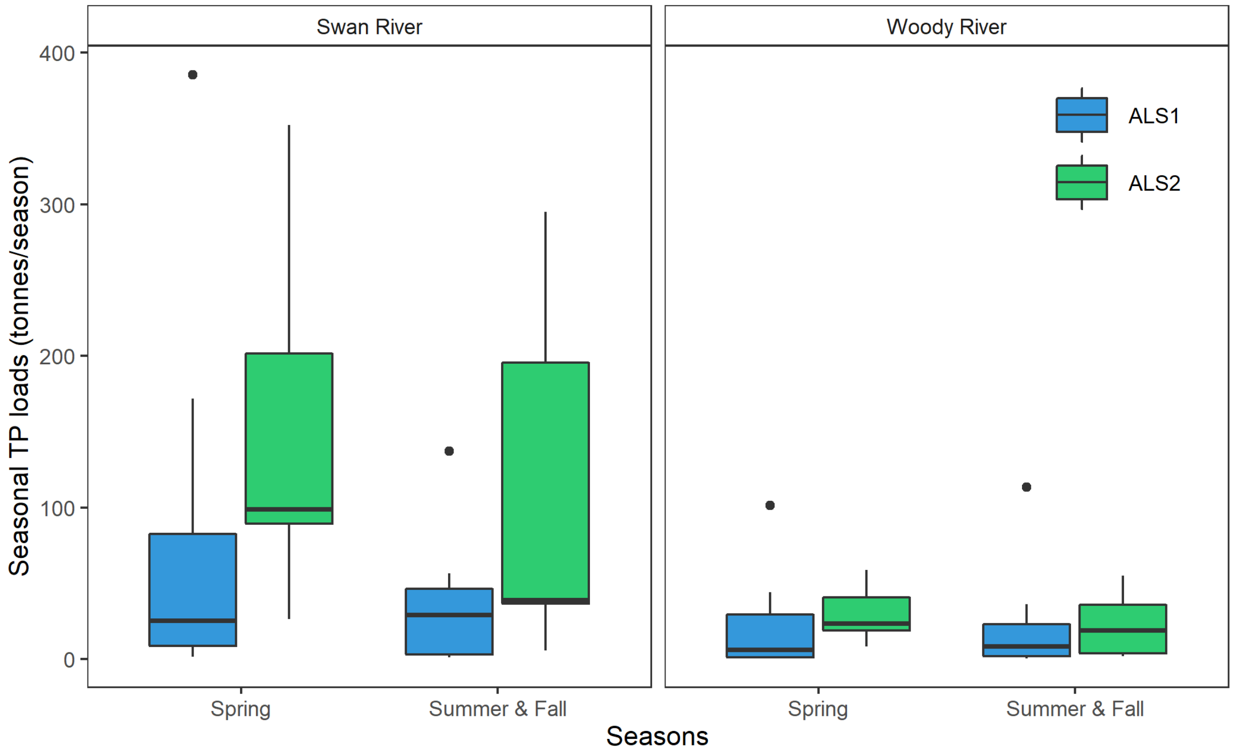

Figure 2.15. Total phosphorus (TP) seasonal loads in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Seasonal values are reported in Appendix D.

2.4.3.2 Particulate Phosphorus

The median and quartiles of annual PP FWMCs are presented in Figure 2.16. In Swan River, annual PP FWMCs increased by 45% from ALS1 to ALS2. This increase is significant (p-value $\leq$ 0.05). Seasonally, PP FWMCs (Figure 2.17) for Swan River in the spring and summer and fall increased by 140% and 26%, respectively, with only spring being statistically significant in ALS2 relative to ALS1 (differences are significant at p-value $\leq$ 0.05). Annual PP loads (Figure 2.18) in Swan River experienced a 237% increase in medians from ALS1 to ALS2. This increase is statistically significant (p-value $\leq$ 0.05). For seasonal PP loads (Figure 2.19), the spring medians increased by 328% in ALS2 relative to ALS1 (differences are significant at p-value $\leq$ 0.05). In the summer and fall season, there is a 42% increase; however, it is not statistically greater (p-value > 0.05).

Regarding Woody River, annual PP FWMCs (Figure 2.16) increased by 35%; this increase is not statistically greater (p-value > 0.05). Spring PP FWMCs (Figure 2.17) experienced a 173% increase in spring from ALS1 to ALS2 which is statistically significant (p-value $\leq$ 0.05). The summer and fall season increased by 23% from ALS1 to ALS2 and is not statistically greater (p-value > 0.05). Annual PP loads (Figure 2.18) in Woody River for ALS1 and ALS2 experienced a 102% increase (differences are not statistically greater at p-value > 0.05). The median seasonal PP load (Figure 2.19) in the spring season experienced an increase of 368% (differences are significant at p-value $\leq$ 0.05), and the summer and fall experienced an increase of 130% (differences are not statistically greater at p-value > 0.05).

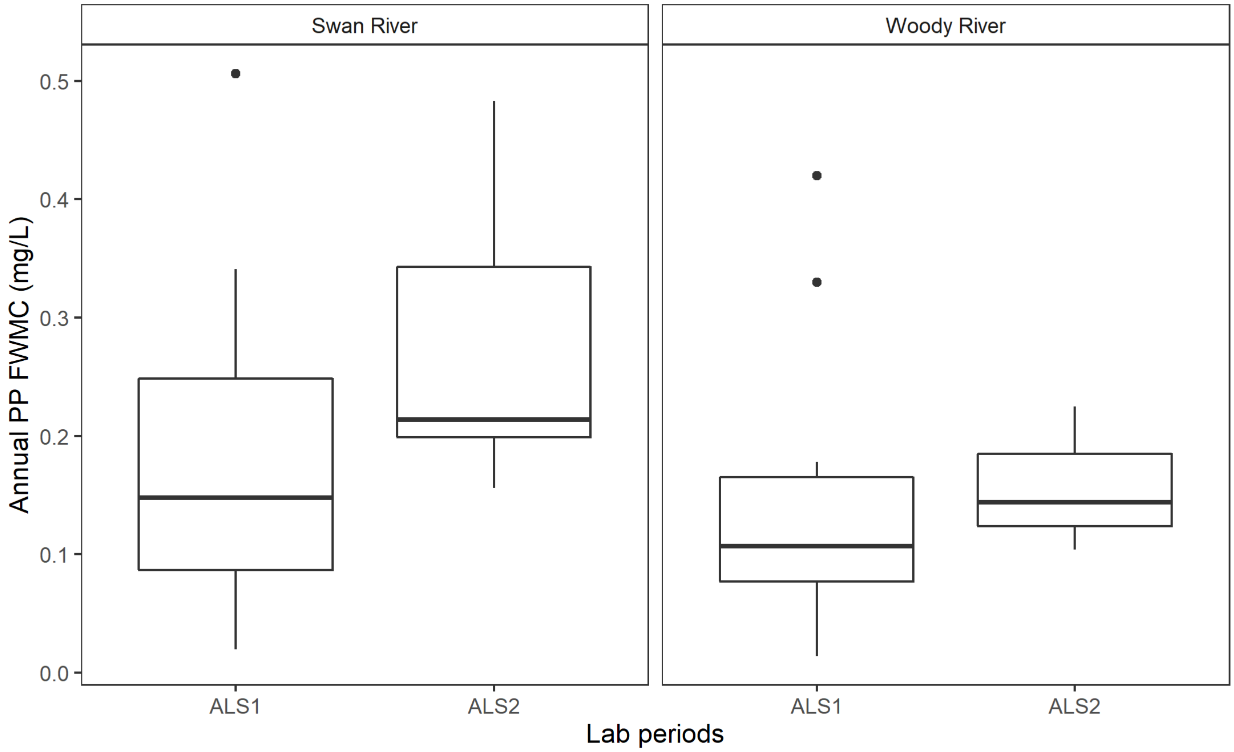

Figure 2.16. Particulate phosphorus (PP) annual flow-weighted mean concentrations (FWMC) in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Annual values are reported in Appendix D.

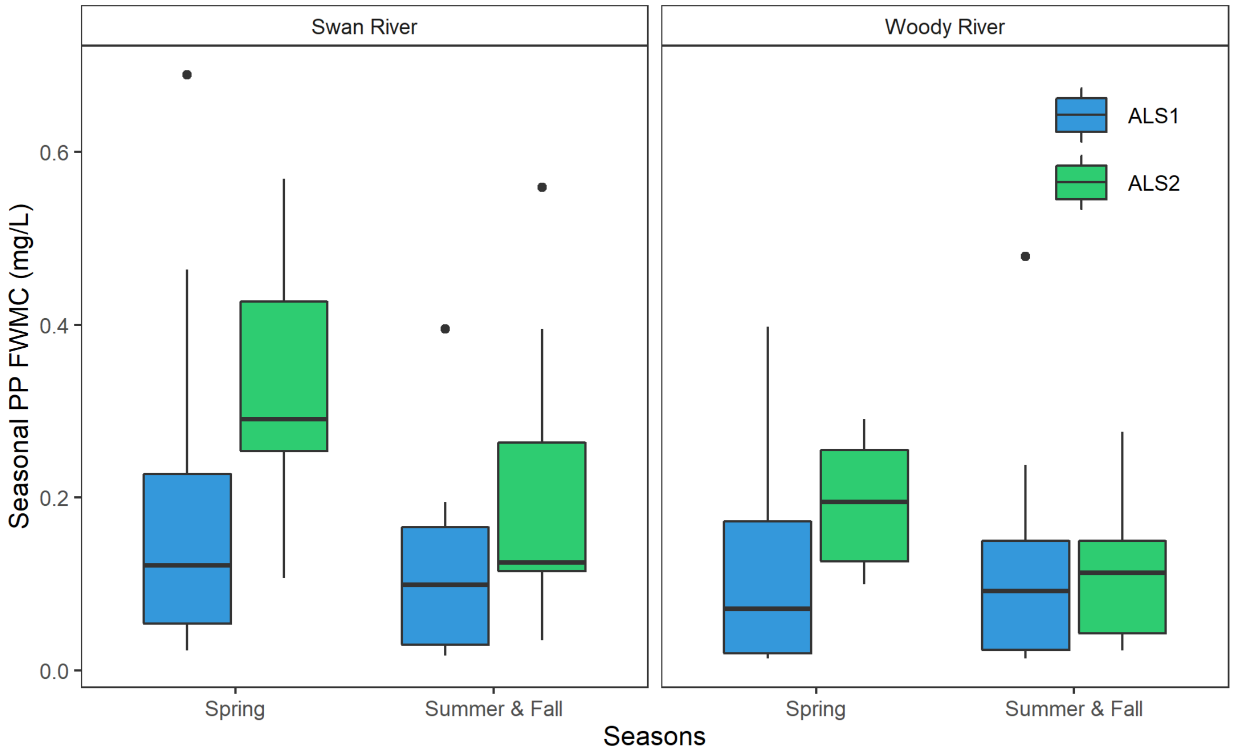

Figure 2.17. Particulate phosphorus (PP) seasonal flow-weighted mean concentrations (FWMC) in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Seasonal values are reported in Appendix D.

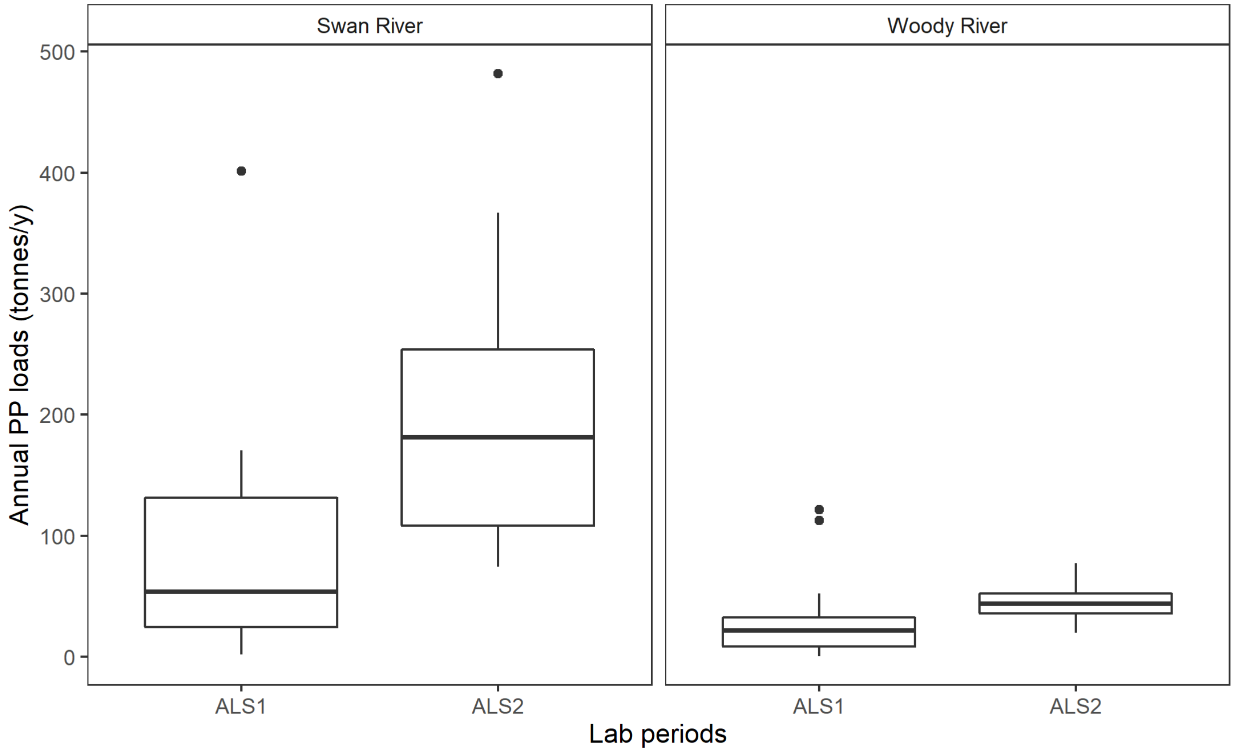

Figure 2.18. Particulate phosphorus (PP) annual loads in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Annual values are reported in Appendix D.

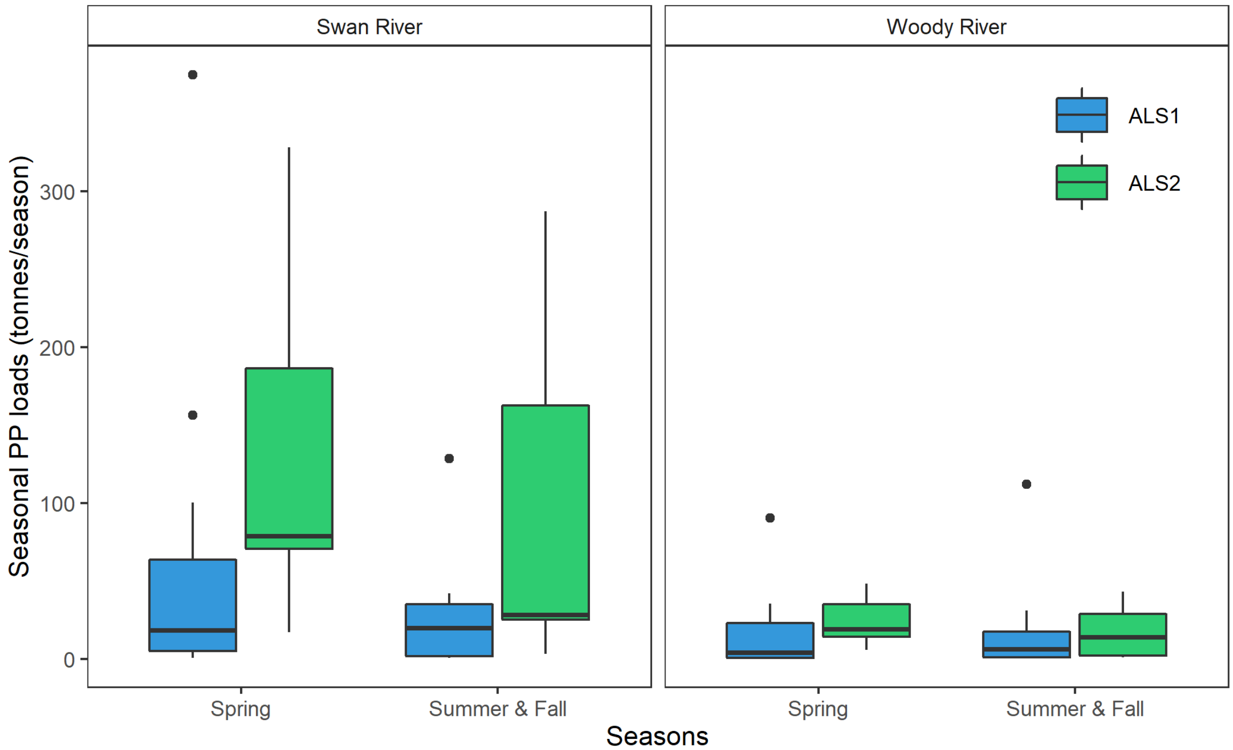

Figure 2.19. Particulate phosphorus (PP) seasonal loads in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Seasonal values are reported in Appendix D.

2.4.3.3 Total Dissolved Phosphorus

Swan River annual TDP FWMCs (Figure 2.20) have increased from ALS1 to ALS2 by 18%. This increase in medians is not statistically greater (p-value > 0.05). Total dissolved phosphorus FWMCs (Figure 2.21) in the spring, and summer and fall season increased by 28% and 51%, respectively. Both seasons are not statistically greater (p-value > 0.05). The medians of annual TDP loads (Figure 2.22) in Swan River experienced a 104% increase from ALS1 to ALS2 which is statistically significant (p-value ≤ 0.05). Spring, and summer and fall seasonal TN loads (Figure 2.23) increased by 174% (differences are significant at p-value ≤ 0.05) and 45% (differences are not statistically greater at p-value > 0.05), respectively.

In comparison to Swan River, Woody River annual TDP FWMCs (Figure 2.20) increased by 14% and are statistically significant (p-value ≤ 0.05) from ALS1 to ALS2. Seasonal TN FWMCs for Woody River (Figure 2.21) in the spring season increased by 26% in ALS2 relative to ALS1 (differences are not statistically greater at p-value > 0.05). The 56% increase from ALS1 to ALS2 summer and fall season is not statistically greater (p-value > 0.05). Woody River annual TDP loads (Figure 2.22) increased by 106% from ALS1 to ALS2 (differences are significant at p-value ≤ 0.05). Seasonal TDP loads (Figure 2.23) increased by 149% from ALS1 to ALS2 in the spring and are not statistically greater (p-value > 0.05). In the summer and fall season, the medians of TDP loads experienced a 299% increase (differences are significant at p-value ≤ 0.05).

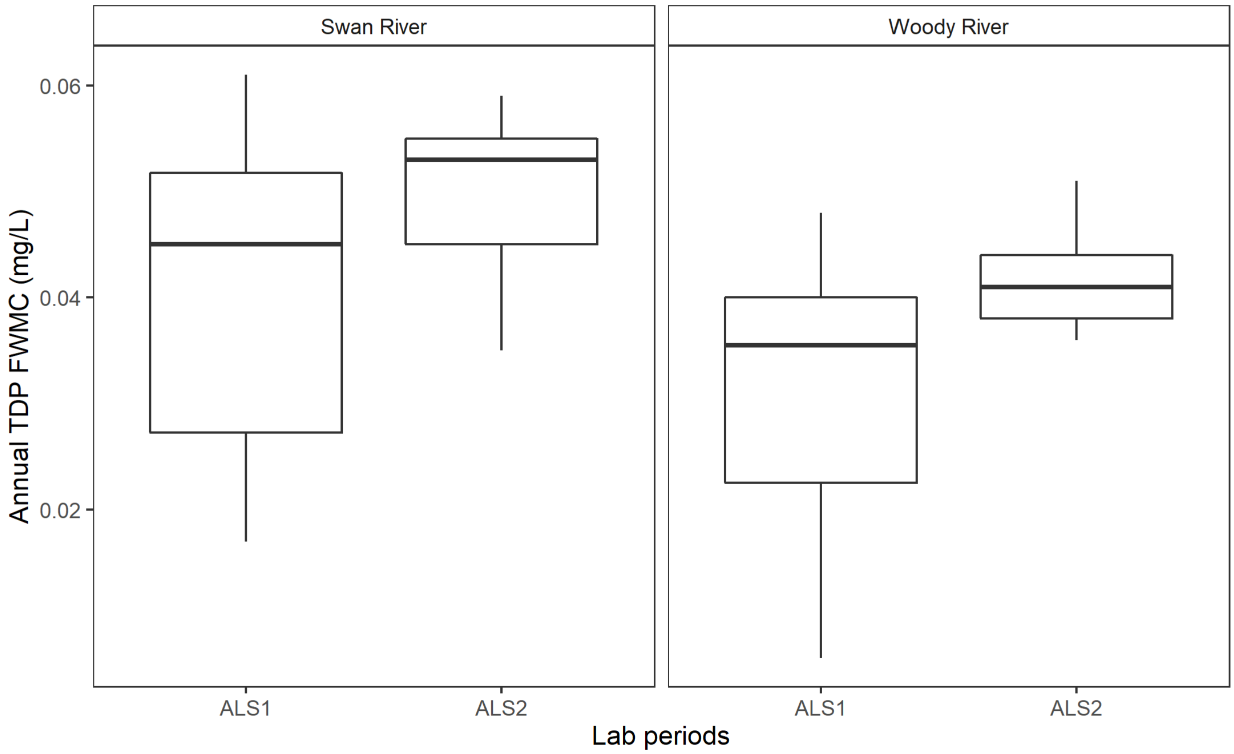

Figure 2.20. Total dissolved phosphorus (TDP) annual flow-weighted mean concentrations (FWMC) in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Annual values are reported in Appendix D.

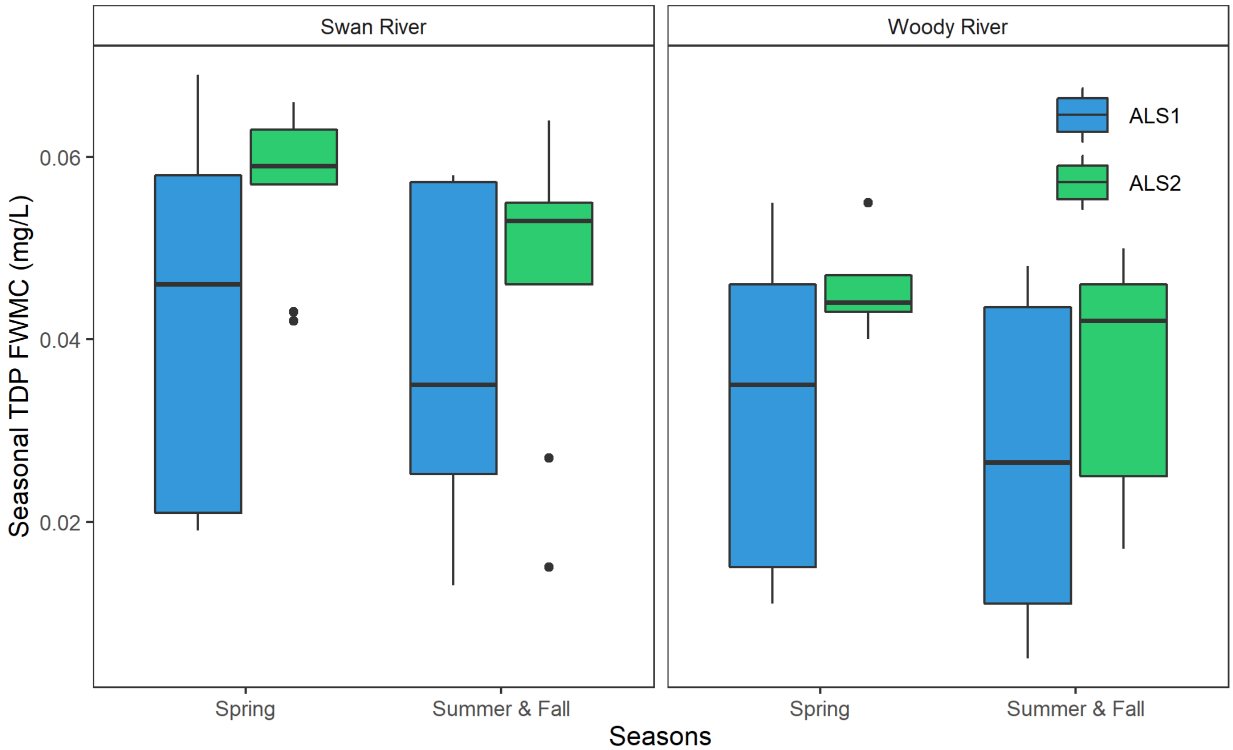

Figure 2.21. Total dissolved phosphorus (TDP) seasonal flow-weighted mean concentrations (FWMC) in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Seasonal values are reported in Appendix D.

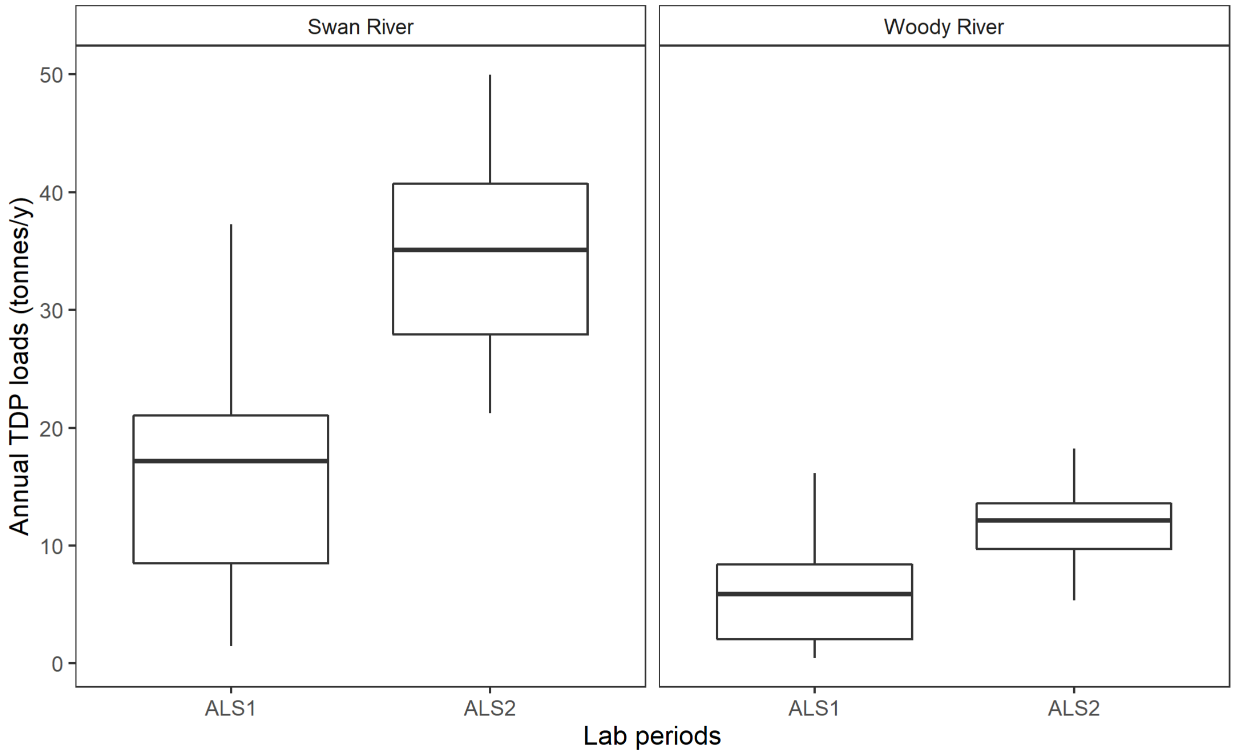

Figure 2.22. Total dissolved phosphorus (TDP) annual loads in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Annual values are reported in Appendix D.

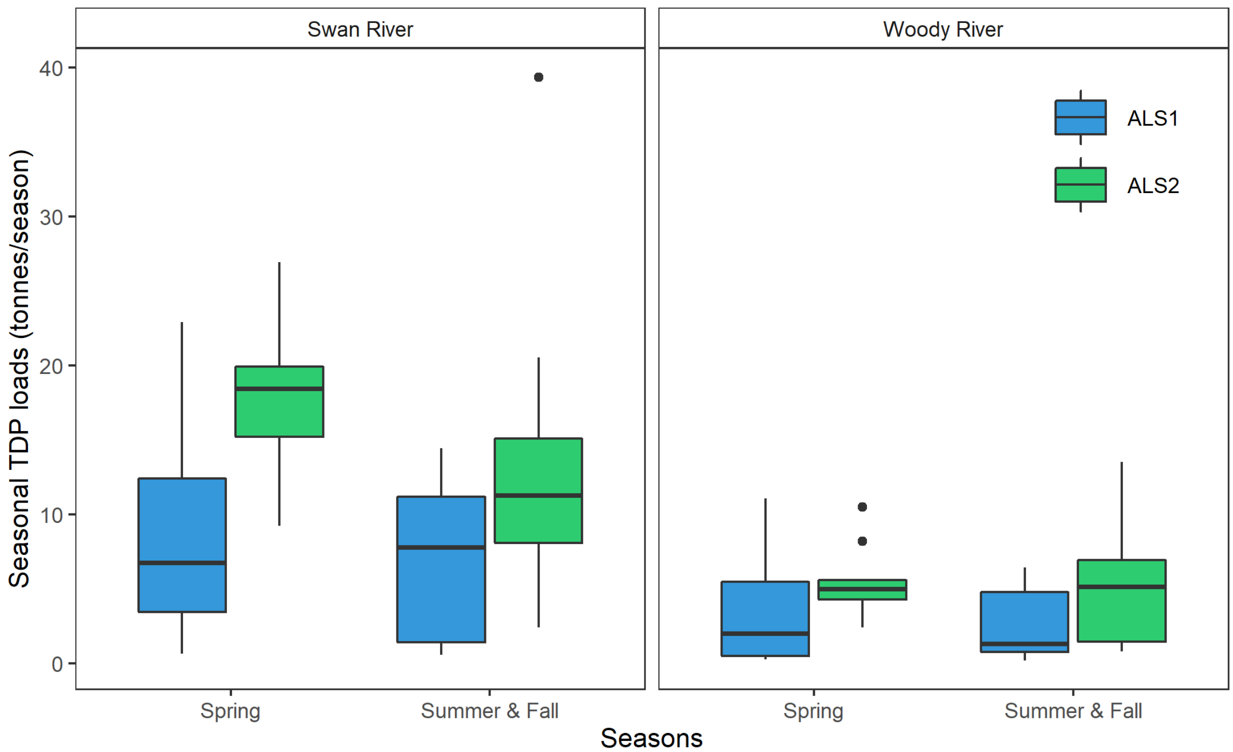

Figure 2.23. Total dissolved phosphorus (TDP) seasonal loads in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Seasonal values are reported in Appendix D.

2.4.3.4 Total Nitrogen

The medians of annual TN FWMCs (Figure 2.24) in Swan River from ALS1 to ALS2 increased by 18% (differences are significant at p-value ≤ 0.05). Seasonal TN FWMCs (Figure 2.25) for Swan River in the spring season experienced an increase of 46% and is statistically significant (p-value ≤ 0.05), whereas the summer and fall season increased by 15% and is not statistically greater (p-value > 0.05). Swan River annual TN load medians in ALS1 and ALS2 (Figure 2.26) experienced a 139% increase from ALS1 to ALS2 (differences are significant at p-value ≤ 0.05). Seasonally, the medians of TN loads (Figure 2.27) in the spring, and summer and fall increased by 221% and 30%, respectively, with only spring being statistically significant (p-value ≤ 0.05).

When examining Woody River, annual TN FWMCs (Figure 2.24) increased in medians from ALS1 to ALS2 by 10%. This increase is not statistically greater (p-value > 0.05). The medians of spring TN FWMCs (Figure 2.25) experienced a 45% increase (differences are statistically greater at p-value ≤ 0.05) and summer and fall experienced an 11% increase (differences are not statistically greater at p-value > 0.05). Annual TN loads and quartiles for Woody River are displayed in Figure 2.26. The increase of annual TN load medians from ALS1 to ALS2 is 87% (differences are significant at p-value ≤ 0.05). The medians of seasonal TN loads for ALS1 and ALS2 (Figure 2.27) in the spring experienced a significant increase of 168% (p-value ≤ 0.05) and the summer and fall experienced a non-statistical increase of 116% (p-value > 0.05).

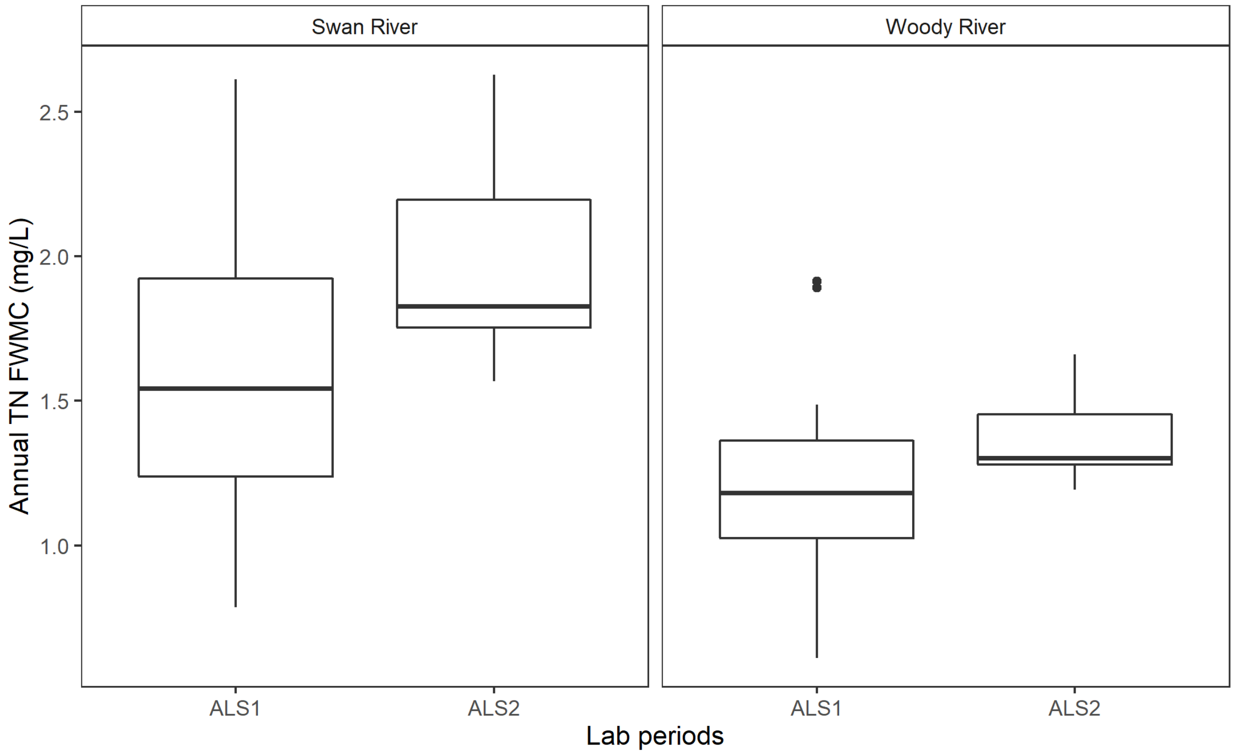

Figure 2.24. Total nitrogen (TN) annual flow-weighted mean concentrations (FWMC) in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Annual values are reported in Appendix D.

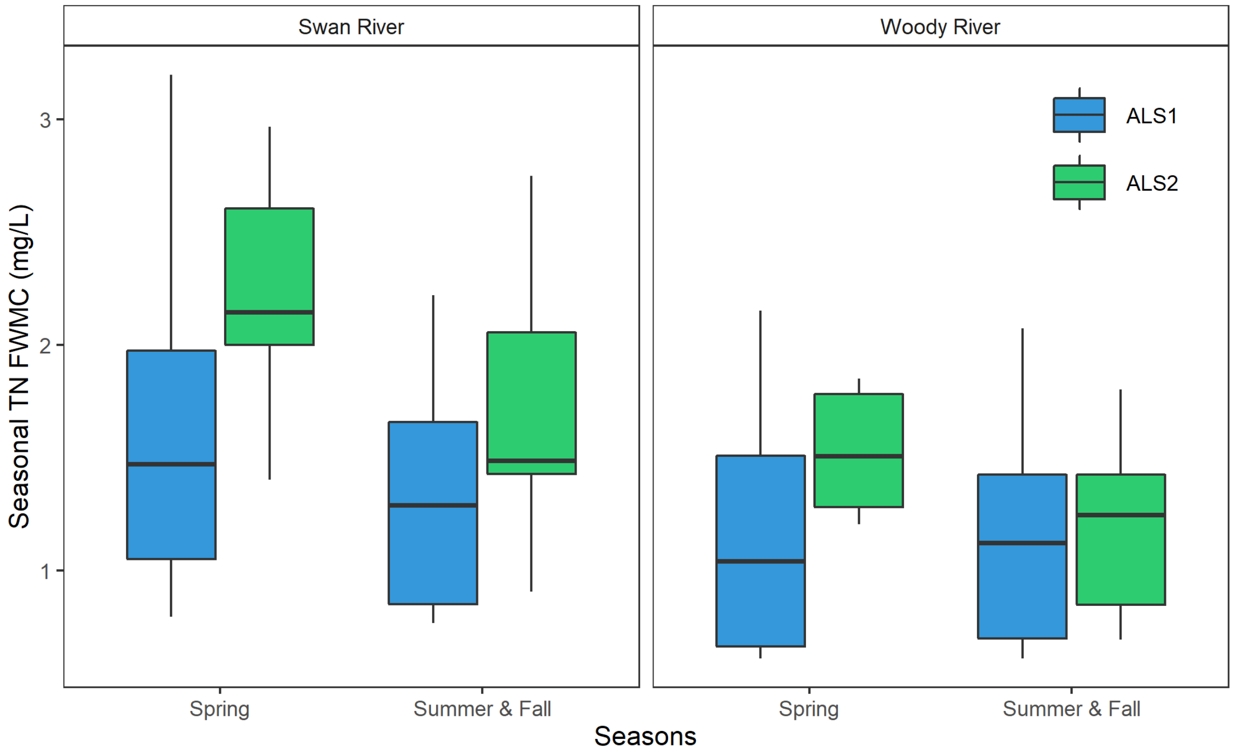

Figure 2.25. Total nitrogen (TN) seasonal flow-weighted mean concentrations (FWMC) in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Seasonal values are reported in Appendix D.

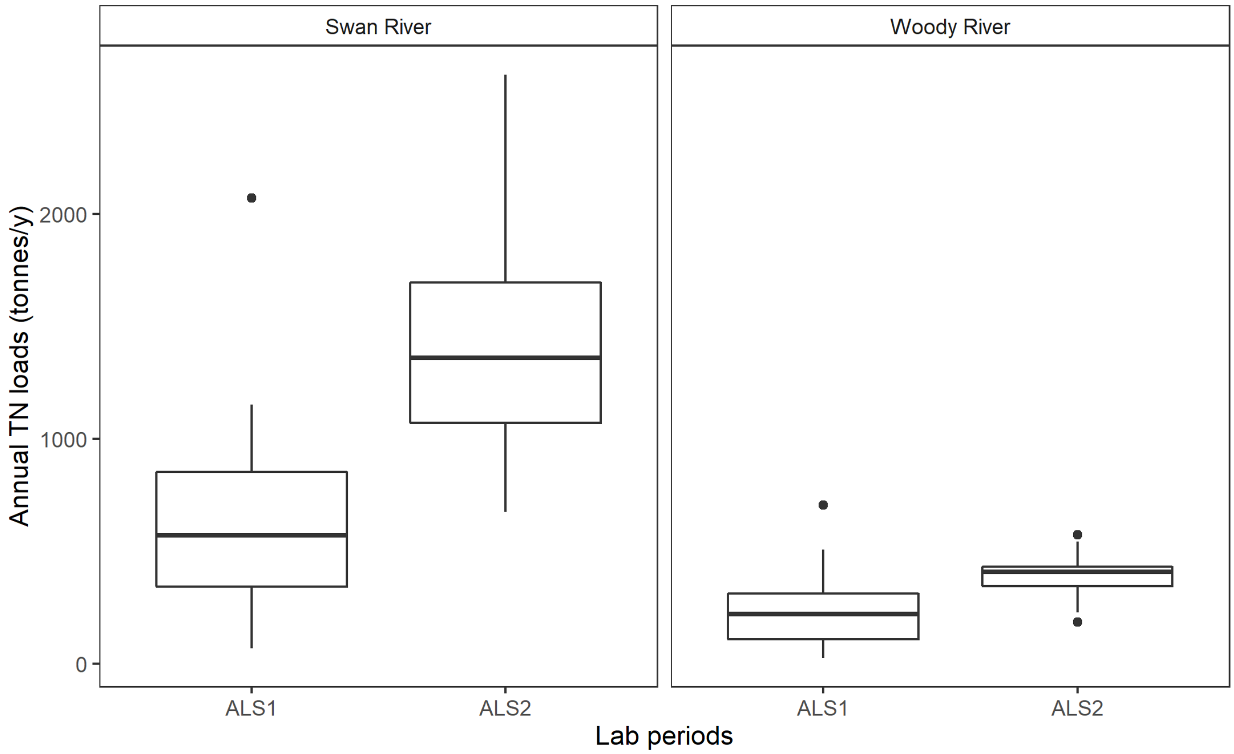

Figure 2.26. Total nitrogen (TN) annual loads in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Annual values are reported in Appendix D.

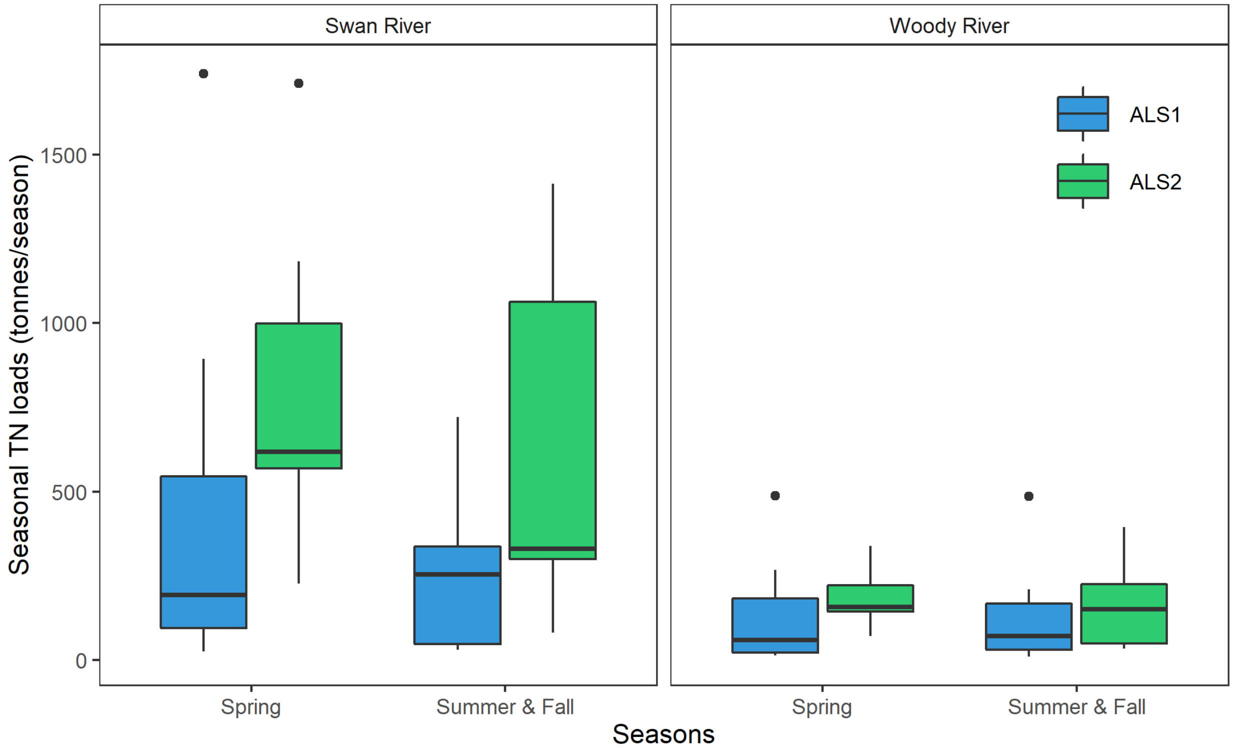

Figure 2.27. Total nitrogen (TN) seasonal loads in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Seasonal values are reported in Appendix D.

2.4.3.5 Total Suspended Solids

Swan River annual TSS FWMCs (Figure 2.28) in the ALS1 and ALS2 increased by 60%. The increase in medians between the two periods is significant (p-value ≤ 0.05). Seasonal TSS FWMCs and quartiles are displayed in Figure 2.29. The spring TN load medians experienced an increase of 223% (difference is significant at p-value ≤ 0.05). For the summer and fall, the 29% increase is not significantly greater (p-value > 0.05). The median annual TSS loads (Figure 2.30) in Swan River increased by 283% and this change is found to be significant (p-value ≤ 0.05). In seasonal TSS loads (Figure 2.31), the spring experienced a 459% increase in ALS2 relative to ALS2 and the summer and fall experienced a 50% increase. The change in spring is found to be statistically significant (p-value ≤ 0.05) and in the summer and fall season is not.

In comparison to Swan River, Woody River annual TSS FWMCs (Figure 2.28) in ALS1 to ALS2 experienced a 44% increase but the difference is not significant (p-value > 0.05). Seasonal TSS FWMCs (Figure 2.29) in the spring season experienced an increase of 224% (differences are significant at p-value ≤ 0.05) and summer and fall season only had a 25% increase (differences are not statistically greater at p-value > 0.05). Woody River annual TSS loads (Figure 2.30) increased by 126% from ALS1 to ALS2. The increase is statistically larger (p-value ≤ 0.05). Median seasonal TSS loads (Figure 2.31) in the spring experienced a 457% increase from ALS1 to ALS2 in the spring and is statistically greater (p-value ≤ 0.05), whereas the summer and fall had an increase of 132% but is not statistically greater (p-value > 0.05).

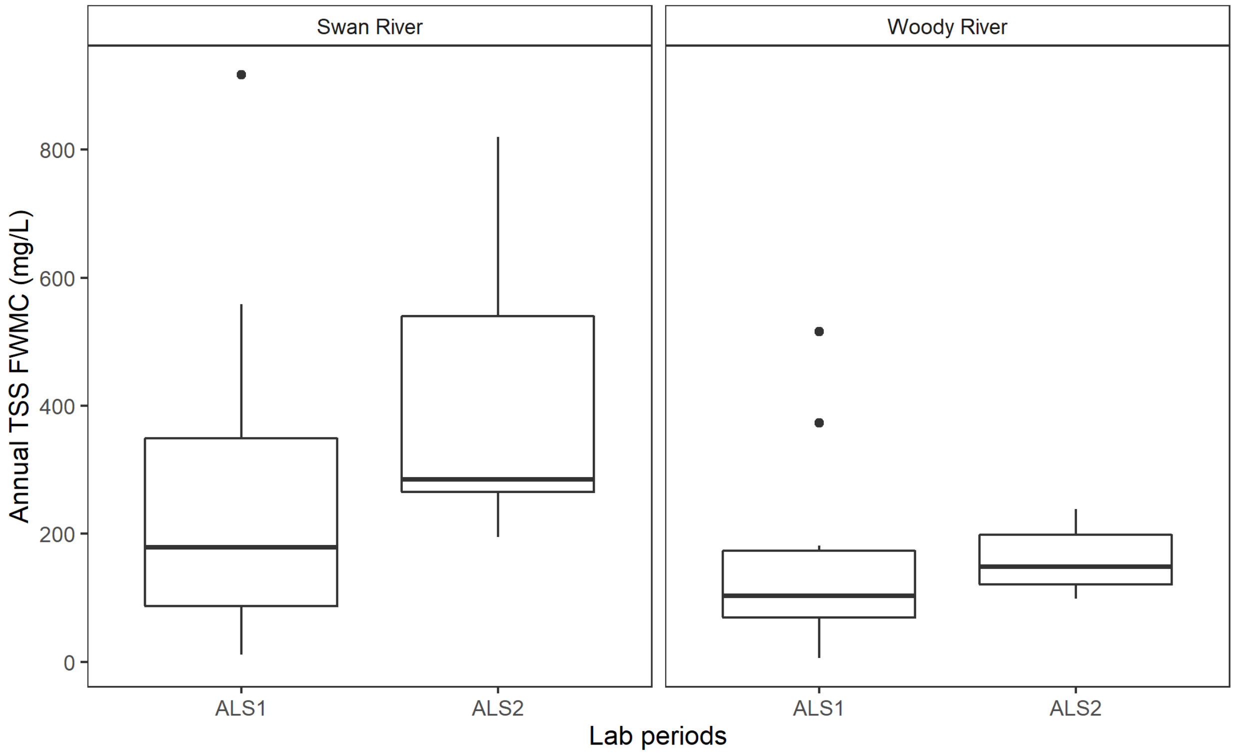

Figure 2.28. Total suspended solids (TSS) annual flow-weighted mean concentrations (FWMC) in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Annual values are reported in Appendix D.

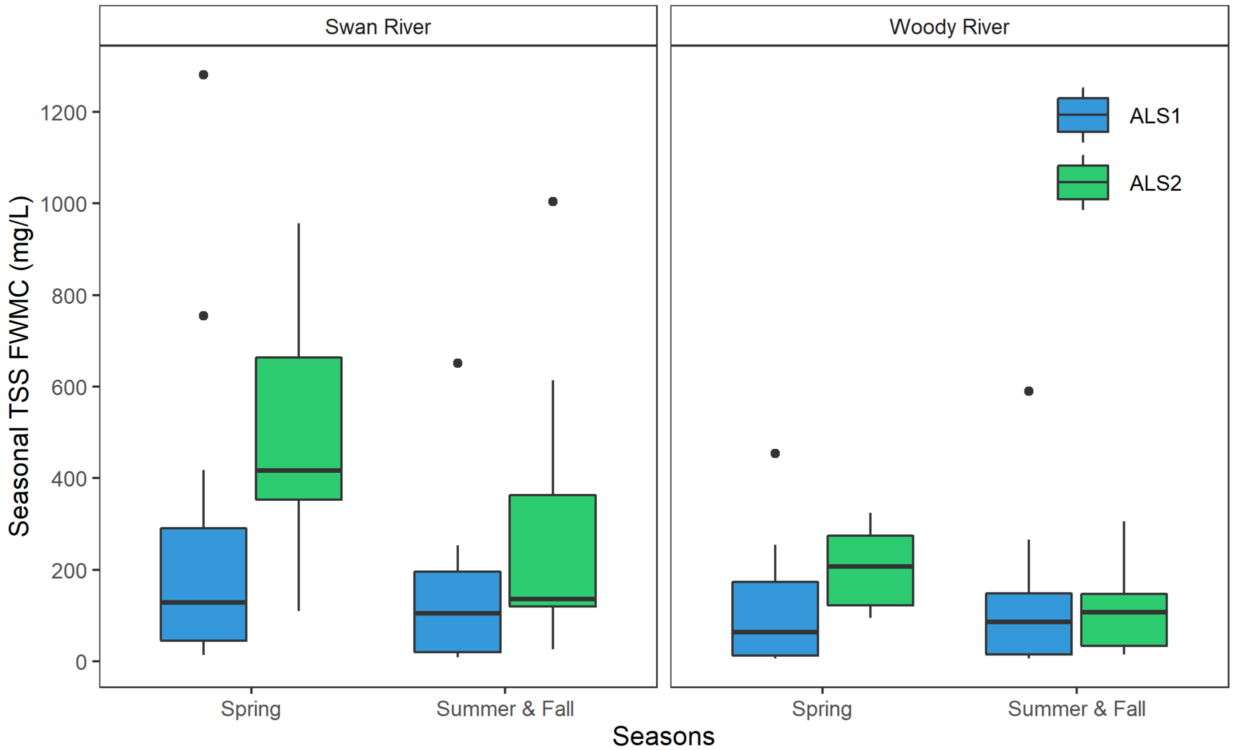

Figure 2.29. Total suspended solids (TSS) seasonal flow-weighted mean concentrations (FWMC) in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Seasonal values are reported in Appendix D.

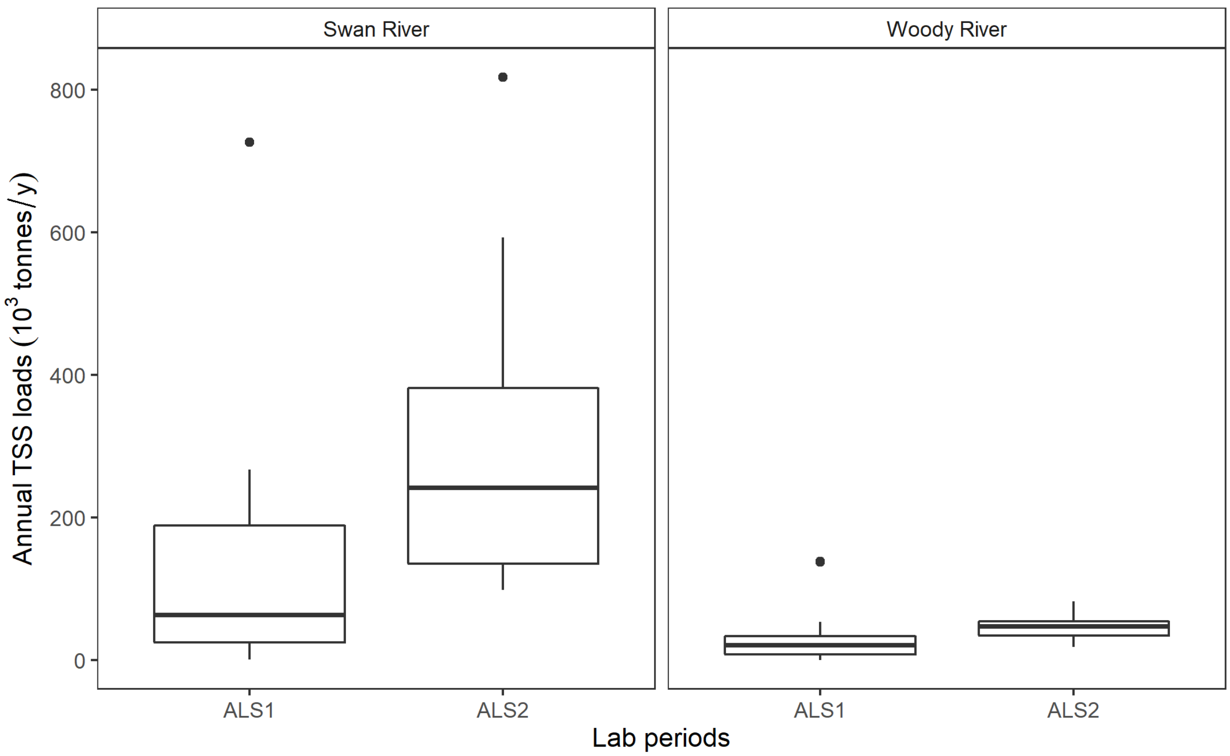

Figure 2.30. Total suspended solids (TSS) annual loads in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Annual values are reported in Appendix D.

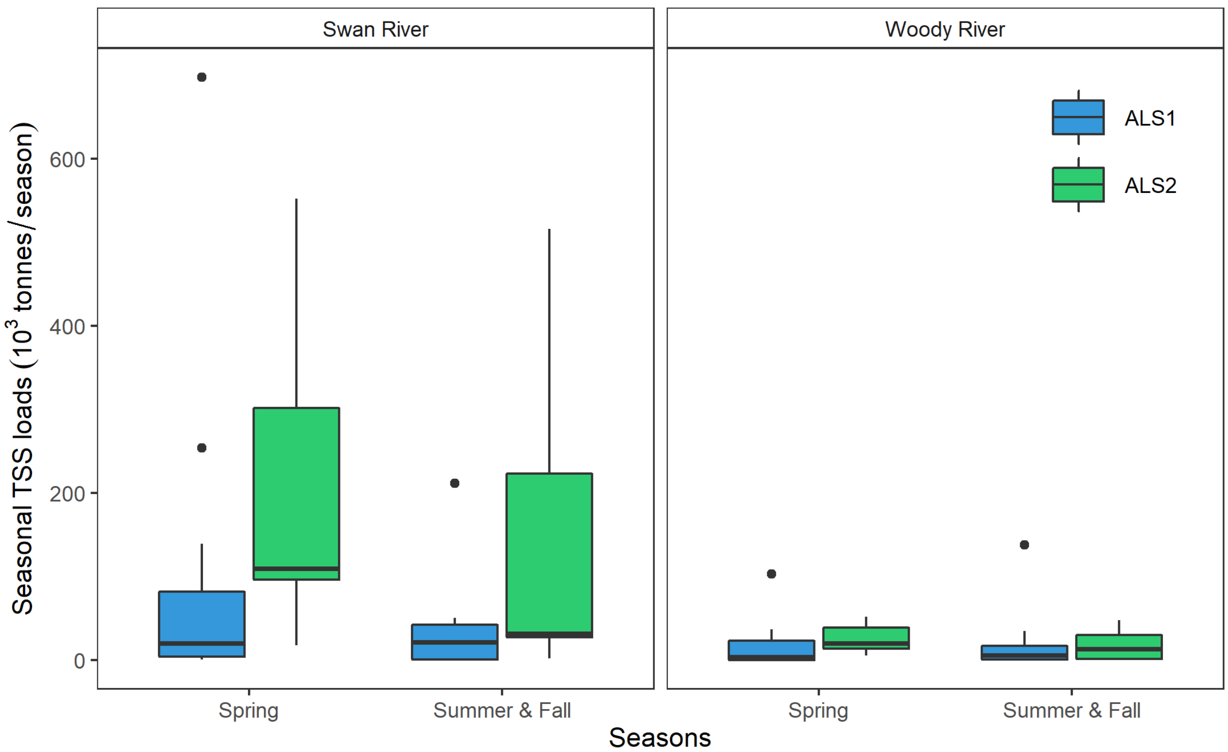

Figure 2.31. Total suspended solids (TSS) seasonal loads in Swan and Woody Rivers during 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2). These boxplots present the median, lower and upper quartile, and any outliers. Seasonal values are reported in Appendix D.

2.5 Discussion

2.5.1 Physical hydrology and its temporal changes in Swan and Woody Rivers watersheds

In the northern latitudes, spring peak flow due to snowmelt typically produces the highest flow rate in each year, and sometimes a second peak occurs in the summer due to rainfall runoff during storm events (Ellison and Brett, 2006; Novotny and Stefan, 2007). These two peaks, historically, occur in the Swan Lake watershed, even though it is believed the effects of land use and climate change are moving them closer together (SLWD, n.d.). However, a small study by Manitoba Conservation and Water Stewardship found the clear separation of the two peaks only occurred one to two times per decade from 1960 – 2012. Based on the results of peak flow in this study, there are two distinct peaks. The first and usually the highest peak occurs in April (Figure 2.7). A second smaller peak occurs in July, with some years equating to or exceeding spring peak flows. Both these peaks lead to increased quantities of nutrients exported to the rivers and lakes. In recent studies, the spring peak is occurring earlier (Gan, 1998; Burn et al., 2008; Zhang et al., 2022). Further analysis should be conducted to determine if these peaks are moving closer or further apart, and for any changes in timing and quantity, and its impact on nutrient loading in Swan and Woody Rivers.

Discharge in Swan River is about two times greater than in Woody River. Swan River is 1.3 times longer (measured from water quality stations; almost two times longer from the mouth of the river) and has a watershed area 2.6 times greater than Woody River (6020 km^2 compared to 2330 km^2, measured upstream of the water quality stations). Consequently, both rivers produce similar water yields (i.e., runoff; Figure 2.32). Woody River appears to yield higher annual runoff rates than Swan River (Table 2.12); however, the difference is not statistically significant (p-value > 0.05). Therefore, both rivers produce similar quantities of river discharge relative to their watershed size. The average annual runoff in this study is within the same range as found by Statistics Canada (2015) for the period from 1971 – 2013.

River discharge in the Swan River increased linearly over the 30-year period, whereas the increase in Woody River was not statistically significant. Between the two ALS periods (Figure 2.10), both rivers were seen to be significantly greater in ALS2 than ALS1 in annual and seasonal discharge. Thirty years of discharge analysis is often considered a long-term analysis; nonetheless, it may not give a good representation of the rivers receiving increasing quantities of flow over a longer period. This period may be cycling through a natural dry (i.e., drought) phase to a wetter (i.e., flood) phase in a longer cyclic pattern. In the northern prairies region, dry and wet phase can last approximately 10 to 15 years (Novotny and Stefan, 2007; Ehsanzadeh et al., 2012). This cycling or periodicity in river discharge is also present in Minnesota Rivers examined for up to 90 years (Novotny and Stefan, 2007). In earlier studies, Prairie Provinces showed a mix of significant trends in discharge. Across the Prairie Provinces, a small negative trend to no trend occurred in annual and summer season discharge from the 1950s to 2000s (Gan, 1998; Burn et al., 2008). In a later study by St. Jacques et al. (2014), 86 Canadian hydrometric stations were examined over varying periods from 1911 – 2010. In Saskatchewan, little to no change occurred to stream flows; however, there was a significant increase in small naturally flowing streams on the eastern portion of the Prairie Provinces (i.e., Manitoba). For a clearer picture of changes in river discharge for the Swan and Woody Rivers, a longer period of analysis will need to be conducted.

This study could not assess long-term trends in precipitation, given numerous data gaps between 2002 and 2009 at some weather stations. Previous studies showed many areas of Manitoba experiencing a significant increase in annual (Millett et al., 2009) and seasonal precipitation (Dibike et al., 2012; McCullough et al., 2012; Dumanski et al., 2015). The differences between 1995 – 2001 (P1) and 2009 – 2015 (P2) at each weather station and the watershed average were very small (0-9%). There was a small increase in annual, spring, and summer and fall precipitation but a decline in winter precipitation across the watershed (Figure 2.6 and Table 2.2). Decreasing winter precipitation was even occurring prior to 1989, over a four-decade period (Gan, 1998). The decline in winter precipitation may be attributed to warmer temperatures (Chang et al., 2001; Dibike et al., 2012; Zhang et al., 2022). Warmer temperatures may lead to decreased flow in the warmer months due to higher evapotranspiration rates reducing rainfall (Zhang et al., 2022) and may be a contributing factor in changes of discharge and indirectly to changes in the nutrient loads. Links between changes in precipitation and runoff are discussed further in Section 2.5.3.

Figure 2.32. Annual water yields in mm/y (i.e., runoff) in Swan River and Woody River watersheds from 1989 – 2018.

Table 2.12. Mean (standard deviation) and median annual runoff (i.e., water yields in mm/y) in Swan River and Woody River watersheds from 1989 – 2018.

	Mean (SD)	Median
Swan (mm/y)	78.4 (42.5)	67.0
Woody (mm/y)	88.4 (47.7)	91.4

2.5.2 Water quality and its temporal changes in Swan and Woody Rivers

Provincial phosphorus guideline for river is 0.05 mg/L (Williamson, 2002).Three years (2010, 2016, and 2017) in Swan River and in one year (2010) in Woody River based on median daily concentration exceeded this phosphorus guideline. For comparison, mean daily concentrations exceeded the Provincial phosphorus guideline 18 of the 30 years (1990, 1993 – 2000, and 2010 – 2018) in Swan River and 12 of the 20 years (1990, 1993, 1995, 1996, 2010 – 2014, and 2016 – 2018) in Woody River. Lake ecology for Swan Lake is not documented. With increases in river phosphorus to Swan Lake, there is potential for increases in loading as seen in Lake Winnipeg causing increased eutrophication, naissance algal bloom development, and overall health issues to the lake.

Swan River produces higher nutrient and TSS concentrations and loads compared to Woody River. Lower concentrations in Woody River, even during the spring peak flow period, are likely due to the watershed having a lower population density, less agricultural land and less intensive agricultural practices (Jones and Armstrong, 2001; Wine and Makhnin, 2022). Lower discharge rates, multiplied by these lower concentrations in Woody River, explain lower nutrient loads and may account for smaller changes in loads compared to Swan River. When comparing annual exports in the two rivers based on yields per unit area (Table 2.13), the Swan River watershed exports slightly more nutrients and TSS than Woody River watershed, but none of the differences are statistically significant (p-value > 0.05 for all variables). That is, even though Swan River is a longer river and has a larger watershed than Woody River, they both export proportionately similar yields of nutrients and TSS, per unit watershed area, to Swan Lake.

Comparing exports from Swan River and Woody River to other watersheds, these two rivers produce higher TP and TN yields than undeveloped streams and its two neighbouring watersheds in western Manitoba. The two rivers in this study generated two to three times the median TP yield of 0.085 kg/ha/y from undeveloped stream watersheds across the United States from 1976 – 1997 (Clark et al. 2000). Median TN yields (0.86 kg/ha/y) were also examined, and Swan and Woody Rivers produce 1.5 times the TN yield of the undeveloped streams. Total phosphorus yields in one neighbouring watershed district, the Intermountain Watershed District, with six river watersheds produced TP yields ranging from 0.01 and 0.07 kg/ha/y in 2019 (LWCBMN, 2020a). Of the six rivers, Vermilion River near Dauphin had an annual discharge rate in 2019 (approximately 70 10^6 m^3/y) similar to Swan River in 2002 (78 10^6 m^3/y). Although the discharge rates are comparable, Swan River produced 1.3 times higher TP yields. In the Assiniboine West Watershed District, TP yields in 2017 and 2018 ranged between 0.02 and 0.16 kg/ha/y (LWCBMN, 2020b). The four sub-watersheds in the Assiniboine West Watershed District had an average of 0.11 kg/ha/y over 2017 and 2018, which is about half of the average TP yield found in Swan and Woody Rivers (0.19 kg/ha/y).

In the south portion of Manitoba, with highly developed agricultural land, 11 river watersheds in the Seine Rat Roseau Watershed District produced an average TP yield of 0.29 kg/ha/y from 2017 to 2018 (LWCBMN, 2020c), which is approximately 1.5 times higher than Swan River and Woody River. In another study examining exports in sub-watersheds of the Red River watershed in 2010, 2013 and 2014, 11 watersheds had a mean TP yield of 0.50 kg/ha/y (Rattan et al., 2017), which is only slightly higher than the average TP yield of the Swan and Woody Rivers for the same years (0.43 kg/ha/y). Rattan et al. (2017) also examined TN yields and found the watersheds had a mean of 2.2 kg/ha/y, which is similar to the average TN yield in Swan River and Woody River of the same years (2.6 kg/ha/y).

Nutrient concentrations and delivery in the Swan and Woody Rivers predominantly occur in the spring season (over 50% of annual loads) in both ALS periods. These large percentages of loads in spring are also seen in prairie streams in the Red River watershed, which occurs over 12-18 days of the snowmelt period (Rattan et al., 2017). The spring season also saw the highest increase with both the two rivers experiencing up to 200% and 400% in concentrations and loads, respectively, between the two lab periods for TSS. The summer and fall season typically experienced lower quantities of nutrient exports which is related to the combination of lower concentrations and lower runoff in the summer and fall. During the spring season, snowmelt runoff is the dominant form of runoff picking up nutrients as it flows over frozen soils (Glozier et al., 2006; Little et al., 2007; Corriveau et al., 2011). In contrast, rainfall runoff is the dominant form during the summer and fall, and typically runoff readily infiltrates the soils so that less runoff and nutrients are exported to rivers. However, in the summer and fall during short, intense rainfall events, high nutrient export can also occur (Guo et al., 2022). The increases are especially seen from the leaching of dissolved P from soils during intensive storms (Michalak et al., 2013; Chen et al., 2015). Higher concentrations of P and N in the spring are also attributed to spring flooding (McCullough et al., 2012).

Total nitrogen and TP concentrations increased from ALS1 to ALS2. In an older report by Jones and Armstrong (2001), TN and TP concentrations were examined in Swan and Woody Rivers from 1988 – 1999 (a similar period to ALS1 in this study). The authors tested residual scores from each sample measurement for trends and found a significant decline in TN and TP concentrations in Swan River and a non-significant decline in TP for Woody River. They reported that TN in Woody River declined; however, the significance of their conclusion is in question because of non-normally distributed residuals. The methods used by Jones and

Armstrong (2001) are different from the methods in this study (discussed later in this section). To emulate a similar trend analysis, seasonal values calculated in this study (spring, summer and fall, and winter values) were plotted (results not reported) and tested for a linear trend analysis using the Mann-Kendall test or the modified Mann-Kendall (TFPW) test. Even though residuals declined over the ALS1 period, the decrease was not significant for either TN or TP in both rivers (p-value > 0.05). In comparison, the absolute values of all the seasonal FWMCs (spring, summer and fall, and winter) in one regression plot from this study experienced a significant increase (p-value ≤ 0.05) for both rivers. Annual TN and TP concentrations in both rivers also had a non-significant increase (p-value > 0.05), and residuals did not change over the ALS1 period. Jones and Armstrong (2001) did not report absolute concentration for Swan and Woody Rivers so that their values could not be compared with the values in this study.

In a later study by Bourne et al. (2002), total changes in loads from 1988 – 1999 were reported in various Manitoba rivers, including absolute TN and TP loads for Swan and Woody Rivers from 1994 – 2001. Of the changes in loads from 1988 – 1999, only TN in Woody River was reported and found not to have changed over this period. After examining the provided TN and TP loads from 1994 – 2001, there appears to be a decline in the absolute TN and TP loads. For comparison, the calculated loads in this study for those years also showed a decrease in TN and TP (results not reported). Although both these studies show a decline over the eight years, values from Bourne et al. (2002) had lower TN and TP loads than the load values calculated in this study, with an annual mean difference around 60% and 90%, respectively, in Swan River and around 50% and 70%, respectively for Woody River. Part of this difference may be explained by the use of different watershed areas represented by the water quality data. In this study, river discharge was prorated by an area multiplier to predict discharge rates at the water quality stations instead of using rates at the upstream hydrometric stations. Prorated loads were 17% larger for the Swan River, and 10% larger for the Woody River, compared to non-prorated loads. Another probable reason for the remaining, large difference in nutrient loads was the method used to calculate concentrations before calculating loads. Both Jones and Armstrong (2001) and Bourne et al. (2002) treated exact concentrations collected by the Province of Manitoba as monthly concentrations. However, since Swan and Woody Rivers were only sampled every three to four months, the months without a measurement were filled using the average nutrient concentrations of the previous and subsequent months. These concentrations were then multiplied by the mean monthly streamflow from WSC to estimated monthly loads. Each monthly load was summed to calculate the annual total load, whereas, in this study, regression analysis between nutrient concentrations and daily discharge was used to determine daily concentrations. Daily concentrations multiplied by daily discharge calculated daily loads and then summed to find total loads. Determining daily loads as a function of daily discharge and daily concentrations estimated by regression allows a better representation of loads during peak flows in the dataset and analyses. With the rivers only sampled quarterly, nutrient concentrations and loads may preferentially represent baseflow conditions (Johnes, 2007). Most samples taken during the snowmelt period occurred after peak flows, missing the period with the highest load. Samples were typically taken after the peak flows subsided. Given the positive correlation of concentrations with discharge, the period of highest flows and highest concentrations is likely to be missed.

All nutrients and TSS annual and seasonal medians of FWMCs and loads in the Swan and Woody Rivers increased in more recent years (ALS2), ranging from 10% to over 200% (Table 2.9). These increases are highest in Swan River. The highest increase in median concentrations for annual FWMCs is TSS. Annual TSS concentrations in Swan River increased by 60%, whereas Woody River increased by 44%. Total suspended solids concentrations also experienced the highest increase between the two ALS periods during the spring season, with changes of over 200% in both rivers. Summer and fall season in both rivers did not experience a significant increase in TSS. More generally, FWMCs were not changed much between ALS1 and ALS2 for most parameters. TDP concentrations had the highest increases between the two periods of over 50%. Increases in all other parameters were limited to 11 – 29%.

Median loads experienced higher increases than FWMCs, with changes from 30% to over 450%. Most increased by over 100% (Table 2.10). Annual TSS loads had the highest increase of 280% in Swan River and 126% in Woody River. The spring season had an even more substantial increase in TSS of around 460% in both rivers. Unlike FWMCs, Woody River had the only significant increase in TDP during the summer and fall season, whereas, in Swan River, median TSS loads increased the most (Table 2.10). Generally, all loads in Woody River are lower in percent change from ALS1 to ALS2 than Swan River. The higher values in the second period may be in part to differences in river discharge, precipitation, or land use; however, land use is not the focus of this study. The focus will be on physical hydrology (river discharge and precipitation) leading to increases in water quality variables between the two periods, see Section 2.5.3.

Table 2.13. Estimated mean (standard deviation) and median annual yields for total phosphorus (TN), particulate phosphorus (PP), total dissolved phosphors (TDP), total nitrogen (TN), and total suspended solids (TSS) in the Swan River and Woody River watersheds over the two ALS periods (1989 – 2000 and 2010 – 2018).

	Swan River (kg/ha/y)		Woody River (kg/ha/y)	
	Mean (SD)	Median	Mean (SD)	Median
TP	0.28 (0.24)	0.23	0.20 (0.16)	0.15
PP	0.24 (0.22)	0.18	0.17 (0.14)	0.11
TDP	0.04 (0.03)	0.03	0.04 (0.02)	0.03
TN	1.7 (1.18)	1.3	1.3 (0.80)	1.2
TSS	360 (390)	230	180 (170)	120

2.5.3 Relationship between concentrations and physical hydrology parameters (discharge and precipitation)

Regression analysis between measured water quality concentrations and river discharge was used to calculate estimated daily concentrations in this study (Figure 2.4) and examine their relationship between each other. All water quality concentrations examined in this study are positively correlation with discharge. Removing concentrations at low flows caused the relationships at high flows to become stronger (Table 2.1). The discussion on concentration and discharge relationships below focuses on the variables in Swan River using measured water quality concentrations from the Province of Manitoba and that day discharge rates from WSC. Woody River displayed similar relationships.

Correlations between concentrations and discharge at high flows are stronger and more accurate than at low flows (Lee et al., 2016). Total phosphorus, PP, and TSS have the strongest positive correlation with river discharge (R^2 ranged from 0.67 to 0.74). Total nitrogen and TDP have weak relationships with discharge (R^2 = 0.46 and 0.29, respectively). These weaker relationships in TN and TDP with discharge indicate that hydrology has a poor influence and other factors are influencing these relationships, such as biogeochemical processes. Since the relationship between TDP and discharge is weak, TDP was estimated using the difference between TP and PP rather than a regression equation. Concentrations at low flows are lower, less variable, and not significantly correlated with discharge. For the Red River in Manitoba at low flows, discharge is inversely correlated (a dilution effect) with TP; however, this is due to point-source loading of the City of Winnipeg wastewater treatment plants (McCullough et al., 2012). This dilution effect and biogeochemical processes in nitrogen, phosphorus, and TSS at low flow also occurred in many French monitoring stations (Moatar et al., 2017). However, the dilution effect does not appear at low flow in the Swan and Woody Rivers (Figure 2.4), suggesting point sources in this sparsely population watershed may not be a strong contributor to nutrient concentrations but rather more influenced by biogeochemical processes.

Infrequent sampling may cause low and insignificant correlations leading to underestimating or overestimating loads. Underestimation may occur when high nutrient and sediment exports during short high-flow events (i.e., short-intense rain events) are missed (Johnes, 2007). Overestimation may occur during dilution of wastewater and point-source loading in heavily populated areas (Johnes, 2007). However, in the Swan and Woody Rivers watershed, most loads occur during the snowmelt period, which spreads out over a longer duration. Furthermore, this watershed is sparsely populated and does not present this dilution effect from point sources. Salvano et al. (2009) examined phosphorus collected by the Province of Manitoba and indicated frequency of sampling by the province is sufficient for examining differences between watersheds; however, most of those rivers are sampled monthly, whereas the Swan and Woody Rivers are sampled less frequently. Although a higher sample frequency than three to four samples per year can improve the relationship coefficient between concentrations and discharge, FWMCs and loads (Figure 2.33A and B) follow closely with discharge (Figure 2.33C) and have much stronger correlations than the measured concentrations (results not provided), although this stronger relationship may be because discharge is included in the calculation of both FWMCs and loads.

Correlation analysis between river discharge and precipitation may help quantify the relationship between these two parameters in connection with the increases in discharge and water quality variables. A time series of river discharge and precipitation are displayed in Figure 2.33. In P1, the time series of precipitation across the Swan Lake watershed is similar to discharge; however, in P2 the two variables do not follow each other at all closely. The correlation between total discharge in Swan River and Woody River and the average precipitation across the watershed annually and seasonally are displayed in Figure 2.34 and Figure 2.35. Summer and fall precipitation were combined and tested against total summer and fall discharge. Total spring discharge was tested against the average watershed winter plus spring total precipitation to improve representation of snow on the ground during spring snowmelt under the assumption of no sublimation. Correlations were also divided into periods to examine for any differences. Annual and seasonal correlations predict higher rates of discharge with higher precipitation amounts in both rivers. Correlation between discharge and precipitation is expected, and both annual and seasonal exhibited strong significant correlations in P1 (Table 2.14) but not P2 (2009-2015). Although correlation analysis examined short periods, correlation coefficients in P2 were within the range of correlation coefficients (0.38 to 0.72) found in four river basins in Minnesota (Novotny and Stefan, 2007). The coefficients seen in P1 were much higher. Over the 30-year study by Novotny and Stefan (2007), the authors found a continuous increase in both annual precipitation and mean annual discharge in the Minnesota River basin. The relationship between discharge and precipitation may relate to weather patterns, such as El Niño-Southern Oscillation. Across the Canadian Prairie Provinces, St. Jacques et al. (2014) found increased discharge during La Niña and decreased discharge during El Niño. Correlations also occurred with other weather patterns, such as Pacific Decadal Oscillation, North Pacific Index, and Pacific North American mode. Temperature and weather patterns are beyond the scope of this study; nonetheless, these variables may help better explain the changes and correlations in river discharge and precipitation in the Swan and Woody Rivers.

Weaker correlations in P2 are due mainly to two outliers, in 2011 and 2014 (Figure 2.34 and Figure 2.35), when exceptionally high discharge was associated with only moderate precipitation in the corresponding water years. These two years are residual outliers in both rivers for annual analysis, while 2011 is a residual outlier in spring and 2014 is a residual outlier in summer and fall seasonal analysis. High precipitation occurred in 2011 during the winter, while the spring, and summer and fall had relatively low precipitation compared to other years in P2. However, 2010 experienced high precipitation rates in both spring, and summer and fall seasons, potentially leading to high water storage flowing into the following year, 2011. Although Swan River may have some discrepancies in 2014 due to a two-month data gap filled differently from other data gaps (i.e., regression from an older upstream Swan River station using water level data), Woody River also displays the same outliers in annual and summer and fall correlations. The year 2014 did not have a substantial amount of precipitation; however, 2013 received relatively high amounts of precipitation in the summer and fall, potentially leading to water storage flowing into 2014. In general, P2 presented the highest precipitation in nearly all years, which may indicate it was a wet year, as mentioned in Section 2.5.1. Multiple linear regression analysis of annual streamflow versus current water year precipitation plus an index of storage from the previous year (i.e., monthly mean discharge from the previous October) in Swan River was investigated for influences of water storage from the previous year on river discharge. Results from this regression analysis produced a similar outcome as the Spearman's ranks correlation test. Discharge and precipitation were strongly correlated in P1 ($r = 0.95$, p-value ≤ 0.05). In P2, the inclusion of water storage produced a high correlation coefficient ($r = 0.61$); however, this correlation was not significant. Further testing with a stronger model may be required to explain these outliers; such modelling is beyond the scope of this study.

Even though the changes in precipitation between the two periods are small and insignificant, small changes in precipitation can make a disproportional change in runoff and discharge. In the Red River, an increase of 20% in precipitation led to a 300% increase in river discharge through the 20^{th} century (Ehsanzadeh et al., 2012). With a 3% increase in annual precipitation between the two precipitation periods within the Swan and Woody River watershed, there was a 59% and 38% increase in river discharge in the same two periods (P1 and P2). The average increase between the two rivers (48.5%) is reasonable, given the disproportional increase in discharge as a function of precipitation reported by Ehsanzadeh et al. (2012).

Of the five water quality variables examined, TSS experienced the most change between the two ALS periods, and the following was TP, with PP being more of an influence on TP change than TDP. Ellison and Brett (2006) found TSS, TP, and PP to be more influenced by river discharge, whereas TN and TDP are more influenced by land cover. Particulate phosphorus was also highly associated with TSS concentrations since PP typically binds to suspended sediment. Furthermore, nutrient exports increased in runoff and stream channels during intense rainfall events due to soil erosion (Ellison and Brett, 2006; Guo et al., 2022); this even included increases in dissolved phosphorus from the soils during intense storms (Michalak et al., 2013; Chen et al., 2015). The more intense the storm was, the more exports were measured in river discharge (Chen et al., 2015). Higher total precipitation in the second period of this study helped explain the increases in river discharge and water quality variables. A higher frequency of surface runoff from snowmelt and rainfall supports the increased discharge and nutrient and suspended sediment transport. However, this is not the case in the Upper Mississippi River basin, where agricultural land use is the primary factor influencing concentrations and loads since the correlation with climate variability was poor (Wine and Makhnin, 2022). Studying climate and land use together will help better understand the many factors potentially influencing the increase of loads within the watershed. Conducting future studies regarding the impacts of rainfall intensity on the duration of flow and water quality in the Swan Lake watershed will help improve the understanding of the changes in nutrient transport in runoff.

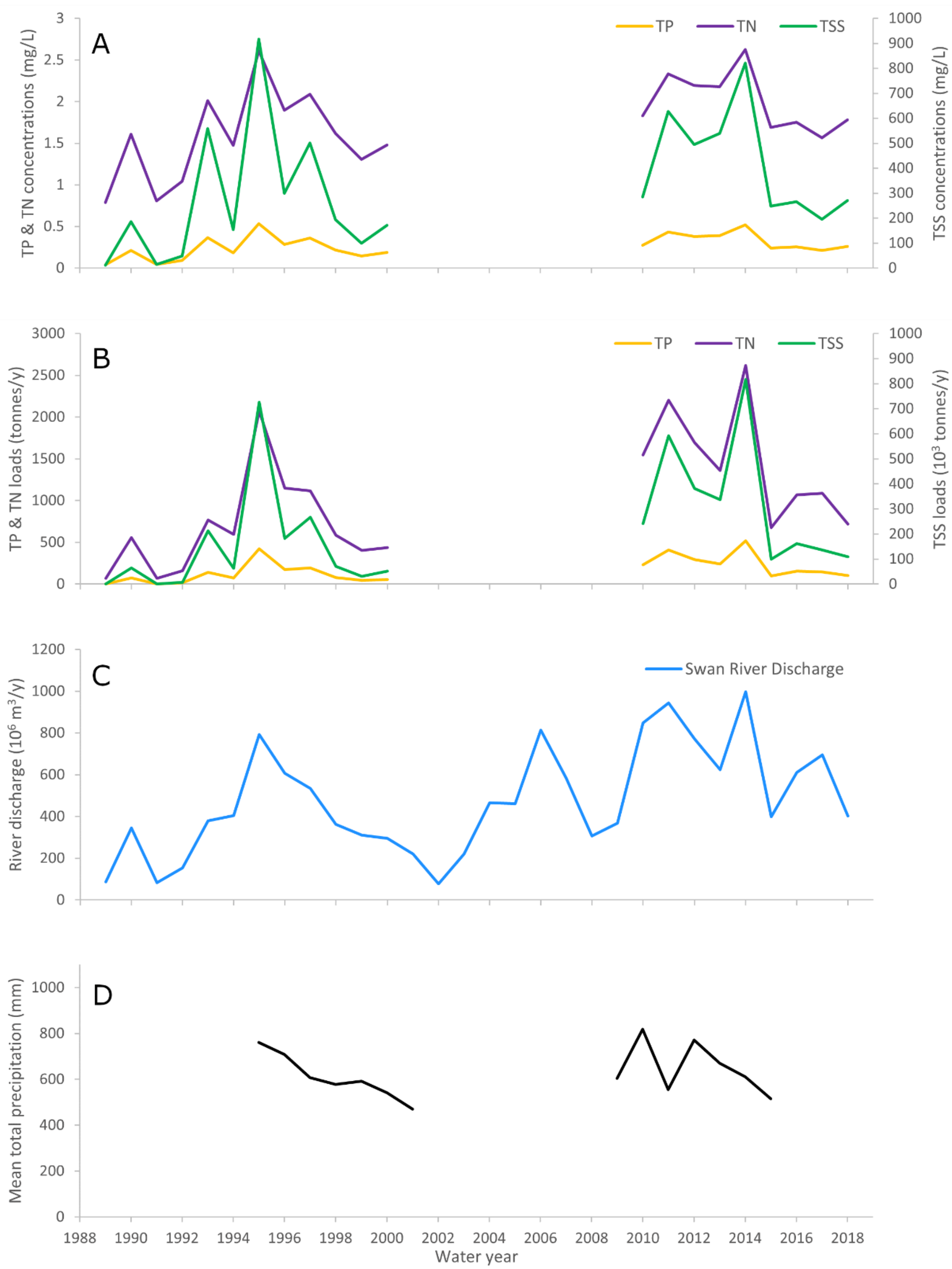

Figure 2.33. Time series of total phosphorus (TP), total nitrogen (TN), and total suspended solid (TSS) flow-weighted mean concentrations (A), TP, TN, and TSS loads (B) and annual total river discharge in Swan River (C) with the mean annual total watershed precipitation (D) across the Swan Lake watershed.

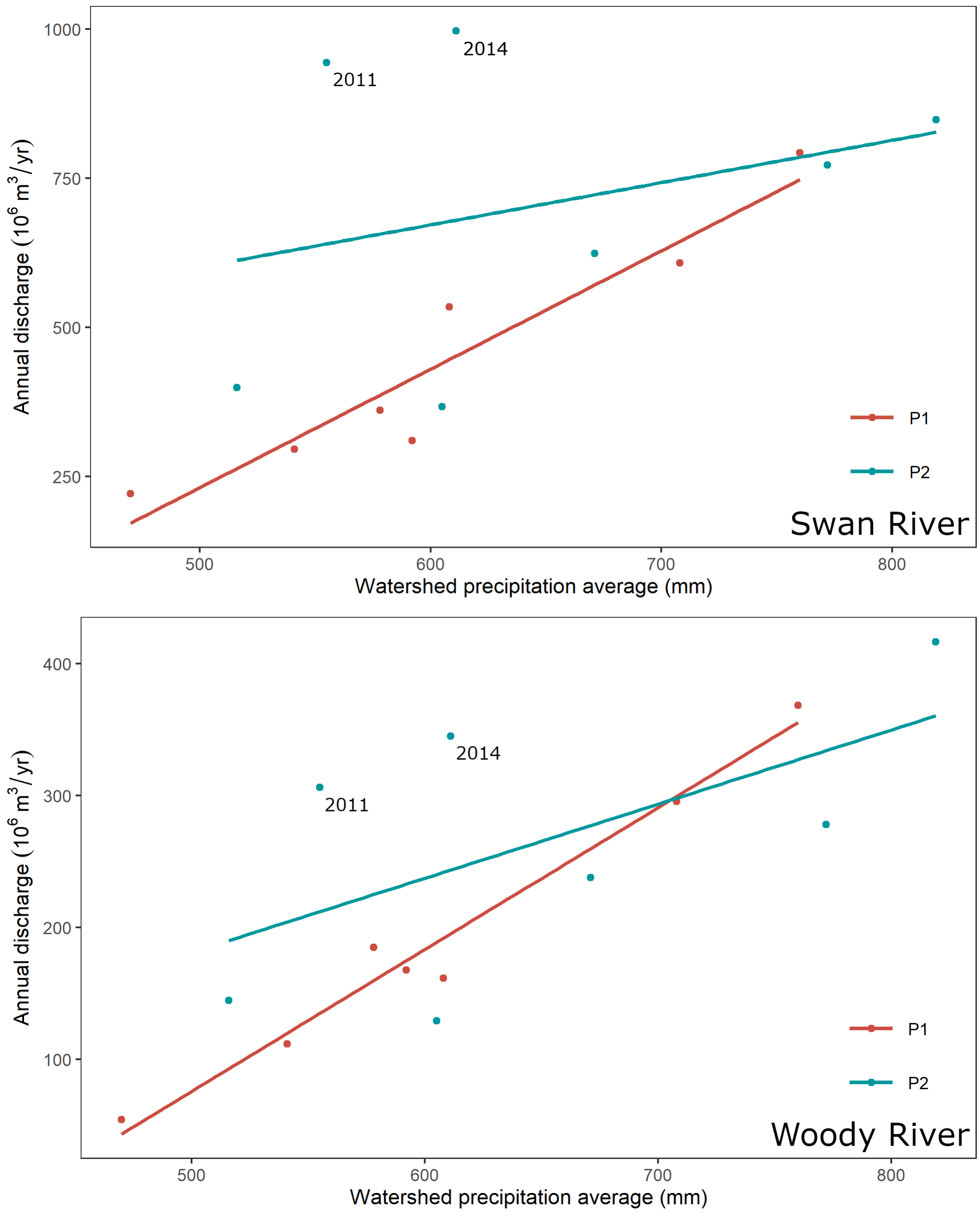

Figure 2.34. Correlation between the annual average precipitation across the watershed and annual prorated discharge in Swan River (top) and Woody River (bottom) for 1995 – 2001 period (P1) and 2009 – 2015 (P2). Residual outliers are indicated with the year beside the point.

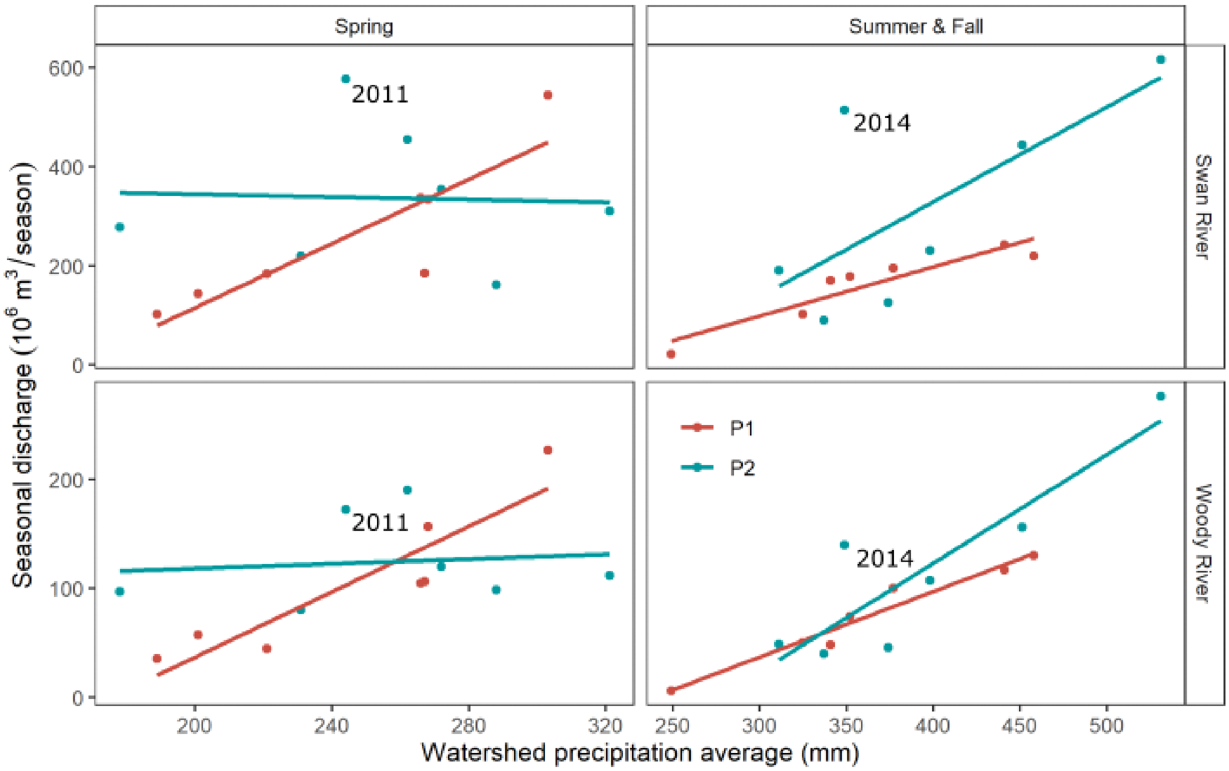

Figure 2.35. Correlation between the seasonal average precipitation across the watershed and seasonal prorated discharge in Swan River (top) and Woody River (bottom) for 1995 – 2001 period (P1) and 2009 – 2015 (P2). Spring discharge was tested against the total winter plus total spring watershed average precipitation. Residual outliers are indicated with the year beside the point.

Table 2.14. Correlation statistics of watershed average precipitation and total discharge for 1995 – 2001 (P1) and 2009 – 2015 (P2) in Swan and Woody Rivers using the Spearman's rank correlation test. Annual and seasonal correlations were examined. Spring discharge was tested against the total winter plus total spring watershed average precipitation. Significance of 5% indicated in bold.

	Swan River		Woody River	
	P1	P2	P1	P2
		Annual		
Rho	0.96	0.25	0.86	0.54
S-stat	2	42	8	26
p-value	**<0.01**	0.59	**0.02**	0.24
		Spring		
Rho	0.89	-0.036	0.96	0.32
S-stat	6	58	2	38
p-value	**0.01**	0.96	**<0.01**	0.50
		Summer/Fall		
Rho	0.96	0.64	0.96	0.75
S-stat	2	20	2	14
p-value	**<0.01**	0.14	**<0.01**	0.07

2.6 Conclusion

2.6.1 Summary and Significant Findings

The Swan Lake watershed is an area that provides substantial economical, social, and environmental services, with many in the community concerned about the health of the ecosystem and individuals within the community. Many are concerned about maintaining or improving water quality in their rivers and lakes. This area has a diverse assortment of land cover from natural forested to heavily modified agricultural land and rural and urban centres. In the current stage of climate change, significant changes are impacting water flows which in turn is also affecting water quality.

This study was undertaken with the objective to examine long-term changes in nutrient exports in the two largest rivers (Swan River and Woody River) of the Swan Lake watershed. Additionally, it seeks to determine if any changes in nutrients were related to changes in river discharge and precipitation. The initial intent was to examine changes over a 30-year period (1989 – 2018). This examination was achieved for river discharge in both rivers. Annual total discharge in Swan River increased significantly by 182% and Woody River increased insignificantly by 103% over the 30 years. Through the spring, and summer and fall seasons, discharge in both rivers increased over 80%; however, only the spring season in the Swan River experienced a significant increase.

Due to changes in laboratories and lab procedures, this study only examined the change in FWMCs and loads of five water quality variables (TP, PP, TDP, TN, and TSS) between 1989 – 2000 (ALS1) and 2010 – 2018 (ALS2) than trends over a complete 30-year analysis. The two periods had identical lab procedures and at least bracketed the 30 years of record. Flow-weighted mean concentrations and loads in both Swan River and Woody River increased between 10%

and 400% from ALS1 to ALS2. Swan River experienced a statistically significant increase in annual and spring season FWMCs and loads. On the contrary, Woody River experienced a significant increase in most annual and spring season loads but not in FWMCs. The highest increase of the five water quality variables was TSS in the spring season, with FWMCs increasing by over 200% and loads increasing by over 450% between the two ALS periods.

Annual precipitation from four meteorological stations were calculated and averaged to determine if any changes occurred across the watershed over 30 years. This study did not accomplish a 30-year trend analysis for precipitation due to large data gaps between 2002 – 2008. Between the two seven-year periods of precipitation (1995 – 2001 and 2009 – 2015), the mean total precipitation across the watershed only experienced a small increase of 3%; however, this small percentage is sufficient explain the large and significant changes in discharge.

Correlations between water quality variables and river discharge were high, particularly for particulate constituents. Annual and seasonal river discharge and precipitation were significantly correlated in 1995 – 2001, but not in 2009 – 2015. Including water storage in this analysis may explain the two outlier years with anomalously high discharge despite only moderate precipitation. Since both nutrient concentrations and loads increased with increasing discharge, higher discharge in the second period explains at least part of the increase in nutrient and sediment exports from the two watersheds into Swan Lake. Precipitation helps explain the increase in discharge directly and, hence, in nutrient loading indirectly. Even though this study cannot say climate change is occurring and impacting nutrient loading in this study area, the increases observed in nutrient loads derived at least in part from the increase in river discharge that itself can be explained by the small increase in precipitation. That is, this study demonstrates and quantifies the effect of climate change to nutrient exports in the Swan Lake Watershed.

2.6.2 Limitations and Uncertainties

The available data and results are subjected to many limitations and uncertainties. The primary limitation present in many historical datasets are the major data gaps. Many datasets in this study required a form of regression or interpolation to fill gaps. Water quality data had approximately one sample measurement per season, and samples typically missed peak flow periods when the highest quantity of nutrient loading usually occurred. Using a regression technique to estimate daily nutrient values based on discharge, there remains uncertainty because of infrequent sampling during the high flow periods, in particular for flow rates above 100 m^3/s. Furthermore, with the water quality data, phosphorus and nitrogen concentrations were not fully comparable between the two laboratories (ALS and CNT) due to CNT predicting higher concentrations than both ALS1 and ALS2 periods (see Appendix A). Furthermore, as shown in McCullough et al. (2015), when using paired observations from both the ALS1 and ALS2 periods, the CNT laboratory reported higher phosphorus concentrations than the ALS laboratory. This uncertainty led to the removal of the CNT period and a continuous long-term study not being achieved.

The large gaps in precipitation data at some stations also limited the ability to perform a long-term trend analysis. Smaller gaps were filled using IDW, while years with larger gaps were completely removed, leading to multiple years in the middle of the 30-year period not being included in the analysis. In fact, this left less than ten years for each period and a weakened assumption that the results would represent a general trend in precipitation across the watershed, that is, whether there was a true increase over time.

A full 30-year analysis was achieved in river discharge data; however, there is some uncertainty in the dataset. Most data gaps during the open-water season were small, except for

Swan River in 2014. The portion of the data with the largest gaps occurred during the ice-cover period, more specifically from November to February, for which there were no records available for this study. Earlier years had ice-cover flow measurements in Swan River but not for Woody River. Even though discharge in the winter typically decreases through the winter months and nutrient loading reduced, flow rates increased annually and seasonally over time.

2.6.3 Recommendations and Future Research

More continuous monitoring would help improve many of the limitations and uncertainties presented. Since nutrient sampling only occurred three to four times a year, many high-flow measurements were missed. Sampling more frequently for nutrients, at least during the spring peak flow period, will reduce uncertainties in nutrient concentrations and loads values during high flow periods. River discharge measurements stopped during the winter ice-covered months, and sampling during this time will help for better interpolation, even if it is one or two measurements. Many gaps also occurred in precipitation data, typically from instrument malfunction. If more reliable instruments cannot be obtained, a few more weather stations in the area would help, especially since many were decommissioned over the last couple of decades.

Historical records for discharge and weather data in the study can date back to 1950s and 1900s, respectively, depending on the station. Analysis of a longer period would help better understand what is currently happening to discharge and precipitation in the watershed and help quantify the link between climate change and nutrient exports. The gaps represented in this study would be small relative to the scale of a longer period analysis. Unfortunately, the period used in this study was determined by the available water quality data, which had more consistent measurements starting in 1988.

As mentioned throughout the discussion, some potential research topics to expand from this study are:

- A longer long-term trend analysis on river discharge and precipitation to obtain a stronger understanding of the changes in these variables. Since nutrient data does not extend earlier than the late 1980s and nutrient and TSS concentrations and loads are correlated with discharge, results from this study could be used with future modelled climate to predict the impact of future climate factors on river discharge and water quality.
- Identifying rainfall intensity impacts on runoff, discharge, and nutrient loading in the Swan Lake watershed may help better understand the changes in nutrient transport.
- Further examining major peak flows in the rivers and the changes over time. These changes may assist in determining if nutrients are transported sooner during snowmelt and if rainfall runoff carries higher quantities in the warmer months due to increased rainfall events.
- Include land use and practices in the study to determine whether climate or land use is more of a dominant factor in runoff, discharge, and water quality changes.

Overall, the interactions of and the changes in climate, land use, discharge, and water quality still need to be further investigated to gather a stronger understanding of the changes and effects to help with future responses and implications of water resources in the Swan Lake watershed.

REFERENCES

Agriculture and Agri-Food Canada – Agri-Environment Services Branch (AAFC-AESB) and Manitoba Agriculture Food and Rural Initiatives (MAFRI). (2011). Agricultural Land Use and Management in the Swan Lake Watershed. Retrieved from https://www.gov.mb.ca/water/watershed/iwmp/swan_lake/documentation/swan_watershed_agriculture_report_mar3_final.pdf.

Akinremi, O. O., McGinn, S. M., & Cutforth, H. W. (1999). Precipitation Trends on the Canadian Prairies*. *Journal of Climate*, *12*(10), 2996–3003. https://doi.org/10.1175/1520-0442(1999)012<2996:PTOTCP>2.0.CO;2

Bortoluzzi, T. (2003). An Annotated Bibliography on Lake Manitoba and Adjoining Waters. Delta Marsh Field Station (University of Manitoba) Occasional Publication No. 3.

Bourne, A., Armstrong, N. and Jones, G. (2002). A preliminary estimate of total nitrogen and total phosphorus loading to streams in Manitoba, Canada. Water Quality Management Section, Water Branch, Manitoba. Manitoba Conservation Report No. 2002-04.

Burn, D. H., Buttle, J. M., Caissie, D., MacCulloch, G., Spence, C., & Stahl, K. (2008). The Processes, Patterns and Impacts of Low Flows Across Canada. *Canadian Water Resources Journal*, *33*(2), 107–124. https://doi.org/10.4296/cwrj3302107

Burn, D. H., Fan, L., & Bell, G. (2008). Identification and quantification of streamflow trends on the Canadian Prairies. *Hydrological Sciences Journal*, *53*(3), 538–549. https://doi.org/10.1623/hysj.53.3.538

Cade-Menun, B. J., Bell, G., Baker-Ismail, S., Fouli, Y., Hodder, K., McMartin, D. W., Perez-Valdivia, C., & Wu, K. (2013). Nutrient loss from Saskatchewan cropland and pasture in spring snowmelt runoff. *Canadian Journal of Soil Science*, *93*(4), 445–458. https://doi.org/10.4141/cjss2012-042

Chang, H., Evans, B. M., & Easterling, D. R. (2001). THE EFFECTS OF CLIMATE CHANGE ON STREAM FLOW AND NUTRIENT LOADING1. *JAWRA Journal of the American Water Resources Association*, *37*(4), 973–985. https://doi.org/10.1111/j.1752-1688.2001.tb05526.x

Chen, F.-W., & Liu, C.-W. (2012). Estimation of the spatial rainfall distribution using inverse distance weighting (IDW) in the middle of Taiwan. *Paddy and Water Environment*, *10*(3), 209–222. https://doi.org/10.1007/s10333-012-0319-1

Chen, N., Wu, Y., Chen, Z., & Hong, H. (2015). Phosphorus export during storm events from a human perturbed watershed, southeast China: Implications for coastal ecology. *Estuarine, Coastal and Shelf Science*, *166*, 178–188. https://doi.org/10.1016/j.ecss.2015.03.023

Clark, G. M., Mueller, D. K., & Mast, M. A. (2000). Nutrient concentrations and yields in undeveloped stream basins of the United States. *Journal of the American Water Resources Association*, *36*(4), 849–860. https://doi.org/10.1111/j.1752-1688.2000.tb04311.x

Corriveau, J., Chambers, P. A., & Culp, J. M. (2013). Seasonal Variation in Nutrient Export Along Streams in the Northern Great Plains. *Water, Air, & Soil Pollution*, *224*(7), 1594. https://doi.org/10.1007/s11270-013-1594-1

Corriveau, J., Chambers, P.A., Yates, A.G., Culp, J.M., 2011. Snowmelt and its role in the hydrologic and nutrient budgets of prairie streams. Water Sci. Technol. 64, 1590–1596.

Dai, A. (2008). Temperature and pressure dependence of the rain-snow phase transition over land and ocean: RAIN-SNOW PHASE TRANSITION. *Geophysical Research Letters*, *35*(12), 1–6. https://doi.org/10.1029/2008GL033295

Dibike, Y., Prowse, T., Shrestha, R., & Ahmed, R. (2012). Observed trends and future projections of precipitation and air temperature in the Lake Winnipeg watershed. *Journal of Great Lakes Research*, *38*, 72–82. https://doi.org/10.1016/j.jglr.2011.04.005

Dodds, W. K., Gido, K., Whiles, M. R., Fritz, K. M., & Matthews, W. J. (2004). Life on the Edge: The Ecology of Great Plains Prairie Streams. *BioScience*, *54*(3), 205. https://doi.org/10.1641/0006-3568(2004)054[0205:LOTETE]2.0.CO;2

Dolan, D. M., Yui, A. K., & Geist, R. D. (1981). Evaluation of River Load Estimation Methods for Total Phosphorus. *Journal of Great Lakes Research*, *7*(3), 207–214. https://doi.org/10.1016/S0380-1330(81)72047-1

Donald, D. B., Parker, B. R., Davies, J.-M., & Leavitt, P. R. (2015). Nutrient sequestration in the Lake Winnipeg watershed. *Journal of Great Lakes Research*, *41*(2), 630–642. https://doi.org/10.1016/j.jglr.2015.03.007

Dumanski, S., Pomeroy, J. W., & Westbrook, C. J. (2015). Hydrological regime changes in a Canadian Prairie basin: Hydrological regime changes in a Canadian Prairie basin. *Hydrological Processes*, *29*(18), 3893–3904. https://doi.org/10.1002/hyp.10567

Durbin, J., & Watson, G. S. (1950). Testing for Serial Correlation in Least Squares Regression: I. *Biometrika*, *37*(3–4), 409–428. https://doi.org/10.2307/2332391

Durbin, J., & Watson, G. S. (1951). Testing for Serial Correlation in Least Squares Regression. II. *Biometrika*, *38*(1–2), 159–177. https://doi.org/10.2307/2332325

Ehrlich, W. A., Pratt, L. E. and Leclaire, F. P. (1962). Report of detailed-reconnaissance soil survey of Swan River map sheet area. Manitoba Department od Agriculture and Conservation. Soils Report No. 13.

Ehsanzadeh, E., Kamp, G., & Spence, C. (2012). The impact of climatic variability and change in the hydroclimatology of Lake Winnipeg watershed. *Hydrological Processes*, *26*(18), 2802–2813. https://doi.org/10.1002/hyp.8327

Ellison, M. E., & Brett, M. T. (2006). Particulate phosphorus bioavailability as a function of stream flow and land cover. *Water Research*, *40*(6), 1258–1268. https://doi.org/10.1016/j.watres.2006.01.016

Gan, T. Y. (1998). Hydroclimatic trends and possible climatic warming in the Canadian Prairies. *Water Resources Research*, *34*(11), 3009–3015. https://doi.org/10.1029/98WR01265

Glozier, N.E., J.A. Elliott, B. Holliday, J. Yarotski, and B. Harker. 2006. Water quality characteristics and trends in a small agricultural watershed: South Tobacco Creek, Manitoba, 1992–2001. Environment Canada, Saskatoon, SK, Canada.

Government of Canada (2020). Concentrations and detection limit information: guide to reporting. Retrieved from https://www.canada.ca/en/environment-climate-change/services/national-pollutant-release-inventory/report/tools-calculating-emissions/concentrations-detection-limit-information.html (Accessed December 2020).

Government of Canada. (2022). Canadian Climate Normals 1981-2010 Station Data. Retrieved from http://climate.weather.gc.ca/climate_normals/ (Accessed April 13, 2022).

Granger, R. J., Gray, D. M., and Dyck, G. E. (1984). Snowmelt infiltration to frozen prairie soils. *Canadian Journal of Earth Sciences*, 21(6), 669–677. https://doi-org.uml.idm.oclc.org/10.1139/e84-073

Gray, D. M., & Landine, P. G. (1988). An energy-budget snowmelt model for the Canadian Prairies. *Canadian Journal of Earth Sciences*, *25*(8), 1292–1303. https://doi.org/10.1139/e88-124

Guo, X., Yan, X., Bao, H., Wu, J., & Kao, S. (2022). Differential Response of Nutrients to Seasonal Hydrological Changes and a Rain Event in a Subtropical Watershed, Southeast China. *Water*, *14*(5), 834. https://doi.org/10.3390/w14050834

Han, H., Allan, J. D., & Bosch, N. S. (2012). Historical pattern of phosphorus loading to Lake Erie watersheds. *Journal of Great Lakes Research*, *38*(2), 289–298. https://doi.org/10.1016/j.jglr.2012.03.004

Hughes, C.E. and Williamson, D.A. 2002. An overview of water quality in Lake Manitoba, Manitoba, Canada. Manitoba Conservation Report No. 2002-05.

Jennings, K. S., Winchell, T. S., Livneh, B., & Molotch, N. P. (2018). Spatial variation of the rain–snow temperature threshold across the Northern Hemisphere. *Nature Communications*, *9*(1), 1148. https://doi.org/10.1038/s41467-018-03629-7

Johnes, P. J. (2007). Uncertainties in annual riverine phosphorus load estimation: Impact of load estimation methodology, sampling frequency, baseflow index and catchment population density. *Journal of Hydrology*, *332*(1–2), 241–258. https://doi.org/10.1016/j.jhydrol.2006.07.006

Jones, G. and Armstrong, N. (2001). Long-term trends in total nitrogen and total phosphorus concentrations in Manitoba streams. Water Quality Management Section, Water Branch, Manitoba. Manitoba Conservation Report No. 2001-07.

Kleinman, P. J. A., Srinivasan, M. S., Dell, C. J., Schmidt, J. P., Sharpley, A. N., & Bryant, R. B. (2006). Role of Rainfall Intensity and Hydrology in Nutrient Transport via Surface

Runoff. *Journal of Environmental Quality*, *35*(4), 1248–1259. https://doi.org/10.2134/jeq2006.0015

Lake Manitoba Regulation Review Advisory Committee (LMRRAC). 2003. Regulation of Water Levels on Lake Manitoba and along the Fairford River, Pineimuta Lake, Lake St. Martin, and Dauphin River and related issues. Main Report, Volume 2. August 22, 2003.

Lake Winnipeg Community-Based Monitoring Network (LWCBMB), 2020a. Intermountain Watershed District, 2019 Regional Report. Retrieved from https://www.lakewinnipegfoundation.org/sites/default/files/2019_Intermountain.pdf

Lake Winnipeg Community-Based Monitoring Network (LWCBMB), 2020b. Assiniboine West Watershed District, 2019 Regional Report. Retrieved from https://www.lakewinnipegfoundation.org/sites/default/files/2019_Assiniboine-West.pdf

Lake Winnipeg Community-Based Monitoring Network (LWCBMB), 2020c. Seine Rat Roseau Watershed District, 2019 Regional Report. Retrieved from https://www.lakewinnipegfoundation.org/sites/default/files/2019_Seine-Rat-Roseau.pdf

Lee, C. J., Hirsch, R. M., Schwarz, G. E., Holtschlag, D. J., Preston, S. D., Crawford, C. G., & Vecchia, A. V. (2016). An evaluation of methods for estimating decadal stream loads. *Journal of Hydrology*, *542*, 185–203. https://doi.org/10.1016/j.jhydrol.2016.08.059

Little, J. L., Nolan, S. C., Casson, J. P., & Olson, B. M. (2007). Relationships between Soil and Runoff Phosphorus in Small Alberta Watersheds. *Journal of Environmental Quality*, *36*(5), 1289–1300. https://doi.org/10.2134/jeq2006.0502

Liu, K., Elliott, J. A., Lobb, D. A., Flaten, D. N., & Yarotski, J. (2013). Critical Factors Affecting Field-Scale Losses of Nitrogen and Phosphorus in Spring Snowmelt Runoff in the Canadian Prairies. *Journal of Environmental Quality*, *42*(2), 484–496. https://doi.org/10.2134/jeq2012.0385

Manitoba Water Stewardship. (2011). Swan Lake Watershed Integrated Watershed Management Plan – Water Quality Report. Retrieved from https://www.gov.mb.ca/sd/water/watershed/iwmp/swan_lake/documentation/surfacewaterquality.pdf

Mann, H. B. (1945). Nonparametric Tests Against Trend. *Econometrica*, *13*(3), 245. https://doi.org/10.2307/1907187

Mann, H. B., & Whitney, D. R. (1947). On a Test of Whether one of Two Random Variables is Stochastically Larger than the Other. *The Annals of Mathematical Statistics*, *18*(1), 50–60. https://doi.org/10.1214/aoms/1177730491

McCullough, G. K. (2015). Analysis of Inter-laboratory Effects on Phosphorus Concentrations Reported for Lakes and Rivers in Manitoba. Prepared for the Manitoba Department of Conservation and Water Stewardship.

McCullough, G. K., Page, S. J., Hesslein, R. H., Stainton, M. P., Kling, H. J., Salki, A. G., & Barber, D. G. (2012). Hydrological forcing of a recent trophic surge in Lake Winnipeg. *Journal of Great Lakes Research*, *38*, 95–105. https://doi.org/10.1016/j.jglr.2011.12.012

Mekis, É., & Vincent, L. A. (2011). An Overview of the Second Generation Adjusted Daily Precipitation Dataset for Trend Analysis in Canada. *Atmosphere-Ocean*, *49*(2), 163–177. https://doi.org/10.1080/07055900.2011.583910

Michalak, A. M., Anderson, E. J., Beletsky, D., Boland, S., Bosch, N. S., Bridgeman, T. B., Chaffin, J. D., Cho, K., Confesor, R., Daloğlu, I., DePinto, J. V., Evans, M. A., Fahnenstiel, G. L., He, L., Ho, J. C., Jenkins, L., Johengen, T. H., Kuo, K. C., LaPorte, E., … Zagorski, M. A. (2013). Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proceedings of the National Academy of Sciences*, *110*(16), 6448–6452. https://doi.org/10.1073/pnas.1216006110

Millett, B., Johnson, W. C., and Guntenspergen, G. (2009). Climate trends of the North American prairie pothole region 1906–2000. Climate Change, 93, 243–267. https://doi.org/10.1007/s10584-008-9543-5

Moatar, F., Abbott, B. W., Minaudo, C., Curie, F., & Pinay, G. (2017). Elemental properties, hydrology, and biology interact to shape concentration-discharge curves for carbon, nutrients, sediment, and major ions. *Water Resources Research*, *53*(2), 1270–1287. https://doi.org/10.1002/2016WR019635

Nielsen, A., Trolle, D., Søndergaard, M., Lauridsen, T. L., Bjerring, R., Olesen, J. E., & Jeppesen, E. (2012). Watershed land use effects on lake water quality in Denmark. *Ecological Applications*, *22*(4), 1187–1200. https://doi.org/10.1890/11-1831.1

Nielsen, E. (1988). Surficial Geology of the Swan River area. Manitoba Energy and Mines, Geological Services, Geological Report GR80-7.

Novotny, E. V., & Stefan, H. G. (2007). Stream flow in Minnesota: Indicator of climate change. *Journal of Hydrology*, *334*(3–4), 319–333. https://doi.org/10.1016/j.jhydrol.2006.10.011

Page, E. (2011). A water quality assessment of Lake Manitoba, a large shallow lake in central Canada. University of Manitoba, Winnipeg, Manitoba, Canada.

Patakamuri, S. K. (2021). Modified Versions of Mann Kendall and Spearman's Rho Trend Tests. R package version 1.6. https://cran.r-project.org/web/packages/modifiedmk/index.html.

Quilbé, R., Rousseau, A. N., Duchemin, M., Poulin, A., Gangbazo, G., & Villeneuve, J.-P. (2006). Selecting a calculation method to estimate sediment and nutrient loads in streams: Application to the Beaurivage River (Québec, Canada). *Journal of Hydrology*, *326*(1–4), 295–310. https://doi.org/10.1016/j.jhydrol.2005.11.008

Rattan, K. J., Corriveau, J. C., Brua, R. B., Culp, J. M., Yates, A. G., & Chambers, P. A. (2017). Quantifying seasonal variation in total phosphorus and nitrogen from prairie streams in the Red River Basin, Manitoba Canada. *Science of The Total Environment*, *575*, 649–659. https://doi.org/10.1016/j.scitotenv.2016.09.073

Salvano, E., Flaten, D. N., Rousseau, A. N., & Quilbe, R. (2009). Are Current Phosphorus Risk Indicators Useful to Predict the Quality of Surface Waters in Southern Manitoba, Canada? *Journal of Environmental Quality*, *38*(5), 2096–2105. https://doi.org/10.2134/jeq2008.0159

Schindler, D. W., Hecky, R. E., & McCullough, G. K. (2012). The rapid eutrophication of Lake Winnipeg: Greening under global change. *Journal of Great Lakes Research*, *38*, 6–13. https://doi.org/10.1016/j.jglr.2012.04.003

Shrestha, R. R., Dibike, Y. B., & Prowse, T. D. (2012). Modeling Climate Change Impacts on Hydrology and Nutrient Loading in the Upper Assiniboine Catchment1: Modeling Climate Change Impacts on Hydrology and Nutrient Loading in the Upper Assiniboine Catchment. *JAWRA Journal of the American Water Resources Association*, *48*(1), 74–89. https://doi.org/10.1111/j.1752-1688.2011.00592.x

St. Jacques, J.-M., Huang, Y. A., Zhao, Y., Lapp, S. L., & Sauchyn, D. J. (2014). Detection and attribution of variability and trends in streamflow records from the Canadian Prairie

Provinces. *Canadian Water Resources Journal / Revue Canadienne Des Ressources Hydriques*, *39*(3), 270–284. https://doi.org/10.1080/07011784.2014.942575

Stanley, M.J. 2017. Spatial variation of water quality and algal production, and the relationship between land use and nutrient loading in Delta Marsh. University of Manitoba, Winnipeg, Manitoba, Canada.

Statistics Canada (2017). Human Activity and the Environment: Freshwater in Canada, 1971 to 2013. Map 1 Average annual runoff in Canada, 1971 to 2013. Retrieved from https://www150.statcan.gc.ca/n1/daily-quotidien/170321/mc-b001-eng.htm (Accessed October 16, 2022)

Statistics Canada (2022). (table). Census Profile. 2021 Census. Statistics Canada Catalogue no. 98-316-X2021001. Ottawa. Released February 9, 2022. Retrieved from https://www12.statcan.gc.ca/census-recensement/2021/dp-pd/prof/index.cfm?Lang=E (Accessed April 15, 2022)

Strickland, T., Fisher, L., & Korleski, C. (2010). *Ohio Lake Erie Phosphorus Task Force Final Report*. 109.

Swan Lake Basin Management Plan (SLBMP). (2004). Swan Lake Basin Management Plan, June 2004. 24p. Retrieved from https://www.gov.mb.ca/water/watershed/iwmp/swan_lake/documentation/swan_lake_basin_plan.pdf.

Swan Lake Watershed District (SLWD). (n.d.). Swan Lake integrated watershed management plan. 50p. Retrieved from http://www.swanlakewatershed.ca/uploads/1/3/0/0/130039784/swan_lake_iwmp.pdf .

Tabios, G. Q., & Salas, J. D. (1985). A COMPARATIVE ANALYSIS OF TECHNIQUES FOR SPATIAL INTERPOLATION OF PRECIPITATION. *Journal of the American Water Resources Association*, *21*(3), 365–380. https://doi.org/10.1111/j.1752-1688.1985.tb00147.x

Tiessen, K. H. D., Elliott, J. A., Yarotski, J., Lobb, D. A., Flaten, D. N., & Glozier, N. E. (2010). Conventional and Conservation Tillage: Influence on Seasonal Runoff, Sediment, and Nutrient Losses in the Canadian Prairies. *Journal of Environmental Quality*, *39*(3), 964–980. https://doi.org/10.2134/jeq2009.0219

Van Der Kamp, G., Stolte, W. J., & Clark, R. G. (1999). Drying out of small prairie wetlands after conversion of their catchments from cultivation to permanent brome grass. *Hydrological Sciences Journal*, *44*(3), 387–397. https://doi.org/10.1080/02626669909492234

Williamson, D. (2002). Manitoba Water Quality Standards, Objectives, and Guidelines, Report 2002-11.

Wine, M. L., & Makhnin, O. (2022). Seasonal watershed-scale influences on nitrogen concentrations across the Upper Mississippi River basin. *Hydrological Sciences Journal*, *67*(2), 263–276. https://doi.org/10.1080/02626667.2021.1999456

Yue, S., Pilon, P., & Cavadias, G. (2002). Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *Journal of Hydrology*, *259*(1–4), 254–271. https://doi.org/10.1016/S0022-1694(01)00594-7

Yue, S., Pilon, P., Phinney, B., & Cavadias, G. (2002). The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological Processes*, *16*(9), 1807–1829. https://doi.org/10.1002/hyp.1095

Zeileis, A., Grothendieck, G., Ryan, J. A., Ulrich, J. M., and Andrews, F. (2022). S3 Infrastructure for Regular and Irregular Time Series (Z's Ordered Observations). R package version 1.8-10.

Zhang, T., Li, D., & Lu, X. (2022). Response of runoff components to climate change in the source-region of the Yellow River on the Tibetan plateau. *Hydrological Processes*, *36*(6). https://doi.org/10.1002/hyp.14633

Zhang, X., Zwiers, F. W., Hegerl, G. C., Lambert, F. H., Gillett, N. P., Solomon, S., Stott, P. A., & Nozawa, T. (2007). Detection of human influence on twentieth-century precipitation trends. *Nature*, *448*(7152), 461–465. https://doi.org/10.1038/nature06025

APPENDICES

Appendix A: Nutrient concentration comparison among lab periods

Initially, data from both CNT and ALS labs were examined each for a power regression of nutrient concentrations during high flow (>7 m^3/s in Swan River and >5 m^3/s in Woody River). Figure A.1 shows the power regression for TP of each lab in Swan River. Cantest Lab in TP, PP, and TN in Swan River and Woody River typically predicted higher daily concentrations at high and low flows than the two ALS lab periods. Although ALS2 appears to predict lower TP values than ALS1, this is not consistent for all the variables. Total nitrogen regressions in Swan and Woody Rivers predicted higher TN at low flow in ALS1 and higher TN at high flow in ALS2. Total dissolved phosphorus in Woody River and TSS in Swan and Woody Rivers (Figure A.2) exhibited CNT to predict higher nutrient concentrations at low flow and lower concentrations at high flow than at least one of the ALS labs. McCullough (2015) performed an inter-laboratory comparative study between the two labs used by the Province of Manitoba and found CNT to have higher percent concentrations of TP and PP by 12% and 37%, respectively, than ALS. These findings initially led to the stratification of the data into lab periods.

Analysis of covariance (ANCOVA) test was performed to assess the differences in regression coefficients between each lab period. Using a post hoc test with ANCOVA, all three coefficients were not significantly different from each other for all nutrient variables (Table A.1), except for TP between ALS1 and ALS2 in Woody River. It was still decided to remove CNT from the analysis given the significant inter-lab differences for TP and PP reported by McCullough (2015) and given the greater nutrient concentrations in the CNT period for most nutrient variables than each ALS period. The two ALS periods were then tested for differences in coefficients and intercepts exclusively. All nutrient variables in both rivers have a non-significant difference in coefficients; however, two out of the five variables in each river had a significant difference in intercepts. Total phosphorus and TDP had statistically different intercepts (p-value < 0.05) in Swan River. For Woody River, TDP was the only variable with statistically different intercepts (p-value < 0.05) between ALS1 and ALS2. Although these variables showed a significantly different trend, it was still decided to merge both ALS periods to estimate nutrients and TSS by finding a new linear regression equation with both periods.

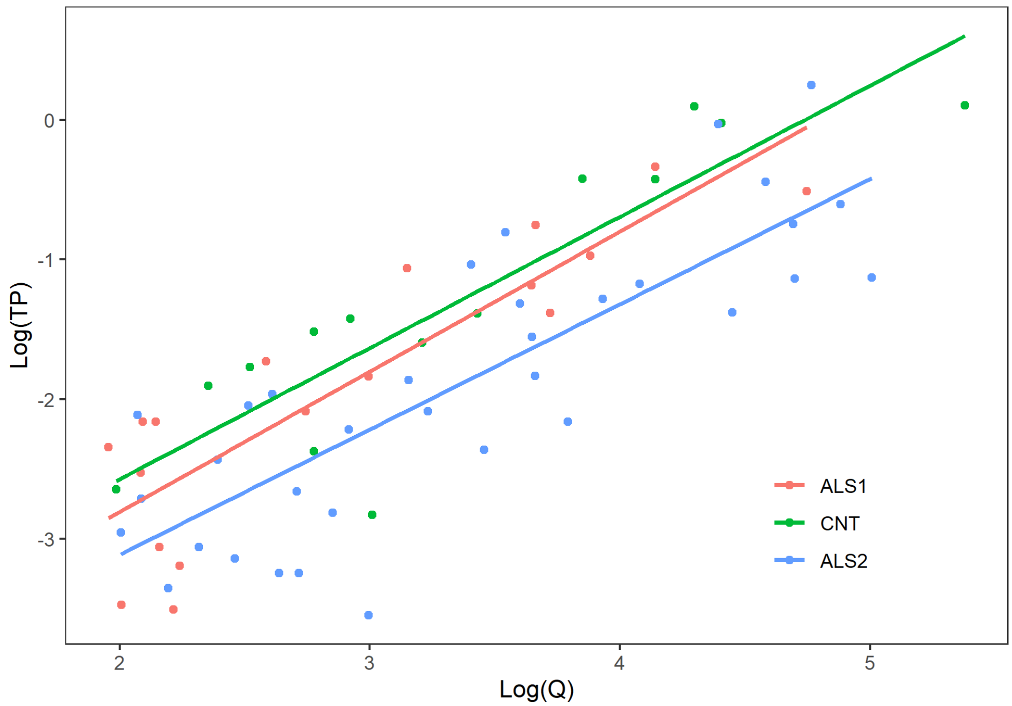

Figure A.1. Linear power regression of ALS1, CNT, and ALS2 periods for total phosphorus (TP) against discharge (Q) in Swan River during high flow days (>7 m^3/s). Total phosphorus and streamflow values are log-transformed.

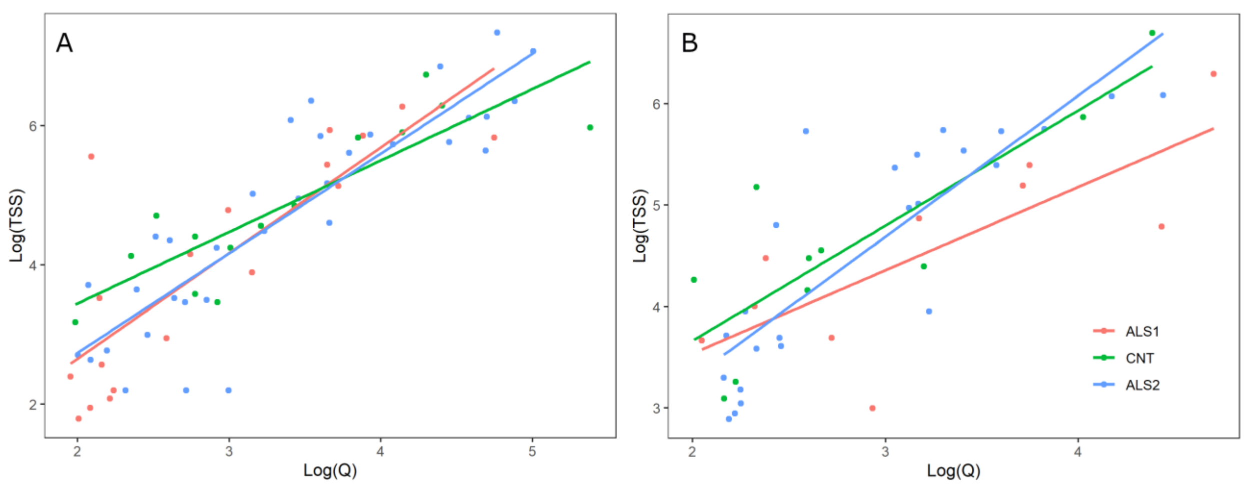

Figure A.2. Linear power regression of ALS1, CNT, and ALS2 for total suspended solids (TSS) against discharge (Q) in Swan River (A) and Woody River (B) during high flow days (>7 m^3/s and >5 m^3/s, respectively) showing CNT predicting higher TSS values at lower flow and lower TSS values at higher flow than at least one of the ALS labs. Total suspended solids and streamflow values are log-transformed.

Table A.1. P-values from ANCOVA to compare the regression coefficient between the three lab periods (ALS1, CNT, ALS2) during high flow days (>7 m^3/s in Swan River and >5 m^3/s in Woody River). Significance of 5% indicated in bold.

	ALS1-CNT	CNT-ALS2	ALS1-ALS2
Swan River			
TP	0.95	0.97	0.83
PP	0.67	0.77	0.95
TDP	1.00	0.28	0.22
TN	0.74	0.99	0.77
TSS	0.27	0.30	0.94
Woody River			
TP	0.34	0.68	0.04
PP	0.39	0.74	0.06
TDP	0.96	0.65	0.41
TN	0.80	0.96	0.56
TSS	0.64	0.71	0.15

References

McCullough, G. K. (2012). Analysis of Inter-laboratory Effects on Phosphorus Concentrations Reported for Lakes and Rivers in Manitoba. *Prepared for the Manitoba Department of Conservation and Water Stewardship*.

Appendix B: Annual and seasonal precipitation in Swan River, Pelly, Pelly 2, and Mafeking stations and the arithmetic average across the watershed. Dotted line indicated break between periods.

Year	Swan River	Pelly	Pelly 2	Mafeking	Watershed Average
			Annual (mm)		
1995	683	864	714	779	760
1996	702	766	640	725	708
1997	611	595	585	640	608
1998	475	601	540	696	578
1999	505	628	543	691	592
2000	370	601	582	612	541
2001	330	559	432	558	470
2009	434	633	626	728	605
2010	633	908	733	1002	819
2011	391	587	656	586	555
2012	652	835	707	894	772
2013	564	645	634	839	671
2014	505	645	567	728	611
2015	424	541	443	654	516
			Spring (mm)		
1995	143	189	167	157	164
1996	148	135	95	234	153
1997	106	126	98	125	114
1998	79	71	75	93	80
1999	202	169	167	192	182
2000	77	131	100	120	107
2001	59	103	78	142	96
2009	99	130	128	127	121
2010	127	194	153	293	192
2011	79	87	122	116	101
2012	176	233	198	272	220
2013	79	122	100	100	100
2014	110	170	152	168	150
2015	51	78	61	80	68
			Summer/Fall (mm)		
1995	424	516	426	464	458
1996	439	538	430	356	441
1997	357	292	336	380	341
1998	284	405	361	459	377
1999	235	364	281	419	325
2000	238	365	410	393	352
2001	199	298	215	284	249
2009	269	378	354	497	374

Year	Swan River	Pelly	Pelly 2	Mafeking	Watershed Average
2010	458	605	464	598	531
2011	223	341	343	336	311
2012	425	485	418	477	451
2013	398	336	353	507	398
2014	332	338	306	420	349
2015	304	317	276	452	337
	Winter (mm)				
1995	116	159	121	159	139
1996	116	93	115	135	115
1997	148	177	151	135	153
1998	113	124	104	144	121
1999	68	95	95	80	84
2000	54	104	71	100	82
2001	72	159	139	131	125
2009	66	125	145	105	110
2010	49	108	117	112	96
2011	88	158	190	135	143
2012	51	117	90	146	101
2013	87	186	181	232	172
2014	62	137	110	139	112
2015	69	147	105	123	111

Appendix C: Annual and seasonal total discharge in Swan and Woody Rivers. Discharge values are prorated to the water quality stations.

	Swan River (10^6 m^3/y)			Woody River (10^6 m^3/y)		
Year	Annual	Spring	Summer/Fall	Annual	Spring	Summer/Fall
1989	87.6	29.8	50.1	46.6	19.9	25.4
1990	345	254	57.3	212	144	46.7
1991	83.4	41.0	36.7	41.2	24.1	16.2
1992	155	103	42.4	84.4	55.4	25.9
1993	380	39.9	325	268	24.3	234
1994	404	105	249	227	37.3	135
1995	792	544	220	367	227	130
1996	608	334	242	296	156	117
1997	534	337	171	162	105	48.1
1998	361	144	195	185	57	100
1999	310	185	102	168	106	50.1
2000	296	102	178	112	35.3	73.9
2001	221	184	22.0	54.1	44.6	6.15
2002	78.2	28.6	42.1	15.1	5.32	9.69
2003	221	184	28.7	51.1	41.1	5.39
2004	465	198	252	236	81.7	148
2005	462	158	271	214	79.0	115
2006	814	613	169	371	302	52.2
2007	582	347	198	250	152	83.1
2008	306	165	121	125	53.7	65.9
2009	367	220	125	129	80.2	45.4
2010	848	162	616	417	98.4	276
2011	944	577	191	306	172	48.6
2012	772	311	444	278	112	156
2013	623	354	231	238	120	107
2014	997	454	514	345	190	140
2015	399	278	89.6	145	97.2	39.8
2016	610	303	274	287	112	161
2017	694	285	165	357	117	60.1
2018	403	181	202	192	58.3	121

Appendix D: Annual and seasonal flow-weighted mean concentrations (FWMC) and loads data for Swan and Woody Rivers. Dotted line indicated break between periods.

		FWMC (mg/L)			Loads (tonnes/y)		
Year	Variable	Annual	Spring	Summer/Fall	Annual	Spring	Summer/Fall
				Swan River			
1989	TP	0.037	0.047	0.032	3.25	1.40	1.63
1990	TP	0.213	0.272	0.059	73.4	69.0	3.37
1991	TP	0.046	0.045	0.048	3.80	1.85	1.78
1992	TP	0.091	0.121	0.030	14.1	12.5	1.29
1993	TP	0.366	0.044	0.421	139	1.74	137
1994	TP	0.185	0.152	0.227	74.6	16.0	56.5
1995	TP	0.534	0.708	0.169	423	385	37.1
1996	TP	0.286	0.370	0.206	174	123	49.7
1997	TP	0.362	0.510	0.121	193	172	20.7
1998	TP	0.217	0.238	0.222	78.3	34.2	43.5
1999	TP	0.144	0.202	0.064	44.5	37.3	6.53
2000	TP	0.190	0.106	0.253	56.3	10.8	45.0
2010	TP	0.273	0.164	0.328	231	26.5	202
2011	TP	0.433	0.611	0.202	409	352	38.5
2012	TP	0.382	0.317	0.441	295	98.6	196
2013	TP	0.388	0.570	0.168	242	202	38.9
2014	TP	0.518	0.486	0.574	517	221	295
2015	TP	0.240	0.321	0.062	95.7	89.2	5.58
2016	TP	0.256	0.354	0.175	156	107	47.9
2017	TP	0.211	0.318	0.137	147	90.7	22.6
2018	TP	0.260	0.374	0.181	105	67.6	36.5
1989	PP	0.020	0.025	0.018	1.78	0.76	0.895
1990	PP	0.156	0.203	0.031	53.9	51.5	1.78
1991	PP	0.024	0.024	0.026	2.01	0.980	0.94
1992	PP	0.056	0.075	0.017	8.61	7.73	0.73
1993	PP	0.341	0.023	0.395	130	0.92	129
1994	PP	0.133	0.102	0.169	53.9	10.7	42.1
1995	PP	0.506	0.689	0.118	401	375	25.8
1996	PP	0.225	0.301	0.148	137	100	35.8
1997	PP	0.319	0.464	0.080	170	156	13.6
1998	PP	0.163	0.181	0.165	58.7	26.1	32.3
1999	PP	0.097	0.141	0.035	30.0	26.0	3.57
2000	PP	0.140	0.064	0.195	41.5	6.51	34.7
2010	PP	0.214	0.107	0.264	181	17.3	163
2011	PP	0.389	0.569	0.147	367	328.	28.0
2012	PP	0.329	0.253	0.395	254	78.6	175
2013	PP	0.343	0.527	0.115	214	186	26.7
2014	PP	0.483	0.427	0.559	482	194	287

		FWMC (mg/L)			Loads (tonnes/y)		
Year	Variable	Annual	Spring	Summer/Fall	Annual	Spring	Summer/Fall
2015	PP	0.187	0.254	0.035	74.5	70.8	3.17
2016	PP	0.199	0.291	0.120	121	88.0	32.8
2017	PP	0.156	0.257	0.088	108	73.3	14.5
2018	PP	0.205	0.315	0.125	82.5	57.0	25.2
1989	TDP	0.014	0.017	0.012	1.21	0.511	0.615
1990	TDP	0.043	0.052	0.022	14.9	13.3	1.24
1991	TDP	0.017	0.017	0.018	1.44	0.704	0.670
1992	TDP	0.026	0.034	0.011	4.10	3.52	0.474
1993	TDP	0.052	0.017	0.059	19.9	0.664	19.1
1994	TDP	0.039	0.037	0.045	15.8	3.85	11.1
1995	TDP	0.069	0.084	0.038	54.4	45.7	8.44
1996	TDP	0.051	0.061	0.043	31.1	20.3	10.4
1997	TDP	0.055	0.070	0.032	29.3	23.6	5.42
1998	TDP	0.043	0.046	0.044	15.5	6.62	8.67
1999	TDP	0.035	0.045	0.023	10.8	8.3	2.31
2000	TDP	0.039	0.031	0.047	11.7	3.12	8.36
2010	TDP	0.050	0.040	0.056	42. 3	6.45	34.7
2011	TDP	0.062	0.078	0.042	58.5	45.0	8.03
2012	TDP	0.059	0.055	0.064	45.6	17.0	28.4
2013	TDP	0.058	0.074	0.039	35.9	26.3	9.12
2014	TDP	0.070	0.070	0.073	69.4	31.6	37.5
2015	TDP	0.044	0.055	0.020	17.6	15.4	1.84
2016	TDP	0.047	0.058	0.040	28.8	17.6	10.9
2017	TDP	0.044	0.055	0.035	30.2	15.6	5.73
2018	TDP	0.047	0.060	0.040	19.1	10.8	8.09
1989	TN	0.786	0.824	0.766	68.9	24.6	38.3
1990	TN	1.61	1.89	0.861	555	479	49.3
1991	TN	0.805	0.802	0.814	67.1	32.9	29.8
1992	TN	1.04	1.17	0.769	161	121	32.6
1993	TN	2.01	0.794	2.22	765	31.7	722
1994	TN	1.48	1.34	1.67	596	141	416
1995	TN	2.61	3.20	1.40	2070	1740	309
1996	TN	1.89	2.24	1.57	1150	746	380
1997	TN	2.09	2.65	1.17	1110	894	200
1998	TN	1.62	1.70	1.66	585	245	323
1999	TN	1.31	1.60	0.897	404	296	91.0
2000	TN	1.48	1.13	1.74	438	115	311
2010	TN	1.83	1.40	2.06	1550	226	1270
2011	TN	2.33	2.97	1.58	2200	1710	300
2012	TN	2.20	1.99	2.40	1700	618	1060
2013	TN	2.18	2.83	1.43	1360	1000	331
2014	TN	2.63	2.61	2.75	2620	1180	1410

		FWMC (mg/L)			Loads (tonnes/y)		
Year	Variable	Annual	Spring	Summer/Fall	Annual	Spring	Summer/Fall
2015	TN	1.69	2.05	0.907	674	569	81.3
2016	TN	1.75	2.14	1.44	1070.	649	395
2017	TN	1.57	2.00	1.29	1090	570	212
2018	TN	1.78	2.22	1.49	718	402	300
1989	TSS	11.0	15.3	8.85	962	457	443
1990	TSS	186	247	20.4	64200	62700	1170
1991	TSS	14.5	14.3	15.8	1210	587	580
1992	TSS	48.3	68.3	8.13	7470	7060	344
1993	TSS	559	13.4	651	212000	532	212000
1994	TSS	154	105	203	62200	11100	50500
1995	TSS	917	1280	132	727000	697000	29100
1996	TSS	299	418	174	182000	139000	41900
1997	TSS	501	754	77.8	268000	254000	13300
1998	TSS	194	225	193	70200	32400	37700
1999	TSS	99.6	153	24.4	30900	28200	2500
2000	TSS	172	54.8	254	50900	5590	45200
2010	TSS	286	110	362	242000	17800	223000
2011	TSS	628	957	167	593000	552000	31800
2012	TSS	495	352	614	382000	110000	272000
2013	TSS	540	872	120	337000	309000	27600
2014	TSS	820	663	1000	818000	301000	516000
2015	TSS	248	347	25.7	98900	96400	2300
2016	TSS	266	416	131	162000	126000	35800
2017	TSS	195	356	86.3	136000	101000	14200
2018	TSS	270	450	136	109000	81300	27400

Woody River

1989	TP	0.027	0.030	0.025	1.26	0.594	0.634
1990	TP	0.161	0.207	0.084	34.3	29.8	3.91
1991	TP	0.025	0.025	0.025	1.03	0.60	0.406
1992	TP	0.067	0.090	0.025	5.69	4.96	0.646
1993	TP	0.426	0.035	0.484	114	0.850	113
1994	TP	0.135	0.073	0.195	30.6	2.74	26.3
1995	TP	0.373	0.446	0.277	138	101	36.0
1996	TP	0.225	0.283	0.187	66.6	44.2	21.8
1997	TP	0.196	0.279	0.046	31.6	29.2	2.19
1998	TP	0.153	0.124	0.205	28.4	7.11	20.6
1999	TP	0.125	0.167	0.061	21.0	17.7	3.04
2000	TP	0.125	0.035	0.171	14.0	1.22	12.7
2010	TP	0.170	0.150	0.199	70.8	14.8	55.0
2011	TP	0.203	0.321	0.040	62.1	55.3	1.92
2012	TP	0.250	0.170	0.322	69.5	19.0	50.2
2013	TP	0.226	0.338	0.121	53.8	40.5	13.0

		FWMC (mg/L)			Loads (tonnes/y)		
Year	Variable	Annual	Spring	Summer/Fall	Annual	Spring	Summer/Fall
2014	TP	0.276	0.310	0.256	95.1	58.9	35.8
2015	TP	0.181	0.239	0.068	26.1	23.2	2.69
2016	TP	0.167	0.199	0.156	47.9	22.3	25.2
2017	TP	0.151	0.243	0.060	53.8	28.5	3.62
2018	TP	0.144	0.141	0.157	27.5	8.23	19.0
1989	PP	0.015	0.017	0.014	0.706	0.333	0.355
1990	PP	0.118	0.154	0.055	25.1	22.2	2.56
1991	PP	0.014	0.014	0.014	0.576	0.337	0.228
1992	PP	0.042	0.056	0.014	3.52	3.12	0.362
1993	PP	0.420	0.02	0.479	112.7	0.481	112.1
1994	PP	0.099	0.045	0.147	22.4	1.69	19.9
1995	PP	0.330	0.398	0.238	121	90.3	31.1
1996	PP	0.178	0.228	0.142	52.5	35.6	16.6
1997	PP	0.161	0.234	0.027	26.0	24.5	1.29
1998	PP	0.115	0.087	0.158	21.2	4.97	15.9
1999	PP	0.089	0.122	0.037	14.9	12.9	1.83
2000	PP	0.092	0.020	0.129	10.2	0.692	9.52
2010	PP	0.126	0.107	0.150	52.6	10.5	41.5
2011	PP	0.167	0.273	0.023	51.0	47.1	1.11
2012	PP	0.206	0.126	0.276	57.2	14.0	43.1
2013	PP	0.185	0.291	0.084	44.1	34.9	8.97
2014	PP	0.225	0.255	0.207	77.5	48.4	28.9
2015	PP	0.144	0.195	0.043	20.8	18.9	1.70
2016	PP	0.124	0.154	0.113	35.7	17.3	18.3
2017	PP	0.113	0.203	0.036	40.2	23.8	2.19
2018	PP	0.104	0.100	0.115	19.9	5.81	13.9
1989	TDP	0.012	0.012	0.011	0.539	0.245	0.279
1990	TDP	0.035	0.042	0.023	7.41	6.08	1.09
1991	TDP	0.011	0.011	0.011	0.45	0.265	0.18
1992	TDP	0.021	0.026	0.011	1.74	1.42	0.285
1993	TDP	0.056	0.014	0.063	15.2	0.330	14.7
1994	TDP	0.030	0.022	0.040	6.83	0.821	5.34
1995	TDP	0.057	0.065	0.045	20.9	14.8	5.91
1996	TDP	0.042	0.050	0.038	12.5	7.86	4.42
1997	TDP	0.037	0.048	0.016	5.90	5.04	0.768
1998	TDP	0.033	0.029	0.041	6.05	1.69	4.06
1999	TDP	0.029	0.036	0.019	4.93	3.84	0.967
2000	TDP	0.028	0.014	0.036	3.16	0.478	2.66
2010	TDP	0.036	0.034	0.040	15.0	3.38	11.2
2011	TDP	0.037	0.053	0.015	11.4	9.05	0.713
2012	TDP	0.044	0.036	0.052	12.3	4.07	8.10
2013	TDP	0.041	0.054	0.029	9.74	6.48	3.14

		FWMC (mg/L)			Loads (tonnes/y)		
Year	Variable	Annual	Spring	Summer/Fall	Annual	Spring	Summer/Fall
2014	TDP	0.048	0.053	0.046	16.6	10.0	6.43
2015	TDP	0.035	0.043	0.020	5.10	4.22	0.81
2016	TDP	0.035	0.039	0.034	10.1	4.42	5.52
2017	TDP	0.033	0.043	0.020	11.9	5.09	1.18
2018	TDP	0.032	0.032	0.034	6.17	1.89	4.14
1989	TN	0.621	0.636	0.610	28.9	12.7	15.5
1990	TN	1.26	1.46	0.945	268	211	44.2
1991	TN	0.610	0.610	0.610	25.1	14.7	9.91
1992	TN	0.847	0.971	0.610	71.5	53.8	15.8
1993	TN	1.89	0.665	2.07	508	16.1	485
1994	TN	1.14	0.887	1.42	259	33.1	191
1995	TN	1.91	2.15	1.61	705	488	210
1996	TN	1.49	1.71	1.36	439	267	159
1997	TN	1.32	1.65	0.727	213	173	35.0
1998	TN	1.22	1.11	1.45	225	63.8	145
1999	TN	1.10	1.30	0.811	185	137	40.6
2000	TN	1.08	0.662	1.30	121	23.4	96.0
2010	TN	1.30	1.25	1.43	542	123	394
2011	TN	1.34	1.79	0.693	409	309	33.7
2012	TN	1.55	1.28	1.80	431	144	281
2013	TN	1.45	1.85	1.09	346	222	117
2014	TN	1.66	1.78	1.61	573	339	225
2015	TN	1.29	1.52	0.848	186	148	33.8
2016	TN	1.28	1.40	1.25	368	157	202
2017	TN	1.20	1.51	0.804	426	177	48.3
2018	TN	1.19	1.21	1.25	229	70.2	151
1989	TSS	7.15	8.68	6.00	333	173	152
1990	TSS	114	152	45.78	24100	21800	2140
1991	TSS	6.00	6.00	6.00	247	144	97.4
1992	TSS	32.6	46.5	6.00	2750	2570	155
1993	TSS	516	11.7	590	139000	285	138000
1994	TSS	93.7	35.9	144	21200	1340	19400
1995	TSS	374	452	266	138000	103000	34600
1996	TSS	182	237	141	53700	37100	16500
1997	TSS	171	255	18.4	27600	26700	884
1998	TSS	112	80.7	158	20700	4630	15900
1999	TSS	81.7	116	27.6	13700	12200	1380
2000	TSS	87.0	11.4	126	9709.24	402	9290
2010	TSS	122	101	147	50900	9880	40800
2011	TSS	179	302	14.5	54900	52200	705
2012	TSS	221	122	305	61300	13600	47600
2013	TSS	199	325	76.9	47300	39000	8230

		FWMC (mg/L)			Loads (tonnes/y)		
Year	Variable	Annual	Spring	Summer/Fall	Annual	Spring	Summer/Fall
2014	TSS	238	274	216	82300	52000	30200
2015	TSS	148	206	33.8	21400	20000	1340
2016	TSS	121	155	107	34700	17400	17200
2017	TSS	112	221	27.4	40000	25900	1650
2018	TSS	98.3	94.4	110	18900	5500	13300