Qu'Appelle Nutrient Mass Balance

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Qu'Appelle Nutrient Mass Balance Report 2018-2020

Executive Summary

Nutrient levels in the Qu'Appelle River watershed are important for understanding and communicating about water quality in the watershed's lakes and rivers. To understand nutrient dynamics, it is necessary to have a detailed understanding of how they move through the watershed. This report summarizes data from a continuation of a previous study, the Qu'Appelle Mass Balance Study (QMBal) conducted from 2013 to 2015, which was designed to understand nutrient sources and their transport and fate in the watershed. The current three-year study (2018-2020) focused on the mid-Qu'Appelle River reach and its findings highlight the critical nature of hydrologic return period for understanding nutrient movement in the watershed. It reports on the significant reduction in nutrients in the treated wastewater effluent from the City of Regina due to treatment plant upgrades and how understanding hydrologic return period is necessary for interpreting downstream changes in nutrient levels.

The Qu'Appelle River begins at the Qu'Appelle River Dam on Lake Diefenbaker where water is transferred from Lake Diefenbaker into the Qu'Appelle River. The amount of water transferred depends on runoff volumes within the Qu'Appelle Watershed with consideration of downstream water demands. Water demands include the management of lake water levels to account for losses, principally due to evaporation, but also to supply industrial and municipal source water. The river can be divided into three sections; the Upper Qu'Appelle, which runs from Lake Diefenbaker to Buffalo Pound; the middle reach, which runs from the outlet of Buffalo Pound to the Calling Lakes (Pasqua, Echo, Mission, and Katepwa lakes); and the downstream reach, which runs from the outlet of Katepwa Lake to its confluence with the Assiniboine River just across the border with Manitoba. The focus of this study is the middle reach.

The middle reach contains the Qu'Appelle River's two largest tributaries, the Moose Jaw River and Wascana Creek, and Last Mountain Lake. Last Mountain Lake is located to the north of the Qu'Appelle River downstream of the City of Regina near the town of Craven. A small channel connects the river and lake. Last Mountain Lake is of particular importance for understanding the system's hydrology and water quality. Depending on the lake's water level, the flow level on the Qu'Appelle River, and management of the Craven water control structure the lake either flows into the river or the lake receives flows from the river. When water levels are high in Last Mountain Lake it can be the dominant source of water entering the Calling Lake during certain periods of the year. When Last Mountain Lake's water levels are low it can receive water from the Qu'Appelle and may not contribute any flows downstream for extended periods.

A central aim of this follow-up study was to quantify changes in nutrient loading following the upgrades to wastewater treatment in Regina, which fully came online in 2017. A major difference between the current study (2018-2020) and the previous QMBal study (2013-

2015) was that streamflows in the watershed were dramatically lower. This difference enabled a deeper understanding on the effect of streamflow on nutrients in the watershed.

Streamflows in the Qu'Appelle River were greater than the long-term 75th percentile in each year at most gauged sites from 2013-2015, but were near to the 25th percentile from 2018-2020. Streamflow volumes in the Qu'Appelle River above Pasqua Lake in 2018-2020 were only 10 % of the streamflow volumes from 2013-2015. Estimates of water retention times for the Calling Lakes chain based on 2013-2015 flows were 0.8 years, meaning it took less than 1 year to replace all the water in the four lakes. For 2018-2020, the retention time was 10.4 years, which means it would take around 10 years to replace all the water in the four lakes.

Outflows from Buffalo Pound Lake were a greater proportion of Qu'Appelle River flows in 2018-2020 than in 2013-2015 because flows from the Moose Jaw River were dramatically reduced. This has important implication to water quality since outflows from Buffalo Pound Reservoir generally have lower nutrients, dissolved organic carbon, and salts compared to flows from the Moose Jaw River. In the previous report (Water Security Agency 2018) it was noted that water quality on the Qu'Appelle River fundamentally changed after the confluence with the Moose Jaw River. With the low inflows from the Moose Jaw River in 2018-2020 this change was minor. More generally, with the exception of Buffalo Pound outflows, which were increased to compensate for lower water levels, total nutrient loads were lower at all sites between 2018-2020 as compared to 2013-2015. Total phosphorus concentrations declined at nearly every site in 2018-2020 compared to 2013-2015. These declines were particularly notable for total reactive phosphorus concentrations.

Outflows from Last Mountain Lake contributed an estimated 33 % of Qu'Appelle River flows at Craven in 2013-2015. However, in 2018-2020, Last Mountain Lake was a net recipient of flow from the Qu'Appelle River, with approximately 35 % of Qu'Appelle River flows above the Last Mountain Creek confluence being diverted into Last Mountain Lake rather than flowing downstream towards the Calling Lakes.

Total nitrogen loads from the Regina WWTP declined by 75 % from 2013-2015 to 2018-2020. This reduction was anticipated due to plant upgrades that included biological nutrient removal and stricter regulatory effluent requirements. As part of the upgrade process, the dominant inorganic N form released became nitrate rather than ammonia. The reduction in effluent nitrogen content resulted in lower TN loads and concentrations in Wascana Creek and in the Qu'Appelle River at Lumsden. However, despite the large reduction in N loads from the wastewater treatment plant and reductions in N loads entering Pasqua Lake, TN concentrations at the inflow to Pasqua Lake were nearly equal in 2013-2015 and 2018-2020. The similar TN concentration above Pasqua Lake is explained by the much greater dilution offered by greater streamflow in 2013-2015 compared to 2018-2020. This includes outflows from Last Mountain Lake from 2013-2015, notably during the winter period. This finding highlights the variable nature of nutrient loading in the watershed because of large changes in flows among years.

Total phosphorus loads from the Regina WWTP were reduced by 41 % in 2018-2020 compared to 2013-2015, however the reductions in TP loads throughout the watershed are greater than can be explained by the WWTP. The decrease in loads is also attributed to lower flow conditions.

An indicator that can be useful for understanding the relative role of nitrogen and phosphorus on the ecosystem is the ratio of TN to TP (TN:TP). Total nitrogen to total phosphorus ratios increased at most sites for the 2018-2020 study. Although ratios of dissolved nutrients need to be interpreted with extreme caution (Dodds 2003) they can be used to inform aspects of nutrient supply ratios. The increase in nutrient ratios of dissolved inorganic N and total reactive P was even greater than the increase in total N and P ratios. The lower concentrations of dissolved P are considered to be a result of reduced runoff. During periods of higher runoff, greater P exports and remobilization of P stored in the river channel are anticipated to raise P concentrations to levels more similar to those observed from 2013-2015.

Total nitrogen and total phosphorus were both retained in the Calling Lakes chain. This means that the load of nutrients entering the lakes from inflowing streams was greater than the load exiting the lakes through the outflow at Katepwa Lake. There was a large difference in the total mass of nutrients entering the Calling Lakes between 2013-2015 and 2018-2020 so the total mass retained differs. However, of more potential interest is how the percent of nutrient retention compares between the two time periods. So, while the total mass retained in the lakes during 2018-2020 was lower than in 2013-2015, it made up a larger percentage of the inflow during that period. A large part of the increase in percent nutrient retention was due to lower relative outflow volumes. Because flows were low from 2018-2020, evaporation from the lakes had a greater impact on outflows, resulting in less water leaving the lakes and a greater percentage of nutrients being retained. The longer hydraulic flushing rate may also provide increased opportunity for a higher proportion of inflowing nutrients to settle in the lakes. Phosphorus concentrations in the Katepwa Lake outflow declined roughly in proportion to the concentration declines at the inflow to Pasqua Lake. In contrast, nitrogen concentrations in the Katepwa Lake outflow increased slightly compared to 2013-2015. Nitrogen inflow concentrations stayed roughly the same between the two periods, so the slight increase is presumed to reflect a slight change of in-lake N cycling.

Overall, this study highlights the importance of variable runoff volumes and the resulting effect on the watershed's hydrology for controlling and understanding nutrient loading in the Qu'Appelle watershed. Reductions in the Regina WWTP effluent nutrient loading were large and loads of both nitrogen and phosphorus were reduced. Interestingly the concentration of total nitrogen at the Pasqua Lake inflow remained similar because under high flows the effluent was more diluted. Simply comparing before and after conditions in the inflow to Pasqua Lake didn't show obvious changes in N concentrations, even though we know a large reduction in N loading to the watershed occurred. This is an important consideration for any future nutrient management efforts. Given the significant load reduction of the Regina WWTP and generally low contributions of other point sources in the watershed, future management is unlikely to result in similar magnitude load reductions. Besides point source management there are ongoing efforts to understand and manage nutrients from non-point sources. Management of non-point sources remains a challenge because they are notoriously difficult to quantify, occur over broad spatial scales, and small improvements in places can be masked or offset by changes in other areas.

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Introduction

The Qu'Appelle River watershed in southern Saskatchewan is an important system economically, socially and environmentally. There is high value placed on the intrinsic value of the ecosystem, First Nations' traditional uses, and recreational opportunities. The watershed also serves as an important source for drinking water, industrial use, and irrigation. Several First Nations' territories are located within the river valley. The Qu'Appelle River is a highly managed system; natural flows are supplemented with water from the South Saskatchewan River system through the Qu'Appelle Dam on Lake Diefenbaker. Lake levels are regulated using water from Lake Diefenbaker in combination with control structures at Buffalo Pound, Craven, Echo, and Crooked lakes. There has been a long history of concern around water quality in the lakes, notably algal blooms on the Calling lakes, and understanding the role of human activities in changing blooms (Qu'Appelle Basin Study Board 1972). Because of the central role of nutrients when understanding algal blooms, the importance of the watershed, and the high degree of management, it is critical to understand the transport and fate of nutrients in the watershed and how management actions influence water quality.

Numerous studies have documented high nutrient concentrations, algal biomass, and frequent algal blooms in the Qu'Appelle Valley lakes (Dillenberg and Dehnel 1960; Atton and Johnson 1962; Hammer 1971; Cross 1978; Allan and Roy 1980). Early reports and paleolimnological studies demonstrate that the lakes are naturally eutrophic (Hind 1859; Gilchrist 1896; Warwick 1980; Hall et al. 1999), but studies have also found that human activities have altered algal species composition and increased biomass (Hall et al. 1999; Dixit et al. 2000; Leavitt et al. 2006). Production of toxins by blue-green algae have been a long-standing concern (Dillenberg and Dehnel 1960), but microcystin concentrations presently in the Qu'Appelle lakes appear to be similar or slightly lower than those in other lakes in Southern Saskatchewan (Hayes et al. 2020).

The Qu'Appelle River watershed receives wastewater effluent from the cities of Regina and Moose Jaw through Wascana Creek and the Moose Jaw River respectively. The importance of urban wastewater to nutrient loading in the Qu'Appelle watershed was recognized by the Qu'Appelle Basin Study Board in the 1970s (Qu'Appelle Basin Study Board 1972), leading to efforts to reduce phosphorus loading. Wastewater treatment processes were upgraded at the Regina WWTP in 1976 to remove P from effluent, and Moose Jaw began using effluent for irrigation in the early 1980s to reduce its effluent contribution to the river. Several studies have documented the high P concentrations in the Qu'Appelle River before, and improved P concentrations after the upgrades (Cross 1978; Tones 1981; Munro 1986a, b). While effluent P concentrations were improved, effluent N loads remained high, with ammonia concentrations often exceeding Canadian guidelines for the protection of aquatic life in Wascana Creek (Waiser et al. 2011). N from urban wastewater has been found to stimulate algal growth, particularly in Pasqua Lake (Leavitt et al. 2006).

In 2016 the Regina WWTP was upgraded to remove N, and convert its primary N form to nitrate rather than ammonia. Reductions in ammonia concentrations in Wascana Creek downstream of the WWTP have been noted (Dylla 2019), as have shifts in plankton species composition in the creek (Bergbusch et al. 2021a, b). Given the magnitude of the nutrient load reductions this presents an excellent opportunity to better understand how loading in the river has changed, which will ultimately inform lake response to nutrient management.

The Qu'Appelle watershed is in an area of relatively flat topography, with large portions of the watershed draining internally and not contributing to streamflow in most years (Pomeroy et al. 2005). Agriculture is the dominant land-use in the watershed, with extensive cultivation of cereals, pulses, oilseeds and use of land as pasture for cattle. Streamflow varies widely from year to year, with many of the minor tributaries in the watershed drying up in low-flow years. The variable streamflow regime of the watershed is expected to have several effects on nutrient transport. First, the proportion of the landscape that contributes flows to the river is highly variable among years. This is because of the flat terrain and prevalence of internal drainage to wetlands (Shaw et al. 2012). The amount of contributing drainage area will change depending on how full wetlands are, the soil moisture, and the speed with which runoff is generated. A wet year on a previously dry landscape can result in minimal flow whereas a year with average precipitation on a saturated landscape will result in higher flows. Second, transport of nutrients from a given area will be modified by flow volumes. During snowmelt, dissolved nutrients are typically the dominant form (Liu et al. 2013), and while total nutrient loads increase with runoff volume, volume-weighted mean nutrient concentrations in edge-of-field runoff may decline with greater runoff volume due to dilution (Liu et al. 2013; Wilson et al. 2019a). Rainfall runoff events may also generate significant nutrient runoff, including more particulate nutrients transported in flow, but may mobilize comparative less N than P compared to snowmelt runoff (Wilson et al. 2019b). Third, many in-stream and in-lake retention processes are dependent on water retention time. Longer retention times allow more time for these processes to occur, many of which depend on water interaction with stream and lake sediments (Saunders and Kalff 2001; Brett and Benjamin 2008; Withers and Jarvie 2008). Lower flows mean longer retention times, and in many situations lower nutrient concentrations due to settling and other loss processes. Fourth, nutrients sequestered in lower flow or dry years along stream channels can become re-mobilized during high flow periods, potentially seeming like new nutrient load despite having been added to the stream system in previous years (Jarvie et al. 2012).

Understanding flows, flow variability among years, and hydraulics of the Qu'Appelle River is fundamental to understanding sources, transport, and fate of nutrients. Flows in the Qu'Appelle River originate at the Qu'Appelle River Dam on Lake Diefenbaker where water is transferred from Lake Diefenbaker into the Qu'Appelle River. The amount of water transferred depends on runoff volumes within the Qu'Appelle Watershed with consideration of downstream water demands. Water demands include the management of lake water levels to account for losses, principally due to evaporation, but also to supply industrial and municipal source water. The river can be divided into three sections; the Upper Qu'Appelle, which runs from Lake Diefenbaker to Buffalo Pound; the mid-section, which runs from the outlet of Buffalo Pound to the Calling Lakes (Pasqua, Echo, Mission, and Katepwa lakes); and the downstream section, which runs from the outlet of Katepwa Lake to its confluence with the Assiniboine River just across the border with Manitoba. The focus of this three-year study (2018-2020) is the mid-reach section. The previous study (2013-2015) included the Upper Qu'Appelle reach, the middle Qu'Appelle reach, and the downstream reach to the outlet of Round Lake. A focus of this study was to quantify how the changes in nutrient loading from Regina affected concentrations and loads in the mid-reach section.

The mid-reach contains the river's three largest tributaries, the Moose Jaw River, Wascana Creek, and Last Mountain Creek. The Moose Jaw River and Wascana Creek subwatersheds are adjacent to each other and are comparable in drainage area. The Moose Jaw River flows through the city of Moose Jaw, and Wascana Creek flows through the city of Regina. Both streams receive urban stormwater runoff, and treated wastewater effluent. Both streams naturally experience periods of near zero flow during dry periods. However, streamflow in Wascana Creek is supplemented by continuous discharge of treated wastewater effluent from the City of Regina, and when natural flows are low, the majority of streamflow is treated wastewater effluent. The Moose Jaw River joins the Qu'Appelle River immediately downstream of Buffalo Pound Lake. During particularly high flows, the Moose Jaw River can cause water to flow backwards in the Qu'Appelle River, entering Buffalo Pound Lake from its downstream end. Backflow from the Moose Jaw River into Buffalo Pound Lake is a natural phenomenon that occurred prior to the construction of control structures at the outlet of Buffalo Pound Lake (Saskatchewan Water Resources Commission 1970). Wascana Creek is the next major tributary to enter the Qu'Appelle River, upstream of the town of Lumsden.

Last Mountain Lake is located to the north of the Qu'Appelle River downstream of the City of Regina near the town of Craven. A small channel connects the river and lake. Last Mountain Lake is of particular importance for understanding the system's hydrology and water quality. Depending on the lake's water level, the Qu'Appelle River water level, and management of the Craven water control structure the lake either has its outflow join the river or Last Mountain Lake receives flows from the river. When water levels are high in Last Mountain Lake it can be the dominant source of water entering the Calling Lakes during certain periods of the year. When Last Mountain Lake's water levels are low it can receive water from the Qu'Appelle resulting in it becoming a nutrient sink. During such periods it may not have outflow for extended periods.

To quantify nutrient loadings to the Qu'Appelle watershed, the Saskatchewan Water Security Agency (WSA) conducted a three year study on the Qu'Appelle River and its major tributaries from Lake Diefenbaker downstream to the outlet of Round Lake (Water Security Agency 2018). That study was conducted from March 2013 to February 2016, which was a period of notably high watershed flows. The study found that the Moose Jaw River and the Wascana Creek were the major tributary sources of nutrients to the Qu'Appelle River. The Moose Jaw River had sufficient flows during the previous study period that water quality in the Qu'Appelle River fundamentally changed downstream of the confluence of the two rivers. The Qu'Appelle River changed from water more reflective of Lake Diefenbaker to that more reflective of a prairie river, meaning it had greater concentrations of nutrients, salts, and suspended sediment. Other tributaries were individually minor contributors, although collectively they were similar in magnitude of nutrient loads to either the Moose Jaw River or Wascana Creek. Last Mountain Lake was a minor source of nutrients to the Qu'Appelle River because the direction of flow changed based on flows in the Qu'Appelle River. During very high river flows, the flow direction was from the Qu'Appelle River to

Last Mountain Lake, while during moderate and low flows, flow direction was from Last Mountain Lake to the Qu'Appelle River. Nutrient loading from the Regina WWTP, particularly N was an important part of the load to the Calling Lakes. Lakes in the watershed all retained N and P. Spring runoff was the most significant period of nutrient loading in the watershed, but summer rains, particularly a large event in 2014 were also important.

This present study follows on from the 2013-2016 study, but focuses on a smaller area of the watershed, from Buffalo Pound Lake downstream to the outlet of Katepwa Lake from March 2018 to February 2021. This region includes the confluences of the two major tributaries to the Qu'Appelle River, the Moose Jaw River and Wascana Creek. It includes the area immediately downstream of the two largest cities (Regina and Moose Jaw), the confluence with outflows from Last Mountain Lake, and includes the Calling Lakes chain (Pasqua, Echo, Mission, and Katepwa lakes), which are the first mainstem lakes downstream of the WWTP effluent from Regina and Moose Jaw. The principal goal of the study was to quantify changes to nutrient loading in the watershed resulting from the upgrade to Regina's WWTP. An unplanned opportunity for comparison arose because the streamflow regime in 2018-2020 was very dry in contrast to the very wet period in 2013-2015. This study therefore examines the large differences in nutrient loading in this reach of the Qu'Appelle River caused by the very different hydrology, in addition to the effects of the WWTP effluent load reduction.

Methods

Sampling Locations

Sampling sites were located in the middle reach of the Qu'Appelle watershed, from Buffalo Pound Lake outlet, to Katepwa Lake outlet (Figure **1**). These sites are a subset of those sampled in 2013-2015 (Water Security Agency 2018), with one additional site (South of Bethune), and one site removed (upstream of Last Mountain Creek confluence). As with the previous study, sites were chosen along the mainstem to provide representation along the length of the river and were targeted to be upstream and downstream of major features, especially lakes and confluences with major tributaries. Where possible, sampling sites were located near hydrometric gauging stations. Tributary sampling sites were located near to hydrometric gauging stations, or near to the confluence of the tributary with the Qu'Appelle River.

Sampling Methods

Discrete water grab samples were collected by lowering sample bottles from bridges into the centre of flow, or by using a reach pole sampler from shore to reach into the main flow of the stream. Water samples were analyzed by ALS Environmental, with samples typically delivered the same day or the day after samples were collected. Samples were analyzed for total phosphorus (TP), total reactive phosphorus (TRP), total nitrogen (TN), total Kjeldahl nitrogen (TKN), nitrate (NO3), nitrite (NO2), ammonia (NH3), dissolved organic carbon

(DOC), total dissolved solids (TDS) and total suspended solids (TSS). Note, in this report 'ammonia' and 'NH3' are both used to mean the total ammonia nitrogen concentration (ie. NH3 and NH4+) unless it is specifically stated as being unionized or ionized ammonia. Beginning in 2020, soluble reactive phosphorus (SRP), rather than TRP was measured. The difference between these two measurements is that SRP is first filtered through a 0.45 µm filter before reagents are added to the sample. Throughout this report TRP will be used to refer to both TRP and SRP measurements. Field measurements of temperature, dissolved oxygen, specific conductance and pH were taken with a YSI Pro-Plus multimeter and turbidity was measured with an Analite NEP 160 turbidity meter for 2013-2015, and primarily with a YSI EXO 1 sonde for 2018-2020.

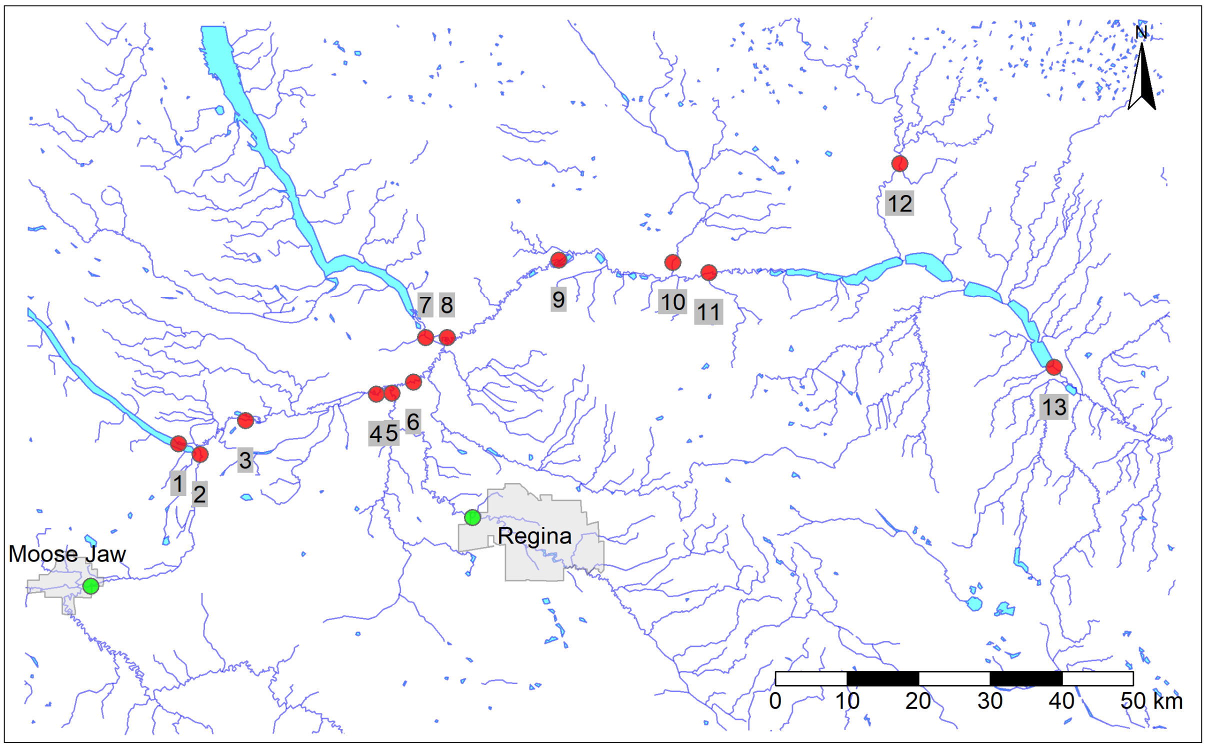


Figure 1: *Map of sampling sites. Sampling sites are represented by red dots. 1: Buffalo Pound Outlet, 2: Moose Jaw River, 3: Qu'Appelle River South of Bethune, 4: Qu'Appelle River above Wascana Creek, 5: Wascana Creek, 6: Qu'Appelle River at Lumsden, 7: Last Mountain Lake Outflow, 8: Qu'Appelle River below Craven Dam, 9: Qu'Appelle River at HWY 6, 10: Loon Creek, 11: Qu'Appelle River above Pasqua Lake, 12: Jumping Deer Creek, 13: Katepwa Lake Outlet. The administrative areas of Regina and Moose Jaw are indicated by grey shading, and the locations of their WWTP outlets by green circles.*

Hydrological Data for Gauged Sites

Daily mean flow data for gauged sites were obtained from the Water Survey of Canada (http://wateroffice.ec.gc.ca) using the R package tidyhydat (Albers 2017). For recent years not available through the Water Survey of Canada historical hydrometric data, data from the Water Security Agency's AQUARIUS database were used. Hydrologic summary statistics were calculated based on the available historic data. For sites currently operated continuously that had historic periods of seasonal operation, only the period of continuous operation was used. For sites with seasonal operation (March 1 – October 31 in most years), data were used beginning when regular seasonal operation of the station began. Total annual discharge was determined by computing daily discharge from the daily mean discharge data and summing the daily discharges. For sites operated seasonally, flow was assumed to be 0 outside of the period of operation.

Flow Determinations for Ungauged Sites

Estimates of flows for ungauged sites were calculated in the same manner as the 2013-2015 study for most sites. Details of those methods are given in Appendix A of that report (Water Security Agency 2018). The following text will just describe where methods differed from the previous report. Flows for the Qu'Appelle River South of Bethune (a new site for 2018-2020) were determined by adding the estimated flows from Buffalo Pound Lake and the Moose Jaw River at its confluence with the Qu'Appelle River. Katepwa Lake outflows were estimated using gauged downstream flows for the Qu'Appelle River at Hyde, and subtracting estimated contributions from the local watershed using the ratio of gauged to ungauged effective drainage area and gauged flows for Pheasant Creek. For the period outside of gauge operation for the Qu'Appelle River at Hyde, flows were determined from lake water levels and a rating curve for the control structure at Katepwa lake. Annual and study period flow values are given in units of hm^3, which equals 1000 dam^3 and 1 000 000 m^3

Nutrient Load Determination

Nutrient loadings were calculated for the period from March 1, 2013 to February 29, 2016 and March 1 2018 to February 28, 2021 using the midpoint method. For the 2013-2016 study several load calculation methods were compared. It was determined that the midpoint method provided the most consistent results. Annual loads are presented using the period of March 1 - February 28/29 as the year (i.e., 2013 refers to March 1 2013 to February 28 2014). Nutrient loading on days with measured nutrient concentrations were determined by multiplying concentrations by flow rates. For days between water sampling, concentrations were assumed to be equal to either the previous or subsequent sampled concentration, depending on which was closer in time. For days equally spaced between two sampling dates, the average concentration of the two sampling dates was used. For spring 2013, sampling began at the onset of spring runoff. For sites with flow between March 1 and the onset of runoff, nutrient concentrations were determined by taking an average of winter concentrations from the 2014 and 2015 study years. Loads for Regina and Moose Jaw WWTP effluents were calculated using mean monthly effluent nutrient concentrations and total discharge volumes submitted by the cities in reports to the Water Security Agency. Volume-weighted nutrient concentrations were determined by dividing total loads by total water discharged.

Results and Discussion

The main findings of this study are presented in figures within the main body of the report. Additional details, including tables of nutrient loads and volume-weighted nutrient concentrations, and figures of flow and nutrients concentrations at individual sites are provided in Appendix A.

General Watershed Overview

The two three-year periods compared in this study (2013-2015 vs. 2018-2020) provide a major contrast in watershed conditions. The 2013-2015 period had well above average streamflow, while 2018-2020 had well below average streamflow. This change in flow regime had major implications for nutrient dynamics in the river, and retention in the Calling Lakes. In addition to these natural changes in the watershed, the Regina wastewater treatment plant was upgraded in 2016, greatly reducing nitrogen loading. Together these changes provide opportunity for new insights into the functioning of the watershed that were not apparent in the 2013-2015 study.

Flow

Flow volumes in the Qu'Appelle River watershed differed greatly for the years 2013-2015 and 2018-2020 (Figures **2** and **3**). For most sites, flows in 2013-2015 were greater than the long-term 75th percentile, while for 2018-2020 they were near the 25th percentile. Graphs of daily flows over the study period, and long-term annual flows are presented in Appendix A, (Figures **19** - **26**). In terms of a direct comparison of flows between study periods, the mean annual flows for 2018-2020 above Pasqua Lake were 10 % of mean annual flows for 2013-2015.

Comparing the relative proportions of inflows to the Qu'Appelle River between the two study periods, the contribution of outflows from Buffalo Pound were much greater in 2018-2020 and those of the minor tributaries smaller than they were in 2013-2015 (Figure **4**). The relative contribution of Regina's WWTP effluent to total flows was also much greater in 2018-2020, because of the low natural flows in the watershed. Outflows from Buffalo Pound Lake and WWTP effluent can be considered largely as supplemental flows to the Qu'Appelle River watershed. Inflows to Buffalo Pound Lake during dry periods are largely derived from Lake Diefenbaker, which is part of the South Saskatchewan River watershed. Regina and Moose Jaw draw their drinking water from Buffalo Pound Lake, so the volume associated with their waste-water effluent can also be considered to largely originate from the South Saskatchewan River watershed. These "supplements" to the natural flow of the Qu'Appelle River were greater than the combined flows of all of the studied tributaries in 2018-2020, but in 2013-2015 were less than flows from any of the Moose Jaw River, Wascana Creek, or Last Mountain Lake outflow. These comparisons highlight the difference in flow sources between wet and dry periods in the Qu'Appelle watershed as it is currently managed. During wet periods, much of the flow is from the local watershed via the main tributaries to the river. During dry periods, much of the flow derives ultimately from the South Saskatchewan River watershed via releases from the Qu'Appelle Dam on Lake

Diefenbaker, passing through Buffalo Pound Lake to the downstream portion of the Qu'Appelle watershed.

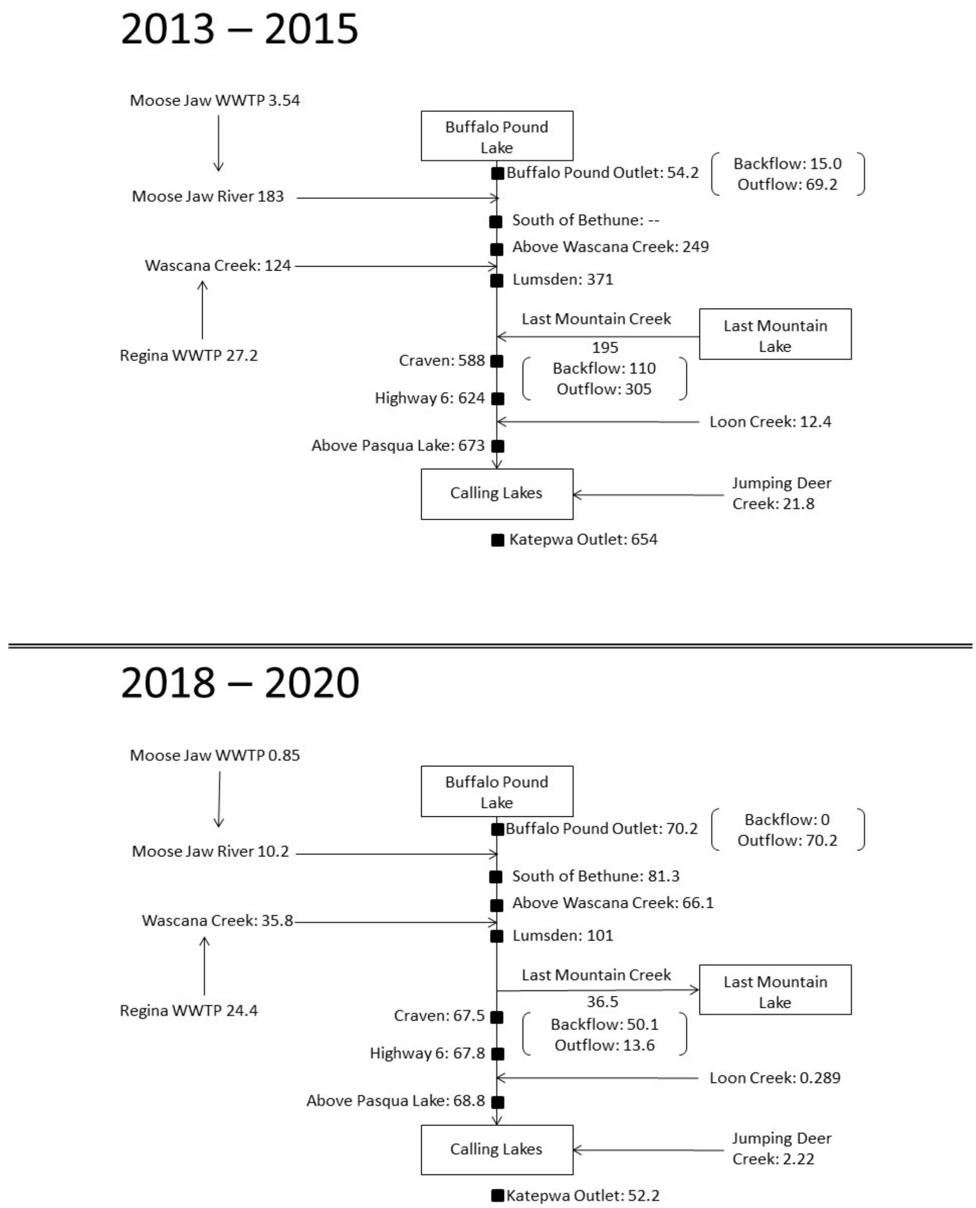


Figure 2: *Diagram of mean annual flows in hm3 for the Qu'Appelle River and tributaries over the 2013-2015 and 2018-2020 study periods. Contributions from the Regina and Moose Jaw wastewater treatment plants (WWTP) are also included. Note that flows occur both to and from Buffalo Pound (2013-2015) and Last Mountain Lake.*

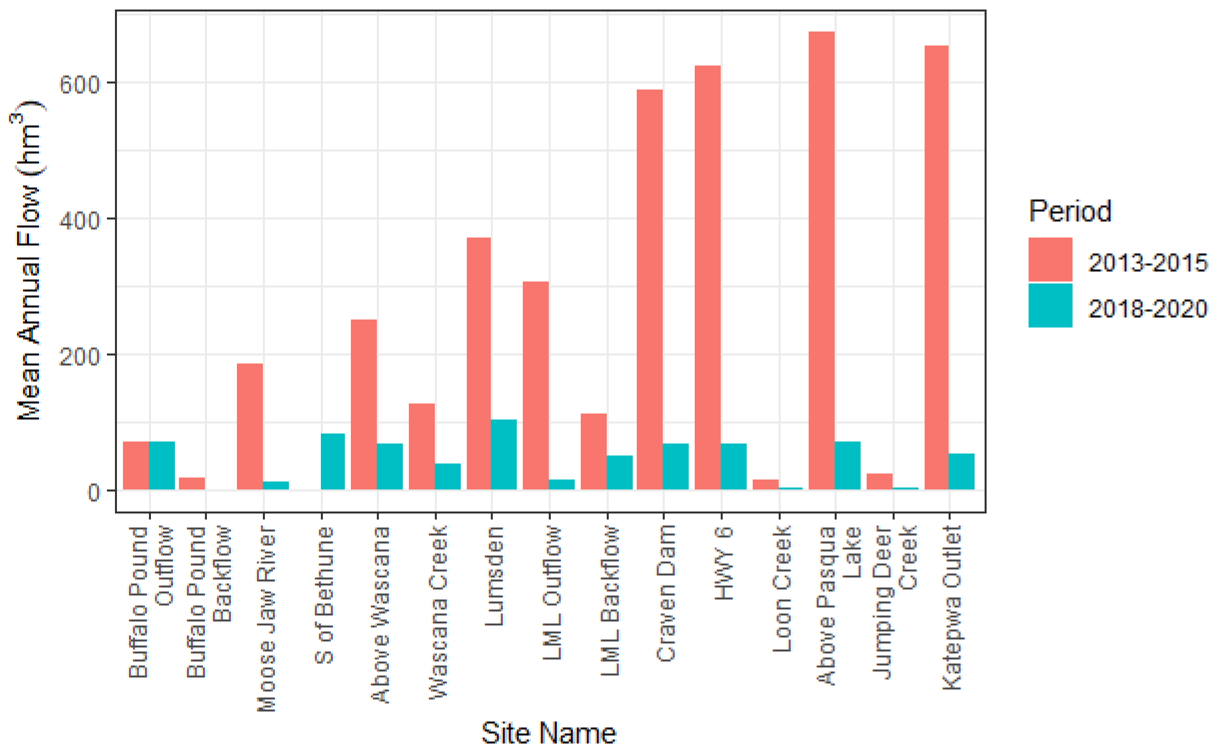


Figure 3: *Mean annual flows for all sites split by study period. Buffalo Pound Outlet and Last Mountain Creek are split into outflow and backflow periods, as flow can occur in two directions at these sites. The Qu'Appelle River S of Bethune site was not sampled in 2013-2015; the lack of bars there does not indicate no flow.*

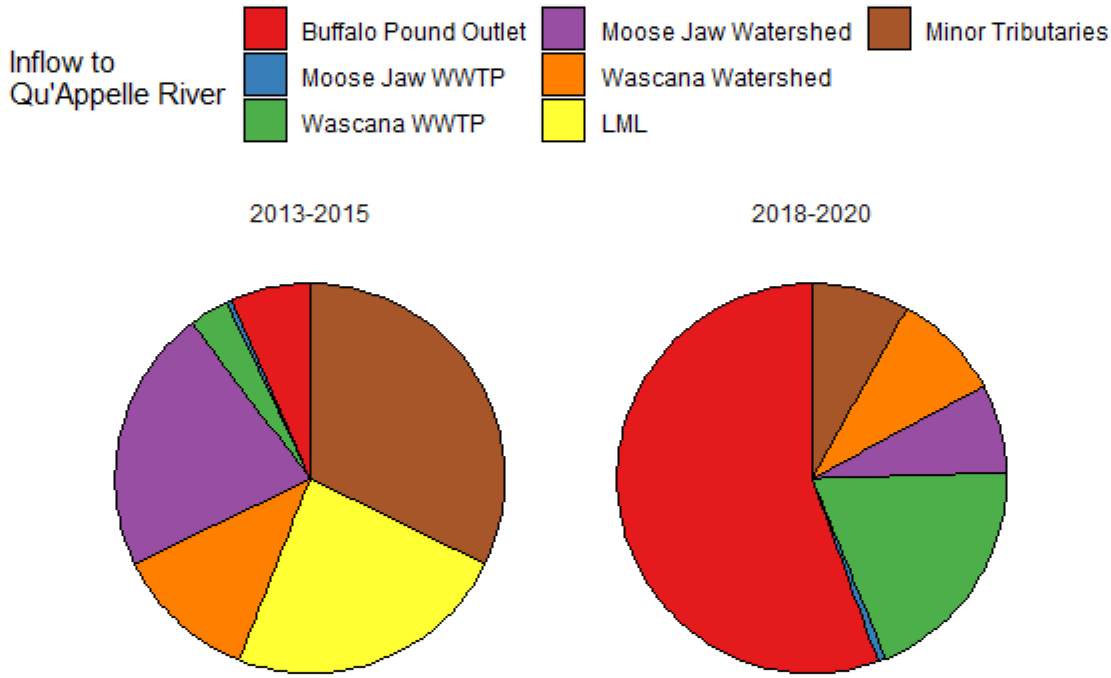


Figure 4: *Proportions of inflows to the Qu'Appelle River. Areas of the circles represent the proportion of flows over the two study periods contributed by each source. For this comparison, Buffalo Pound was considered as a source to the Qu'Appelle River, since we are primarily considering areas downstream of that lake. Tributaries outside of the 2018-2020 study area, that were part of the 2013-2015 study were included to better compare differences in flow proportions for smaller tributaries. The tributaries grouped together as Minor Tributaries are: Ridge Creek, Iskwao Creek, Loon Creek, Jumping Deer Creek, Indian Head Creek, Red Fox Creek, Pheasant Creek, Pearl Creek, and Ekapo Creek. Flows from Buffalo Pound and Last Mountain lakes are net flows (i.e. backflows were subtracted from outflows). For 2018-2020, there was net flow from the Qu'Appelle River into Last Mountain Lake, but LML is simply represented as 0 contribution for 2018-2020. Moose Jaw River and Wascana Creek flows have been separated into proportions contributed by WWTP effluent and those from the watershed (i.e., total streamflow minus WWTP effluent volume).*

Stream Chemistry

Suspended sediment, total dissolved solids, dissolved organic carbon, and nutrient concentrations differed between the 2013-2015 and 2018-2020 study periods. These differences tended to be consistent with the expectation that higher streamflows will lead to higher concentrations of both particulate and dissolved constituents. Volume-weighted TSS concentrations were higher at every site in 2013-2015 than in 2018-2020 (excluding the outflow from Last Mountain Lake) (Figure **5**). The differences between periods tended to be greater at tributary sites (e.g. Moose Jaw River, Wascana Creek) and lesser at lake outlet sites (Buffalo Pound, Katepwa). This pattern is expected because the higher flow velocities in the tributaries are able to carry a greater sediment load while lakes act as large settling basins and their outflows generally carry a low sediment load.

Figure 5: *Volume-weighted total suspended solids concentrations for all sites split by study period. Buffalo Pound Outlet and Last Mountain Creek are split into outflow and backflow periods, as flow can occur in two directions at these sites.*

Total dissolved solids concentrations varied by site and period in ways consistent with the major flow sources and processes affecting TDS concentrations (Figure **6**). TDS concentrations were low at the outflow of Buffalo Pound Lake, reflecting the large percentage of water ultimately derived from the South Saskatchewan River through Lake Diefenbaker, which has lower TDS concentrations than are typical in the Qu'Appelle River watershed. Tributary sites generally had higher TDS concentrations in 2018-2020 compared to 2013-2015. Periods of freshwater input (rainfall, snow melt) generally reduce TDS concentrations in streamflow in the Qu'Appelle watershed. During low flow periods, TDS concentrations tend to be higher, likely because water has had greater time to interact with soils, may have greater connectivity to groundwater, and may also have experienced concentration of dissolved solids through evaporation. It makes sense, therefore, for 2013-2015 to have lower volume-weighted TDS concentrations in general because a greater proportion of annual flows occurred in connection with snow melt and large precipitation events. Sites downstream along the Qu'Appelle River show patterns consistent with flow volumes from various sources. Water volume releases from Buffalo Pound Lake were greater in 2018-2020, leading to lower TDS concentrations downstream (e.g. above the Wascana Creek confluence). Last Mountain Lake was a greater contributor to watershed flows in 2013-2015, and it tends to have relatively high TDS concentrations. Qu'Appelle

River sites downstream of Last Mountain Lake and upstream of Pasqua Lake had higher TDS concentrations in 2013-2015 than 2018-2020 consistent with proportionally less flow from Buffalo Pound Lake, and more flow from Last Mountain Lake in 2013-2015. While tributary flows in 2018-2020 had higher TDS, these flows were comparatively small in terms of volume.

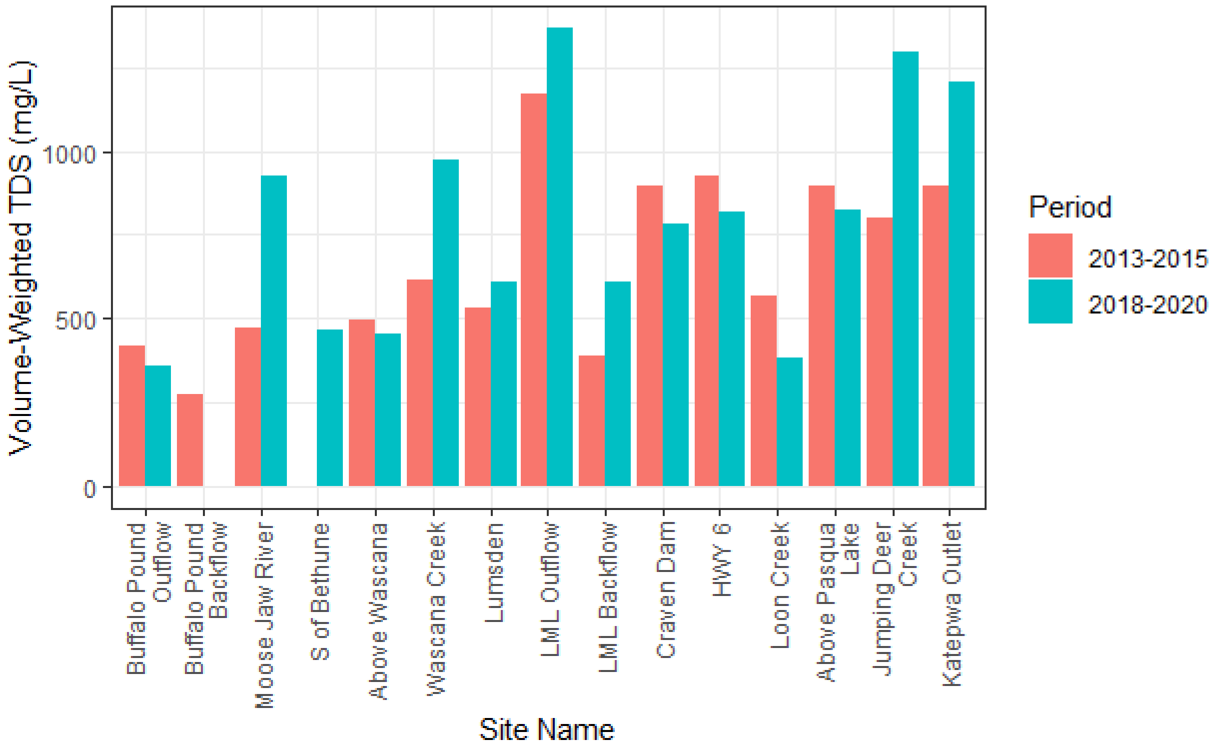


Figure 6: *Volume-weighted total dissolved solids concentrations for all sites split by study period. Buffalo Pound Outlet and Last Mountain Creek are split into outflow and backflow periods, as flow can occur in two directions at these sites.*

Volume-weighted total phosphorus concentrations were lower in 2018-2020 than 2013-2015 at most sites (Figure **7**). The differences are generally consistent with the expectation of higher P concentrations in the river with higher flows. Loon Creek and Jumping Deer Creek were exceptions to this pattern, with higher TP concentrations in 2018-2020. Inflowing and outflowing TP concentrations to the Calling Lakes were both lower in 2018-2020 than 2013-2015, and TP concentrations were lower in the outflow than in the inflow for both periods. Total reactive phosphorus concentrations were also generally lower in 2018-2020 than 2013-2015 (Figure **8**), and were often a smaller proportion of total phosphorus (Figure **64** or compare Figures **7** and **8**).

Figure 7: *Volume-weighted total phosphorus concentrations for all sites split by study period. Buffalo Pound Outlet and Last Mountain Creek are split into outflow and backflow periods, as flow can occur in two directions at these sites.*

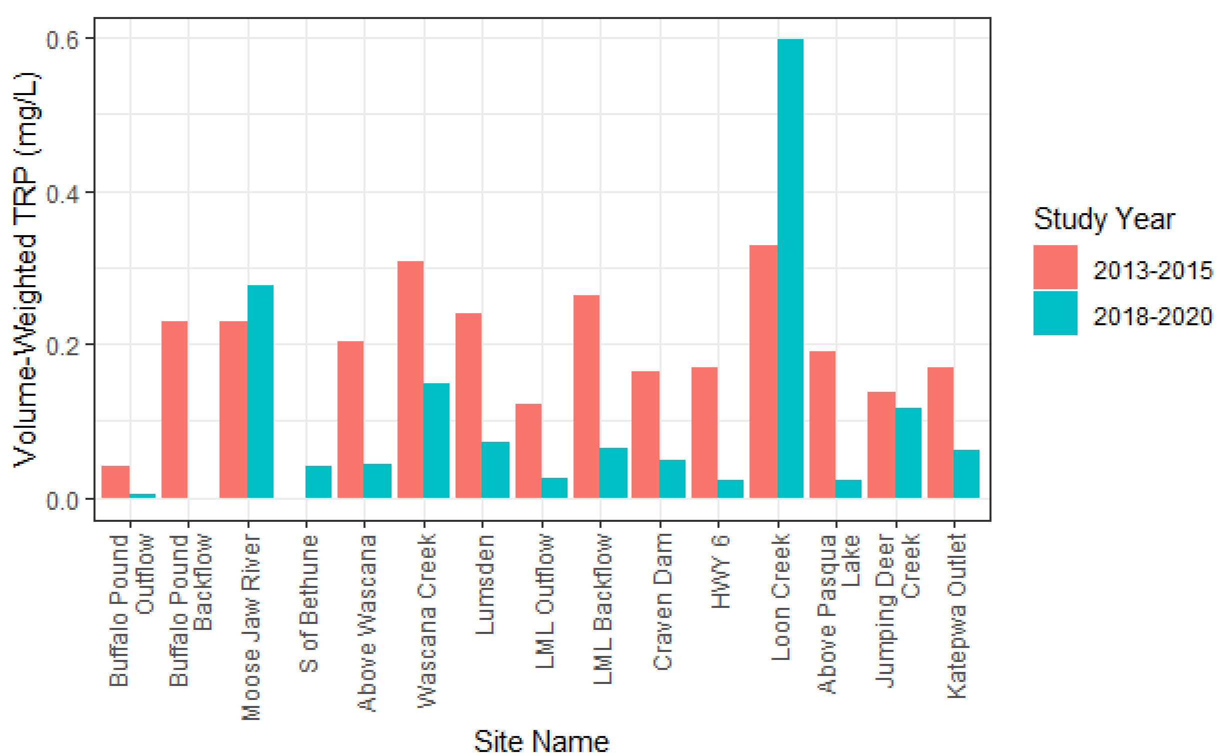


Figure 8: *Volume-weighted total reactive phosphorus concentrations for all sites split by study period. Buffalo Pound Outlet and Last Mountain Creek are split into outflow and backflow periods, as flow can occur in two directions at these sites.*

Total nitrogen concentrations were often lower in 2018-2020 than 2013-2015 (Figure **9**), but this was not as consistent across sites as it was for TP. Volume-weighted TN concentrations were lower during 2018-2020 than 2013-2015 for the sites upstream of the Wascana Creek confluence. Measurements at the Wascana Creek and Lumsden sites had decreases in TN concentrations that were greater and consistent with lower wastewater effluent TN concentrations from Regina. Further downstream, the difference in TN concentrations between 2013-2015 and 2018-2020 was reduced, and TN concentrations were similar between the two periods at Craven to downstream above Pasqua Lake. Ammonia concentrations in particular were lower in 2018-2020 beginning in Wascana Creek, and extending downstream to the inflow to Pasqua Lake (Figure **10**), consistent with the upgrades to Regina's wastewater treatment plant. Nitrate concentrations were similar between the two periods in Wascana Creek, but were higher in 2018-2020 than 2013-2015 upstream of Pasqua Lake (Figure **11**).

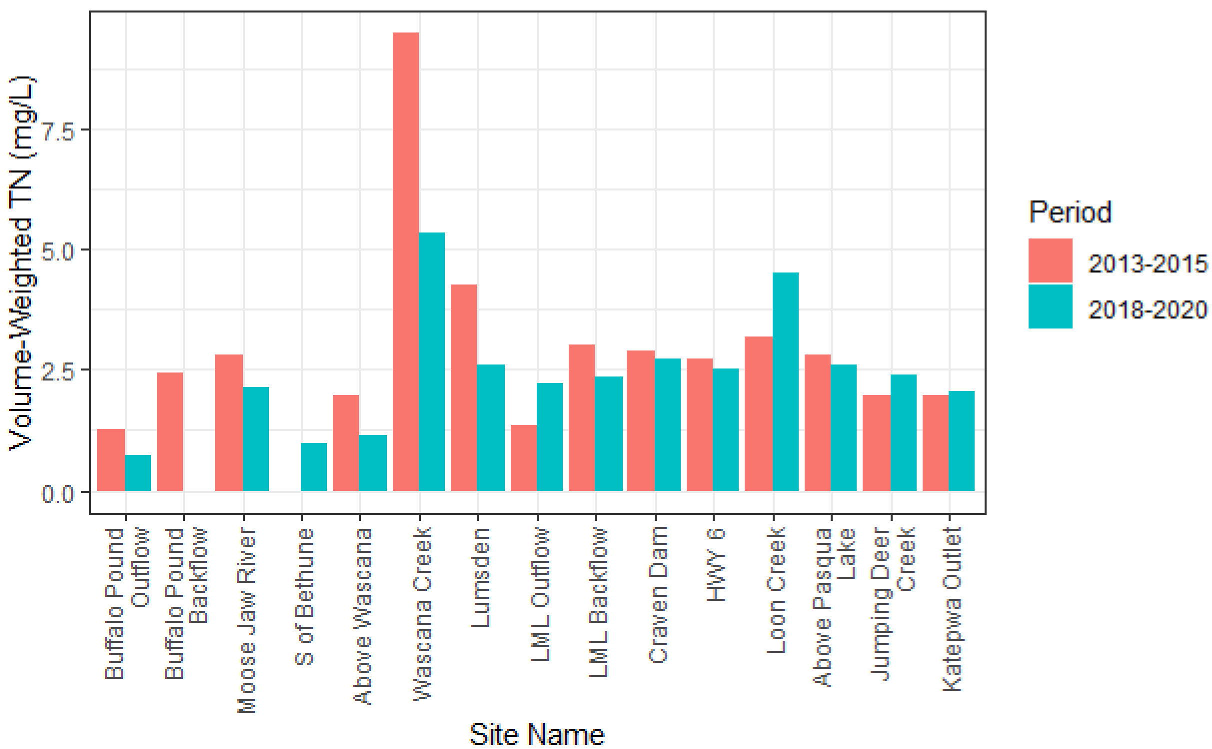


Figure 9: *Volume-weighted total nitrogen concentrations for all sites split by study period. Buffalo Pound Outlet and Last Mountain Creek are split into outflow and backflow periods, as flow can occur in two directions at these sites.*

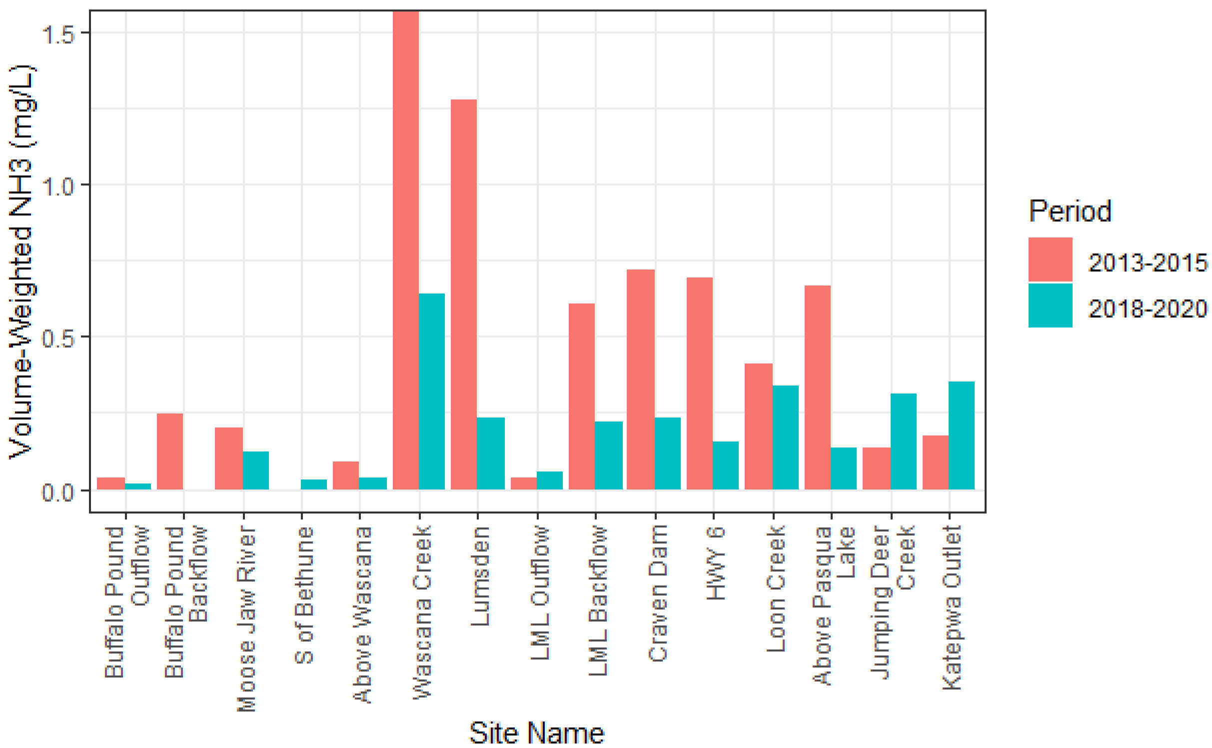


Figure 10: *Volume-weighted ammonia-N concentrations for all sites split by study period. Buffalo Pound Outlet and Last Mountain Creek are split into outflow and backflow periods, as flow can occur in two directions at these sites. Note that the bar for Wascana Creek is cut off and would extend to 4.3 mg/L*

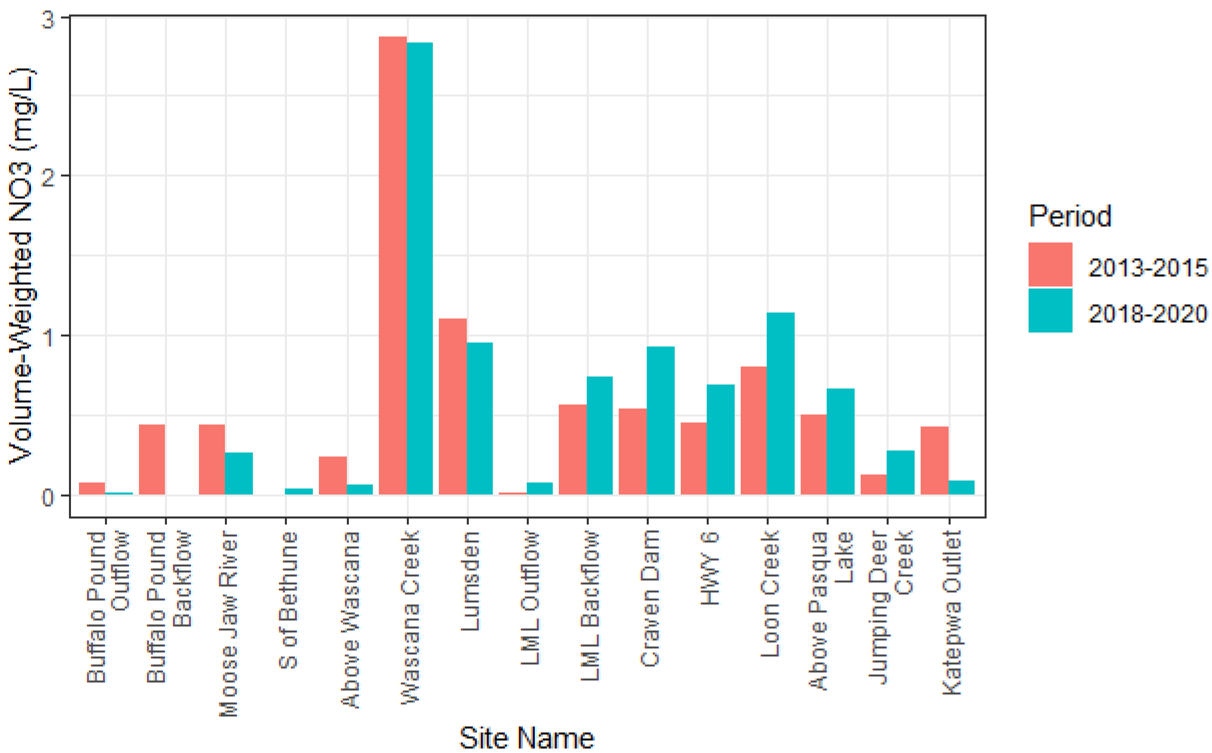


Figure 11: *Volume-weighted nitrate-N concentrations for all sites split by study period. Buffalo Pound Outlet and Last Mountain Creek are split into outflow and backflow periods, as flow can occur in two directions at these sites.*

Dissolved organic carbon concentrations were lower in 2018-2020 than in 2013-2015 at most sites (Figure **12**). DOC concentrations increased with distance along the Qu'Appelle River from Buffalo Pound Outlet to the inflow to Pasqua Lake for 2018-2020. During 2013-2015, DOC at Buffalo Pound Outlet was lower than at other sites, but downstream sites had similar concentrations to each other. During both study periods, Loon and Jumping Deer creeks had higher DOC concentrations than other sites.

Figure 12: *Volume-weighted total dissolved solids concentrations for all sites split by study period. Buffalo Pound Outlet and Last Mountain Creek are split into outflow and backflow periods, as flow can occur in two directions at these sites.*

Loading

Total nutrient loads were lower at all sites in 2018-2020 than in 2013-2015, consistent with the very large difference in flows between the two periods (Figures **13**, **14**, **15**, and **16**). Differences in total load among sites and between the two study periods were similar for TP and TN, and were driven largely by patterns in flow. A notable difference between the two study periods was the role of Last Mountain Lake in the watershed. In both periods flow occurred in both directions at Last Mountain Creek, but in 2013-2015 Last Mountain Lake was a net contributor of nutrients to the Qu'Appelle River. In 2018-2020 Last Mountain Lake acted as a net sink of nutrients. The Calling Lakes retained nutrients (inflow loads were greater than outflow loads) during both study periods.

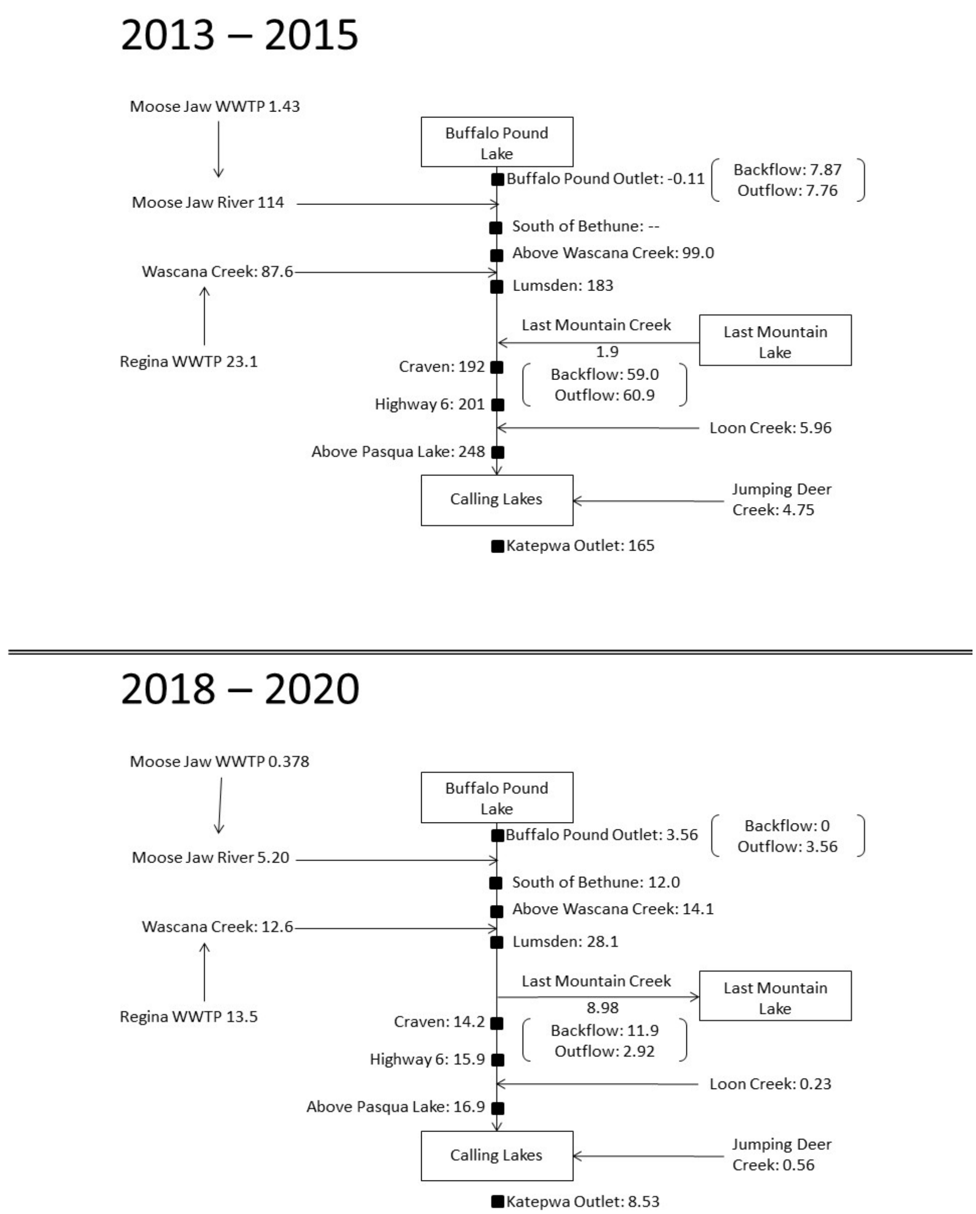
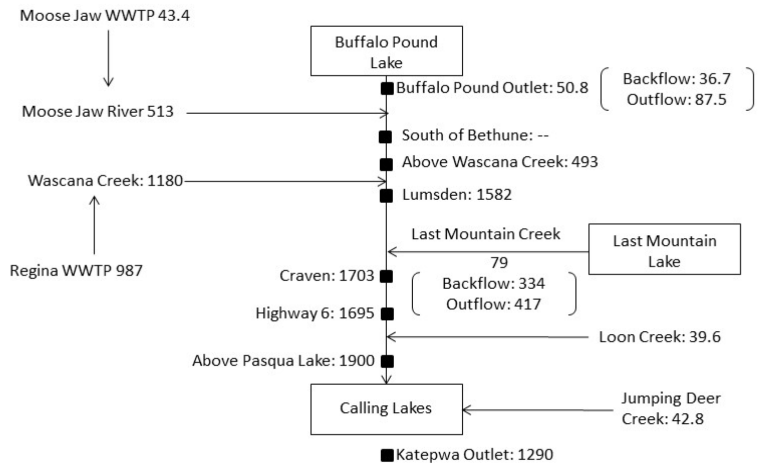


Figure 13: *Diagram of mean annual total phosphorus loads in tonnes for the Qu'Appelle River and tributaries over the 2013-2015 and 2018-2020 study periods. Contributions from the Regina and Moose Jaw wastewater treatment plants (WWTP) are also included. Note that loads occur both to and from Buffalo Pound (2013-2015) and Last Mountain Lake.*

Figure 14: *Mean annual total phosphorus loads for all sites split by study period. Buffalo Pound Outlet and Last Mountain Creek are split into outflow and backflow periods, as flow can occur in two directions at these sites.*

2013 – 2015



2018 – 2020

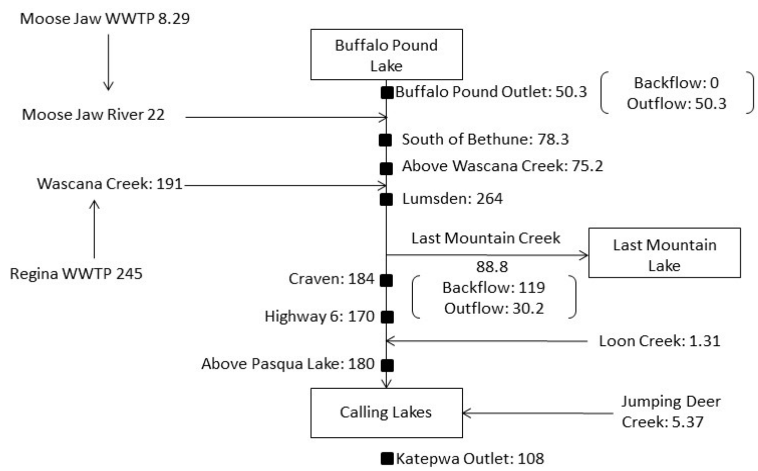


Figure 15: *Diagram of mean annual total nitrogen loads in tonnes for the Qu'Appelle River and tributaries over the 2013-2015 and 2018-2020 study periods. Contributions from the Regina and Moose Jaw wastewater treatment plants (WWTP) are also included. Note that loads occur both to and from Buffalo Pound (2013-2015) and Last Mountain Lake.*

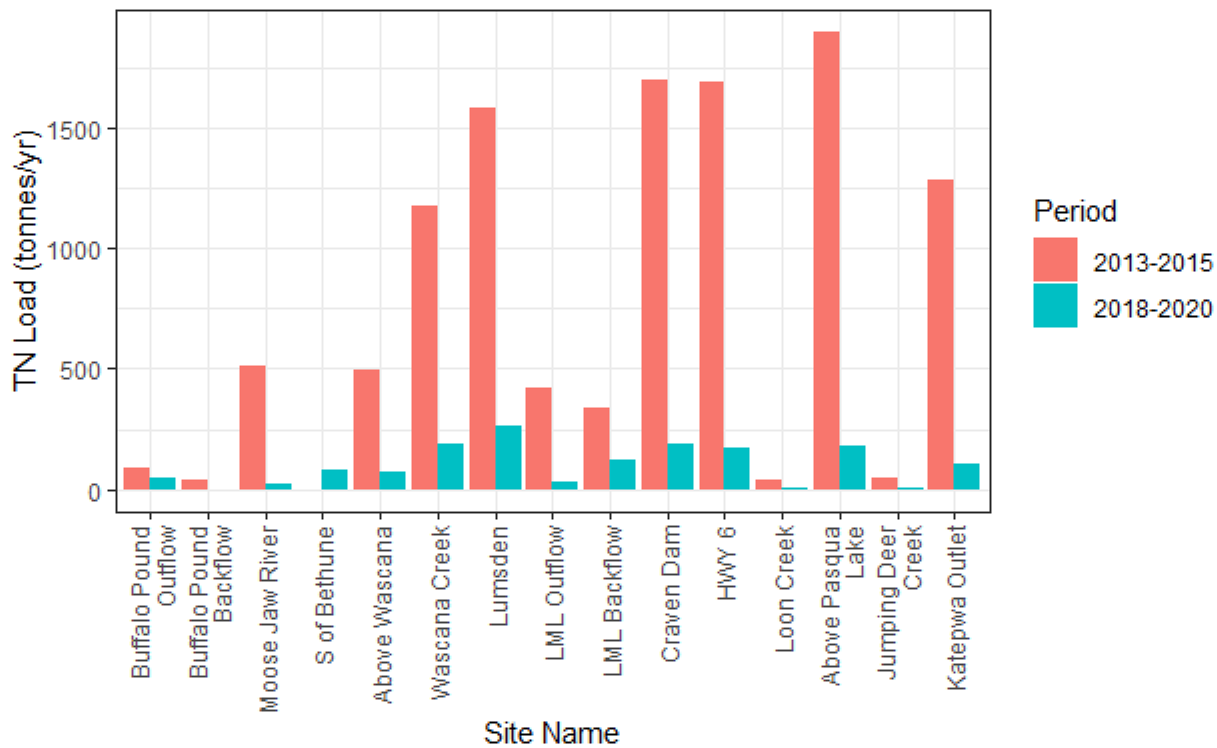


Figure 16: *Mean annual total nitrogen loads for all sites split by study period. Buffalo Pound Outlet and Last Mountain Creek are split into outflow and backflow periods, as flow can occur in two directions at these sites.*

Wastewater Treatment Plants

Total nutrient loads for Regina and Moose Jaw wastewater treatment plants (WWTPs) were lower in 2018-2020 than 2013-2015 (Figure **17**, Table **8**), with the TN load reduction from Regina being particularly notable. Effluent volumes discharged to the watershed were slightly lower for Regina 2018-2020 compared to 2013-2015. Moose Jaw had a larger reduction in effluent discharge volumes (Figure **68**) due to greater use of effluent irrigation and the availability of effluent storage capacity in their lagoons. Effluent for both Regina and Moose Jaw represented a larger proportion of streamflow in 2018-2020 compared to 2013-2015 (Figure **69**). As a proportion of stream load (Wascana Creek for Regina, Moose Jaw River for Moose Jaw), wastewater TP and TN loads were greater in 2018-2020 for both Regina and Moose Jaw WWTPs (Figure **18**). Effluent TP loads from Regina in 2018 and 2019, and TN loads in 2018, 2019, and 2020 exceeded loads measured in Wascana Creek downstream near the confluence with the Qu'Appelle River.

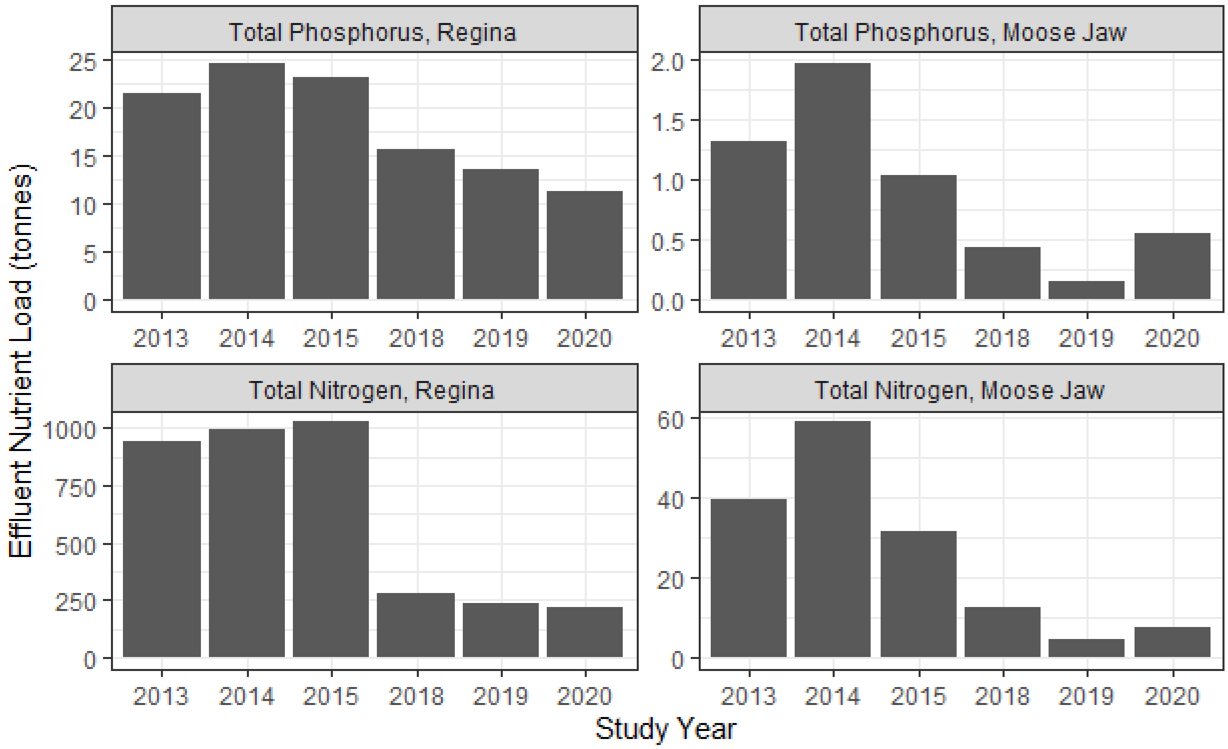


Figure 17: *Effluent nutrient loading loading for Regina and Moose Jaw wastewater treatment plants.*

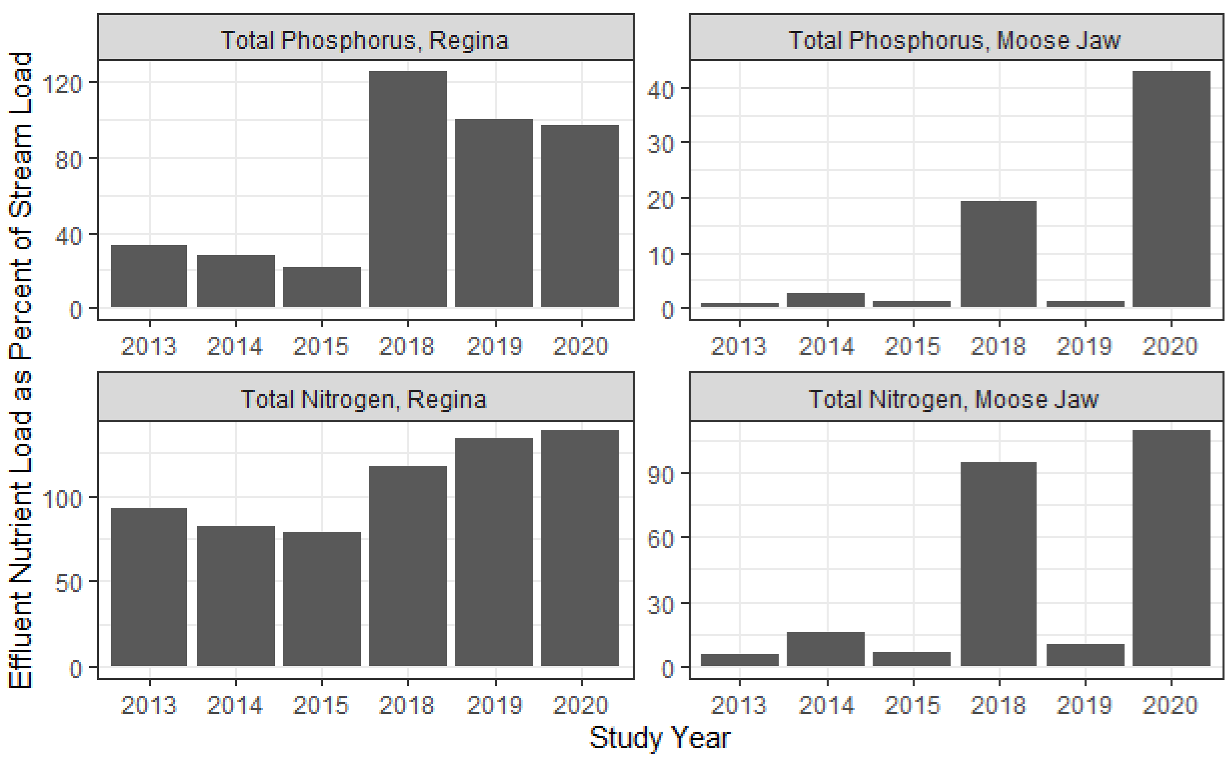


Figure 18: *Effluent nutrient loading as a percentage of stream nutrient load for Regina (Wascana Creek), and Moose Jaw (Moose Jaw River). Stream load was measured near the confluences with the Qu'Appelle River, some distance downstream of the wastewater treatment plant outflows.*

Regional Results/Discussion

Buffalo Pound Outlet, Moose Jaw River, and Wascana Creek

The sampling sites from Buffalo Pound Outlet to Wascana Creek all had lower flow (Figure **3**), total phosphorus (Figure **7**) and nitrogen concentrations (Figure **9**), and loads (Figures **14** and **16**) in 2018-2020 compared to 2013-2015, with the exception of Buffalo Pound Outlet. Buffalo Pound Lake received considerable backflow from the Qu'Appelle River (due to high flows from the Moose Jaw River) in spring 2013 and 2015. The backflows were sufficiently large that Buffalo Pound Lake was a net sink of TP from the downstream Qu'Appelle River over the 2013-2015 period. However, outflows from Buffalo Pound from 2013-2015 exceeded backflows for water volume and TN load. This situation of large backflows is atypical, and did not occur from 2018-2020. Ignoring the backflow periods from 2013-2015, the outflow volume from Buffalo Pound Lake was slightly greater in 2018-2020 as compared to 2013-2015.

Buffalo Pound Lake is an important intermediary in the conveyance of water from Lake Diefenbaker through the Qu'Appelle watershed. In years with low watershed runoff, more water is released from Lake Diefenbaker through the Qu'Appelle Dam. It then passes through the upstream reaches of the Qu'Appelle River, Buffalo Pound Lake, and a portion is released downstream to supplement flows in the watershed. The patterns in flows and nutrients in the region downstream of Buffalo Pound Lake from 2018 to 2020 are consistent with expectations given this management regime and several successive years with low watershed runoff.

Nutrient concentrations in the outflow of Buffalo Pound Lake were lower in 2018-2020, with TP less than half of 2013-2015 concentrations, and TN slightly greater than half of 2013-2015 concentrations. These declines reflect changes in lake nutrient concentrations, and a gradual shift in lake water chemistry to more closely resemble Lake Diefenbaker water chemistry, rather than local watershed runoff chemistry. Prior to and during the 2013-2015 study a larger proportion of inflows to Buffalo Pound were from its local watershed, including backflows from the Moose Jaw River. The water chemistry in Buffalo Pound Lake reflected that of runoff from its watershed, including water with higher salinity, nutrients, and dissolved organic carbon. After the 2013-2015 study period, the local watershed contributed a small proportion of the inflows to Buffalo Pound. Instead, flows were primarily from Lake Diefenbaker and the lake water chemistry changed, including a significant reduction in nutrient concentrations. Downstream of Buffalo Pound, nutrient loads and concentrations in the Qu'Appelle River begin to increase, both as new sources of water enter the river, but also because of increased flow velocities picking up suspended sediment and nutrients from the streambed.

The Moose Jaw River and Wascana Creek are the two most important tributaries of the Qu'Appelle River in terms of flow and nutrient loading. For the 2013-2015 period, their flows accounted for 83 % of the Qu'Appelle River flow at Lumsden, while from 2018-2020 they accounted for 45 % of flows. The proportion each stream contributed also changed between these two periods. During 2013-2015 the Moose Jaw River and Wascana Creek, respectively, accounted for 49 % and 33 % of flows on the Qu'Appelle River at Lumsden. These changed to 10 % and 35 %, respectively, of the flows from 2018-2020. These proportions show that between the two study periods, Wascana Creek represented a similar proportion of the total flow at Lumsden, while the Moose Jaw River made a much smaller contribution in 2018-2020. Wascana Creek continued to account for roughly one third of the flow at Lumsden because of the volume of WWTP effluent, which was a proportionally greater contribution to flow during the low-flow conditions of 2018-2020 (Figure **4**). The remainder of flows in the Qu'Appelle River at Lumsden are derived largely from releases from Buffalo Pound Lake, which, during the 2018-2020 study represented close to half the flows at Lumsden but from 2013-2015 were less than 20% of the total flows. This pattern fits with the expectation of flows from Buffalo Pound Lake being proportionally greater in dry periods compared to wet periods.

The influence of the Moose Jaw River on nutrients, TDS and DOC in the Qu'Appelle River declined dramatically in 2018-2020 compared to 2013-2015. In 2013-2015, the Moose Jaw River was the largest tributary source of TP loading to the Qu'Appelle River, and the second largest source of TN loading (behind Wascana Creek). For 2018-2020, the Moose Jaw River had lower TP loading than Wascana Creek, and lower TN loading than both Wascana Creek and the outflow from Buffalo Pound Lake. This decline in nutrient loading was mainly due to the decrease in flow volume from the Moose Jaw River between the two periods (Figure **3**, although volume-weighted nutrient concentrations did decline slightly for both TP and TN (Figures **7** and **9**).

Our TP loading rates for the Moose Jaw River 2018-2020 were lower than for any year estimated by Cross (1978). Munro (1986a) estimated Moose Jaw sewage effluent TP loads of 32 to 40 tonnes per year. These estimates greatly exceed the current effluent P loading (1.4 and 0.4 t/yr for 2013-2015 and 2018-2020 Table **8**), and the total annual Moose Jaw River P load for 2018-2020 (5.2 t/yr). The reduction in P load for Moose Jaw effluent is due to the use of effluent irrigation instead of discharging effluent to the Moose Jaw River, and P removal in the effluent that does get discharged into the Moose Jaw River. Volume-weighted nutrient concentrations for the Moose Jaw River in 2018-2020 were high relative to other sites in the period (except Loon Creek). Total and total reactive phosphorus concentrations often exceeded those of the 2013-2015 period, and were notably high in summer and fall 2019 and 2020 (Figure **40**). The sample site was often pond-like in 2018-2020 due to low flows and beaver dams, and the water was green with algae at times. While nutrient concentrations in rivers are often expected to decrease as flows decrease, it makes sense that that relationship would break down as flows become very low and the water becomes stagnant. Thus, the elevated concentrations in 2018-2020 may reflect nutrient release from sediments near the sample site.

Total phosphorus loading in Wascana Creek for 2018-2020 was roughly equal to TP loading from the Regina WWTP effluent, while the effluent TN load exceeded the downstream TN load. During this period, WWTP effluent accounted for 68 % of streamflow, and so considerable retention of nitrogen must occur between the WWTP outflow and the confluence with the Qu'Appelle River. N retention can occur through biological uptake, or settling of particulate N, but also through microbial N transformations, including denitrification and anammox (anaerobic ammonium oxidation), which result in N loss as N_2 gas (Kuypers et al. 2018). Dylla (2019) found denitrification to be an important process in Wascana Creek, both before and after Regina WWTP upgrades, with the highest denitrification rates occurring closer to the WWTP outfall. Some retention of P would also occur since the WWTP effluent only represents a portion of the total TP load in the stream. P retention often occurs in rivers and can occur through a variety of biotic and abiotic processes, generally associated with the sediments (Withers and Jarvie 2008).

Concentrations of TP and TN were lower in the Regina WWTP effluent following treatment plant upgrades (Figure **17**). The TN reduction has been particularly large, and reductions in downstream TN concentrations in Wascana Creek and the Qu'Appelle River at Lumsden are evident (Figures **9**, **47**, and **49**). The WWTP upgrades have specifically greatly reduced ammonia concentrations in Wascana Creek, which were elevated in winter before the upgrades (Figure **47**) and often exceeded guidelines for the protection of aquatic life. The change to primarily nitrate in the WWTP effluent has been associated with a shift from phytoplankton to periphyton in Wascana Creek downstream of the WWTP (Bergbusch et al. 2021a). Shifts in the ratio of nitrate to ammonium could impact algal species composition in downstream waterbodies (Donald et al. 2011; Glibert et al. 2016). Whether the change in supply ratio from the Regina WWTP effluent will substantially affect downstream lakes remains to be seen and will likely depend on a variety of factors, including processes related to hydrologic conditions (lake flushing rate, variable contributions of N and P from other watershed sources), and N cycle processes in the river and lakes that modify the amounts and forms of N.

Last Mountain Lake

The natural flow regime of the Qu'Appelle River near Last Mountain Lake is such that during high flow events, water from the Qu'Appelle River flows into Last Mountain Lake, but during normal flow conditions, water flows from Last Mountain Lake into the Qu'Appelle River. A control structure downstream of Craven allows the water level on the Qu'Appelle River to be raised, directing water from the Qu'Appelle River into Last Mountain Lake, or slowing the rate of flow from Last Mountain Lake into the Qu'Appelle River. During the 2013-2015 period, flows were primarily from Last Mountain Lake into the Qu'Appelle River other than during high flow periods, when flows were from the Qu'Appelle River into Last Mountain Lake (Figures **27** and **28**). During the 2018-2020 period, flows in both directions were lower than the 2013-2015 period. Net flows were from the Qu'Appelle River to Last Mountain Lake in 2018-2020, with a net estimated 35 % of flows in the Qu'Appelle River at the confluence with Last Mountain Creek being diverted to Last Mountain Lake during 2018-2020. This contrasts with 2013-2015, when an estimated 33 % of the Qu'Appelle River flow below Craven was derived from Last Mountain Creek.

The balance of nutrient loading into and out of Last Mountain Lake via the Qu'Appelle River differed greatly between the two study periods, consistent with the water flow patterns as described previously. During 2013-2015, Last Mountain Creek was a net contributor of TP and TN to the Qu'Appelle River, but for 2018-2020 more TP and TN flowed from the Qu'Appelle River to Last Mountain Lake than left the lake flowing to the Qu'Appelle River (Figures **13** and **15**). For 2013-2015, Last Mountain Creek contributed an additional net total phosphorus load equivalent to 1 % of the load at Lumsden. For 2018-2020, 32 % of the net TP load at Lumsden was lost from the Qu'Appelle River to Last Mountain Lake. For TN over the 2013-2015 period, Last Mountain Creek added a net 5 % of the load at Lumsden to the Qu'Appelle River, but in the 2018-2020 period a net 33 % of the TN load at Lumsden left the Qu'Appelle River to Last Mountain Lake.

The magnitude of loading from Last Mountain Lake to the Qu'Appelle River in 2013-2015 was small in comparison to other major tributaries. Last Mountain Lake is not likely to be a large source of nutrients to the Qu'Appelle River in most flow scenarios. In the wet period of 2013-2015, Qu'Appelle River backflows during spring runoff and storm events were enough to nearly offset nutrient loading from the lake over the rest of the year. In the dry period of 2018-2020, the Qu'Appelle River was managed such that Last Mountain Lake acted as a sink for Qu'Appelle River nutrients. For net loads from Last Mountain Lake to the Qu'Appelle River to be large, outflows from LML would need to greatly exceed backflows from the Qu'Appelle River. This scenario would only likely occur if water levels on Last Mountain Lake were high, and flows on the Qu'Appelle River were low. This scenario would probably be fairly rare at the annual timescale, because years with high water levels on the lake would usually also be high flow years on the Qu'Appelle River.

Despite the low contribution of Last Mountain Lake to nutrient loading in the Qu'Appelle River, outflows from LML did provide meaningful dilution of high N concentrations, particularly during winters 2014-2015 and 2015-2016. The effect was such that volume-weighted TN concentrations were lower at Craven, downstream of the confluence of the LML Channel and the Qu'Appelle River, compared to upstream at Lumsden. As a result of the dilution in 2013-2015, volume-weighted TN concentrations were roughly equal between 2013-2015 and 2018-2020 below Craven, despite the large reduction in TN loading from Regina's WWTP. Volume-weighted TN concentrations continued to be roughly equal between 2013-2015 and 2018-2020 downstream to the inflow to Pasqua Lake.

Last Mountain Lake acted as a sink of nutrients and water from the Qu'Appelle River in 2018-2020, reducing the total mass of nutrients entering the downstream lakes, but not changing the inflowing nutrient concentrations. This would presumably reduce the total mass of nutrient being deposited into the sediments of Pasqua Lake, and allow more time for in-lake processes to regulate nutrient concentrations because of the reduced flows leading to longer water residence times. The reduction in total nutrients deposited in sediments may help keep nutrient concentrations lower in future years if it reduces the resupply of nutrients from the sediments to the rest of the lake. The degree to which this specifically impacts nutrient concentrations would be difficult to determine in isolation from the much larger change in inflows between wet and dry years.

Minor Tributaries

The minor tributaries sampled in 2018-2020 were Loon and Jumping Deer creeks. Both creeks had much lower flows and longer periods with no flows from 2018-2020 compared to 2013-2015 (Figure **30**). Taken together, total flow volumes for the two creeks in 2018-2020 were 7.3 percent of 2013-2015 flows. Flows from these minor tributaries were a smaller proportion of total river flows in 2018-2020 compared to 2013-2015. Using flow volumes for the Qu'Appelle River above Pasqua Lake as a point of comparison, the combined flow from Loon and Jumping Deer creeks amounted to 3.7 % of the flow above Pasqua Lake for 2018-2020, and 5.1 % of the flow for 2013-2015. Volume-weighted nutrient concentrations were greater in 2018-2020 for both Jumping Deer and Loon creeks (Table **1**). In particular, Loon Creek had a much higher volume-weighted TP concentration in 2018-2020 compared to 2013-2015. However, the periods of flow for both creeks were shorter in 2018-2020, especially for Loon Creek.

The relative importance of minor tributaries to nutrient loads in wet vs. dry years is difficult to assess well with our data. Because of the river reach we sampled, only two minor tributaries were monitored, and many of the tributaries monitored in 2013-2015 were just downstream of our study area between Katepwa and Crooked lakes (Indian Head, Red Fox, Pheasant, and Pearl Creeks). Clearly nutrient loads from the tributaries were much lower in 2018-2020 compared to 2013-2015, but that was true at all sites in the watershed due to the greatly reduced flows. As a percentage of the load to Pasqua Lake, Loon and Jumping Deer creeks contributed very roughly similar load percentages in 2018-2020 and in 2013-2015 (Table **7**). Because loads were so small, minor changes in flow estimates could yield a large change in percentages. This is especially relevant at Loon Creek, which is ungauged and did not flow at all in 2019. Loon and Jumping Deer Creeks also had higher volume-weighted concentrations in 2018-2020 vs. 2013-2015, but again these calculations are sensitive to flow estimates. For Loon Creek, spring nutrient concentrations were roughly similar between the two periods (Figures **56** and **57**), but in 2013-2015 there were periods of flow after the initial spring melt when concentrations were lower, leading to lower volume-weighted concentrations than in 2018-2020 when the only flow occurred during the spring snowmelt.

Speculating from the data collected, we would expect to see lower tributary loads of suspended solids during drier low flow periods, as we found for the Moose Jaw River. For streams that tend to have large TSS loads, this would likely lead to a reduction in volume-weighted TP concentrations, which was also observed in the Moose Jaw River. Total reactive phosphorus concentrations increased for the Moose Jaw River and at Loon Creek in 2018-2020, and we might expect to see similar increases in other tributaries depending on specific characteristics of the stream. For nitrogen, expectations are less clear. Nitrate and ammonia concentrations were often elevated in spring, but low during the rest of the year, and the extent to which spring flows dominate the annual flow may determine the relative importance of ammonia and nitrate in stream loading.

Nutrient loading from the tributaries was clearly much lower in 2018-2020 compared to 2013-2015. Volume-weighted nutrient concentrations decreased in some streams, but increased in others, and presumably the unmeasured tributaries would also be variable in these changes. Whether the tributary loads in dry periods represent a lower proportion of the total load depends on the details of changes in nutrient concentrations in the tributaries and how those changes compare to changes in the Qu'Appelle River mainstem. The minor tributaries contributed proportionally less to flows on the Qu'Appelle River in 2018-2020 than in 2013-2015 (Figure **4**), largely because of the increased importance of outflows from Buffalo Pound Lake. Because of their lower contribution to streamflow volumes, it would be reasonable to assume that the minor tributaries contributed proportionally less to nutrient loading too. The amount of that reduction might be less than it at first seems. For example TP concentrations in the Qu'Appelle River were lower in 2018-2020 than 2013-2015. If nutrient concentrations in the tributaries were similar in 2018-2020 and 2013-2015, they would contribute a higher proportion of nutrients compared to their flow contribution when comparing the two periods. The proportional contribution of the minor tributaries to nutrient loading would differ also depending on how the comparisons were made. For example, comparing a tributary's nutrient load to the Qu'Appelle River load near the tributary's confluence might give a different result than comparing the tributary's load to those of the other tributaries each above their confluence with the Qu'Appelle River. Part of the reason these comparisons would be different is that retention processes are acting along the length of the river, and the nutrient load in the river at a given point is not simply the sum of all of the loads upstream of that point. These retention processes would also be operating differently in wet and dry periods, with retention expected to be greater during low-flow periods.

Calling Lakes

Inflows and outflows from the Calling Lakes were much lower in 2018-2020 than 2013-2015 (Figure **29**). Using the outflow from Katepwa Lake and a volume of 541.75 hm^3 for the Calling Lakes and assuming hydraulic residence time equals the lake volume divided by the outflow (Garrels et al. 1975), the four Calling Lakes had their water volume replaced 3.6 times from 2013-2015, but only approximately 0.3 of the water was replaced from 2018-2020. These values represent retention times of 0.8 and 10.4 years for the Calling Lakes in 2013-2015 and 2018-2020, respectively. The general expectation in lakes over the long term, is for lakes with longer residence times to have lower nutrient concentrations given the same inflowing nutrient concentrations. This is because nutrient retention processes (e.g., particle settling, denitrification) have longer to act (Saunders and Kalff 2001; Brett and Benjamin 2008). The extent to which these changes in hydraulic residence time over successive years might influence nutrient concentrations in the Qu'Appelle Valley lakes is unknown. We would, however, expect in-lake processes regulating nutrient concentrations to be more important during periods of longer water retention times than when the lakes are rapidly flushed.

Total phosphorus loads to the Calling Lakes chain (Pasqua, Echo, Mission, Katepwa) were much lower in 2018-2020 than 2013-2015 (Figures **13** and **14**), consistent with the much lower flow volumes in the watershed. Expressed as volume-weighted concentrations, TP concentrations in the inflow to Pasqua Lake were lower in 2018-2020 compared to 2013-2015 (0.246 mg/L vs. 0.368 mg/L, Figure **7**). Total reactive phosphorus concentrations in the inflow also declined (0.021 mg/L 2018-2020 vs. 0.189 mg/L 2013-2015, Figure **8**), and so did the proportion of TRP to TP (Figure **64**). TRP represented 9 % of TP in 2018-2020, but 51 % in 2013-2015 at the inflow to Pasqua Lake.

The reductions in TP and TRP loads and concentrations upstream of Pasqua Lake from 2013-2015 to 2018-2020, happened over a period where TP loading from Regina's WWTP was also reduced. To what extent can the improvements above Pasqua Lake be attributed to improvements in wastewater treatment? While the wastewater treatment plant upgrades represent a 41 % reduction in TP load discharged, several lines of evidence suggest the lower concentrations of TP, and especially TRP, are also part of a larger system-wide effect of lower flows. First, TP and TRP concentrations were also lower on the Qu'Appelle River upstream of the Wascana Creek confluence during the 2018-2022 period (Figures **7**, **8** and **44**). Second, retention of P within the river channel appears to be an important process during low flows. Evidence for this comes from 2018-2020 study period when the load of TP contributed from the WWTP was nearly equal to the downstream TP load measured at the Wascana Creek confluence with the Qu'Appelle River (Figures **13** and **18**). Since flows in the creek are greater than the discharge volume from the WWTP (Figure **2**) and the non-WWTP flow (average of 11.4 hm^3/yr for 2018-2020) has nutrients, it means that a portion of the TP must be retained along the creek. Third, TRP concentrations decline from Wascana Creek downstream to above Pasqua Lake. This is more than just the dilution of effluent, because the proportion of TP as TRP also declines. TRP concentrations in the inflow to Pasqua Lake in 2018-2020 were low compared to those encountered throughout the watershed in 2013-2015 (Figure **8**) and compared to those generally found in the Calling Lakes themselves (WSA unpublished data). This decline in TRP concentrations suggests P transformation processes and likely retention occurring in the river.

If reductions in phosphorus concentrations are largely related to the low flow conditions, the question might be asked: "How will concentrations change when a period of wet years returns?" Based on assessment of the study data it is considered most likely that phosphorus concentrations will return to levels similar to those in 2013-2015. Dissolved phosphorus is a major component of prairie runoff (Baulch et al. 2019), so during years with higher runoff volumes more dissolved phosphorus will enter streams. Dissolved phosphorus in streams also interacts with stream sediments, and the sediments can be net sources or sinks for dissolved P (Palmer-Felgate et al. 2009). In many catchments, sediments have the capacity to be net sinks for dissolved P (Simpson et al. 2021). When flows are low, water will have more time to interact with sediments, allowing these retention processes to occur. Our data, with declining TRP concentrations from Wascana Creek downstream to Lumsden, Craven, and upstream of Pasqua Lake in 2018-2020 are consistent with progressive retention of dissolved P. When high flows occur, concentrations of particulate and dissolved P increase, and the proportion of dissolved P in TP increases, consistent with observations elsewhere (Williamson et al. 2021). During high flows, dissolved P will also have less time to interact with sediments and more is likely to remain in dissolved form. There may also be remobilization of P sequestered during low flow periods.

Total nitrogen loads to Pasqua Lake declined from 2013-2015 to 2018-2020 (Figures **15** and **16**), but TN concentrations were similar between the two periods (2.823 mg/L for

2013-2015 vs. 2.618 mg/L for 2018-2020, Figure **9**). Volume-weighted NO3 concentrations increased between the two study periods (0.493 mg/L for 2013-2015 vs. 0.662 mg/L for 2018-2020, Figure **11**), but NH3 concentrations declined (0.666 for mg/L 2013-2015 vs.0.132 for mg/L 2018-2020, Figure **10**). One of the recent Regina WWTP upgrades included the conversion of ammonia to nitrate, so the greater nitrate concentration observed in 2018-2020 was not unexpected. The dissolved inorganic nitrogen concentration (ammonia + nitrate) decreased slightly in the 2018-2020 study period. Overall, the ratio of dissolved inorganic nitrogen to total nitrogen at the Pasqua Lake inflow declined slightly between the two periods (0.41 in 2013-2015 vs. 0.3 in 2018-2020, Figure **65**).

A reduction in the inflowing TN concentration to Pasqua Lake was anticipated after upgrades to Regina's WWTP that saw significant reductions in TN loads and concentrations. However, volume-weighted TN concentrations remained similar in 2018-2020 compared to 2013-2015. We estimate that 742 fewer tonnes/yr of TN were released through Regina's wastewater effluent in 2018-2020 compared to 2013-2015 (Figure **15**). This reduction in loading is roughly 3 times the annual TN load to Pasqua Lake for 2018-2020. The reason for the lack of reduction in TN concentration is the much smaller dilution of wastewater with natural watershed flows in 2018-2020. While the TN concentration at the inflow to Pasqua Lake did not change from 2013-2015 to 2018-2020, the inorganic nitrogen shifted from being primarily NH3, to being primarily NO3. Ratios of TN:TP, DIN:TP, and DIN:TRP in the inflow to Pasqua Lake all increased between 2013-2015 and 2018-2020, indicating relatively more N in the inflow compared to P. This change in N:P ratios was the reverse of what was expected since a known large point source of N to the watershed was reduced. However, as discussed above, P concentrations declined in the inflow to Pasqua Lake, while N concentrations remained similar to 2013-2015. These patterns in nutrient inflows are largely explained by the differences in watershed flow regimes in 2013-2015 and 2018-2020.

The comparison of 2013-2015 and 2018-2020 is not ideal for assessing the downstream effects of enhanced N removal at the Regina WWTP because of the different flow regimes. Ideally, the two periods would have experienced similar hydrology. Munro (1986b) quantified nutrient loads to the Calling Lakes from April 1980 to June 1983. In 1981 flow volumes were 55 hm^3, which were somewhat lower than the 69 hm^3/yr of 2018-2020. In 1981, volume-weighted TN at the inflow to Pasqua Lake was 5.33 mg/L (calculated from their total N load and inflow volumes), which may give an indication of what volume-weighted TN concentrations would have been in a dry year before the Regina WWTP upgrade. This compares to the three-year volume-weighted TN concentration of 2.62 mg/L flowing into Pasqua Lake from 2018-2020. Munro's value of 5.33 mg/L in 1981 is also considerable greater than the volume-weighted TN concentration for the inflow to Pasqua Lake taken over their entire study period of 2.88 mg/L (discussed below). In 1982 and 1983, flows were considerably higher than in 1981, causing the overall study volume-weighted TN concentration to be lower, and highlighting the effect of variable hydrology on nutrient concentrations in the Qu'Appelle River. Munro (1986a) provides an estimate of 24 hm^3 for Regina WWTP effluent discharge in 1981, essentially equal to our 2018-2020 average rate of 24.4 hm^3/yr for 2018-2020. Regardless, we would expect comparisons of two dry periods to show the greatest difference between before and after upgrades because of the low dilution from other watershed sources. The comparison with Munro's study shows that current inflowing total nitrogen concentrations to Pasqua Lake are around half of what was measured in the low flow year of 1981.

The Calling Lakes chain retained both phosphorus and nitrogen in both study periods (Table **5**). Expressed as a percentage of inflows, TP and TN were retained at similar rates to each other, but the percentage of inflowing load retained was greater from 2018-2020 compared to 2013-2015. When expressed as changes in volume-weighted concentrations, TP and TN concentrations declined by 31 and 30 percent between the inflow to Pasqua Lake and the outflow of Katepwa Lake in 2013-2015, respectively. For 2018-2020, these declines were 35 and 21 percent for TP and TN, respectively (Table **6**). For phosphorus, decreases in flow-weighted concentrations at the inflow have been roughly matched by changes at the outflow, even though the time between our two study periods was less than the estimated retention time of the lake chain. This could indicate that P retention is occurring to a greater extent than before and/or internal phosphorus loading is declining over time. Under these assumptions we might expect P concentrations to continue to decline if the period of low inflows continues. Such a continued decline at the outflow would be due to the lake chain moving towards a steady state with inflowing P concentrations. For nitrogen, inflowing concentrations have remained the same between the two study periods. Despite the increase in lake retention time, N concentrations in the outflow have not declined, suggesting that N retention processes have not increased with the increase in retention time or there has been an increase in the net N-fixation in the Calling Lakes.

Retention of nutrients is the expected long-term pattern for lakes, but years of net nutrient export can occur, especially after nutrient loads are substantively reduced (Sondergaard et al. 2001). Following P loading reductions in 1977, the Calling Lakes were net exporters of TP from 1980-1983 (Munro 1986b). The percent of inflowing TP and TN retained in the Calling Lakes increased from 2013-2015 to 2018-2020, which is expected because lower flows in 2018-2020 would lead to longer hydraulic residence times in the lakes. Longer residence times are expected to lead to more nutrient retention because they allow more time for nutrient removal processes to occur (Seitzinger et al. 2002; Brett and Benjamin 2008). For the Calling Lakes in 2018-2020, some of the additional estimated nutrient retention may be due to changes in lake storage and/or error in the outflow estimate for Katepwa Lake. The difference in flows between the inflow and outflow to the Calling Lakes was larger in 2018-2020 than in 2013-2015, and since the total inflows were much lower, that difference represent a much larger proportion of the total inflows. That difference will influence the estimated retention of N and P and is most apparent when looking at retention as a percentage of inflowing nutrient loads (Table **5**).

Volume-weighted nutrient concentrations in the inflow to Pasqua Lake were similar between our study and Munro (1986b). Their study doesn't directly report volume-weighted nutrient concentrations, but these can be calculated from their load estimates and recorded flows for that period from the Water Survey of Canada. During their study (April 1980 - June 1983), volume-weighted TP and TN concentrations in the inflow to Pasqua Lake were 0.312 and 2.88 mg/L respectively. These concentrations are very similar to ours, with the TP concentration being between our 2013-2015 (0.368 mg/L) and 2018-2020 concentrations (0.246 mg/L), and the TN concentration effectively equal to both 2013-2015 (2.82 mg/L) and 2018-2020 (2.62 mg/L) concentrations.

During the early 1980's TP concentrations in the outflow of Katepwa Lake were higher than the present concentrations, with Munro reporting average concentrations of 0.387 mg/L compared to our values of 0.253 and 0.160 mg/L for 2013-2015 and 2018-2020, respectively. That TP increased in concentration from the inflow to the outflow (Munro 1986b) is consistent with elevated resupply of P from lake sediments (internal loading) following the recent reductions in wastewater P loading at that time. TN concentrations during the Munro study were lower than present concentrations: (1.01 mg/L compared to our values of 1.97 and 2.06 mg/L for 2013-2015 and 2018-2020, respectively). The 1.01 mg/L of TN appears low relative to known concentrations of other lakes along the Qu'Appelle River for that time and knowing that inflows were of similar concentrations. That said it does suggest TN concentrations were relatively low compared to those at the inflow to Pasqua Lake. These differences in nutrient concentrations at the outflow of Katepwa Lake suggest in-lake processes operating differently between our two studies (e.g., less particulate N sedimentation and burial, lower denitrification, or greater N fixation).

Looking at nutrient forms at the inflow to the Calling Lakes, we see some differences between our two study periods. TRP concentrations declined slightly between the inflow and outflow in 2013-2015, but increased between the inflow and outflow in 2018-2020 (Figure **8**, Table **2**). There are several processes that may account for this pattern of increasing TRP concentrations from inflow to outflow in 2018-2020. For one, the low flow conditions from 2018-2020 mean that the hydraulic residence time of the Calling Lakes is much longer (estimated at 10.4 for 2018-2020 compared to 0.8 years for 2013-2015). Nutrient concentrations at the outflow of Katepwa Lake would not yet be in balance with the inflow concentrations because the duration of the relatively dry period has been less than the residence time of the lakes. They would still partially reflect the earlier period, when inflows of dissolved P were greater. Another explanation for the increase in TRP concentrations from inflow to outflow in the Calling Lakes is the influence of in-lake processes on P forms acting to break down non-reactive P and cycle it back to the water column in reactive form. We know that lake TP and TRP concentrations tend to follow a seasonal pattern in the Calling Lakes (WSA unpublished data), which is reflected in the outflow nutrient concentrations for Katepwa Lake (Figure **62**). TP and especially TRP concentrations decline over summer, likely through uptake by plankton and settling to the lake bottom. Near the end of summer or early in fall, when Katepwa Lake overturns, P concentrations increase. This coincides with P that has been released from the sediment and accumulated in the lower layer of the lake over the summer mixing with the whole lake. P concentrations then remain high over late fall and winter, because plankton uptake is lower and the process of P uptake and settling operates much more slowly, and because P is more effectively circulated throughout the water column. It makes sense that the TRP to TP ratio in the inflow will not be matched at the outflow because P cycling operates differently in lakes vs. rivers. We might also expect that these in-lake processes will have a greater effect at changing the TRP:TP ratio during dry periods because the longer hydraulic residence time allows more time for these processes to occur. Generally, there is an expectation that changes in TP at the outflow will be roughly proportional to changes to the inflow (Brett and Benjamin 2008), which is what we've observed. We also expect to see the TRP:TP ratio decline in lakes where TP loading declines (Jeppesen et al. 2005), and we have. The exact balance of TRP:TP in the inflow has not been matched at the outflow. This ratio may progressively approach the inflow ratio if low-flow conditions continue, however in-lake processes may also act to keep inflow and outflow ratios different from each other.

Nitrogen forms in the inflows and outflows of the Calling Lakes also differed between 2013-2015 and 2018-2020. Inflow nitrate concentrations increased (Figure **11**), while ammonia concentrations decreased (Figure **10**) from 2013-2015 to 2018-2020. The reverse pattern was observed at the outflow: nitrate concentrations decreased from 2013-2015 to 2018-2020 and ammonia concentrations increased. Concentrations of N forms in the Calling Lakes appear to be much more driven by N cycling processes than inflow concentrations of DIN forms. As expected, nitrate and ammonia concentrations at the outflow of Katepwa Lake tend to decline after spring peaks due to uptake by plankton, with a portion of nutrients eventually settling to the bottom of the lake. After fall overturn, ammonia concentrations increase. Over the winter in 2013-2015, ammonia concentrations declined while nitrate concentrations increased, most reasonably explained by nitrification. Winter rates of nitrification are known to be significant in the Qu'Appelle Lakes (Cavaliere and Baulch 2019), but it is unclear why rates appear to have been rapid enough to largely replace ammonia with nitrate in 2013-2015, but not in 2018-2020. In 2018-2020, nitrate concentrations increased over the winter, but at lower rates than in 2013-2015. In 2018-2020 ammonia concentrations remained elevated.

Summary

Our study extends the work of previous nutrient load quantification in the Qu'Appelle watershed (Water Security Agency 2018). Our results from this very dry period highlight the variability in nutrient loading, in-stream, and in-lake processing that occurs as streamflows vary. We document the large reductions in N and to a lesser extent P loadings from the Regina WWTP. Nutrient loading from the Moose Jaw River in particular declined in importance compared to 2013-2015, while the importance of outflows from Buffalo Pound Lake increased. Last Mountain Lake was a net sink of nutrients for the Qu'Appelle River during this period, unlike during the period from 2013-2015. Despite the reductions in wastewater N loading during the 2018-2020 period, TN concentrations in the inflow to Pasqua Lake did not decline, mainly because of high dilution from natural streamflow that decreased nutrient concentration measurements entering Pasqua Lake prior to the wastewater treatment plant upgrades. If the period from 2013-2015 had similar flow conditions to those experienced from 2018-2020 the TN concentrations would have decreased. TP concentrations declined in the inflow to Pasqua Lake, likely reflecting watershed differences between different flow periods and potentially some in-stream processing. These were considered of greater importance in determining the reduction in TP as compared to the effect of decreased phosphorus loads due to WWTP upgrades. The

Calling Lakes continued to retain both N and P in a roughly similar manner to the wet period of 2013-2015.

Understanding the impact of the wastewater load reductions brought on by Regina's WWTP upgrades will take longer. Comparing pre/post conditions during concurrent wet/dry periods confounds the ability to readily measure the effect of the upgrades on nutrient concentrations in the Qu'Appelle River. However, the different return period highlighted important processes other than WWTP effluent nutrient loading that affect nutrient concentrations and provided a better overall understanding of the complexities of nutrient dynamics in the Qu'Appelle River system.

It is hypothesized that when periods of higher runoff and flows occur in the future a rapid change in nutrient conditions in the Qu'Appelle River will occur. Under such conditions, the rapid flushing of the Calling Lakes will cause their nutrient concentrations to more closely resemble inflowing concentrations. The observed decrease in phosphorus concentrations in the Qu'Appelle's river and lakes may be readily reversed in the next wet period. Ongoing monitoring will continue to provide data to better understand the drivers of nutrient concentrations in the river and over the long-term in the Calling Lakes.

Literature Cited

Albers S (2017) Tidyhydat: Extract and tidy canadian hydrometric data. The Journal of Open Source Software 2: doi: 10.21105/joss.00511

Allan RJ, Roy M (1980) Lake water nutrient chemistry and chlorophyll a in Pasqua, Echo, Mission, Katepwa, Crooked and Round lakes on the Qu'Appelle River, Saskatchewan. Environment Canada, National Water Research Institute, Inland Waters Directorate, Regina, Saskatchewan

Atton FM, Johnson RP (1962) Report on limnology and fisheries of six lakes of the lower Qu'Appelle valley in southern Saskatchewan. Saskatchewan Fisheries Laboratory, Department of Natural Resources, Saskatoon, Saskatchewan

Baulch HM, Elliott JA, Cordeiro MR, Flaten DN, Lobb DA, Wilson HF (2019) Soil and water management: Opportunities to mitigate nutrient losses to surface waters in the northern great plains. Environmental Reviews 27:447–477

Bergbusch NT, Hayes NM, Simpson GL, Leavitt PR (2021a) Unexpected shift from phytoplankton to periphyton in eutrophic streams due to wastewater influx. Limnology and Oceanography

Bergbusch NT, Hayes NM, Simpson GL, Swarbrick VJ, Quiñones-Rivera ZJ, Leavitt PR (2021b) Effects of nitrogen removal from wastewater on phytoplankton in eutrophic prairie streams. Freshwater Biology

Brett MT, Benjamin MM (2008) A review and reassessment of lake phosphorus retention and the nutrient loading concept. Freshwater Biology 53:194–211

Cavaliere E, Baulch HM (2019) Winter nitrification in ice-covered lakes. Plos one 14:e0224864

Cross PM (1978) The application of nutrient loading-productivity models to the Qu'Appelle valley lakes of Saskatchewan. Environment Canada, Winnipeg, Manitoba

Dillenberg H, Dehnel M (1960) Toxic waterbloom in saskatchewan, 1959. Canadian Medical Association Journal 83:1151

Dixit AS, Hall RI, Leavitt& PR, Quinlan R, Smol JP (2000) Effects of sequential depositional basins on lake response to urban and agricultural pollution: A palaeoecological analysis of the qu'appelle valley, saskatchewan, canada. Freshwater Biology 43:319–337

Dodds WK (2003) Misuse of inorganic n and soluble reactive p concentrations to indicate nutrient status of surface waters. Journal of the North American Benthological Society 22:171–181

Donald DB, Bogard MJ, Finlay K, Leavitt PR (2011) Comparative effects of urea, ammonium, and nitrate on phytoplankton abundance, community composition, and toxicity in hypereutrophic freshwaters. Limnology and Oceanography 56:2161–2175

Dylla NP (2019) Downstream effects on denitrification and nitrous oxide from an advanced wastewater treatment plant upgrade. Master's thesis, University of Saskatchewan

Garrels Robert Minard, Mackenzie FT, Hunt C (1975) Chemical cycles and the global environment: Assessing human influences. William Kaufmann Inc.

Gilchrist FC (1896) Diary of F.C. Gilchrist (1859-1896). Copied by the Archives of Saskatchewan from the original in the possession of Mrs. Una G. Nichols, San Diego California

Glibert PM, Wilkerson FP, Dugdale RC, Raven JA, Dupont CL, Leavitt PR, Parker AE, Burkholder JM, Kana TM (2016) Pluses and minuses of ammonium and nitrate uptake and assimilation by phytoplankton and implications for productivity and community composition, with emphasis on nitrogen-enriched conditions. Limnology and Oceanography 61:165–197

Hall RI, Leavitt PR, Quinlan R, Dixit AS, Smol JP (1999) Effects of agriculture, urbanization, and climate on water quality in the northern great plains. Limnology and Oceanography 44:739–756

Hammer U (1971) Limnological studies of the lakes and streams of the upper Qu'Appelle River system, Saskatchewan, Canada. Hydrobiologia 37:473–507

Hayes NM, Haig HA, Simpson GL, Leavitt PR (2020) Effects of lake warming on the seasonal risk of toxic cyanobacteria exposure. Limnology and Oceanography Letters 5:393–402

Hind HY (1859) North-west Territory: Reports of progress; together with a preliminary and general report on the Assiniboine and Saskatchewan exploring expedition, made under instructions from the provincial secretary, Canada. J. Lovell

Jarvie HP, Sharpley AN, Scott JT, Haggard BE, Bowes MJ, Massey LB (2012) Within-river phosphorus retention: Accounting for a missing piece in the watershed phosphorus puzzle. Environmental science & technology 46:13284–13292

Jeppesen E, Søndergaard M, Jensen JP, Havens KE, Anneville O, Carvalho L, Coveney MF, Deneke R, Dokulil MT, Foy B, et al (2005) Lake responses to reduced nutrient loading–an analysis of contemporary long-term data from 35 case studies. Freshwater biology 50:1747–1771

Kuypers MM, Marchant HK, Kartal B (2018) The microbial nitrogen-cycling network. Nature Reviews Microbiology 16:263–276

Leavitt PR, Brock CS, Ebel C, Patoine A (2006) Landscape-scale effects of urban nitrogen on a chain of freshwater lakes in central North America. Limnology and Oceanography 51:2262–2277

Liu K, Elliott JA, Lobb DA, Flaten DN, 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 42:484–496

Munro DJ (1986a) Phosphorus loading in the Qu'Appelle River, 1971 to 1983. Environment Canada, Inland Waters Directorate, Western; Northern Region, Regina, Saskatchewan

Munro DJ (1986b) Qu'Appelle Fishing lakes nutrient loading study, 1980 to 1983. Environment Canada, Water Qualtiy Branch, Western; Northern Region, Regina, Saskatchewan

Palmer-Felgate EJ, Jarvie HP, Withers PJ, Mortimer RJ, Krom MD (2009) Stream-bed phosphorus in paired catchments with different agricultural land use intensity. Agriculture, ecosystems & environment 134:53–66

Pomeroy J, Boer D de, Martz L (2005) Hydrology and water resources of Saskatchewan. Citeseer

Qu'Appelle Basin Study Board (1972) Report of the Qu'Appelle basin study board. Qu'Appelle Basin Study Board. Canada-Saskatchewan-Manitoba, Regina, Saskatchewan

Saskatchewan Water Resources Commission (1970) A brief summary of Qu'Appelle system operation and effect of water development projects in the Qu'Appelle River basin up to 1970. Saskatchewan Water Resources Commission, Saskatchewan

Saunders D, Kalff J (2001) Nitrogen retention in wetlands, lakes and rivers. Hydrobiologia 443:205–212

Seitzinger SP, Styles RV, Boyer EW, Alexander RB, Billen G, Howarth RW, Mayer B, Van Breemen N (2002) Nitrogen retention in rivers: Model development and application to watersheds in the northeastern USA. Biogeochemistry 57/58:199–237

Shaw DA, Vanderkamp G, Conly FM, Pietroniro A, Martz L (2012) The fill–spill hydrology of prairie wetland complexes during drought and deluge. Hydrological Processes 26:3147–3156

Simpson ZP, McDowell RW, Condron LM, McDaniel MD, Jarvie HP, Abell JM (2021) Sediment phosphorus buffering in streams at baseflow: A meta-analysis. Journal of Environmental Quality 50:287–311

Sondergaard M, Jensen JP, Jeppesen E (2001) Retention and internal loading of phosphorus in shallow, eutrophic lakes. The Scientific World 1:427–442

Tones PJ (1981) The effect of the Regina tertiary treatment plant on water quality in Wascana Creek. Saskatchewan Environment Water Pollution Control Branch, Regina, Saskatchewan

Waiser MJ, Tumber V, Holm J (2011) Effluent-dominated streams. Part 1: Presence and effects of excess nitrogen and phosphorus in Wascana Creek, Saskatchewan, Canada. Environmental toxicology and chemistry 30:496–507

Warwick W (1980) Pasqua lake, southeastern saskatchewan: A preliminary assessment of trophic status and contamination based on the Chironomidae (Diptera). In: Chironomidae. Elsevier, pp 255–267

Water Security Agency (2018) Qu'Appelle nutrient mass balance 2013-2016. Saskatchewan Water Security Agency, Water Quality and Habitat Assessment Services, Regina, Saskatchewan

Williamson TN, Dobrowolski EG, Kreiling RM (2021) Phosphorus sources, forms, and abundance as a function of streamflow and field conditions in a Maumee River tributary, 2016–2019. Journal of Environmental Quality

Wilson H, Elliott J, Macrae M, Glenn A (2019a) Near-surface soils as a source of phosphorus in snowmelt runoff from cropland. Journal of Environmental Quality 48:921–930

Wilson HF, Casson NJ, Glenn AJ, Badiou P, Boychuk L (2019b) Landscape controls on nutrient export during snowmelt and an extreme rainfall runoff event in northern agricultural watersheds. Journal of environmental quality 48:841–849

Withers P, Jarvie H (2008) Delivery and cycling of phosphorus in rivers: A review. Science of the total environment 400:379–395

Appendix A

Tables

Table 1: *Mean nutrient loads for the Qu'Appelle River and tributary sites split into periods from 2013-2015, 2018-2020.*

Site	Period	Flow (hm3/yr)	TP Load (t/yr)	TN Load (t/yr)	TRP Load (t/yr)	NO3 Load (t/yr)	NH3 Load (t/yr)	TSS Load (t/yr)	TDS Load (t/yr)	DOC Load (t/yr)
Buffalo Pound Outflow	2013-2015	69.2	7.76	87.5	2.89	4.85	2.68	1176	28896	570
Buffalo Pound Outflow	2018-2020	70.2	3.56	50.3	0.370	0.557	1.09	719	25088	366
Buffalo Pound Backflow	2013-2015	15	7.87	36.7	3.42	6.50	3.67	2788	4088	179
Buffalo Pound Backflow	2018-2020	0	0	0	0	0	0	0	0	0
Moose Jaw River	2013-2015	183	114	513	42	80.3	37.2	37202	86305	2575
Moose Jaw River	2018-2020	10.2	5.20	22	2.80	2.69	1.22	197	9441	143
S of Bethune	2018-2020	81.3	12.0	78.3	3.33	2.92	2.56	3390	37844	533
Above Wascana	2013-2015	249	99.0	493	50.7	57.2	22.4	32355	123388	3247
Above Wascana	2018-2020	66.1	14.1	75.2	2.86	3.44	2.30	7378	29965	435
Wascana Creek	2013-2015	124	87.6	1180	38.3	356	537	37448	76493	1861
Wascana Creek	2018-2020	35.8	12.6	191	5.26	101	23.0	1686	34840	405
Lumsden	2013-2015	371	183	1582	89.2	409	475	70526	196515	4948
Lumsden	2018-2020	101	28.1	264	7.31	96.6	23.4	11053	61451	812
LML Outflow	2013-2015	305	60.9	417	37.4	3.36	11.9	6778	356618	3880
LML Outflow	2018-2020	13.6	2.92	30.2	0.336	0.983	0.760	355	18646	180
LML Backflow	2013-2015	110	59.0	334	28.9	61.8	67.2	23443	42622	1408
LML Backflow	2018-2020	50.1	11.9	119	3.25	37	11.2	3190	30495	419
Craven Dam	2013-2015	588	192	1703	96.3	314	425	57274	527220	8174
Craven Dam	2018-2020	67.5	14.2	184	3.23	62.1	15.9	2945	52554	609

Site	Period	Flow (hm3/yr)	TP Load (t/yr)	TN Load (t/yr)	TRP Load (t/yr)	NO3 Load (t/yr)	NH3 Load (t/yr)	TSS Load (t/yr)	TDS Load (t/yr)	DOC Load (t/yr)
HWY 6	2013-2015	624	201	1695	106	278	432	73605	578974	8488
HWY 6	2018-2020	67.8	15.9	170	1.46	46.4	10.6	5678	55334	620
Loon Creek	2013-2015	12.4	5.96	39.6	4.07	9.88	5.10	646	7017	278
Loon Creek	2018-2020	0.289	0.233	1.31	0.173	0.329	0.0974	2.87	110	6.63
Above Pasqua Lake	2013-2015	673	248	1900	127	332	448	81521	601495	9418
Above Pasqua Lake	2018-2020	68.8	16.9	180	1.46	45.6	9.06	6886	56713	665
Jumping Deer Creek	2013-2015	21.8	4.75	42.8	2.99	2.63	2.98	526	17422	471
Jumping Deer Creek	2018-2020	2.22	0.564	5.37	0.260	0.595	0.692	38.9	2877	41.1
Katepwa Outlet	2013-2015	654	165	1290	110	273	112	12630	586320	8833
Katepwa Outlet	2018-2020	52.2	8.35	108	3.19	4.36	18.3	421	62874	726

Table 2: *Mean volume- weighted nutrient concentrations for the Qu'Appelle River and tributary sites split into periods from 2013-2015, 2018-2020.*

Site	Period	TP (mg/L)	TN (mg/L)	TRP (mg/L)	NO3 (mg/L)	NH3 (mg/L)	TSS (mg/L)	TDS (mg/L)	DOC (mg/L)
Buffalo Pound Outflow	2013-2015	0.112	1.27	0.0417	0.0702	0.0387	17.0	418	8.25
Buffalo Pound Outflow	2018-2020	0.0508	0.717	0.00528	0.00794	0.0156	10.2	358	5.22
Buffalo Pound Backflow	2013-2015	0.525	2.45	0.228	0.433	0.245	186	273	11.9
Buffalo Pound Backflow	2018-2020								
Moose Jaw River	2013-2015	0.624	2.80	0.229	0.438	0.203	203	471	14.0
Moose Jaw River	2018-2020	0.511	2.16	0.275	0.264	0.120	19.3	928	14.1
S of Bethune	2018-2020	0.148	0.963	0.0410	0.0359	0.0315	41.7	466	6.56
Above Wascana	2013-2015	0.398	1.98	0.204	0.230	0.0898	130	496	13.0

Site	Period	TP (mg/L)	TN (mg/L)	TRP (mg/L)	NO3 (mg/L)	NH3 (mg/L)	TSS (mg/L)	TDS (mg/L)	DOC (mg/L)
Above Wascana	2018-2020	0.213	1.14	0.0433	0.0521	0.0348	112	453	6.59
Wascana Creek	2013-2015	0.705	9.50	0.308	2.87	4.32	301	615	15
Wascana Creek	2018-2020	0.351	5.34	0.147	2.83	0.643	47.1	972	11.3
Lumsden	2013-2015	0.494	4.26	0.240	1.10	1.28	190	529	13.3
Lumsden	2018-2020	0.277	2.61	0.0721	0.954	0.231	109	607	8.02
LML Outflow	2013-2015	0.200	1.37	0.123	0.0110	0.0391	22.2	1169	12.7
LML Outflow	2018-2020	0.214	2.21	0.0246	0.0721	0.0557	26.1	1367	13.2
LML Backflow	2013-2015	0.535	3.03	0.262	0.560	0.610	213	387	12.8
LML Backflow	2018-2020	0.238	2.37	0.0648	0.738	0.224	63.7	609	8.36
Craven Dam	2013-2015	0.326	2.89	0.164	0.533	0.722	97.3	896	13.9
Craven Dam	2018-2020	0.210	2.73	0.0478	0.920	0.236	43.6	779	9.03
HWY 6	2013-2015	0.322	2.71	0.169	0.445	0.692	118	927	13.6
HWY 6	2018-2020	0.234	2.51	0.0215	0.684	0.157	83.8	817	9.15
Loon Creek	2013-2015	0.481	3.20	0.328	0.796	0.411	52.1	566	22.4
Loon Creek	2018-2020	0.805	4.52	0.597	1.14	0.337	9.91	382	22.9
Above Pasqua Lake	2013-2015	0.368	2.82	0.189	0.493	0.666	121	894	14
Above Pasqua Lake	2018-2020	0.246	2.62	0.0212	0.662	0.132	100	824	9.67
Jumping Deer Creek	2013-2015	0.218	1.96	0.137	0.120	0.137	24.1	799	21.6
Jumping Deer Creek	2018-2020	0.254	2.41	0.117	0.268	0.312	17.5	1294	18.5
Katepwa Outlet	2013-2015	0.253	1.97	0.169	0.417	0.172	19.3	897	13.5
Katepwa Outlet	2018-2020	0.160	2.06	0.0612	0.0835	0.350	8.07	1204	13.9

Table 3: *Annual nutrient loads for the Qu'Appelle River and tributary sites. Loads were calculated using a Mar 1 - Feb 28/9 year.*

Site	Study Year	Flow (hm3)	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 Load (t)	NH3 Load (t)	TSS Load (t)	TDS Load (t)	DOC Load (t)
Buffalo Pound Outflow	2013	49.3	3.94	45.5	1.94	5.18	2.27	673	17752	230
Buffalo Pound Outflow	2014	91.1	9.14	122	1.52	3.73	2.57	2005	38583	784
Buffalo Pound Outflow	2015	67.2	10.2	95.6	5.20	5.64	3.19	851	30355	698
Buffalo Pound Outflow	2018	44.8	1.96	26.7	0.649	0.179	0.458	317	18838	247
Buffalo Pound Outflow	2019	80.8	3.35	52.9	0.327	0.232	0.921	559	27444	407
Buffalo Pound Outflow	2020	84.9	5.39	71.3	0.135	1.26	1.89	1281	28983	445
Buffalo Pound Backflow	2013	34.6	17.9	79	7.33	13.1	7.07	7439	8816	396
Buffalo Pound Backflow	2014	0	0	0	0	0	0	0	0	0
Buffalo Pound Backflow	2015	10.3	5.67	31.2	2.93	6.39	3.95	925	3448	141
Buffalo Pound Backflow	2018	0	0	0	0	0	0	0	0	0
Buffalo Pound Backflow	2019	0	0	0	0	0	0	0	0	0
Buffalo Pound Backflow	2020	0	0	0	0	0	0	0	0	0
Moose Jaw River	2013	242	162	651	42.8	78.5	52.2	70196	87666	2601
Moose Jaw River	2014	136	74.2	381	37.7	86.9	15.8	16495	81723	2263
Moose Jaw River	2015	172	107	508	45.5	75.4	43.8	24916	89526	2860
Moose Jaw River	2018	7.08	2.22	13.5	1.11	1.25	0.832	132	8201	93.5
Moose Jaw River	2019	20.8	12.1	45.6	6.65	5.97	2.68	411	17502	300
Moose Jaw River	2020	2.68	1.30	6.95	0.630	0.841	0.158	47.1	2620	35.7

Site	Study Year	Flow (hm3)	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 Load (t)	NH3 Load (t)	TSS Load (t)	TDS Load (t)	DOC Load (t)
S of Bethune	2018	52.5	5.99	45.6	0.872	2.42	1.62	2436	34047	355
S of Bethune	2019	103	19.3	103	8.80	3.63	3.43	3496	47679	772
S of Bethune	2020	87.8	10.7	85.9	0.321	2.70	2.63	4240	31805	472
Above Wascana	2013	246	90	355	55.3	46.9	13.8	29354	101946	2661
Above Wascana	2014	261	109	591	46.3	45.4	19.9	39293	138947	3370
Above Wascana	2015	240	97.8	532	50.5	79.2	33.3	28419	129270	3710
Above Wascana	2018	34.8	6.62	40.8	1.13	4.15	1.08	4453	18239	260
Above Wascana	2019	88.4	19.1	96.8	6.91	4.35	3.79	8064	42138	672
Above Wascana	2020	75.0	16.5	87.9	0.531	1.82	2.03	9618	29517	373
Wascana Creek	2013	115	65.8	1011	32.1	295	476	36204	67937	1711
Wascana Creek	2014	118	89.1	1219	39.2	365	585	32981	82539	1684
Wascana Creek	2015	140	108	1311	43.6	409	549	43160	79002	2188
Wascana Creek	2018	36.2	12.5	240	5.96	135	37.2	1585	46763	484
Wascana Creek	2019	41.7	13.6	178	5.45	80.1	21.5	1862	34085	418
Wascana Creek	2020	29.6	11.7	157	4.37	89.0	10.4	1612	23671	314
Lumsden	2013	360	153	1266	93.3	319	400	64078	164822	3998
Lumsden	2014	378	192	1764	82.1	429	567	71626	224516	5085
Lumsden	2015	377	206	1715	92.2	478	458	75876	200208	5762
Lumsden	2018	70.4	19.4	250	6.25	116	28.7	7760	53854	645
Lumsden	2019	130	33.6	289	10.7	84.7	27.3	12620	78013	1066
Lumsden	2020	104	31.3	254	4.94	89.6	14.1	12778	52486	725
LML Outflow	2013	148	38.3	210	25.1	2.30	6.11	4910	189302	1786
LML Outflow	2014	408	76.3	550	47.5	5.10	10.0	7708	484416	4994
LML Outflow	2015	359	68.3	491	39.5	2.68	19.6	7718	396135	4859
LML Outflow	2018	25.9	7.41	63.7	0.865	0.181	0.445	912	35306	353
LML Outflow	2019	11.1	0.843	17.0	0.113	0.939	0.386	85.9	15597	142
LML Outflow	2020	3.94	0.508	9.73	0.0288	1.83	1.45	68.2	5034	44.5
LML Backflow	2013	120	52.2	280	29.9	54.3	52.9	20835	43520	1313
LML Backflow	2014	86.1	50.5	309	19.0	49.3	72.5	24273	39328	1027

Site	Study Year	Flow (hm3)	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 Load (t)	NH3 Load (t)	TSS Load (t)	TDS Load (t)	DOC Load (t)
LML Backflow	2015	125	74.4	413	37.7	81.8	76.4	25220	45019	1884
LML Backflow	2018	35.9	8.16	125	2.72	47.1	17.3	1688	27157	373
LML Backflow	2019	68.3	17.0	149	5.42	44.4	11.2	3791	42009	599
LML Backflow	2020	46.2	10.6	81.7	1.61	19.5	5.13	4091	22319	285
Craven Dam	2013	401	127	1131	75.6	254	295	51240	319514	4632
Craven Dam	2014	725	228	1967	112	319	459	57324	697009	10731
Craven Dam	2015	640	220	2011	102	369	521	63258	565138	9158
Craven Dam	2018	62.2	15.4	191	2.52	53	13	2884	62719	675
Craven Dam	2019	75	13	175	4.11	59.4	20.3	2687	56036	639
Craven Dam	2020	65.3	14.2	187	3.05	73.9	14.5	3264	38907	513
HWY 6	2013	408	142	1208	71.0	217	379	76367	346877	5125
HWY 6	2014	792	256	2035	137	250	495	79959	782563	10735
HWY 6	2015	673	206	1841	109	366	422	64490	607483	9606
HWY 6	2018	63.5	18.4	166	0.985	32.6	4.86	5839	68570	699
HWY 6	2019	74.3	13.0	172	2.06	48.2	19.4	5058	56298	645
HWY 6	2020	65.4	16.1	172	1.32	58.3	7.68	6136	41134	516
Loon Creek	2013	10.9	5.53	35.6	3.74	11.0	3.51	533	6176	245
Loon Creek	2014	16.8	7.56	52.7	5.26	12.2	6.48	671	11007	404
Loon Creek	2015	9.49	4.80	30.6	3.20	6.39	5.32	734	3868	186
Loon Creek	2018	0.465	0.235	1.85	0.164	0.527	0.191	4.57	224	9.88
Loon Creek	2019	0	0	0	0	0	0	0	0	0
Loon Creek	2020	0.403	0.464	2.07	0.354	0.460	0.101	4.03	107	10.0
Above Pasqua Lake	2013	424	163	1404	88.2	291	492	50715	354742	5491
Above Pasqua Lake	2014	863	335	2276	172	310	486	120664	814398	11842
Above Pasqua Lake	2015	733	244	2019	122	395	367	73185	635347	10922
Above Pasqua Lake	2018	67.5	17	179	1.11	33.2	6.14	6843	72482	754

Site	Study Year	Flow (hm3)	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 Load (t)	NH3 Load (t)	TSS Load (t)	TDS Load (t)	DOC Load (t)
Above Pasqua Lake	2019	72.7	12.1	175	1.77	50	15.4	5195	55208	634
Above Pasqua Lake	2020	66.2	21.7	186	1.49	53.6	5.70	8621	42449	608
Jumping Deer Creek	2013	6.30	0.852	13.6	0.475	2.24	1.22	82.8	7244	132
Jumping Deer Creek	2014	30.1	6.67	59.2	4.48	1.65	2.68	540	26643	702
Jumping Deer Creek	2015	29.0	6.74	55.6	4.03	3.99	5.05	953	18379	578
Jumping Deer Creek	2018	1.92	0.626	6.77	0.306	1.55	0.940	77.2	2311	37.6
Jumping Deer Creek	2019	2.25	0.318	3.41	0.161	0.141	0.358	10.3	3749	41.2
Jumping Deer Creek	2020	2.49	0.748	5.92	0.314	0.0909	0.780	29.1	2570	44.6
Katepwa Outlet	2013	550	169	1240	112	370	94.0	28516	509563	7369
Katepwa Outlet	2014	797	189	1497	123	189	163	5740	708672	10505
Katepwa Outlet	2015	614	138	1131	95.5	260	79.6	3635	540726	8625
Katepwa Outlet	2018	50.9	8.38	95.2	3.38	3.13	12.3	418	60477	694
Katepwa Outlet	2019	78.4	11.9	170	4.08	6.15	30.2	622	94746	1095
Katepwa Outlet	2020	27.4	4.72	58.2	2.11	3.80	12.3	224	33398	390

Table 4: *Volume-weighted nutrient concentrations for the Qu'Appelle River and tributary sites calculated annually. Calculations were done using a Mar 1 - Feb 28/29 year.*

Site	Study Year	TP (mg/L)	TN (mg/L)	TRP (mg/L)	NO3 (mg/L)	NH3 (mg/L)	TSS (mg/L)	TDS (mg/L)	DOC (mg/L)
Buffalo Pound Outflow	2013	0.0799	0.924	0.0394	0.105	0.0461	13.7	360	4.66
Buffalo Pound Outflow	2014	0.100	1.33	0.0166	0.0410	0.0282	22.0	424	8.61
Buffalo Pound Outflow	2015	0.152	1.42	0.0775	0.0840	0.0475	12.7	452	10.4

Site	Study Year	TP (mg/L)	TN (mg/L)	TRP (mg/L)	NO3 (mg/L)	NH3 (mg/L)	TSS (mg/L)	TDS (mg/L)	DOC (mg/L)
Buffalo Pound Outflow	2018	0.0438	0.596	0.0145	0.00400	0.0102	7.08	420	5.50
Buffalo Pound Outflow	2019	0.0414	0.655	0.00405	0.00287	0.0114	6.92	340	5.04
Buffalo Pound Outflow	2020	0.0634	0.840	0.00159	0.0148	0.0223	15.1	341	5.24
Buffalo Pound Backflow	2013	0.518	2.28	0.212	0.378	0.204	215	254	11.4
Buffalo Pound Backflow	2014								
Buffalo Pound Backflow	2015	0.548	3.02	0.283	0.618	0.382	89.4	333	13.7
Buffalo Pound Backflow	2018								
Buffalo Pound Backflow	2019								
Buffalo Pound Backflow	2020								
Moose Jaw River	2013	0.669	2.69	0.177	0.325	0.216	290	363	10.8
Moose Jaw River	2014	0.548	2.81	0.278	0.641	0.116	122	603	16.7
Moose Jaw River	2015	0.622	2.95	0.264	0.437	0.254	144	519	16.6
Moose Jaw River	2018	0.313	1.90	0.157	0.176	0.117	18.6	1158	13.2
Moose Jaw River	2019	0.583	2.20	0.320	0.288	0.129	19.8	843	14.4
Moose Jaw River	2020	0.485	2.59	0.235	0.313	0.0588	17.6	977	13.3
S of Bethune	2018	0.114	0.868	0.0166	0.0461	0.0308	46.4	648	6.76
S of Bethune	2019	0.187	0.998	0.0850	0.0351	0.0332	33.8	461	7.46
S of Bethune	2020	0.122	0.978	0.00365	0.0307	0.0299	48.3	362	5.37
Above Wascana	2013	0.366	1.45	0.225	0.191	0.0563	119	414	10.8
Above Wascana	2014	0.419	2.26	0.177	0.174	0.0763	150	532	12.9
Above Wascana	2015	0.408	2.22	0.211	0.330	0.139	118	539	15.5
Above Wascana	2018	0.190	1.17	0.0326	0.119	0.0310	128	525	7.49

Site	Study Year	TP (mg/L)	TN (mg/L)	TRP (mg/L)	NO3 (mg/L)	NH3 (mg/L)	TSS (mg/L)	TDS (mg/L)	DOC (mg/L)
Above Wascana	2019	0.216	1.09	0.0781	0.0492	0.0429	91.2	476	7.60
Above Wascana	2020	0.219	1.17	0.00708	0.0243	0.0271	128	393	4.97
Wascana Creek	2013	0.572	8.79	0.279	2.57	4.14	315	591	14.9
Wascana Creek	2014	0.754	10.3	0.332	3.09	4.96	279	699	14.3
Wascana Creek	2015	0.773	9.38	0.312	2.92	3.93	309	565	15.7
Wascana Creek	2018	0.345	6.63	0.165	3.73	1.03	43.8	1292	13.4
Wascana Creek	2019	0.326	4.26	0.131	1.92	0.515	44.6	817	10.0
Wascana Creek	2020	0.395	5.29	0.148	3.01	0.353	54.5	800	10.6
Lumsden	2013	0.424	3.52	0.259	0.886	1.11	178	458	11.1
Lumsden	2014	0.507	4.67	0.217	1.14	1.50	190	594	13.5
Lumsden	2015	0.547	4.55	0.245	1.27	1.21	201	531	15.3
Lumsden	2018	0.276	3.55	0.0887	1.64	0.407	110	765	9.16
Lumsden	2019	0.260	2.23	0.0828	0.653	0.211	97.4	602	8.22
Lumsden	2020	0.301	2.45	0.0475	0.863	0.136	123	505	6.98
LML Outflow	2013	0.259	1.42	0.170	0.0156	0.0413	33.2	1281	12.1
LML Outflow	2014	0.187	1.35	0.116	0.0125	0.0245	18.9	1187	12.2
LML Outflow	2015	0.190	1.37	0.110	0.00746	0.0546	21.5	1103	13.5
LML Outflow	2018	0.286	2.46	0.0334	0.00700	0.0172	35.2	1364	13.7
LML Outflow	2019	0.0761	1.54	0.0102	0.0847	0.0349	7.75	1407	12.8
LML Outflow	2020	0.129	2.47	0.00730	0.464	0.368	17.3	1277	11.3
LML Backflow	2013	0.435	2.33	0.249	0.453	0.441	174	363	10.9
LML Backflow	2014	0.587	3.60	0.221	0.573	0.842	282	457	11.9
LML Backflow	2015	0.596	3.31	0.302	0.655	0.612	202	361	15.1
LML Backflow	2018	0.227	3.48	0.0758	1.31	0.482	47.1	757	10.4
LML Backflow	2019	0.250	2.19	0.0793	0.650	0.164	55.5	615	8.77
LML Backflow	2020	0.230	1.77	0.0347	0.421	0.111	88.6	483	6.16
Craven Dam	2013	0.318	2.82	0.188	0.634	0.734	128	796	11.5
Craven Dam	2014	0.315	2.72	0.154	0.440	0.633	79.1	962	14.8
Craven Dam	2015	0.344	3.14	0.159	0.576	0.814	98.9	884	14.3

Site	Study Year	TP (mg/L)	TN (mg/L)	TRP (mg/L)	NO3 (mg/L)	NH3 (mg/L)	TSS (mg/L)	TDS (mg/L)	DOC (mg/L)
Craven Dam	2018	0.248	3.08	0.0406	0.852	0.209	46.4	1009	10.9
Craven Dam	2019	0.173	2.33	0.0548	0.792	0.270	35.8	747	8.53
Craven Dam	2020	0.217	2.86	0.0467	1.13	0.222	50.0	596	7.86
HWY 6	2013	0.348	2.96	0.174	0.533	0.928	187	850	12.6
HWY 6	2014	0.324	2.57	0.173	0.316	0.625	101	988	13.6
HWY 6	2015	0.306	2.74	0.162	0.544	0.627	95.8	903	14.3
HWY 6	2018	0.290	2.62	0.0155	0.513	0.0765	91.9	1079	11.0
HWY 6	2019	0.175	2.31	0.0278	0.649	0.260	68.0	757	8.68
HWY 6	2020	0.247	2.62	0.0202	0.890	0.117	93.8	629	7.89
Loon Creek	2013	0.506	3.25	0.342	1.01	0.321	48.7	564	22.4
Loon Creek	2014	0.451	3.14	0.314	0.728	0.386	40.0	656	24.1
Loon Creek	2015	0.506	3.23	0.337	0.673	0.561	77.4	407	19.5
Loon Creek	2018	0.506	3.98	0.354	1.13	0.411	9.83	483	21.3
Loon Creek	2019	0	0						
Loon Creek	2020	1.15	5.14	0.877	1.14	0.251	10.0	266	24.8
Above Pasqua Lake	2013	0.386	3.31	0.208	0.687	1.16	120	837	13
Above Pasqua Lake	2014	0.388	2.64	0.199	0.360	0.564	140	944	13.7
Above Pasqua Lake	2015	0.334	2.76	0.167	0.539	0.501	99.9	867	14.9
Above Pasqua Lake	2018	0.251	2.65	0.0164	0.491	0.0909	101	1074	11.2
Above Pasqua Lake	2019	0.166	2.41	0.0244	0.688	0.211	71.5	759	8.72
Above Pasqua Lake	2020	0.327	2.81	0.0226	0.810	0.0861	130	641	9.19
Jumping Deer Creek	2013	0.135	2.15	0.0754	0.355	0.193	13.1	1149	21
Jumping Deer Creek	2014	0.222	1.97	0.149	0.0547	0.0891	18	886	23.3
Jumping Deer Creek	2015	0.232	1.91	0.139	0.138	0.174	32.8	633	19.9
Jumping Deer Creek	2018	0.325	3.52	0.159	0.807	0.488	40.1	1201	19.6
Jumping Deer Creek	2019	0.141	1.51	0.0715	0.0625	0.159	4.59	1664	18.3
Jumping Deer Creek	2020	0.300	2.38	0.126	0.0365	0.313	11.7	1032	17.9
Katepwa Outlet	2013	0.306	2.25	0.204	0.672	0.171	51.8	926	13.4
Katepwa Outlet	2014	0.238	1.88	0.154	0.237	0.205	7.20	889	13.2

Site	Study Year	TP (mg/L)	TN (mg/L)	TRP (mg/L)	NO3 (mg/L)	NH3 (mg/L)	TSS (mg/L)	TDS (mg/L)	DOC (mg/L)
Katepwa Outlet	2015	0.225	1.84	0.155	0.423	0.130	5.92	881	14.0
Katepwa Outlet	2018	0.165	1.87	0.0665	0.0615	0.242	8.21	1189	13.6
Katepwa Outlet	2019	0.152	2.16	0.0521	0.0785	0.385	7.94	1209	14
Katepwa Outlet	2020	0.172	2.12	0.0770	0.139	0.447	8.16	1218	14.2

Table 5: *Water and nutrient inflows and outflows for the Calling Lakes chain. Retention has been calculated in hm^3 or tonnes, and as a percentage of inflows.*

Variable	Period	Inflow (hm3 or t)	Outflow (hm3 or t)	Retention (hm3 or t)	Retention (percent)
Flow	2013-2015	2019	1961	57.9	2.87
Flow	2018-2020	206	157	49.7	24.1
TP Load	2013-2015	743	496	247	33.2
TP Load	2018-2020	50.7	25.0	25.6	50.6
TN Load	2013-2015	5699	3869	1830	32.1
TN Load	2018-2020	540	323	217	40.2

Table 6: *Inflow and outflow volume-weighted TP and TN concentrations for the Calling Lakes chain. The reduction in concentrations between the inflow and outflow is presented in mg/L and as a percentage of the inflow concentration.*

Variable	Period	Inflow (mg/L)	Outflow (mg/L)	Reduction (mg/L)	Reduction (percent)
TP	2013-2015	0.368	0.253	0.115	31.2
TP	2018-2020	0.246	0.160	0.0858	34.9
TN	2013-2015	2.82	1.97	0.850	30.1
TN	2018-2020	2.62	2.06	0.556	21.2

Table 7: *Total phosphorus and nitrogen loading for Loon and Jumping Deer Creeks. Loads are also given as a percentage of the Qu'Appelle River inflow to Pasqua Lake. Note that Jumping Deer Creek enters Pasqua Lake separately and doesn't contribute directly to the flow of the Qu'Appelle River upstream of Pasqua Lake.*

Site	Period	TP Load (t/yr)	TN Load (t/yr)	% TP Load Above Pasqua	% TN Load Above Pasqua
Loon Creek	2013-2015	5.96	39.6	2.41	2.09
Loon Creek	2018-2020	0.233	1.31	1.38	0.726
Jumping Deer Creek	2013-2015	4.75	42.8	1.92	2.25

Site	Period	TP Load (t/yr)	TN Load (t/yr)	% TP Load Above Pasqua	% TN Load Above Pasqua
Jumping Deer Creek	2018-2020	0.564	5.37	3.34	2.98

Table 8: *Wastewater effluent volumes, mean concentrations, total phosphorus and total nitrogen loading, and loading as a percentage of load above Pasqua Lake.*

Site	Period	Discharge (hm3/yr)	Mean TP (mg/L)	Mean TN (mg/L)	TP Load (t/year)	TN Load (t/year)	% TP Load Above Pasqua	% TN Load Above Pasqua
Moose Jaw	2013-2015	3.54	0.405	12.3	1.43	43.4	0.579	2.28
Moose Jaw	2018-2020	0.845	0.447	9.82	0.378	8.29	2.24	4.61
Regina	2013-2015	27.2	0.848	36.3	23.1	987	9.32	51.9
Regina	2018-2020	24.4	0.555	10.0	13.5	245	80.1	136

Figures

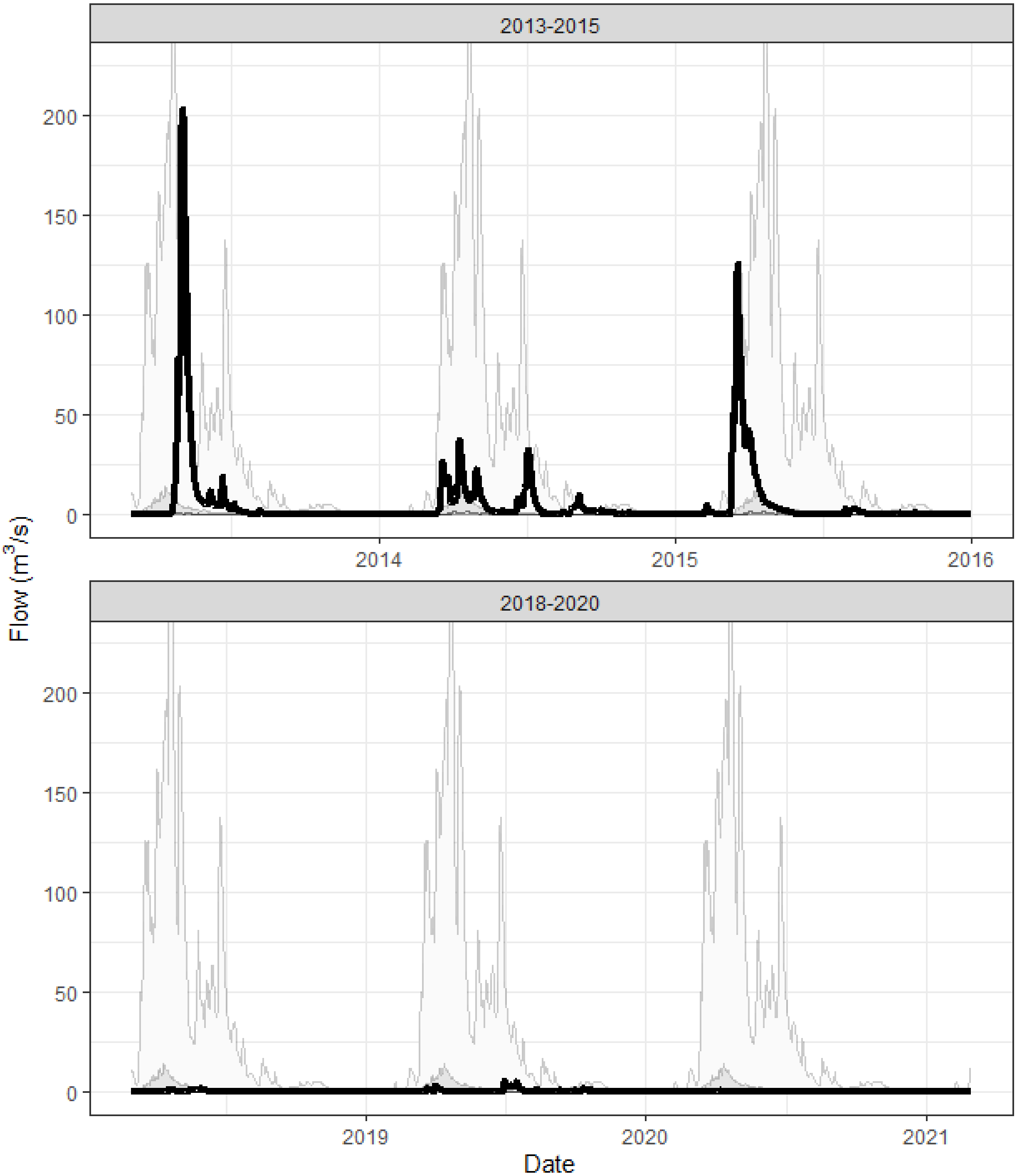


Figure 19: *Flows for the Moose Jaw River (at hydrometric station near Burdick) for the study periods 2013-2015 and 2018-2020. Shading indicates quantiles of historic flows. The lightest shading represents the 0-25th and 75-100th percentiles. Darker shading represents the 25-75th percentile, with a thin line representing median flows.*

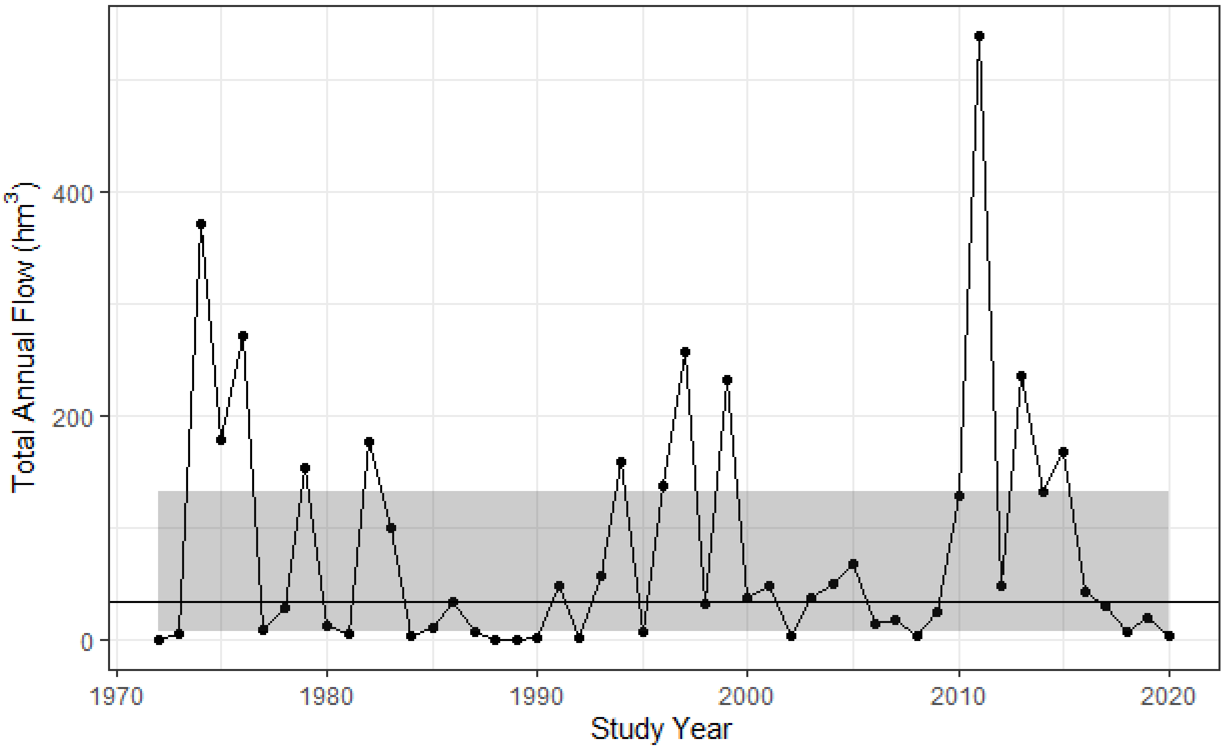


Figure 20: *Total annual flow for the Moose Jaw River (at hydrometric station near Burdick). Grey band represents the 25th - 75th percentile range of the data.*

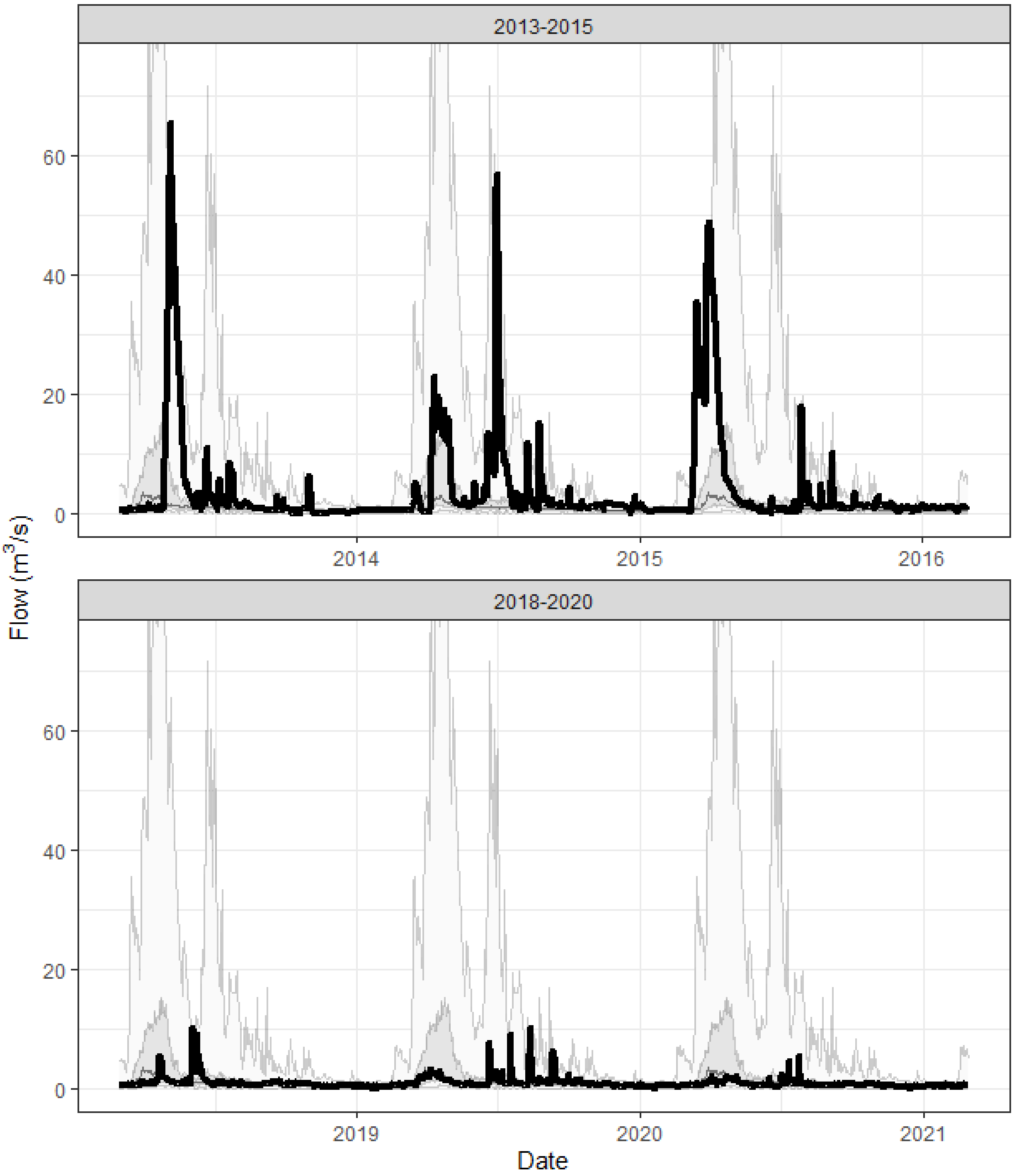


Figure 21: *Flows for Wascana Creek at Highway 641 for the study periods 2013-2015 and 2018-2020. Shading indicates quantiles of historic flows. The lightest shading represents the 0-25th and 75-100th percentiles. Darker shading represents the 25-75th percentile, with a thin line representing median flows.*

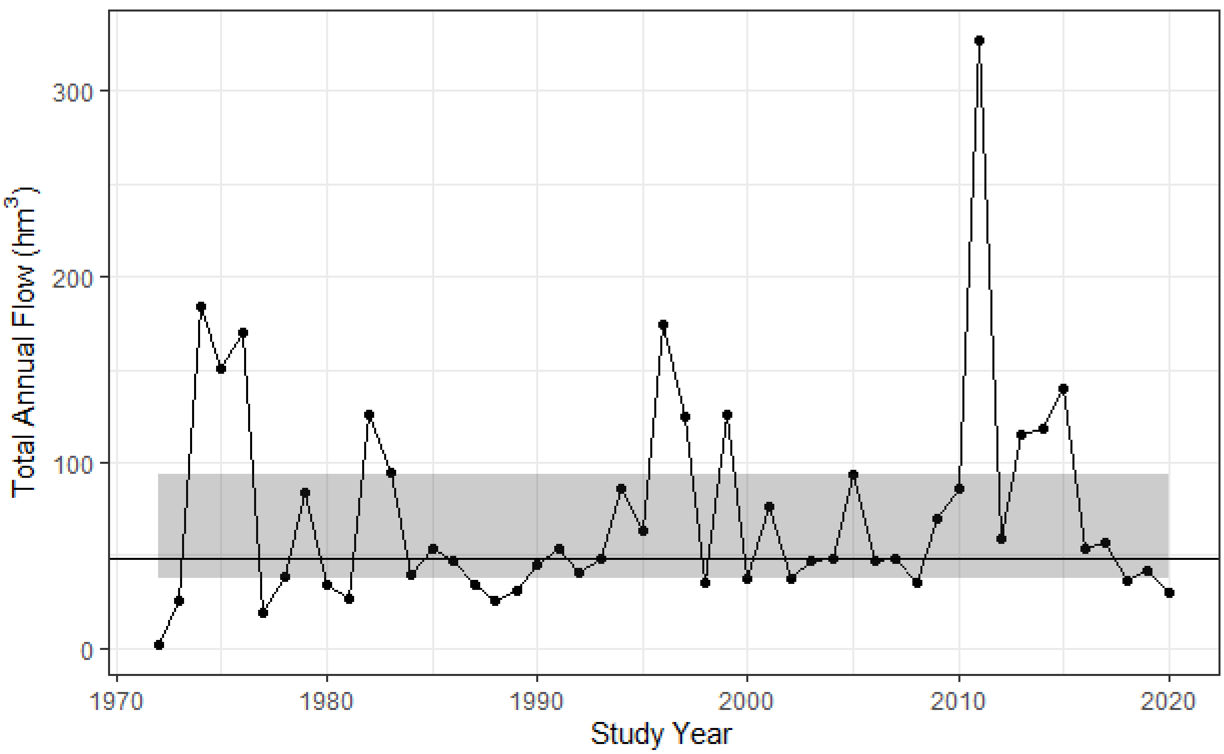


Figure 22: *Total annual flow for Wascana Creek. Grey band represents the 25th - 75th percentile range of the data.*

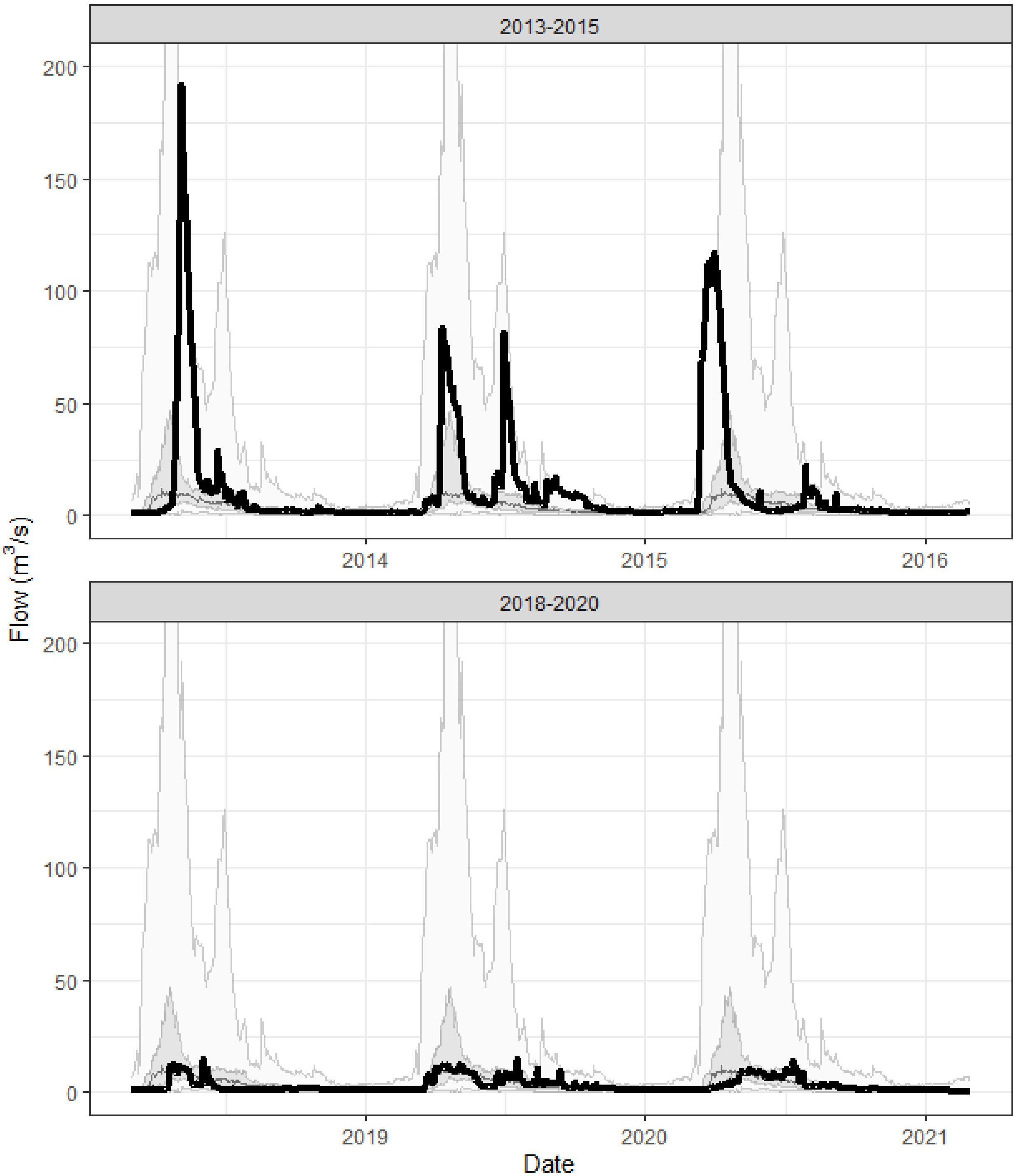


Figure 23: *Flows for the Qu'Appelle River at Lumsden for the study periods 2013-2015 and 2018-2020. Shading indicates quantiles of historic flows. The lightest shading represents the 0-25th and 75-100th percentiles. Darker shading represents the 25-75th percentile, with a thin line representing median flows.*

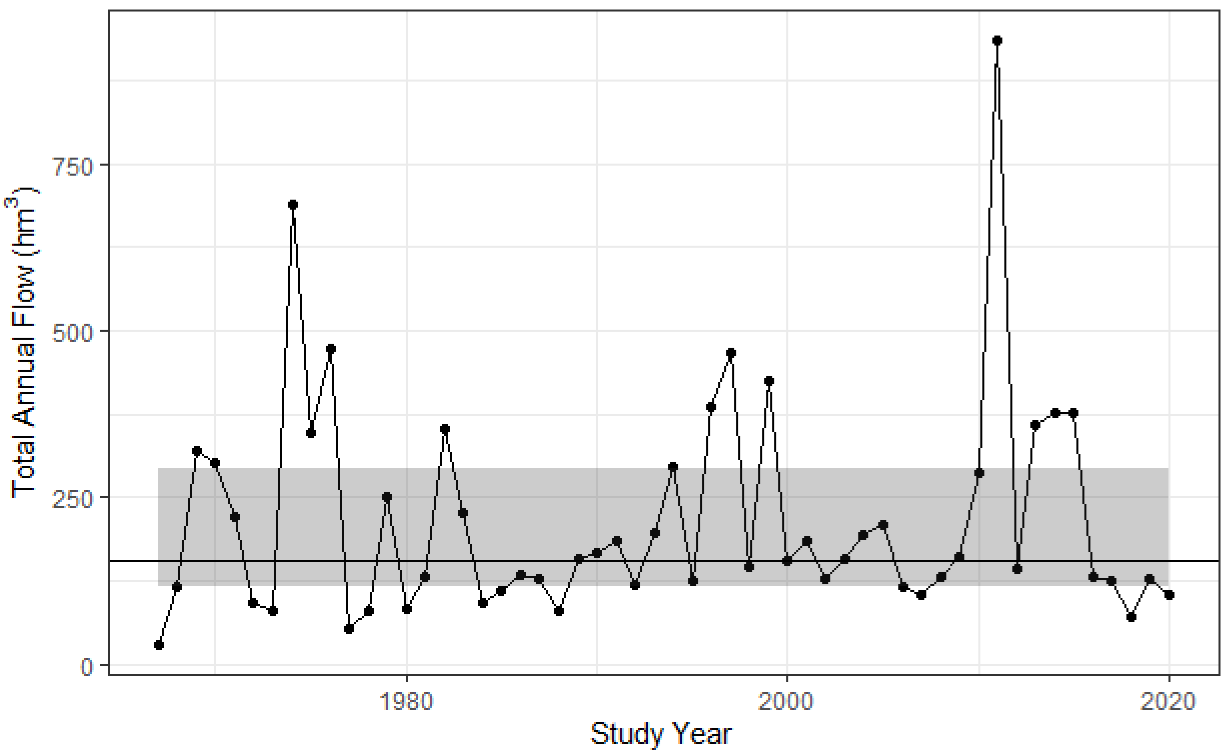


Figure 24: *Total annual flow for the Qu'Appelle River at Lumsden. Grey band represents the 25th - 75th percentile range of the data.*

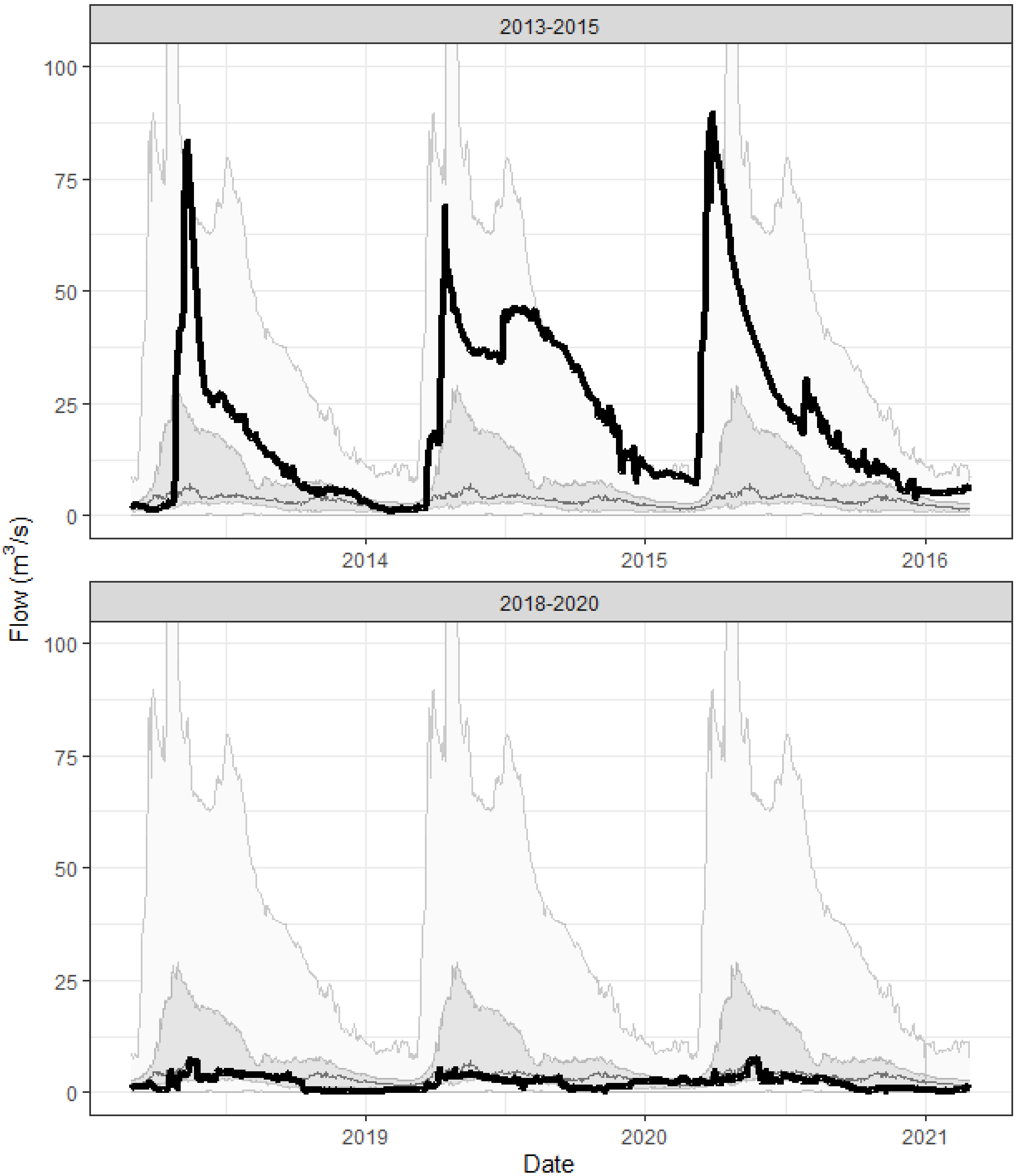


Figure 25: *Flows for the Qu'Appelle River above Pasqua Lake for the study periods 2013-2015 and 2018-2020. Shading indicates quantiles of historic flows. The lightest shading represents the 0-25th and 75-100th percentiles. Darker shading represents the 25-75th percentile, with a thin line representing median flows.*

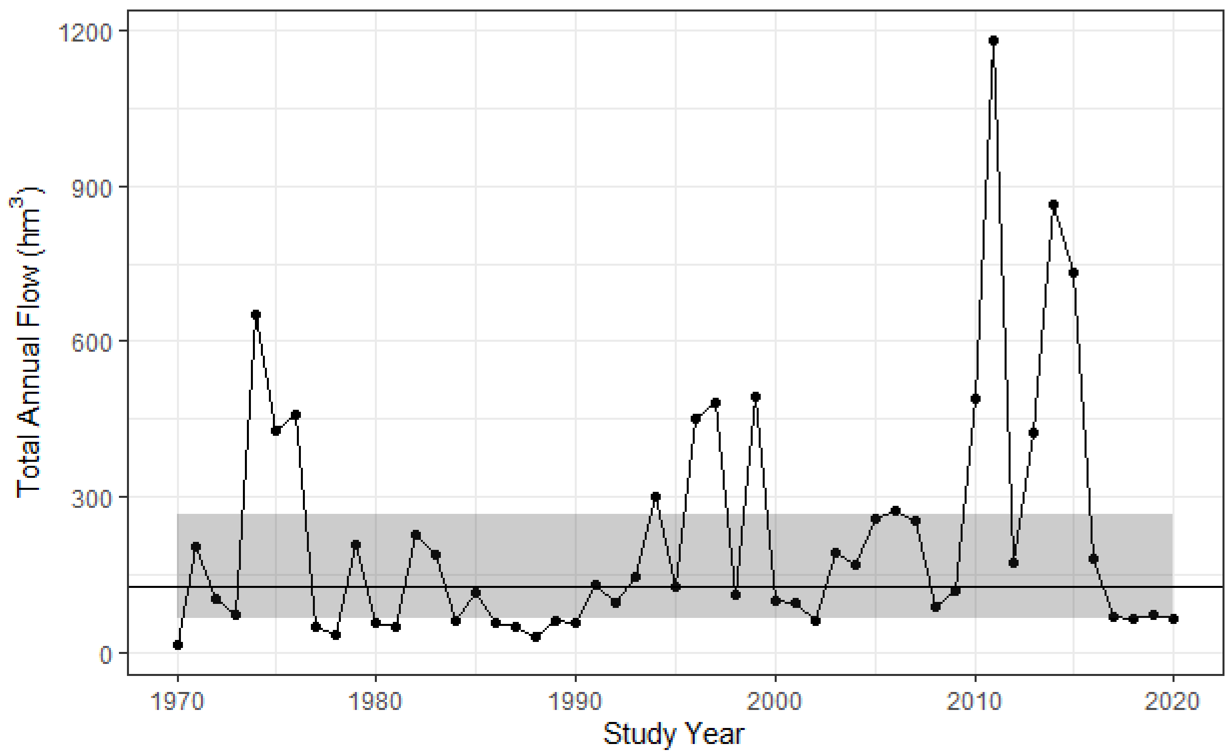


Figure 26: *Total annual flow for the Qu'Appelle River above Pasqua Lake. Grey band represents the 25th - 75th percentile range of the data.*

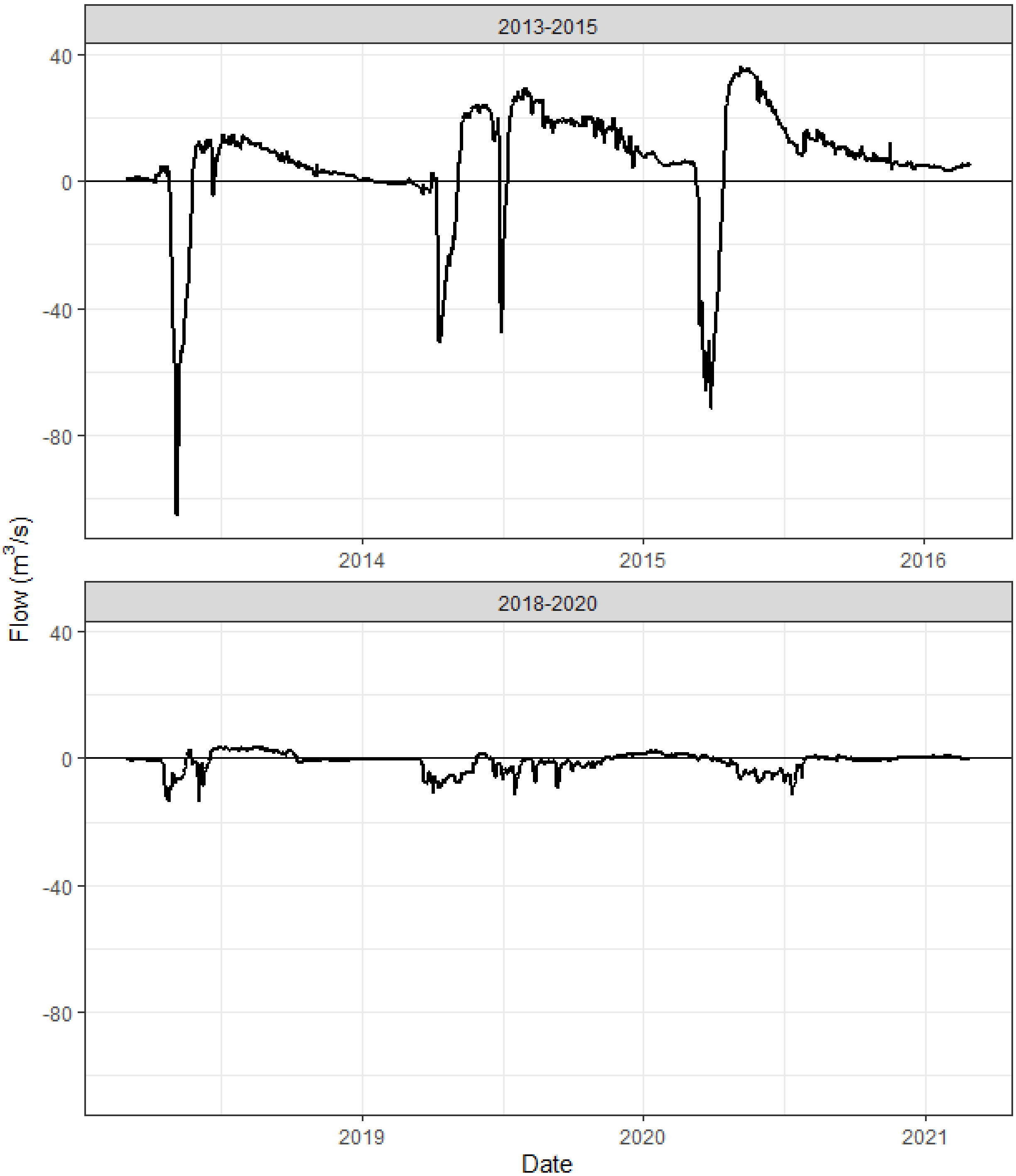


Figure 27: *Flows at Last Mountain Creek for the study periods 2013-2015 and 2018-2020. Positive flow values indicate flow from Last Mountain Lake towards the Qu'Appelle River, negative flow values indicate flow from the Qu'Appelle River towards Last Mountain Lake. A horizontal line at 0 has been added for easier interpretation.*

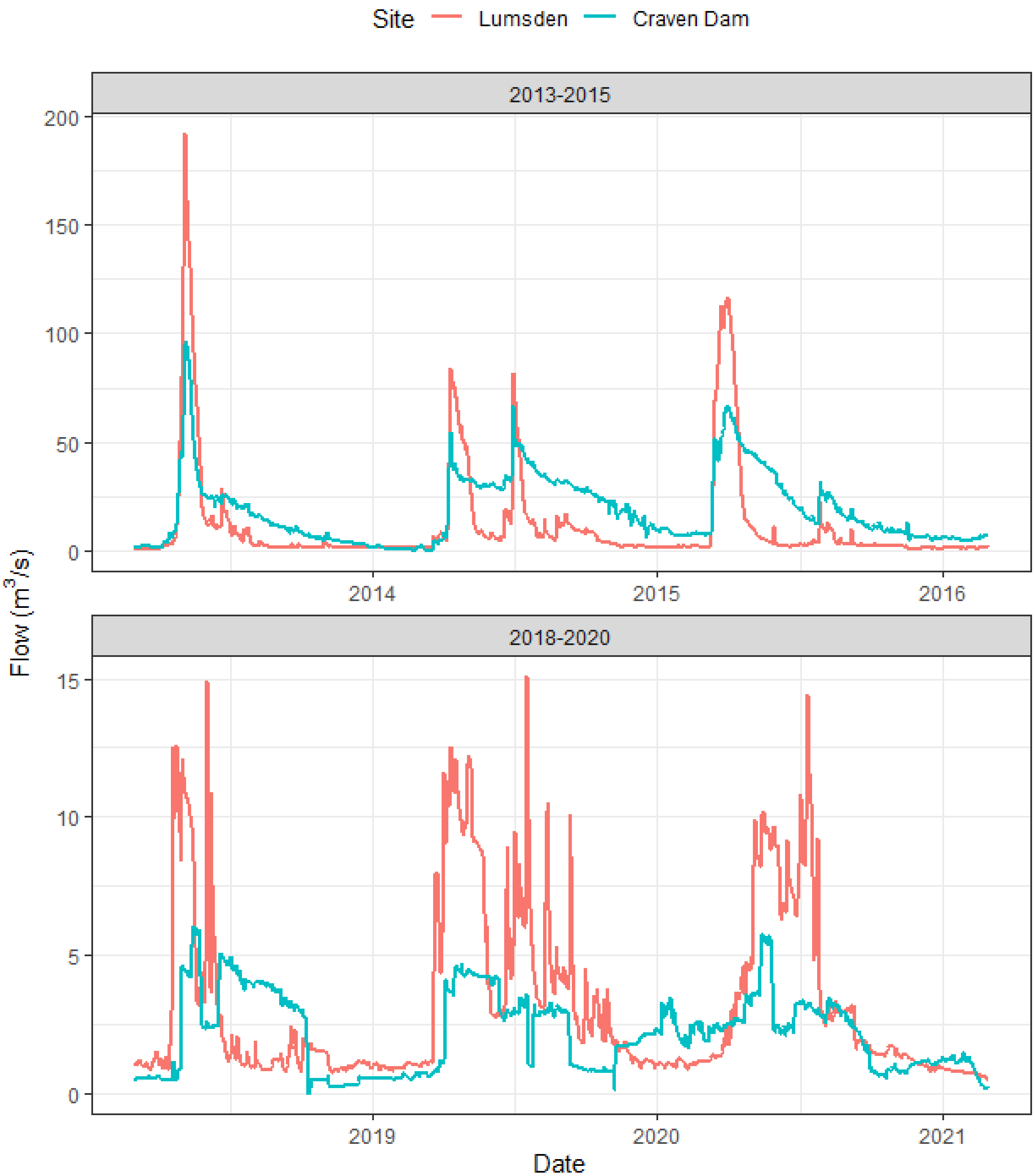


Figure 28: *Flows for the Qu'Appelle River at Lumsden and below Craven Dam study periods 2013-2015 and 2018-2020. Note the change in y-axis scales between the two periods. When flows at Lumsden exceed flows below Craven Dam, a portion of Qu'Appelle River flows are diverted to Last Mountain Lake. When flows below Craven Dam exceed flows at Lumsden, the Last Mountain Lake outflow contributes to the Qu'Appelle River flow (in addition to some local runoff from the watershed between Lumsden and Craven).*

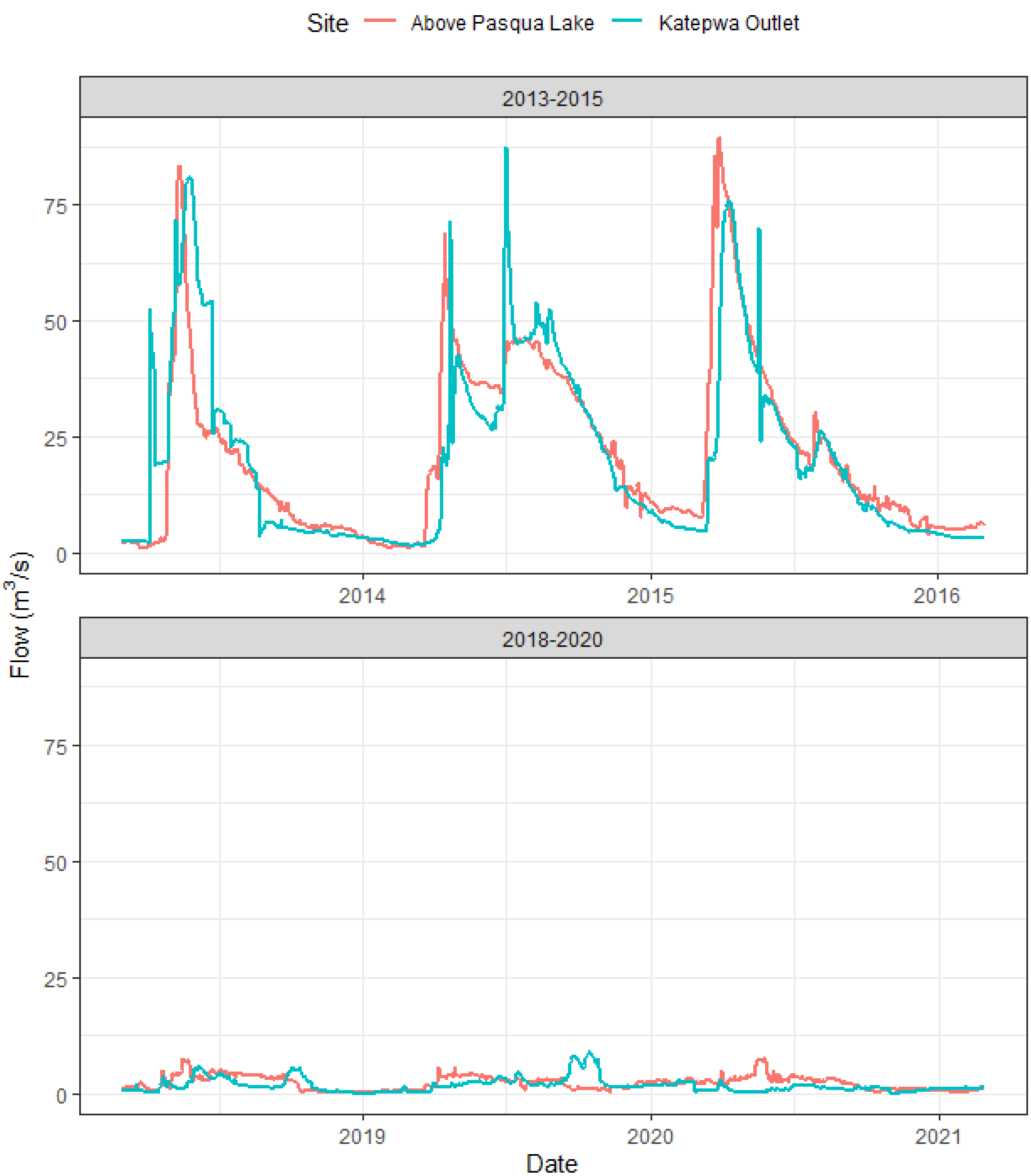


Figure 29: *Flows for the Qu'Appelle River above Pasqua Lake and Katepwa Lake Outlet for the study periods 2013-2015 and 2018-2020.*

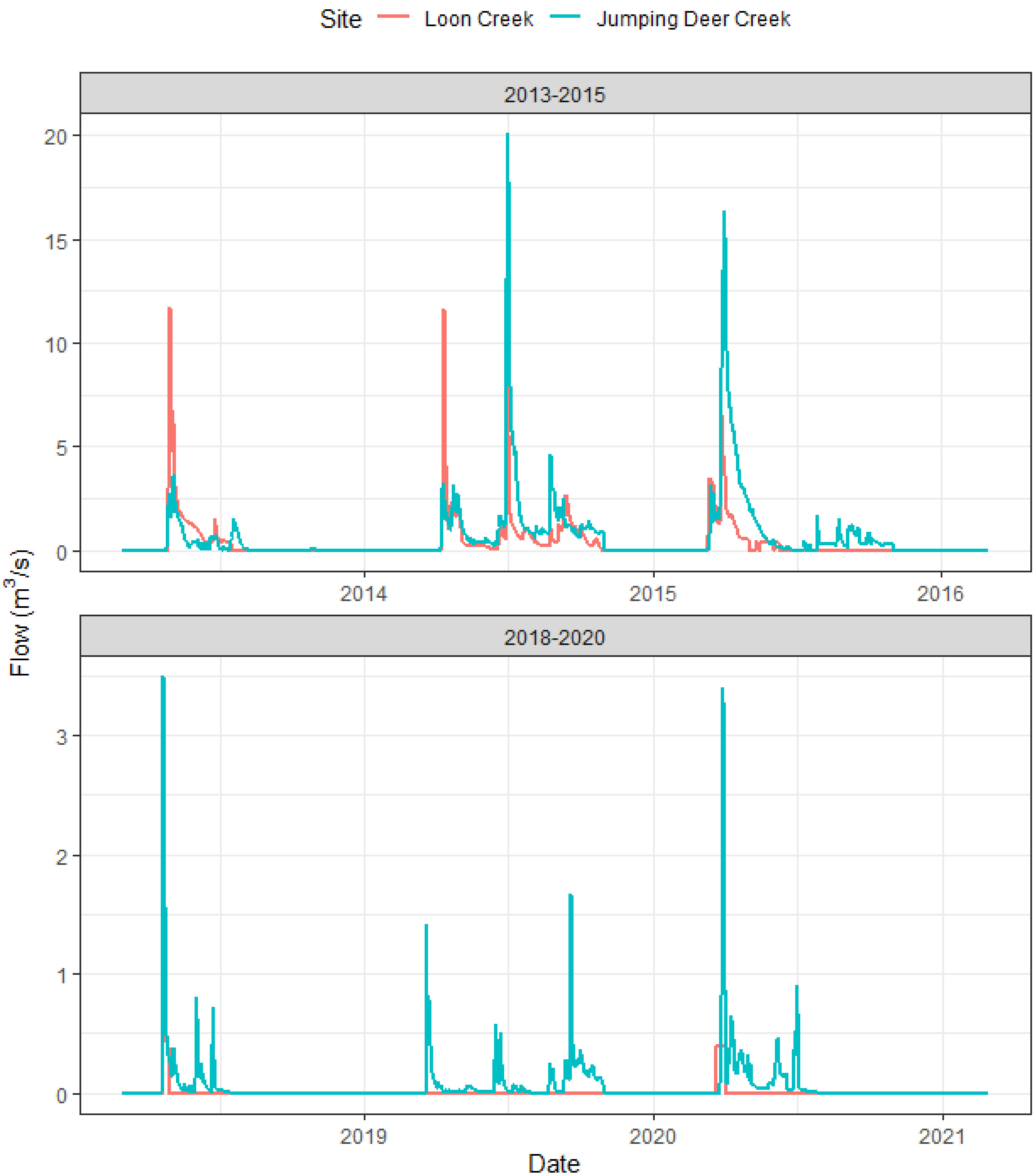


Figure 30: *Flows for Jumping Deer and Loon creeks during the study periods 2013-2015 and 2018-2020.*

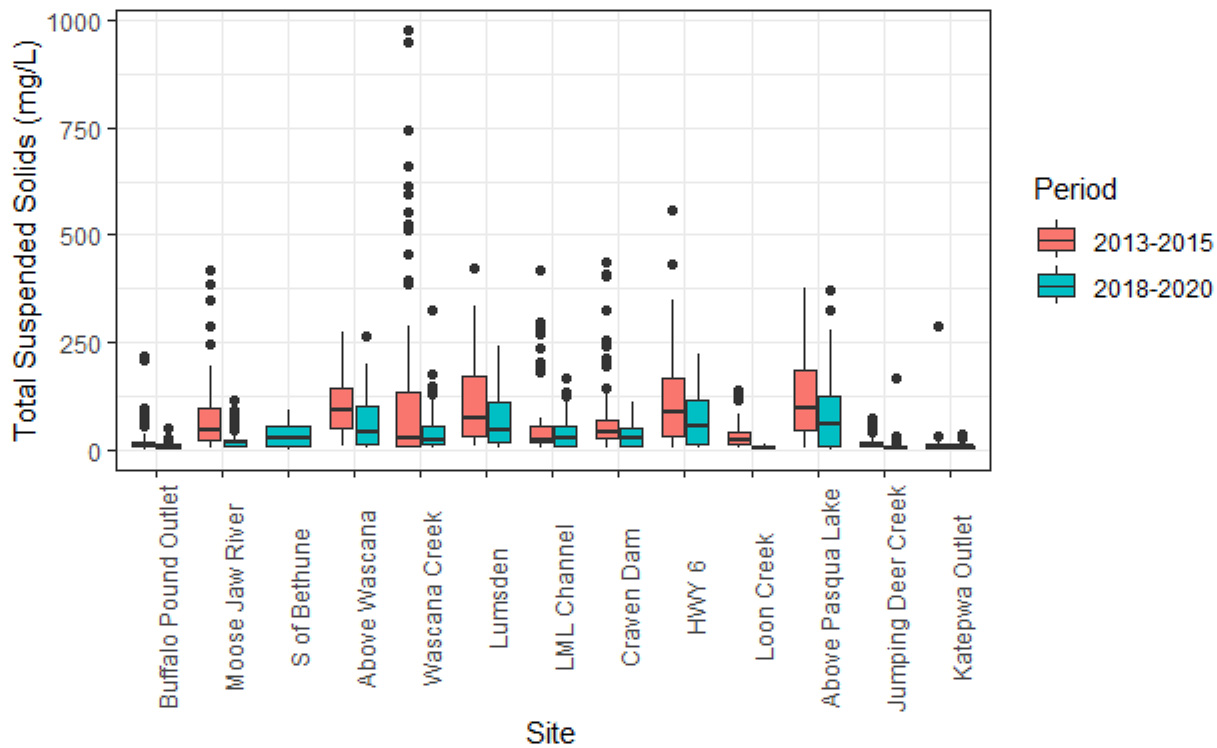


Figure 31: *Boxplots of total suspended solids concentrations split into the periods 2013-2015 and 2018-2020.*

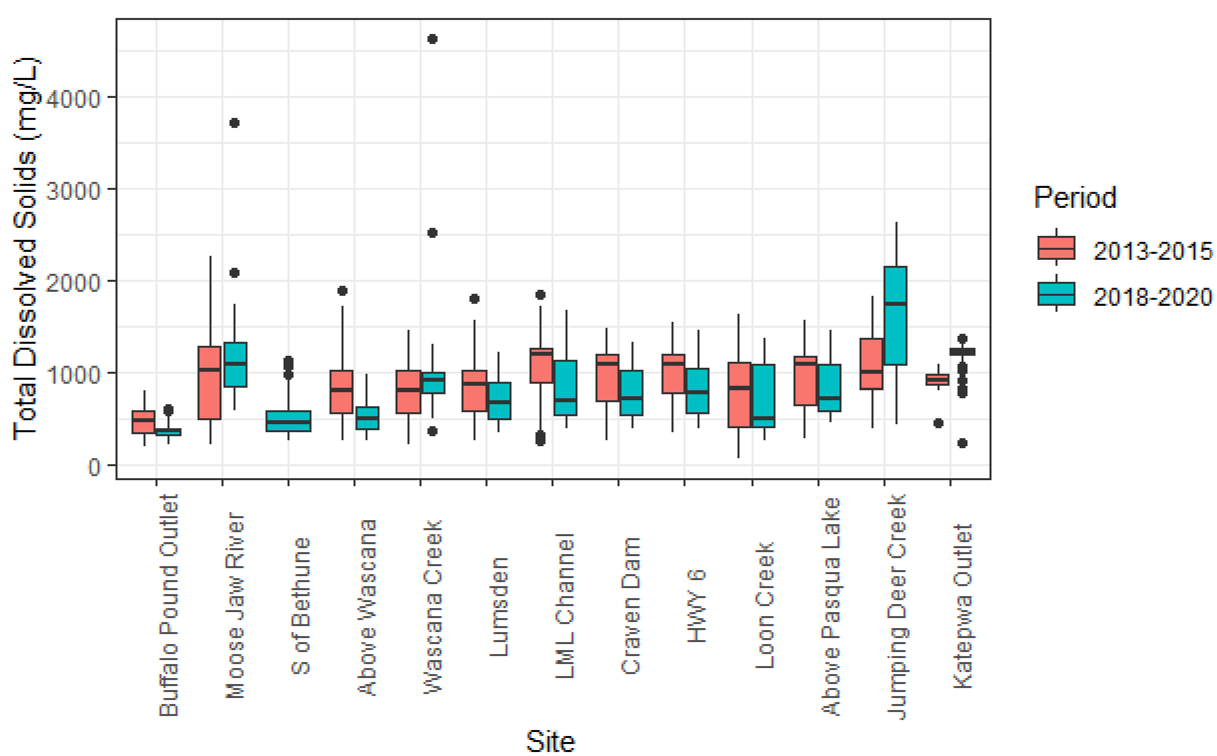


Figure 32: *Boxplots of total dissolved solids concentrations split into the periods 2013-2015 and 2018-2020.*

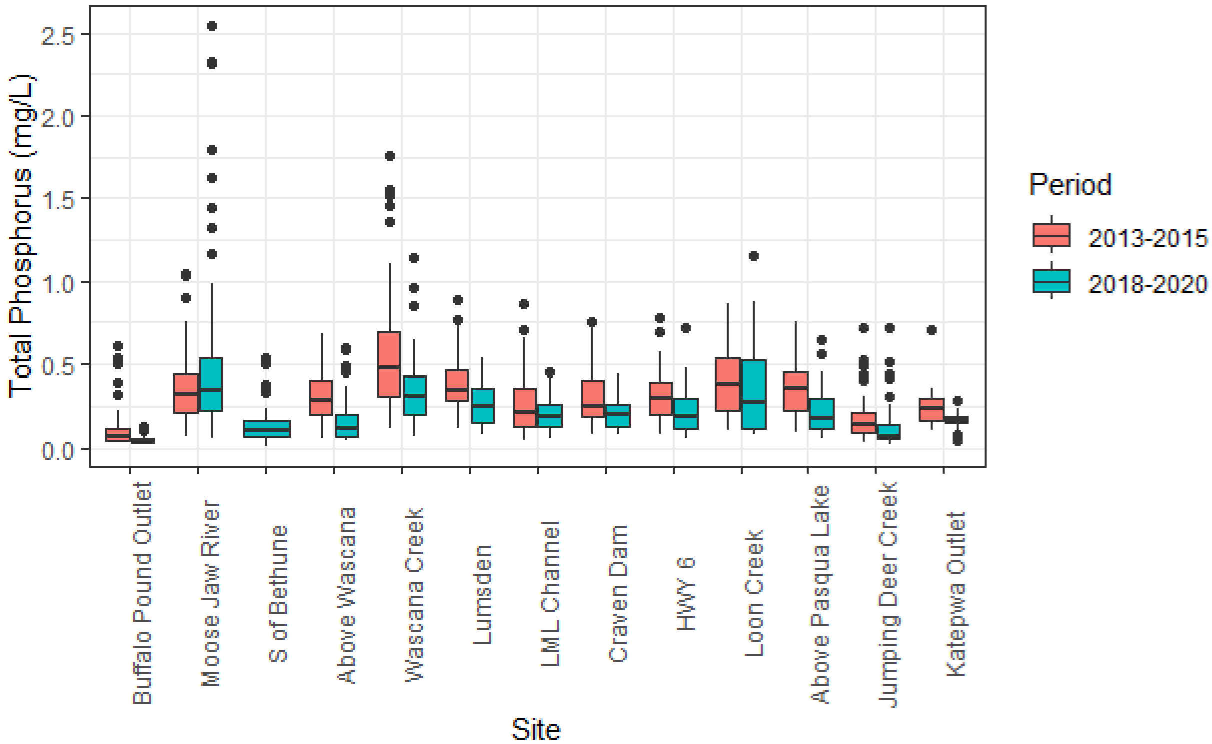


Figure 33: *Boxplots of total phosphorus concentrations split into the periods 2013-2015 and 2018-2020.*

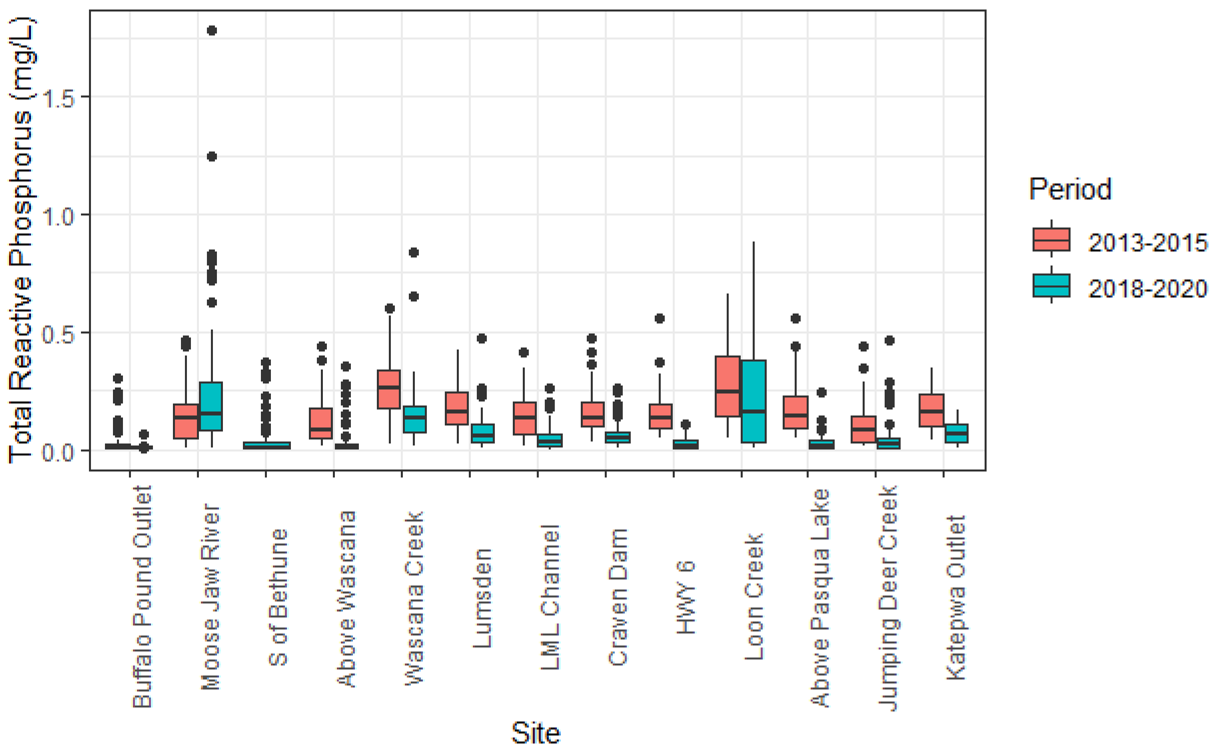


Figure 34: *Boxplots of total reactive phosphorus concentrations split into the periods 2013-2015 and 2018-2020. Note that most of 2020, soluble reactive phosphorus was measured rather than total reactive phosphorus.*

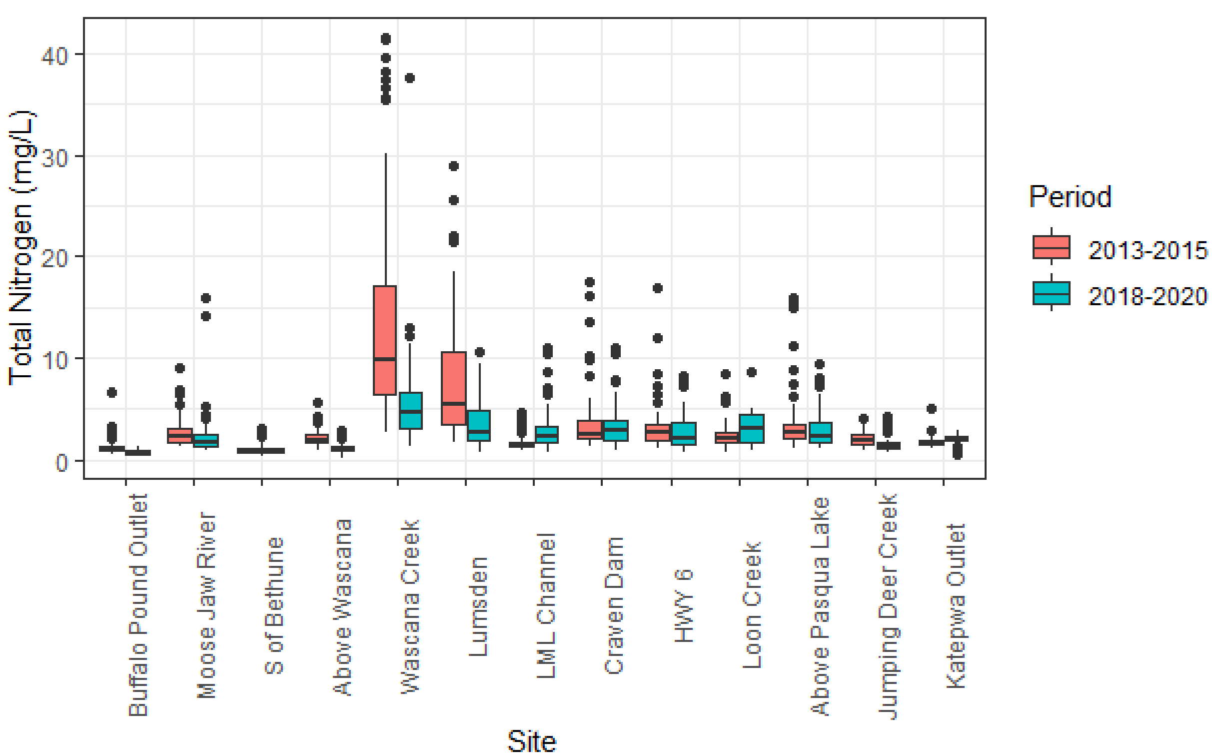


Figure 35: *Boxplots of total nitrogen concentrations split into the periods 2013-2015 and 2018-2020.*

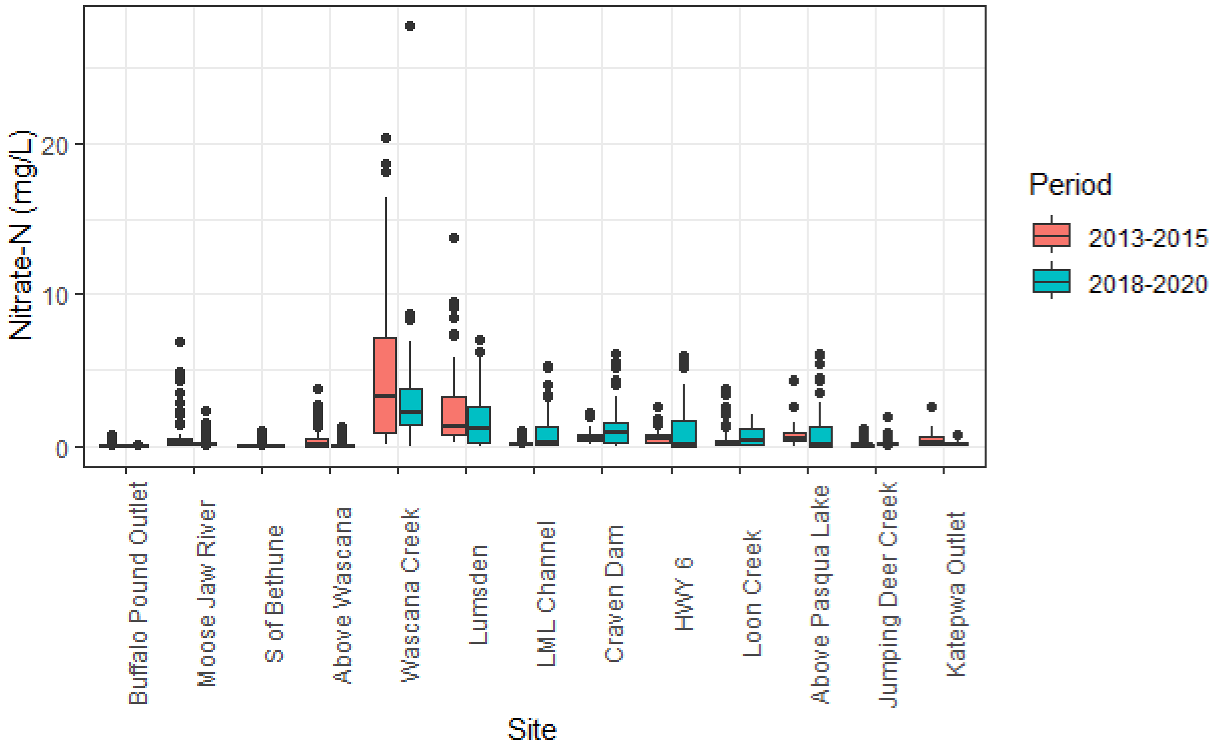


Figure 36: *Boxplots of nitrate N concentrations split into the periods 2013-2015 and 2018-2020.*

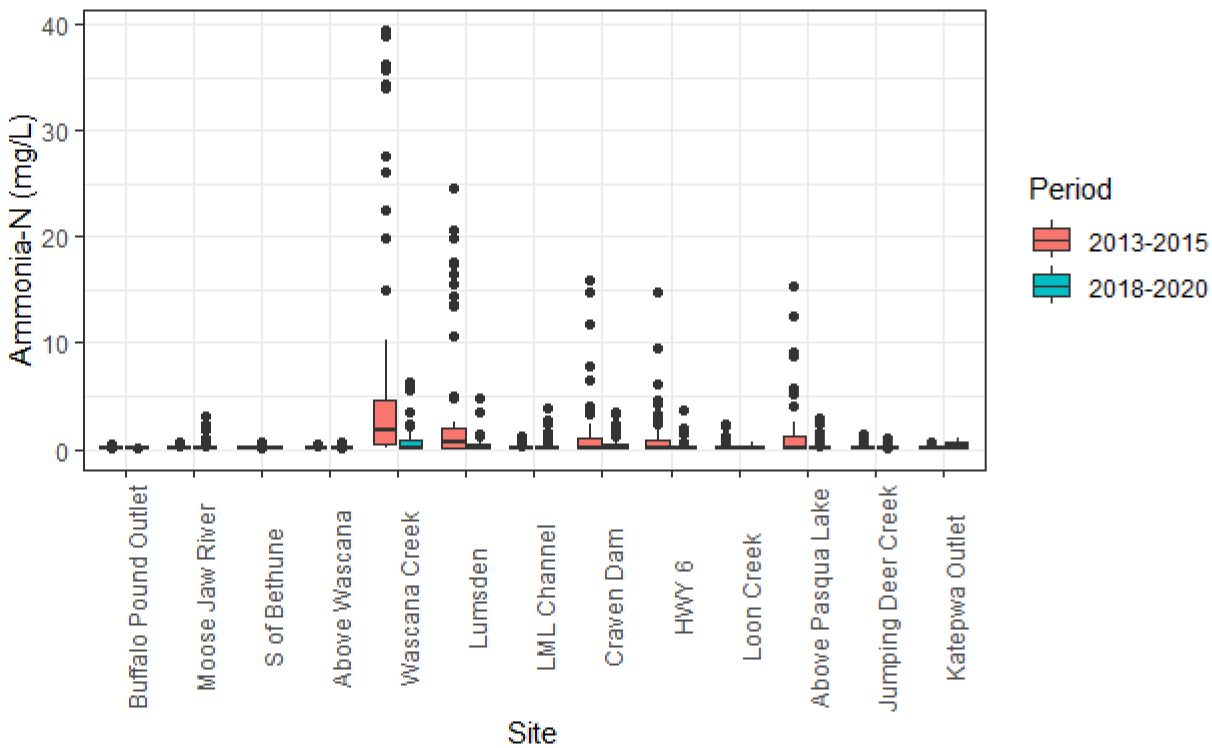


Figure 37: *Boxplots of ammonia N concentrations split into the periods 2013-2015 and 2018-2020.*

Figure 38: *Total phosphorus and total reactive phosphorus concentrations for Buffalo Pound Outlet.*

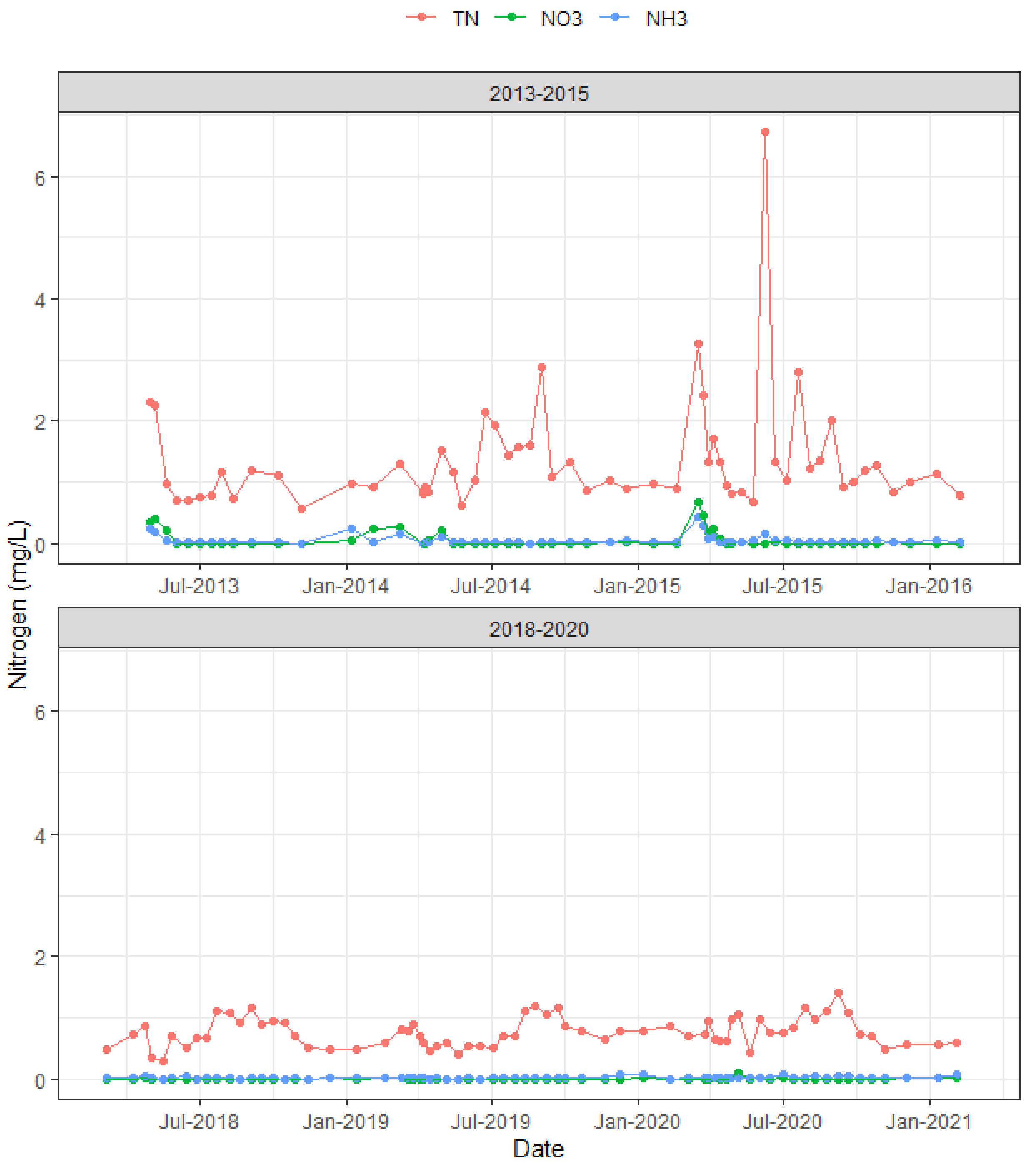


Figure 39: *Total nitrogen, nitrate-N, and total ammonia-N concentrations for Buffalo Pound Outlet.*

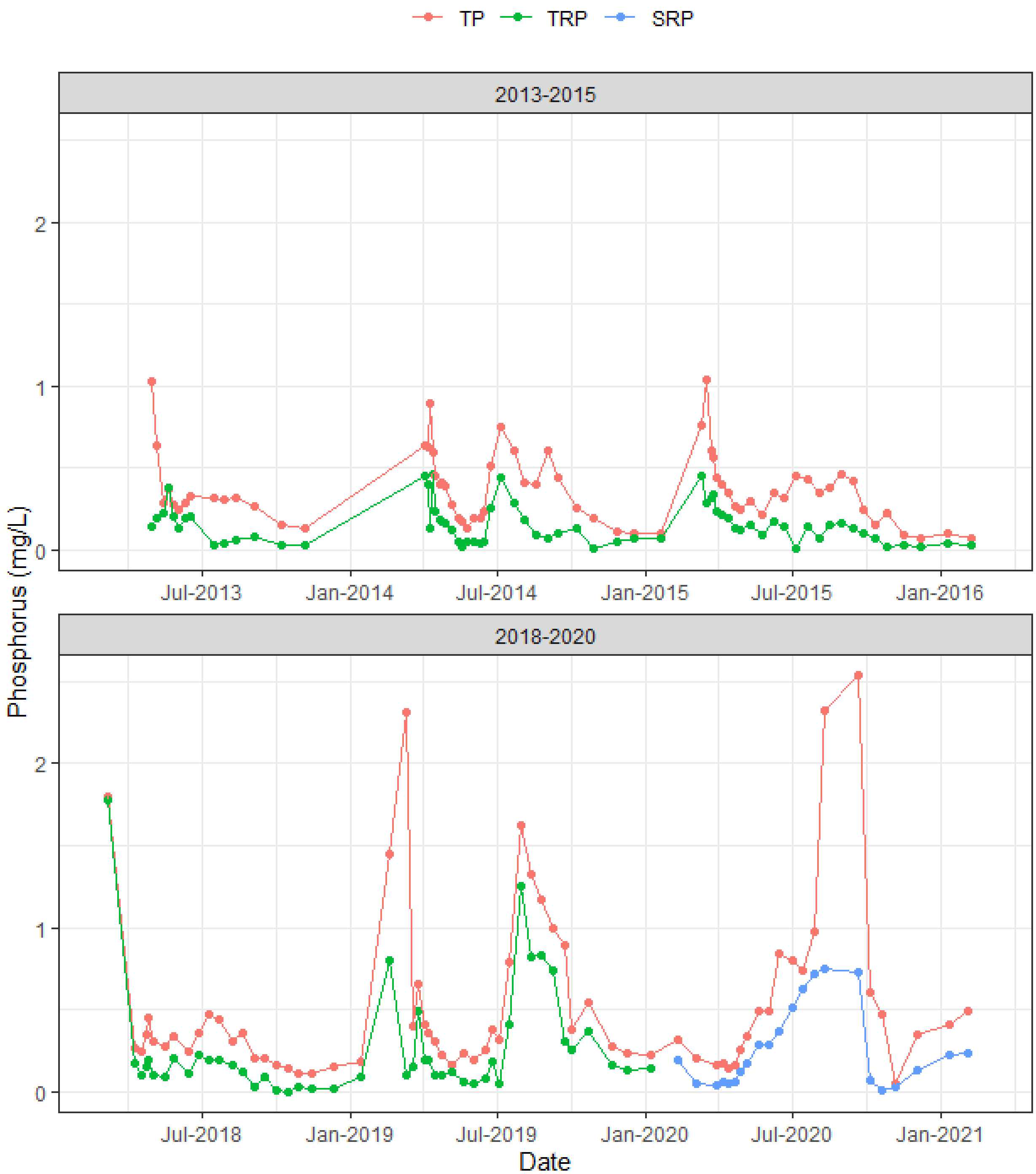


Figure 40: *Total phosphorus and total reactive phosphorus concentrations for the Moose Jaw River at TWP RD 184.*

Figure 41: *Total nitrogen, nitrate-N, and total ammonia-N concentrations for the Moose Jaw River at TWP RD 184.*

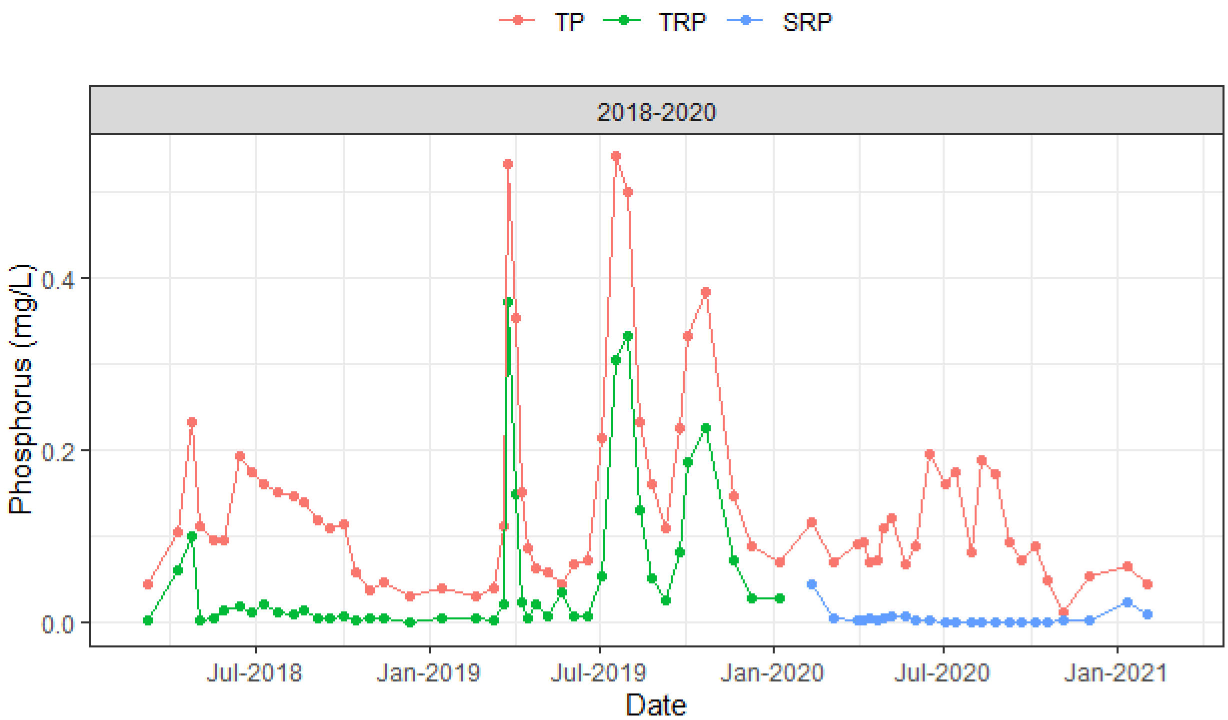


Figure 42: *Total phosphorus and total reactive phosphorus concentrations for the Qu'Appelle River South of Bethune.*

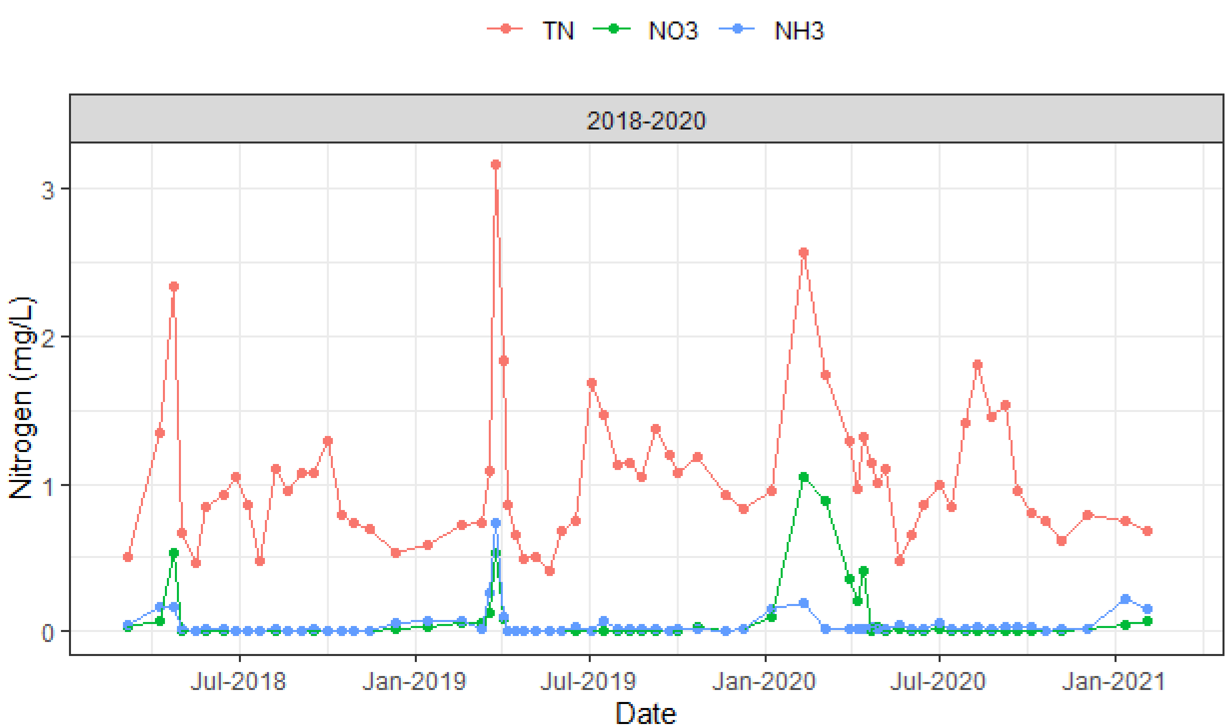


Figure 43: *Total nitrogen, nitrate-N, and total ammonia-N concentrations for the Qu'Appelle River South of Bethune.*

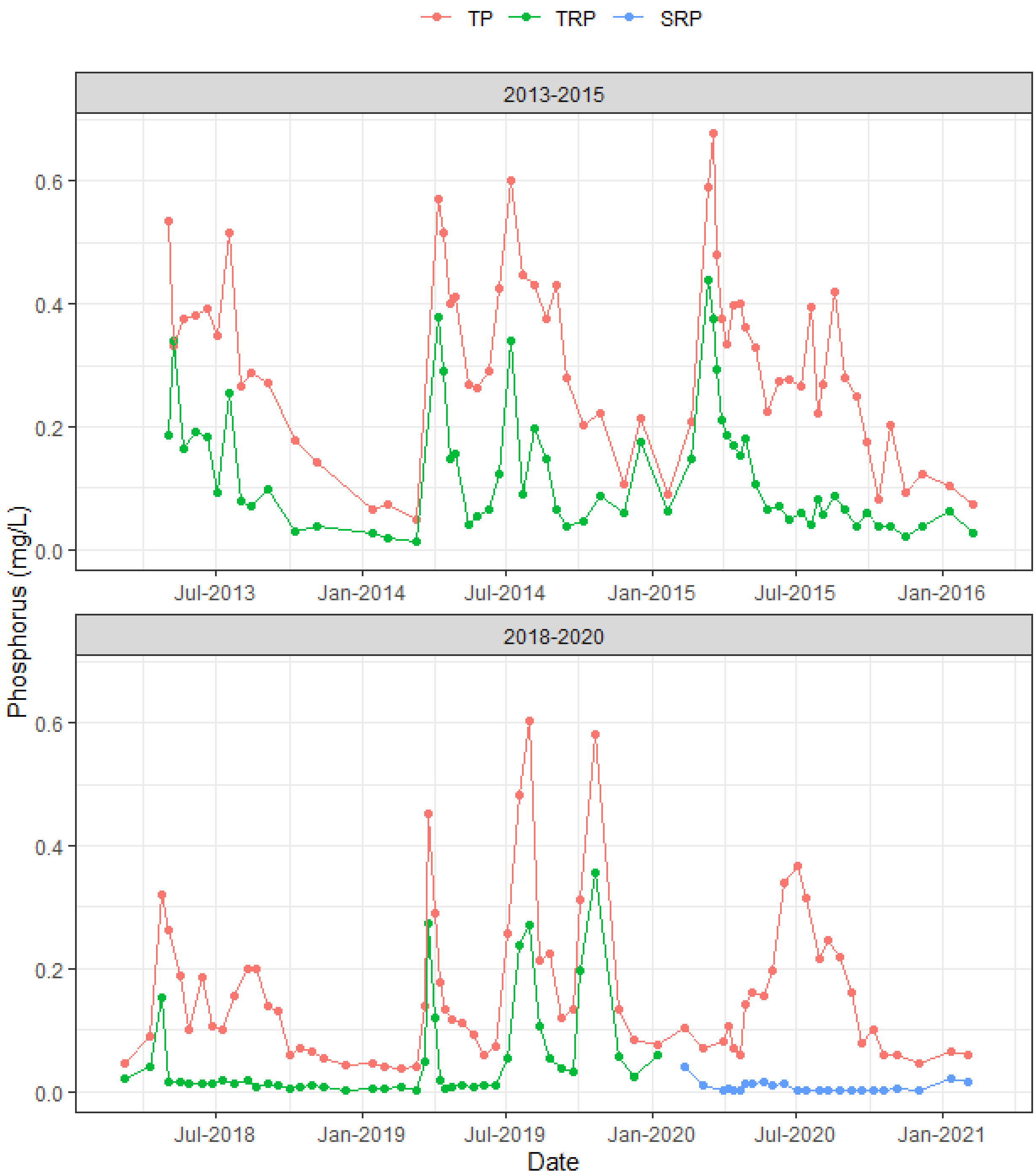


Figure 44: *Total phosphorus and total reactive phosphorus concentrations for the Qu'Appelle River above Wascana Creek.*

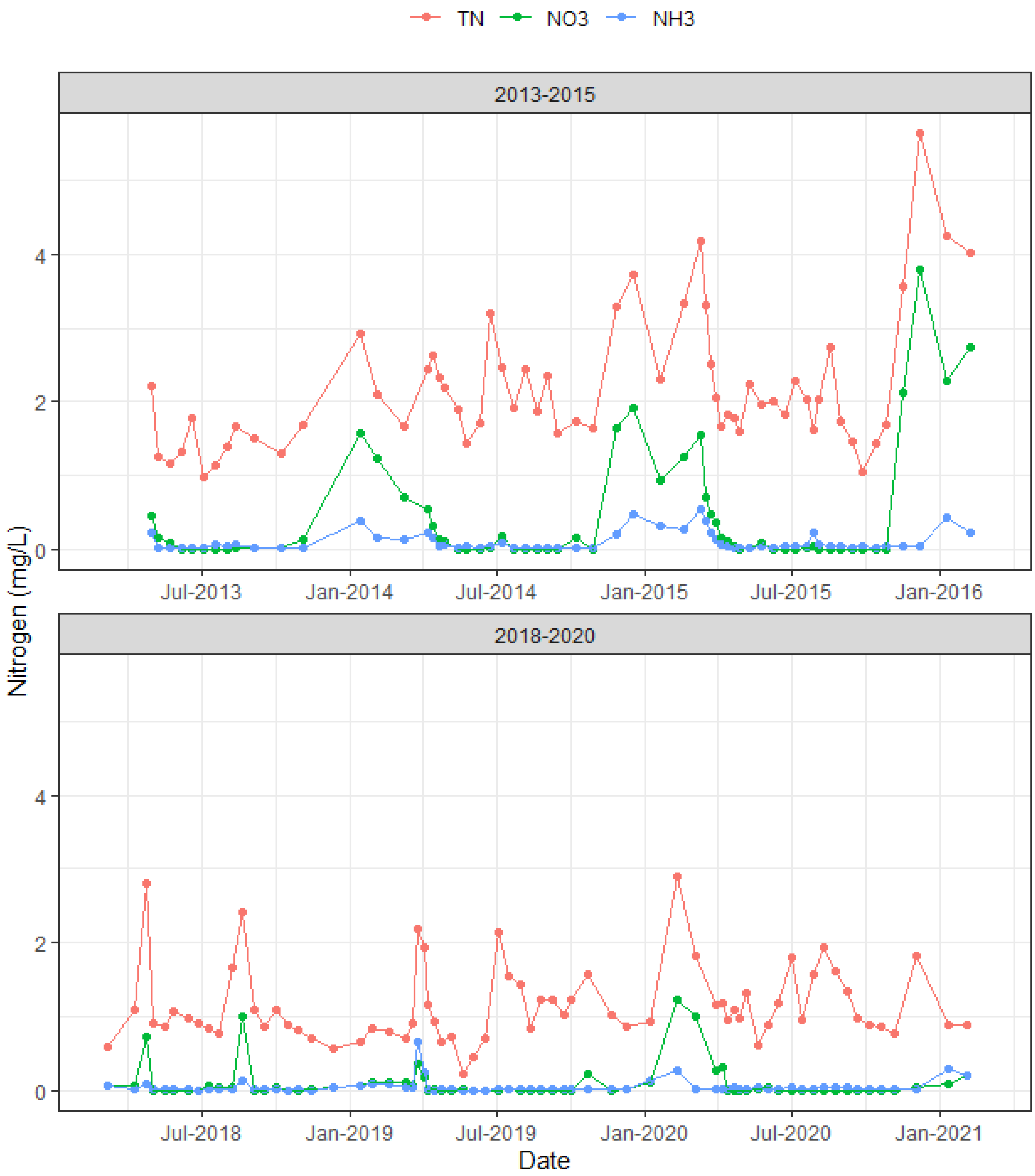


Figure 45: *Total nitrogen, nitrate-N, and total ammonia-N concentrations for the Qu'Appelle River above Wascana Creek.*

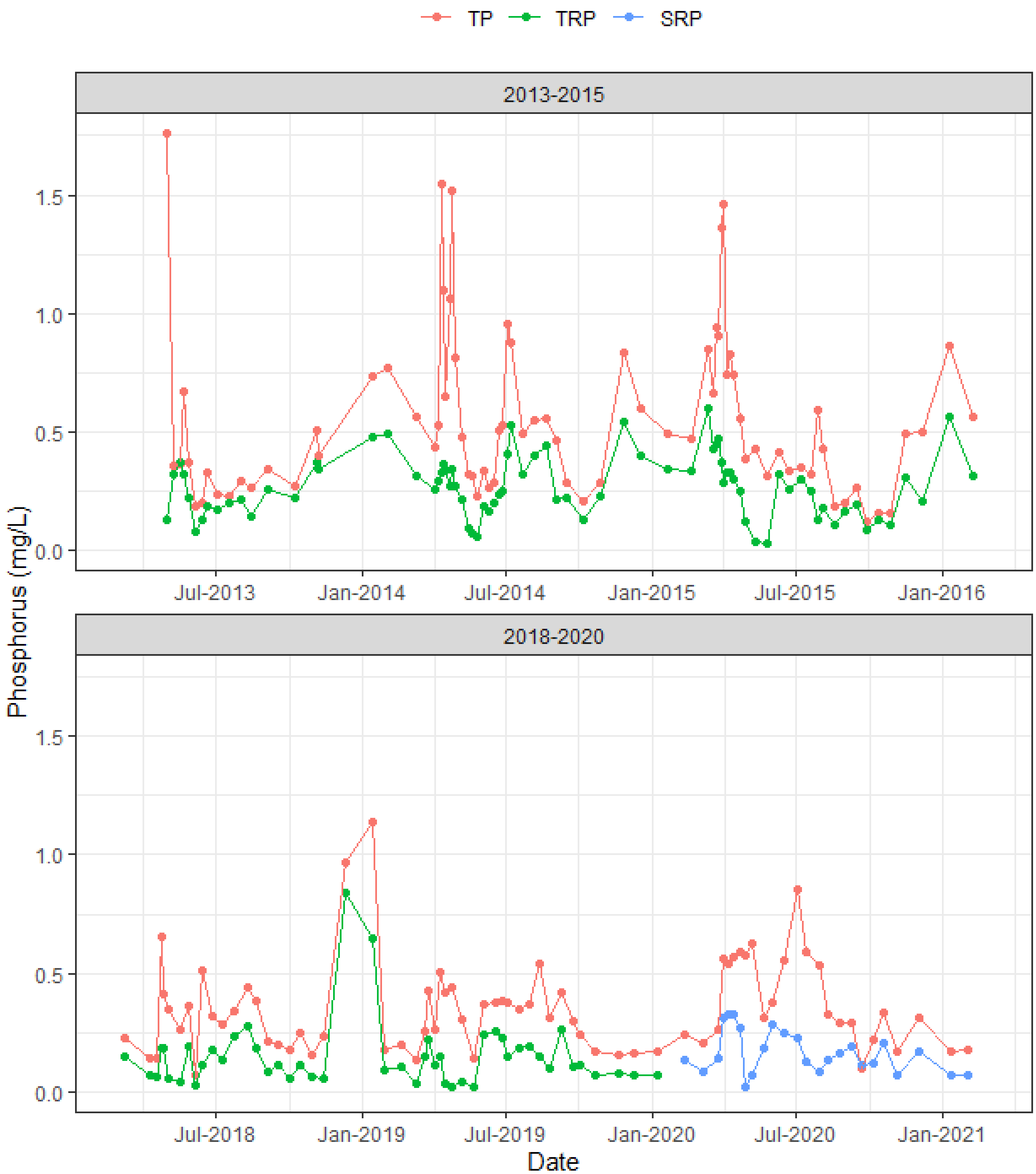


Figure 46: *Total phosphorus and total reactive phosphorus concentrations for Wascana Creek.*

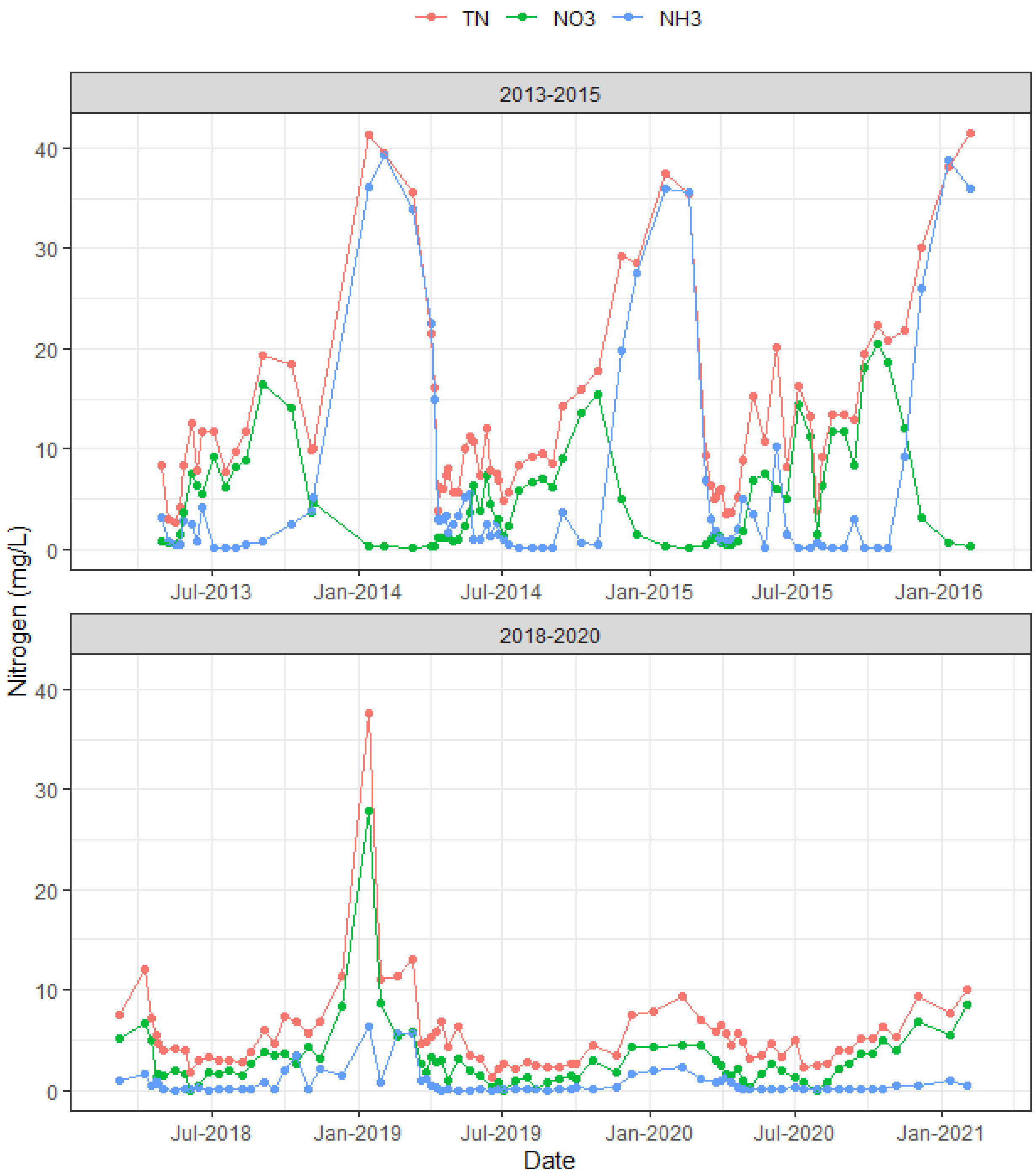


Figure 47: *Total nitrogen, nitrate-N, and total ammonia-N concentrations for Wascana Creek.*

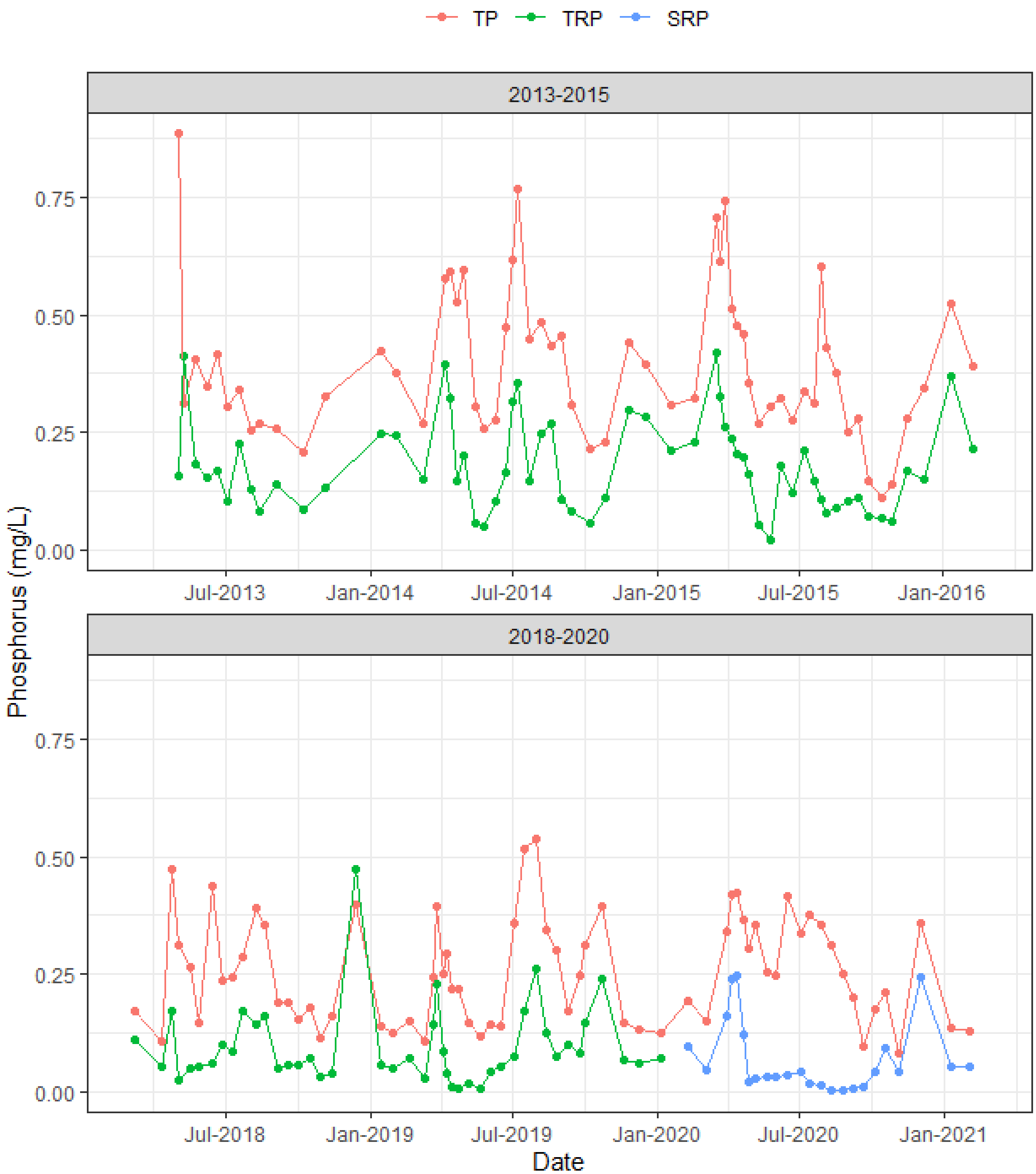


Figure 48: *Total phosphorus and total reactive phosphorus concentrations for the Qu'Appelle River at Lumsden.*

Figure 49: *Total nitrogen, nitrate-N, and total ammonia-N concentrations for the Qu'Appelle River at Lumsden.*

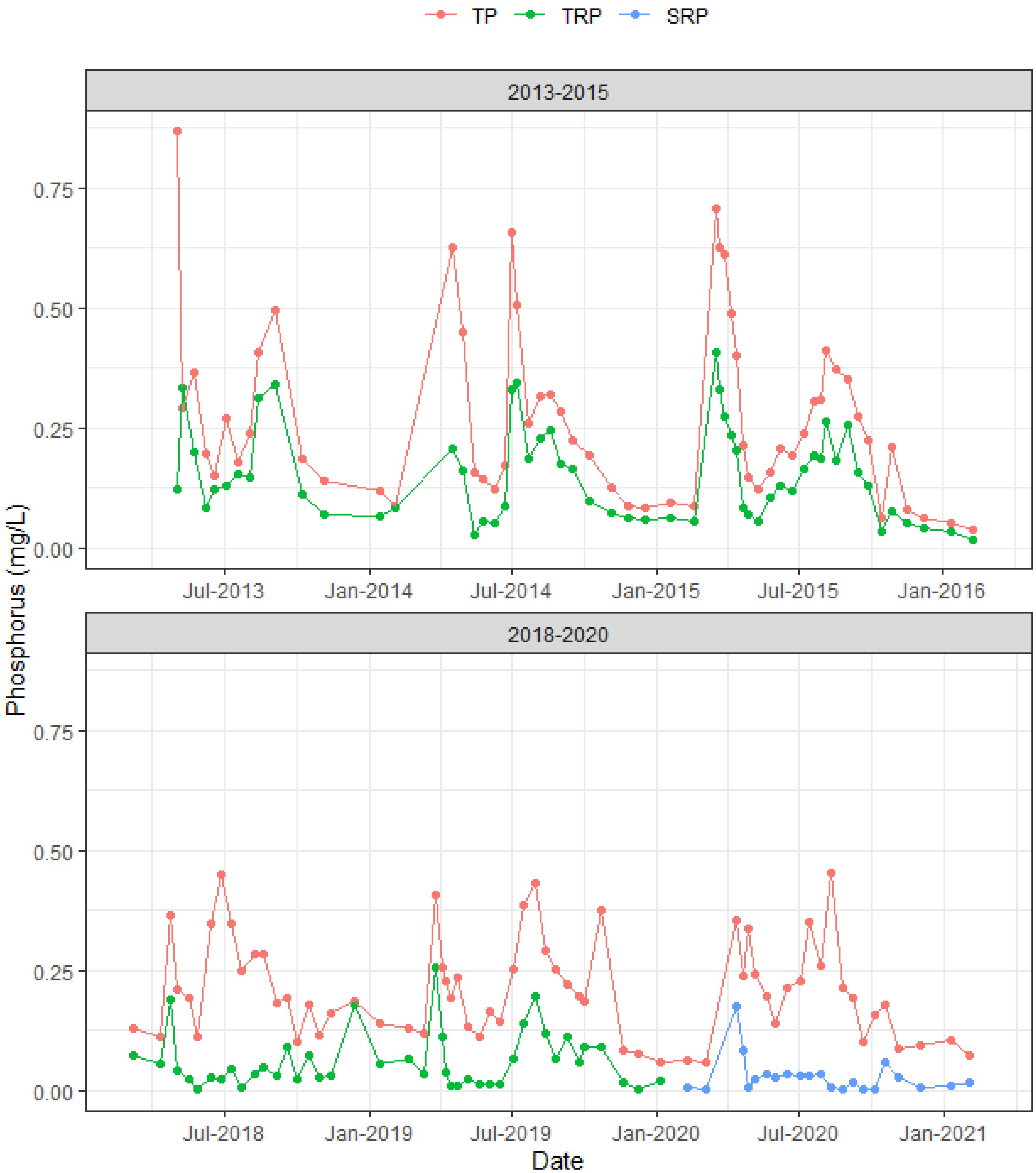


Figure 50: *Total phosphorus and total reactive phosphorus concentrations for Last Mountain Creek.*

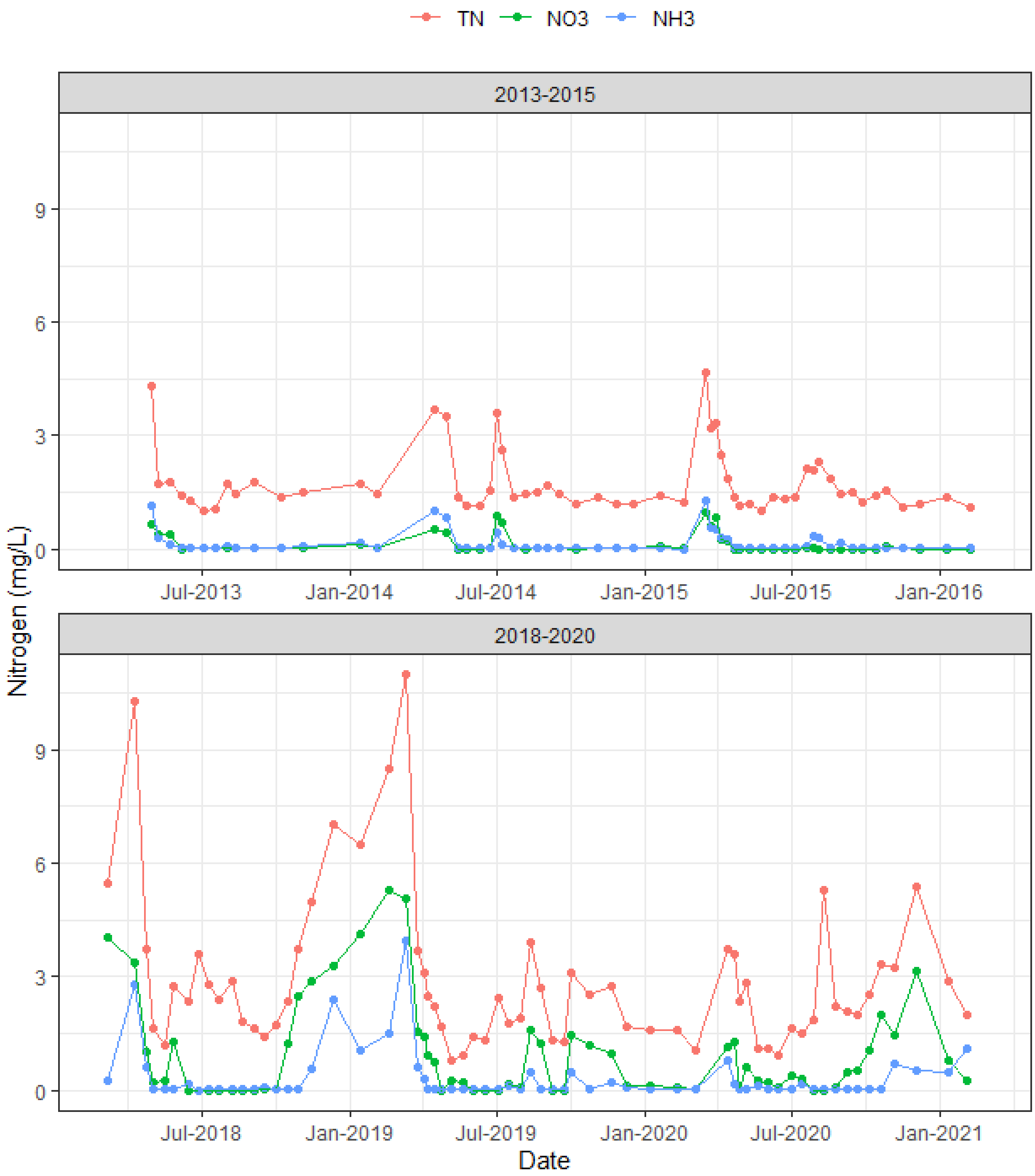


Figure 51: *Total nitrogen, nitrate-N, and total ammonia-N concentrations for Last Mountain Creek.*

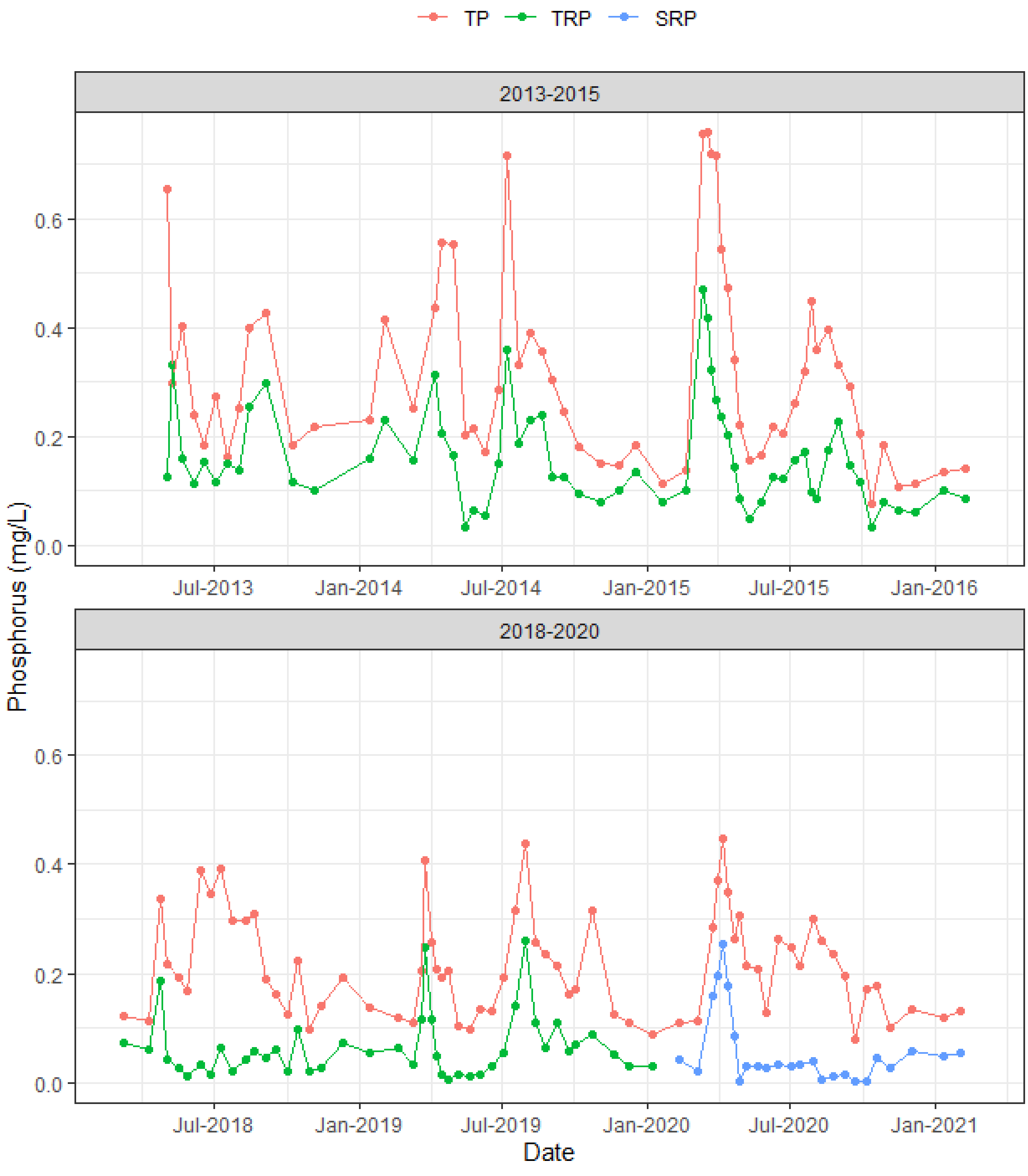


Figure 52: *Total phosphorus and total reactive phosphorus concentrations for the Qu'Appelle River below Craven Dam.*

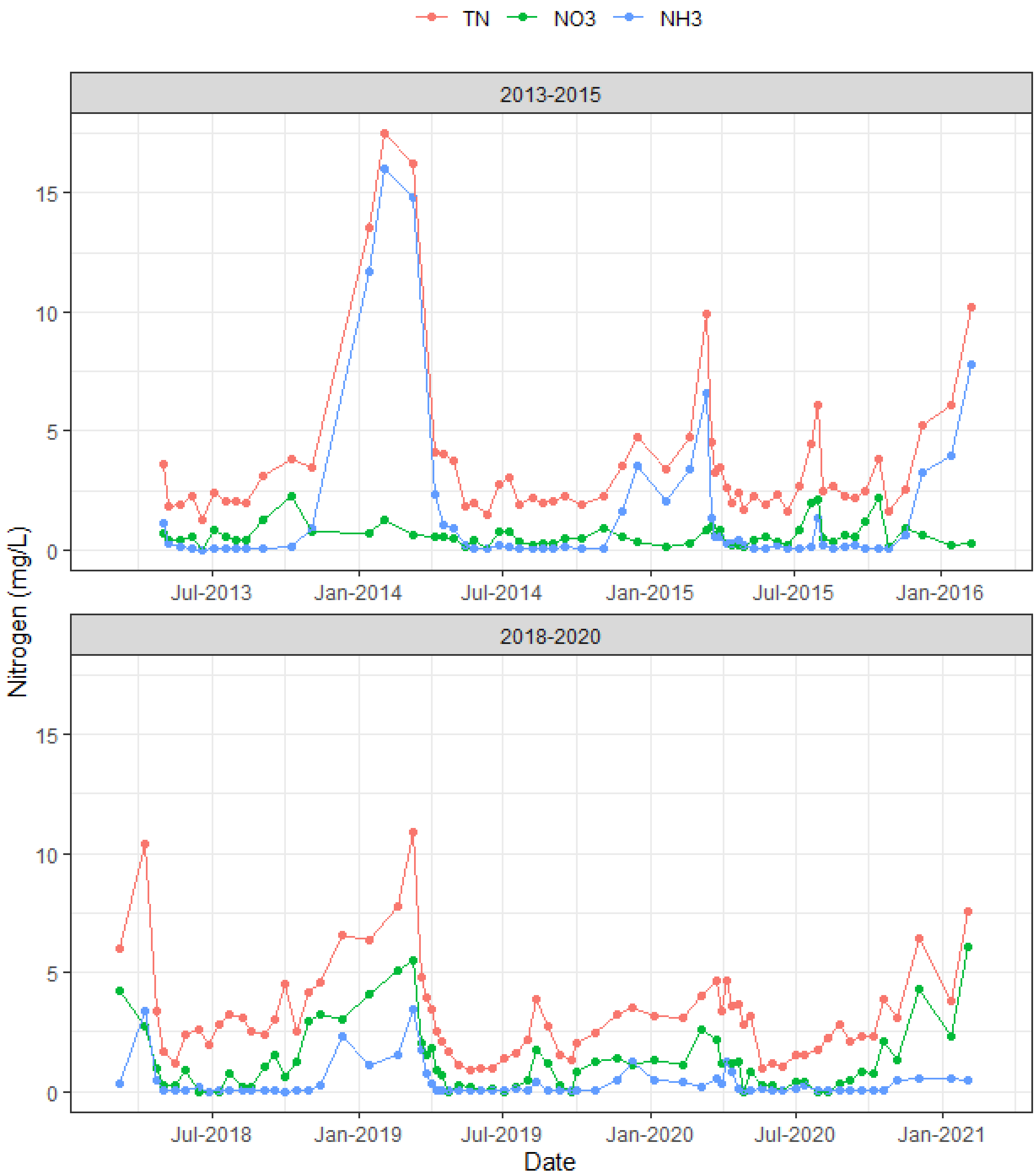


Figure 53: *Total nitrogen, nitrate-N, and total ammonia-N concentrations for the Qu'Appelle River below Craven Dam.*

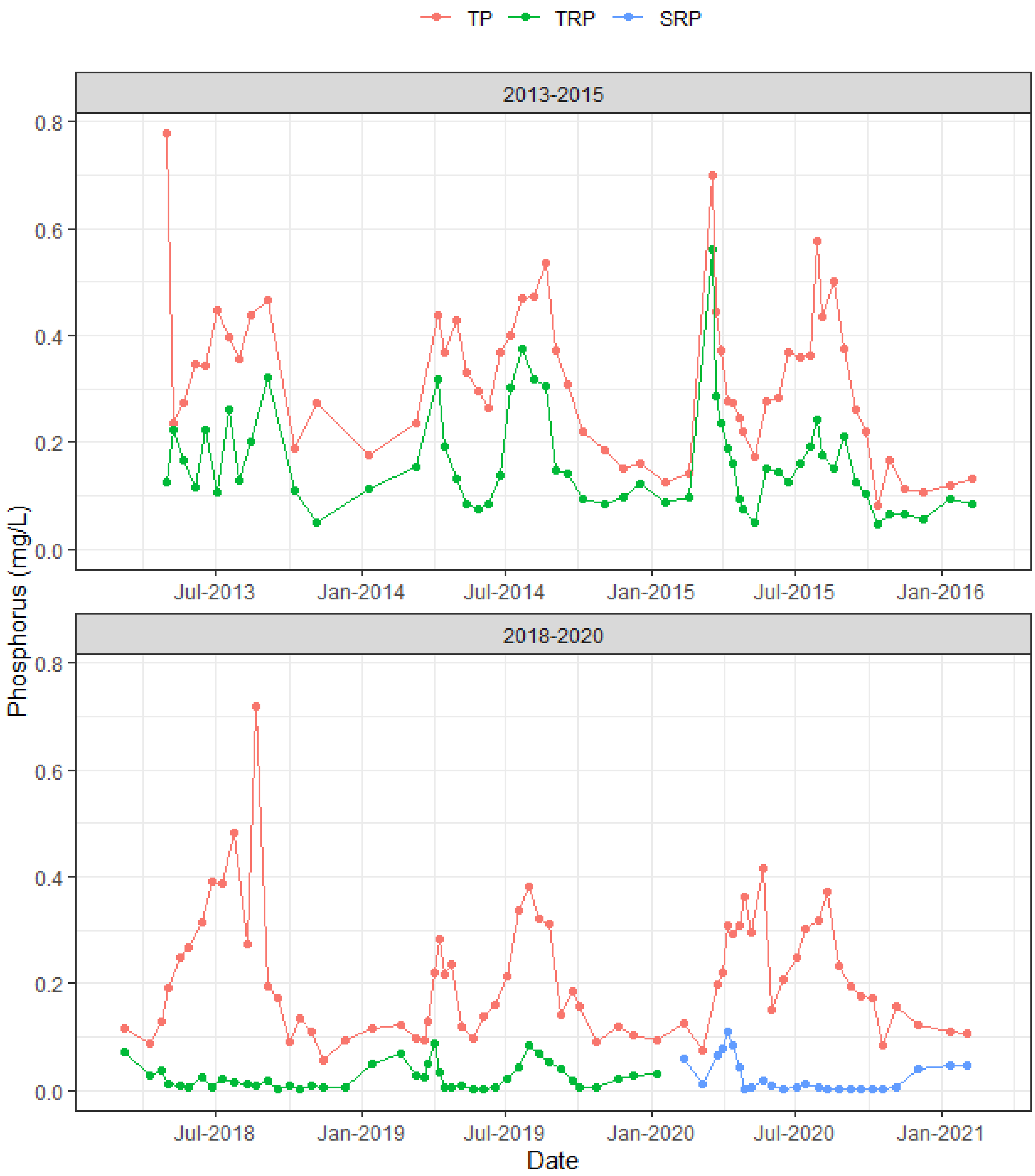


Figure 54: *Total phosphorus and total reactive phosphorus concentrations for the Qu'Appelle River at Highway 6.*

Figure 55: *Total nitrogen, nitrate-N, and total ammonia-N concentrations for the Qu'Appelle River at Highway 6.*

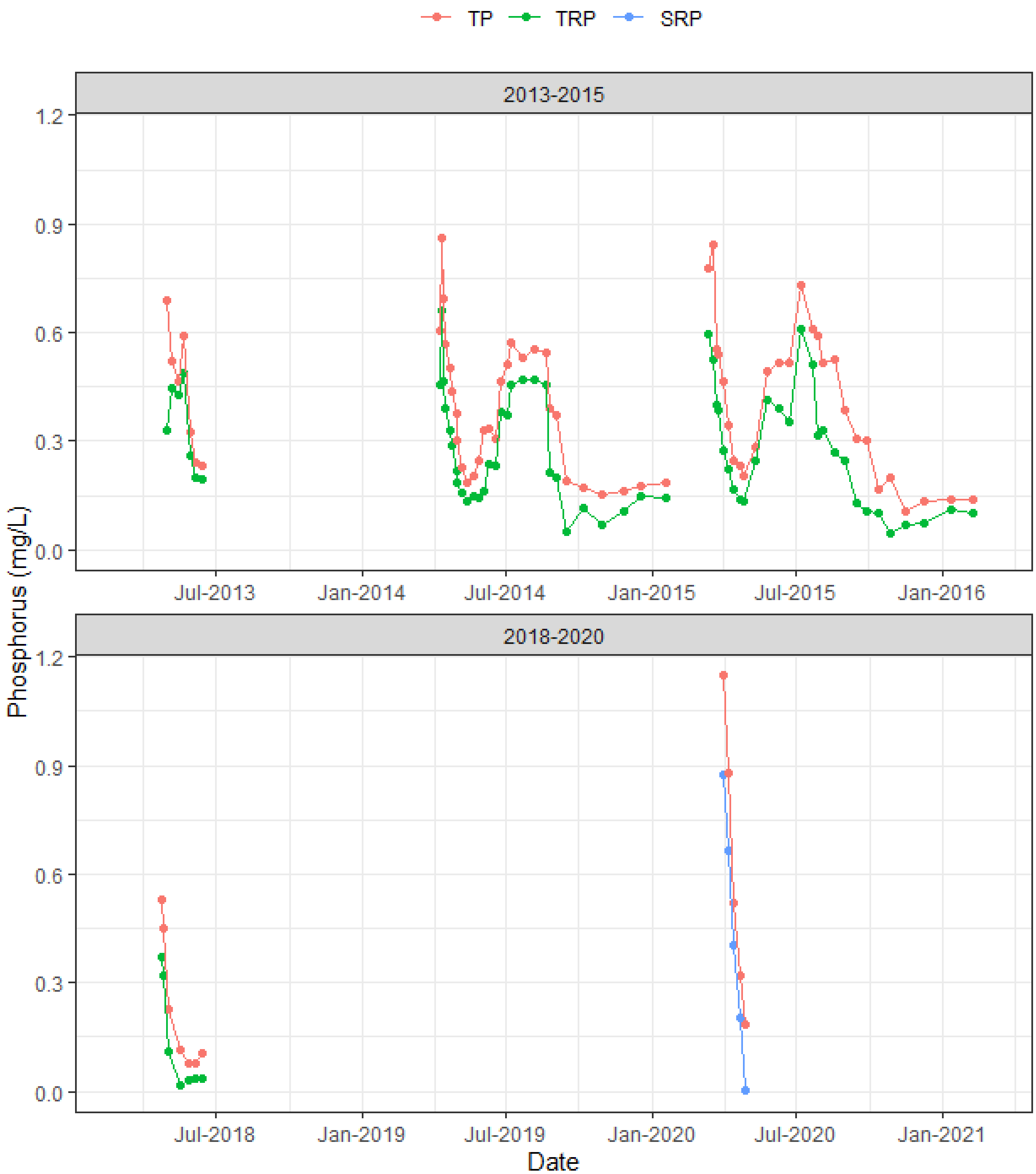


Figure 56: *Total phosphorus and total reactive phosphorus concentrations for Loon Creek.*

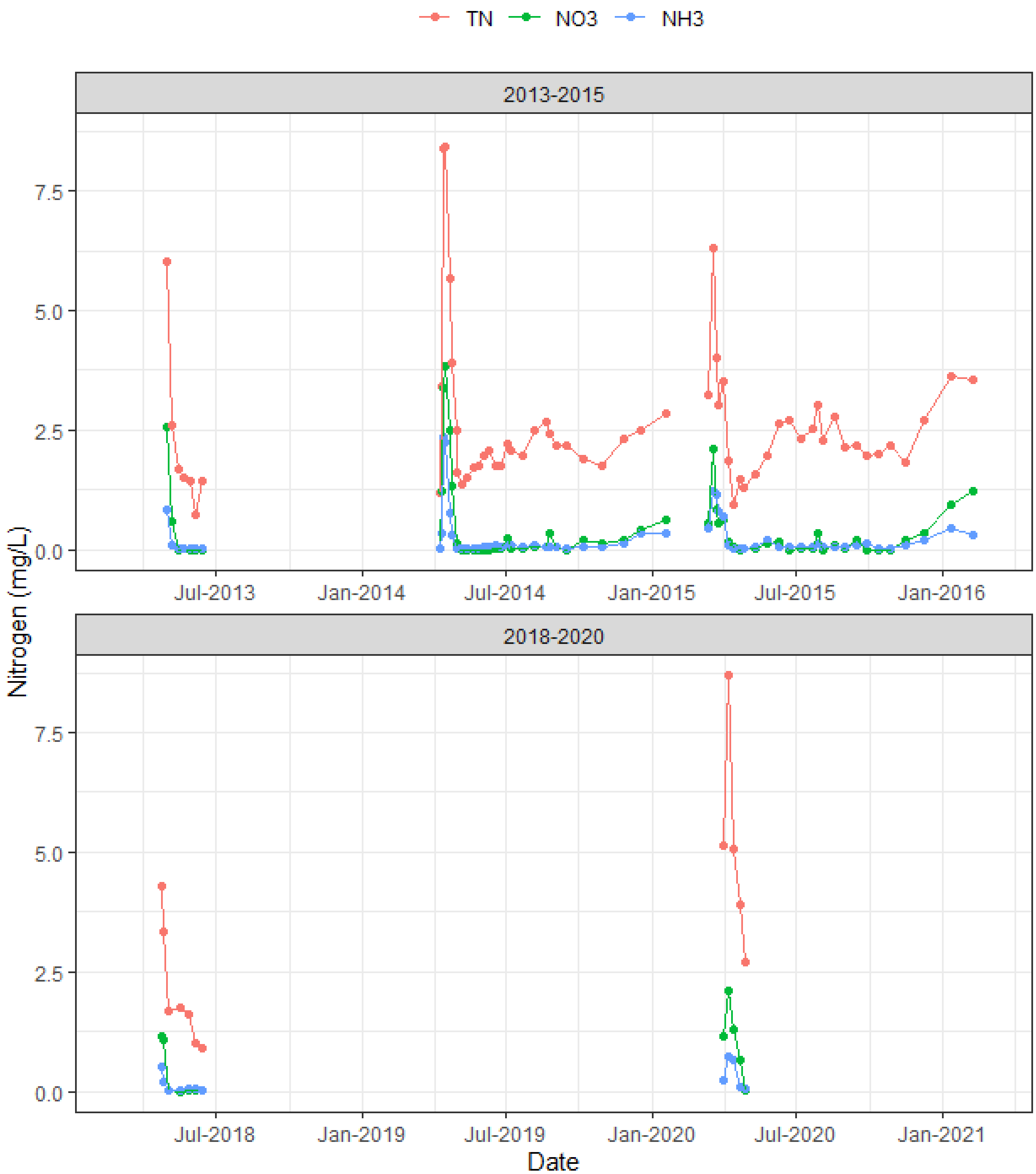


Figure 57: *Total nitrogen, nitrate-N, and total ammonia-N concentrations for Loon Creek.*

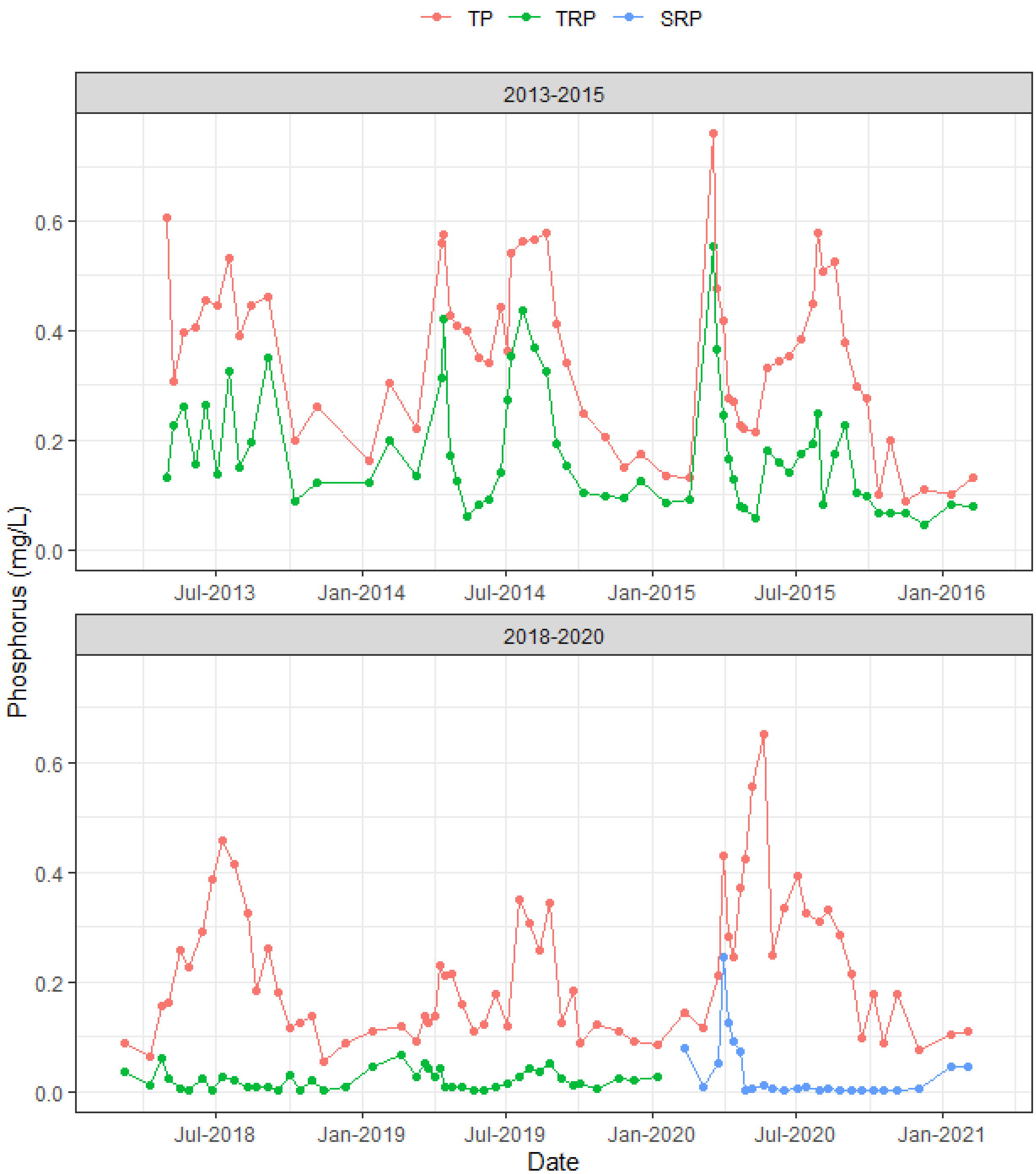


Figure 58: *Total phosphorus and total reactive phosphorus concentrations for the Qu'Appelle River above Pasqua Lake.*

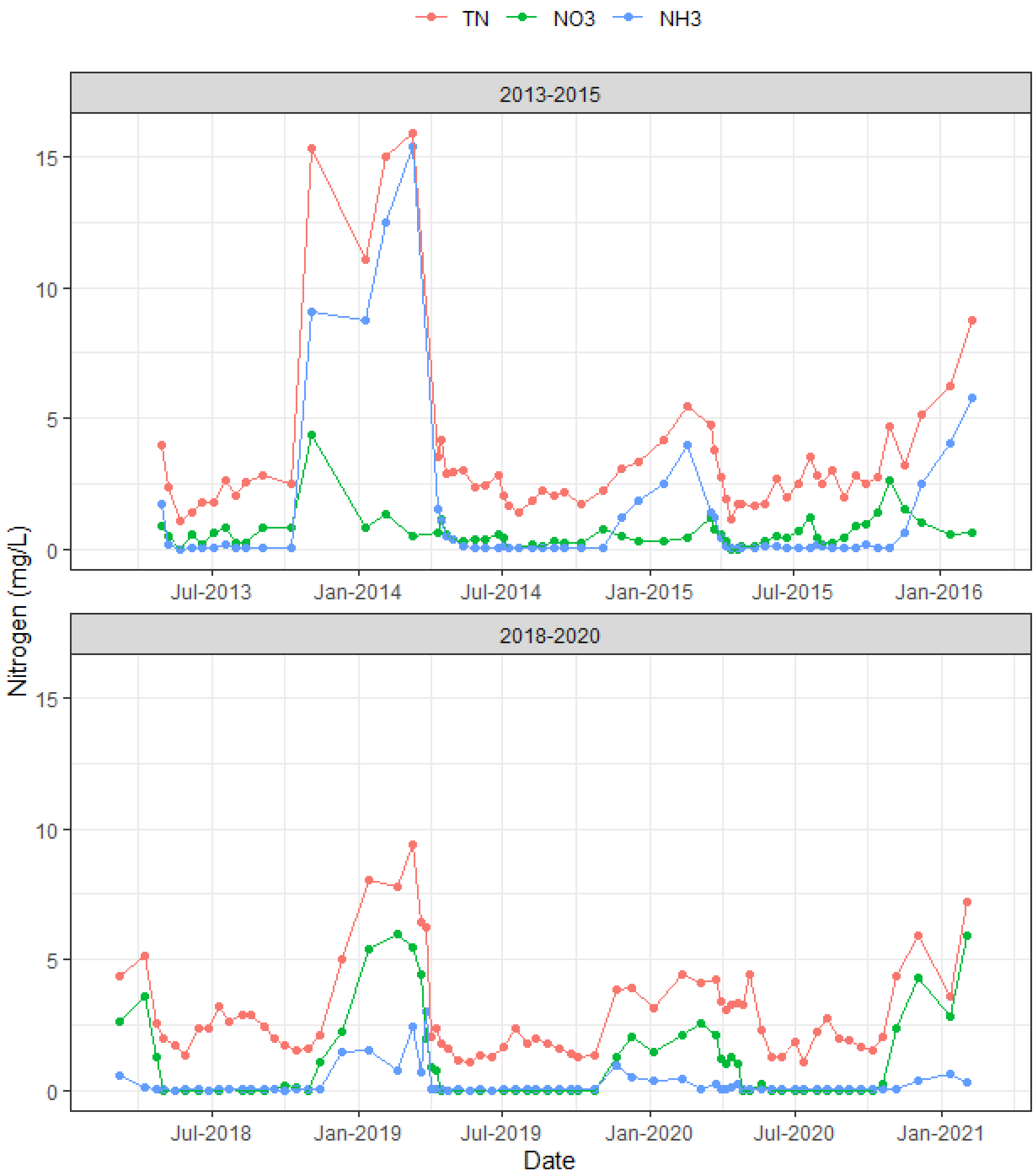


Figure 59: *Total nitrogen, nitrate-N, and total ammonia-N concentrations for the Qu'Appelle River above Pasqua Lake.*

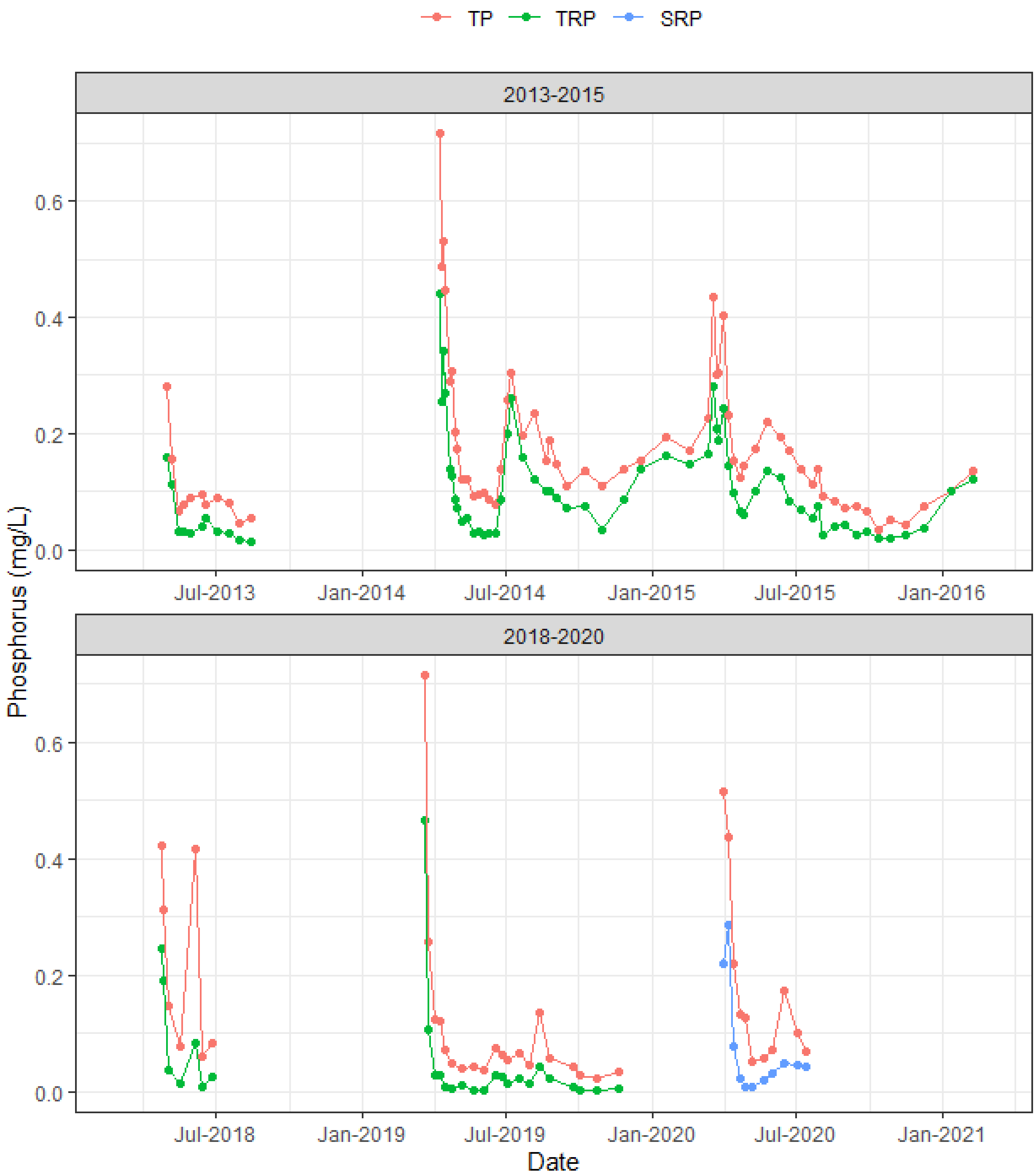


Figure 60: *Total phosphorus and total reactive phosphorus concentrations for Jumping Deer Creek.*

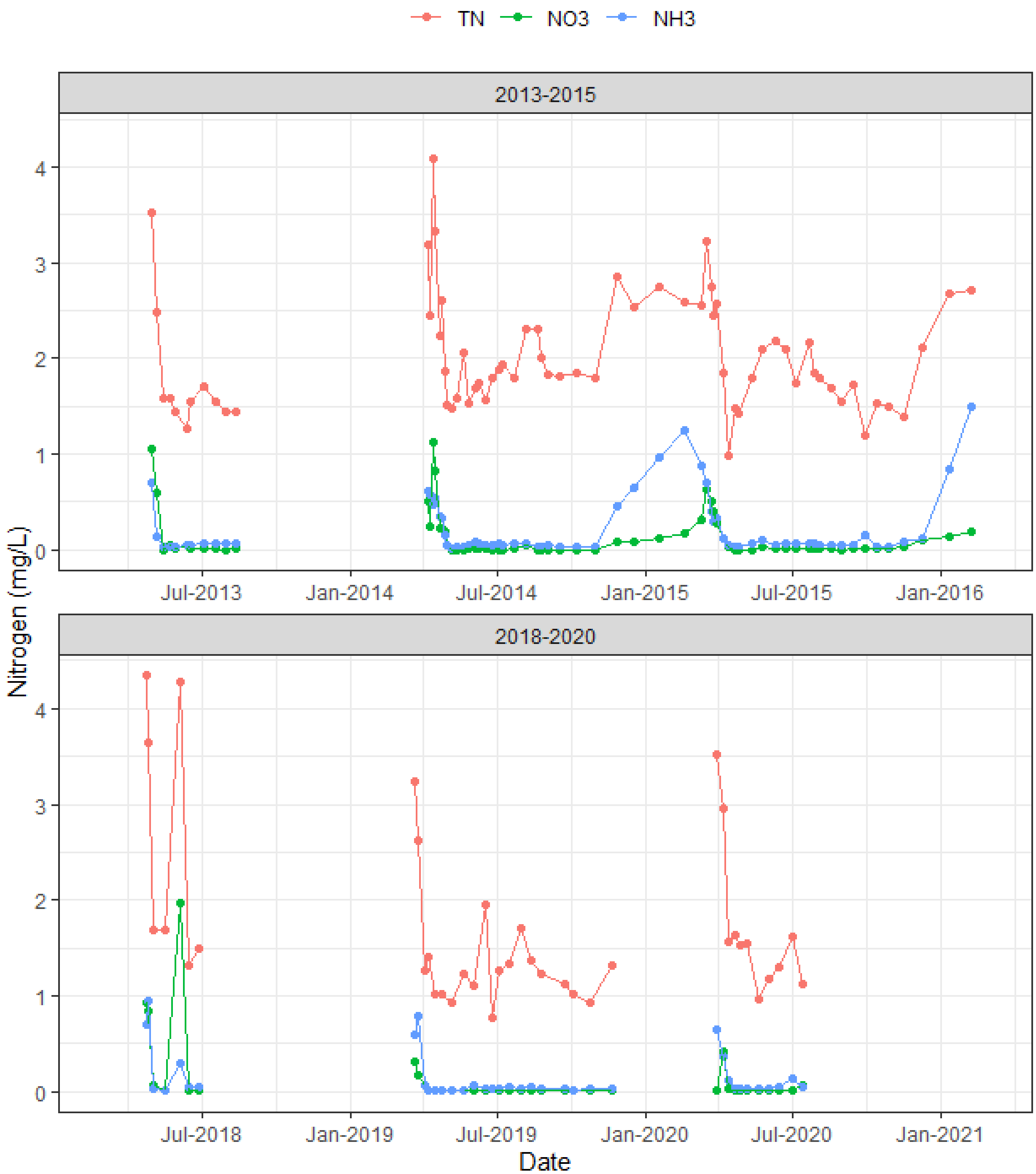


Figure 61: *Total nitrogen, nitrate-N, and total ammonia-N concentrations for Jumping Deer Creek.*

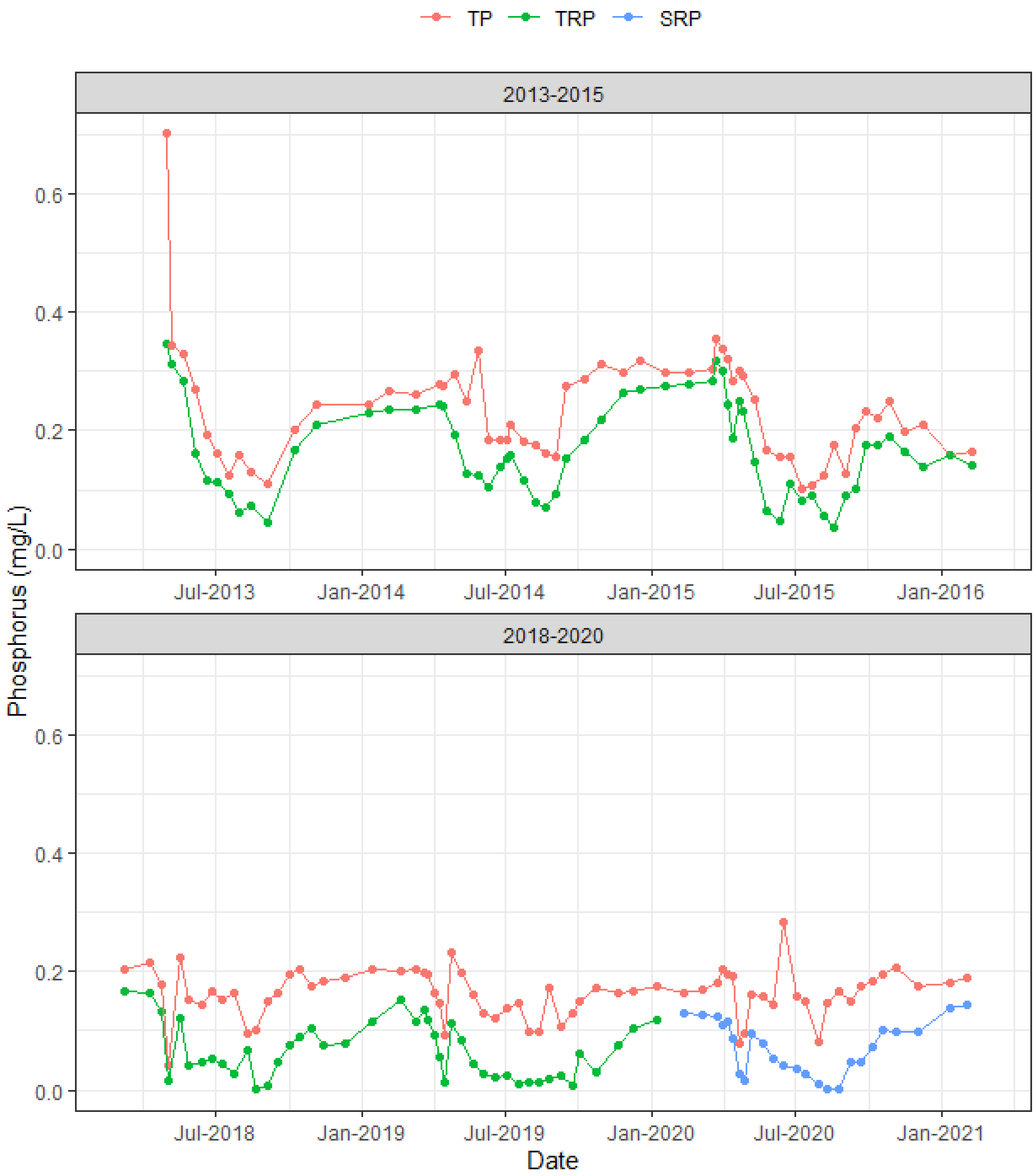


Figure 62: *Total phosphorus and total reactive phosphorus concentrations for Katepwa Lake Outlet.*

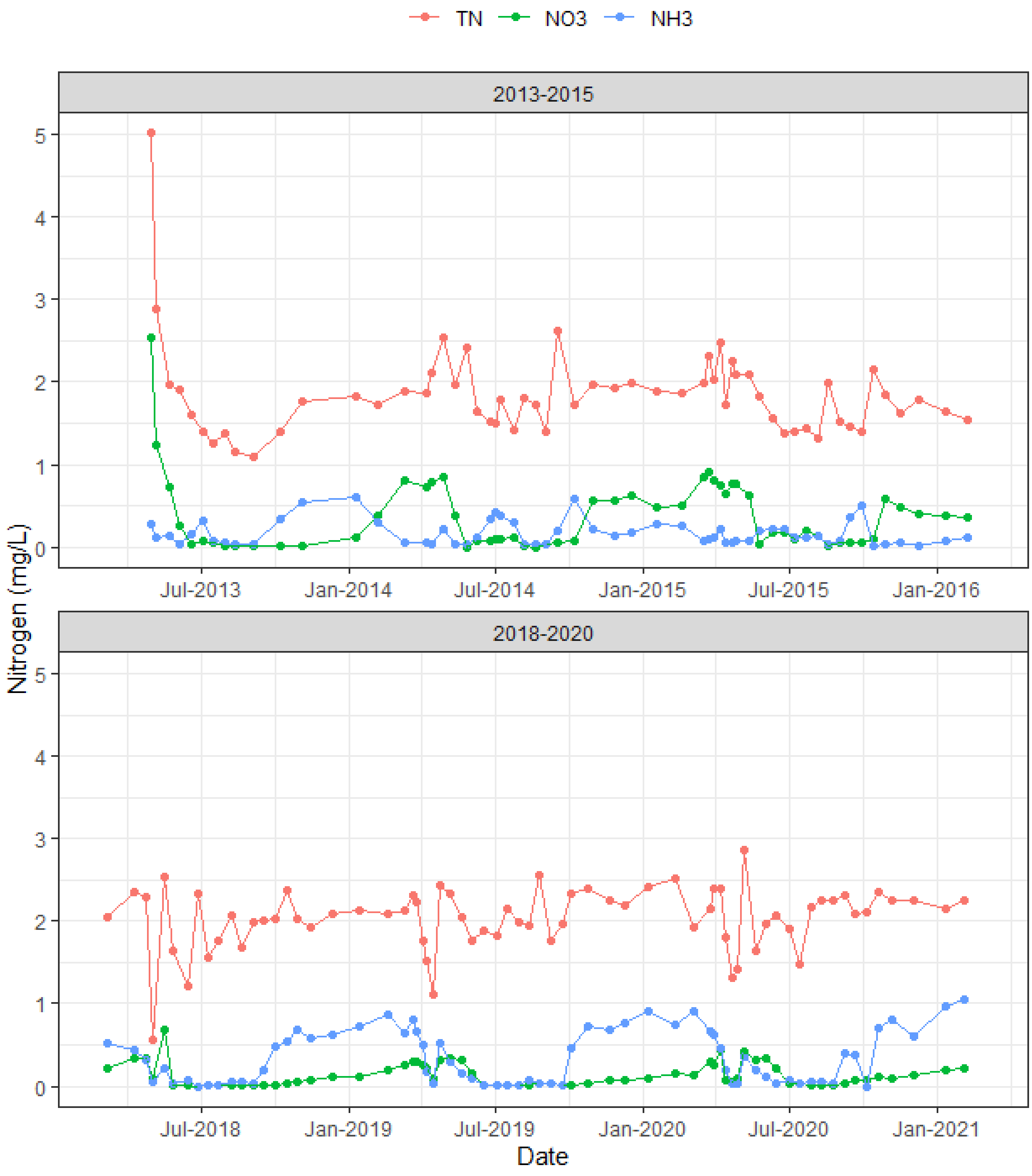


Figure 63: *Total nitrogen, nitrate-N, and total ammonia-N concentrations for Katepwa Lake Outlet.*

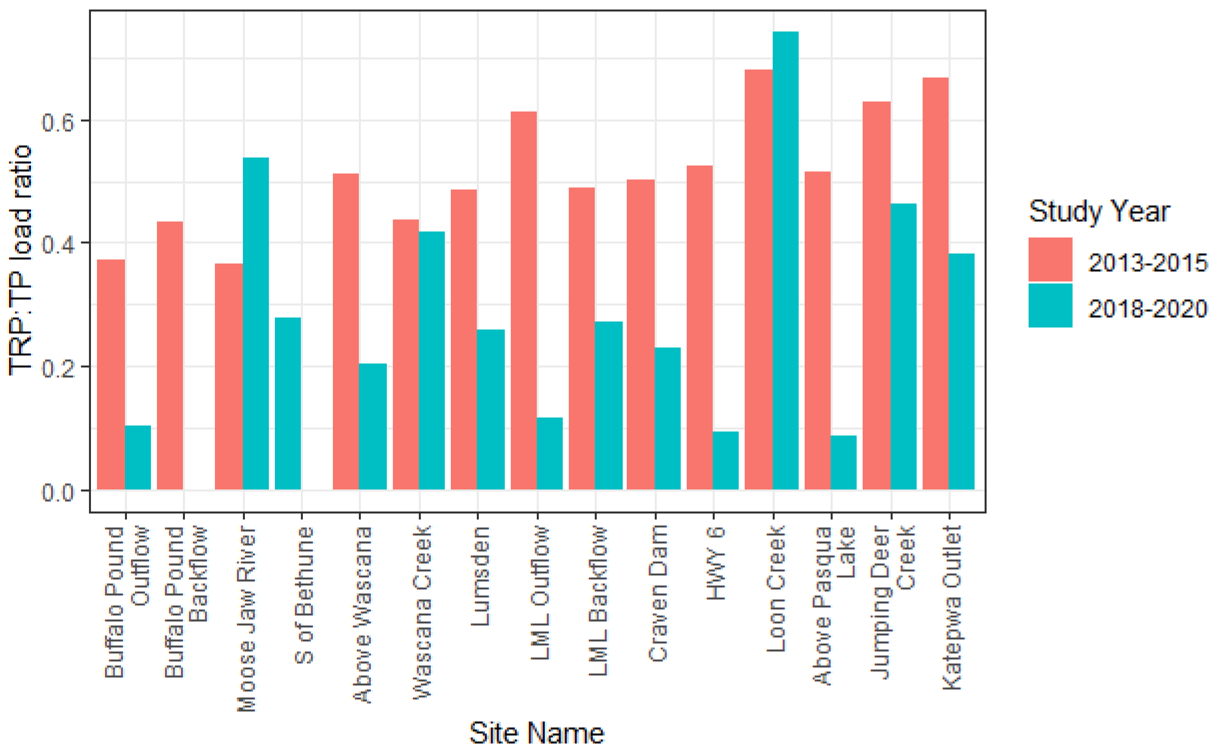


Figure 64: *Ratio of total reactive phosphorus to total phosphorus loads for all sites split by study period. Buffalo Pound Outlet and Last Mountain Creek are split into outflow and backflow periods, as flow can occur in two directions at these sites.*

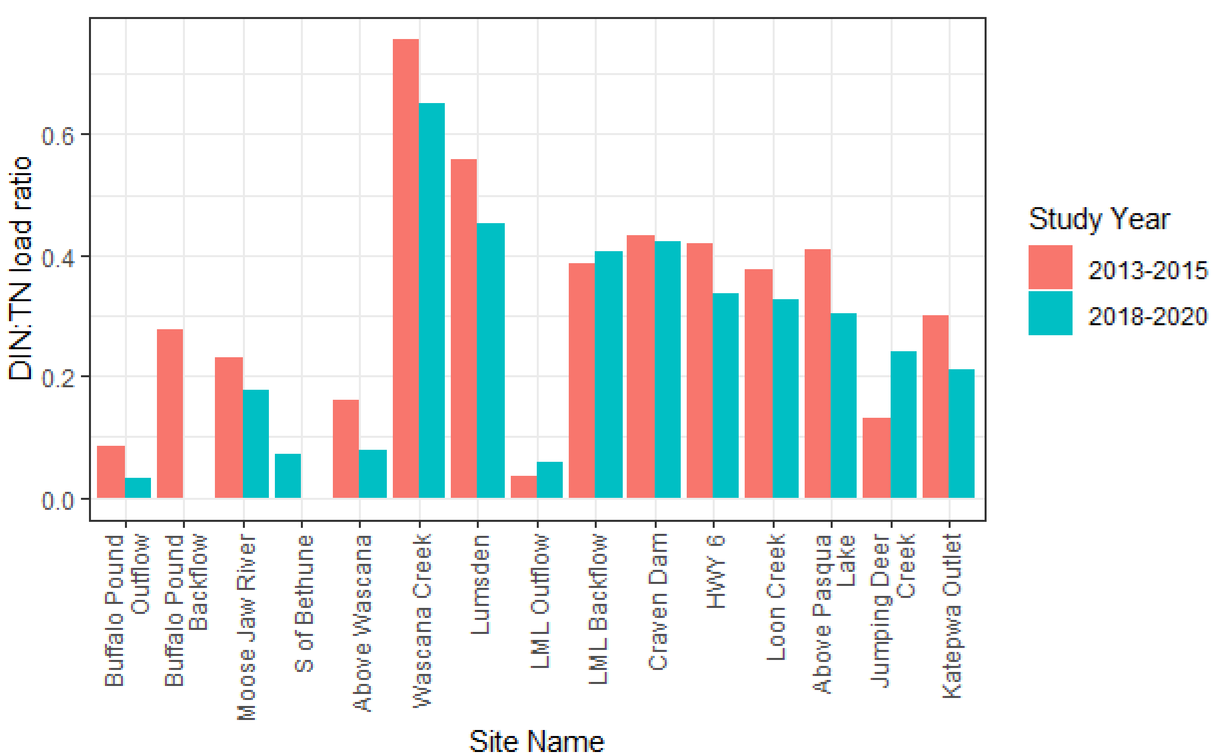


Figure 65: *Ratio of dissolved inorganic nitrogen to total nitrogen loads for all sites split by study period. Buffalo Pound Outlet and Last Mountain Creek are split into outflow and backflow periods, as flow can occur in two directions at these sites.*

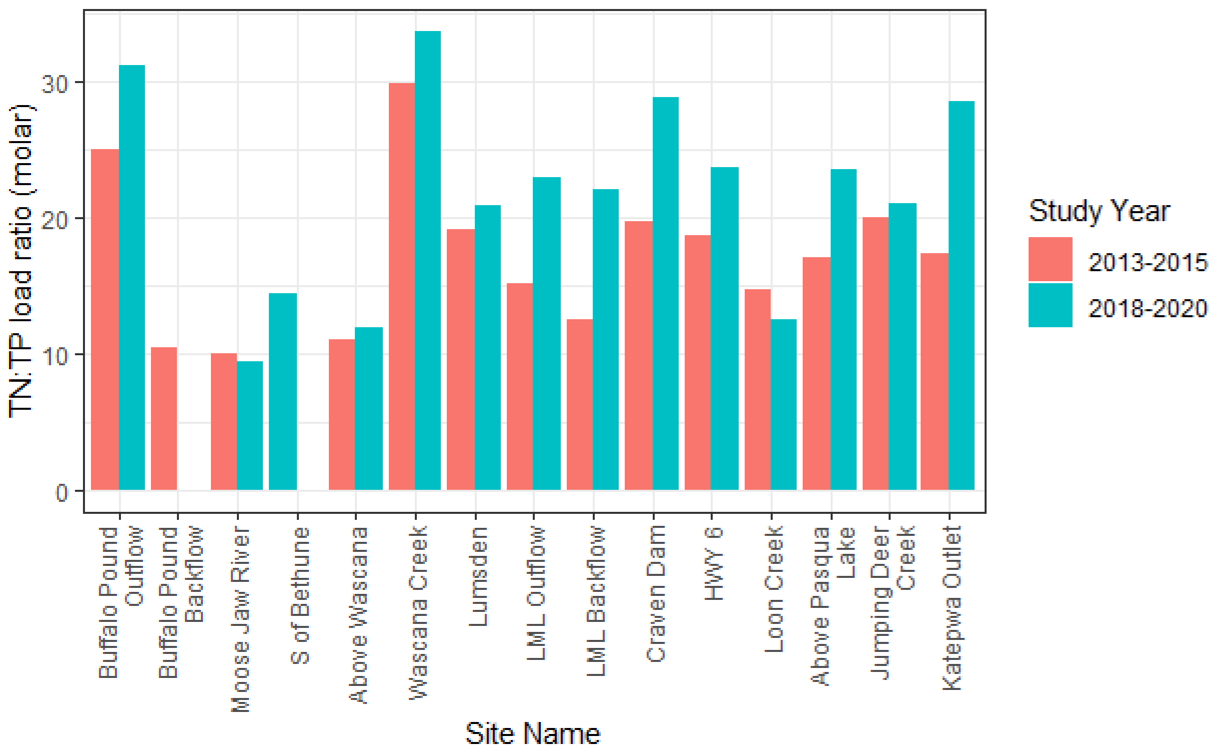


Figure 66: *Ratio of total nitrogen to total phosphorus loads (molar) for all sites split by study period. Buffalo Pound Outlet and Last Mountain Creek are split into outflow and backflow periods, as flow can occur in two directions at these sites.*

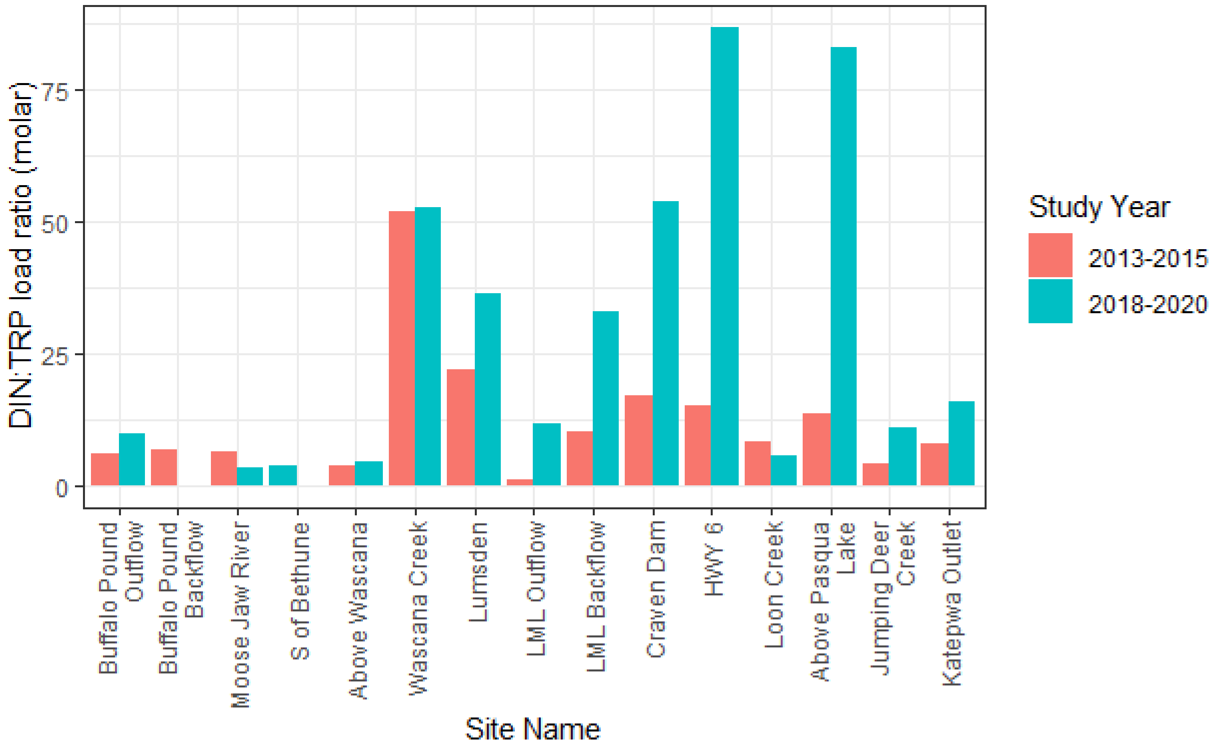


Figure 67: *Ratio of dissolved inorganic nitrogen to total reactive phosphorus loads (molar) for all sites split by study period. Buffalo Pound Outlet and Last Mountain Creek are split into outflow and backflow periods, as flow can occur in two directions at these sites.*

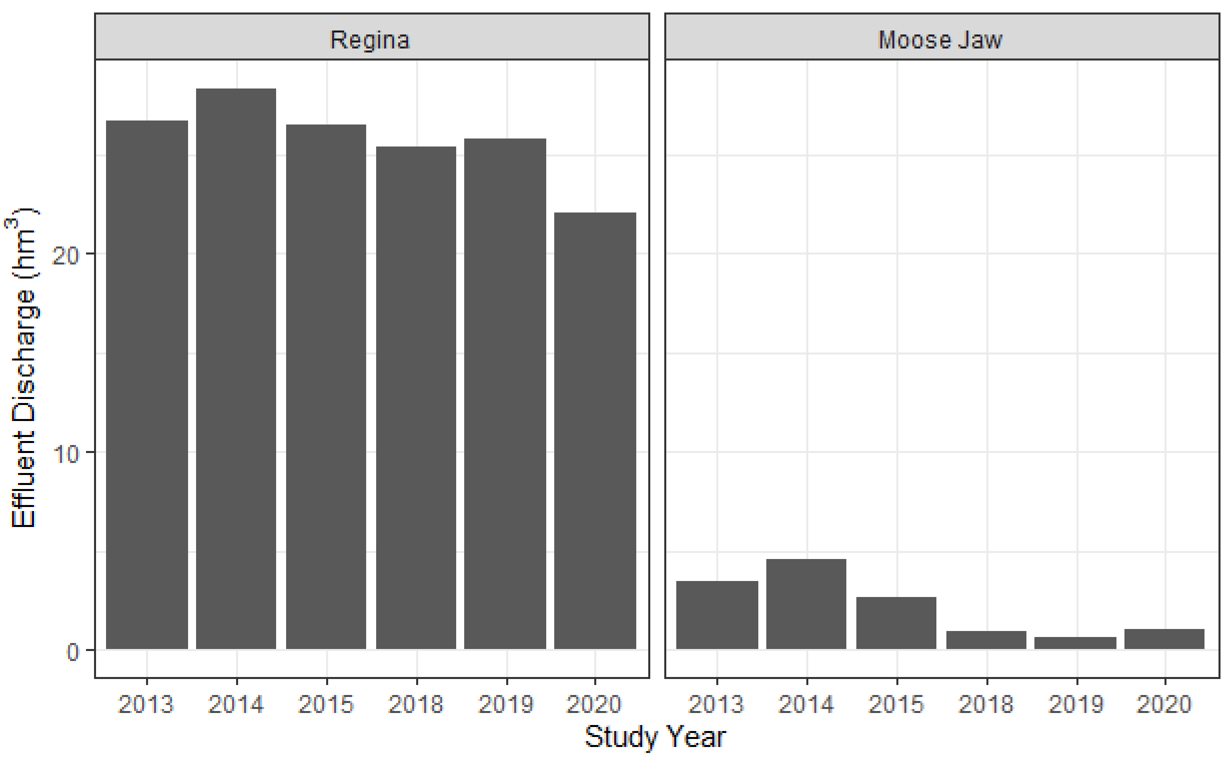


Figure 68: *Total effluent discharge for Regina and Moose Jaw wastewater treatment plants by study year.*

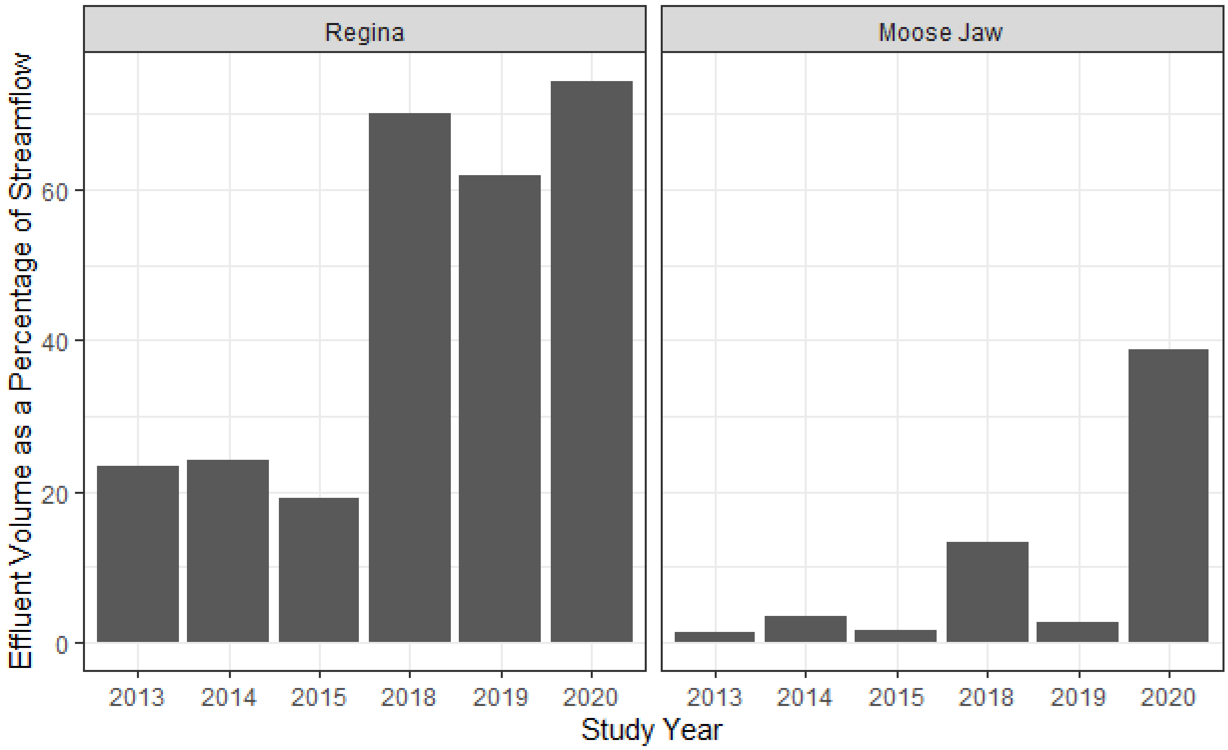


Figure 69: *Effluent discharge as a percentage of streamflow for Regina (Wascana Creek) and Moose Jaw (Moose Jaw River) wastewater treatment plants.*