Qu'Appelle Nutrient Mass Balance

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Water Security Agency

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Executive Summary

The Qu'Appelle River, and lakes within its river valley, are critical natural resources in Saskatchewan. Their significance spans that from their environmental and cultural importance to their role as source water. The lakes along the main channel of the Qu'Appelle River are known to be naturally nutrient rich and susceptible to algal blooms. The lakes and river have also been affected by development within the basin, including the discharge of treated effluent from wastewater treatment plants. This study was undertaken to quantify nutrient sources to the Qu'Appelle River and measure changes in nutrients along the length of the Qu'Appelle River from Lake Diefenbaker to the outlet of Round Lake. This study is part of the process of updating the notional nutrient objectives established for the lakes in the lower Qu'Appelle River basin as part of the provincial watershed planning process (WSA 2013) and improving understanding of how best to manage nutrients in this watershed.

Sampling of nutrient concentrations (nitrogen and phosphorus) was carried out at 15 sites along the Qu'Appelle River and 13 tributary sites from March 2013 – February 2016. The Qu'Appelle mainstem sites were sampled weekly during spring freshet, every two weeks during summer, and monthly during winter. Tributary sites were sampled twice weekly to weekly during freshet, every two weeks during low flow periods during the summer, and monthly during winter. Sites were not sampled when there was no flow.

Mainstem sites were selected based on key points along the watershed, including upstream/downstream of major tributaries and upstream/downstream of lakes. Major tributaries from Ridge Creek near Lake Diefenbaker to the inlet of Round Lake were selected for monitoring. Nutrient loads were determined from measured concentrations using gauged streamflow measurements at sites with gauges or calculated streamflow for sites without gauges.

The Qu'Appelle River transitions downstream of Buffalo Pound Lake from a regulated river with characteristics influenced by Lake Diefenbaker, to a more typical prairie stream with higher salinity (as measured by Total Dissolved Solids, TDS), dissolved organic carbon and nutrient concentrations. The Moose Jaw River and Wascana Creek were the largest contributors of total phosphorus (P) and nitrogen (N) to the Qu'Appelle River. Loads from each of these tributaries exceeded Buffalo Pound Lake outflow loads and loads from any of the other tributaries. Nutrient loading from Regina's wastewater effluent was equivalent to 9.3 % of the P load and 52 % of the N load above Pasqua Lake. The study period was conducted prior to the recent upgrades at Regina's Wastewater Treatment Plant (WWTP) that improved the effectiveness of nutrient removal, notably for N. If post-upgrade effluent nutrient concentrations (based on July 2017 - June 2018 data) had been achieved during our study, Regina's wastewater effluent loading would have been 6 % of the P load and 15 % of the N load above Pasqua Lake. The Qu'Appelle Nutrient Mass Balance Study is continuing along mid-reach locations (Buffalo Pound outlet to Katepwa outlet) to assess how the WWTP upgrades affect nutrient loading in the Qu'Appelle River.

The other tributaries were less important individually, but collectively were important contributors of P and N to the river. Individual tributary phosphorus loads, relative to those leaving Round Lake, were: Moose Jaw River 44 %, Wascana Creek 34 %, and all other measured tributaries 53 %. The corresponding values for N were: Moose Jaw River: 30 %, Wascana Creek 68 %, and all other tributaries: 46 % of N. The sum of the tributary loads is greater than the loading leaving Round Lake because of nutrient sequestration along the river, which largely occurs in the lakes.

The lakes along the Qu'Appelle River all retained a portion of inflowing nutrients. This is typical for many lakes and reservoirs, including those on the prairies (e.g. Donald et al. 2015). As a percentage of inflows, Buffalo Pound Lake retained the most P, but the comparison is complicated because during certain periods of high flow water flowed from the downstream Moose Jaw River/Qu'Appelle River into Buffalo Pound through its outlet. This occurred during spring in two of the study years. For the other lakes studied, P and N retention was greatest in the Lower Qu'Appelle Basin's chain of four lakes (Pasqua, Echo, Mission, and Katepwa; also known as the Calling Lakes), followed by Crooked Lake, then Round Lake. Not all retained nutrient is permanently sequestered; retained nutrients, especially P, become available in subsequent years perpetuating conditions of nutrient enrichment.

The study was carried out during a wet period, and many sites recorded their greatest daily and annual flows during this period (2011 was also often the record year for flow volumes). While 2011 was not included in this study's measurements, the wet conditions preceding this study are important because the landscape had more water on it and therefore more areas in the basin contributed to flow than they would have under drier conditions. A large rain event in 2014 contributed to higher than normal summer flows, especially in downstream portions of the watershed. In drier years, we expect that releases from Lake Diefenbaker makeup a greater proportion of the total flow and therefore load. During drier years, the absolute nutrient loading from tributaries would also be substantially lower.

Qu'Appelle Nutrient Mass Balance

Table of Contents

Introduction

The Qu'Appelle River is a high-value system from economic, social, and environmental perspectives. Regionally and provincially, the Qu'Appelle River is an economic pillar with municipalities, agriculture and industry dependent on the river for source water. Continued economic growth is reliant on careful water management of the system. This requires improved monitoring data that will provide information to address specific concerns about management implications to water quality. With the exception of years with high spring runoff, the system is highly managed through most of the year with inter-basin water transfers from Lake Diefenbaker. Despite these inputs, the mid- to lower portion of the Qu'Appelle River retains its original prairie characteristics including warm-water lakes, and a meandering river with high sediment and nutrient loads. The net impact of anthropogenic activities over the last century is thought to be negative, especially with respect to nutrient loading (e.g. Leavitt et al. 2006), although improvements have been and continue to be made (e.g. Davies 2006). With increasing demands on the system from economic development, and consideration of possible climate change, management of the system is coming under increased scrutiny to meet the sometimes-conflicting economic, social and environmental objectives.

It is well known from many studies that multiple human stressors negatively affect water quality. Many of these stressors are present in the Qu'Appelle River watershed, including effects from urban centres, industry, agriculture, and flow manipulation. High nutrient concentrations, which result in aesthetically displeasing algal blooms, are considered one of the highest priority water quality concerns in the Qu'Appelle River system. However, it is also known that historically the Qu'Appelle River system had naturally high concentrations of nutrients and algal blooms (Hind 1859; Gilchrist 1896; Warwick 1980; Hall et al. 1999). There are also many studies showing the effects of human activities on water quality in the Qu'Appelle lakes (e.g. Hall et al. 1999; Leavitt et al. 2006). A challenge remains in understanding the specific nutrient contributions of human activities, notably from non-point sources, and the effect of flow management on nutrient concentrations and downstream loads so that a strong scientific basis can be developed to set regionally appropriate nutrient objectives and manage for nutrients in the river and lakes. Several actions in Province's 25 Year Water Security Plan (WSA 2012) relate directly and indirectly to this study, including defining water quality objectives for high priority water bodies and watercourses (Action 3.1e).

To build a meaningful nutrient mass balance model it is necessary to undertake a detailed study that quantifies major nutrient sources. The two necessary requirements are measurements of nutrient concentrations and discharges over time. One approach to studying the mass balance of lakes is to focus on quantifying loads from the major inflows and the outflow (e.g. Donald et al. 2015). It is known that in-lake (i.e. internal) loading is also an important component. Having both inflow and outflow concentrations is necessary because some lakes act as a nutrient sink (net sedimentation of nutrients), while others can act as nutrient sources. Studying a whole watershed necessarily requires a greater number of sampling points. Given the complexity of the Qu'Appelle River system, this study represents a first step towards developing a comprehensive understanding of nutrients in the river, including an understanding of background nutrient concentrations in the river and a means for identifying anthropogenic nutrient sources that can be managed. This report represents a summary of nutrient concentration and loads within the Qu'Appelle Watershed.

Study Site

The Qu'Appelle River watershed occupies an area of 52 000 km^2 in southern Saskatchewan, Canada. The watershed is located in the prairie pothole region within the Great Plains of North America. The topography of the watershed is relatively flat with abundant shallow wetlands being a prominent natural landscape feature. Large portions of the watershed drain internally and do not contribute to the Qu'Appelle River in most years (Pomeroy et al. 2005). The climate in the region is characterized by long, cold winters and short warm summers. Mean annual temperature for the period 1981-2010 at Regina was 3.1 °C, with a January mean of -14.8 °C and a July mean of 18.2 °C. Mean annual precipitation was 389.7 mm, with 308.9 mm falling as rain and 80.8 mm as snow (Environment Canada 2017). Agriculture is the dominant land-use in the watershed, with extensive cultivation of cereals, pulses, oilseeds and use of land as pasture for cattle.

The Qu'Appelle River is a relatively small, meandering river that flows through a wide valley that originated as a glacial spillway (Christiansen et al. 1977; WSA 2007). Along its course eastward to the Assiniboine River in Manitoba, the river flows through seven lakes: Buffalo Pound, Pasqua, Echo, Mission, Katepwa, Crooked and Round. Last Mountain Lake is the largest lake in the watershed and is connected to the Qu'Appelle River by Last Mountain Creek near Craven. Major tributaries to the Qu'Appelle River include the Moose Jaw River, Wascana Creek and Last Mountain Creek, with numerous minor tributaries including: Ridge, Iskwao, Boggy, Loon, Jumping Deer, Echo, Indian Head, Red Fox, Pheasant, Adair, Thompson, Pearl, Ekapo, Kaposvar, and Cutarm creeks. The natural headwaters of the Qu'Appelle River are now part of Lake Diefenbaker, a large reservoir on the South Saskatchewan River. The primary outflow of Lake Diefenbaker is to the South Saskatchewan River, but water is also discharged to the Qu'Appelle River via the Qu'Appelle Dam. Flows to the Qu'Appelle River are managed based on water needs in the watershed and are generally higher in years with low local run-off.

Cyanobacteria (blue-green algae) blooms are one of the primary water quality concerns in the Qu'Appelle lakes. Paleolimnological studies suggest that the Qu'Appelle lakes were naturally eutrophic and therefore had such blooms prior to European settlement, but that the lakes have become more nutrient enriched since that time (Hall et al. 1999; Leavitt et al. 2006). Numerous studies in past decades have reported frequent algal blooms, high nutrient concentrations and high algal biomass (Dillenberg and Dehnel 1960; Atton and Johnson 1962; Hammer 1971; Cross 1978; Allan and Roy 1980). High algal biomass is a major concern for drinking water treatment at Buffalo Pound Lake and for recreational use in all the Qu'Appelle lakes. Algal blooms were recognized as one of the most important problems in the Qu'Appelle lakes by a review undertaken in the early 1970s (Qu'Appelle Basin Study Board 1972). That study made preliminary recommendations for nutrient targets in the Qu'Appelle lakes, recommending further study for the development of site-specific nutrient targets. More recently, during formation of the Lower Qu'Appelle River

Watershed Plan, the need for comprehensive study was identified to enable development of site-specific objectives, and notional nutrient targets were set based on the 90th percentile of current nutrient concentrations (WSA 2013).

Nutrient inputs from municipal wastewater, particularly Regina and Moose Jaw, are recognized as an important part of the nutrient load to the downstream Qu'Appelle lakes (Warwick 1967; Hammer 1971; Leavitt et al. 2006). The Qu'Appelle Basin Study Board (1972) estimated that 70 % of phosphate and nitrogen contributed to the Qu'Appelle River were from municipal sewage and recommended the removal of phosphorus (P) from the municipal effluent. Cross (1978) estimated that approximately one third of P loading to the lower Qu'Appelle lakes was from municipal sources. The Regina WWTP began removing P from its effluent in 1977 after the establishment of a 1.0 mg P/L effluent quality permit requirement, which lead to significant reduction of P loading downstream of Regina and some reduction of other water quality variables, including N (Tones 1981; Munro 1986a; Davies 2006). Despite these reductions, N loading to downstream lakes remained high (Leavitt et al. 2006). The nutrient reductions (esp. P) appear not to have reduced the potential for algal bloom formation in the Qu'Appelle lakes (Allan 1980; Hall et al. 1999).

Despite the importance of the Qu'Appelle River system for water supply and recreation in southern Saskatchewan, research has not focused on a detailed direct measurement of both total and dissolved nutrient sources to the system. Flows in the Qu'Appelle River are managed and there is a need to understand how flow impacts nutrient loading to downstream lakes, and how the river's tributaries contribute to the overall load. The goal of this study was the determination of nutrient concentration and loading along the Qu'Appelle River within Saskatchewan, and in its major tributaries. This allows for nutrient characterization of tributaries and different reaches of the river. It also provides a means to quantify nutrient sequestration in lakes and provides data needed as part of the process of establishing nutrient objectives for the Qu'Appelle Lakes. With management improvements, notably the recent upgrade of the Regina WWTP it provides a basis for comparing post-upgrade changes in water quality. These improvements include removal of P (permit criteria of 0.75 mg/L as a monthly arithmetic mean) and N (permit requirement in summer and winter of 10 and 14 mg/L, respectively, as a monthly arithmetic mean).

Methods

Sampling Locations

Sampling sites were located along the mainstem of the Qu'Appelle and on major tributaries to the Qu'Appelle River (Figure 1). Mainstem sites were chosen to provide representation along the length of the Qu'Appelle River and were particularly 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 on gauged streams, or near to the confluence with the Qu'Appelle River for ungauged streams. For gauged streams, if the gauging station was not located near the confluence with the Qu'Appelle River, alternate sampling sites nearer to the confluence were sampled occasionally to examine differences in water chemistry between water near the confluence and the gauging station. These alternate sites were sampled infrequently except for the Moose Jaw River, where it was sampled regularly, and loads were calculated as for other tributary sites.

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 sent to ALS Environmental laboratory in Winnipeg, with samples typically arriving the day after samples were collected. The Winnipeg lab was selected because it offered lower reporting limits compared to laboratories available in Saskatchewan. Samples were analyzed for total phosphorus (TP), total reactive phosphorus (TRP), total nitrogen (TN), total Kjeldahl nitrogen (TKN), nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_3), dissolved organic carbon (DOC), total dissolved solids (TDS) and total suspended solids (TSS). At select sites, water samples were also sent to the Saskatchewan Disease Control Lab to compare nutrient concentrations between labs. 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.

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). Station numbers corresponding to our sample sites are given in Table 1. Gross and effective drainage areas for stations are from the station information table from the Water Survey of Canada's website.

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 was used beginning when regular seasonal operation of the station began. Summary statistics for these sites were calculated using the available data, without taking into account the period when no data was collected. Total annual discharge was determined by computing daily discharge from the daily mean discharge data and summing the daily discharges. Peak discharges were taken as the maximum daily mean discharge in a year. Annual runoff was calculated by dividing total annual discharge by the effective drainage area and converting to mm. The 7Q10 statistic was computed by determining the minimum mean flow over a consecutive seven-day period in each year and taking the 10^{th} percentile of that data. The number of days with no flow indicates the number of days where the mean daily flow was equal to zero.

Flow Determinations for Ungauged Sites

A brief description of flow calculations is given here. A more detailed description of flow estimation calculations is given in Appendix A.

At ungauged tributary sites, flows were estimated using several techniques, depending on the availability of supporting data. For Loon Creek and Indian Head Creek, flow measurements were determined in 2014 using ISCO 2150 area velocity flow modules set up in culverts at the sampling sites. Flows for 2014 are based on these measurements, while flows for 2013 and 2015 were estimated by relating the measured 2014 to flows from nearby gauged streams and using the relationship to calculated flows in 2013 and 2015. For Iskwao Creek, a historic stream gauge station was used to establish a relationship between flows on Iskwao Creek and a nearby gauged stream. This relationship was used to calculate flows for 2013-2015 and an adjustment for an increase in catchment area was made, as the historic station was located upstream of the sampling site. For Red Fox Creek, no historical data were available, and flows were estimated using flows at a nearby gauged stream corrected for the difference in drainage area between the two catchments. For the Moose Jaw River sampling site at Township Road (TWP RD) 184, flows from the Moose Jaw River at Highway 301 were used and adjusted for the increased drainage area of the downstream site. Flows at Pearl Creek were estimated using Crooked Lake inflows estimated using outflow rating curves and lake level data in combination with gauged flows for the Qu'Appelle River at Hyde.

For Jumping Deer, Pheasant, and Ekapo creeks, flows were available from a gauging station. The gauging stations are located a considerable distance upstream of the confluence of these creeks from the Qu'Appelle River. To estimate flows entering the Qu'Appelle River from these creeks, mean daily flows were multiplied by the ratio of the effective drainage area of the creek to the effective drainage area of the creek upstream of the hydrometric station. These multiplication factors were 1.37, 1.49, and 1.07 for Jumping Deer, Pheasant, and Ekapo creeks, respectively.

Flows along the Qu'Appelle River were estimated in a number of ways depending on available data. Ungauged flows in the Upper Qu'Appelle River above Buffalo Pound Lake were estimated based on gauged flows from Ridge Creek, Iskwao Creek, the Elbow Diversion Canal, and the Qu'Appelle River gauge above Buffalo Pound, which were all operated between the years 1972-1995. A multiple regression model was developed to estimate ungauged flows during the study years. Ungauged flow estimates derived from the regression model were using in combination with gauged flows during the study years, and ratios of effective drainage areas to estimate flows for the Qu'Appelle River at Tugaske and at Marquis. Outflows at Buffalo Pound were estimated using operating logs and relationships between lake water level, Moose Jaw River flow, and historical flow data from the Qu'Appelle River downstream of the Moose Jaw River confluence.

Flow on the Qu'Appelle River upstream of Wascana Creek was calculated by subtracting Wascana Creek flows from flows in the Qu'Appelle River at Lumsden. Flows in the Qu'Appelle River above the Last Mountain Lake confluence were estimated by adding flows at Lumsden to flows from Boggy Creek, with an addition to account for ungauged flows downstream of the gauge for Boggy Creek. Flows from the Last Mountain Lake Channel were calculated by subtracting flows above the confluence from flows below Craven Dam. Flows at HWY 6 were calculated by estimating the ungauged flow between the Qu'Appelle River below Craven and the Qu'Appelle River above Pasqua Lake, adjusting this value by the ratio of drainage areas and adding it to the flows at Craven.

Outflows from Katepwa Lake were estimated using a modified rating curve based on Katepwa Lake water levels. An existing rating curve was modified to better match with estimates obtained by routing inflows through the four Calling Lakes and accounting for ungauged inflows and evaporation. Outflows from Crooked Lake were estimated with an existing rating curve. Inflows to Crooked Lake were estimated with hydrometric data for the Qu'Appelle River at Hyde and inflow estimated from outflows and changes in lake level. Inflows and outflows to Round Lake were estimated using a rating curve for the outflow, and accounting for changes in storage to estimate the inflows.

Nutrient Load Determination

Nutrient loadings were calculated for the period from March 1, 2013 to February 29, 2016 using three methods: the midpoint method, the Beale ratio estimator and LOADEST modelling. Loadings were calculated for TP, TRP, TN, nitrate plus nitrite ($NO_3^- + NO_2^-$), NH_3 and TSS. Note, that within this report total ammonia nitrogen (NH_4^+-N + NH_3-N) will collectively be referred to as NH_3. When measurements were below detection limit, a value of half of the detection limit was used in calculations, with the exception of the LOADEST method, which is able to use censored data in its modelling.

For the midpoint method, 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, if the first sampling point occurred after the start of spring runoff and there was flow prior to spring runoff, the concentration before spring runoff was determined by taking an average of winter concentrations from the 2014 and 2015 study years. For Red Fox Creek, sampling in spring 2013 began after the hydrograph peak had passed. This creek has very flashy flow, with high turbidity and suspended sediment loads when flows are high. The 2013 samples taken after the hydrograph peak are unlikely to represent nutrient concentrations that occurred during peak flow. To make a reasonable load estimation for this period, the LOADEST determined loads were used prior to the first sampling point in spring 2013. At Round Lake in June 2013 one TP measurement was removed from the load calculations as it was deemed to be an outlier. The measured concentration of 0.951 µg/L was substantially greater than concentrations on all other dates at this site. In review of whether this point should be considered an outlier, several factors were considered including TRP/TP, the TSS concentration, the ratio of total N (TN) to TP, where the value occurred on the hydrograph, and the relationship between flow and TP. Total reactive P on that date was 0.043, which is similar to other dates, but was an atypically low percentage of the 0.951 µg/L value reported by the lab. If the reported total P concentration was accurate, it would most likely be due to particulate P; however, TSS concentrations were not high for the flow rate. Critically, excluding the data point produced results more in alignment with the LOADEST and Beale calculation methods.

The Beale ratio estimator was calculated after Quilbé et al. (2006). Data were stratified using the scheme presented by Lee et al. (2016). Briefly, data were first separated into two groups using the 80th percentile of flow within each study year. If either group had < 10 samples, flow stratification was not used. Next, seasonal strata were determined. For our study, seasons were defined using March - May for spring, June - August for summer, September - November for fall and December - February for winter. If the season with the fewest samples had < 10 samples, it was combined with the adjacent season with the fewest samples. This procedure was repeated until all strata had at least 10 samples. For total load calculations over the whole study period, this strategy usually divided the data into the two flow categories and one to three seasonal strata within each flow category. For calculation of annual loads, sample numbers were generally too small for flow stratification and only seasonal stratification was used.

Nutrient loads calculated using the LOADEST software (Runkel et al. 2004) were done using automated model selection. This approach uses Akaike's Information Critera to select the best model using the parameters of the seven-parameter model of Cohn et al. (1992). The AMLE calculation method was used. The validity of the model was assessed by examining the model R^2, load bias and Nash Sutcliffe Efficiency Index provided in the software output, by examining residual plots to check model assumptions, and by checking the reasonableness of predicted concentrations against the observed concentrations.

Additional Loading Calculations

Loads were also determined for the Regina WWTP effluent and for the Qu'Appelle River at Welby. Loads for the Regina WWTP effluent were calculated using mean monthly effluent nutrient concentrations and total discharge volumes submitted in reports to the Water Security Agency. Load estimates for a hypothetical scenario in which recent Regina WWTP upgrades had been done prior to our study were also determined. To estimate these loads, effluent discharge volumes from 2013-2015 were used, with mean monthly effluent concentration data from July 2017 - June 2018 used in place of the actual 2013-2015 data. July 2017- June 2018 was selected as the representative year because final permitted effluent requirements for TP and TN concentrations came into effect July 1, 2017. Loading for the Qu'Appelle River at Welby was determined from 1975-2016 using nutrient data obtained from the Prairie Provinces Water Board and hydrometric data from the Water Survey of Canada. Nutrient loads at Welby were calculated using the midpoint, Beale and LOADEST methods.

Results

Hydrology

The study period from March 2013 – February 2016 was wetter than average, total annual discharge and peak discharges at gauged sites being higher than long-term means at most sites (compare Tables 2 and 3).

Gauged Qu'Appelle River Stations

Qu'Appelle River at Highway 19

The Qu'Appelle River at Highway 19 sampling site is immediately downstream from the Qu'Appelle Dam on Lake Diefenbaker. Flows are therefore nearly entirely a result of releases from Lake Diefenbaker. Discharge at the Qu'Appelle River at Highway 19 was below the long-term average in all three study years (Tables 2 and 3). The typical flow regime at this site is to have minimal flows during spring run-off, higher flows during summer and then moderate releases over the winter (Figure 2). Compared to typical flow conditions, there were longer periods with minimal flow during 2013-2015 particularly during the summer of 2014 and fall of 2015. Total annual flows were between the 25th percentile and the median for all three years (Figure 3).

Qu'Appelle River at Lumsden

Annual discharges in the Qu'Appelle River at Lumsden were above average in each study year and were similar in each of the three years (Tables 2 and 3). Peak flows in each year were also above average. The spring peak of 2013 was the highest during the study period and was later than the median peak date, occurring on May 6 (Figure 4). A summer storm in late June 2014 caused flows to rise to a similar level as the spring peak in that year. Spring flows in 2015 were relatively high and early, with peak flows occurring on April 1st. Compared to the historical record of total annual flow 2013-2015 flows were above the 75th percentile but were exceeded by several previous years (Figure 5). In particular, 2011 was the year with the highest flow, with a total flow of 937 hm^3.

Qu'Appelle River above Pasqua Lake

As at Lumsden, total annual discharges and peak discharges were above the long-term averages for the Qu'Appelle River above Pasqua Lake (Tables 2 and 3). The typical flow pattern for this site is for peak flows to occur in spring and steadily declining flows for the remainder of the year. For 2013 and 2015, this pattern was generally followed, but with above median flows for most of the year (Figure 6). In 2014 however, the early summer storm event caused an increase in flows. Flows remained well above median for the remainder of the year, with flows during fall and winter 2014 being the highest on record for that time of year. Compared with flows at Lumsden, flows above Pasqua Lake had less extreme peaks, but much longer periods of elevated flow. This pattern is consistent with peak flows from the Qu'Appelle River being diverted into Last Mountain Lake, with a subsequent steady release of water from Last Mountain Lake later in the year. Total annual flows were above the 75th percentile in all three study years, with 2014 and 2015 having the second and third highest annual flows in the record (Figure 7). As with the Qu'Appelle River at Lumsden, the highest annual flows occurred in 2011.

Qu'Appelle River at Welby

Total and peak discharges were above long-term averages in all three study years (Tables 2 and 3). Compared to median flow conditions, flows were above median for nearly the entire study period (Figure 8). The exception to this was spring 2013, when peak flows occurred later than the median peak. In contrast, the spring run-off peak in 2015 occurred earlier than the median. The dominant hydrological event at Welby during the study period was the rainstorm of late June 2014, which caused the highest peak flow in the continuous record. Flows remained at the highest on record for the time of year for the remainder of 2014 and until the spring run-off of 2015. Total annual flows were above the 75th percentile in all three years (Figure 9), with 2014 having the second greatest annual flow on record. As at Lumsden, the greatest annual flow occurred in 2011.

Gauged Tributary Stations

Moose Jaw River at Highway 301

Total annual discharge for the Moose Jaw River was higher than average in all three study years (Tables 2 and 3). Spring peaks were relatively high in 2013 and 2015 (Figure 10). The timing of the spring peak was relatively late in 2013 and early in 2015. The spring peak was lower in 2014, but there were a greater number of small flow events in that year. In general, after spring, flows for the Moose Jaw River were very low, with the exception of major rain events. Compared to previous years, total annual flow was high, but not extreme during the study period. As with many other locations in the Qu'Appelle watershed, 2011 was the year with the highest total annual flow (Figure 11).

Wascana Creek

Total annual and peak discharges were above average for Wascana Creek in all three study years (Tables 2 and 3). In a pattern similar to the Moose Jaw River, spring peaks were higher in 2013 and 2015 than in 2014, with spring being relatively late in 2013 and early in 2015 (Figure 12). The late June rain event in 2014 caused peak flows greater than the spring peak in that year. Total annual flows were above the 75th percentile in all three years but were less than half of the total flow in 2011 (Figure 13).

Minor Tributaries

The minor gauged tributaries to the Qu'Appelle River (Ridge, Jumping Deer, Pheasant and Ekapo creeks) generally had above average peak and total flows during the study years 2013-2015. These tributaries generally flow during the spring and during major rain events and may be dry in summer and winter. The hydrograph for Pheasant Creek during the study period is given as an example (Figure 14). The rain event of late June 2014 was the dominant event at Pheasant Creek and is the highest peak flow on record. This rain event was also significant at Ekapo Creek but was less dramatic at Jumping Deer and Ridge creeks. Total annual flows were also well above the 75th percentile at Pheasant Creek with 2014 being the year with the greatest flow on record (Figure 15).

Flow Patterns by River Section

Total discharge volumes for the three study years combined are presented for each study site in Figure 16.

Upper Qu'Appelle River

Over the study years 2013-2015, releases from Lake Diefenbaker were 58 % of the total flow in the Qu'Appelle River at Marquis. Flows in the Upper Qu'Appelle River peaked each spring during snowmelt (Figure 17). In 2013, releases from Lake Diefenbaker were 83 % of flows at Marquis, while in 2014 and 2015, releases were 40 and 57 % of flows at Marquis respectively. In 2013 spring runoff contributions to flow were comparatively minor, while in 2014 and 2015 larger spring runoff events and in 2014 a large rain event contributed to a greater proportion of flows being derived from the local watershed. Ridge and Iskwao creeks contributed similar amounts of total discharge for most of the study period, with Iskwao Creek contributing more during the rain event of summer 2014.

Buffalo Pound Lake

Inflow to Buffalo Pound Lake is primarily through the Qu'Appelle River at the north west of the lake. However, when flows on the Moose Jaw River are high, flow direction in the Qu'Appelle River immediately southeast of Buffalo Pound Lake can be reversed and flow back into the lake through the lake's outlet. Backflow of water into Buffalo Pound Lake occurred in 2013 and 2015 (Figure 18). Peak discharge for the backflow exceeded peak discharge from the Upper Qu'Appelle River in 2013. Backflow in 2013 accounted for an estimated 28 % of total inflows in 2013. In 2015, backflows were an estimated 8.7 % of total inflows. Based on the inflow and outflow estimates, 59.5 % of water entering Buffalo Pound Lake by the Qu'Appelle River and by backflow left by the outlet. Water withdrawal from the lake for drinking water and industrial are estimated to be approximately 176 hm^3, or approximately 50.4 % of inflows during the study period.

Lumsden Area

The Moose Jaw River and Wascana Creek are the major contributors to flow in the Qu'Appelle River at Lumsden (Figure 19). In general, the spring runoff period contributes most of the total flow in the Qu'Appelle River in this area. In 2014, a rain event in early July resulted in peak flows comparable to those of the spring in that year.

Last Mountain Lake

Flows in the Qu'Appelle River above the Last Mountain Creek confluence were similar to those upstream at Lumsden (Figure 20). Significant flow from the Qu'Appelle River into Last Mountain Lake occurred in spring of each study year, and after a rain event in summer 2014. Outflow from Last Mountain Lake was particularly high in 2014, with higher flows sustained throughout the fall and winter in that year. This demonstrates the dynamic nature of the Qu'Appelle River and has critical implications for understanding nutrient loading and the effect on nutrient concentrations within the river and downstream lakes.

Above Pasqua Lake

Flows in the Qu'Appelle River below Craven were similar to flows estimated at Highway 6. Total flow was slightly greater above Pasqua Lake than at Craven and Highway 6. Loon Creek was a minor contributor to flows in this section of the river (Figure 21).

Calling Lakes

Inflows to Pasqua Lake and outflows from Katepwa Lake were generally similar (Figure 22). Outflow from Katepwa Lake exceeded inflow to Pasqua Lake in 2013, but over the three-year study period inflows to Pasqua Lake exceeded outflows from Katepwa Lake. Jumping Deer Creek, which enters the east end of Pasqua Lake, was a greater contributor to inflows in 2014 and 2015 than in 2013. Mean net evaporation from the Calling Lakes over the three study years was 505 mm/yr. These calculations do not consider groundwater contributions because such contributions are poorly understood in these lakes.

Between Katepwa and Crooked Lakes

Numerous small creeks enter the Qu'Appelle River between Katepwa and Crooked lakes, including four tributaries that were included in our study. Of these, Pheasant and Pearl creeks were larger contributors of flow, while Indian Head and Red Fox creeks made a smaller contribution (Figure 23). Over the study period, flow from the four studied tributaries was equal to 55 % of the increase in flow from Katepwa Lake to Crooked Lake. The remaining increase in flow is attributable principally to non-studied tributaries. The rain event in summer 2014 was atypically large in this region of the Qu'Appelle River, and resulted in comparatively large peak flows entering Crooked Lake relative to those leaving Katepwa Lake.

Crooked and Round Lakes

Outflows for Crooked Lake slightly exceeded Qu'Appelle River inflows over the study period (Figure 24). The additional flow at the outflow is from local inflows and possible groundwater influence. There is also considerable uncertainty in the estimation of flows at these ungauged sites. Peaks in flow generally occurred in spring, with two peaks occurring in springs 2014 and 2015. The greatest flow rates occurred after the rain event in summer 2014. Flows at Round Lake had similar patterns to those at Crooked Lake (Figure 25).

Spatial Patterns in Water Quality Parameter Concentrations

Total suspended solids, TDS, and nutrient concentrations varied spatially along the length of the Qu'Appelle River. Total suspended solids concentrations were lower at the outlet of lakes and higher in reaches that are distant from upstream lakes (Figure 26). Concentrations were similar among years at most sites (Figure 27).

Median TDS concentrations were lowest in the upstream portion of the Qu'Appelle River, and highest in the reach between the Last Mountain Creek confluence and Pasqua Lake. The range of concentrations was highest in the Upper Qu'Appelle, where both the lowest and highest values were measured. Downstream of Katepwa Lake, median concentrations were consistent moving downstream, and concentrations were within a narrower range compared to other sites (Figure 28). There were some important differences among years; in the Upper Qu'Appelle, TDS concentrations were higher in 2014 and 2015 than in 2013, while downstream of Katepwa Lake, TDS concentrations were higher in 2013 than in 2014 and 2015 (Figure 29).

Dissolved organic carbon concentrations followed a similar patter to TDS concentrations (Figures 30 and 31). DOC concentrations and variability in concentrations increased along the Upper Qu'Appelle River downstream to Buffalo Pound Lake. Downstream of Buffalo Pound, concentrations became greater. Median concentrations remained similar from above the Wascana Creek confluence downstream to Round Lake outlet. Variability in DOC concentration was lower at Highway 6 and sites further downstream.

Median TP concentrations were lowest in the Upper Qu'Appelle and higher in the middle reach of the river (Figure 32). Downstream of Katepwa Lake, concentrations tended to be lower than upstream of Pasqua Lake. There was some variation among study years, particularly in the Upper Qu'Appelle, where concentrations were lower in 2013 than in the other years (Figure 33). Total reactive P concentrations had a similar spatial pattern to TP (Figure 34). The main difference in the pattern was that median TRP concentrations downstream of Katepwa Lake were similar or slightly higher than concentrations upstream of Pasqua Lake, which is the reverse of the pattern for TP. As with TP, the largest difference among years was in the Upper Qu'Appelle, where concentrations were greater in 2014 and 2015 than in 2013 (Figure 35).

Total N concentrations were greatest downstream of the Wascana Creek confluence with the Qu'Appelle River (Figure 36). Median concentrations were somewhat lower in the reach between the Craven Dam and Pasqua Lake, and lower again downstream of Katepwa Lake. The Upper Qu'Appelle River had the lowest median TN concentrations, while the Qu'Appelle River upstream of Wascana Creek had similar concentrations to the Qu'Appelle River downstream of Katepwa Lake. As with P, TN concentrations in the Upper Qu'Appelle were lower in 2013 than in 2014 and 2015 (Figure 37), while differences among years were less pronounced at downstream sites. Nitrate + nitrite concentrations declined from upstream to downstream in the Upper Qu'Appelle and were lowest at the outlet of Buffalo Pound Lake (Figure 38). Nitrate + nitrite concentrations were highest downstream of the Wascana Creek confluence with the Qu'Appelle River, and declined moving further downstream. Median concentrations varied somewhat among years (Figure 39), with 2015 having lower concentrations than the other years in the Upper Qu'Appelle, and 2013 having lower concentrations than the other years downstream of Katepwa Lake. Median concentrations were lower in 2014 than the other years in the reach between Craven Dam and Pasqua Lake. Ammonia concentrations were highest downstream of the Wascana Creek confluence and lowest in the Upper Qu'Appelle (Figure 40). Concentrations had a wide range in the whole reach from Lumsden to Pasqua Lake and were similar among study years at most sites (Figure 41).

Temporal Patterns in Nutrient Concentrations

Previous figures and descriptions have highlighted the distribution of concentrations measured at the various sampling sites. Here we present concentration results over time at selected sites to highlight representative patterns in the watershed. We also present concentration vs. flow relationships. Results are presented first for the Qu'Appelle mainstem from upstream to downstream, then for the tributaries.

In the Qu'Appelle River at Highway 19, TP and TN concentrations were comparatively low most of the year, with periods of high concentrations occurring when releases from Lake Diefenbaker were terminated (e.g. spring 2014; Figure 42). Total reactive P concentrations were often below detection limits (typically 1 µg/L) when releases from Lake Diefenbaker were occurring. Nitrate was generally the form of inorganic N with the greater concentration. For P at Highway 19, concentrations appeared to fall into two categories; concentrations were greatest (median = 88 µg/L) when flows were low (less than 0.1 m^3/s) and were low (median = 13 µg/L) when flows were over 0.2 m^3/s (Figure 43). Total N concentrations declined with higher flows, as did NH_3 concentrations, but NO_3^- concentrations were greater when water was being released from Lake Diefenbaker.

Further downstream at Lumsden, nutrient concentrations more closely followed flow patterns. Total P concentrations peaked in spring and after rain events. TRP was typically a dominant component of TP (Figure 44). Total N concentrations increased in fall and winter when flows were low. Ammonia was the dominant N form in winter, while in late summer and early fall, NO_3^- concentrations were high. Overall, N concentrations are very high and show patterns similar to Wascana Creek (discussed below), indicative of municipal wastewater effluent dominating N concentrations during periods of low flow. Consistent with expectations for rivers with point source inputs of nutrients, TP and TRP concentrations declined with increasing flows when flows were initially low. Phosphorus concentrations increased as flows increased during high flow periods (Figure 45). This pattern suggests that slightly elevated flows act to dilute the wastewater effluent during low flow periods, but as flows increase, P concentrations increase due to greater export from the watershed and greater suspension of particulates. Total N concentrations declined with increasing flows at Lumsden. However, N concentrations were always high compared to sites that did not receive the same volume of treated wastewater. Ammonia and NO_3^- had an opposing pattern at low flows which is related to the seasonal pattern of inorganic N speciation in the Regina WWTP effluent and biogeochemical cycling along Wascana Creek. During winter, when flows were low, NH_3 was the dominant N form in the effluent. During winter (under ice) oxygen levels were hypoxic to anoxic at the Wascana Creek monitoring station, thereby limiting the conversion of ammonia to nitrate by nitrifying bacteria. Nitrate concentrations were a greater proportion of TN concentrations during spring, summer, and fall, when flows were higher and oxygenation of water occurred.

Above Pasqua Lake, TP concentrations peaked during high flow periods and were lower when flows were low. Total reactive P typically constituted a high proportion of TP, but was a small proportion during certain periods, such as after spring run-off 2014 and during summer 2015 (Figure 46). Total N concentrations peaked in winter but were higher in winter of 2013/2014 than in the winters of 2014/2015 and 2015/2016. TP and TRP increased with flow (Figure 47) but the pattern was inconsistent. TN and NH_3 concentrations declined with increasing flows at low flows but varied less with flow during higher flow periods.

Phosphorus concentrations at Katepwa Lake outlet showed a strong seasonal pattern, declining in summer and increasing in winter, with TRP being a high proportion of TP (Figure 48). Total N concentrations also appeared to decline in summer and increase in winter, although the magnitude of change was lower. Nitrate concentrations were also low in summer, but high in winter. Flow-concentration relationships were not strong for Katepwa outlet, notably for TN and NH_3 (Figure 49). Round Lake inflow concentrations are summarized in figures 50 and 51. At Round Lake outlet, some aspects of nutrient concentration patterns were similar to Katepwa Lake outlet, but there were important differences. Phosphorus concentrations declined in spring and rose in winter for 2013. Concentrations declined in spring 2014, rose somewhat in summer but then remained relatively low in winter 2014-2015. In spring 2015, concentrations peaked around the time of peak flows, then declined, but rose again in summer and declined over winter 2015-2016 (Figure 52). A few dates with high flow measurements extend the concentration-flow figures for Round Lake compared to Pasqua inflow/Katepwa outflow (Figure 53). The influence of the Regina WWTP decreases further downstream and the influence of upstream lakes increases and changes seasonal nutrient patterns. The outlet of Round Lake had similar patterns of a high ratio of TRP to TP and winter increases in nitrate. Flow-concentration relationships were similar between Round Lake outflow and Katepwa outflow for flows less than 100 m^3/s, notably the lack of a strong relationship for TN.

The inflow and outflow nutrient concentrations of the lower Qu'Appelle lakes are shown for each lake on the same graph (Figures 54 to 56). Phosphorus concentrations in the outflow of Katepwa Lake exceeded concentrations in the inflow to Pasqua Lake during winters 2014-2015 and 2015-2016 (Figure 54), and inflow and outflow P concentrations were similar to each other in winter 2013-2014. Phosphorus concentrations in the inflow to Pasqua Lake usually exceeded outflowing concentrations for Katepwa Lake during the open water season. Total N concentrations in the inflow to Pasqua Lake nearly always exceeded outflow concentrations from Katepwa Lake, except for a few brief periods, most notably in spring 2013 and 2015. Winter TN concentrations in the Pasqua Lake inflow greatly exceeded concentrations in the Katepwa outflow.

Phosphorus concentrations in the inflow to Crooked Lake usually exceeded those the outflow, except in winter 2013-2014 when outflow TP concentrations were higher (Figure 55). Total N concentrations were typically slightly higher in Crooked Lake inflows than in outflows. For Round Lake, inflow and outflow nutrient concentrations were similar to each other, but concentrations tended to be slightly higher in the inflows than the outflows (Figure 56).

In the Moose Jaw River, TP concentrations peaked during spring and after summer rain events but were also high in summer 2015 when flows were low (Figure 57). Total reactive P was a major component of TP, except in summer 2015 when it was a smaller proportion of TP. Total N concentrations became much greater during periods of low flow, when NO_3^- was the dominant N form. Total P concentrations generally increased with increasing flow, but the pattern was variable (Figure 58). Total N concentrations declined with flows above around 1 m^3/s. Ammonia concentrations tended to be low, while NO_3^- was elevated at low flows.

For Wascana Creek, patterns were similar to Lumsden. Total P concentrations peaked during high flow periods but also became elevated in the winter (Figure 59). Total N was always elevated relative to other sites but peaked in the winter. Nitrate was the dominant N form in summer and fall, while NH_3 was most important in winter. Phosphorus concentrations decreased with increasing flows when flows were low, then increased as flows became greater (Figure 60). Total N declined with increasing flows. Nitrate and NH_3 concentrations were variable at low flow, reflecting the importance of seasonality rather than flow in determining NO_3^- and NH_3 concentrations. Nitrogen in all three forms declined at higher flow rates.

Total P concentrations in Last Mountain Creek peaked during spring and other high flow periods but were also elevated in summer 2015 (Figure 61). Total N concentrations varied little through time other than during high flow periods. During high flow periods, flows were generally coming from the Qu'Appelle River rather than from Last Mountain Lake, explaining the changes in concentrations. When flows were from Last Mountain Lake, TP and TRP increased with increasing flows at lower flow rates, but this pattern did not continue at high flow rates (Figure 62). Phosphorus concentrations generally increased with increasing flows when flows were towards Last Mountain Lake and tended to be higher than when flows were coming from Last Mountain Lake. Nitrogen concentrations varied little across the flow range when flows were from Last Mountain Lake, but were higher and more variable, generally increasing with flow when flows were coming from the Qu'Appelle River.

In Pheasant Creek, nutrient concentrations appeared to depend more strongly on flow rates. Phosphorus concentrations peaked during spring flows and after summer rain events, though concentrations were elevated during low flows in summer 2015 (Figure 63). Total N concentrations were elevated during spring run-off but were also elevated during lower flow periods in summer and winter. TP and TRP generally increased with increasing flows (Figure 64). Nitrogen concentrations did not have a strong pattern associated with flows, including the inorganic N forms, which were variable across the range of flows.

Nutrient Loading

Total nutrient loadings are presented in Table 4 and are depicted diagrammatically for TP and TN in Figures 65 and 66. Volume-weighted nutrient concentrations for each site are presented in Table 5. Tables 6 and 7 present total loads and volume-weighted concentrations calculated for each study year. Comparisons of TN:TP ratios (Figures 67 and 68), TRP:TP (Figures 69 and 70) ratios and DIN (dissolved inorganic nitrogen):TN ratios (Figures 71 and 72) are presented for Qu'Appelle mainstem and tributary sites. These are discussed further in the sections below.

Comparison of Load Calculation Methods

The three load calculations used (Midpoint, Beale ratio estimator, and LOADEST), generally gave similar results (Table 8, Figure 73). Sites differed in how close agreement was among the three methods, and differences were often greater at tributary sites. We chose to use the midpoint method primarily for discussing and reporting results. The midpoint method was preferred because of its simplicity, the relatively frequent data we were able to collect, and the observation that LOADEST was often a poor predictor of nutrient concentrations at some sites. We also found for total N in Wascana Creek, that the Beale method underestimated N at times, since the loads from Regina's WWTP effluent exceeded loads calculated downstream with our sampling results by a large amount. The midpoint method also has the advantage that loads can be compared continuously over time, while the Beale method only allows a total load result over the period for which it is calculated. Overall, the major results and interpretations in this study do not change if different load calculation methods are used.

Upper Qu'Appelle

Nutrient loading in the Upper Qu'Appelle from the Qu'Appelle Dam and sampled tributaries was low compared to downstream sites. Total P loading at Highway 19 was lower than at any other Qu'Appelle River or tributary site. Total N loadings at Highway 19 were similar to several of the minor tributaries. Volume-weighted nutrient concentrations at Highway 19 were lower than any other site. In terms of total load to the Qu'Appelle Watershed, Ridge and Iskwao creeks were also relatively minor contributors. However, they are important contributors within the Upper Qu'Appelle. These two creeks were comparable to the other tributaries in terms of volume-weighted nutrient concentrations.

Total P and total N loads increased from upstream to downstream in the Upper Qu'Appelle, with loads at Highway 19 accounting for only 3.2 and 22 % of loads at Marquis (Buffalo Pound inflow) for TP and TN, respectively. The total loads contributed by Ridge and Iskwao creeks were greater in 2014 and 2015 compared to 2013, due to increased flow in those years. Spring loading peaks were greater in 2014 and 2015 than in 2013 (Figures 74 and 75). The summer rain event of 2014 also a period of high loading in Iskwao Creek and the Qu'Appelle River at Marquis but had less effect at Ridge Creek and the Qu'Appelle River at Tugaske.

Buffalo Pound Lake

Nutrient loading to Buffalo Pound Lake from the Upper Qu'Appelle River greatly exceeded the nutrient load in the outflow (Figures 65 and 66). Nutrient loading to Buffalo Pound Lake from backflow during high flows on the Moose Jaw River in springs 2013 and 2015 was significant, particularly for TP. Net TP outflow from Buffalo Pound Lake was actually negative, at -0.323 tonnes over the study period. If backflows are ignored, the outflow from Buffalo Pound Lake was 23.3 tonnes, which amounts to 28 % of the upstream load entering the lake. For TN, the net load to the Qu'Appelle River was positive, at 263 tonnes. This net TN load amounts to 33 % of the upstream TN load. The outflowing TN load was 57 % of the inflowing load from upstream if backflows are ignored.

Total P and N loading to Buffalo Pound Lake from upstream plus the backflows were 107 and 570 tonnes of TP and TN, respectively. Estimates of water withdrawals for domestic and industrial use from Buffalo Pound Lake provided by the Water Security Agency's Licensing and Water Use Unit were 175,662 dam^3 over the study period. If this volume is multiplied by average TP and TN concentrations in the Buffalo Pound Lake Outflow, estimates for TP and TN removed through water withdrawals are 14.3 and 222 tonnes, respectively. Taking these withdrawals into account, nutrient retention in Buffalo Pound Lake over the study period is estimated to be 64.7 %for TP and 15 % for TN.

The majority of nutrient loading to Buffalo Pound Lake occurred in short periods during spring run-off and a major rain event in 2014. In particular, backflow in 2013 and 2015, contributed a high load over a very short period (Figures 76 and 77). Nutrient loads in the outflow from Buffalo Pound Lake also peaked in the spring, when water was released more rapidly from the lake. The backflow of TP and TN exceeded outflow in 2013, but the 2015 backflow event was comparatively minor and backflow loading was less than outflow loading in 2015.

Lumsden Area

Nutrient load in the middle reach of the Qu'Appelle River was dominated by loading from the Moose Jaw River and Wascana Creek. For both TP and TN, the sum of loads from the Moose Jaw River and Wascana Creek was greater than nutrient loading at Lumsden. Nutrient loads from the Moose Jaw River and Wascana Creek also greatly exceeded loading from the outflow of Buffalo Pound Lake. Compared to the other tributaries to the Qu'Appelle River, the Moose Jaw River had the highest TP loading, while Wascana Creek had the highest TN load.

Nutrient loads from the Regina WWTP effluent totalled 69 and 2960 tonnes of TP and TN respectively over the three-year study period (Table 9). These loads amount to 26.3 and 83.6 % of the TP and TN loads measured in Wascana Creek upstream of its confluence with the Qu'Appelle River. If effluent concentrations from July 2017 - June 2018 are used to estimate what loads might have been if plant upgrades had been present during our study, reduced loading estimates are 44.5 and 837 tonnes of TP and TN, respectively, over the study period. These amount to 17 and 24 % of TP and TN loads in Wascana Creek, respectively.

Total P loading exhibited spring seasonal peaks each year and a peak after the summer 2014 rain event (Figure 78). Total N loading showed strong seasonal peaks in the Moose Jaw River, but Wascana Creek had a consistently high TN load (Figure 79). Volume-weighted TN concentrations in Wascana Creek were 9496 μg/L, which is much greater than all other sites, and greater than double the next highest volume-weighted TN concentration, which was 3860 μg/L at Indian Head Creek. TN to TP ratios were higher in Wascana Creek than the other tributary sites (Figure 68) and the DIN:TN ratio was higher in Wascana Creek than at any other site (Figure 72).

Last Mountain Creek

During periods of high flow on the Qu'Appelle River, water flowed from the Qu'Appelle River into Last Mountain Creek, reversing flow direction of the lake's outlet. Over the entire study period, the net load of TP and TN was from Last Mountain Creek into the Qu'Appelle River, but this varied among years. In 2013 and 2015 for TP, and in 2013 for TN, loading through the lake's outlet into Last Mountain Lake exceeded loading from the lake to the Qu'Appelle River.

During spring run-off in each year, and during the summer 2014 rain event, loading to Last Mountain Creek from the Qu'Appelle River occurred (Figures 80 and 81). These periods contributed relatively high loads over a short time, as nutrient concentrations and flows were high. Over the remainder of the year, loading from Last Mountain Creek to the Qu'Appelle River occurred in a gradual manner.

As a result of the reversal of flow direction at Last Mountain Creek, nutrient loading at Craven was reduced in the spring compared to upstream of the Last Mountain Creek confluence. During the winter, nutrient loading at Craven exceeded loading upstream of the Last Mountain Creek confluence. Total N loading in this region of the Qu'Appelle River was relatively high over the entire year, reflecting the wastewater N input from Wascana Creek.

Upstream of Pasqua Lake

Nutrient loading increased moderately between Craven and upstream of Pasqua Lake (Figures 82 and 83). Loon Creek is the only studied tributary entering the river in this area, and it contributed nutrient loads similar to the other minor tributaries. The Qu'Appelle River also flows through the Fairy Hill marsh area between Highway 6 and Pasqua Lake. Volume-weighted TP concentrations increased slightly, from 326 to 368 µg/L, between Craven and upstream of Pasqua Lake. Volume-weighted TN concentrations were nearly identical between Craven and upstream of Pasqua Lake (Table 5).

Calling Lakes (Pasqua, Echo, Mission, and Katepwa)

Nutrient loads to the four Calling Lakes were calculated by treating the four lakes as one unit, without determining loading to and from each individual lake. Nutrient loading from the Qu'Appelle River upstream of Pasqua Lake plus Jumping Deer Creek exceeded loads in the outflow for both TP and TN. For the study period, nutrient retention was 38 % of inflows for TP and 37 % for TN.

Total P loads to the Calling Lakes were highest in spring, generally declined over the course of summer, and were at a minimum during winters (Figure 84). Total P loading was also elevated for a period following the summer 2014 rain event. Total N loads also peaked each spring but did not decline to the same proportion during winter as TP loads (Figure 85). Unlike TP, the period following the 2014 summer rain event was not a period of increased N loading, and N concentrations in inflowing water were lower during that period. Figure 85 shows a period of high N loading during late 2013. This period of high load is based on one relatively high TN value, which may result in a higher calculated load than what occurred. This period of apparent high loading illustrates one weakness of the midpoint method; it is easily impacted by one outlying measurement. If LOADEST is used to calculate loading, there is only a minor increase in TN load for this period.

Between Katepwa and Crooked Lakes

Nutrient loading upstream of Crooked Lake was substantially higher than loads exiting Katepwa Lake for both TP and TN (Figures 86 and 87). Volume-weighted nutrient concentrations also increased over this region of the Qu'Appelle River, but this increase was greater for TP than for TN (Table 5). The sum of tributary inputs in this region accounts for 58 % of the increase in TP, and 66 % of the increase in TN. Volume-weighted nutrient concentrations upstream of Crooked Lake (Highway 47) were lower than volume-weighted concentrations upstream of Pasqua Lake.

Spring runoff was an important period for loading in this region. The summer rain event of 2014 contributed significantly to loading in this region of the Qu'Appelle (Figures 86 and 87). The period after this rain event was particularly significant in causing a difference in the total loads between Katepwa Lake outlet and the inflows to Crooked Lake.

Crooked and Round Lakes

Both Crooked and Round lakes retained P and N over the study period. Total P retention was 25 % for Crooked Lake and 4.9 % for Round Lake. Total N retention was 15 % for Crooked Lake and 7 % for Round Lake. The summer rain event of 2014 caused higher peak loads in this portion of the watershed (Figures 88, 89, 90, and 91).

Qu'Appelle River at Welby

Monthly nutrient concentration data for Welby since 1975 for TP and 1993 for TN were obtained from the Prairie Provinces Water Board. The method used to analyze for TN changed in 1993 resulting in a significant step-trend in data (Glozier et al. 2004). Nutrient loads and volume-weighted nutrient concentrations for the Qu'Appelle River at Welby vary considerably among years (Tables10 and 11). The period 2010-2015 stands out from most of the historical record as a period of substantively greater TP and TN loading (Figure 92). This period of high loading corresponds with the high flows at Welby (Figure 9). The different load calculation methods gave similar results to each other, but LOADEST tended to give higher loads than the other two methods in years of high total flow. Volume-weighted TP concentrations appear to have declined at the beginning of the period and then increased towards the end of the period (Figure 93). Volume-weighted TN concentrations appear to have been gradually increasing since the early 1990s. Nutrient loads for 2013-2015 at Welby (837 for TP, 5640 t for TN) were similar to and slightly higher than our calculated loads at Round Lake outlet (782 and 5240 t for TP and TN, respectively). The volume-weighted concentrations at Welby are lower than further upstream (e.g. Above Pasqua Lake). There were greater differences between Welby and Round Lake outlet in the individual years (compare Tables 6 and 10).

Seasonal Loading Patterns

Seasonal patterns of flow and loading in the Qu'Appelle River varied among sites, but generally followed the pattern of load in the spring > summer > fall > winter for most constituents (Figure 94). The Qu'Appelle River at HWY 19 had a different flow pattern, with spring being the season with the least flow. At HWY 19, releases from Lake Diefenbaker are used to supplement water levels and so were lower during spring and higher in the other seasons. Moving downstream in the Upper Qu'Appelle River, spring flows progressively became more important. Outflowing load from Buffalo Pound, and at sites downstream to above the Last Mountain Creek Confluence at Last Mountain Creek, tended to follow the spring > summer >fall > winter pattern for most parameters. From Craven and downstream, summer loads were approximately equal to spring loads for TP and TN. Ammonia loading during winter was notably high in the region from Lumsden downstream to above Pasqua Lake, consistent with the high load from the Regina WWTP.

The tributaries to the Qu'Appelle River generally had a greater proportion of their loading occur during spring than compared to the Qu'Appelle River itself (Figure 95). For most of the tributaries, spring and summer were the primary periods of flow, with only trace amounts occurring in fall and winter. Last Mountain Creek followed a different pattern, with summer and fall being the more important periods for loading to the Qu'Appelle River. Wascana Creek had relatively large proportions of its N loading in summer, fall, and winter. Pheasant, Pearl and Ekapo creeks all had summer TP and TN loads similar to spring loads or greater than spring loads. These creeks had high loading in the period following the major rain event in summer 2014.

Nutrients were retained in the Lower Qu'Appelle Valley lakes in most seasons. For P, spring and summer were the periods of higher retention (Figure 96). In winter for the Calling Lakes, and fall for Round Lake, there was net release of P, though the amount of release was comparatively small. For Round Lake, winter inflows and outflows of P were approximately equal. The difference between inflow and outflow volume-weighted TP concentrations was greatest at the Calling lakes in summer (Figure 98). Outflowing volume-weighted TP concentrations exceeded inflowing concentrations for the Calling lakes in winter, but this did not occur in Crooked or Round Lakes. For TN, inflows exceeded outflows in all seasons except winter at Round Lake (Figure 97). Outflowing volume-weighted TN concentrations were always lower than inflowing concentrations (Figure 99). For the Calling Lakes, volume-weighted TN concentrations were much higher in winter than in other seasons.

Discussion

This study provides an overview of nutrient concentrations and loadings in the Qu'Appelle River and its major Saskatchewan tributaries. For nutrient concentrations, we document a change in character from the Upper Qu'Appelle River, where concentrations are strongly influenced by releases from Lake Diefenbaker to the middle and lower reaches of the river where concentrations are higher and more typical of prairie streams. We highlight the relative importance of the Moose Jaw River and Wascana Creek in terms of both flows and loads in the middle portion of the Qu'Appelle River. This study also quantifies the high contribution of N from the Regina WWTP to the overall N load in the mid-reach of the Qu'Appelle, notably above Pasqua Lake. We found that during the period of this study Last Mountain Creek was a minor contributor of nutrient load compared to the Moose Jaw River and Wascana Creek, because during high flow events there was substantial loading from the Qu'Appelle River to Last Mountain Lake. The smaller tributaries had relatively minor load contributions individually, though collectively they are a significant contributor of nutrient loads to the Qu'Appelle River.

General Patterns in the Watershed

Nutrient concentration patterns suggested an area of transition in the watershed at the confluence of the Moose Jaw River with the Qu'Appelle River. This is particularly evident in concentrations of TDS, DOC, and TP (Figs 28, 30, and 32). Upstream of Buffalo Pound Lake, these parameters have lower median concentrations, are more similar to the water chemistry of Lake Diefenbaker, though these vary depending on the proportion of flows from Lake Diefenbaker. For example, TP concentrations differed among years at the

Qu'Appelle River at Marquis (Figure 33). If flows at Highway 19 are compared with flows at Marquis for the three study years, 2014 had the lowest proportion of flows derived from Lake Diefenbaker, and also showed the highest median TP, and the greatest variability in the distribution of TP concentrations. Downstream of the Moose Jaw River confluence, TDS, DOC and TP concentrations were higher. These concentrations tended to be more variable between the Moose Jaw River confluence and upstream of Pasqua Lake. Downstream of Katepwa Lake dissolved parameters (TDS, DOC) were less variable, while TP and TSS were low at lake outlets but increased after some distance downstream. This river discontinuum pattern of TSS due to in-channel lakes is also described by Phillips et al. (2016) in their assessment of ecosystem health indicators in the Qu'Appelle River.

Nitrogen to P concentration ratios reveal some interesting differences among sites (Figure 67). Although nutrient concentrations were lower in Diefenbaker outflow, the N:P ratios were greater than any other site. The outflow from Buffalo Pound Lake had a higher TN:TP ratio than the other lake outflows. Wascana Creek also had high TN:TP ratios, consistent with the large point-source of N from Regina's WWTP. Among the other tributaries, Loon and Jumping Deer creeks had relatively high TN:TP, while the tributaries downstream of Katepwa Lake (Indian Head, Red Fox, Pheasant, Pearl and Ekapo creeks) had TN:TP ratios lower than those in the Qu'Appelle River in this region.

Total reactive phosphorus generally made up around half of the TP concentration (mean of all sites 53 %, Figure 69). This finding suggests that a high proportion of P exists in biologically available form. The TRP:TP ratio tended to be higher at lake outflows than inflows, consistent with a greater proportion of P being in particulate form in lake inflows. However, even at inflow sites where TSS concentrations tended to be high (e.g. Qu'Appelle River above Pasqua Lake) both TRP and TP tended to increase with increasing flows, and TRP was often a large proportion of TP (Figures 46, 47).

The importance of inorganic N in the total N load varied among sites. The DIN:TN ratio was highest in Wascana Creek (Figure 105), consistent with the loading of inorganic N from Regina WWTP effluent. This inorganic N was present primarily as nitrate for most of the open water season, and ammonia in winter (Figure 59). Elevated DIN:TN persisted downstream from Wascana Creek to upstream of Pasqua Lake. This inorganic N would be readily available for biological uptake.

Specific Watershed Areas

Three studies will be referred to frequently in the discussion below: Cross (1978), Munro (1986a), and Munro (1986b). Cross (1978) studied nutrient loading in the Qu'Appelle River from 1970-1976, particularly emphasizing P budgets for Pasqua, Echo, Mission, Katepwa, Crooked, and Round lakes. Cross presents P loading for many of the mainstem and tributary sites we have sampled downstream of Buffalo Pound Lake. Munro (1986a) studied P loading in the Qu'Appelle River from upstream of the Wascana Creek confluence to downstream above Pasqua Lake. Munro presents data from 1971 - 1983 gathered from several agencies, which would include some of the same data used by Cross (1978). The Munro (1986a) study includes data from before and after tertiary upgrades to remove more P from the Regina WWTP effluent in 1977. Munro (1986b) studied P and N loading to

Pasqua Lake and from Katepwa Lake with an intensive sampling campaign from April 1980 - June 1983. Summaries from these studies are provided for P (Table 12) and N (Table 13).

Upper Qu'Appelle

The Upper Qu'Appelle River is a highly managed system supplemented with water diverted from the South Saskatchewan River system via the Qu'Appelle Dam on Lake Diefenbaker. During our study, the amount of water released from the Qu'Appelle Dam was below average (Figure 3), while total discharge from Ridge Creek was above average in 2014 and 2015 (Tables 2 and 3). Given the relatively wet conditions, it is likely that inflows from other sources in the Upper Qu'Appelle, such as Iskwao Creek, minor tributaries, wetlands in the Qu'Appelle Valley and groundwater, were also above average. It is therefore likely that during our study period a greater proportion of the flow in the Upper Qu'Appelle River was derived from local watershed sources than in drier years, when more water is released from the Qu'Appelle Dam and a greater proportion of flow originates from the South Saskatchewan River system.

Nutrient concentrations in the Upper Qu'Appelle tended to increase from upstream to downstream and appeared to depend on how much water was released from the Qu'Appelle Dam. Median TP and TN concentrations and the ranges of TP and TN concentrations increased from Highway 19 to Tugaske to Marquis (Figures 32, 36). Releases from the Qu'Appelle Dam were higher in 2013 than 2014 and 2015; in particular, summer 2014 and fall 2015 had long periods with no releases. This pattern matches well with the higher median concentrations and higher variability in TP, TN and TDS in 2014 and 2015 compared to 2013.

Buffalo Pound Lake

Nutrient loading to Buffalo Pound from 2013-2015 was likely atypical. Releases from Lake Diefenbaker were below average in all three years, suggesting that a larger part of the water entering the lake was derived from the local watershed. Backflow from the Moose Jaw River occurred in both 2013 and 2015, which was particularly significant for P loading. The backflow load from the two years approximated the total outflowing P load.

Phosphorus retention in Buffalo Pound Lake, at 65 %, was higher than in the lower Qu'Appelle lakes. This elevated P retention may be due to the way the lake is managed. Natural inflows are supplemented with releases from Lake Diefenbaker to the Upper Qu'Appelle River. The additional inflowing water picks up a sediment load in the river, much of which is likely sedimented in the upper portion of Buffalo Pound Lake. The transfer of flow would add an additional sediment load to the lake, and P tends to be bound in sediments more than N. It is also likely that we found high P retention due to the input of relatively high-P water from backflow in springs 2013 and 2015. These inflows presented a non-typical loading source and occurred during high flow conditions, carrying a high sediment load, much of which would have settled within the lake.

Lumsden Area

The confluence of the Moose Jaw River with the Qu'Appelle River downstream of Buffalo Pound Lake was a place of transition in the Qu'Appelle River. Nutrients, TDS and TSS concentrations increased in this reach and become more similar to downstream sites than they were in the Upper Qu'Appelle. Based on our flow estimates, flows from the Moose Jaw River made up 74 % of flows upstream of the Wascana Creek confluence. Because the Moose Jaw River made up such a large percentage of flows, it makes sense that chemical parameters would be more similar to the Moose Jaw River than to the Upper Qu'Appelle or the outlet of Buffalo Pound Lake. Thus, the conclusion that water quality in the Qu'Appelle River fundamentally changes at the confluence with Moose Jaw Creek is due in part to the higher than average runoff in the Qu'Appelle Watershed during this study. If runoff and concomitant flows from the tributaries were lower, than it is expected the difference in water quality would be less pronounced but see Cross (1978). Wascana Creek was also a large contributor of water to the Qu'Appelle River, with flows making up 33 % of flows at Lumsden. Together, Wascana Creek and Moose Jaw Creek contributed 83 % of the total flow at Lumsden, making the relative importance of loading from the Upper Qu'Appelle small. This may not be universal across all years, notably years with low runoff, when it is expected that releases from Buffalo Pound Lake would constitute a larger proportion of downstream flow.

The nutrient load from the Moose Jaw River was greater than loads downstream on the Qu'Appelle River above Wascana Creek for both N and P. Loads from the Moose Jaw River were approximately 15 times greater than loads from Buffalo Pound Lake for P, and six times greater for N. Cross (1978) also found loading from the Moose Jaw River to be much greater than loading from Buffalo Pound Lake. When converted from export to load, mean P load in the Moose Jaw River below Moose Jaw for 1970-1976 was 100.2 t/yr, while the outflowing mean P load from Buffalo Pound Lake was 11.6 t/yr. Our mean P load for the Moose Jaw River is similar at 114 t. Our volume-weighted P concentration is lower than Cross (1978) (623 µg/L vs. 1275 µg/L), but they are similar if the concentration from 1973 is removed from Cross (1978). Flows in the Moose Jaw River were very low in 1973, and the volume-weighted TP concentration was 4848 µg/L. When this year is removed, the mean volume-weighted concentration from 1970-1976 was 679 µg/L.

Wascana Creek had lower TP loading than the Moose Jaw River, but higher TN loading. However, with the exception of Indian Head Creek, volume-weighted TP concentrations in Wascana Creek were higher than the other tributaries. Volume-weighted TN concentrations were higher than all other tributary and Qu'Appelle River sites. Prior to the beginning of tertiary treatment (P removal) in the 1970's at the Regina WWTP, volume-weighted TP concentrations in Wascana Creek were more than double those in the Moose Jaw River (Cross 1978) (Table 12). Not surprisingly, they were also greater than all other historic Qu'Appelle River and tributary sites for which volume-weighted P concentrations were calculated (Cross 1978; Munro 1986a) (Table 12). After tertiary treatment in 1977, mean volume-weighted P concentrations were nearly equal (604 vs. 614.5 µg/L) in the Qu'Appelle River above Wascana Creek and in Wascana Creek, respectively (Munro 1986a).

Cross (1978) found a mean TP load in Wascana Creek below Regina of 234.5 t/yr which exceeded the average load at Lumsden of 210.9 t/yr. Together, with consideration of the loading above Wascana Creek, the difference in these loads suggest considerable sequestration of P along downstream portions of Wascana Creek and between Wascana Creek and Lumsden. In fact, in that study, P loading at Wascana Creek > Lumsden > Craven > Above Pasqua Lake, suggesting continual sequestration along the Qu'Appelle River to Pasqua Lake. Munro (1986a) found somewhat lower TP loading in Wascana Creek prior to 1977, even though his study used similar data to Cross (1978). Munro (1986a) did not observe decreasing loading from Wascana Creek downstream to Pasqua Lake. Expressed as volume-weighted concentrations, both Cross (1978) and Munro (1986a) found concentrations at Wascana Creek > Lumsden > Craven > Above Pasqua Lake. This pattern is consistent with progressive dilution of wastewater effluent with distance downstream. We found a similar pattern, for both P and N, except that between Craven and Pasqua Lake, volume-weighted P concentrations increased, and N concentrations remained similar. In the period after tertiary treatment, Munro (1986a) also found that volume-weighted TP concentrations declined from Wascana Creek to Lumsden to Craven but increased from Craven to upstream of Pasqua Lake.

Last Mountain Creek

Last Mountain Creek contributed a small net load of TP and TN to the Qu'Appelle River compared to other tributaries during our study. This small contribution was, in part, due to the backflow of water from the Qu'Appelle River into Last Mountain Lake, which occurred during periods of high flow. Cross (1978) and Munro (1986a) both found that TP loads declined between Lumsden and Craven, suggesting loading of nutrients from the Qu'Appelle River to Last Mountain Lake. If flows in the outlet of Last Mountain Lake, Last Mountain Creek, are estimated by subtracting flows at Lumsden and Boggy Creek from those at Craven, since 1968, 33 of the 48 years have had greater flows into Last Mountain Lake than from Last Mountain Lake. This suggests that, in the long term, Last Mountain Lake is a regular nutrient sink of Qu'Appelle River nutrients. Many of the years with net outflow from Last Mountain Lake have been in recent years, including 2003, 2005-2007 and 2010-2016. In comparatively dry periods, Last Mountain Lake acts as a net recipient of flows from the Qu'Appelle River; spring flows are directed back into the lake through the operation of the Craven control structure, and little water from the lake flows downstream because the structure maintains a higher water elevation. In wetter periods, the Craven control structure is maintained at a lower elevation. Spring flows from the Qu'Appelle River often still enter Last Mountain Lake through its outlet, but steady outflows can occur through the remainder of the year, as we observed during our study.

We found that volume-weighted TP and TN concentrations decreased downstream of the Last Mountain Creek confluence, as did Cross (1978) and Munro (1986a). This finding suggests that when there is outflow, the outflow of Last Mountain Creek acts to dilute nutrient concentrations in the Qu'Appelle River. The effects of this dilution are expected to be greater when flows from Last Mountain Lake are high. For example, we measured lower N concentrations in the Qu'Appelle River above Pasqua Lake in winters 2014-2015 and 2015-2016 than in 2013-2014 and attribute the difference to increased outflow from Last Mountain Creek diluting the Qu'Appelle River flows. In drier years, when the Craven control structure is operated at a higher elevation, we might also expect to see a reduction in suspended sediment load below Craven, as the structure would reduce flow velocity directly upstream and should result in more suspended material settling.

Calling Lakes

Nutrient loading to Pasqua Lake was high compared to other measured loads in this study. For TP there was a total (over the three-year period) 743 t of TP and 5700 t of TN (an average of 248 and 1900 t/yr, respectively). Expressed as volume-weighted concentrations, inflows had 368 µg/L of TP and 2820 µg/L of TN. Loading varied among years, ranging from 163 - 335 t of TP and 1400 - 2280 t of TN. These TP loads exceeded those reported by Cross (1978), Munro (1986a), and Munro (1986b). However, average flows during our study were more than double (mean 673 hm^3/yr) those for the periods 1970-1976 (mean 316.9 hm^3/yr) and 1977-1982 (mean 103.2 hm^3/yr). Given the critical role of flow in determining load, the increased loading during our study is not unexpected. Given the difference in flows, comparison of volume-weighted concentrations is of more direct relevance. Volume-weighted TP concentrations were lower during our study above Pasqua Lake than was found by Cross (1978) from 1970-1976 and Munro (1986a) from 1977-1982. However, we found higher concentrations than Munro (1986a) from 1974 to 1976 and Munro (1986b) from April 1980 to Jun 1983. It is surprising that we found volume-weighted TP concentrations to be higher than Munro (1986a) from 1974-1976 since 1974-1976 was before tertiary treatment of Regina sewage effluent began. However, Cross (1978) also reports lower volume-weighted TP than our study for 1974-1976 specifically (mean 311.7 µg/L). Curiously, when we compare data from Wascana Creek for 1974-1976, we calculate very different volume-weighted TP from that reported by Cross (1978) (2324 µg/L) and Munro (1986b) (782 µg/L). The concentration from Cross (1978) is more consistent with expectations given the known elevated P concentrations in the Regina WWTP effluent. Both studies still report comparatively low volume-weighted TP concentrations above Pasqua Lake though. One limitation of those two studies is that their loads were determined using monthly mean data. Some of the inconsistency could come from error due to their relatively infrequent sampling.

Munro (1986b), measured TP and TN loading to Pasqua Lake from April 1980 to June 1983. During their study period of 3 years and 3 months, they measured loadings of 135 t of TP and 1244 t of TN to Pasqua Lake. These loadings from more than a three-year period are lower than the loadings we calculated for any one-year period. Over their study period, inflows to Pasqua Lake were 433 hm^3 and if their loads are converted to volume-weighted concentrations, we obtain concentrations of 312 µg/L of TP and 2877 µg/L of TN (Tables 12 and 13). Their volume-weighted TP concentration is somewhat lower than our value of 368 µg/L, and their TN concentrations were slightly higher than ours (2877 vs. 2820 µg/L). These similar volume-weighted nutrient concentrations may suggest that the processes contributing to loading were similar during these two study periods, even though flows were very different. During our study, nutrient concentrations above Pasqua Lake were poorly related to flow, with TP increasing with flow somewhat at low flow rates, and with TN appearing to decline slightly with increases in flow (Figure 47). These patterns of relatively small changes in concentration with flow may explain why we found similar volume-weighted concentrations in periods with very different flows.

Leavitt et al. (2006) estimate TN inflow to Pasqua Lake based on a stable isotope mass balance approach as 151 t/yr over the years 1994-2002 for the portion of the year from day 137 to 233. If we restrict our loading estimates to that period of the year, we have TN loadings of 396, 709, and 558 t/yr in 2013, 2014 and 2015 respectively. Our loading estimates are approximately four times greater over the same period of the year; however, river discharge was also greater during our study period. For DOY 137-233, discharges were 231, 342, and 230 hm^3 from 2013-2015. In contrast, mean discharge for this period of the year for 1994 to 2002 was 89.4 hm^3. Expressed as volume-weighted concentrations, for 2013-2015, volume-weighted TN concentrations were 2070 µg/L, whereas the mean volume-weighted TN concentration based on a mean load of 151 t and a mean discharge of 89.4 hm^3 is 1690 µg/L. Some of the difference between these values is attributed to the different approaches of the studies.

We determined retention of P and N in the Calling Lakes to be 38 and 37 % of inflows, respectively, over the three-year study period. Munro (1986b) found a net export of P during their study period, with the outflowing TP load being 32 % greater than the inflowing load. They found N retention rates much higher than our study, at 62 % of inflows. Our two studies show an interesting contrast: Munro (1986b) studied a drier period and found P export rather than P retention, while we found high P retention during a period of high flow. For N the comparison is reversed: the low flow period had high N retention compared to the wetter period. Two reasons likely account for the P retention in our study and export in Munro (1986b). First, the Munro (1986b) study was conducted in the early 1980s, shortly after P loading from the Regina WWTP was reduced. There is an expectation that internal loading from the lakes would release P from sediments that had accumulated over years of high P loading. Second, during our study, higher flows are known to have contributed a greater proportion of particulate P including that in suspended sediment. This sediment largely settles in Pasqua Lake. In a lower flow scenario, the percentage of incoming P that settles out is expected to be lower. Donald et al. (2015) using sparse data provided an initial P retention estimate in the Calling Lakes of 27 %. Cross (1978) calculated P retention for each of the Calling Lakes separately. Using inflow loads for Pasqua Lake, and outflow from Katepwa, the Calling Lakes were a net source of P from 1970 to 1976, with outflows exceeding inflows by 8 %.

Urban wastewater effluent was an important point source of N during both our study and that of Munro's (1986b). During the low flow period of the early 1980s, N retention may have been higher because water residence times in the lakes was longer. In theory, longer residence increases opportunity for N removal by denitrification and sedimentation (Saunders and Kalff 2001). Using the same dataset as for P, Donald et al. (2015) estimated 66 % N retention in the Calling Lakes, with a mean N sequestration of 418 t/yr. As a percentage of inflows, the percent retention of N was lower from our study, but as a total amount, we found an N retention of 724 t/yr, which is considerably higher than the estimate by Donald et al. (2015). Their retention estimates were based on data from four samples per year and were considered preliminary by the authors. Their data for lake inflows were also taken from the Qu'Appelle River at Lumsden, some distance upstream from Pasqua Lake. In addition to variability from different flow conditions, the preliminary nature of their estimates may account for the differences we observed. Leavitt et al. (2006)

estimate retention of 36 % for N for the Calling Lakes, if river inflows from Pasqua Lake are compared directly to outflows at Katepwa. These retention rates are similar to ours but are based on summer data specifically.

Downstream of Katepwa Lake

The increase in nutrient loads and volume-weighted concentrations between the outlet of Katepwa Lake and the inflow to Crooked Lake is consistent with the hydrology of the area. This area receives inputs from four of the studied tributaries, in addition to several smaller tributaries, including Mitchell, Wolfe, Adair, Roselane, and Summerberry creeks. At the outlet of Katepwa Lake, suspended sediment concentrations were low, as is generally expected at the outlet of lakes, where the sediment load from upstream in the river has largely settled out in the lake (Jones 2010). The Qu'Appelle River downstream of Katepwa Lake would be expected to increase in sediment load and particulate nutrient load from tributary inputs, but also from streambed erosion as the river re-establishes its normal sediment load.

Cross (1978) included P loading estimates for many of the tributaries we sampled. Her study reports tributary P export in mg/m^2. When these are converted to loading in t using the effective drainage areas provided in the report, her loadings for minor tributaries (Jumping Deer, Indian Head, Loon, Pheasant, and Ekapo Creeks) were noticeably lower for most sites than the ones in this study. When compared, as volume-weighted TP concentrations, Jumping Deer Creek had lower concentrations in our study (210 µg/L vs. 298 µg/L), but Pheasant and Ekapo Creeks had higher concentrations in her study (455 vs. 327 µg/L for Pheasant Creek; 545 vs. 238 µg/L for Ekapo Creek). These differences in volume-weighted TP in Pheasant and Ekapo creeks are reasonable given the large difference in flow between our two studies. For example, mean annual discharge for Pheasant Creek at Highway 22 from 1970-1976 was 13.4 hm^3, but was 47.4 hm^3 during our study period (estimated 70.6 hm^3 at Qu'Appelle River confluence). For both Pheasant and Ekapo creeks, flows after the summer rain event of 2014 were the highest mean daily flows on record.

We found nutrient retention in the lower Qu'Appelle Lakes to follow the following pattern: Calling Lakes > Crooked Lake > Round Lake. This pattern is expected based on the hydraulic residence time of the lakes and lake order on the river. Residence time is greatest for the Calling Lakes collectively, then Crooked Lake, and finally Round Lake (estimated residence times during our study were 0.8, 0.12, and 0.07 years for the Calling Lakes, Crooked Lake, and Round Lake, respectively). Increased residence time generally leads to increased retention for both P (Brett and Benjamin 2008) and N (Saunders and Kalff 2001). Another reason to expect lower retention downstream is the cumulative effect of each lake on the river downstream. At the outlet of Katepwa Lake suspended sediments and volume-weighted nutrient concentrations were lower than above Pasqua Lake. At the inflow to Crooked Lake, these concentrations had increased, but were still lower than those above Pasqua Lake. Suspended sediment and nutrient concentrations at the outlet of Crooked Lake were lower that its inflow. The river distance to Crooked to Round Lake is comparatively short (45 km), and nutrient concentrations did not increase to the levels they were at the Crooked Lake inflow. This sequential retention of nutrients and sediments reduces the amount available further downstream.

Unlike our findings, Cross (1978), found that nutrient retention in the lower Qu'Appelle Lakes followed the pattern Round Lake > Crooked Lake > Calling Lakes. This difference in our studies could be the result of different hydrological conditions but could also be the result of the different P loading regime in the Qu'Appelle lakes between our two studies. P loading from Regina sewage effluent declined dramatically after P removal began in 1977 (Munro 1986a), and P concentrations in the Qu'Appelle valley lakes have declined significantly (WSA unpublished data). Cross (1978) may have found P export from the Calling Lakes exceeding inputs due to accumulation of P in sediments that happened to have been exported in large quantities during their study. If such exports from the Calling Lakes were previously greater, then there would have been greater potential for Crooked and Round lakes to retain additional P.

Qu'Appelle River at Welby

Nutrient loading patterns in the Qu'Appelle River at Welby highlight the high nutrient loading in the Qu'Appelle River during our study period (Figure 92). The pattern of nutrient loading is similar to the pattern of annual discharge at Welby (Figure 9). Both flows and nutrient loading were particularly low in the late 1980s and early 1990s. From the mid-1990s through the 2000's flows and loads varied year to year but tended to be higher than the previous period. The period from 2010-2015 stands-out, with flows well above the median. This longer-term record of nutrient loading provides context for the rest of our study sites, where longer term loading records are lacking. In general, we can infer that our nutrient loads determined for 2013-2015 are higher than the long-term average, and particularly for the period 1977-2009.

Volume-weighted nutrient concentrations appear to have been rising recently for TP, and more gradually over a longer period for TN (Figure 93). If this pattern is also occurring in the rest of the Qu'Appelle watershed, it might be reasonable to expect that our volume-weighted concentrations would also be a bit higher than past years. The apparent decline in volume-weighted TP from 1976 to the mid-1990s may be the result of P removal from Regina's WWTP, which began in 1977 and resulted in lower P loads in the Qu'Appelle River (Munro 1986a). The recent increases in volume-weighted P and N may be related to flows, which have also tended to be higher recently. It is reasonable to expect higher nutrient concentrations when flows are high, and both TP and TN concentrations increased with increasing flow at Welby.

Seasonal Patterns

Our study occurred during a period of above average flows and, based on the available evidence, above average loading. A recent study of hydrologic trends at Smith Creek in Southeast Saskatchewan has suggested that recent years have had higher streamflow volumes, peak discharges and higher proportions of streamflow derived from rainfall compared to historical averages (Dumanski et al. 2015). Increases in streamflow can affect total nutrient loads both because increased total flow will transport a larger mass of nutrients if concentrations remain similar, and because nutrient concentrations often increase with increased flows (e.g. Rattan et al. 2017; Ontkean et al. 2005). Our relatively high nutrient loadings are therefore an expected result of the high flows that occurred during the study period. Changes in flow regime to one of greater flows has been suggested as major contributor in increases in TP concentrations in Lake Winnipeg (McCullough et al. 2012) and changes in precipitation have been identified as a major driver of changes in N export in the Mississippi River (Donner and Scavia 2007).

Nutrient loading at most sites was greatest in spring, followed by summer, with fall and winter loading being minor (Figures 94 and 95). The Qu'Appelle River at Highway 19 and Last Mountain Creek were exceptions to this, due to differences in the timing of flows at these sites. At Highway 19, flows are managed to supplement water in the Qu'Appelle watershed and water is generally released when natural flows are low. At Last Mountain Creek, flows were generally towards Last Mountain Lake during high flow periods in spring or summer, but flows were towards the Qu'Appelle River during the remainder of the year. Winter N loading was greater in Wascana Creek and downstream to above Pasqua Lake, which is explained by the high N loading from Regina WWTP. In general, the spring snowmelt period is expected to be the period of greatest nutrient loading in prairie streams (Corriveau et al. 2013). The seasonality of loading we found generally matches this expectation, but we found a relatively high proportion of loading during summer at many sites. The rainstorm of late June 2014 was a particularly important contributor to summer loading in our study. The importance of summer runoff events has increased (Dumanski et al. 2015).

Seasonal nutrient retention patterns in the Lower Qu'Appelle Valley lakes (Calling Lakes, Crooked Lake, and Round Lake) differed among lakes and between TP and TN. For TP, most retention occurred in spring and summer (Figure 96), consistent with periods of higher inflows. This higher retention is in part due to higher sediment particulate P loading to, and in-lake settling of, sediments. Biological uptake of P, with sedimentation as plankton die also contributes to the greater retention in spring and summer. The volume-weighted TP concentrations suggest that inflowing P concentrations were particularly high in summer, and that outflowing concentrations were comparatively low in the Calling lakes (Figure 98). The Calling Lakes had net release of P during the winter, and Round Lake had net P release in fall and winter. For TN, the Calling Lakes stand out as having a large difference in inflowing and outflow TN load in fall and winter (Figure 97). This is consistent with the large load of N from Regina WWTP, which would be a larger proportion of the total load in winter when other flow sources are low. The large load of urban N is also reflected in winter volume-weighted TN concentrations, which are high in the inflow to the Calling lakes (Figure 99).

Conclusion

We measured nutrient concentrations and determined nutrient loading at key points along the Qu'Appelle River in Saskatchewan and its major tributaries. These determinations were made during a wet period. Flows at most sites over the three-year study were above the historic 75th percentile. The study also occurred immediately prior to the upgrade of the Regina WWTP designed to enhance N removal and significantly reduce N loading to the

Qu'Appelle Watershed. This study allows for a basin-wide understanding of nutrient sources and dynamics in the Qu'Appelle Watershed. It provides critical information for understanding load sources to the river and downstream lakes, which will form part of the basis for updating nutrient objectives and making nutrient management decisions in the watershed. It also provides a reference point to evaluate the effects of the recent upgrades to the Regina WWTP.

The Qu'Appelle River was found to have a point of transition at its confluence with the Moose Jaw River. Upstream of this confluence water chemistry was influenced by the transfer of water from Lake Diefenbaker, having lower nutrient, TDS, and DOC concentrations. However, this varied depending on the proportion of flow from Lake Diefenbaker versus that received from runoff in the local watershed. Downstream of the Moose Jaw River, the Qu'Appelle River tends to have higher nutrient concentrations, higher DOC and TDS, which is more typical of a prairie streams and rivers.

Moose Jaw River and Wascana Creek were the two major contributors of flows and nutrients to the Qu'Appelle River during this study. The minor tributaries were small contributors of nutrients individually, but together contributed loads that were similar to those of the Moose Jaw River or Wascana Creek. Wascana Creek contributed a disproportionately high N load compared to its flow and TP loads. Volume-weighted TP concentrations were relatively high for the Moose Jaw River and Wascana Creek, but they were lower than at Indian Head Creek and were near the concentrations from other tributaries. For TN, the Moose Jaw River had concentrations similar to other tributaries, but Wascana Creek had concentrations greater than double any other tributary. Regina WWTP contributed an estimated 83.6 % of the TN load to Wascana Creek. It is expected that improvements in N removal will reduce N loading in Wascana Creek considerably.

The lakes along the Qu'Appelle River all retained nutrients during our study period. This is generally the expected behaviour in most lakes. The Calling lakes retained more nutrients than Crooked and Round lakes, consistent with their residence times and positions in the watershed. Retention of nutrients does not necessarily cause permanent loss of that nutrient; a portion of the retained nutrients can become available in future years through sediment release processes.

Figures

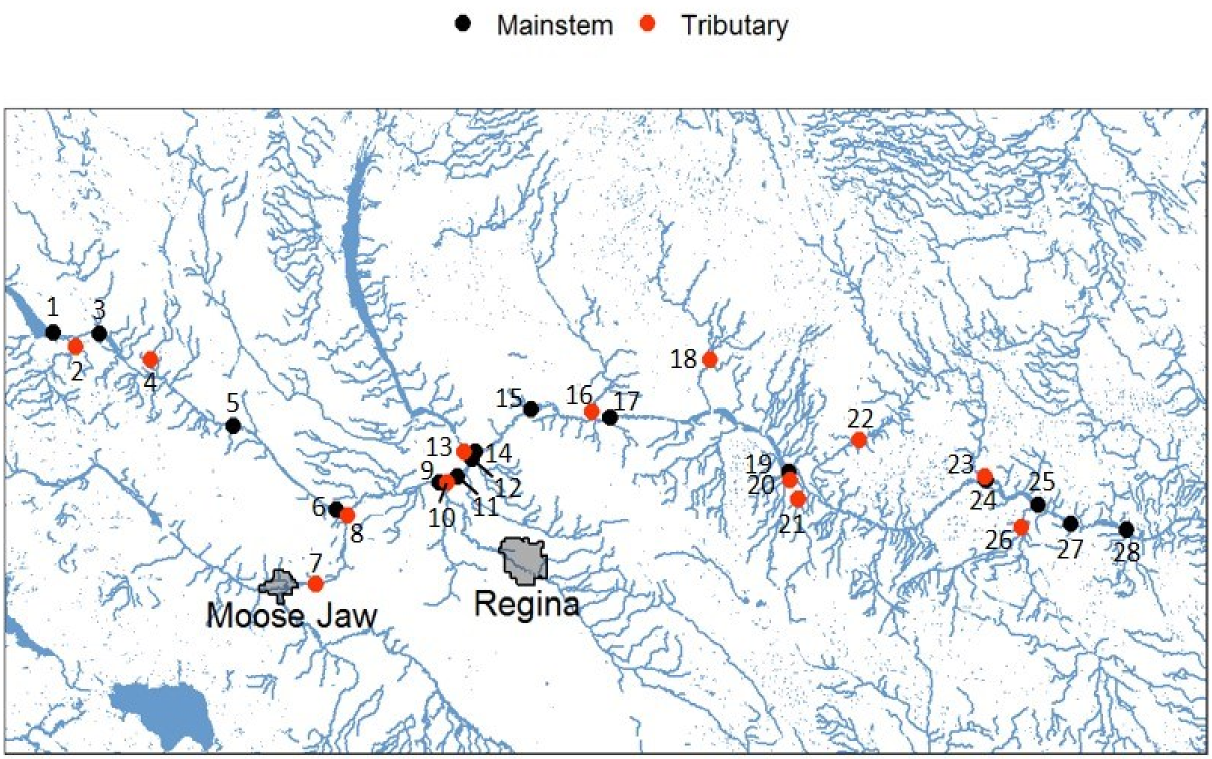


Figure 1: Map of Qu'Appelle River mainstem (black) and tributary sites (red). Administrative boundaries of the Cities of Regina and Moose Jaw are also indicated. 1: Qu'Appelle River at Highway 19, 2: Ridge Creek, 3: Qu'Appelle River at Tugaske, 4: Iskwao Creek, 5: Qu'Appelle River at Marquis, 6: Buffalo Pound Lake outlet, 7: Moose Jaw River at Highway 301, 8: Moose Jaw River at TWP RD 184, 9: Qu'Appelle River above Wascana Creek, 10: Wascana Creek, 11: Qu'Appelle River at Lumsden, 12: Qu'Appelle River above Last Mountain Creek, 13: Last Mountain Creek, 14: Qu'Appelle River below Craven, 15: Qu'Appelle River at Highway 6, 16: Loon Creek, 17: Qu'Appelle River above Pasqua Lake, 18: Jumping Deer Creek, 19: Katepwa Lake outlet, 20: Indian Head Creek, 21: Red Fox Creek, 22: Pheasant Creek, 23: Pearl Creek, 24: Qu'Appelle River at Highway 47, 25: Crooked Lake outlet, 26: Ekapo Creek, 27: Qu'Appelle River at Highway 201, 28: Round Lake outlet.

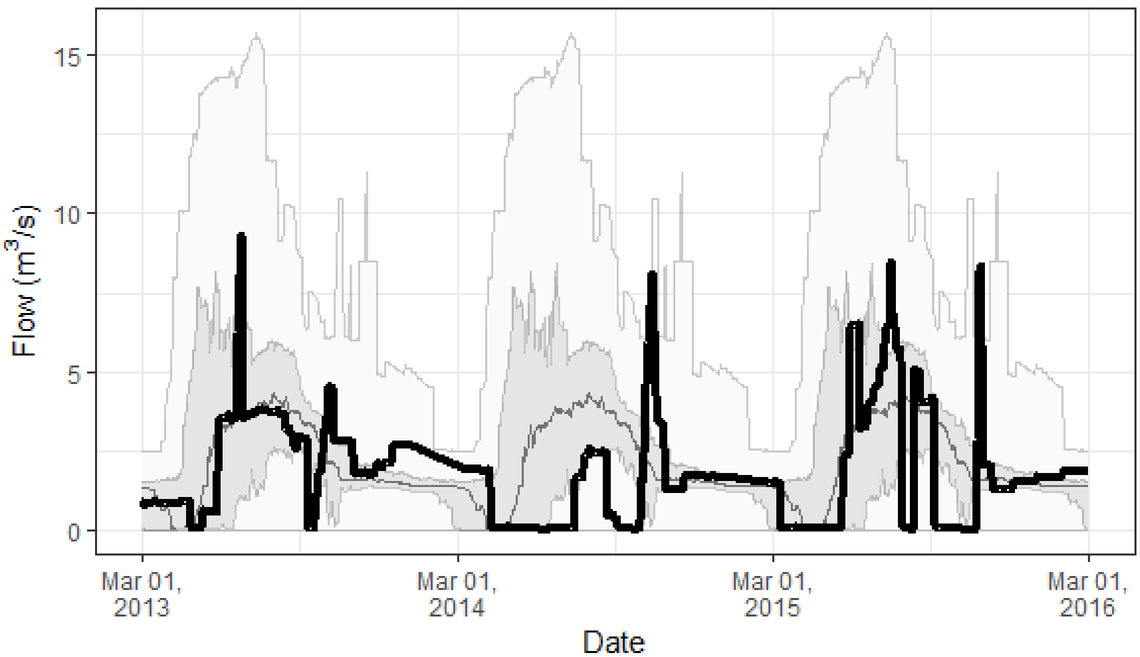


Figure 2: Flows for the Qu'Appelle River at Highway 19. Shading indicates quantiles of historic flows. The lightest shading represents the 0-25th and 75-100th percentiles. Darker shading represents the 25-75th percentile, with a thin line representing median flows.

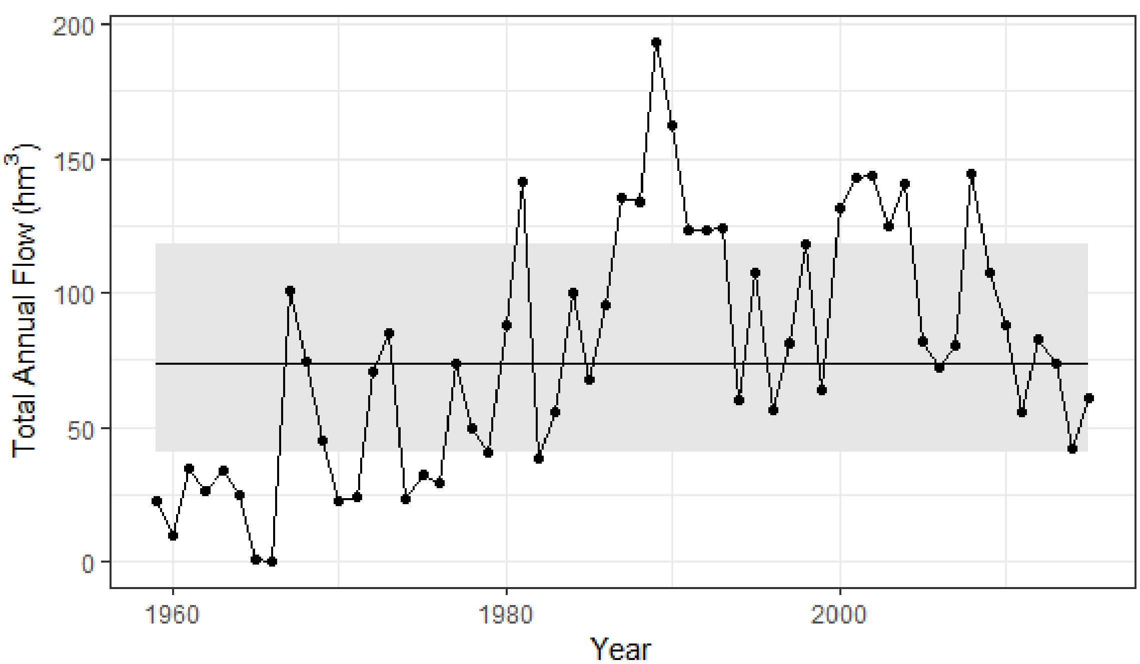


Figure 3: Total annual flow for the Qu'Appelle River at Highway 19. Total flow was calculated using years determined from March - February. The median annual flow is indicated by a horizontal line, with the shaded area around the median indicated the 25-75th percentile range. Lighter shading indicates the 0-25th and 75-100th percentile ranges.

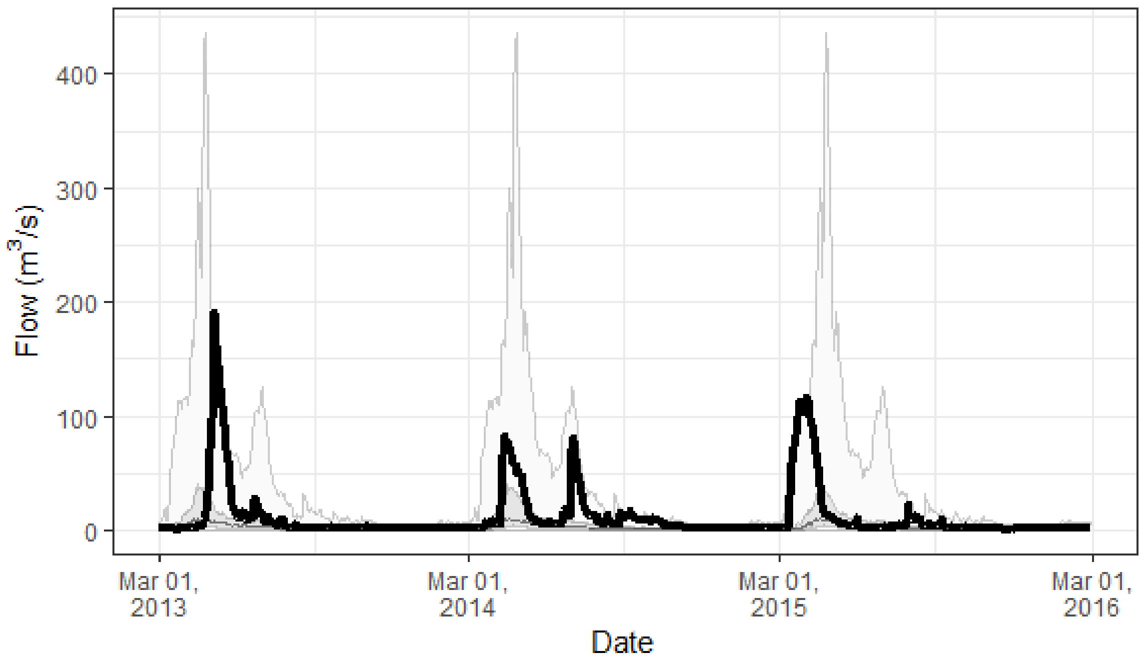


Figure 4: Flows for the Qu'Appelle River at Lumsden. Shading indicates quantiles of historic flows. The lightest shading represents the 0-25th and 75-100th percentiles. Darker shading represents the 25-75th percentile, with a thin line representing median flows.

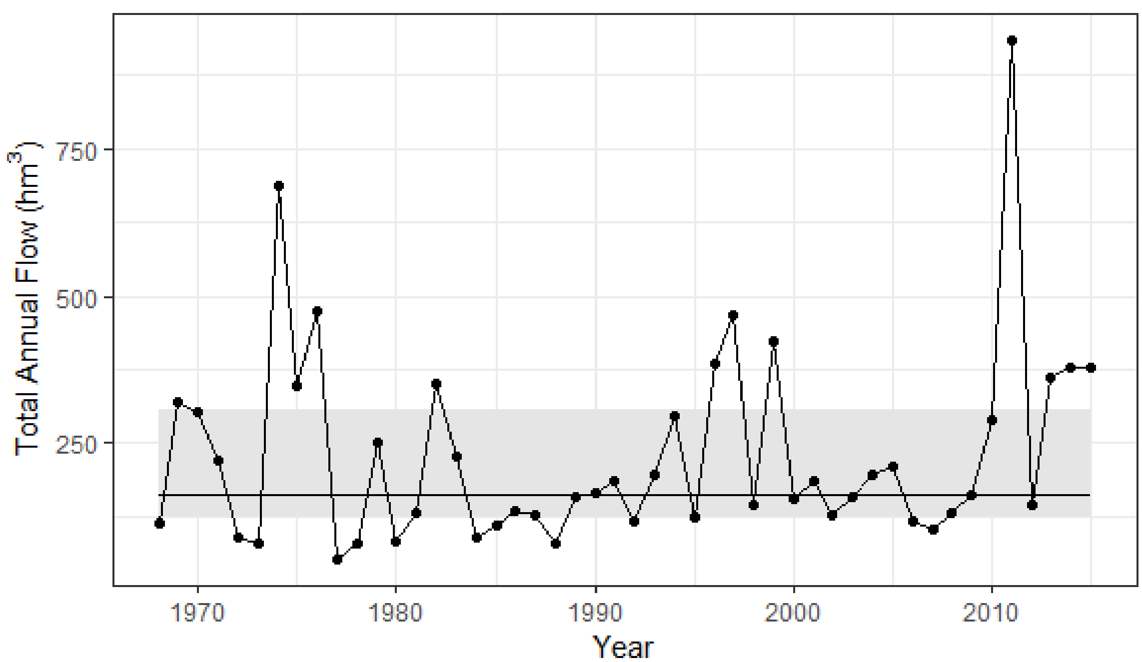


Figure 5: Total annual flow for the Qu'Appelle River at Lumsden. Total flow was calculated using years determined from March - February. The median annual flow is indicated by a horizontal line, with the shaded area around the median indicated the 25-75th percentile range. Lighter shading indicates the 0-25th and 75-100th percentile ranges.

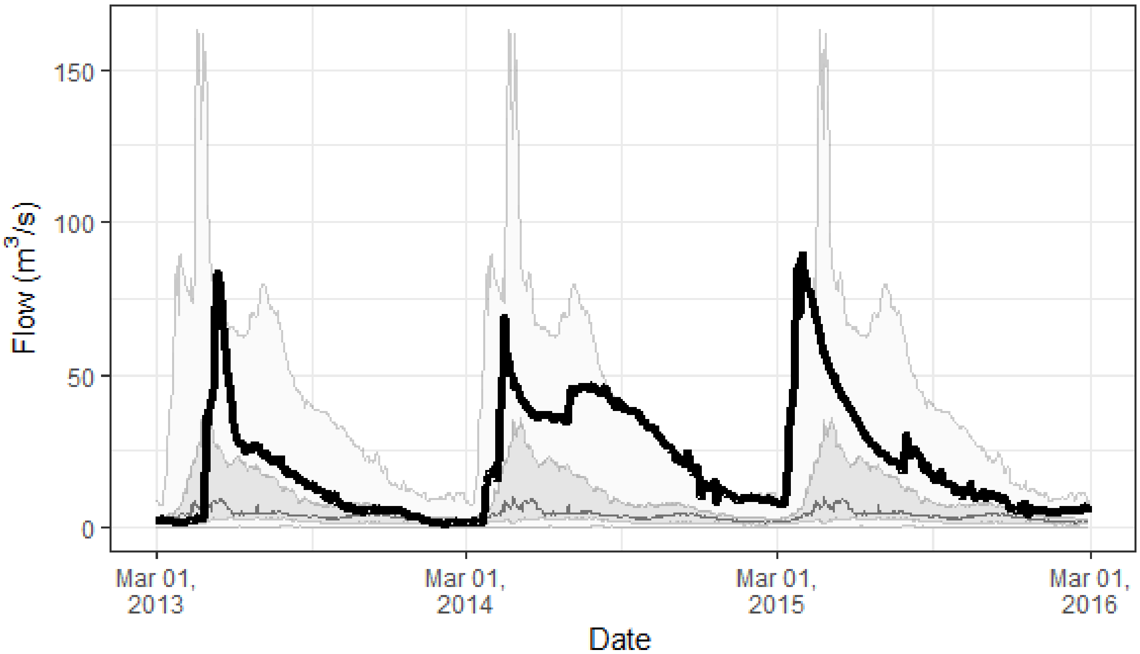


Figure 6: Flows for the Qu'Appelle River above Pasqua Lake. Shading indicates quantiles of historic flows. The lightest shading represents the 0-25th and 75-100th percentiles. Darker shading represents the 25-75th percentile, with a thin line representing median flows.

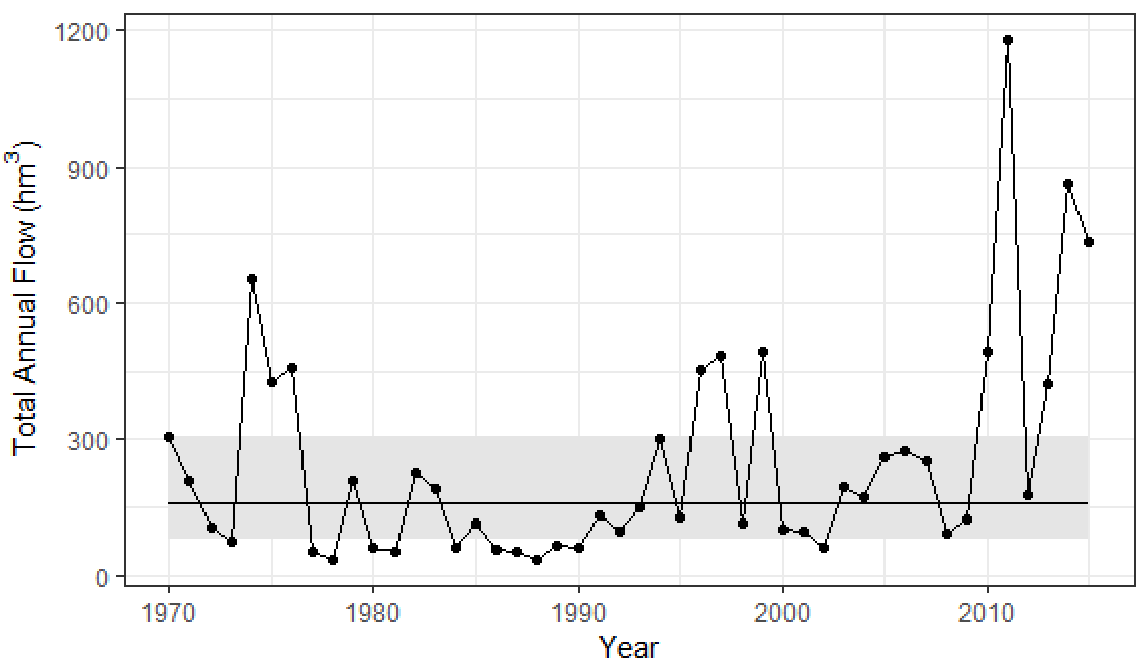


Figure 7: Total annual flow for the Qu'Appelle River above Pasqua Lake. Total flow was calculated using years determined from March - February. The median annual flow is indicated by a horizontal line, with the shaded area around the median indicated the 25-75th percentile range. Lighter shading indicates the 0-25th and 75-100th percentile ranges.

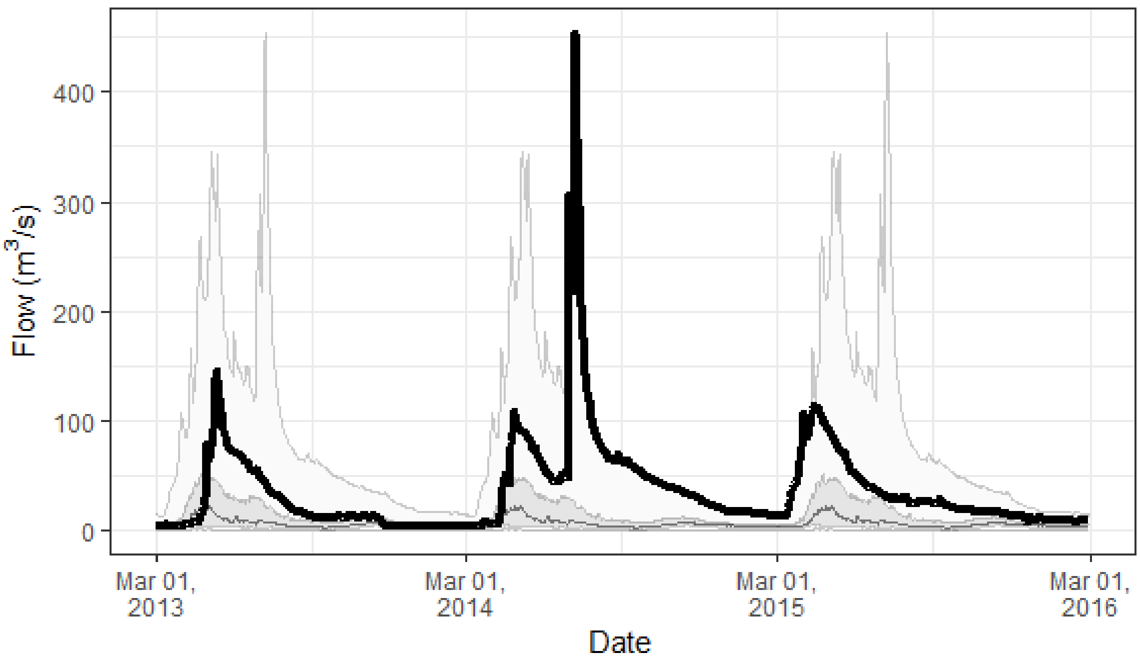


Figure 8: Flows for the Qu'Appelle River at Welby. Shading indicates quantiles of historic flows. The lightest shading represents the 0-25th and 75-100th percentiles. Darker shading represents the 25-75th percentile, with a thin line representing median flows.

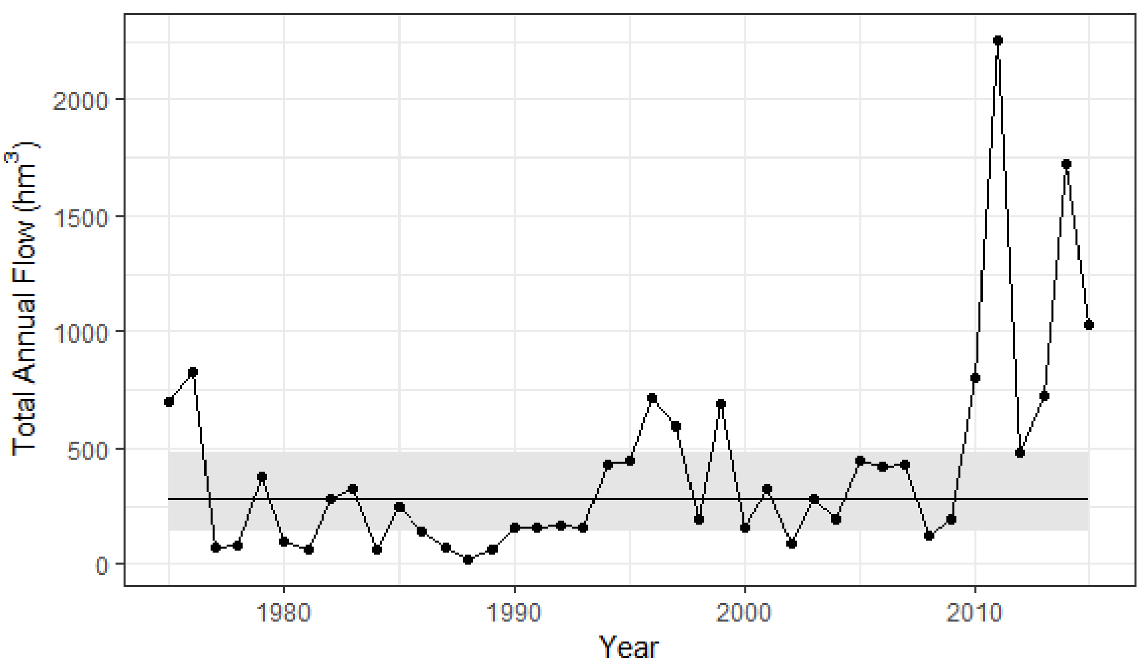


Figure 9: Total annual flow for the Qu'Appelle River at Welby. Total flow was calculated using years determined from March - February. The median annual flow is indicated by a horizontal line, with the shaded area around the median indicated the 25-75th percentile range. Lighter shading indicates the 0-25th and 75-100th percentile ranges.

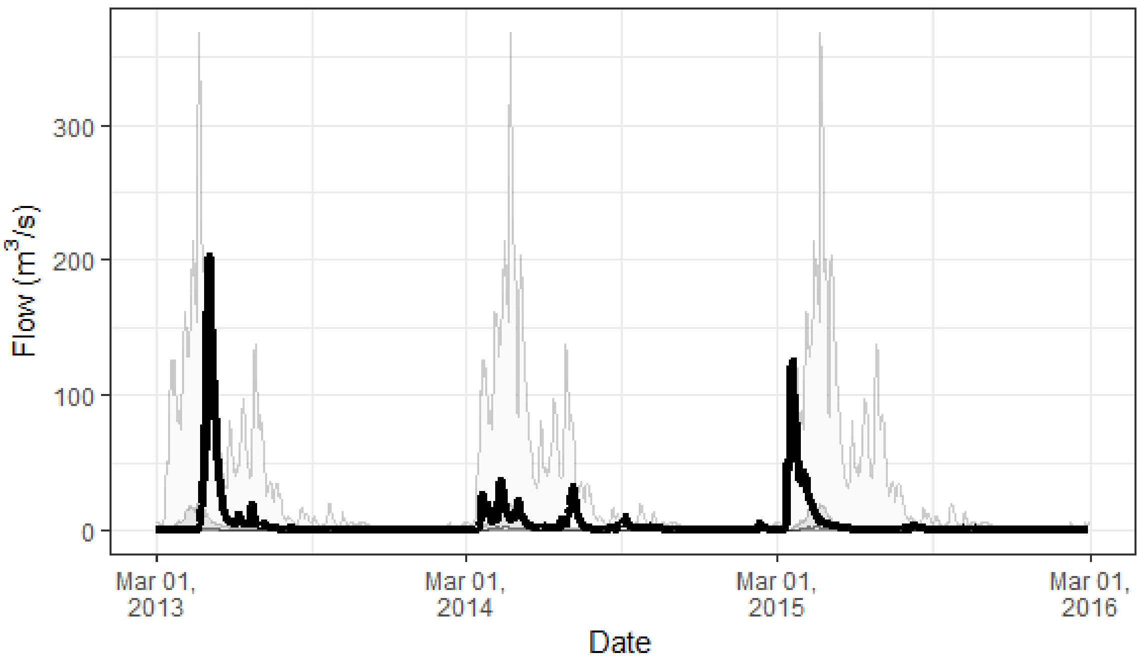


Figure 10: Flows for the Moose Jaw River at Highway 301. Shading indicates quantiles of historic flows. The lightest shading represents the 0-25th and 75-100th percentiles. Darker shading represents the 25-75th percentile, with a thin line representing median flows.

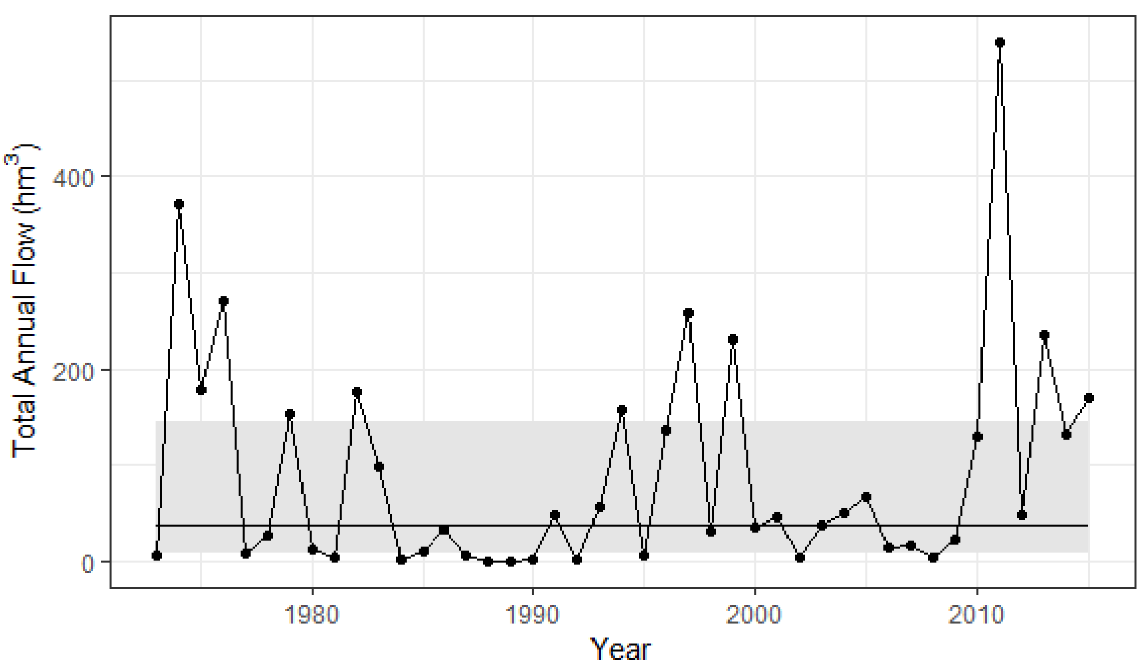


Figure 11: Total annual flow for the Moose Jaw River at Highway 301. Total flow was calculated using years determined from March - February. The median annual flow is indicated by a horizontal line, with the shaded area around the median indicated the 25-75th percentile range. Lighter shading indicates the 0-25th and 75-100th percentile ranges.

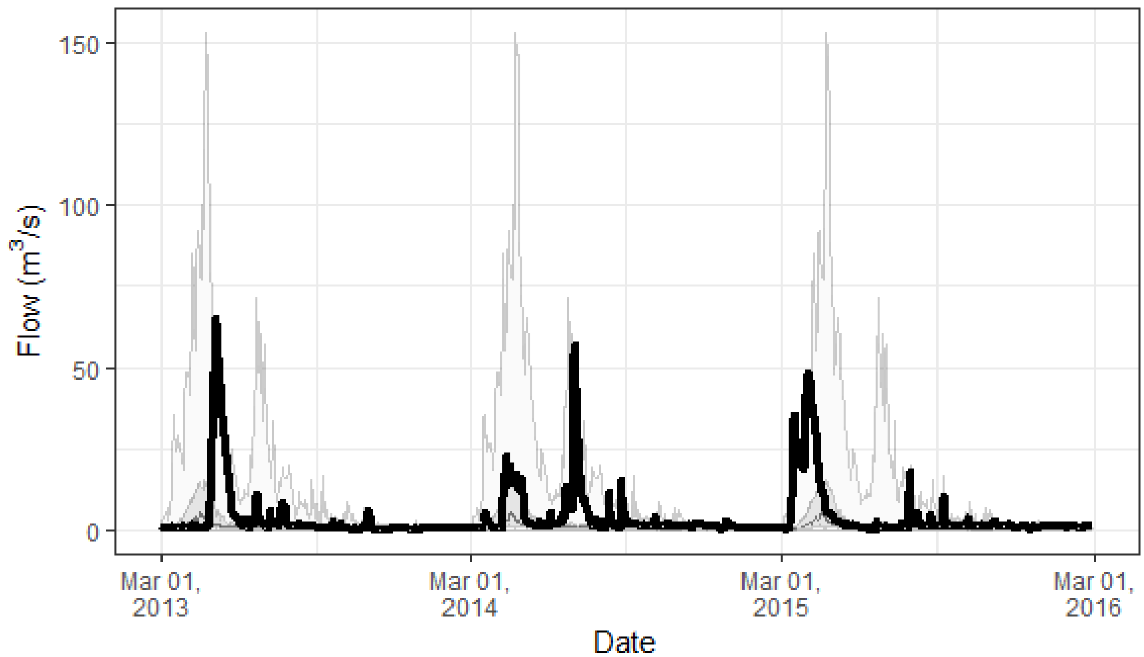


Figure 12: Flows for Wascana Creek at Highway 641. Shading indicates quantiles of historic flows. The lightest shading represents the 0-25th and 75-100th percentiles. Darker shading represents the 25-75th percentile, with a thin line representing median flows.

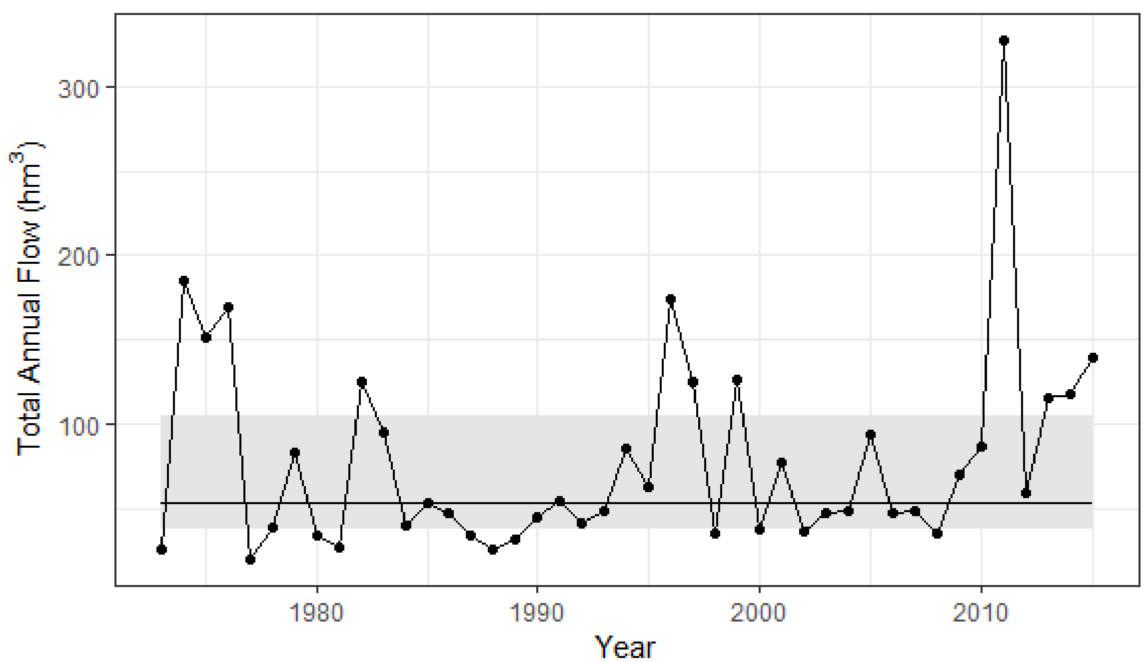


Figure 13: Total annual flow for Wascana Creek at Highway 641. Total flow was calculated using years determined from March - February. The median annual flow is indicated by a horizontal line, with the shaded area around the median indicated the 25-75th percentile range. Lighter shading indicates the 0-25th and 75-100th percentile ranges.

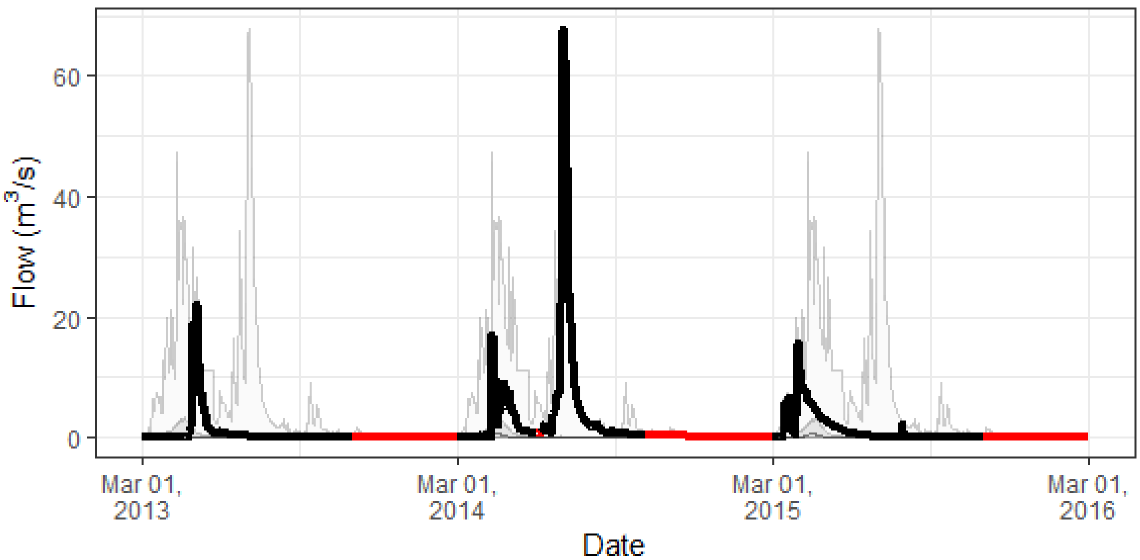


Figure 14: Flows for Pheasant Creek. Red segments indicate periods where data were missing and were estimated using interpolation. Shading indicates quantiles of historic flows. The lightest shading represents the 0-25th and 75-100th percentiles. Darker shading represents the 25-75th percentile, with a thin line representing median flows.

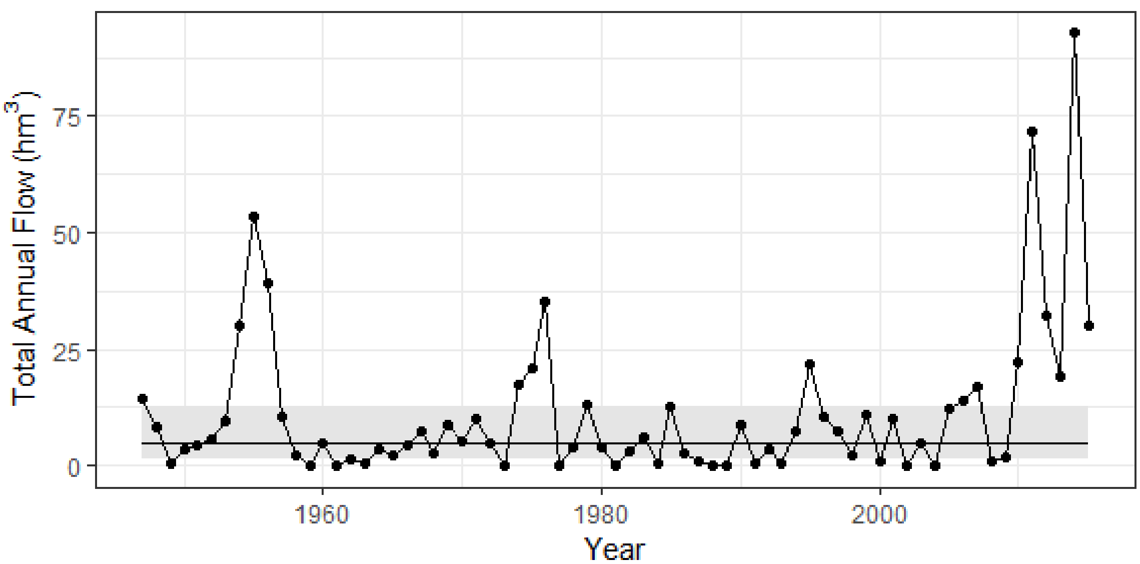


Figure 15: Total annual flow for Pheasant Creek. Total flow was calculated using years determined from March - February. The gauge at Pheasant Creek is operated seasonally; data is from March 1 to October 31 only. The median annual flow is indicated by a horizontal line, with the shaded area around the median indicated the 25-75th percentile range. Lighter shading indicates the 0-25th and 75-100th percentile ranges.

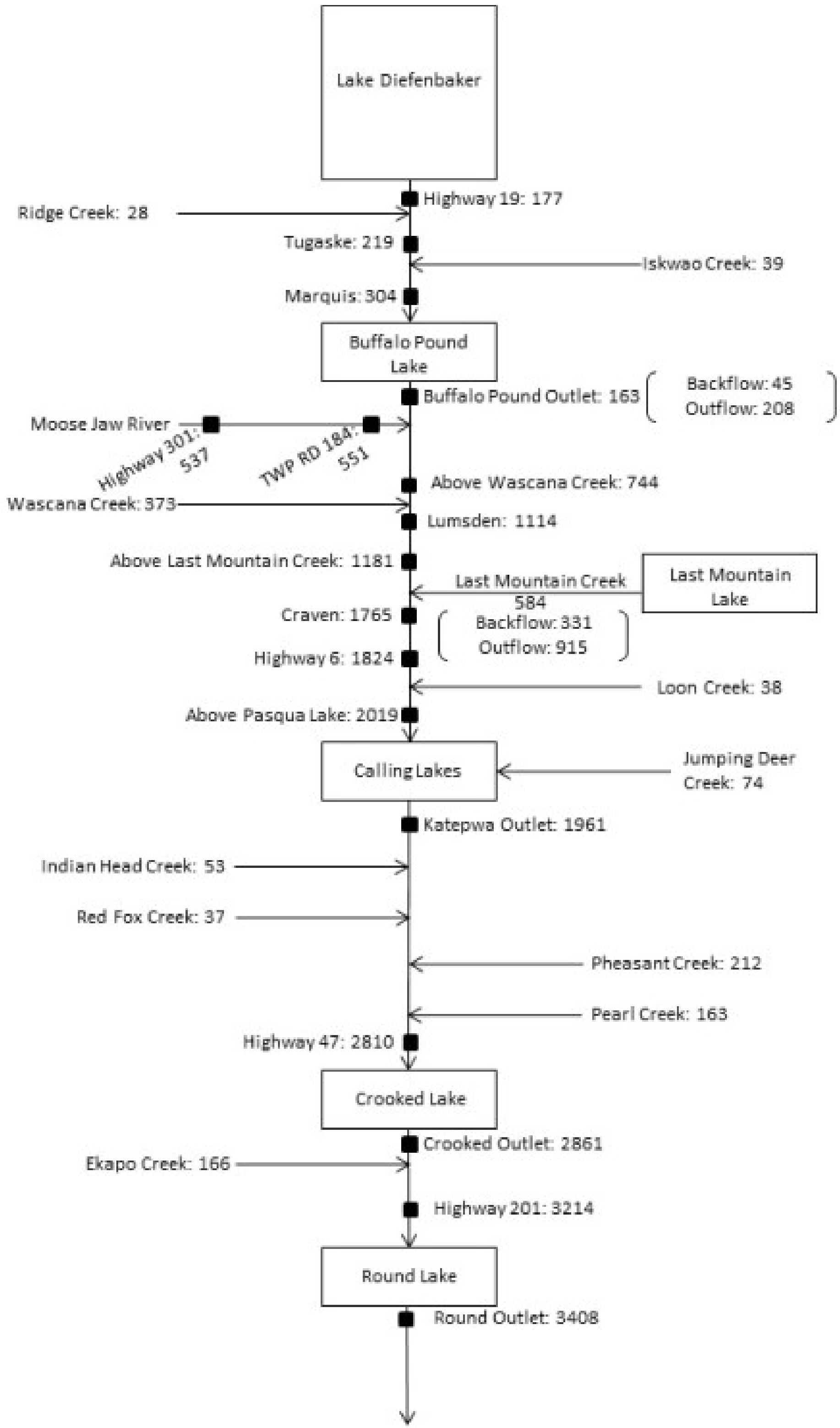


Figure 16: Total discharge in the Qu'Appelle River and tributaries March 1, 2013 to February 29, 2016. Discharge is in cubic hectometres (=1000 dam^3) for the total three-year period. Arrows indicate the direction of flow.

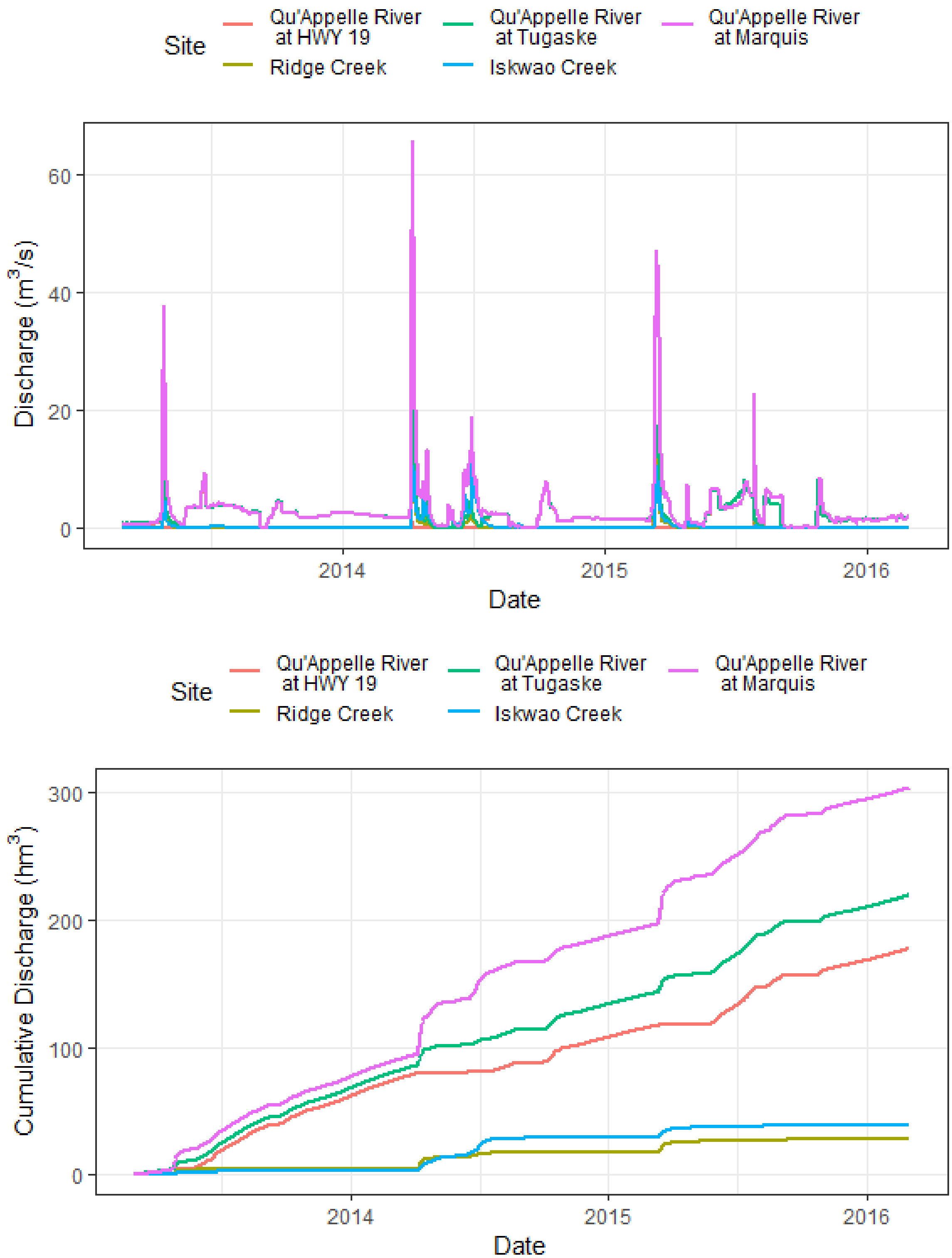


Figure 17: Discharge and cumulative discharge in the Upper Qu'Appelle River.

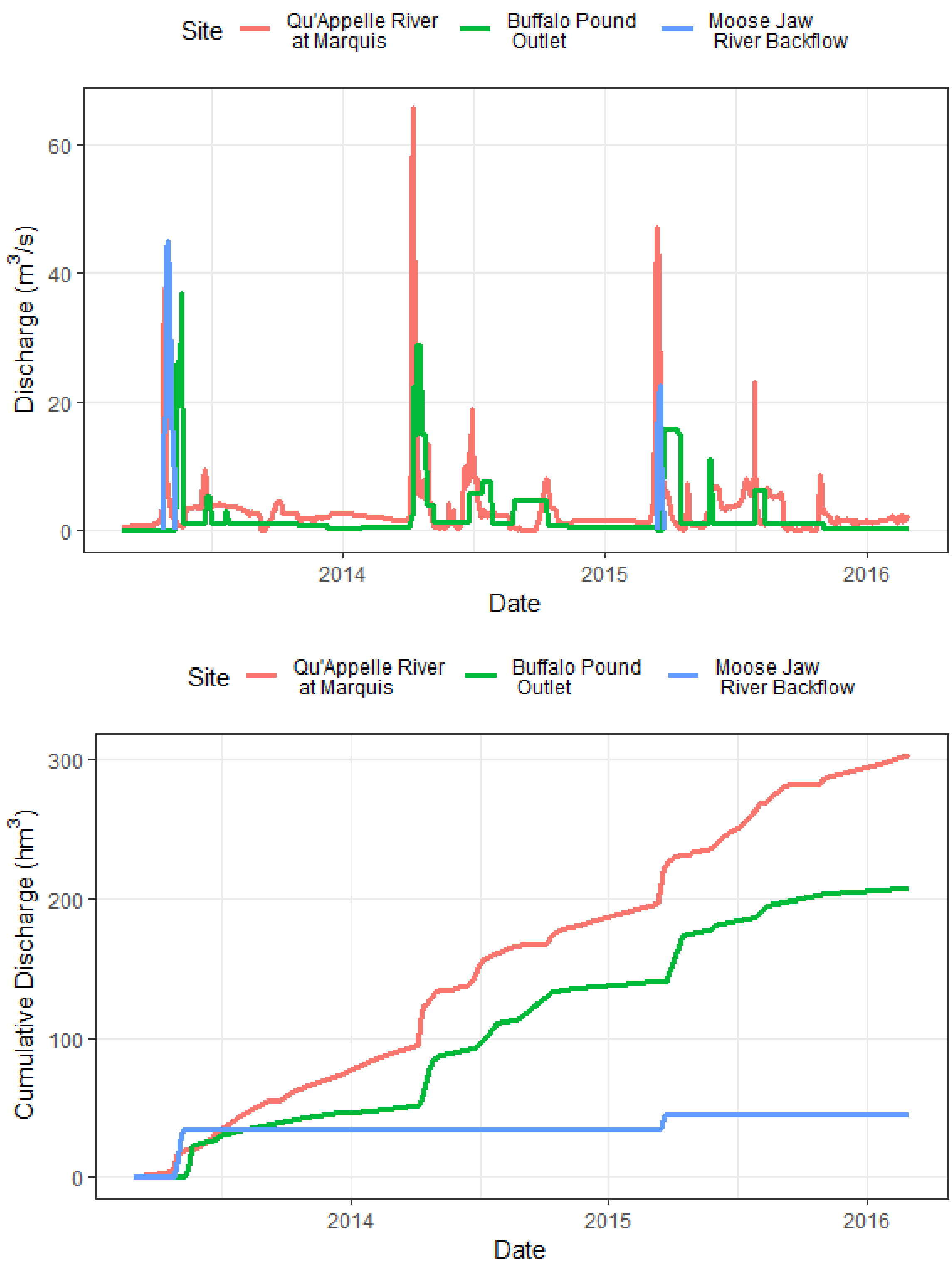


Figure 18: Discharge and cumulative discharge to and from Buffalo Pound Lake. The Qu'Appelle River at Marquis and Moose Jaw River backflow are inputs to the lake, and the Buffalo Pound outlet represents outflow from the lake.

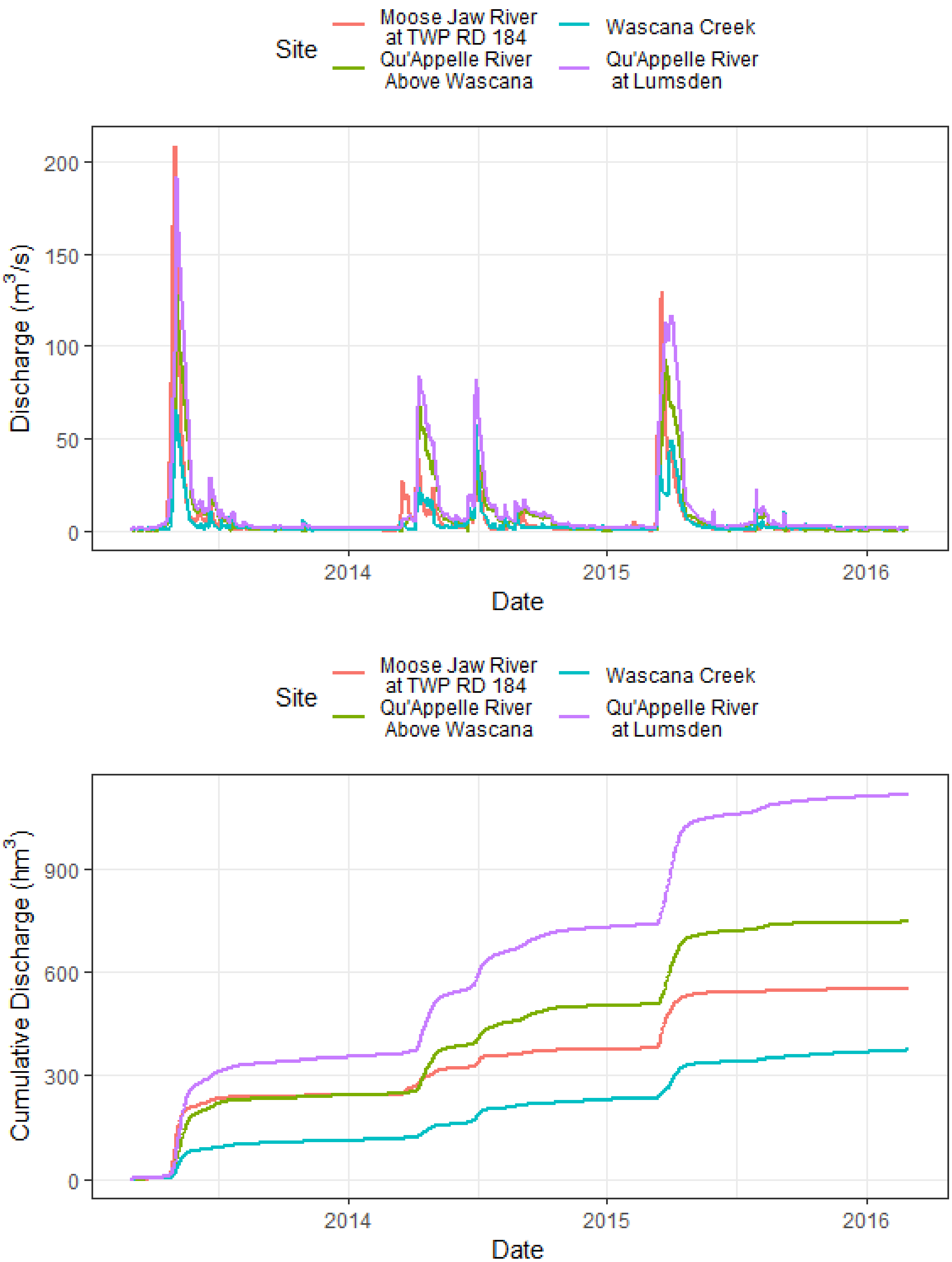


Figure 19: Discharge and cumulative discharge in the Qu'Appelle River in the Lumsden area.

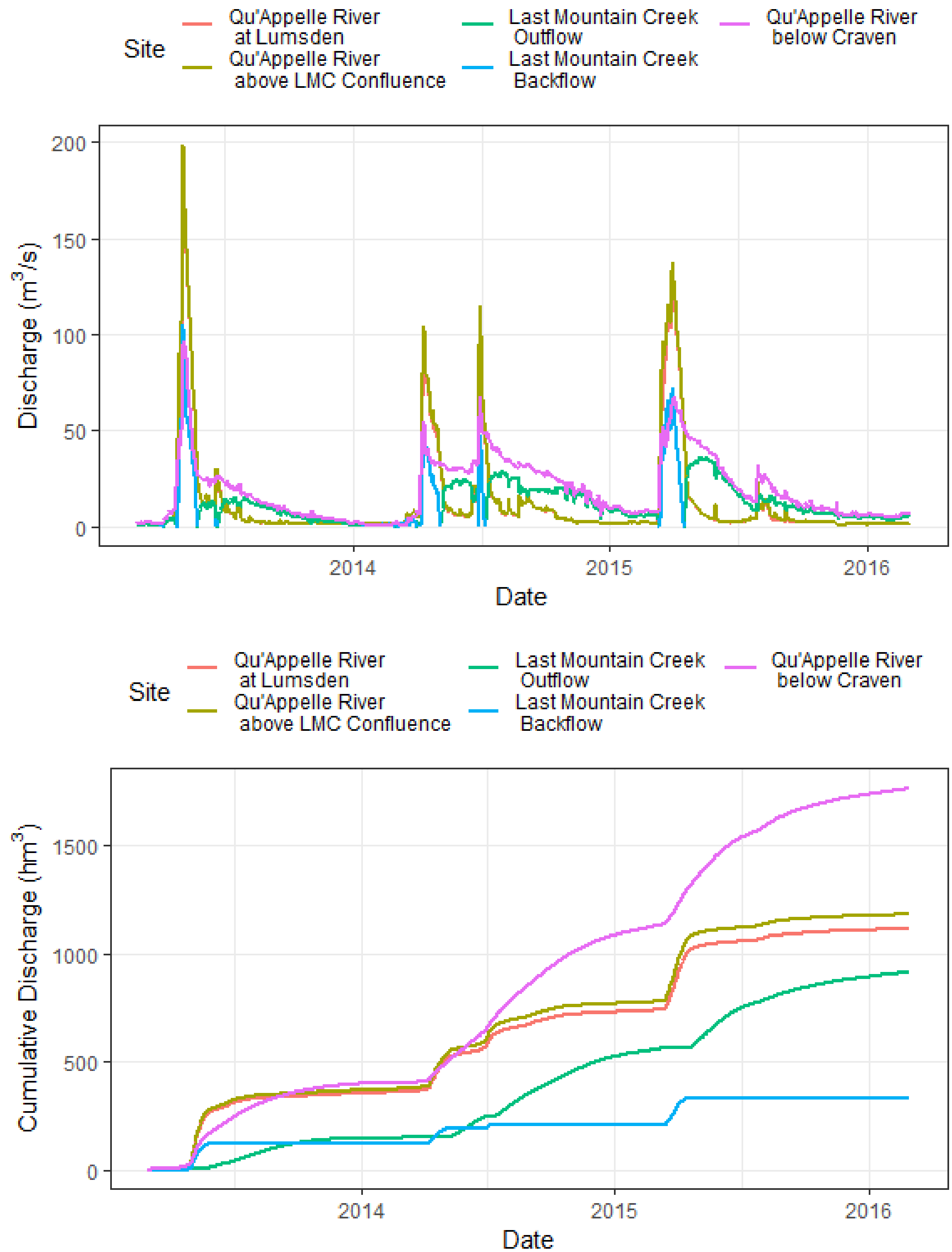


Figure 20: Discharge and cumulative discharge in the Qu'Appelle River near the Last Mountain Creek confluence.

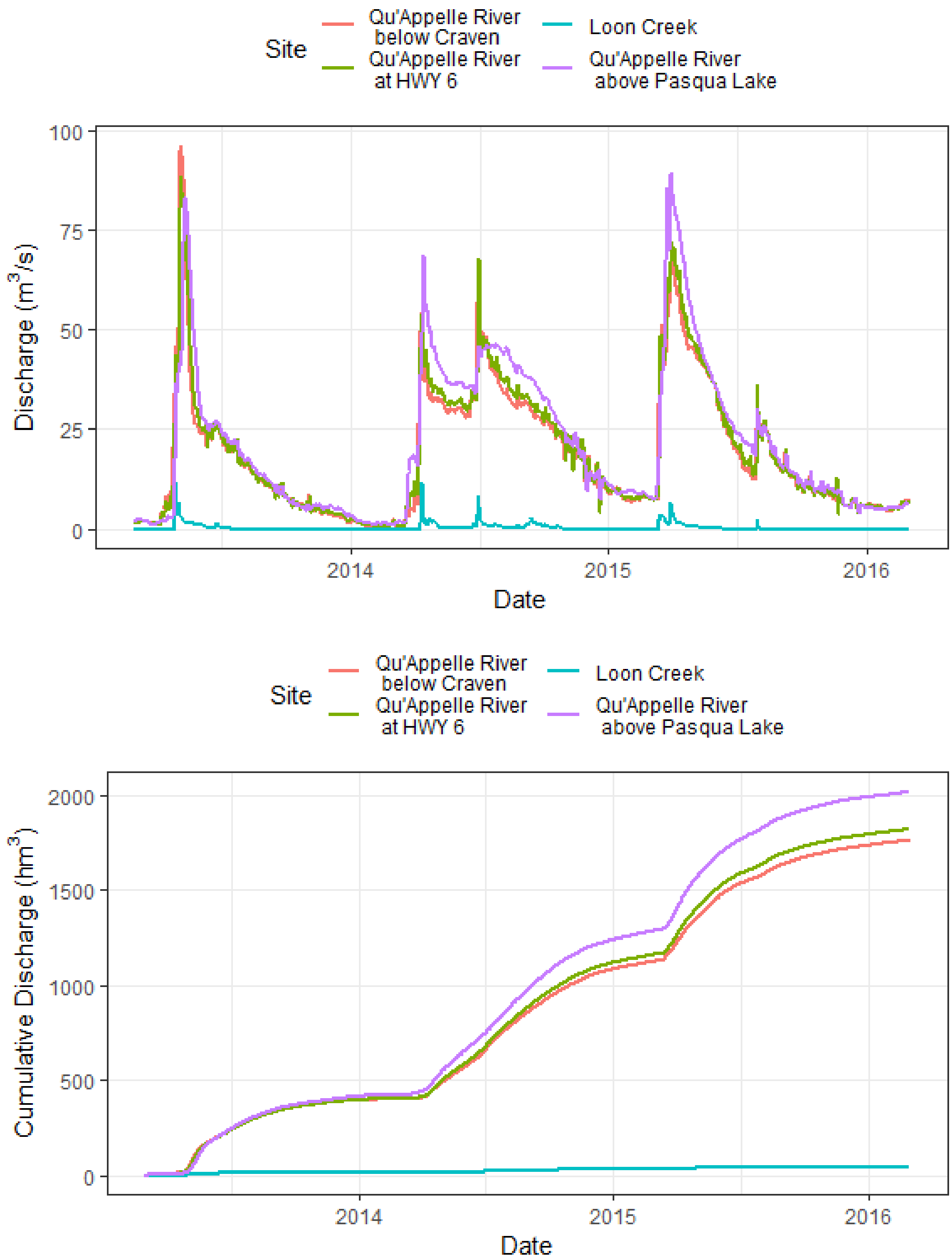


Figure 21: Discharge and cumulative discharge in the Qu'Appelle River above Pasqua Lake.

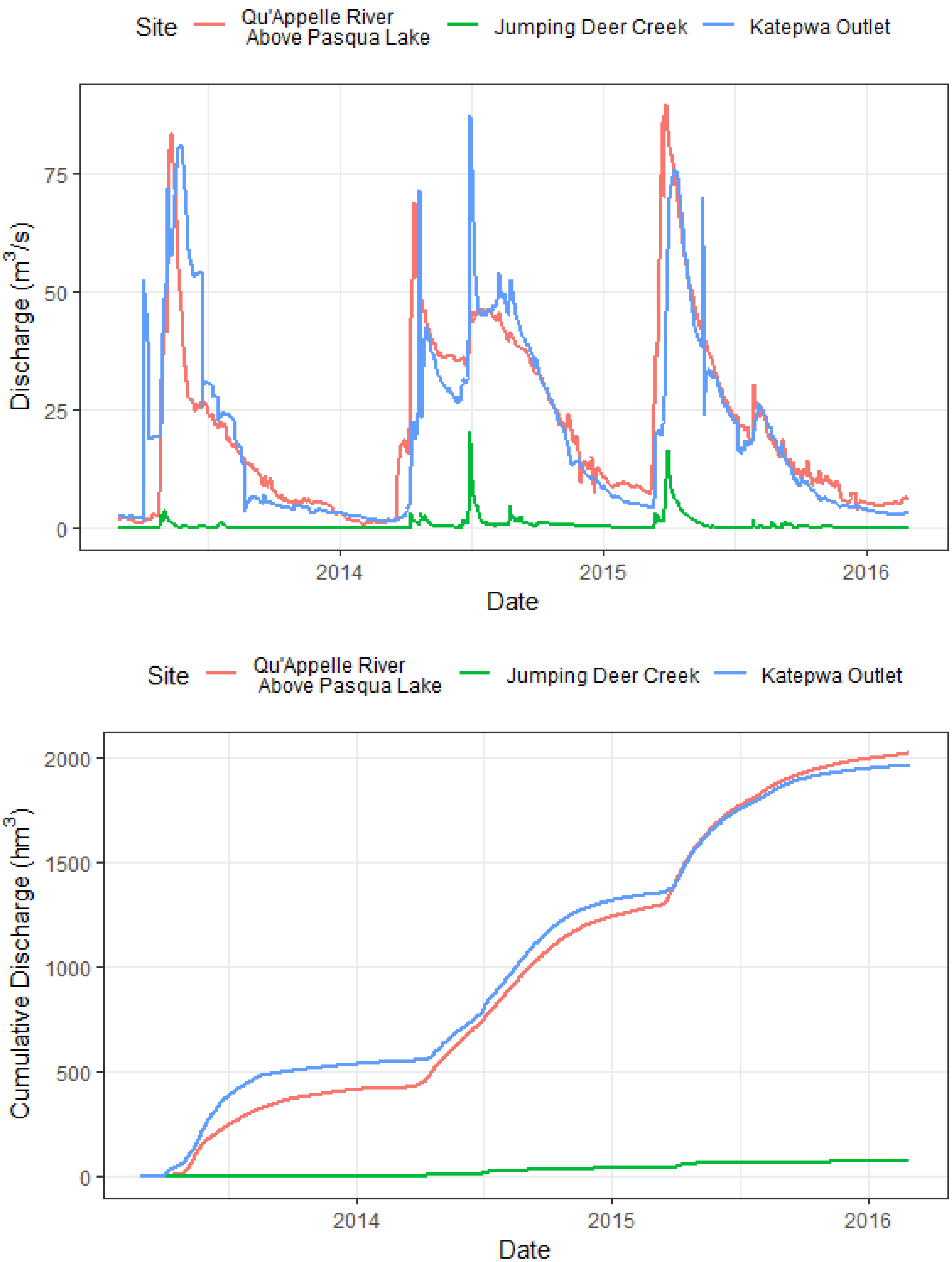


Figure 22: Discharge and cumulative discharge in the Calling Lakes.

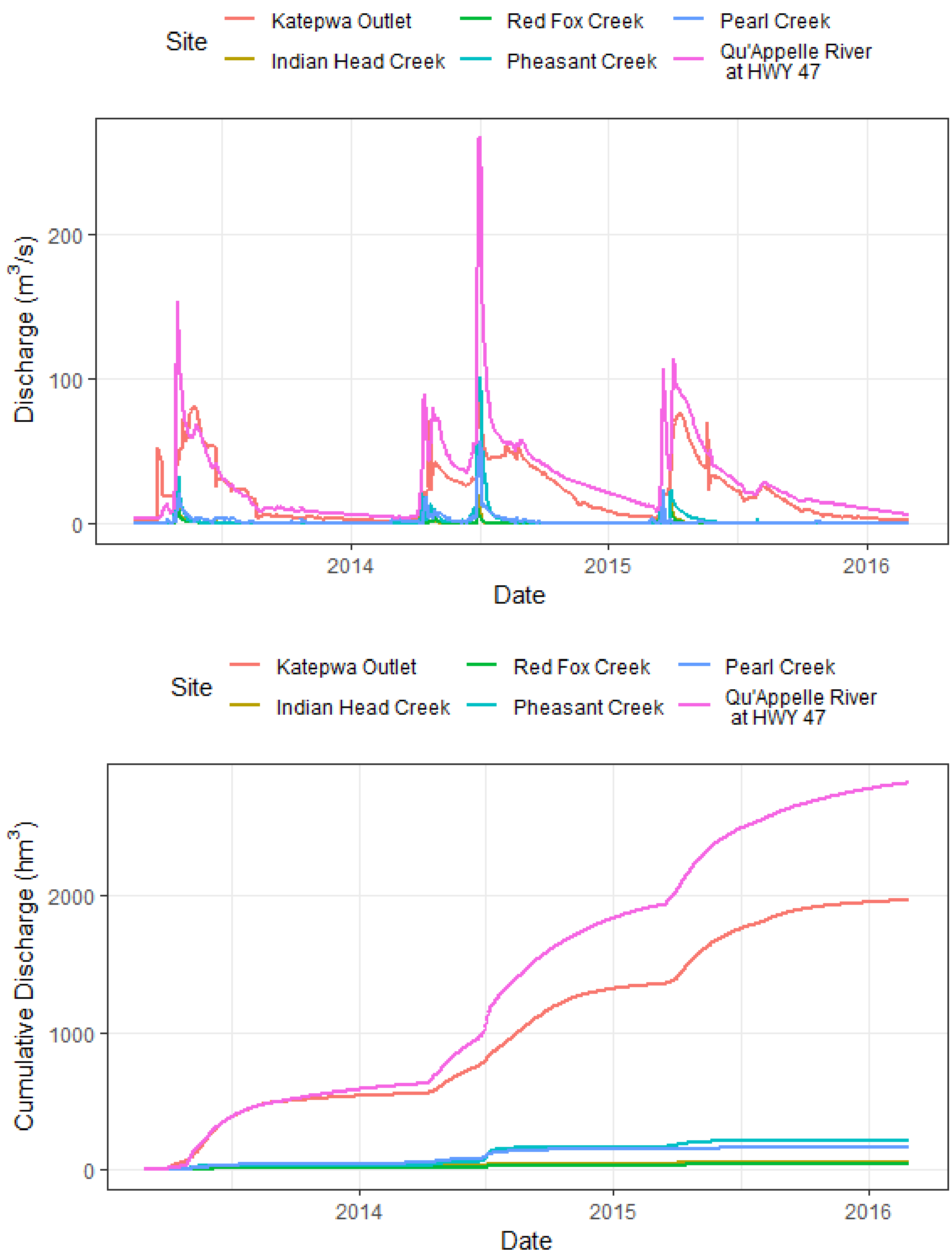


Figure 23: Discharge and cumulative discharge in the Qu'Appelle River between Katepwa and Crooked lakes.

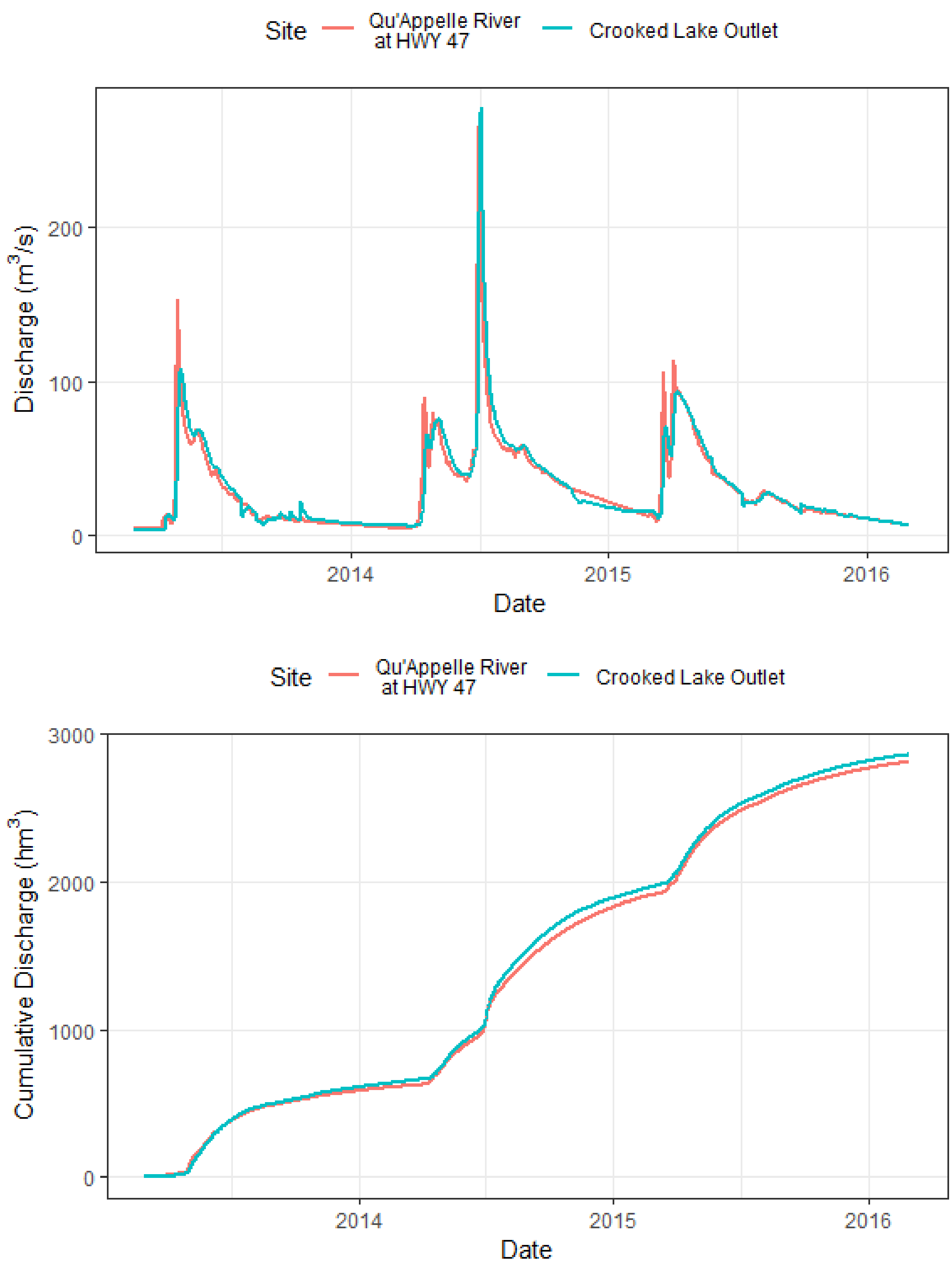


Figure 24: Discharge and cumulative discharge in the Qu'Appelle River around Crooked Lake.

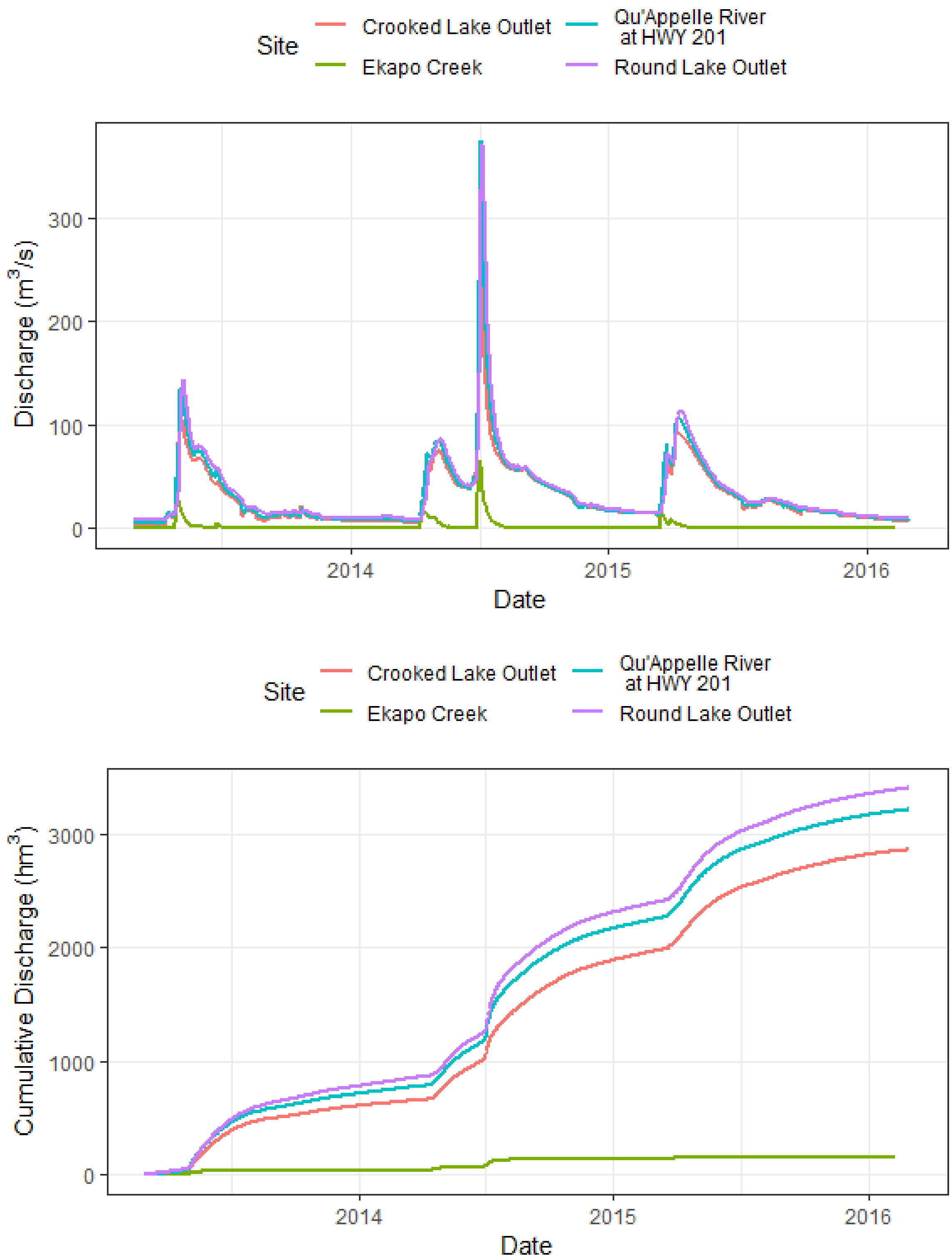


Figure 25: Discharge and cumulative discharge in the Qu'Appelle River around Round Lake.

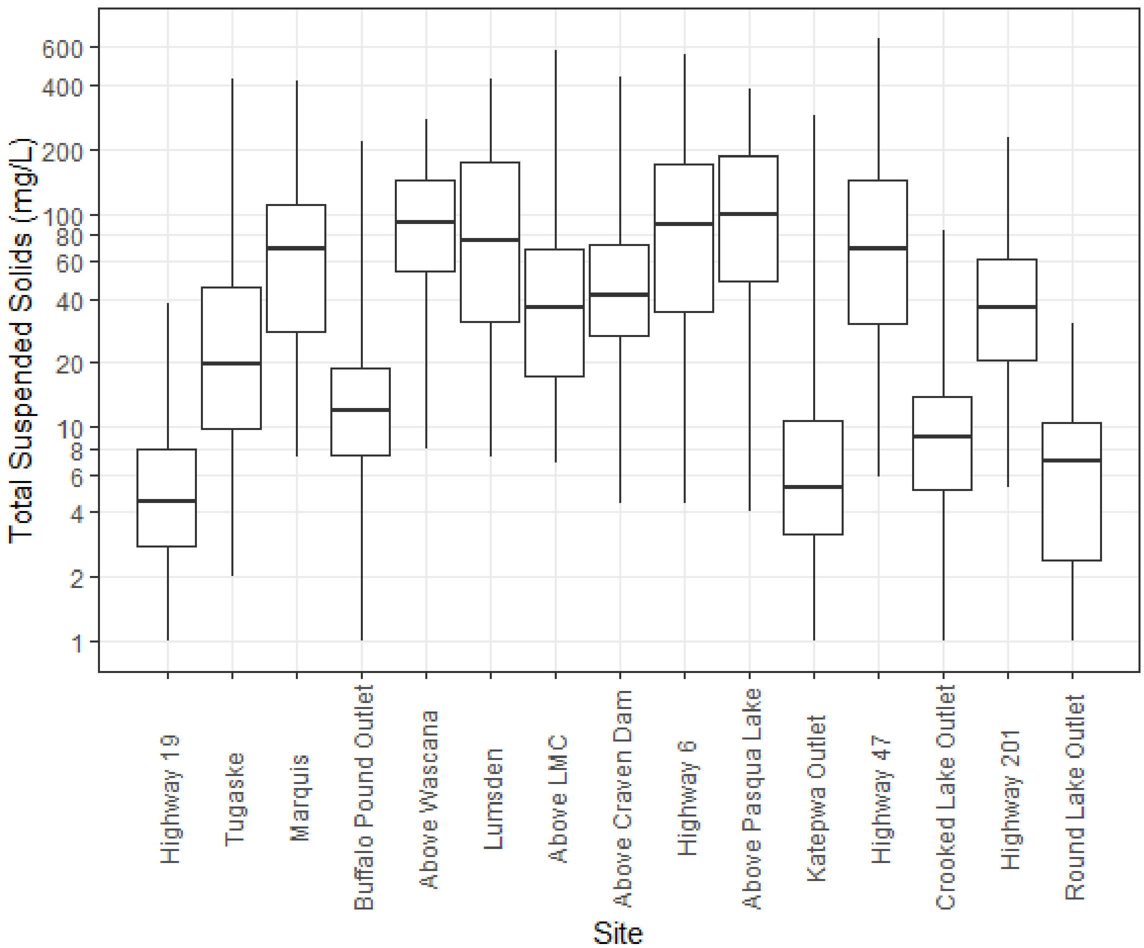


Figure 26: Boxplots of total suspended solids at sites along the Qu'Appelle River. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. Note the logarithmic scale on the y-axis. LMC = Last Mountain Creek.

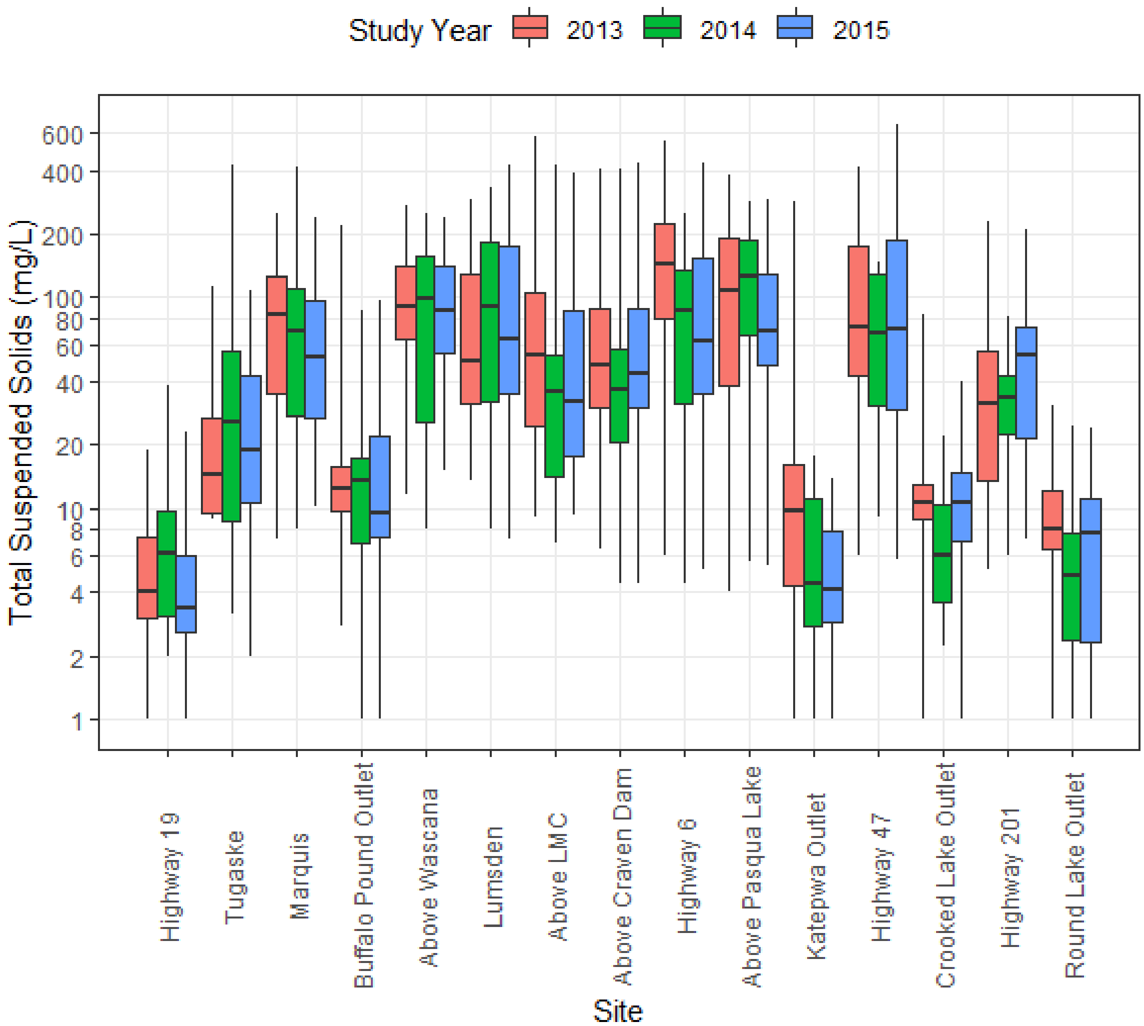


Figure 27: Boxplots of total suspended solids at sites along the Qu'Appelle River split by study year. Study years are based on the March-February period. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. Note the logarithmic scale on the y-axis. LMC = Last Mountain Creek.

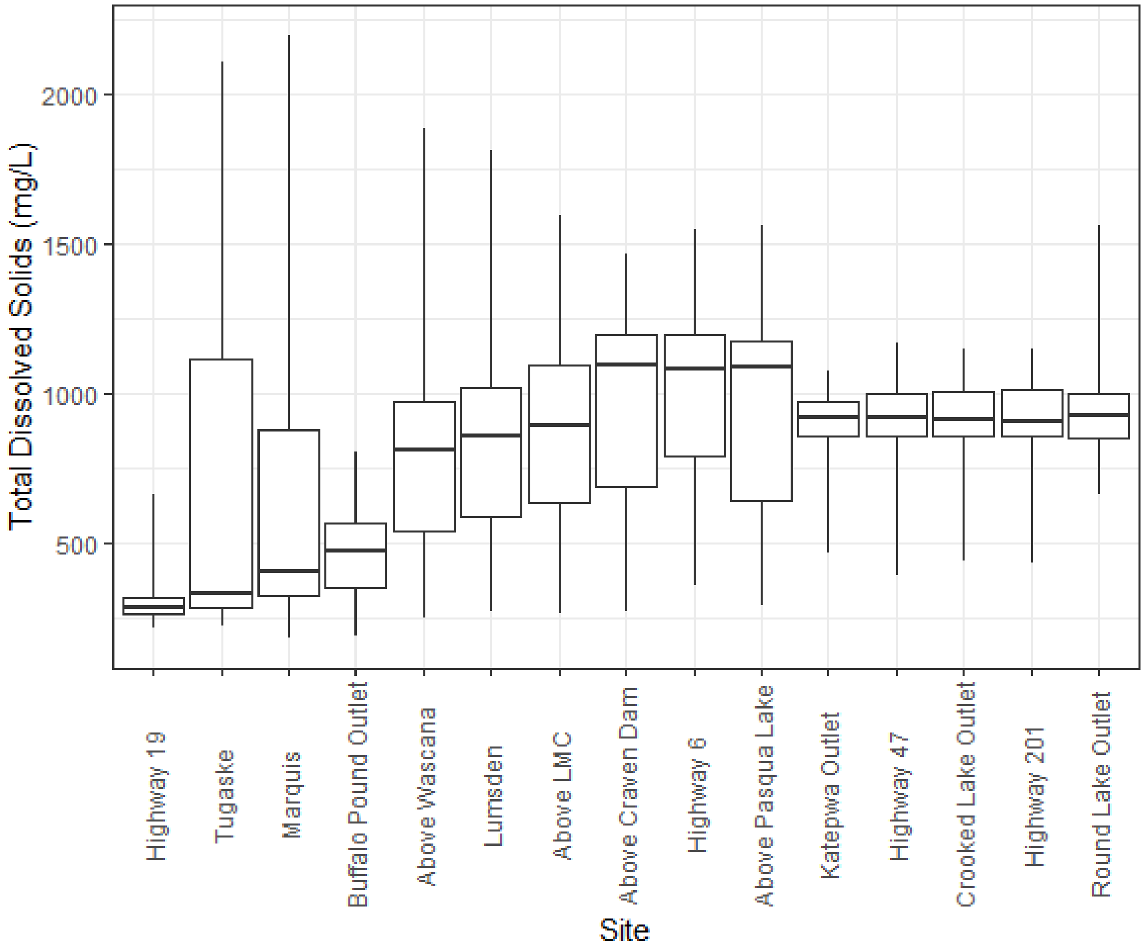


Figure 28: Boxplots of total dissolved solids at sites along the Qu'Appelle River. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. LMC = Last Mountain Creek.

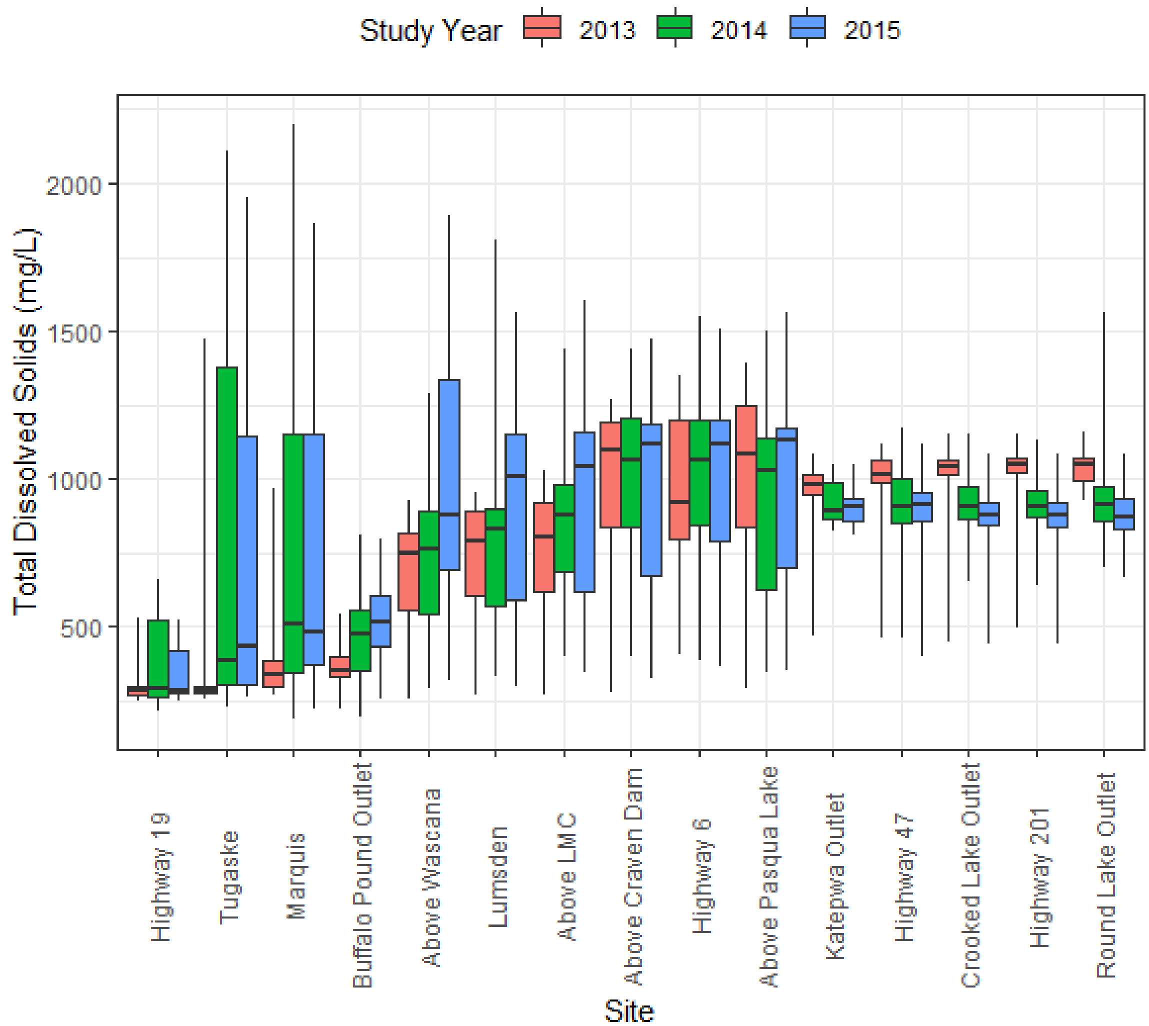


Figure 29: Boxplots of total dissolved solids at sites along the Qu'Appelle River split by study year. Study years are based on the March-February period. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. LMC = Last Mountain Creek.

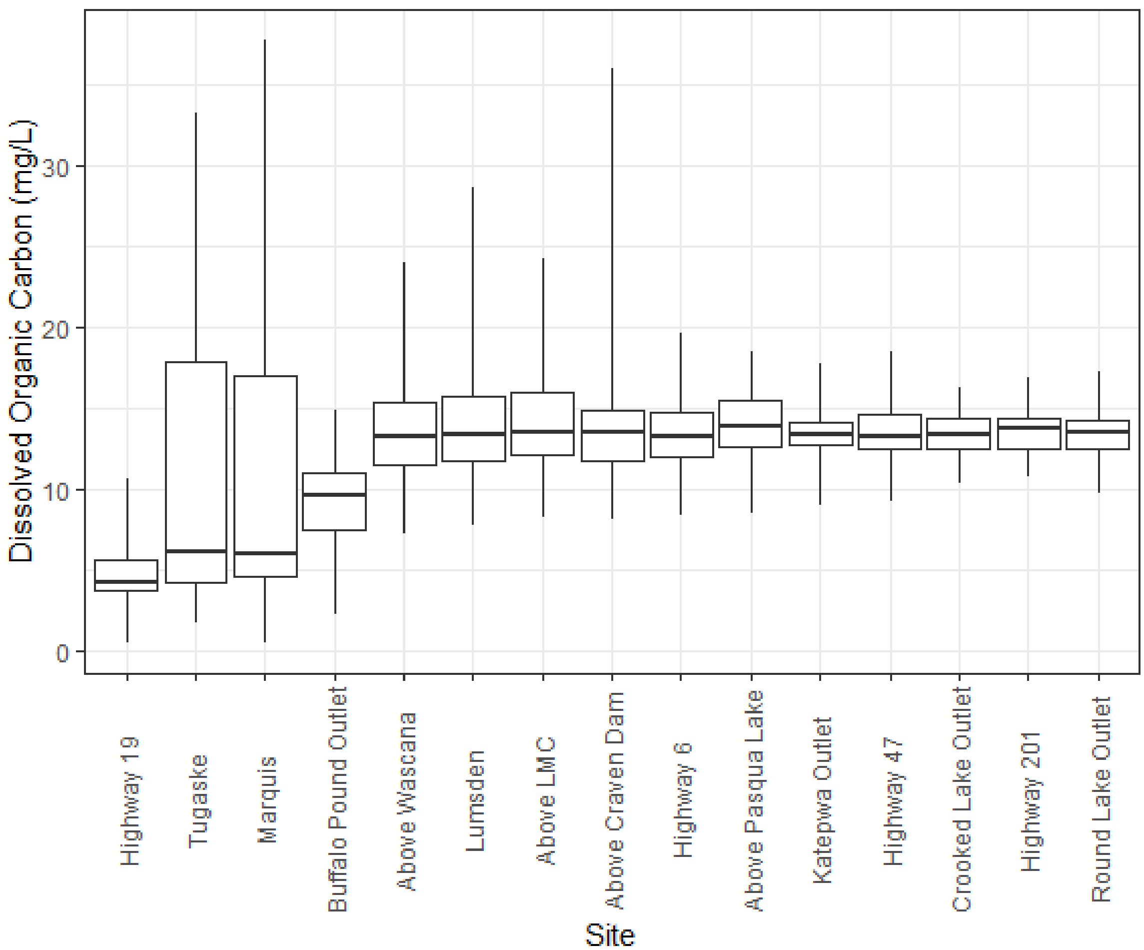


Figure 30: Boxplots of dissolved organic carbon at sites along the Qu'Appelle River. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. LMC = Last Mountain Creek.

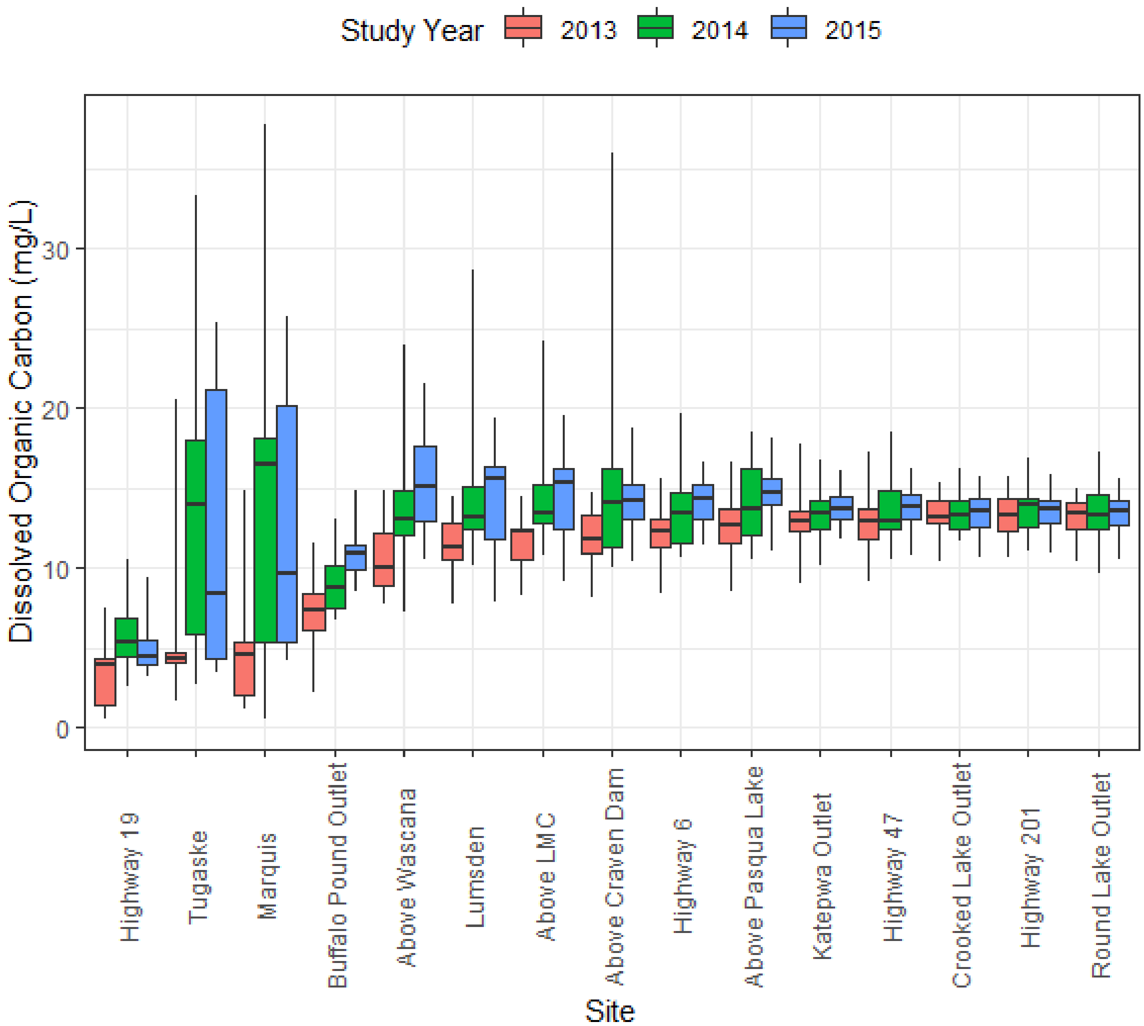


Figure 31: Boxplots of dissolved organic carbon at sites along the Qu'Appelle River split by study year. Study years are based on the March-February period. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. LMC = Last Mountain Creek.

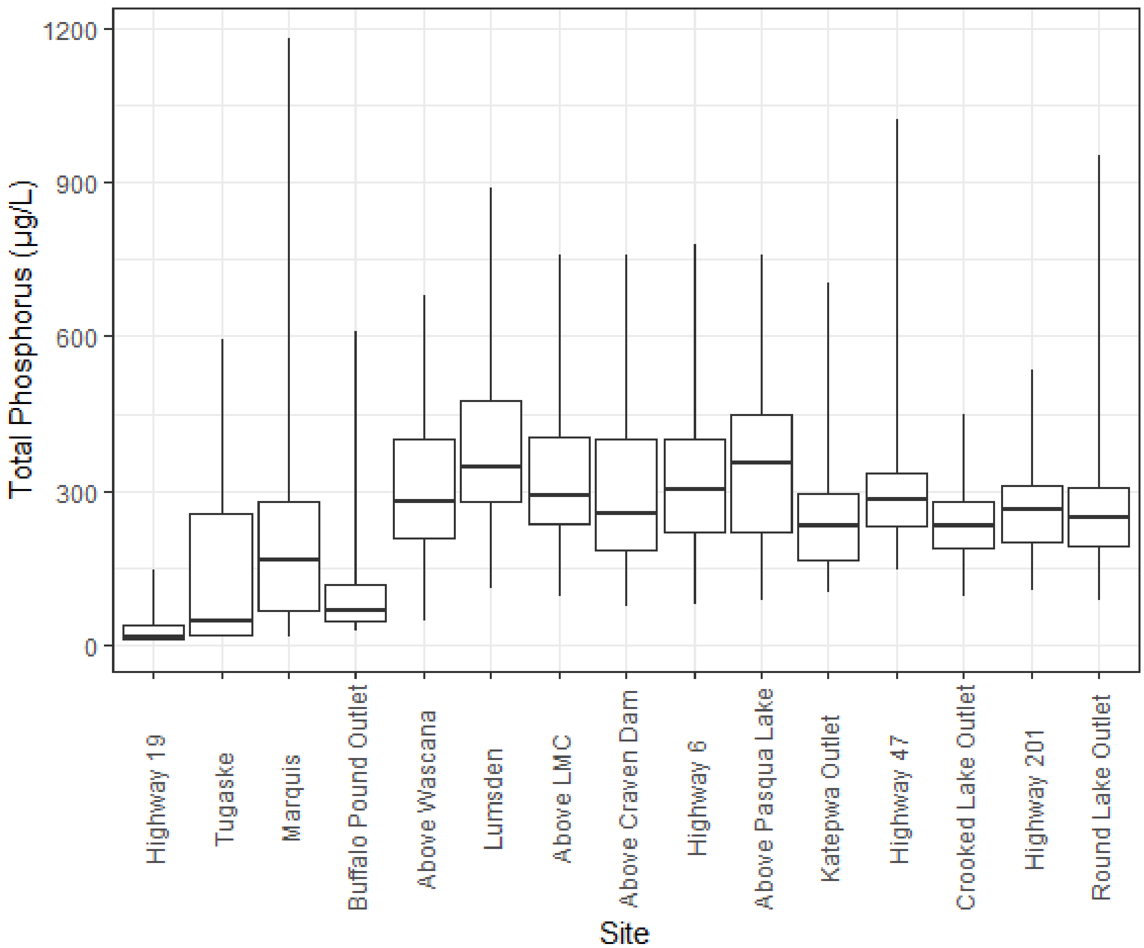


Figure 32: Boxplots of total phosphorus at sites along the Qu'Appelle River. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. LMC = Last Mountain Creek.

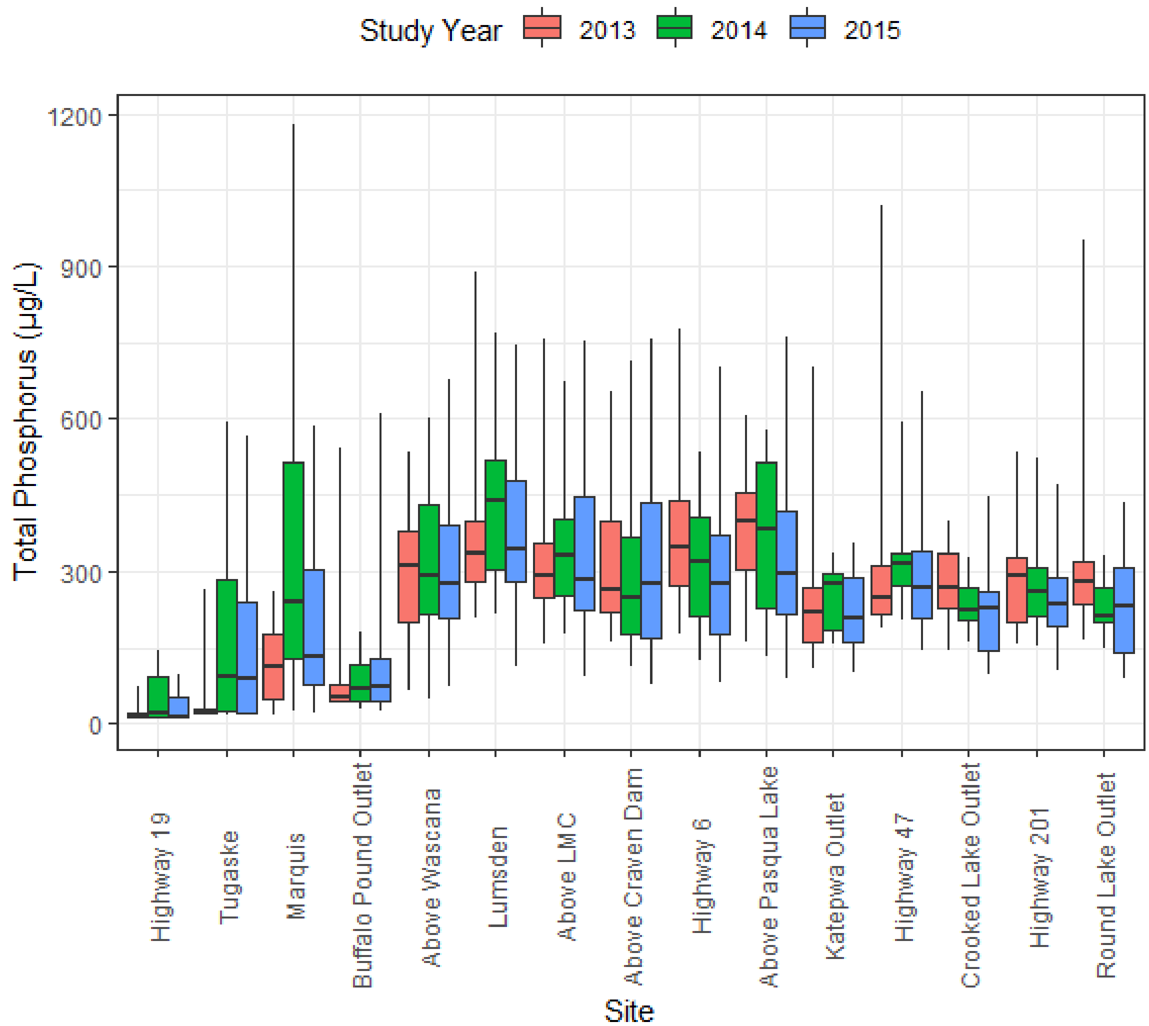


Figure 33: Boxplots of total phosphorus at sites along the Qu'Appelle River split by study year. Study years are based on the March-February period. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. LMC = Last Mountain Creek.

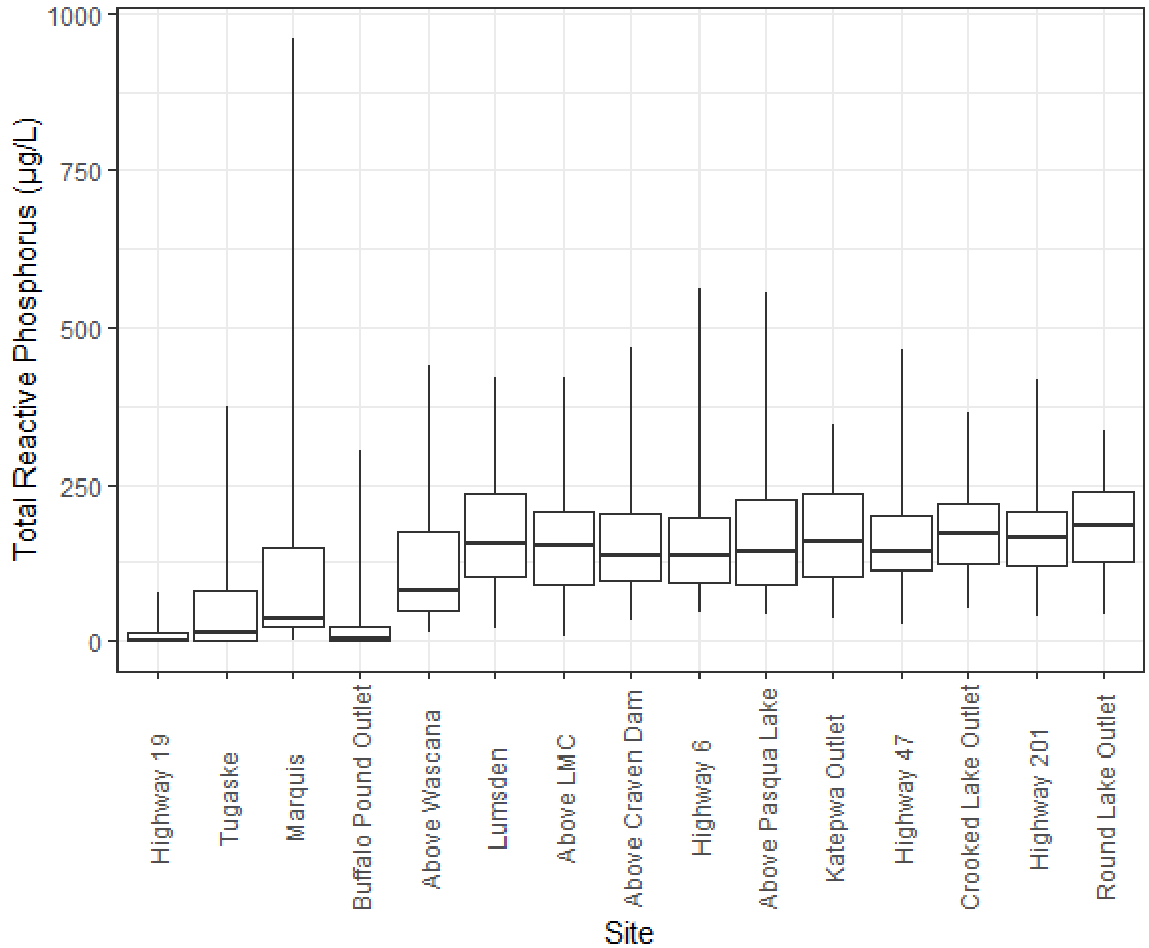


Figure 34: Boxplots of total reactive phosphorus at sites along the Qu'Appelle River. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. LMC = Last Mountain Creek.

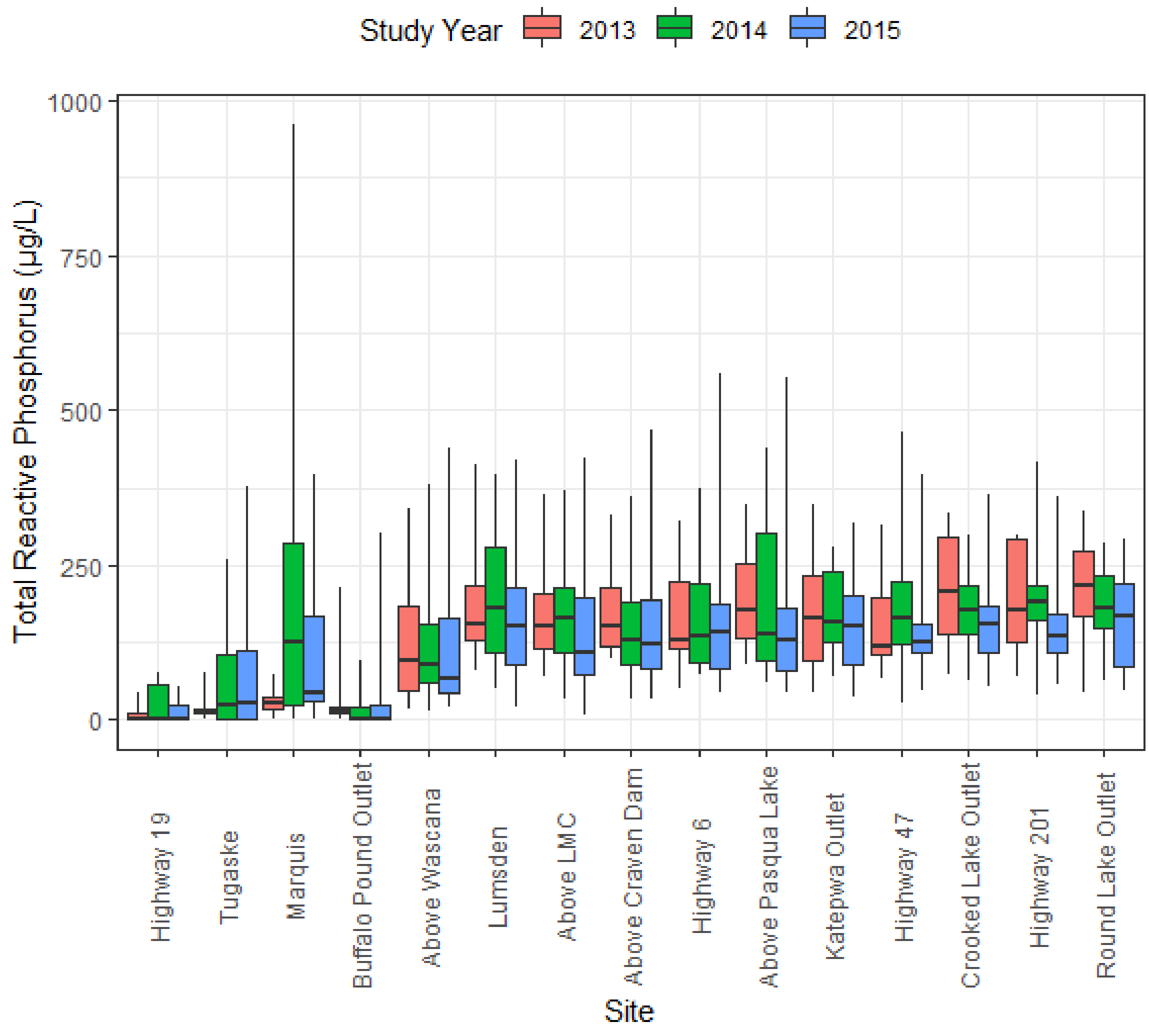


Figure 35: Boxplots of total reactive phosphorus at sites along the Qu'Appelle River split by study year. Study years are based on the March-February period. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. LMC = Last Mountain Creek.

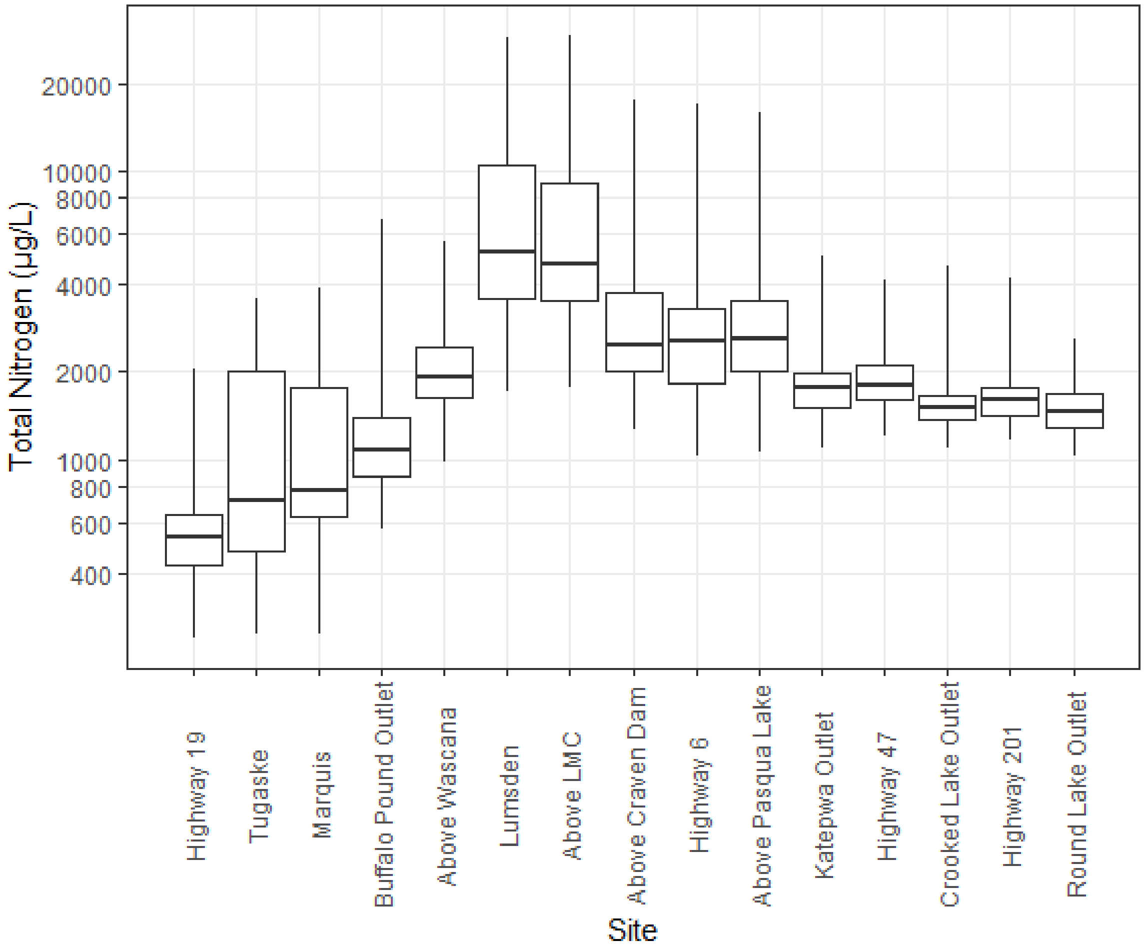


Figure 36: Boxplots of total nitrogen at sites along the Qu'Appelle River. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. Note the logarithmic scale on the y-axis. LMC = Last Mountain Creek.

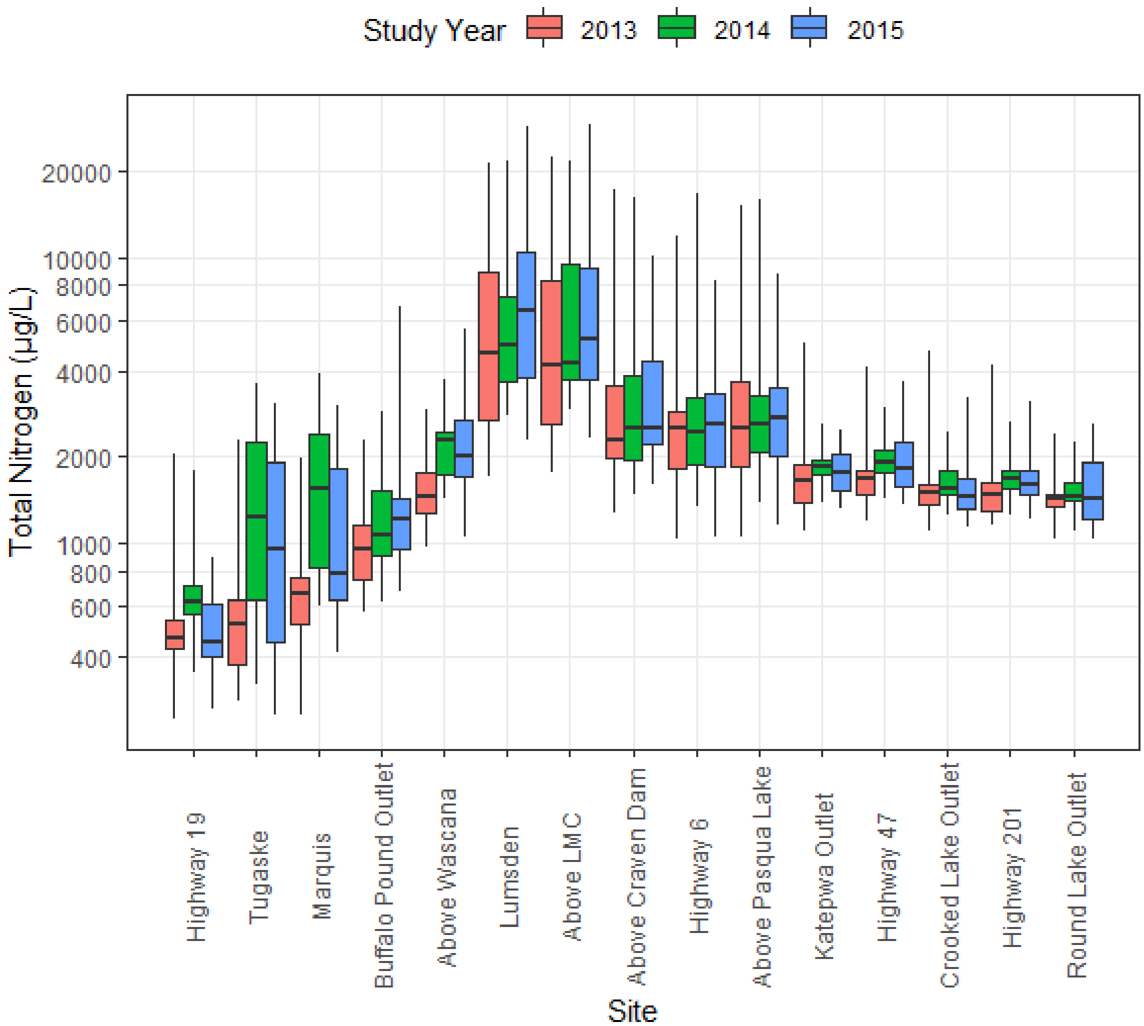


Figure 37: Boxplots of total nitrogen at sites along the Qu'Appelle River split by study year. Study years are based on the March-February period. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. Note the logarithmic scale on the y-axis. LMC = Last Mountain Creek.

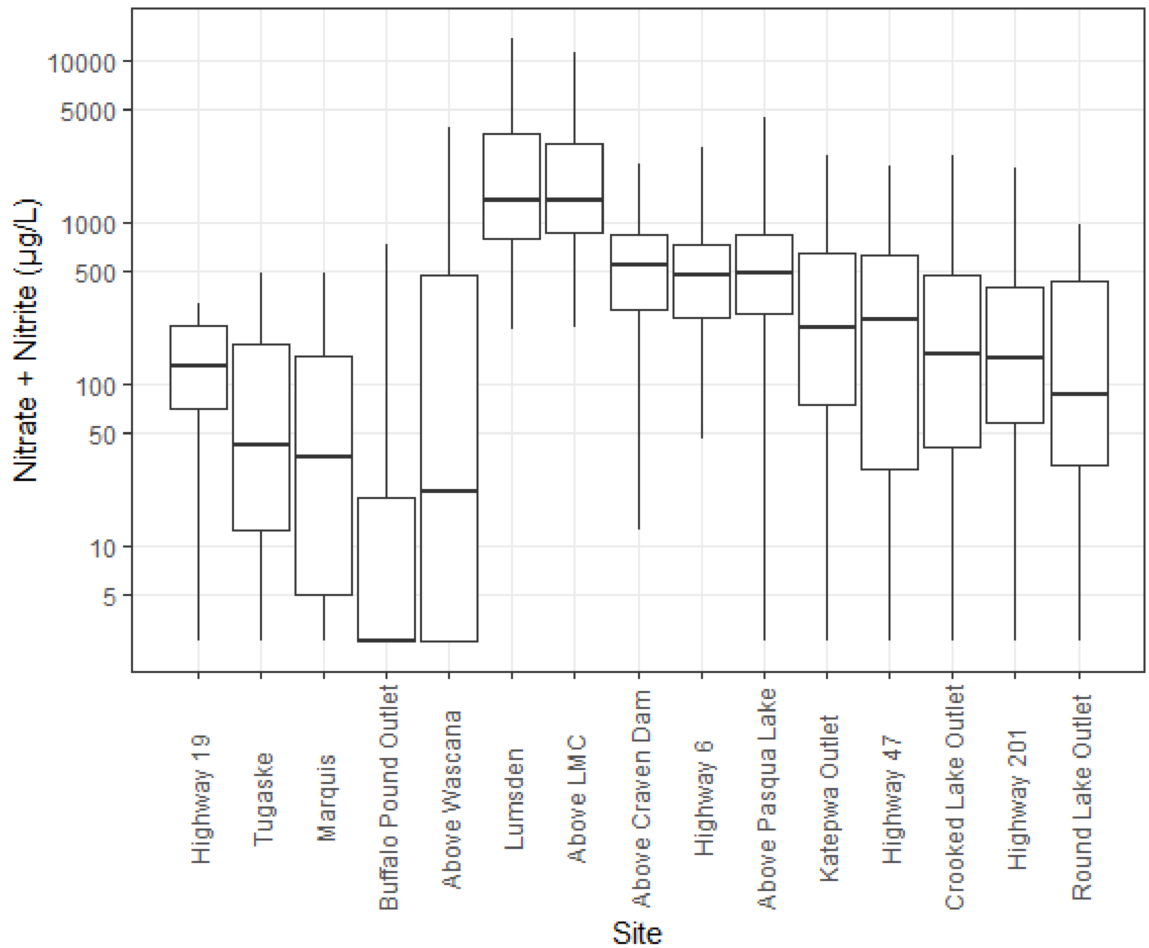


Figure 38: Boxplots of nitrate + nitrite at sites along the Qu'Appelle River. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. Note the logarithmic scale on the y-axis. LMC = Last Mountain Creek.

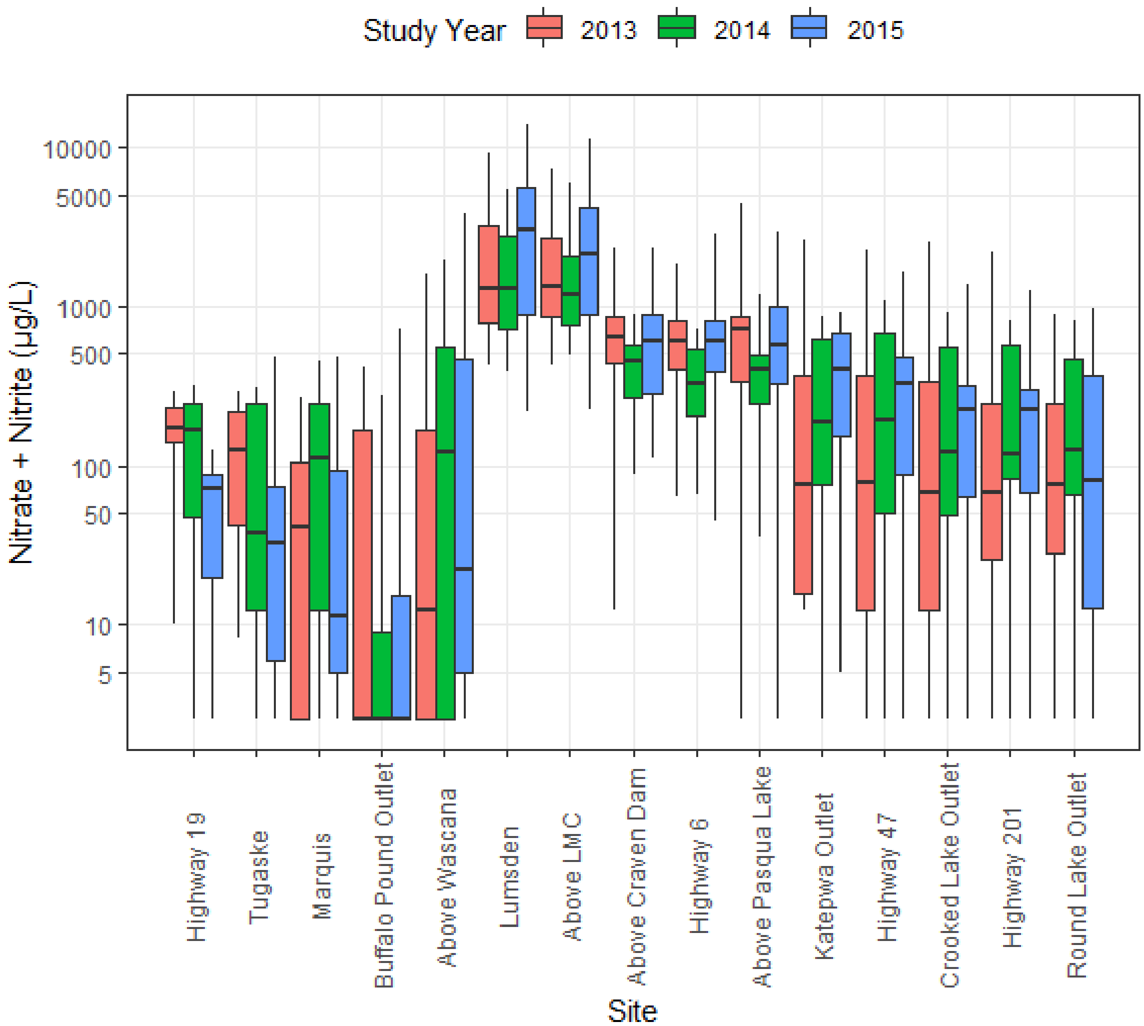


Figure 39: Boxplots of nitrate + nitrite at sites along the Qu'Appelle River split by study year. Study years are based on the March-February period. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. Note the logarithmic scale on the y-axis. LMC = Last Mountain Creek.

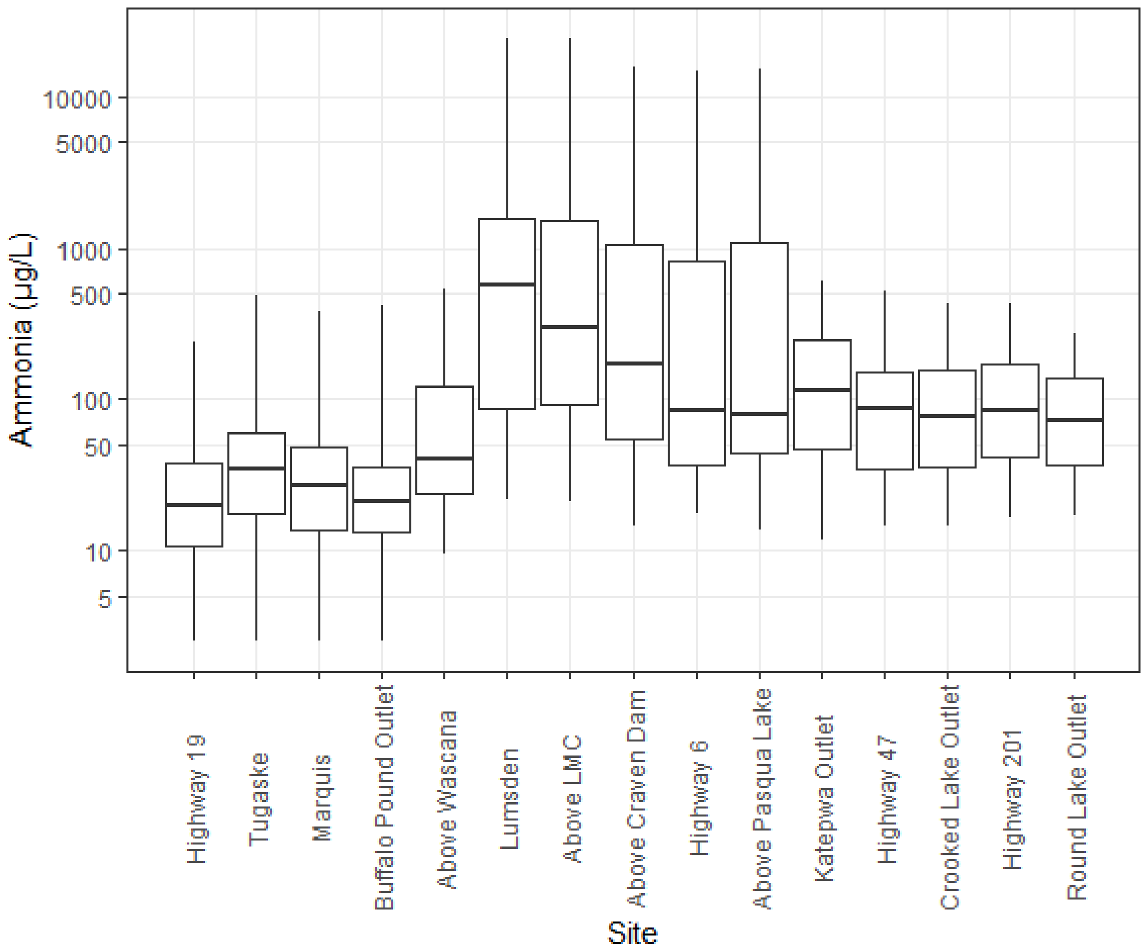


Figure 40: Boxplots of ammonia at sites along the Qu'Appelle River. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. Note the logarithmic scale on the y-axis. LMC = Last Mountain Creek.

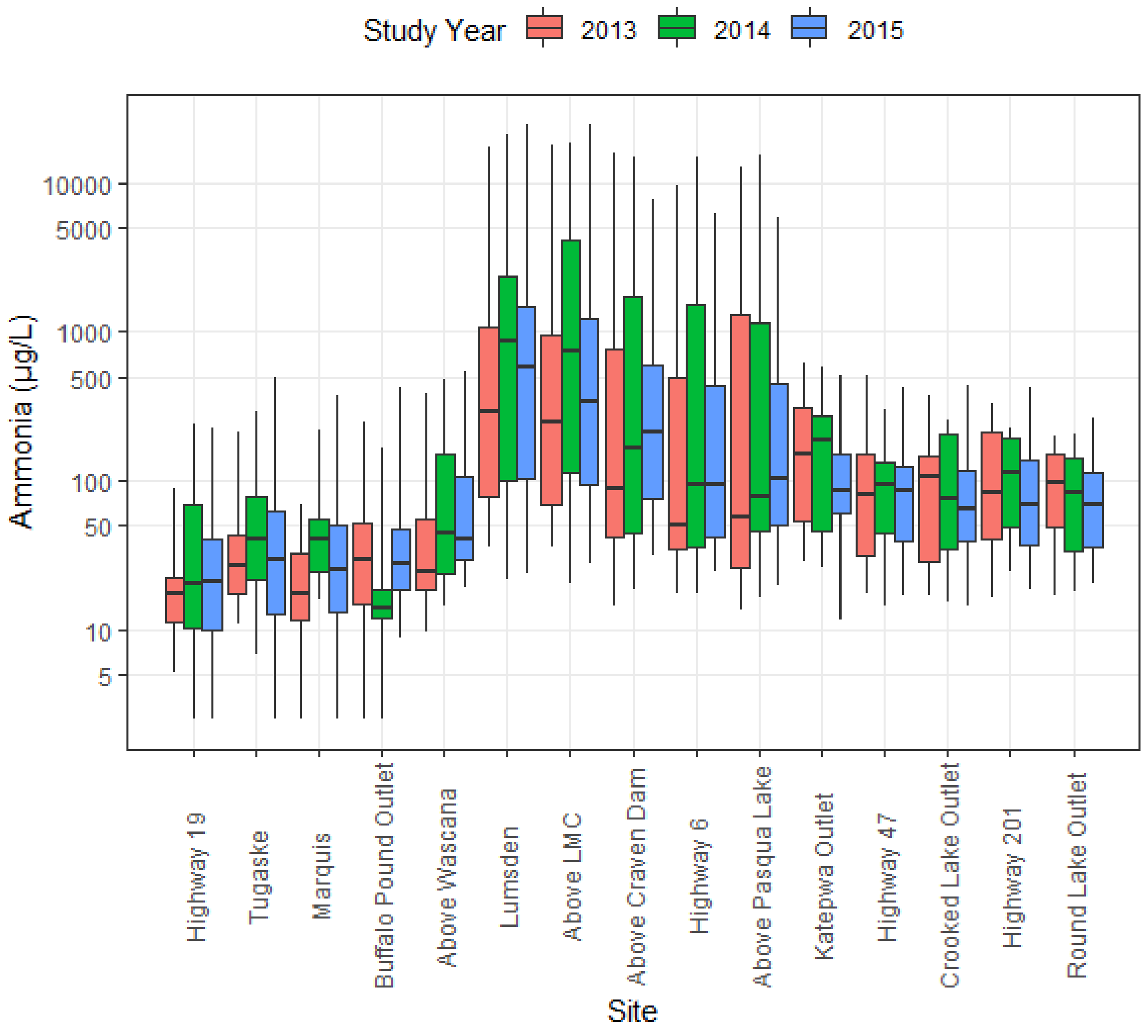


Figure 41: Boxplots of ammonia at sites along the Qu'Appelle River split by study year. Study years are based on the March-February period. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. Note the logarithmic scale on the y-axis. LMC = Last Mountain Creek.

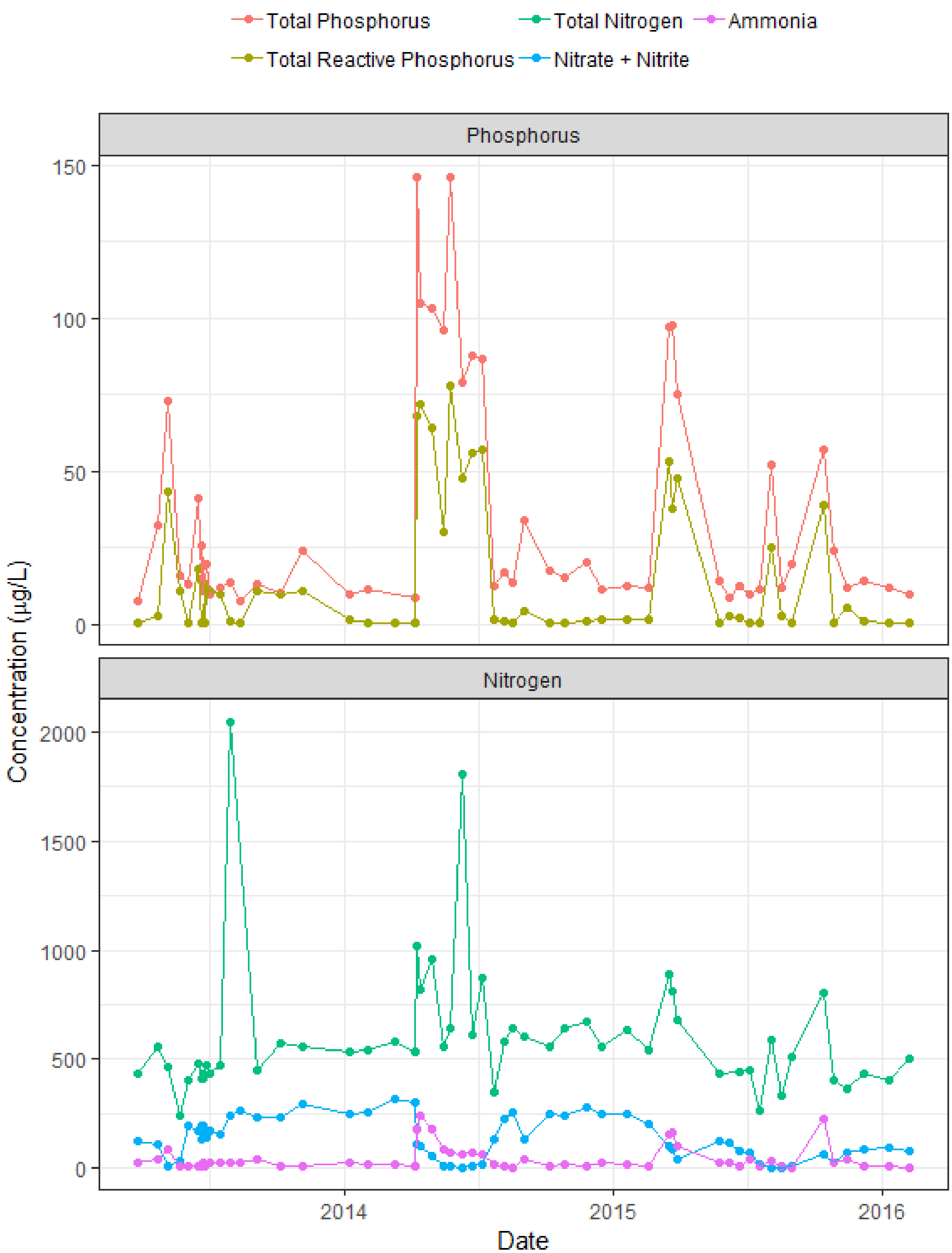


Figure 42: Concentration over time for phosphorus and nitrogen in the Qu'Appelle River at Highway 19.

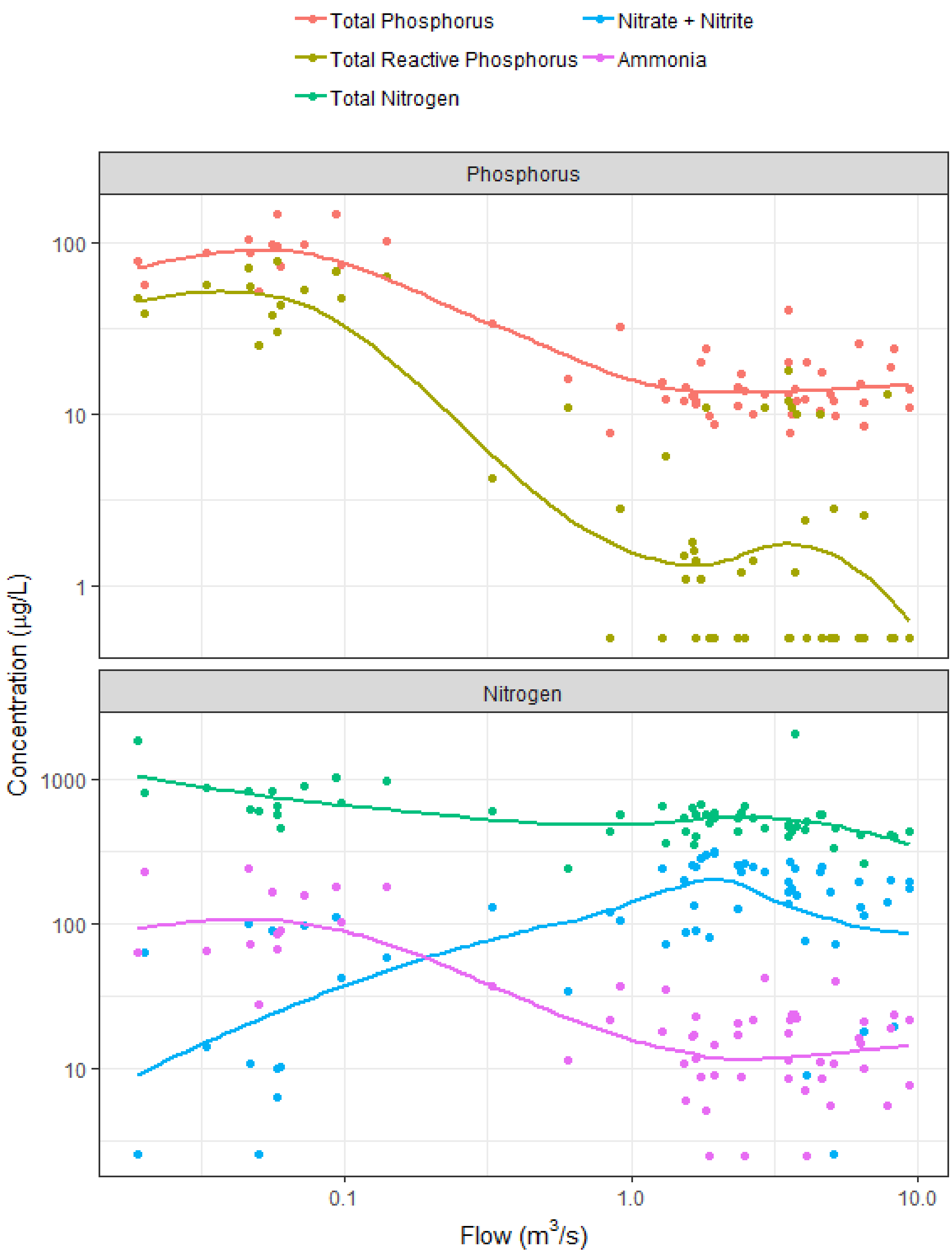


Figure 43: Concentration as a function of flow for phosphorus and nitrogen in the Qu'Appelle River at Highway 19. Lines represent a LOESS fit through the data. Note that both axes have log-transformed scales.

Figure 44: Concentration over time for phosphorus and nitrogen in the Qu'Appelle River at Lumsden.

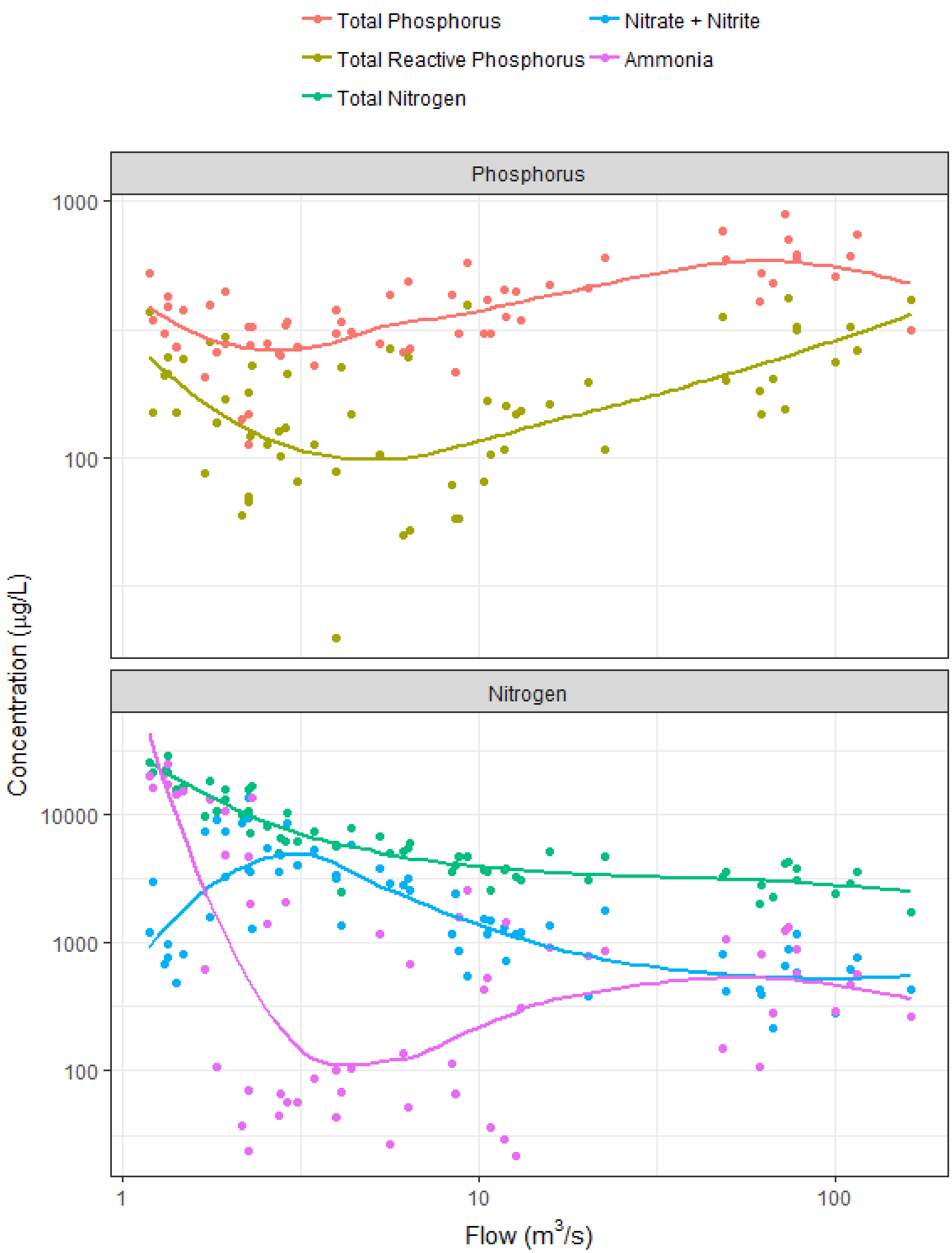


Figure 45: Concentration as a function of flow for phosphorus and nitrogen in the Qu'Appelle River at Lumsden. Lines represent a LOESS fit through the data. Note that both axes have log-transformed scales.

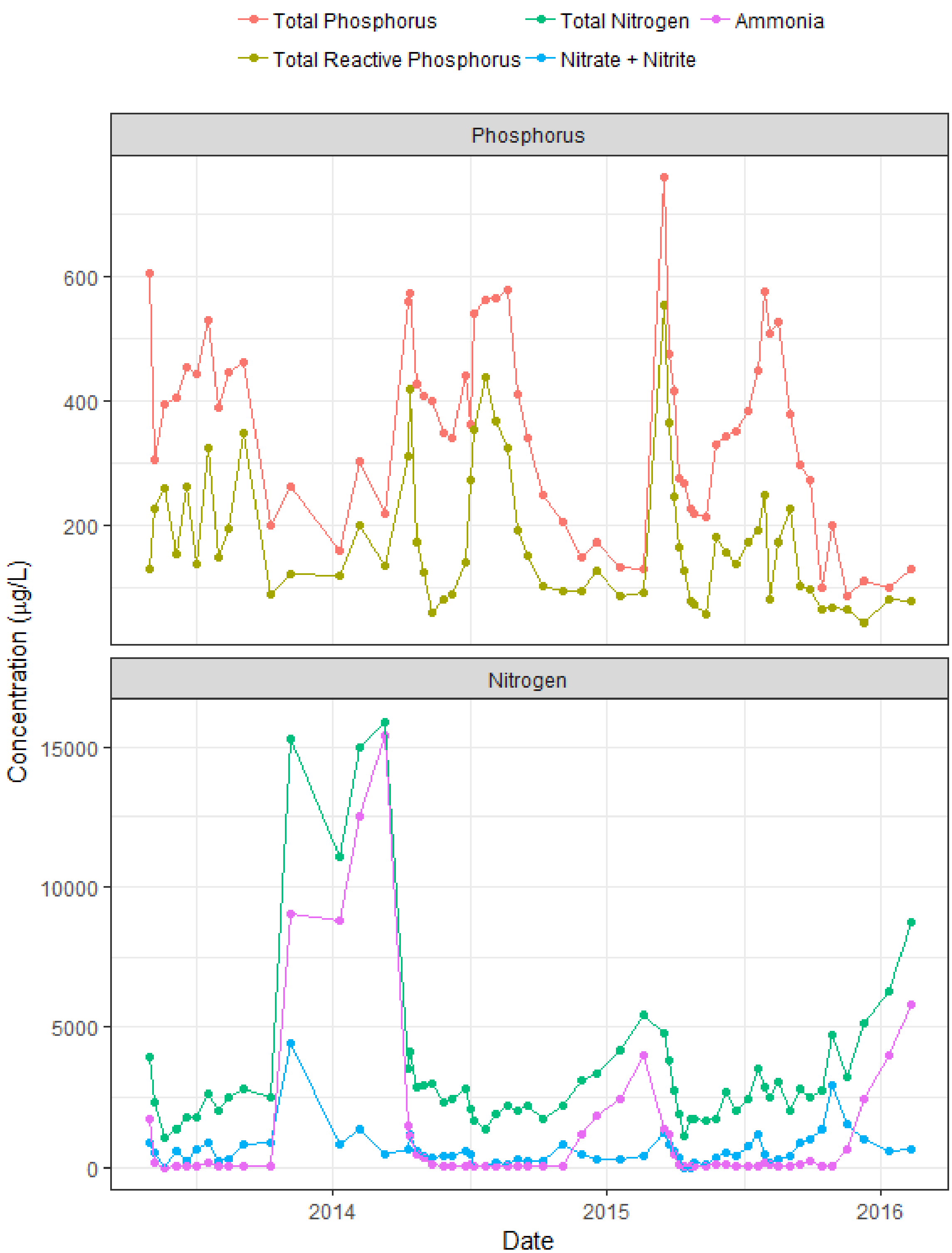


Figure 46: Concentration over time for phosphorus and nitrogen in the Qu'Appelle River above Pasqua Lake.

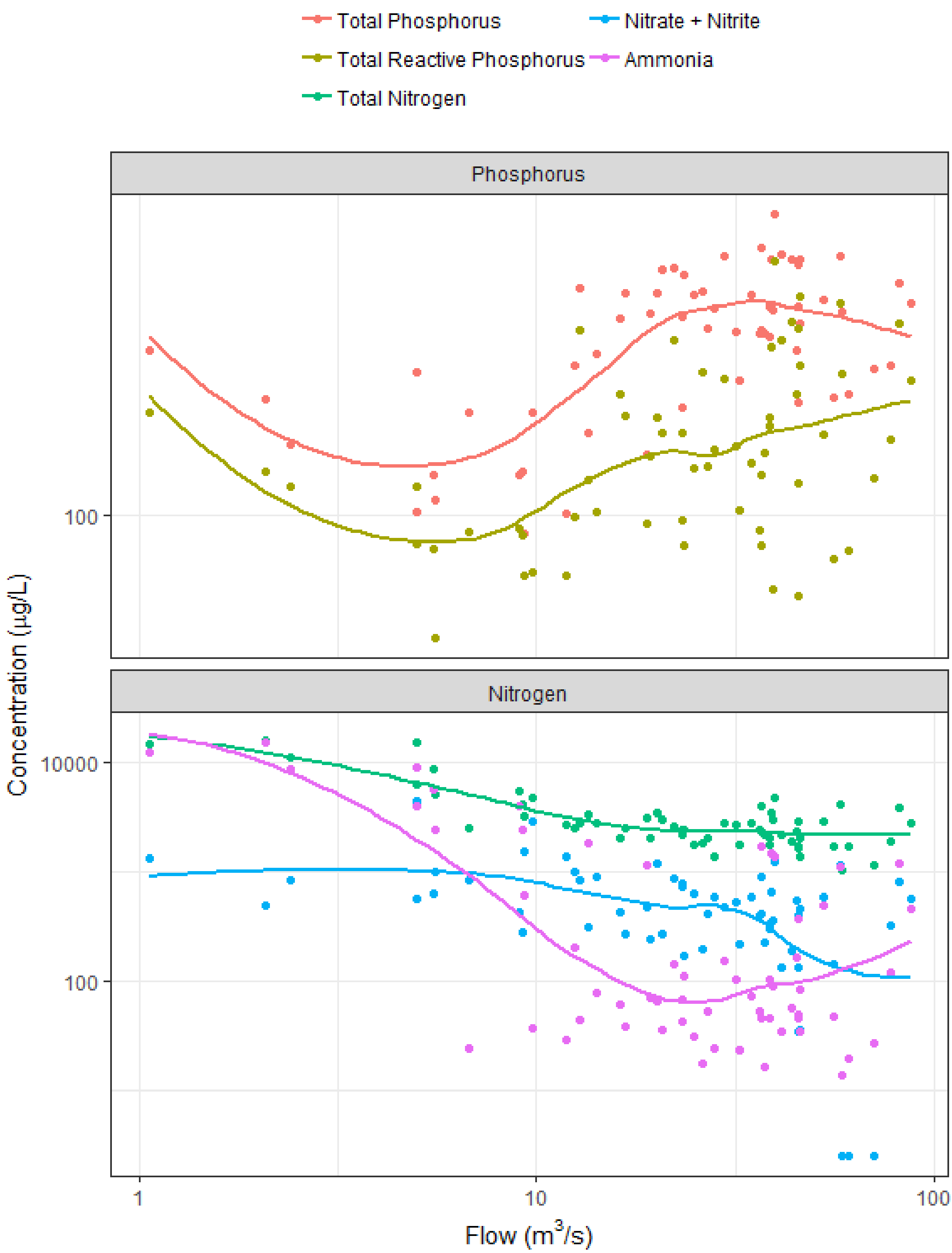


Figure 47: Concentration as a function of flow for phosphorus and nitrogen in the Qu'Appelle River above Pasqua Lake. Lines represent a LOESS fit through the data. Note that both axes have log-transformed scales.

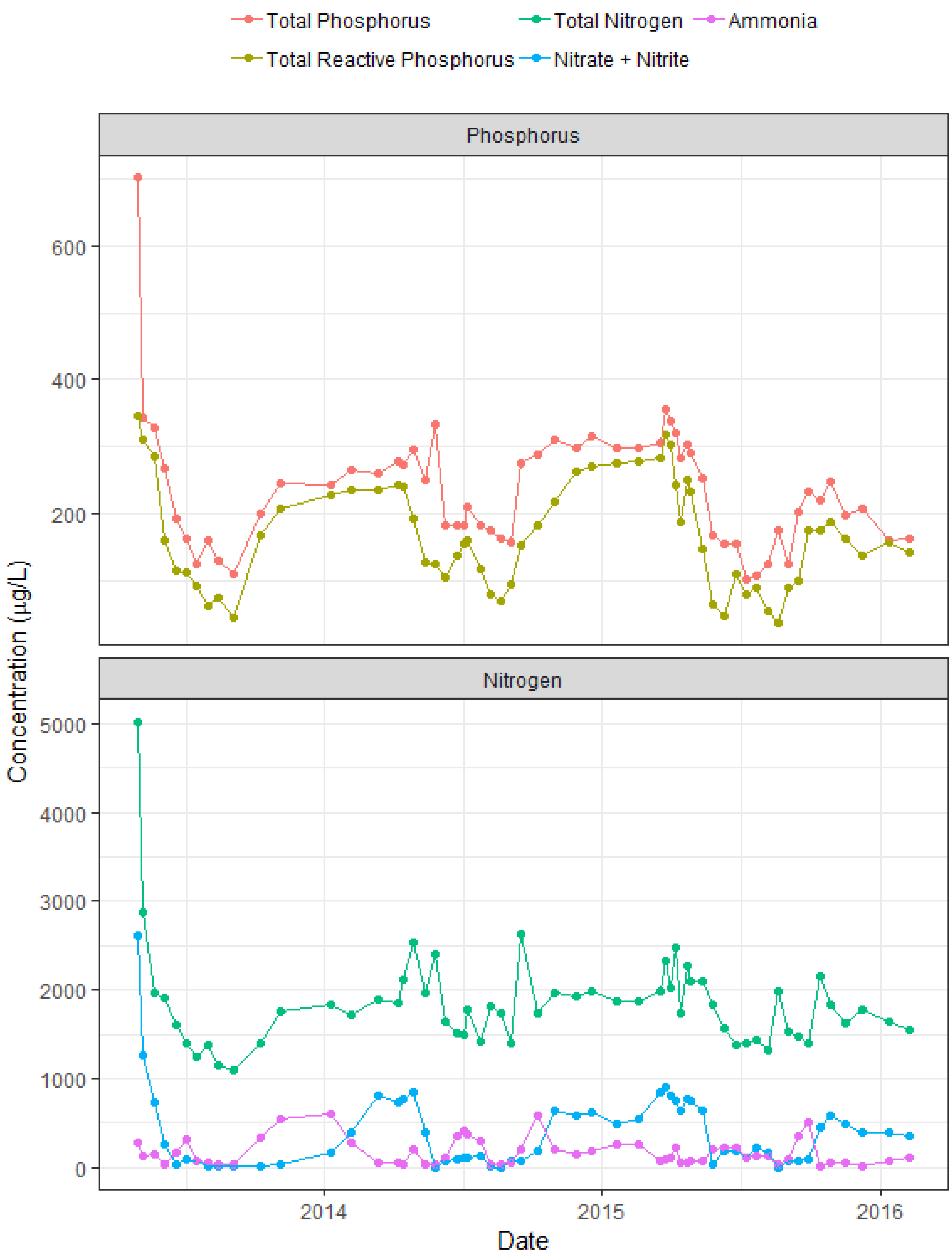


Figure 48: Concentration over time for phosphorus and nitrogen in the Qu'Appelle River at Katepwa Lake outlet.

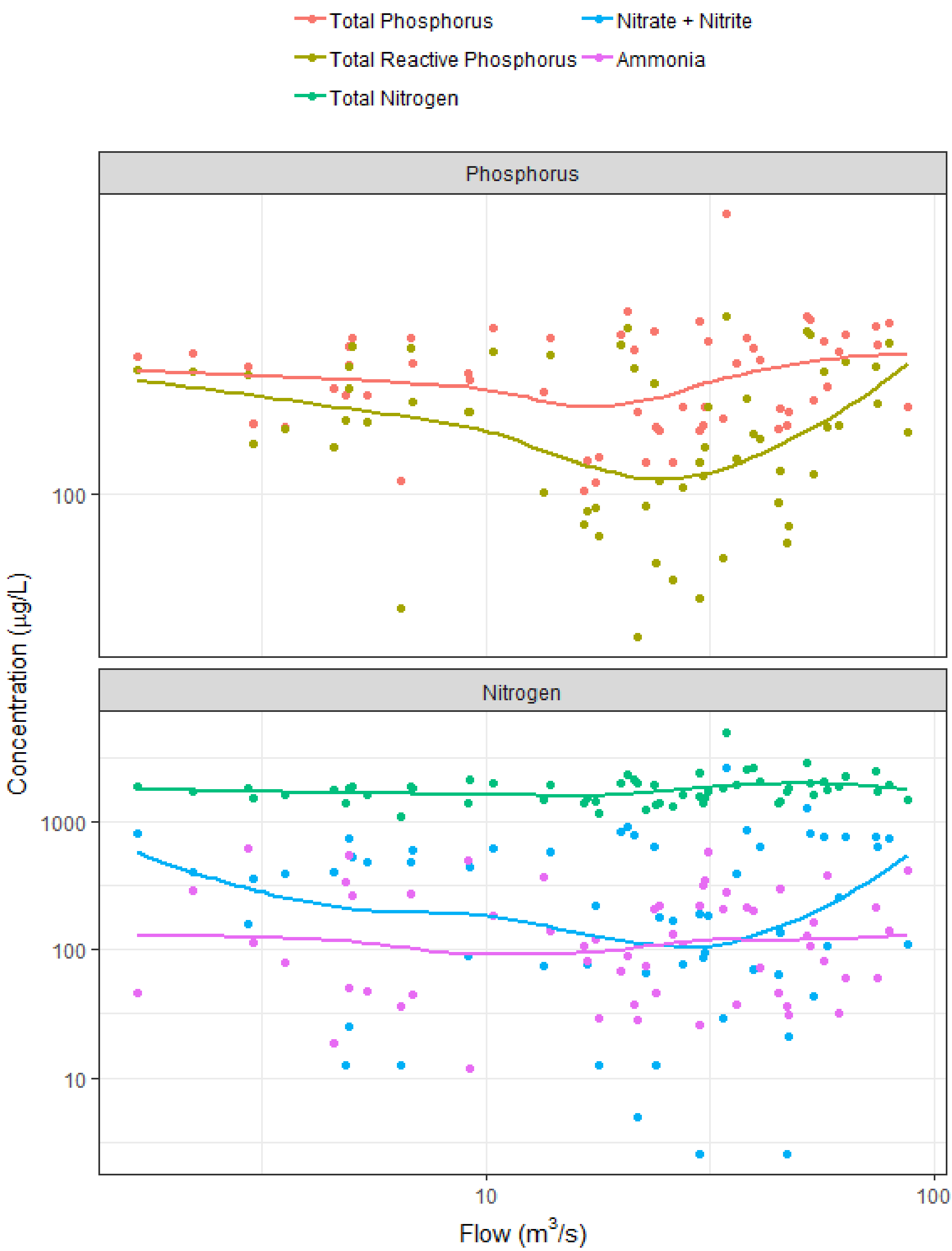


Figure 49: Concentration as a function of flow for phosphorus and nitrogen in the Qu'Appelle River at Katepwa Lake outlet. Lines represent a LOESS fit through the data. Note that both axes have log-transformed scales.

Figure 50: Concentration over time for phosphorus and nitrogen in the Qu'Appelle River at Highway 201 (upstream of Round Lake).

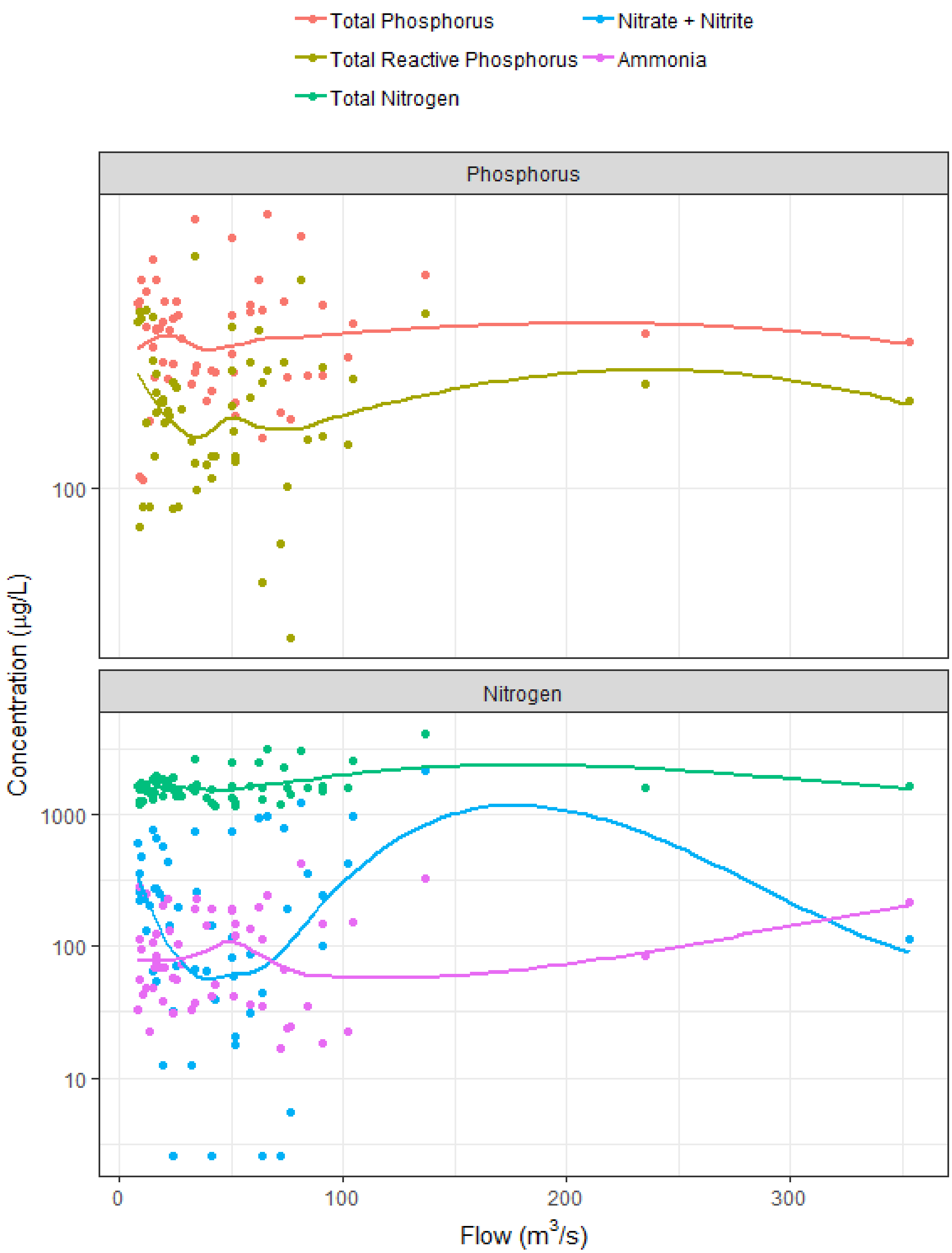


Figure 51: Concentration as a function of flow for phosphorus and nitrogen in the Qu'Appelle River at Highway 201 (upstream of Round Lake). Lines represent a LOESS fit through the data. Note that both axes have log-transformed scales.

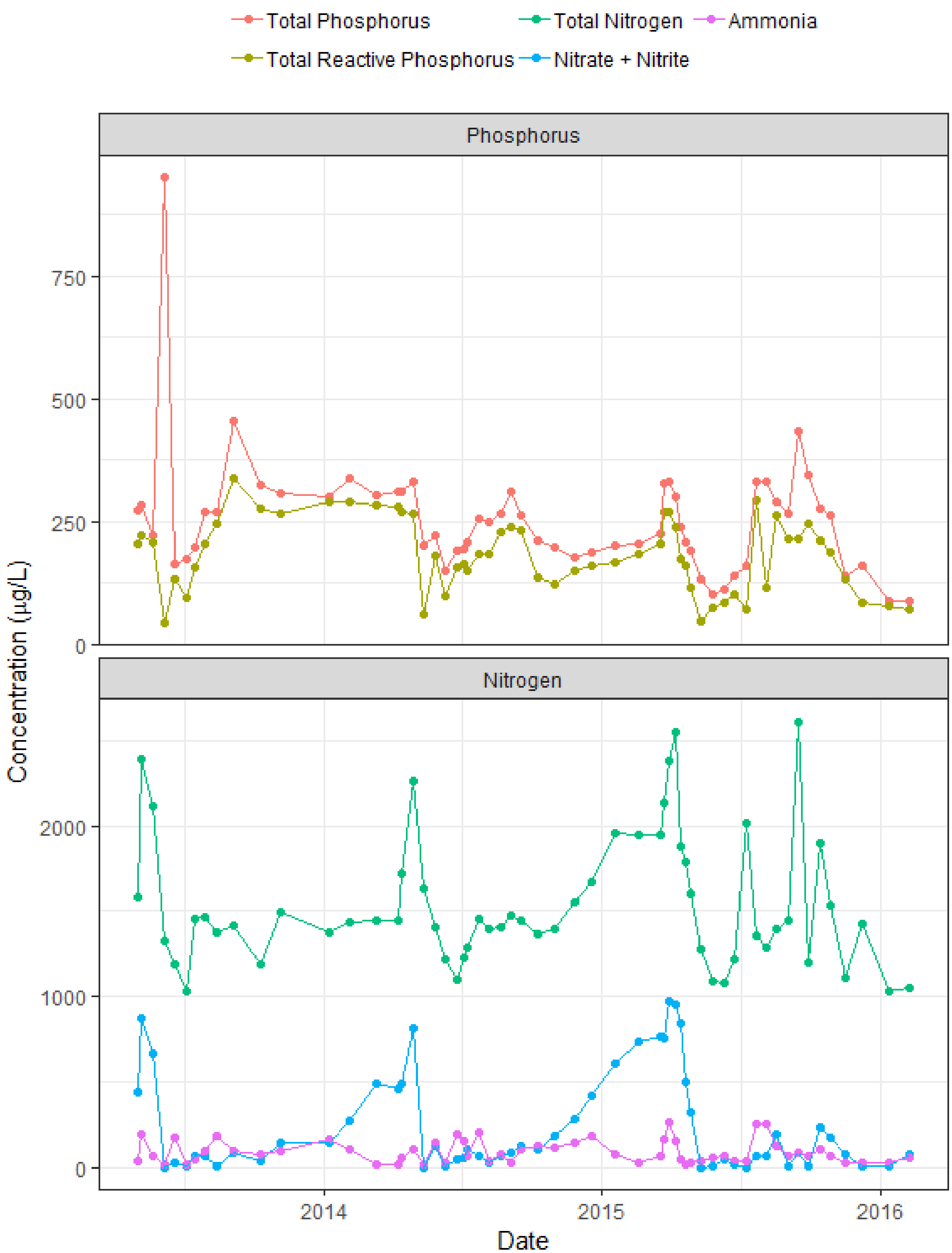


Figure 52: Concentration over time for phosphorus and nitrogen in the Qu'Appelle River at Round Lake outlet.

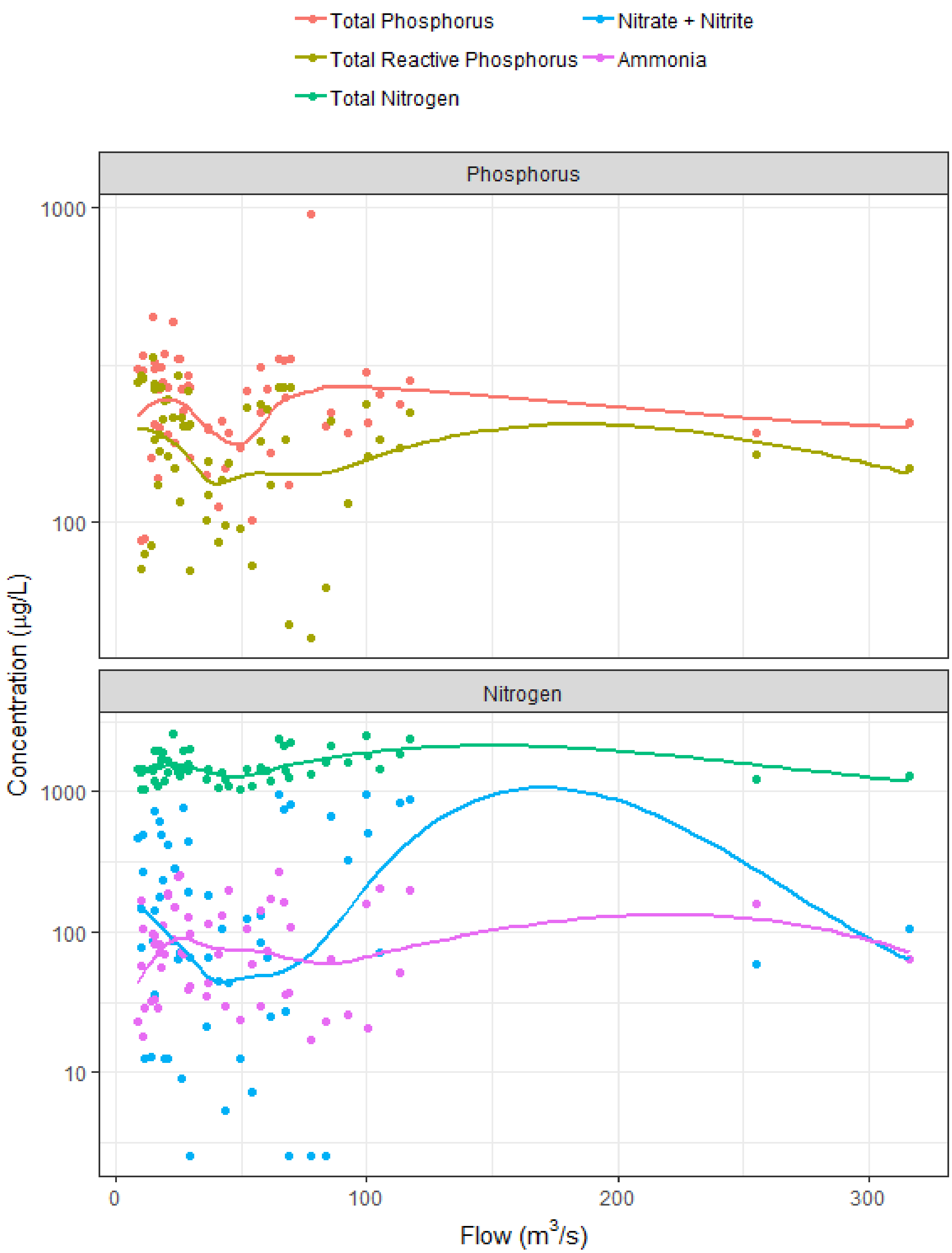


Figure 53: Concentration as a function of flow for phosphorus and nitrogen in the Qu'Appelle River at Round Lake outlet. Lines represent a LOESS fit through the data. Note that both axes have log-transformed scales.

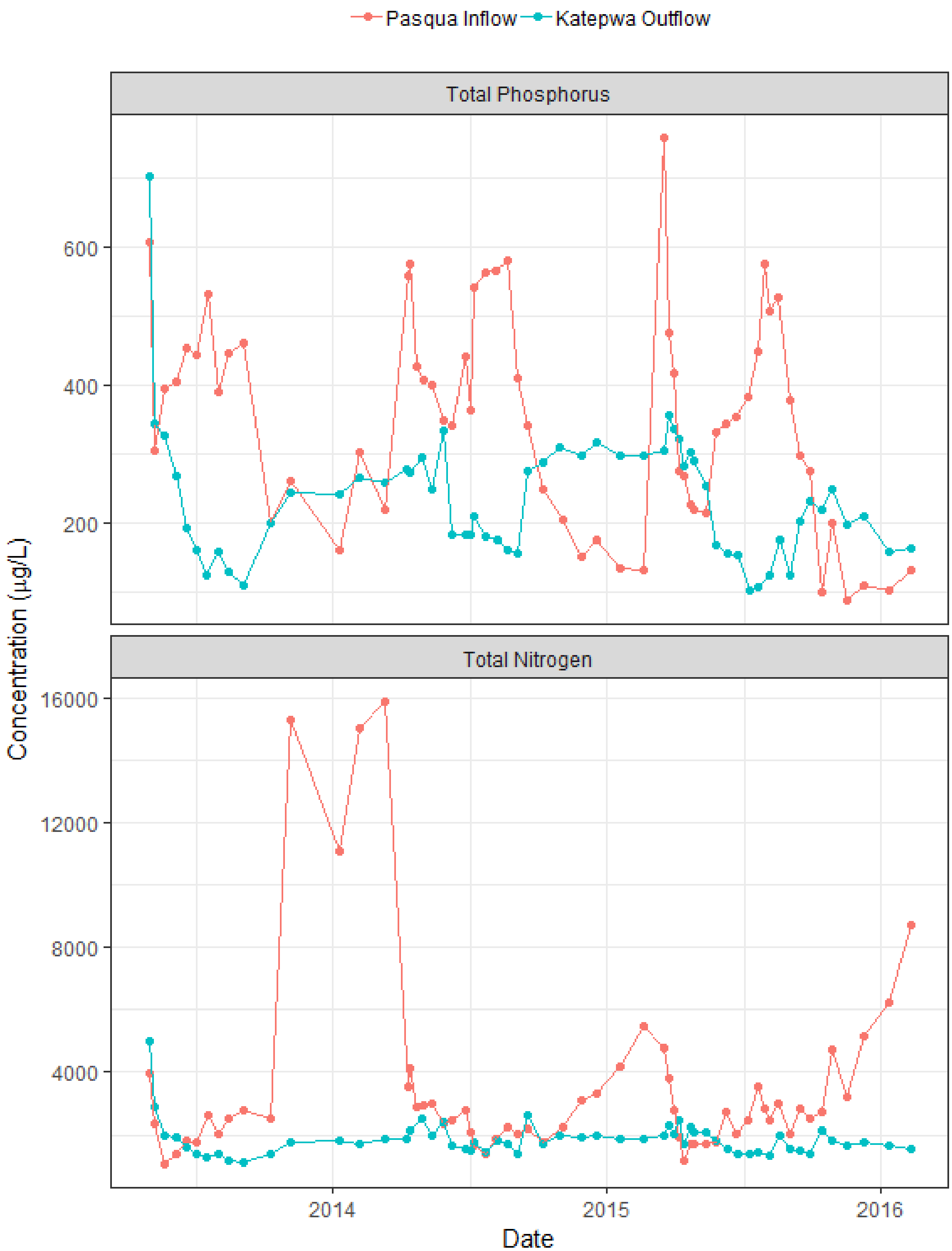


Figure 54: Total phosphorus and total nitrogen concentrations over time at the inflow to Pasqua Lake (Qu'Appelle River above Pasqua Lake) and at the outflow of Katepwa Lake.

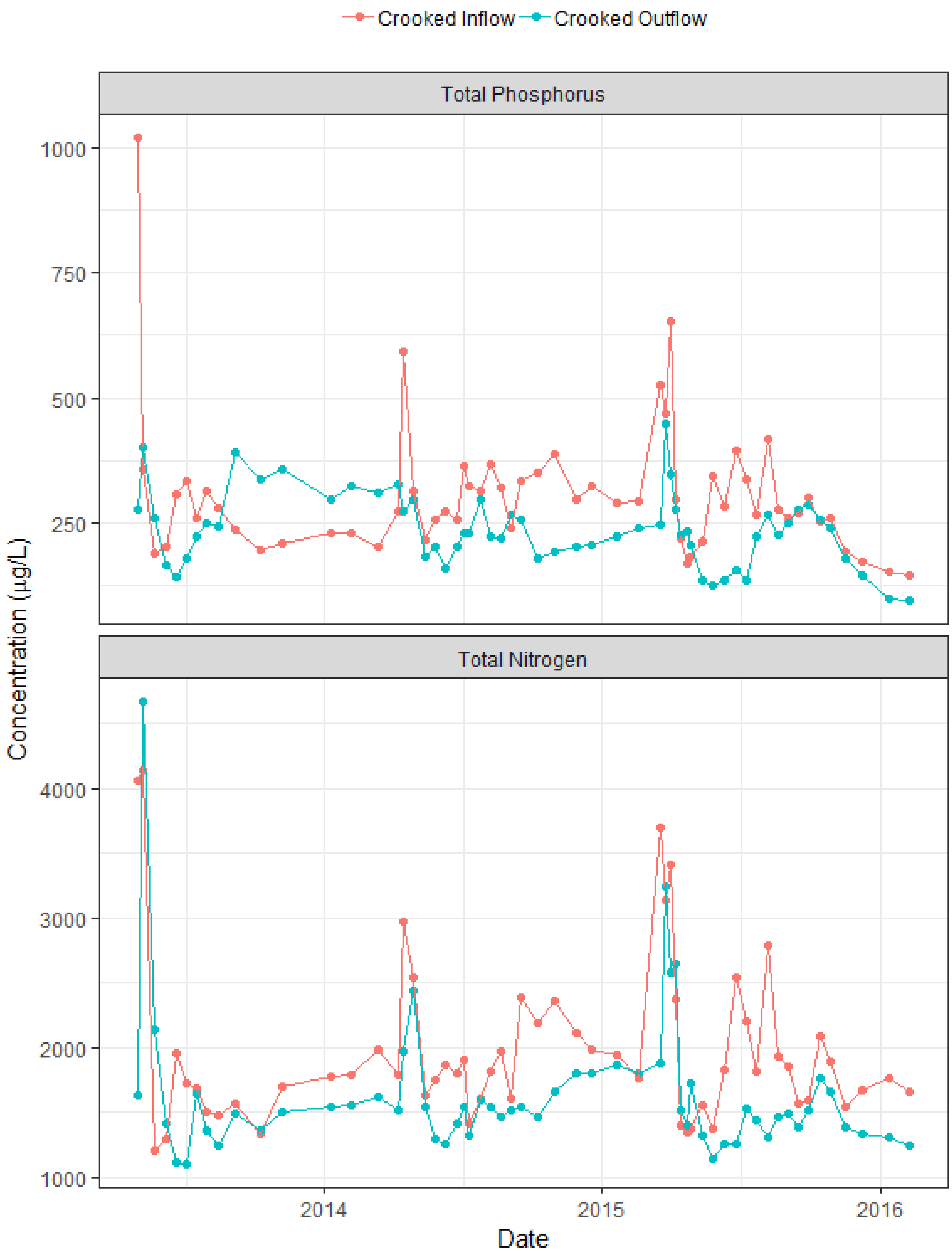


Figure 55: Total phosphorus and total nitrogen concentrations over time at the inflow to Crooked Lake (Qu'Appelle River at Highway 47) and at the outflow of Crooked Lake.

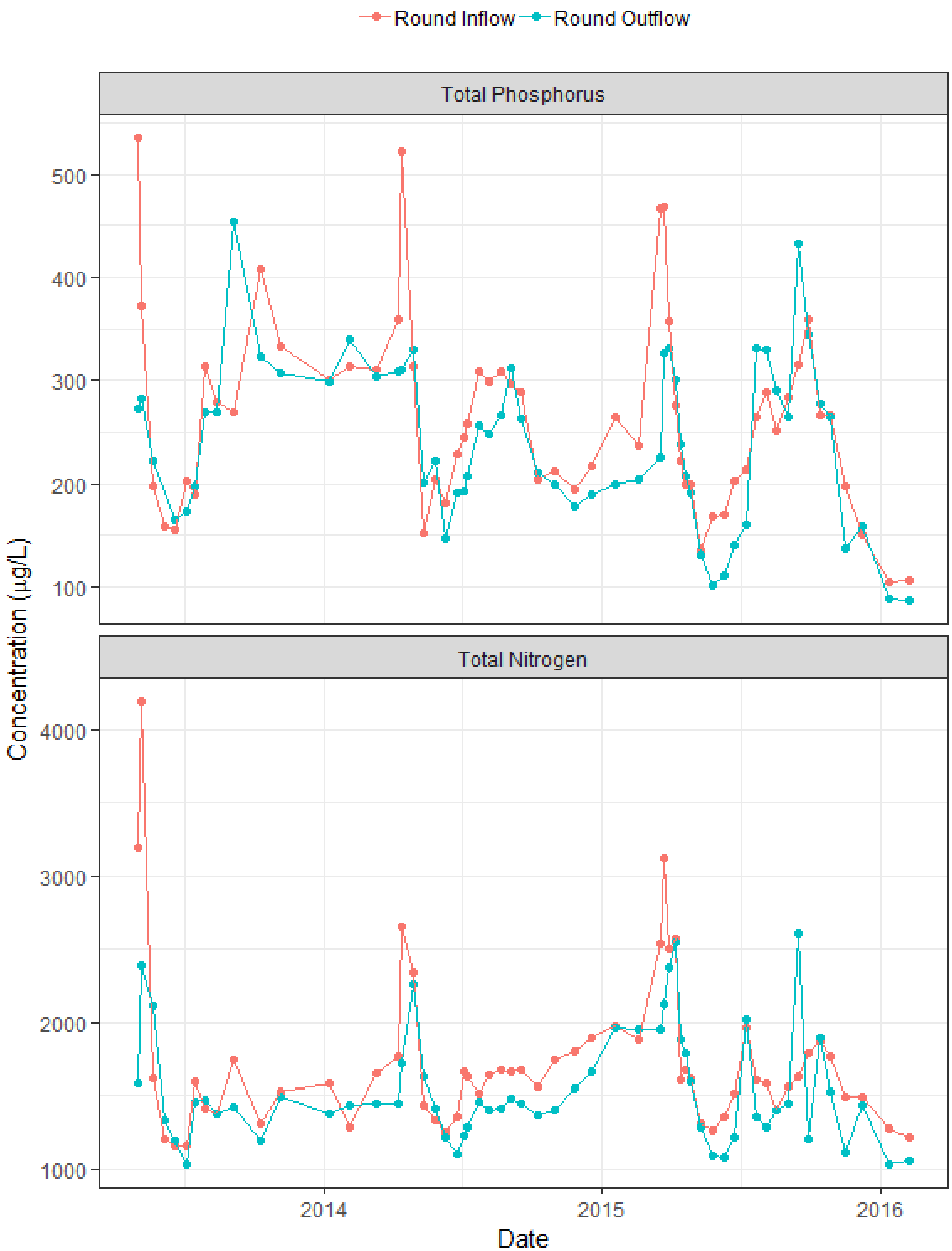


Figure 56: Total phosphorus and total nitrogen concentrations over time at the inflow to Round Lake (Qu'Appelle River at Highway 201) and at the outflow of Round Lake.

Figure 57: Concentration over time for phosphorus and nitrogen in the Moose Jaw River at TWP RD 184.

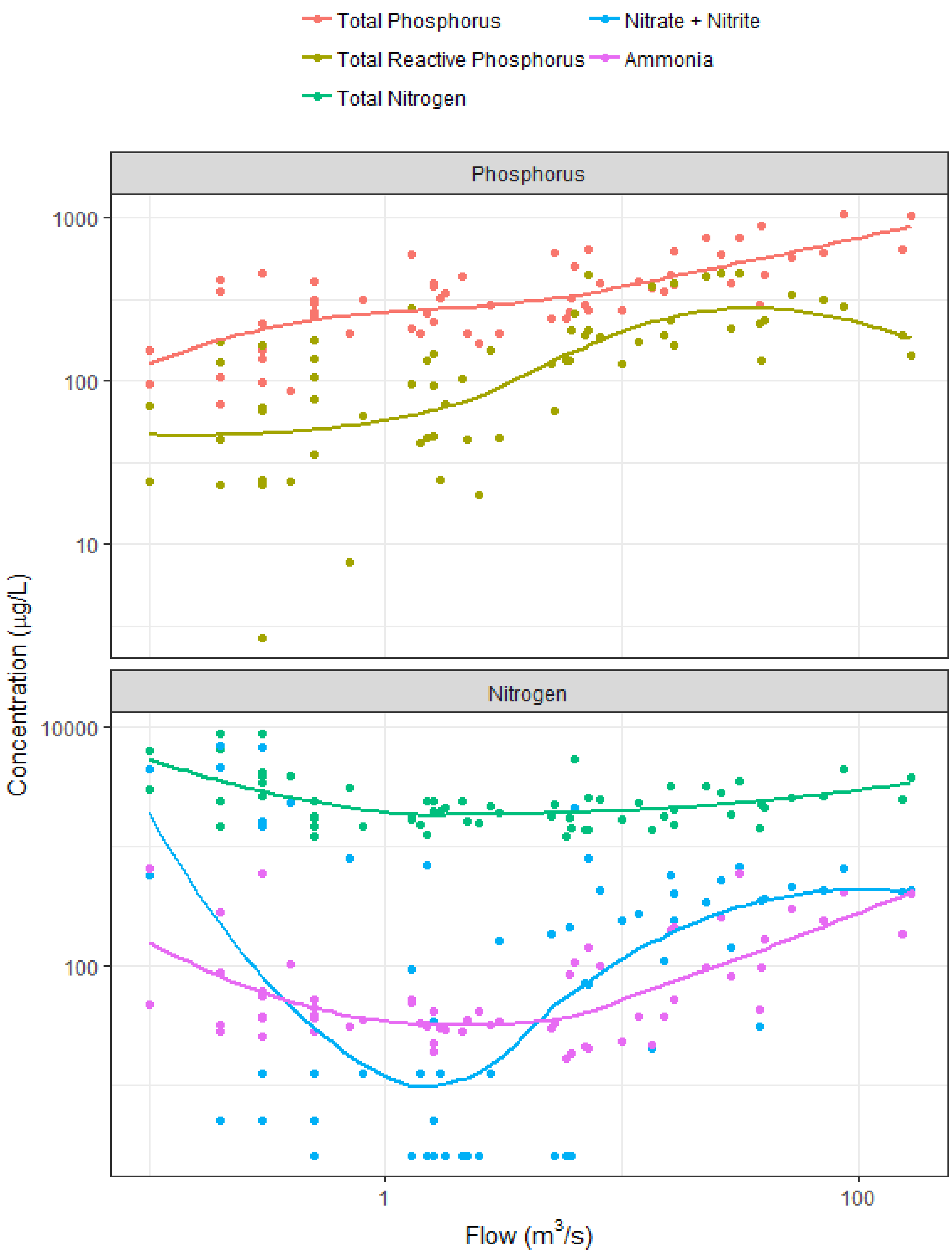


Figure 58: Concentration as a function of flow for phosphorus and nitrogen in the Moose Jaw River at Highway 301. Lines represent a LOESS fit through the data. Note that concentration is presented on a log scale.

Figure 59: Concentration over time for phosphorus and nitrogen in Wascana Creek.

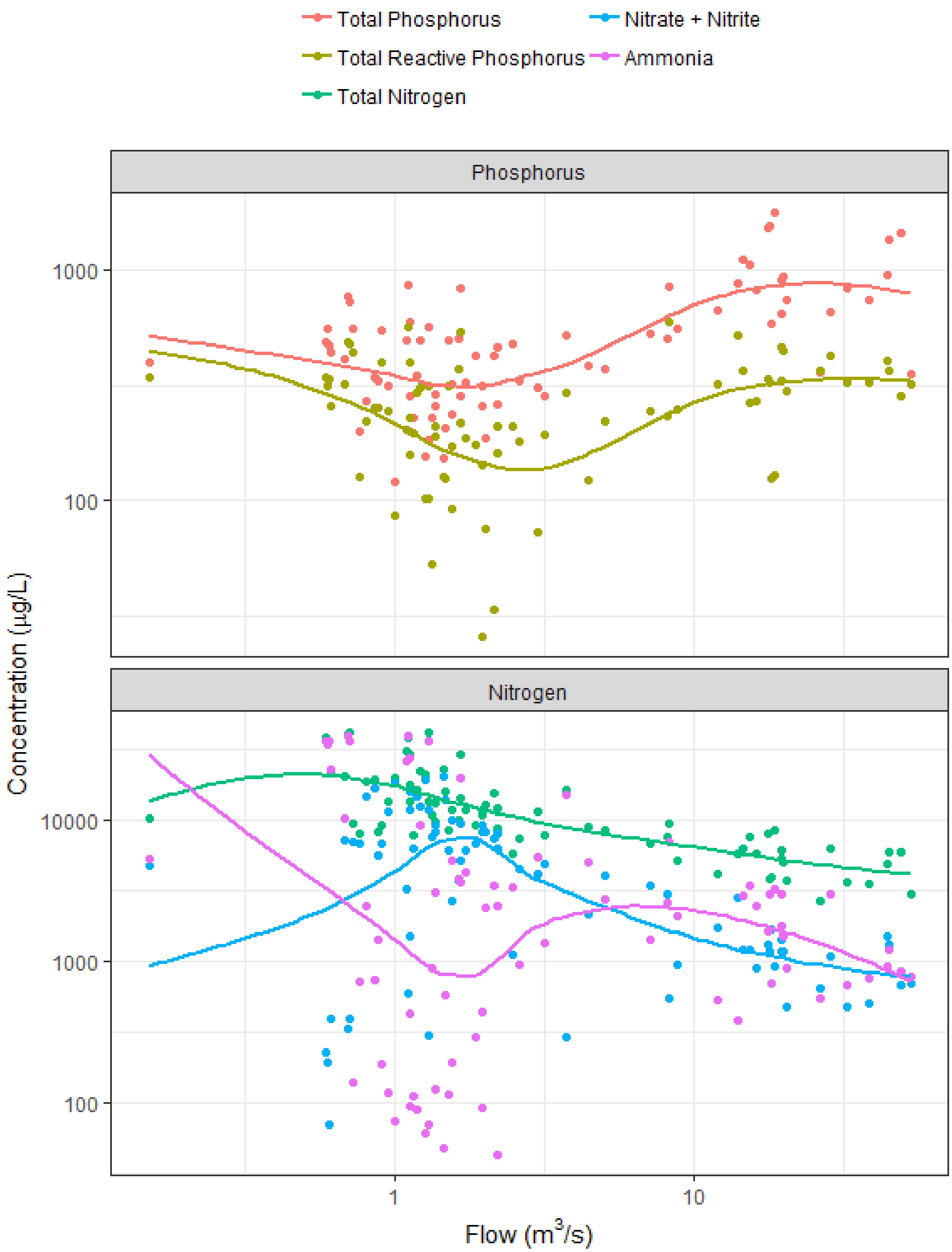


Figure 60: Concentration as a function of flow for phosphorus and nitrogen in Wascana Creek. Lines represent a LOESS fit through the data. Note that both axes have log-transformed scales.

Figure 61: Concentration over time for phosphorus and nitrogen in Last Mountain Creek.

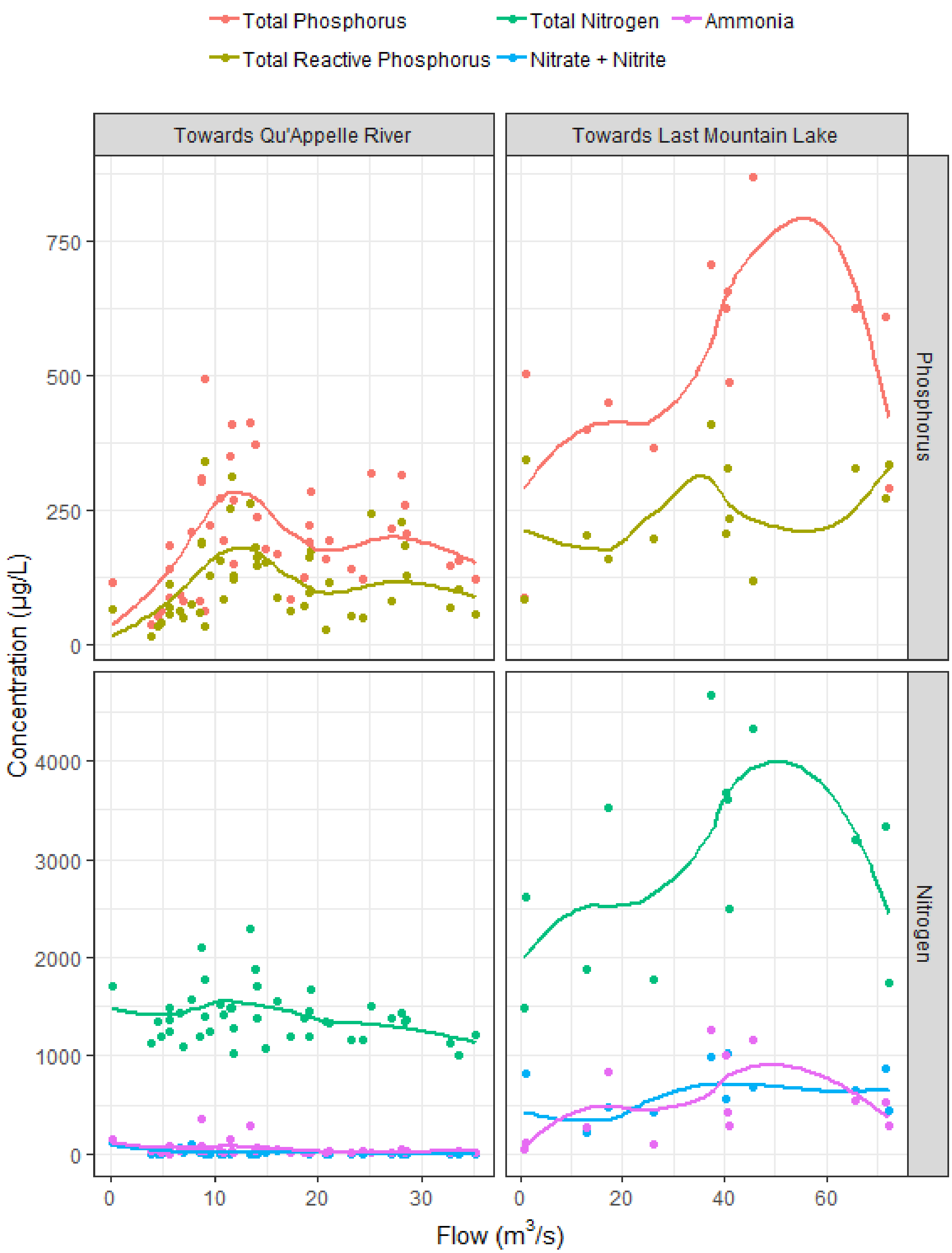


Figure 62: Concentration as a function of flow for phosphorus and nitrogen in Last Mountain Creek above the Qu'Appelle River. Lines represent a LOESS fit through the data.

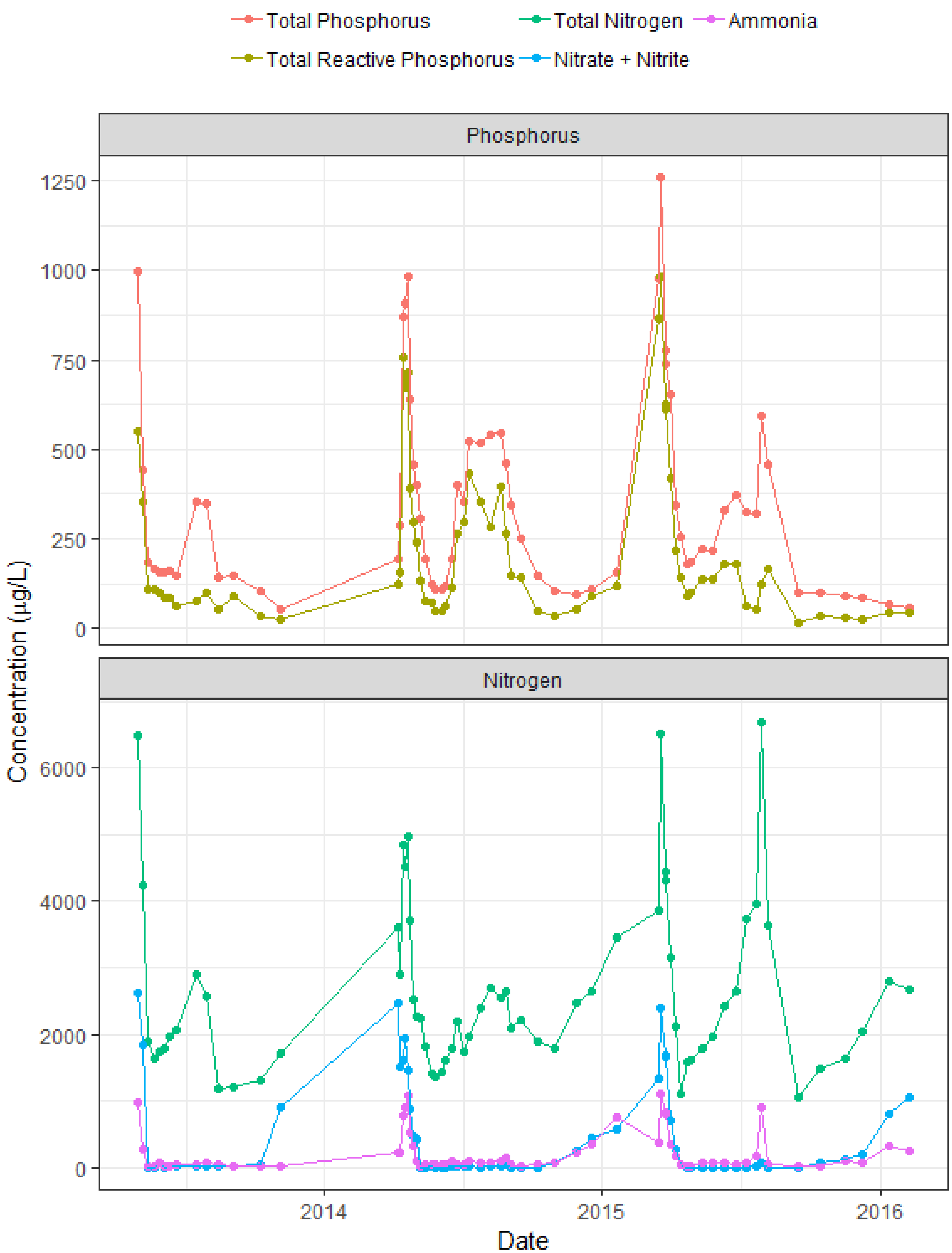


Figure 63: Concentration over time for phosphorus and nitrogen in Pheasant Creek.

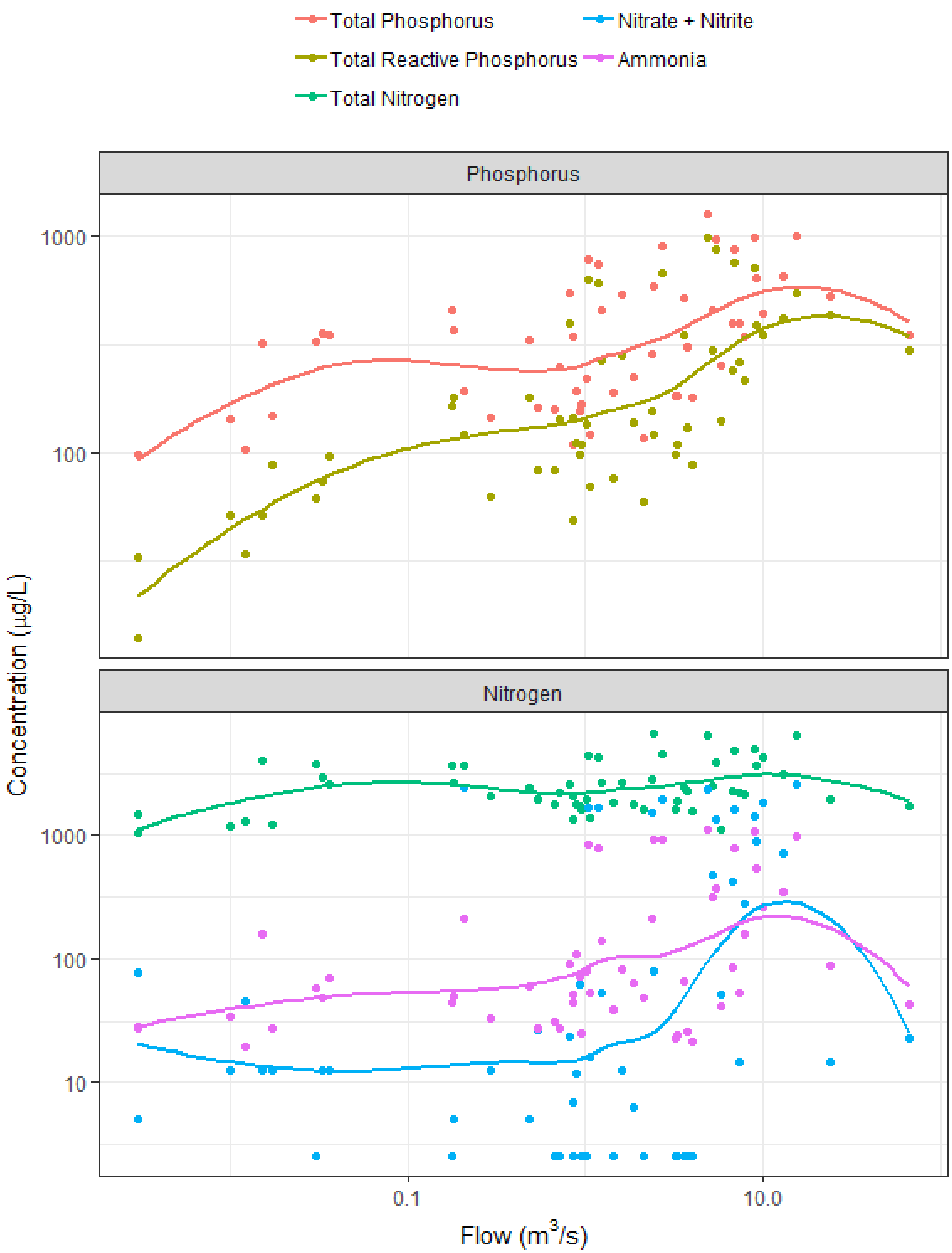


Figure 64: Concentration as a function of flow for phosphorus and nitrogen in Pheasant Creek. Lines represent a LOESS fit through the data. Note that the concentration axis has a log-transformed scale.

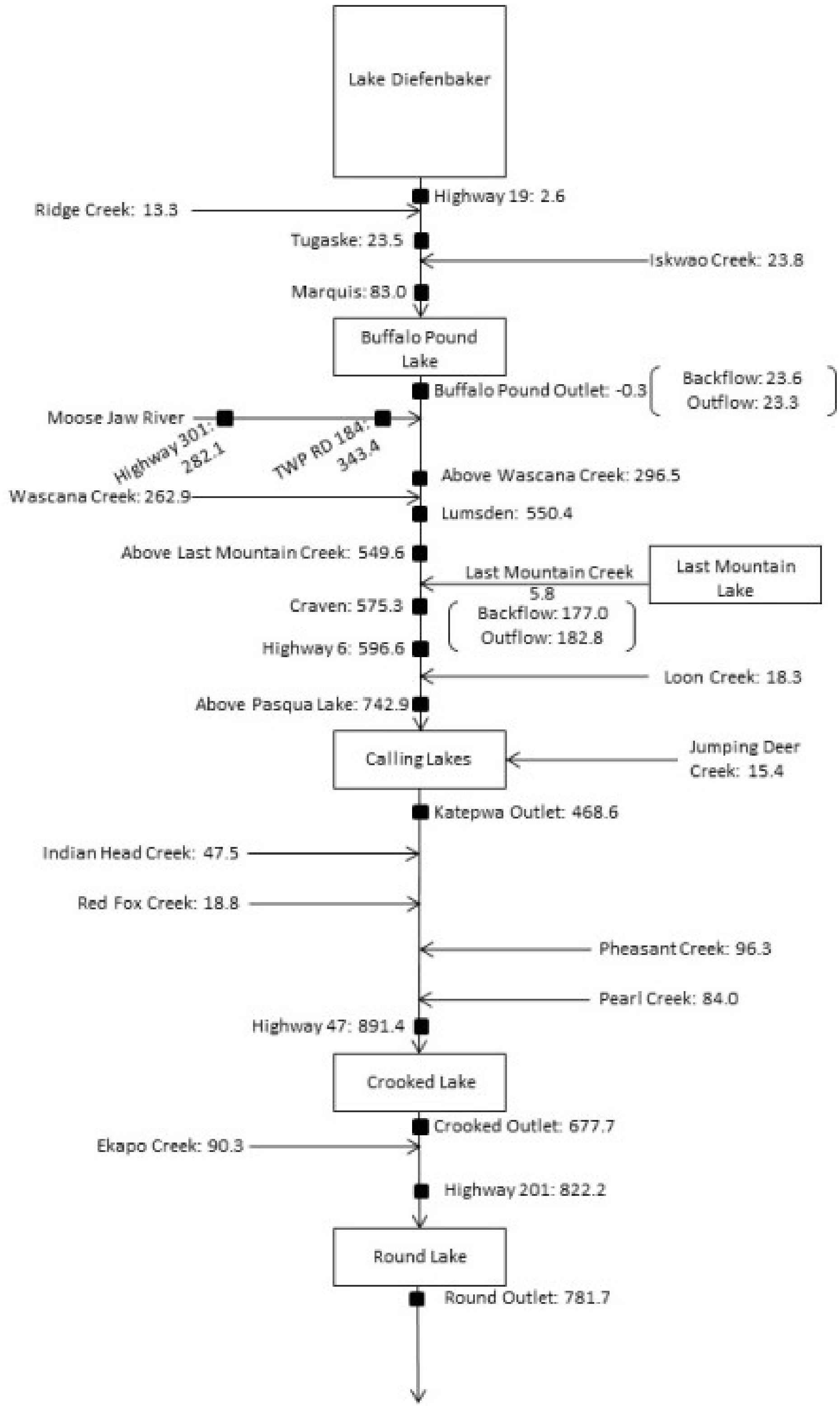


Figure 65: Total phosphorus loading in the Qu'Appelle River and tributaries March 1, 2013 to February 29, 2016. Loads are in tonnes for the whole three-year period. Arrows indicate the direction of flow.

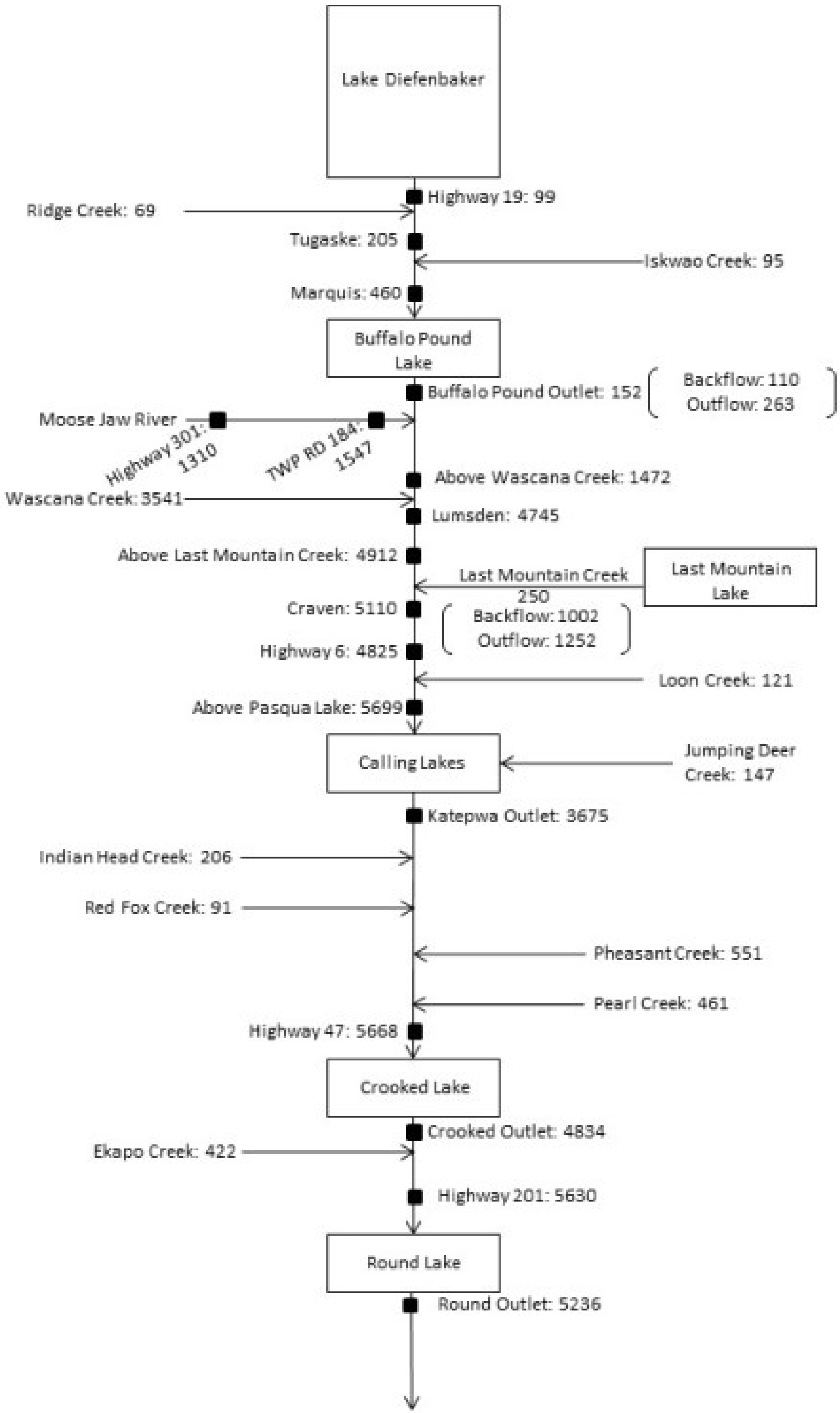


Figure 66: Total nitrogen loading in the Qu'Appelle River and tributaries March 1, 2013 to February 29, 2016. Loads are in tonnes for the whole three-year period. Arrows indicate the direction of flow.

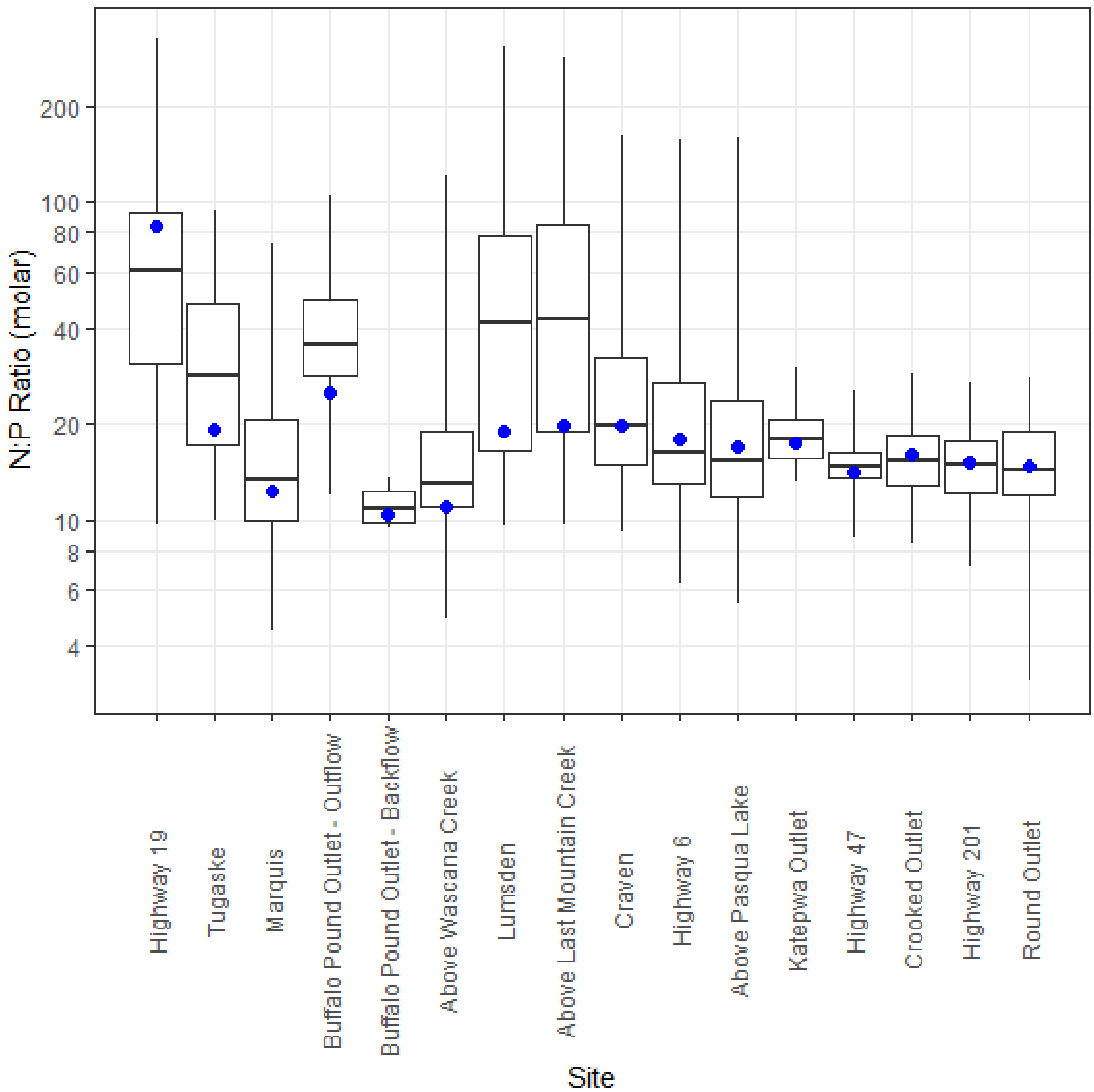


Figure 67: Boxplots for total nitrogen to total phosphorus ratios in the Qu'Appelle River. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. Blue dots indicate the TN:TP ratio calculated from volume-weighted concentrations over the duration of the study. Note the logarithmic scale for the y-axis.

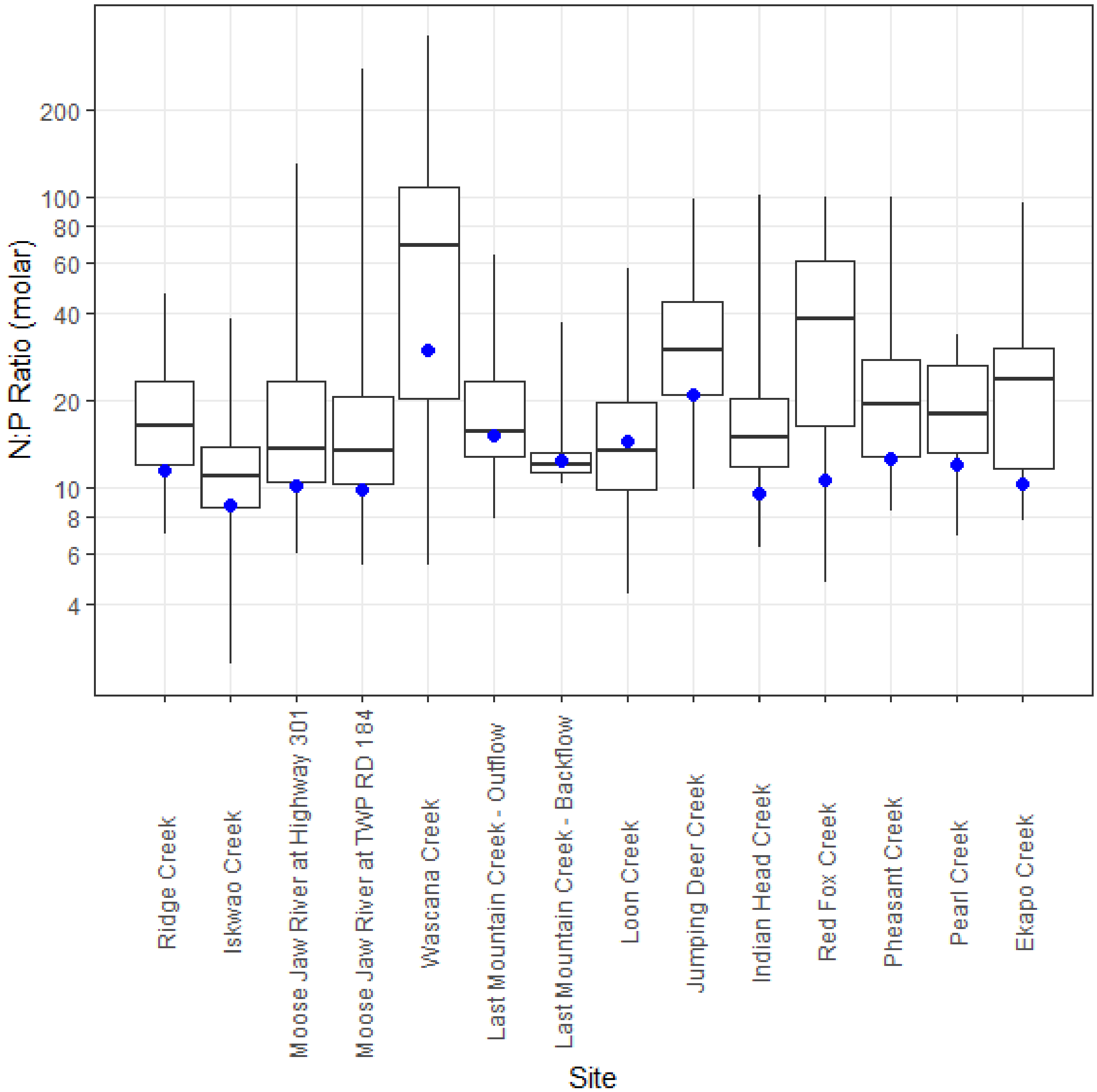


Figure 68: Boxplots for total nitrogen to total phosphorus ratios for tributary sites. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. Blue dots indicate the TN:TP ratio calculated from volume-weighted concentrations over the duration of the study. Note the logarithmic scale for the y-axis.

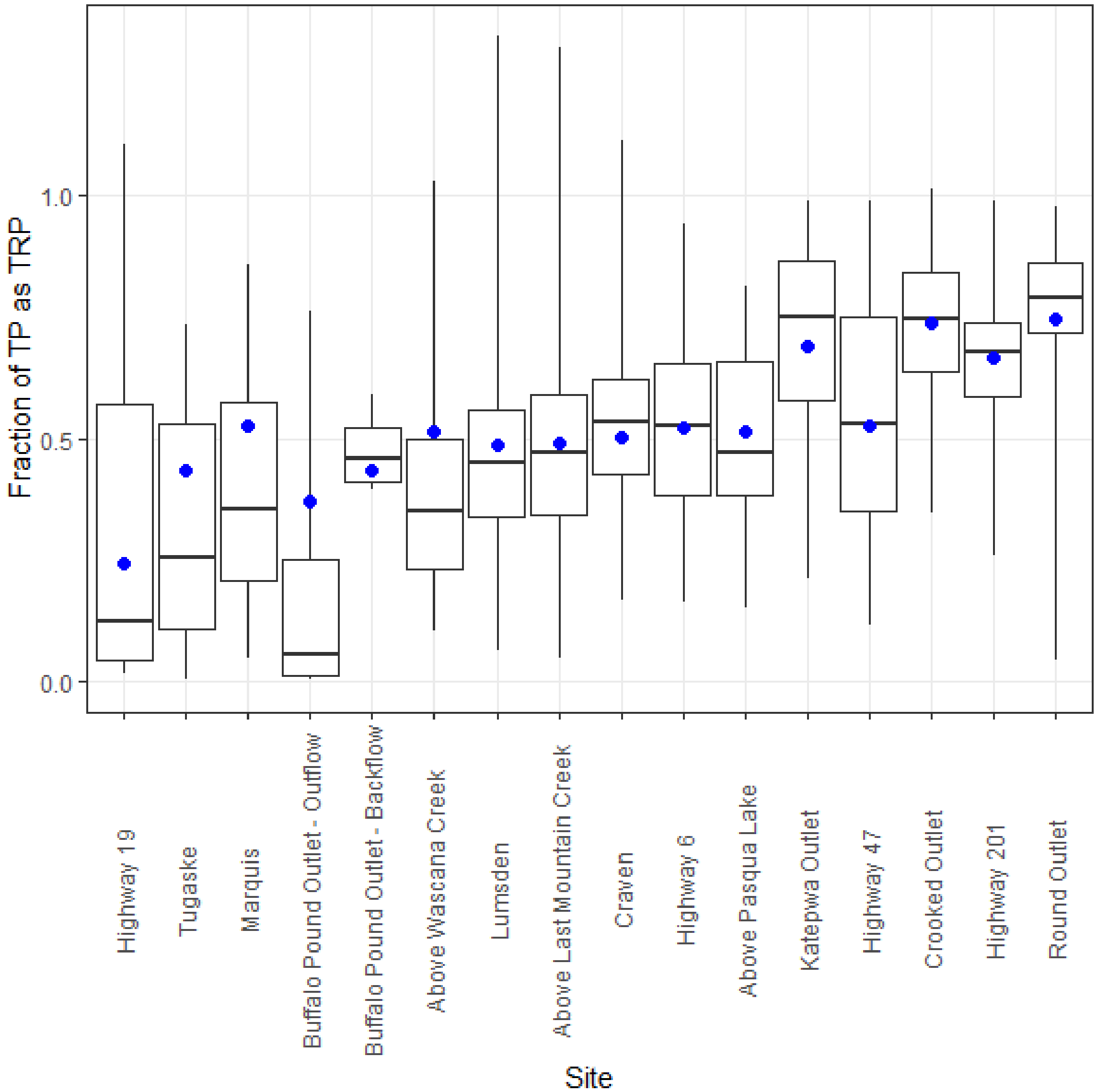


Figure 69: Boxplots for total reactive phosphorus to total phosphorus ratios in the Qu'Appelle River. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. Blue dots indicate the TRP:TP ratio calculated from volume-weighted concentrations over the duration of the study.

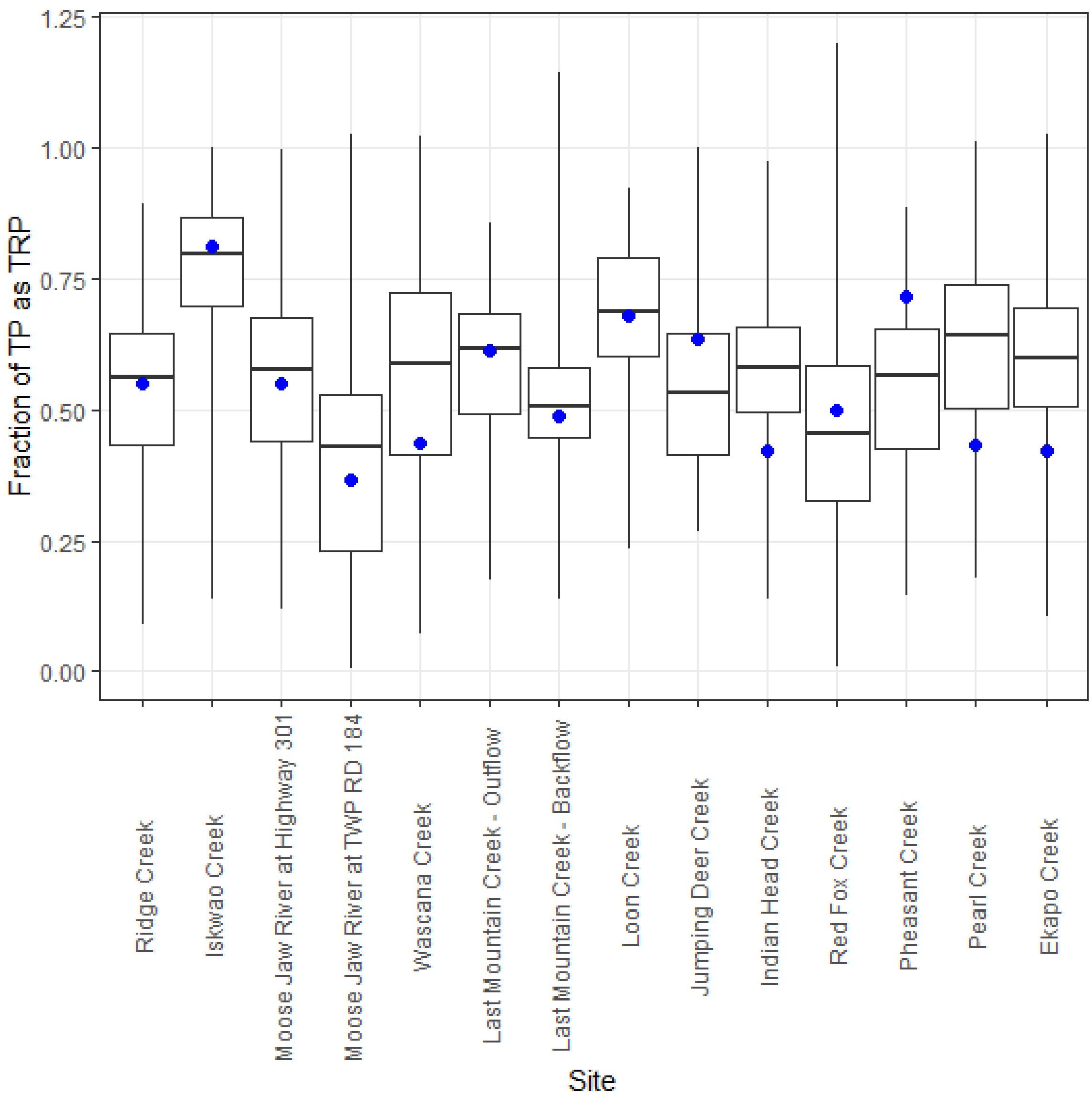


Figure 70: Boxplots for total reactive phosphorus to total phosphorus ratios for tributary sites. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. Blue dots indicate the TRP:TP ratio calculated from volume-weighted concentrations over the duration of the study.

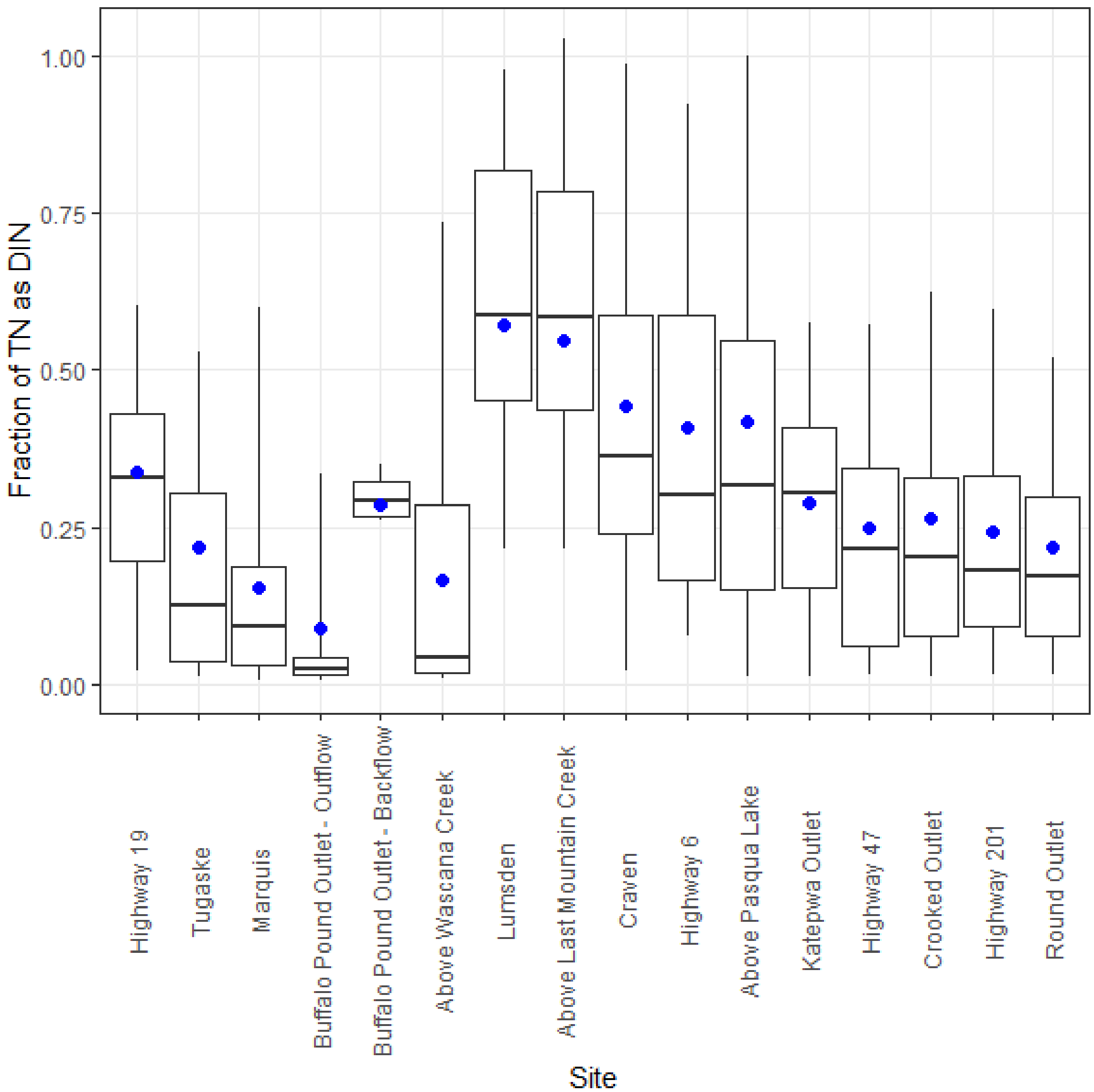


Figure 71: Boxplots for dissolved inorganic nitrogen to total nitrogen ratios in the Qu'Appelle River. Sites are arranged from upstream to downstream moving left to right. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. Blue dots indicate the DIN:TN ratio calculated from volume-weighted concentrations over the duration of the study.

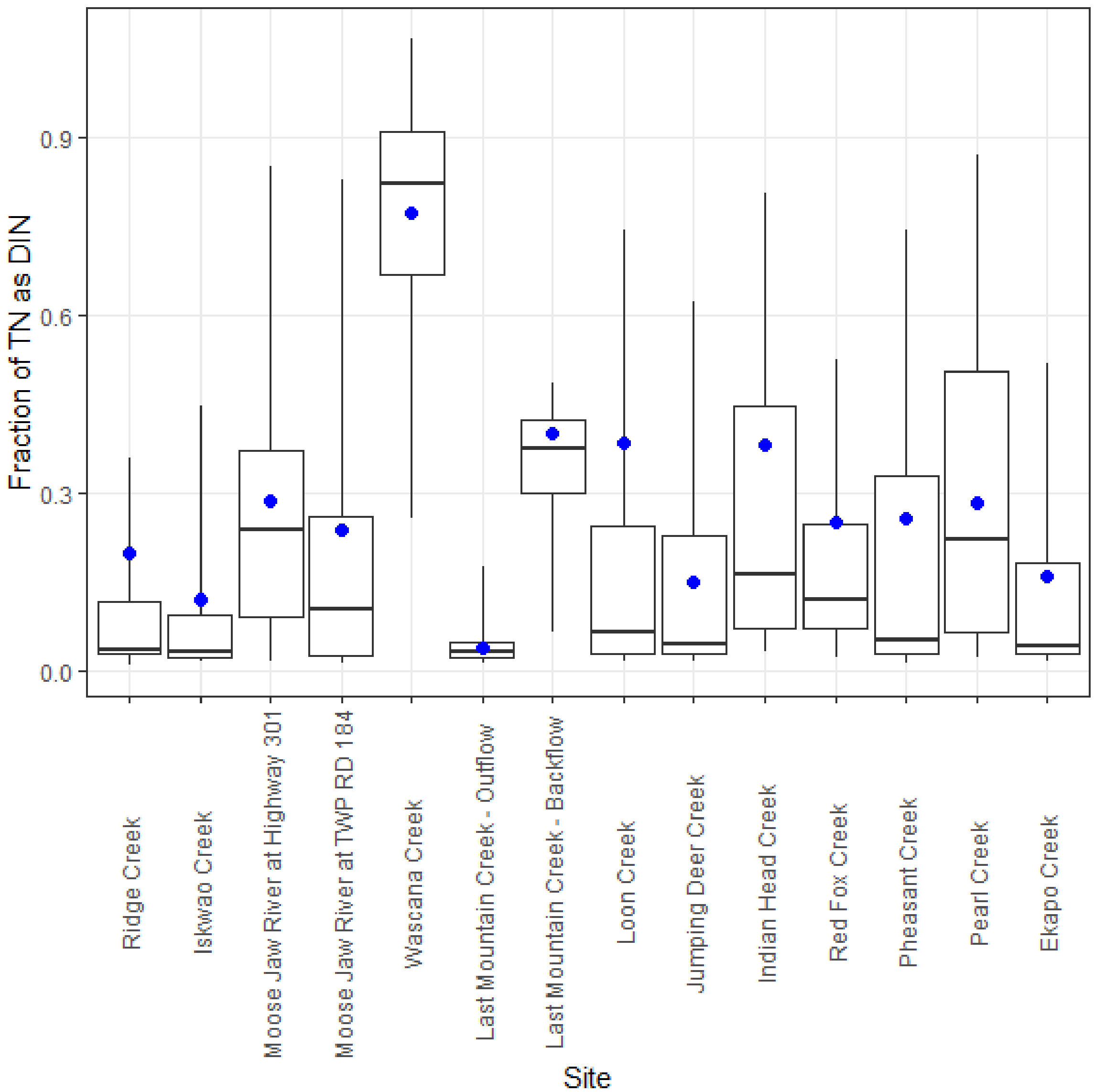


Figure 72: Boxplots for dissolved inorganic nitrogen to total nitrogen ratios for tributary sites. Boxes outline the 25-75th percentile range and whiskers extend to the minimum and maximum measurements. The central line indicates the median. Blue dots indicate the DIN:TN ratio calculated from volume-weighted concentrations over the duration of the study.

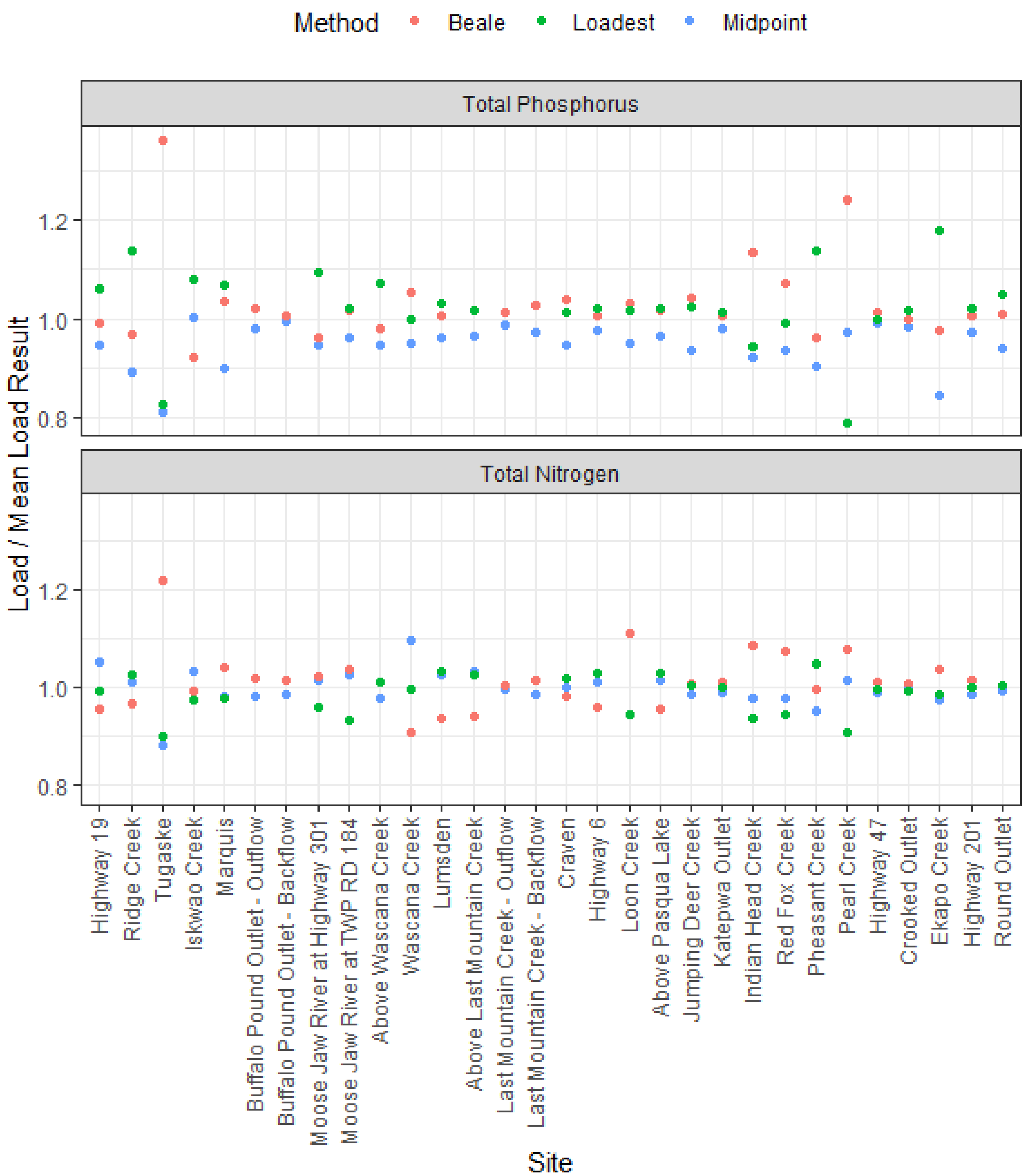


Figure 73: Comparison of load calculation results determined using the Beale Ratio Estimator, LOADEST, and Midpoint methods. Results for each method are plotted as the result divided by the mean of the 3 methods for each site. For Buffalo Pound outlet and Last Mountain Creek, only the Beale and Midpoint methods were used, as LOADEST is not appropriate for use at sites with periods of reversed flow.

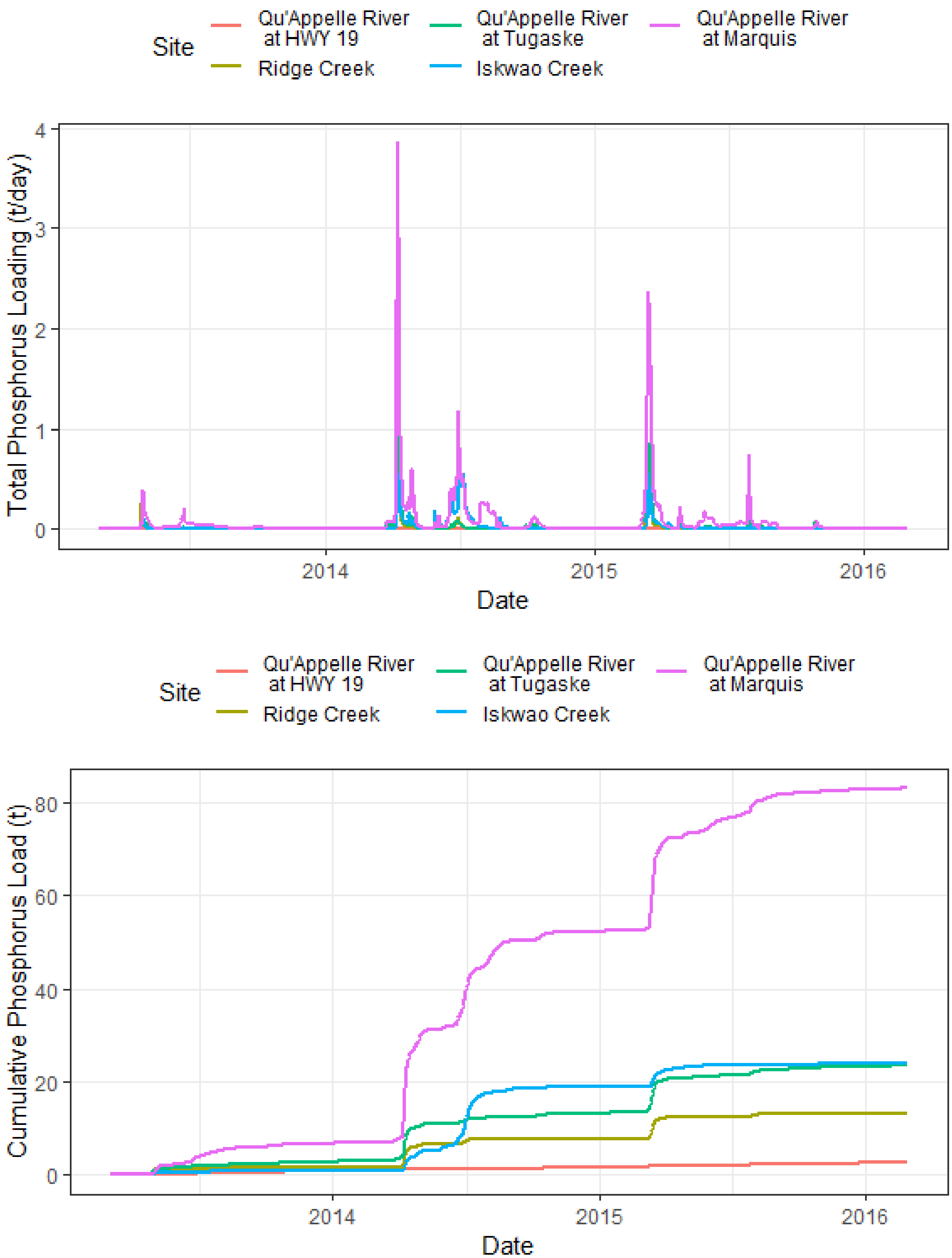


Figure 74: Total phosphorus and cumulative total phosphorus loading in the Qu'Appelle River from HWY 19 to Marquis. Loads were calculated using the midpoint method.

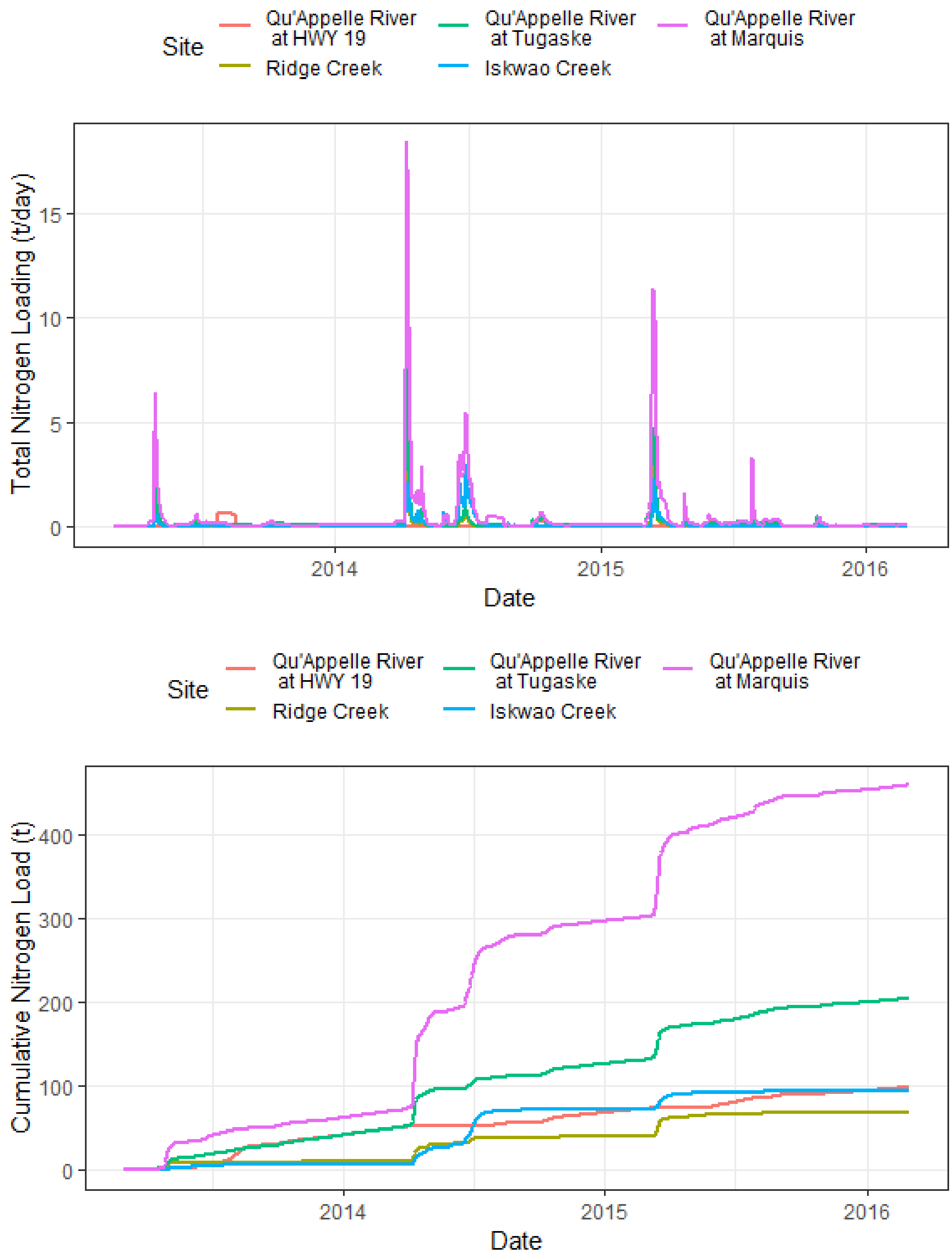
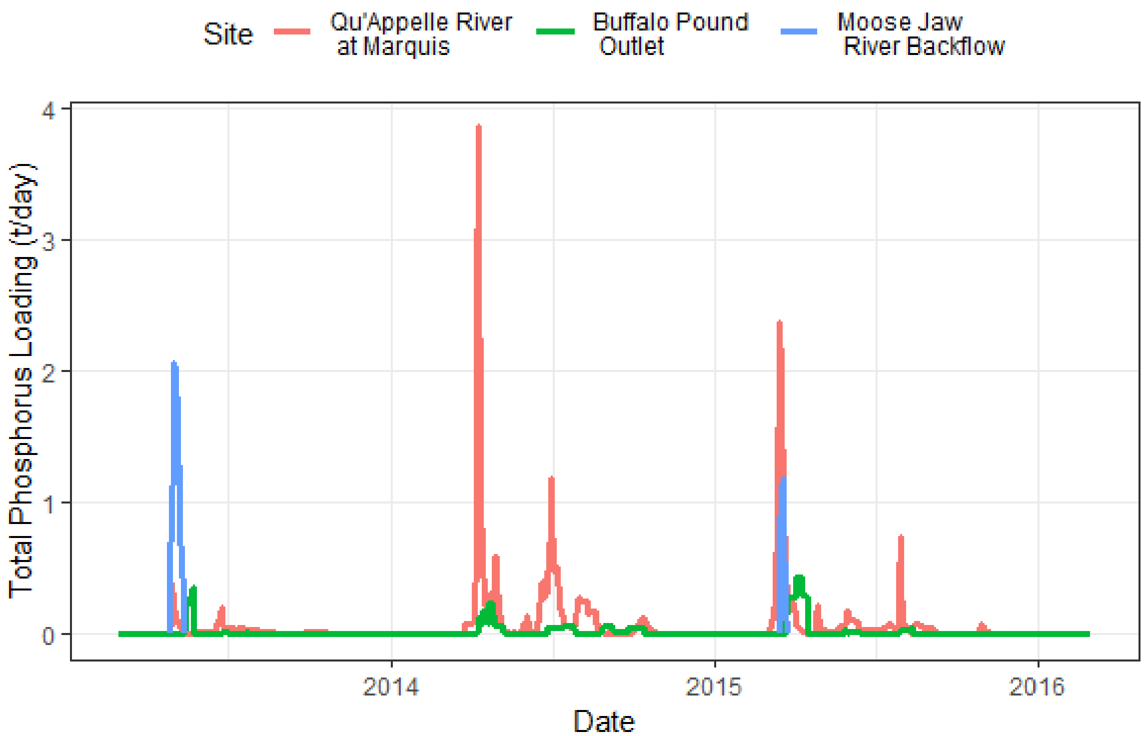


Figure 75: Total nitrogen and cumulative total nitrogen loading in the Qu'Appelle River from HWY 19 to Marquis. Loads were calculated using the midpoint method.



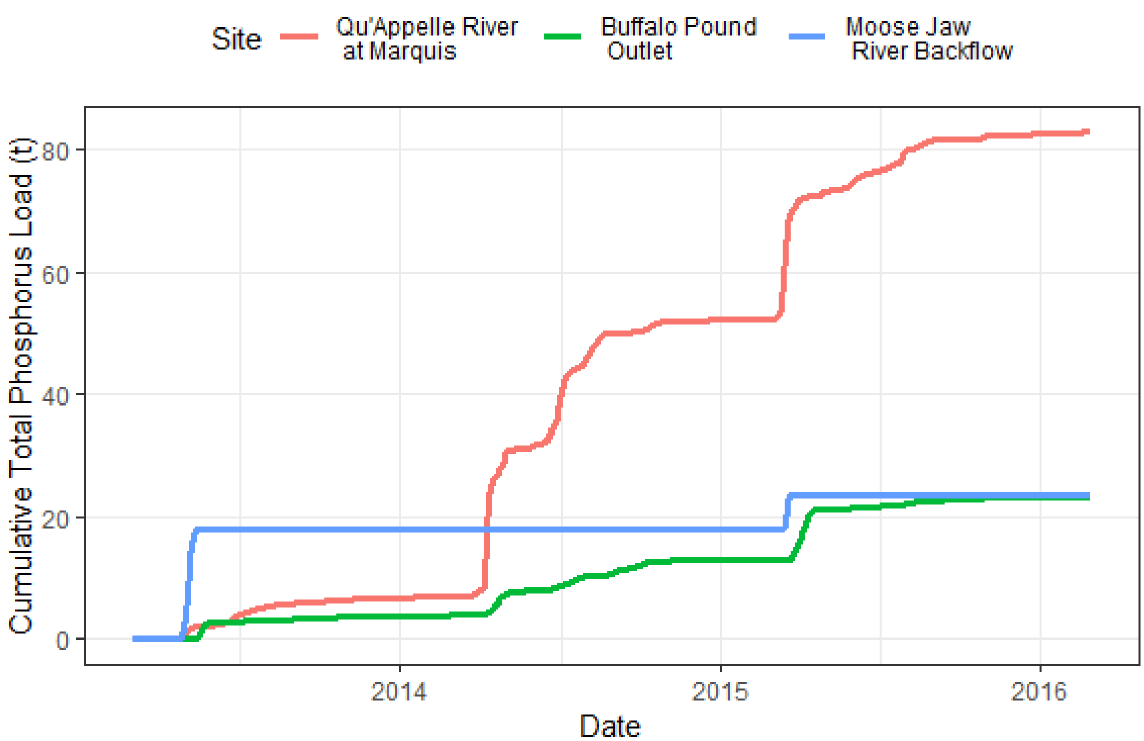


Figure 76: Total phosphorus and cumulative total phosphorus loading to and from Buffalo Pound Lake. The Qu'Appelle River at Marquis and Moose Jaw River Backflow are inflows to the lake, and Buffalo Pound outlet is the outflow. Loads were calculated using the midpoint method.

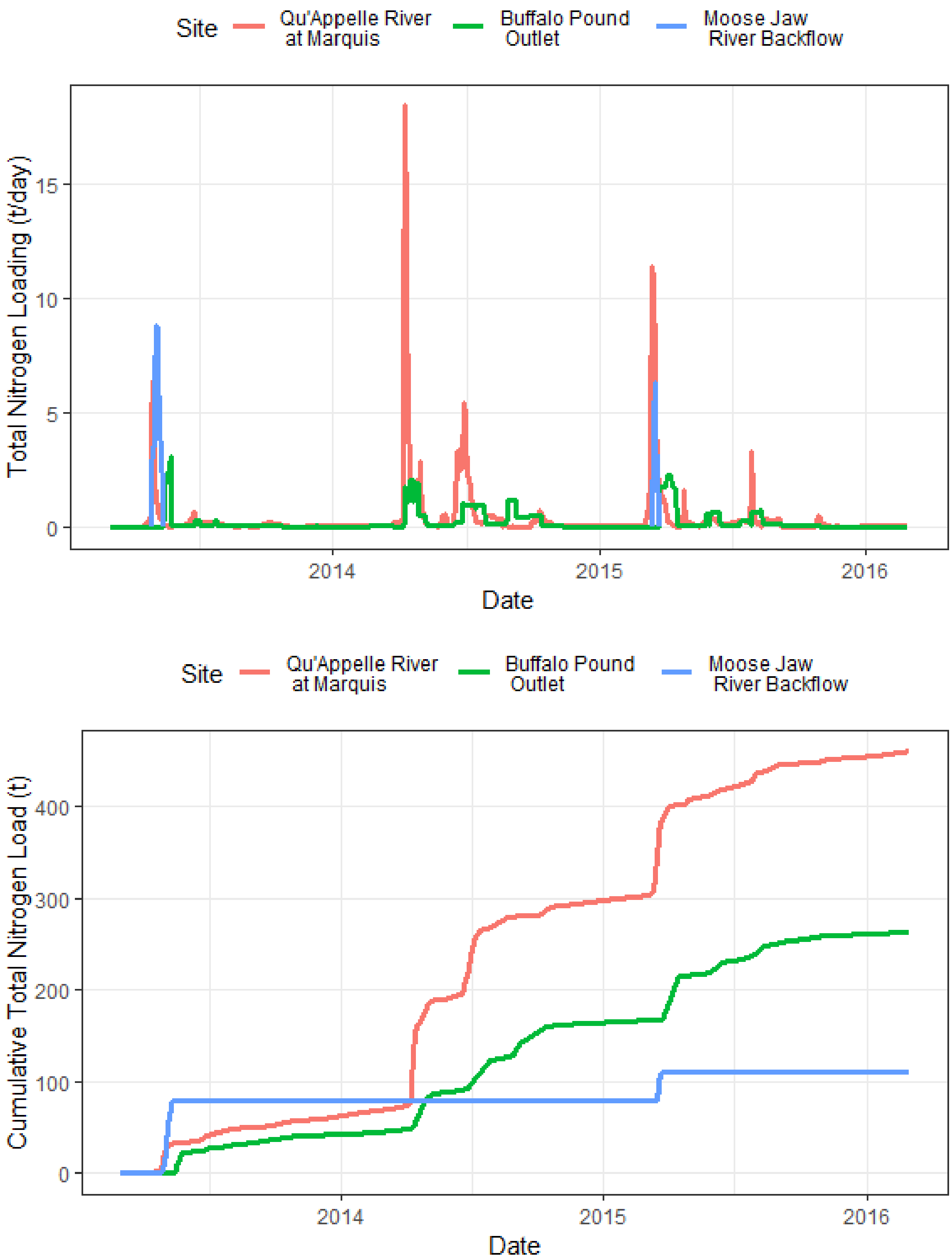
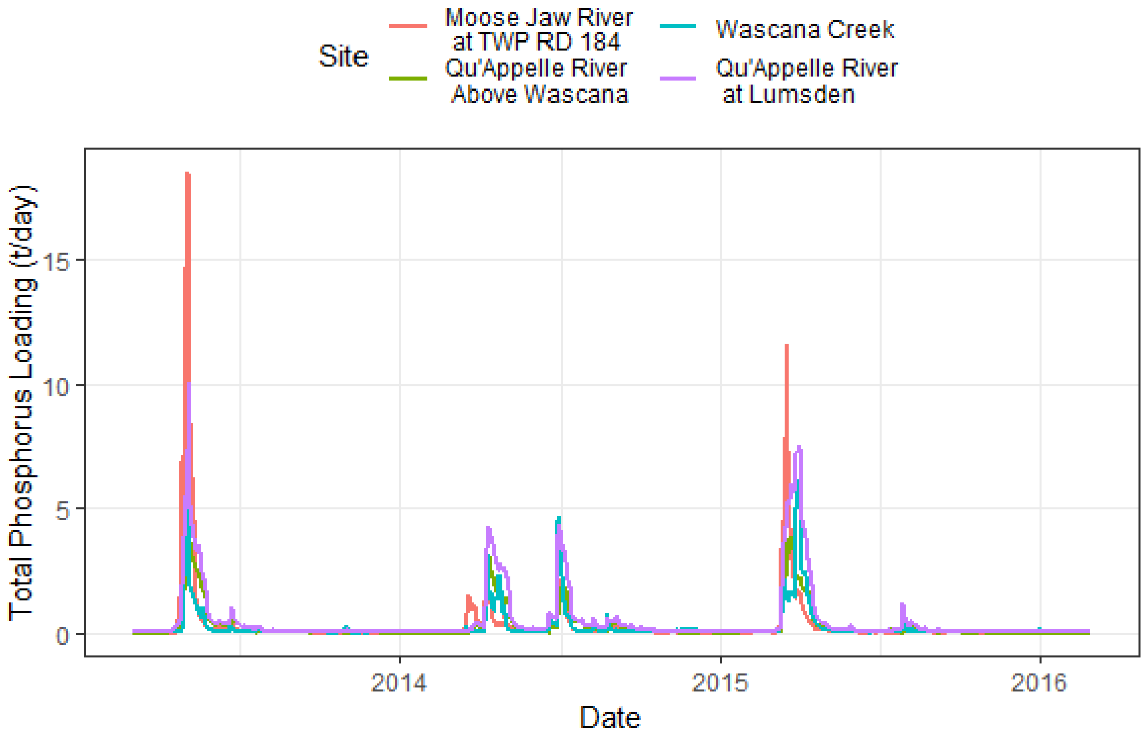


Figure 77: Total nitrogen and cumulative total nitrogen loading to and from Buffalo Pound Lake. The Qu'Appelle River at Marquis and Moose Jaw River Backflow are inflows to the lake, and Buffalo Pound outlet is the outflow. Loads were calculated using the midpoint method.



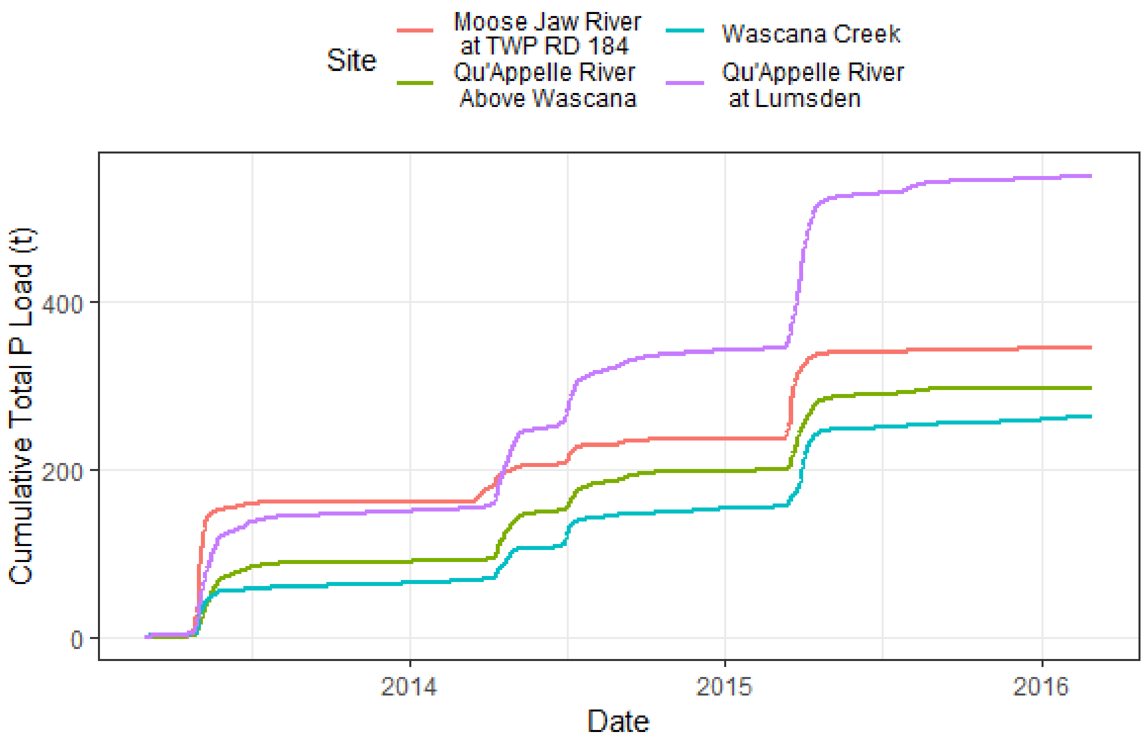
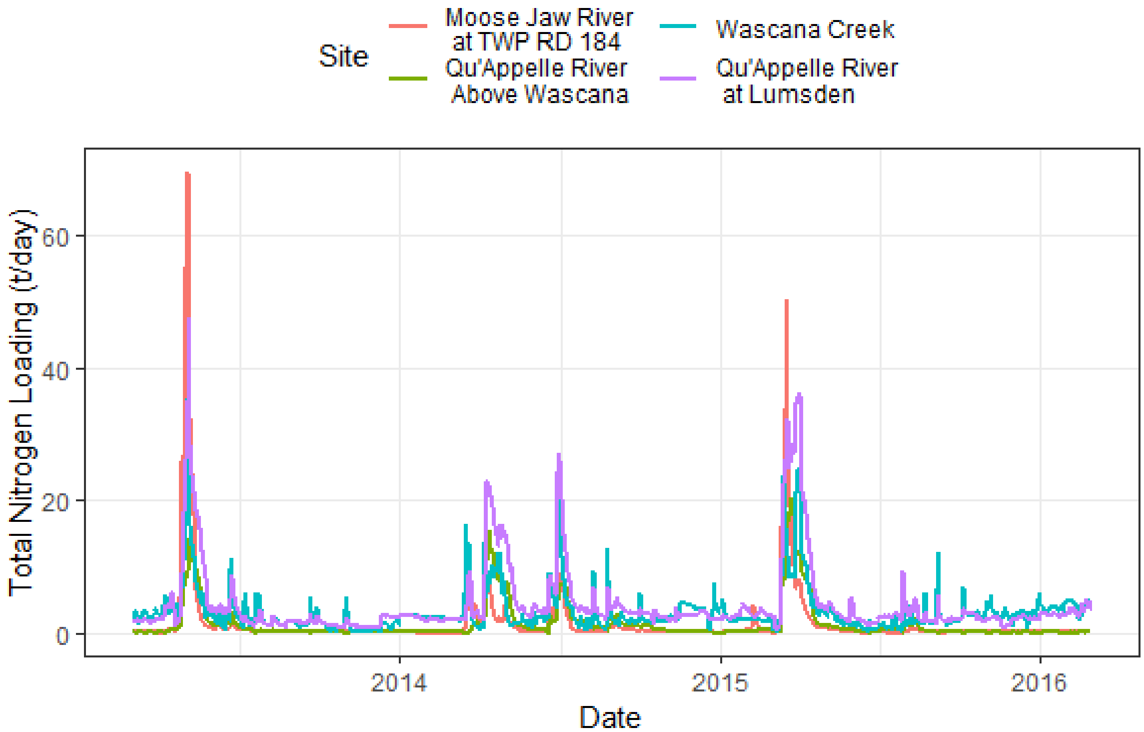


Figure 78: Total phosphorus and cumulative total phosphorus loading in the Lumsden area. Loads were calculated using the midpoint method.



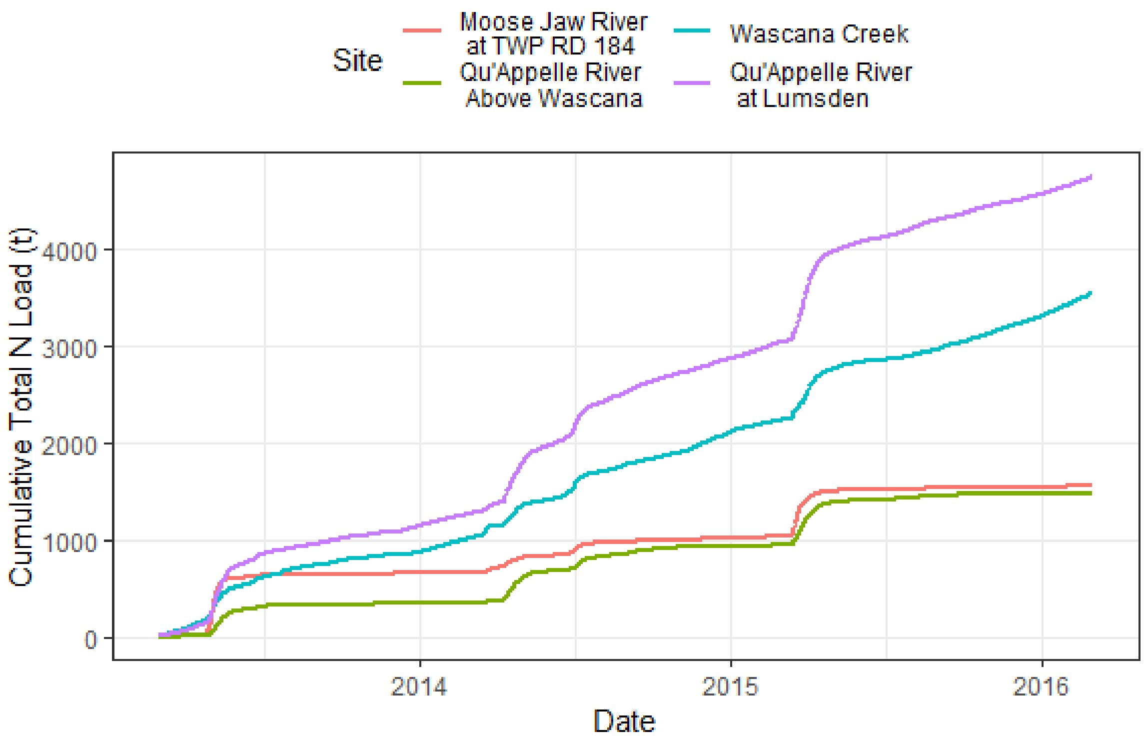
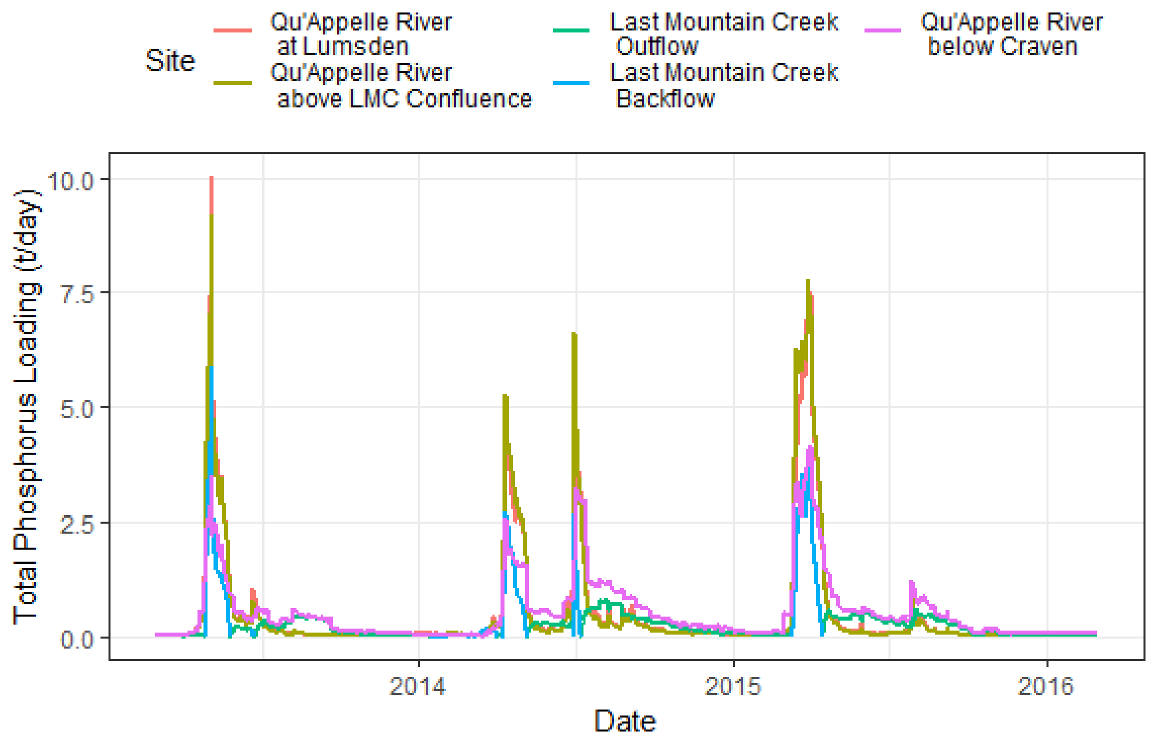


Figure 79: Total nitrogen and cumulative total nitrogen loading in the Lumsden area. Loads were calculated using the midpoint method.



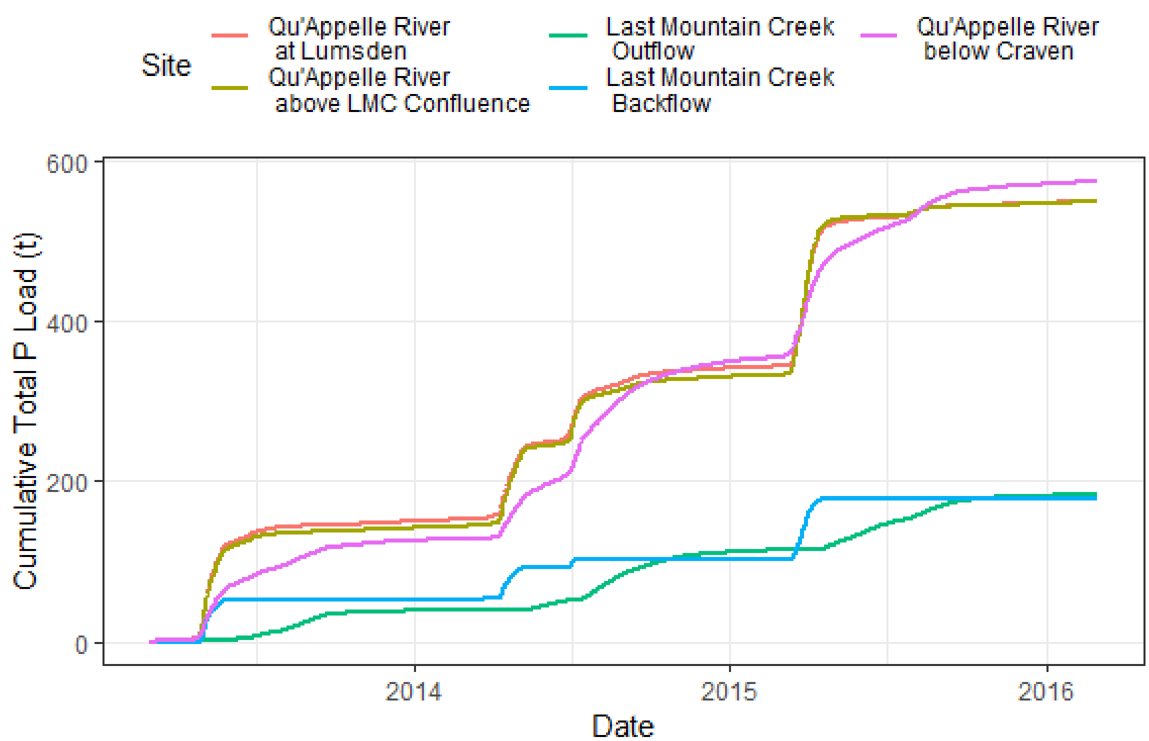


Figure 80: Total phosphorus and cumulative total phosphorus loading in the Last Mountain Lake area. Loads were calculated using the midpoint method.

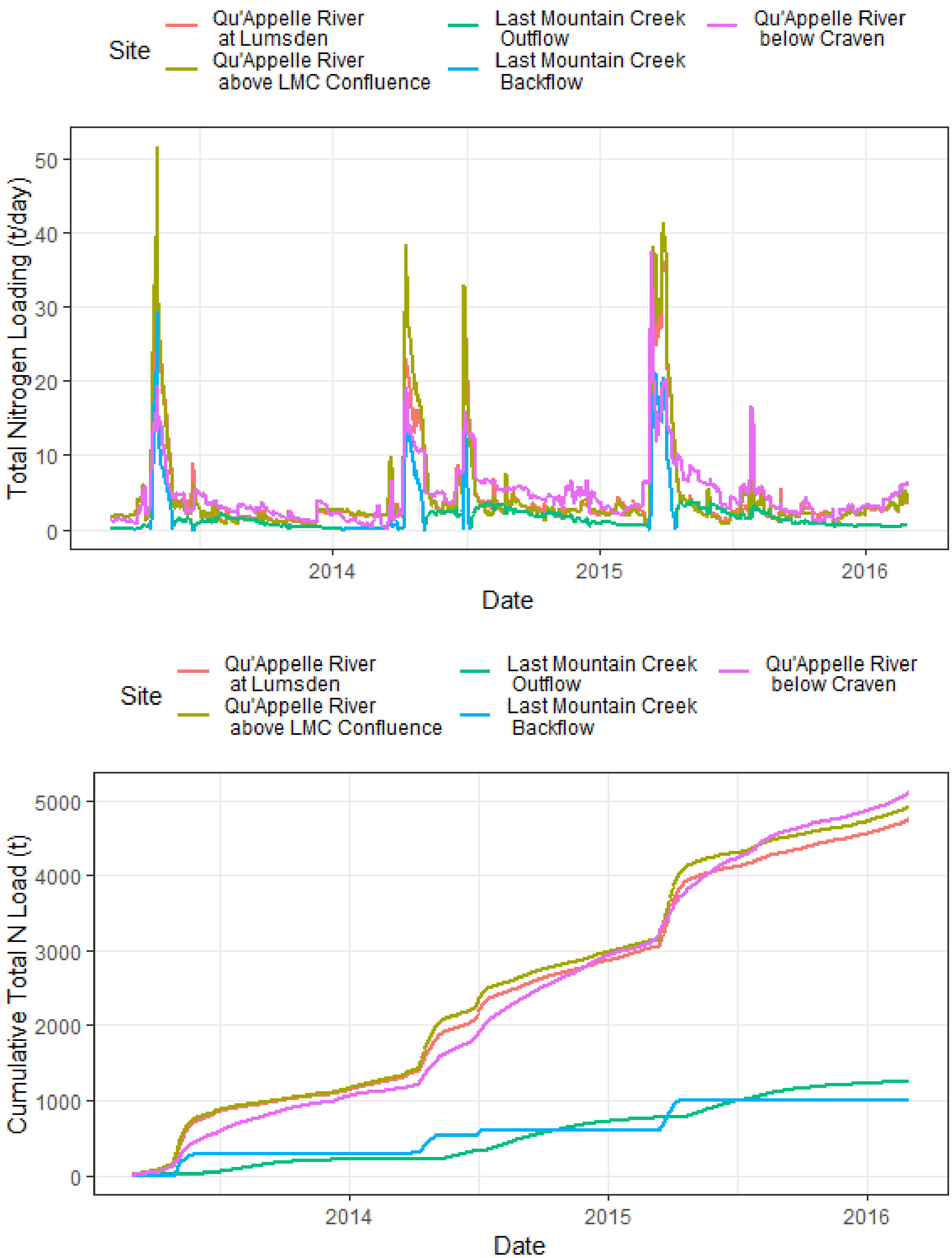
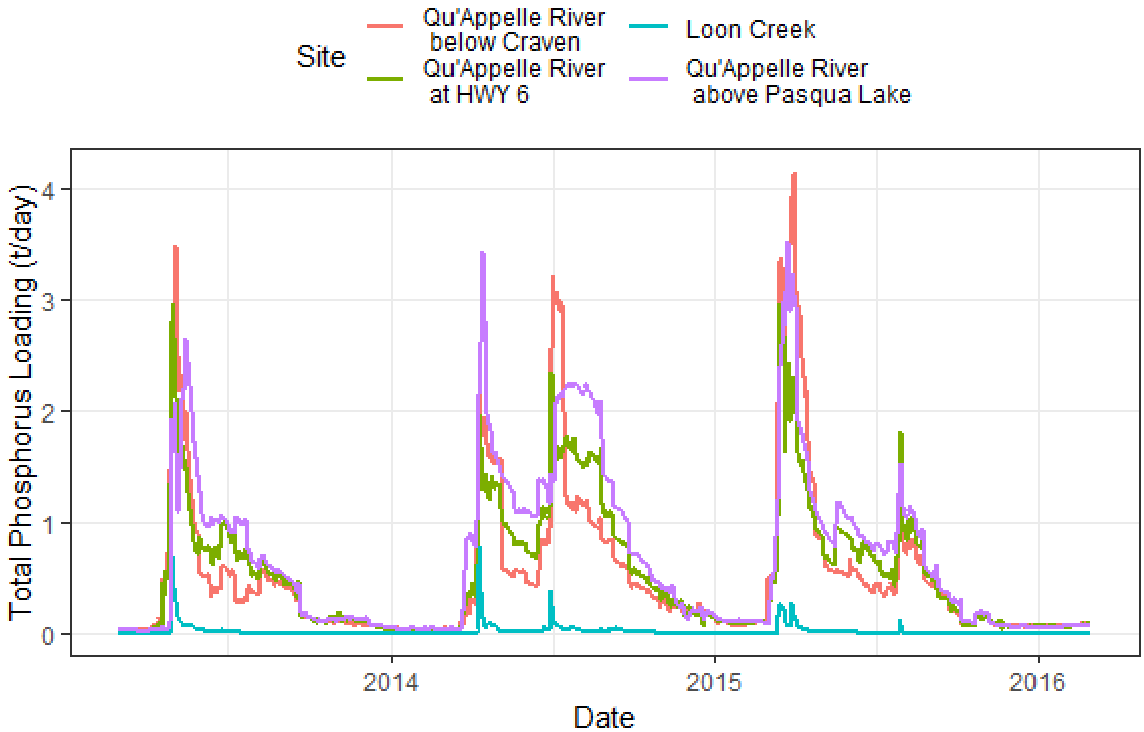


Figure 81: Total nitrogen and cumulative total nitrogen loading in the Last Mountain Lake area. Loads were calculated using the midpoint method.



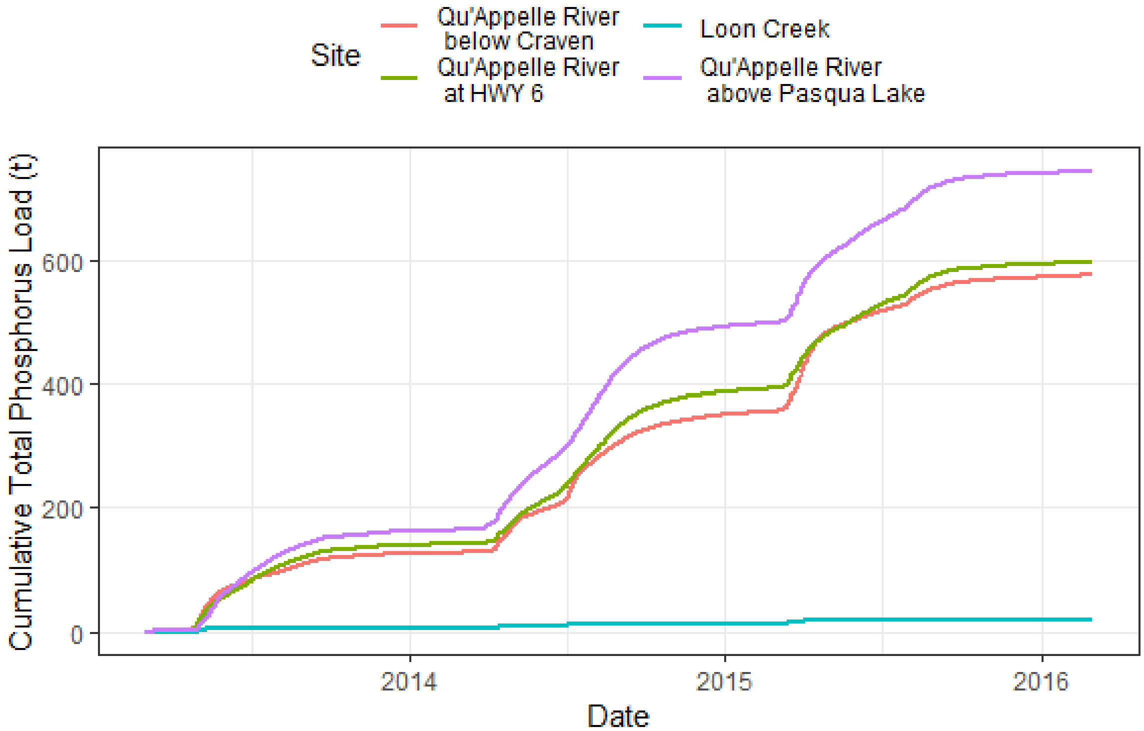


Figure 82: Total phosphorus and cumulative total phosphorus loading in the Qu'Appelle River between Craven and above Pasqua Lake. Loads were calculated using the midpoint method.

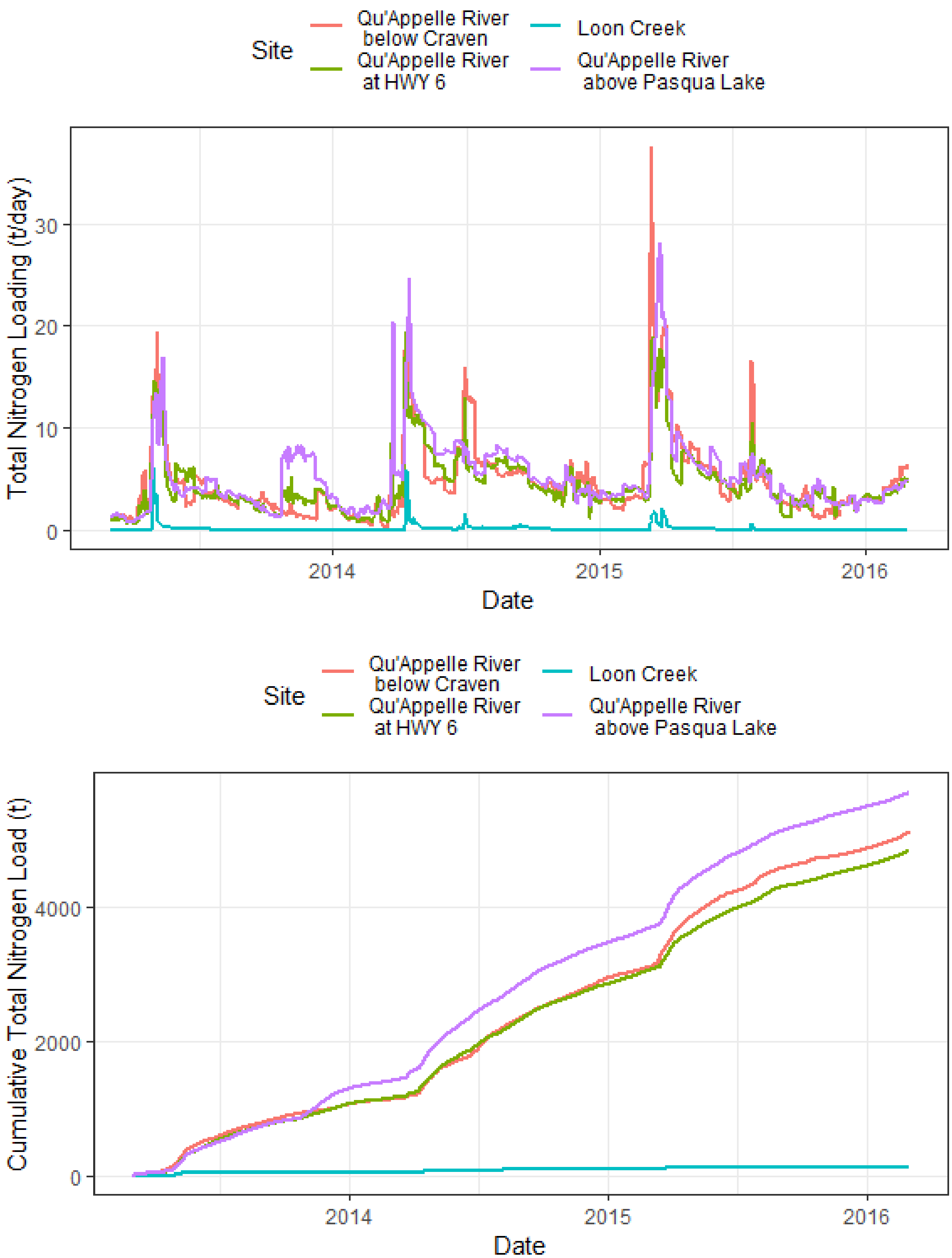


Figure 83: Total nitrogen and cumulative total nitrogen loading in the Qu'Appelle River between Craven and above Pasqua Lake. Loads were calculated using the midpoint method.

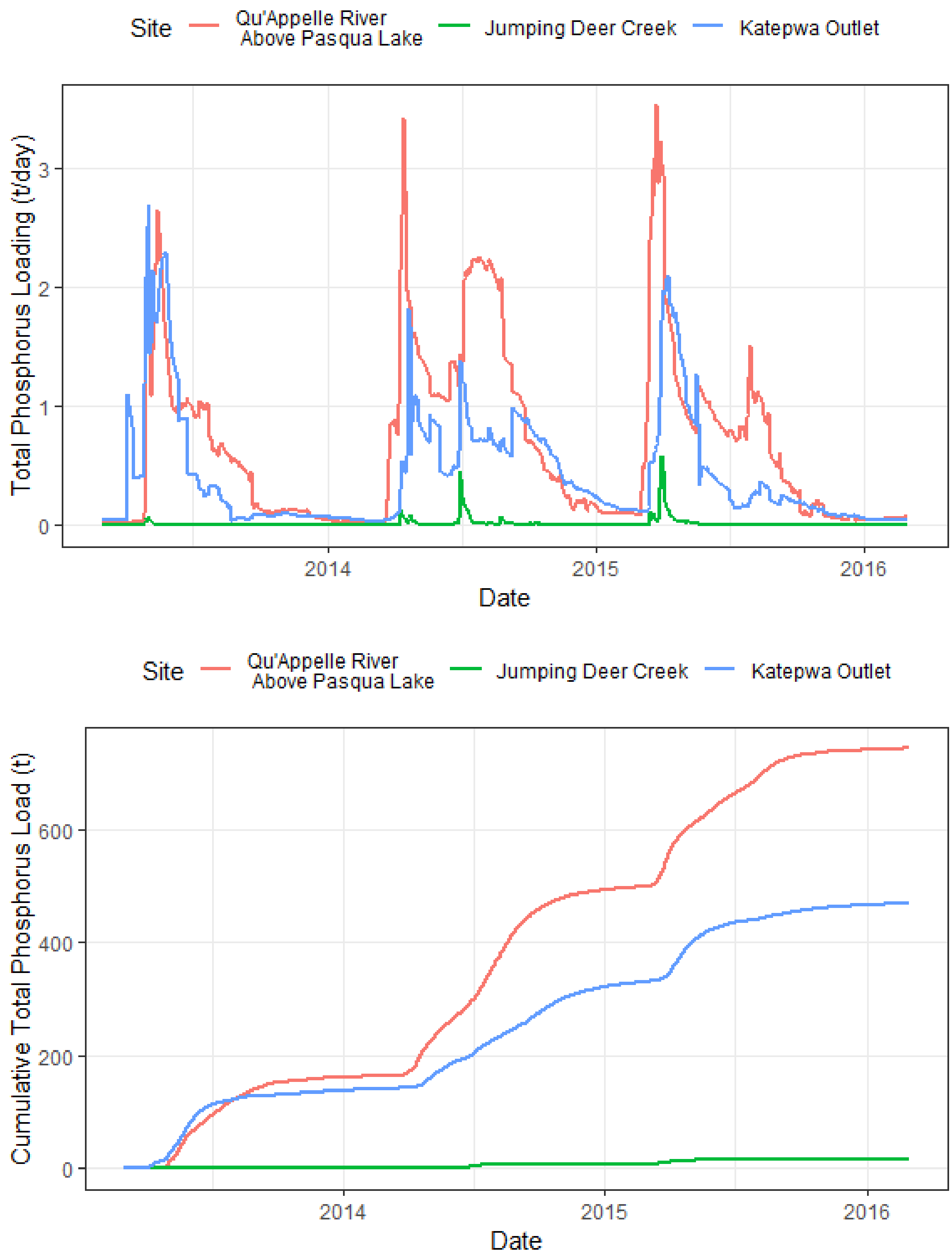
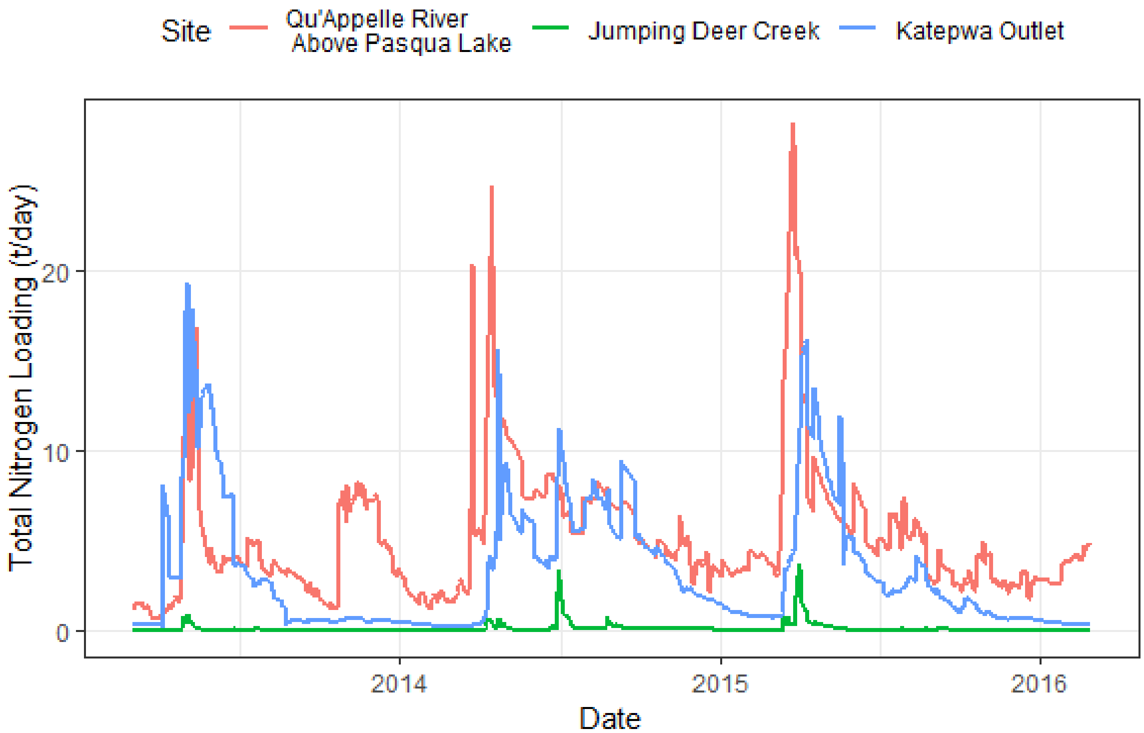


Figure 84: Total phosphorus and cumulative total phosphorus loading to and from the Calling Lakes. The Qu'Appelle River above Pasqua Lake and Jumping Deer Creeks are inflows, and Katepwa outlet is the outflow. Loads were calculated using the midpoint method.



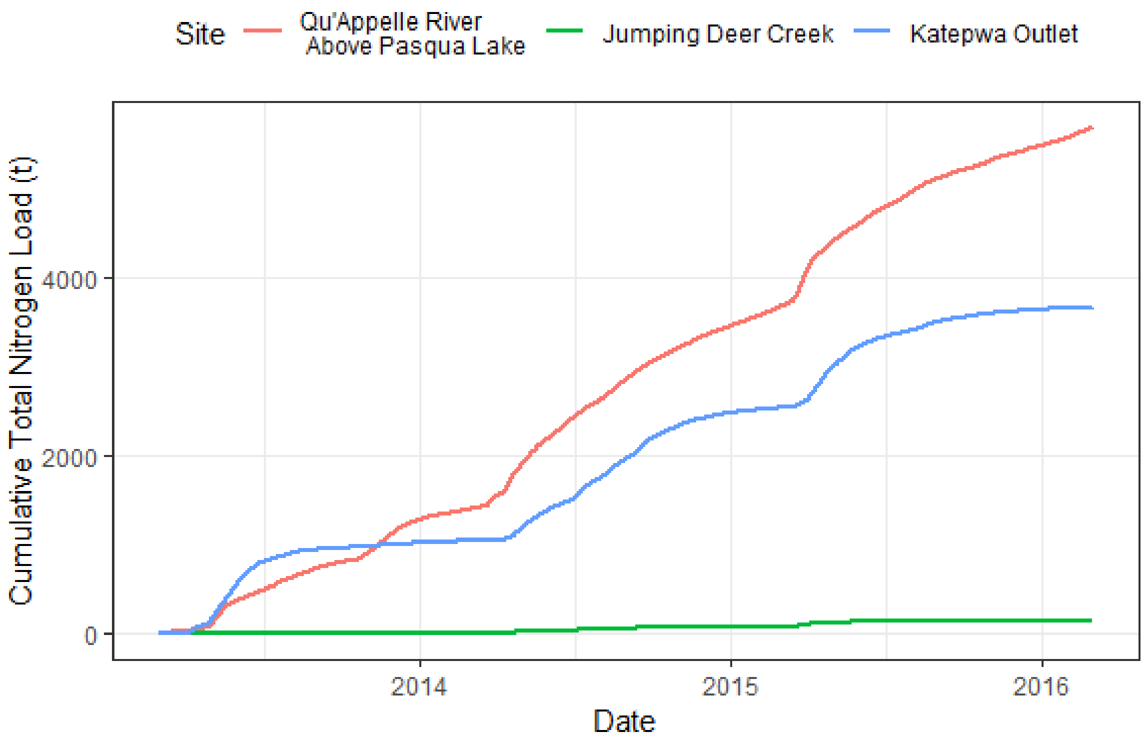


Figure 85: Total nitrogen and cumulative total nitrogen loading to and from the Calling Lakes. The Qu'Appelle River above Pasqua Lake and Jumping Deer Creeks are inflows, and Katepwa outlet is the outflow. Loads were calculated using the midpoint method.

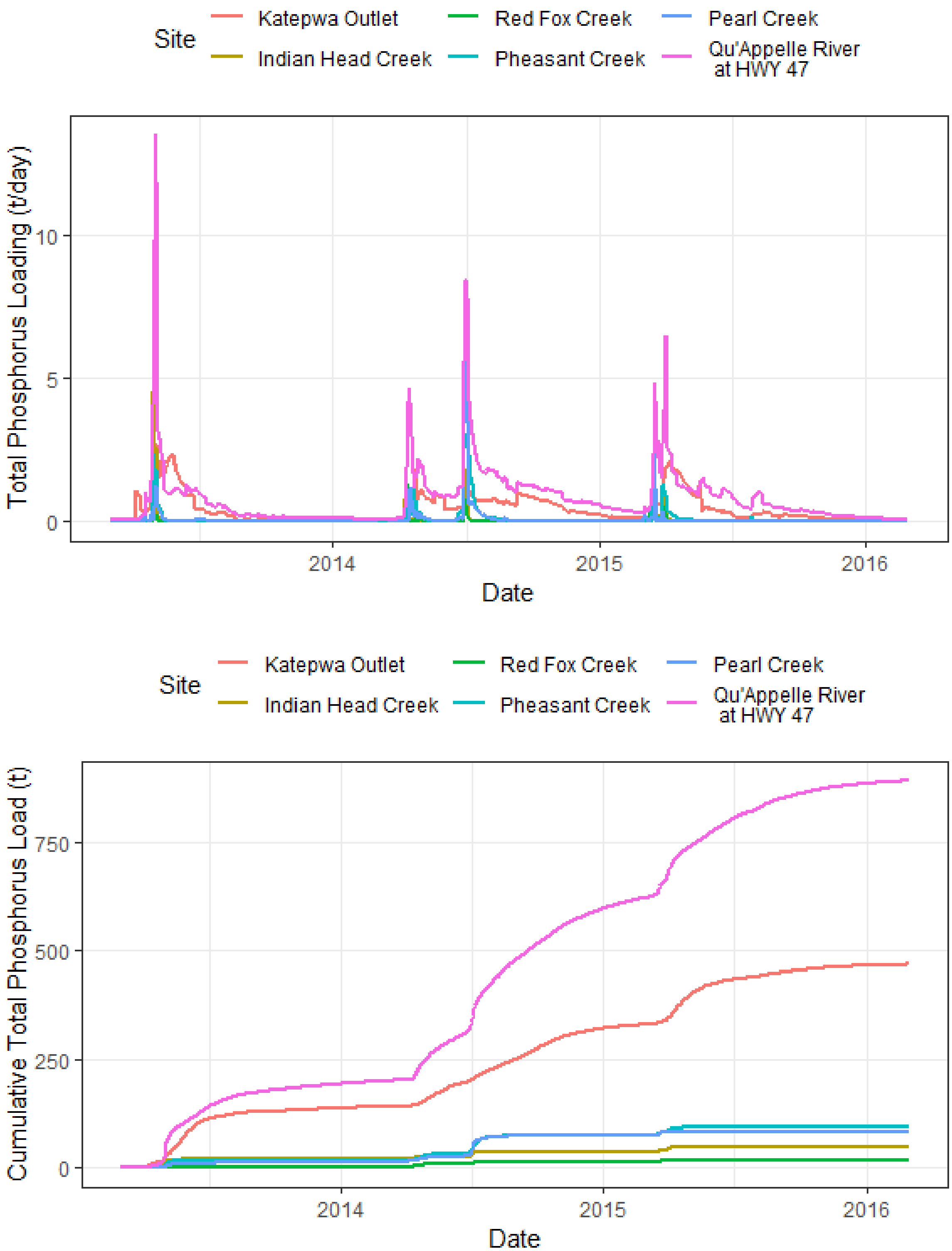


Figure 86: Total phosphorus and cumulative total phosphorus loading in the Qu'Appelle River and tributaries between Katepwa Lake and Crooked Lake. Loads were calculated using the midpoint method.

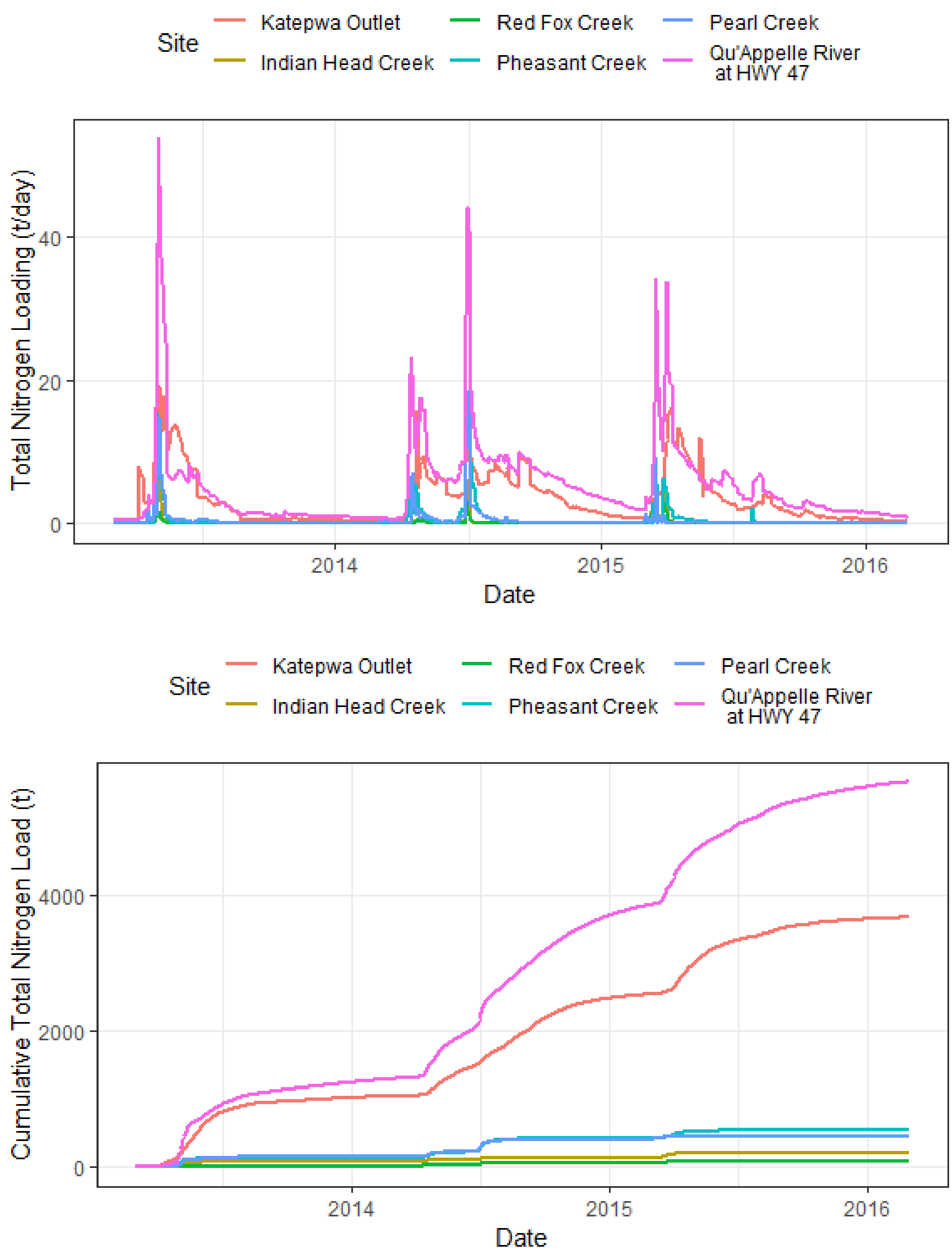


Figure 87: Total nitrogen and cumulative total nitrogen loading in the Qu'Appelle River and tributaries between Katepwa Lake and Crooked Lake. Loads were calculated using the midpoint method.

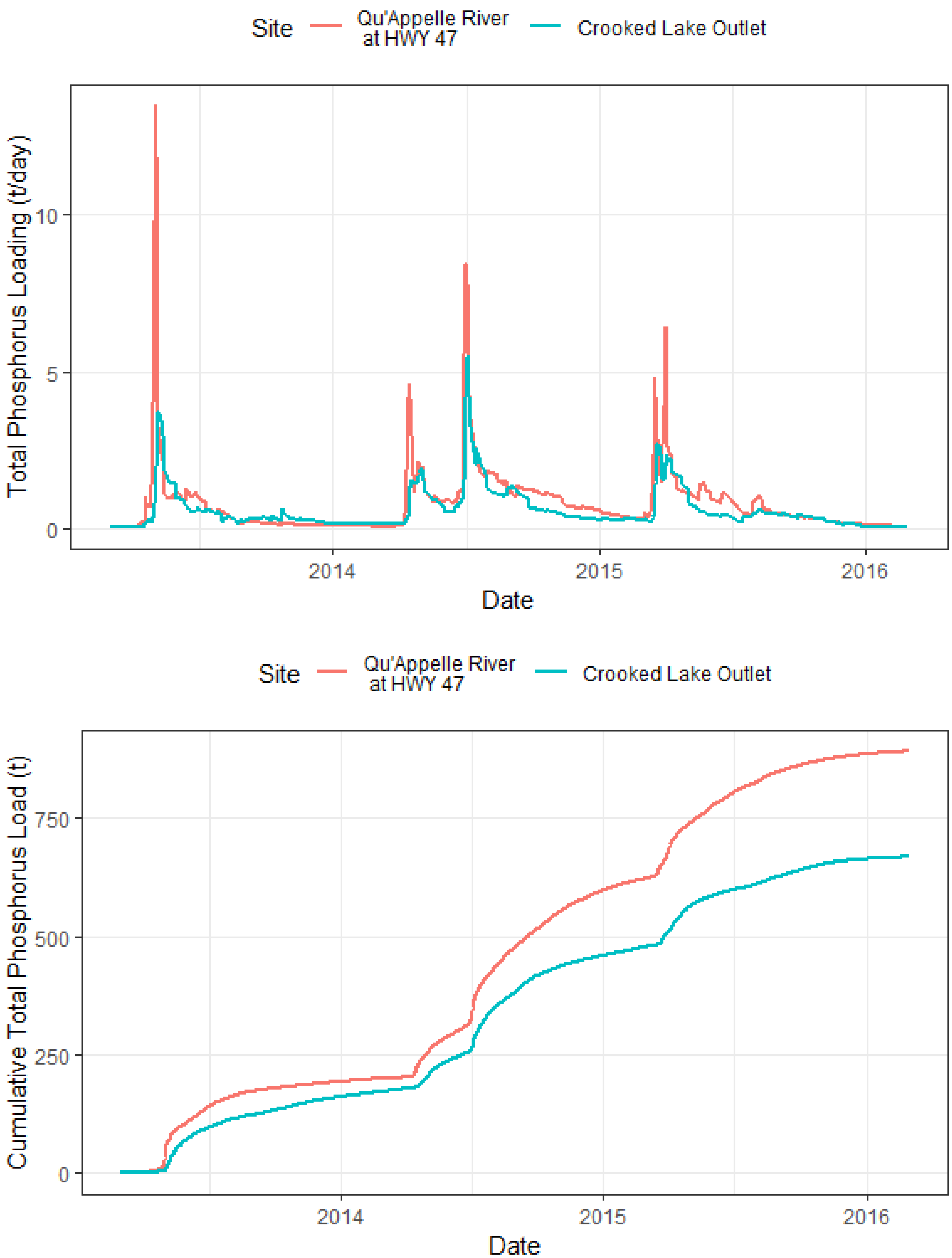


Figure 88: Total phosphorus and cumulative total phosphorus loading to and from Crooked Lake. Loads were calculated using the midpoint method.

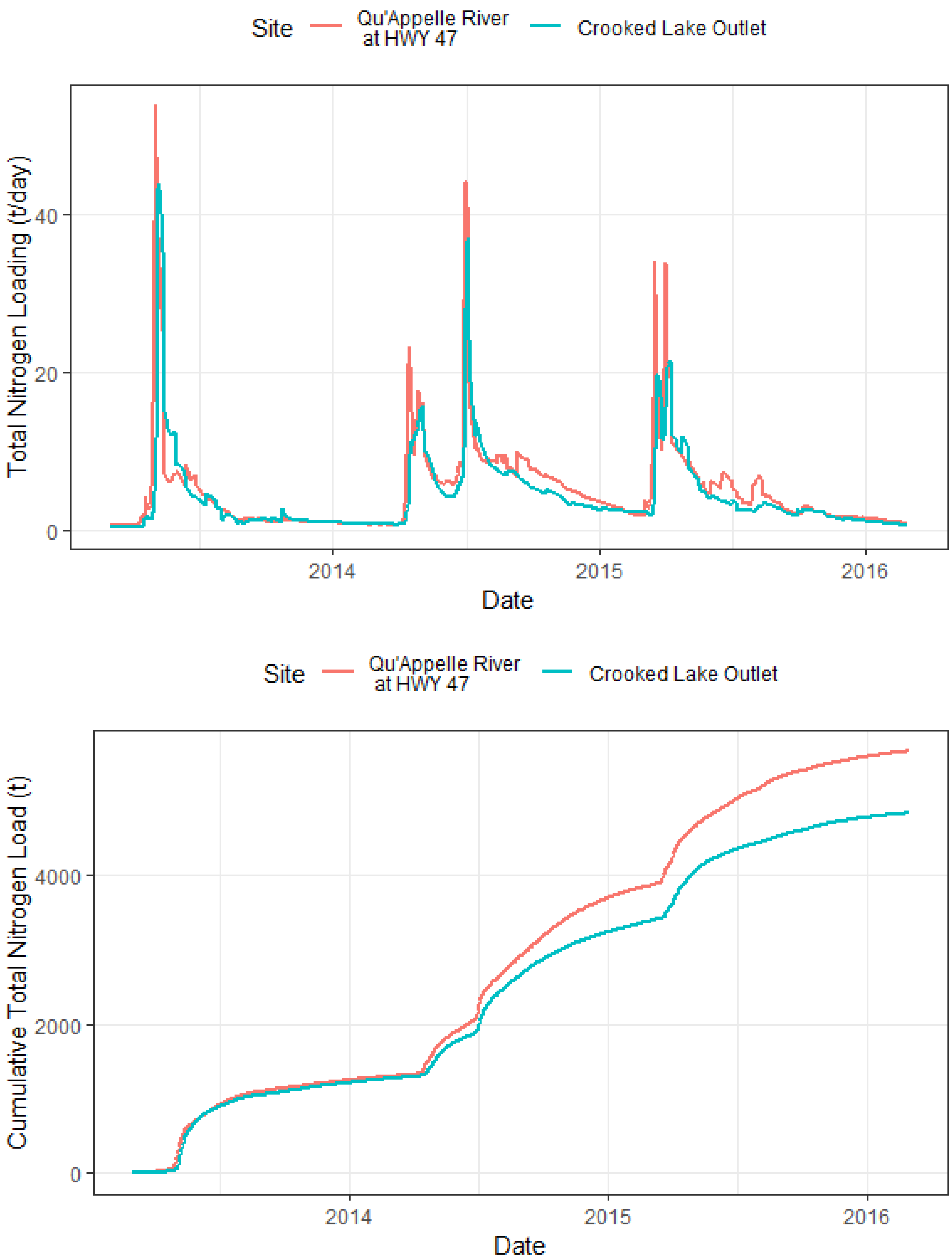


Figure 89: Total nitrogen and cumulative total nitrogen loading to and from the Crooked Lake. Loads were calculated using the midpoint method.

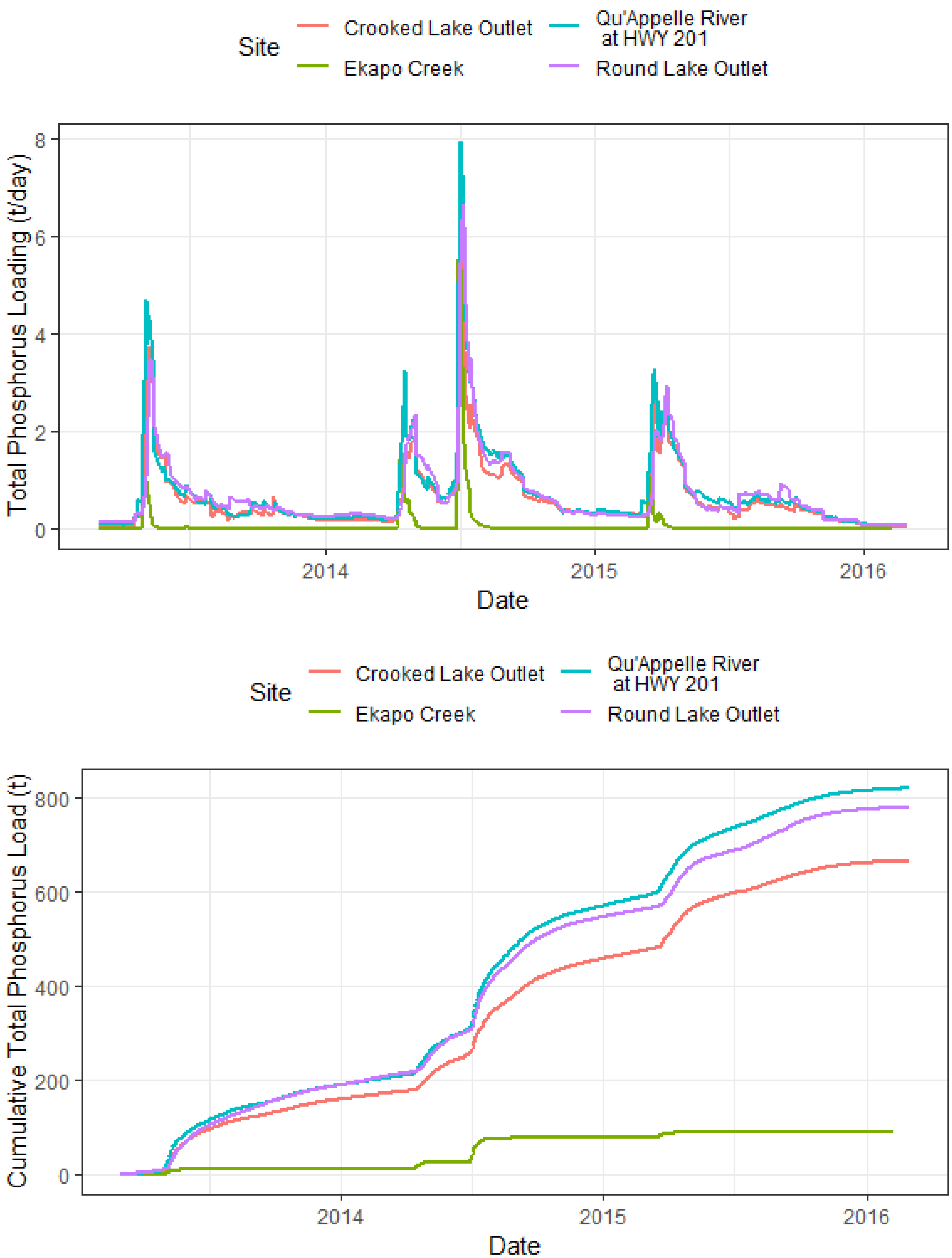
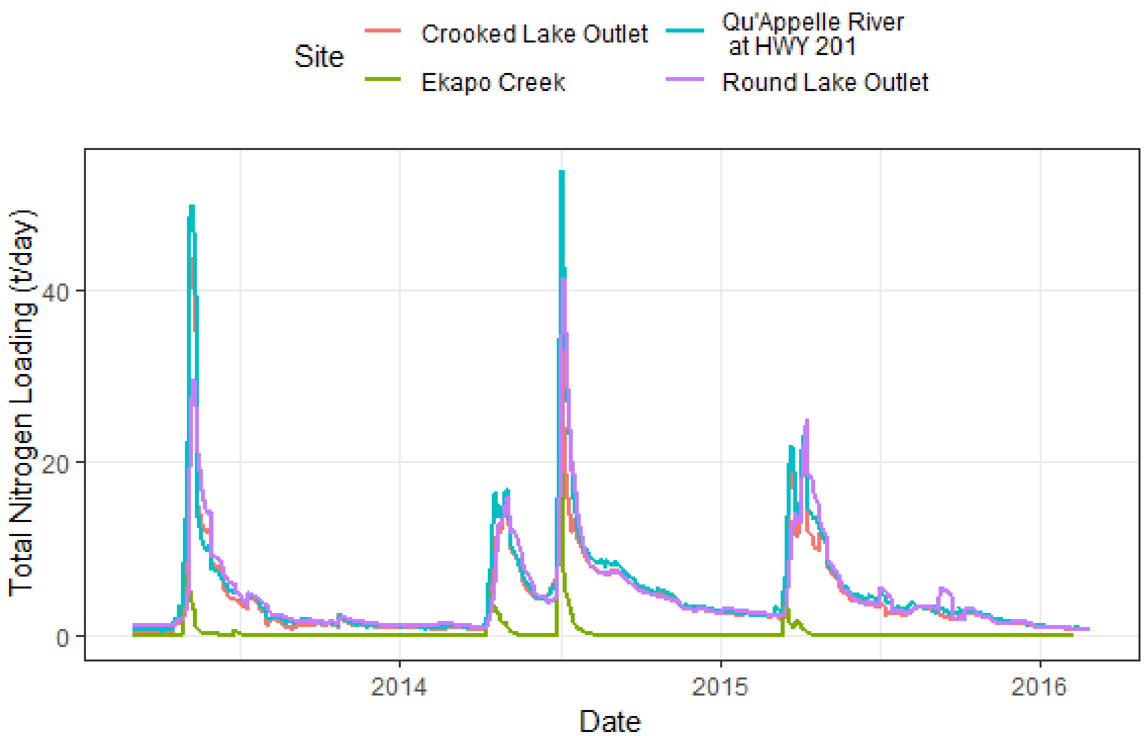


Figure 90: Total phosphorus and cumulative total phosphorus loading to and from Round Lake. Loads were calculated using the midpoint method. Note that the loading peak in spring 2013 is the result of one unusually high TP concentration measurement, not due to an increase in flows in that period.



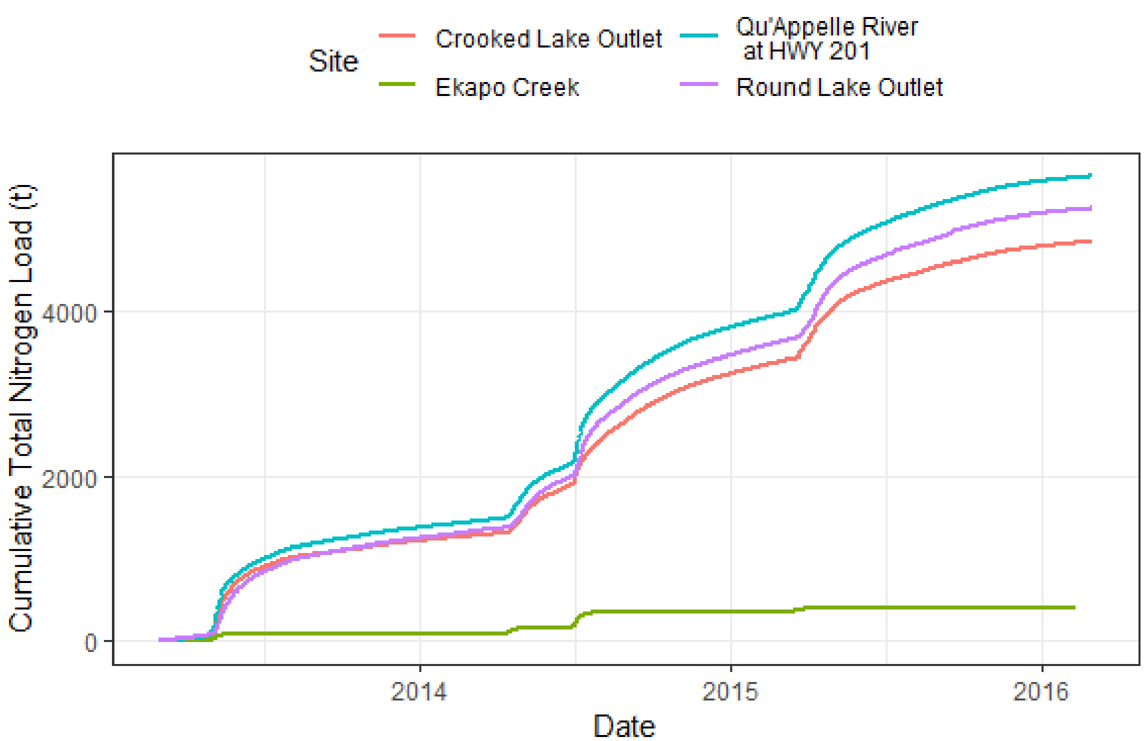


Figure 91: Total nitrogen and cumulative total nitrogen loading to and from the Round Lake. Loads were calculated using the midpoint method.

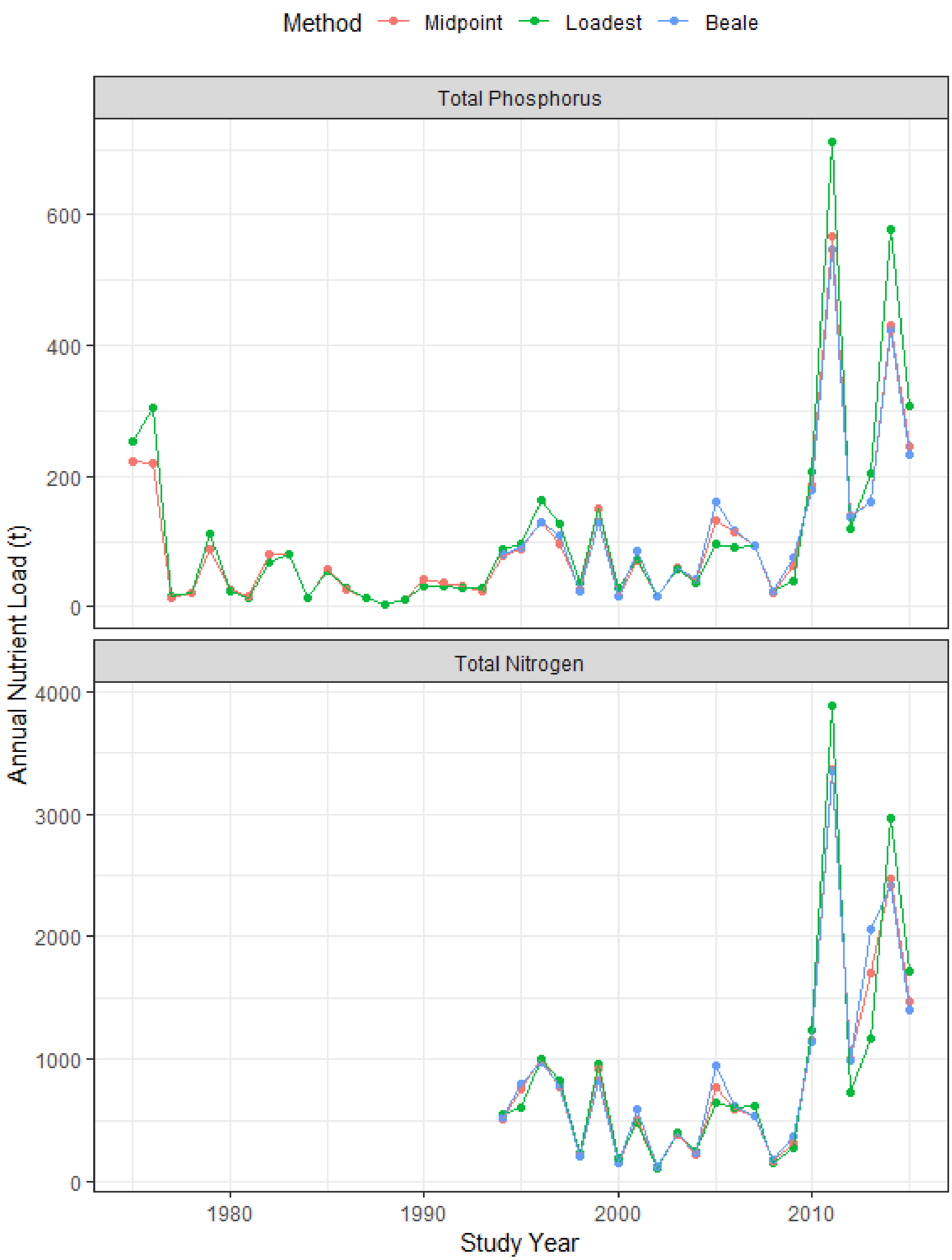


Figure 92: Annual nutrient loads for the Qu'Appelle River at Welby. Loads are calculated using monthly sampling data from the Prairie Provinces Water Board. Results from three calculation methods are presented. Loads were calculated using a year from March 01 - February 28/29 to match our study.

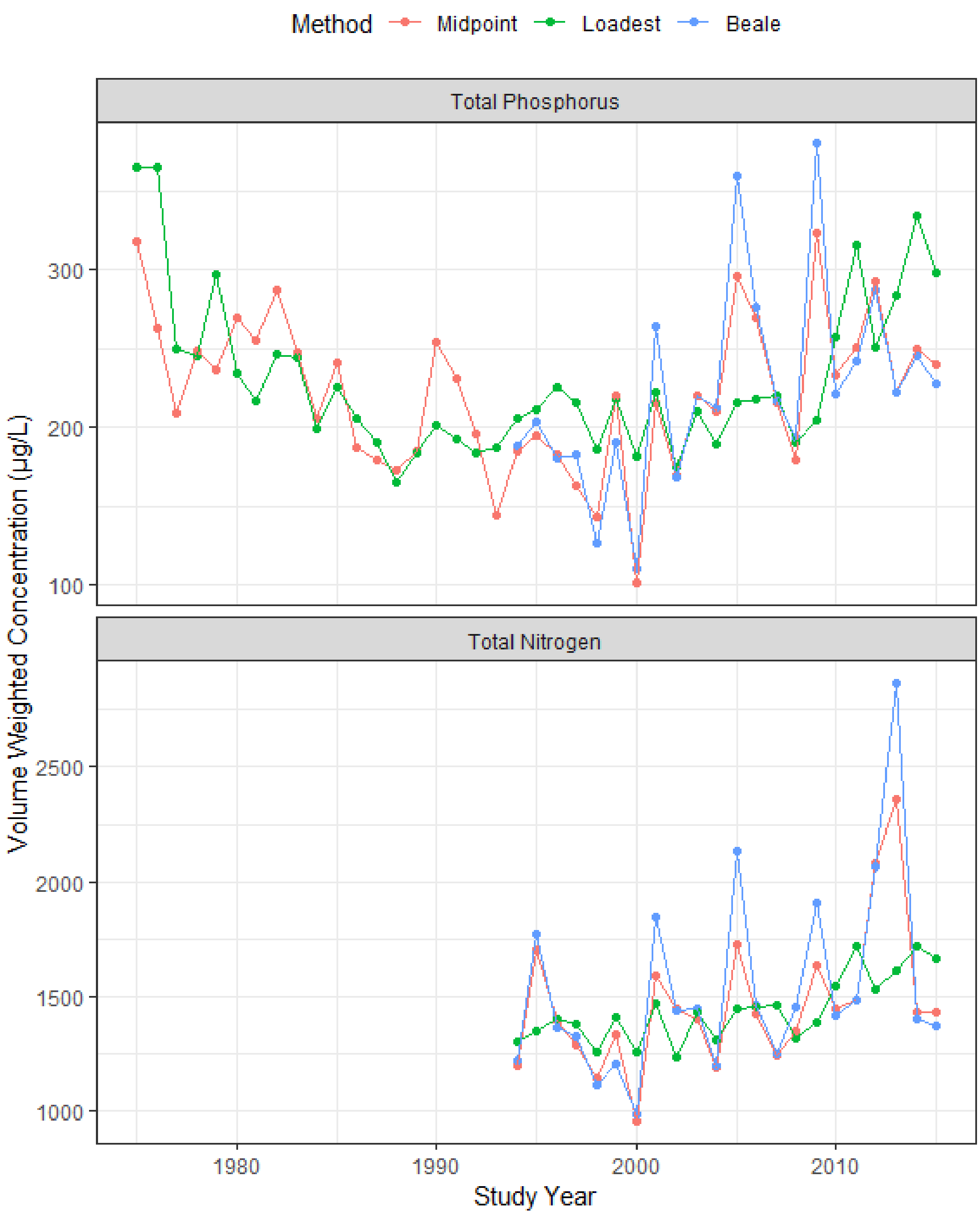


Figure 93: Volume-weighted nutrient concentrations calculated annually for the Qu'Appelle River at Welby. Volume-weighted concentrations were calculated using monthly sampling data from the Prairie Provinces Water Board. Results from three calculation methods are presented. Concentrations were calculated using a year from March 01 - February 28/29 to match our study.

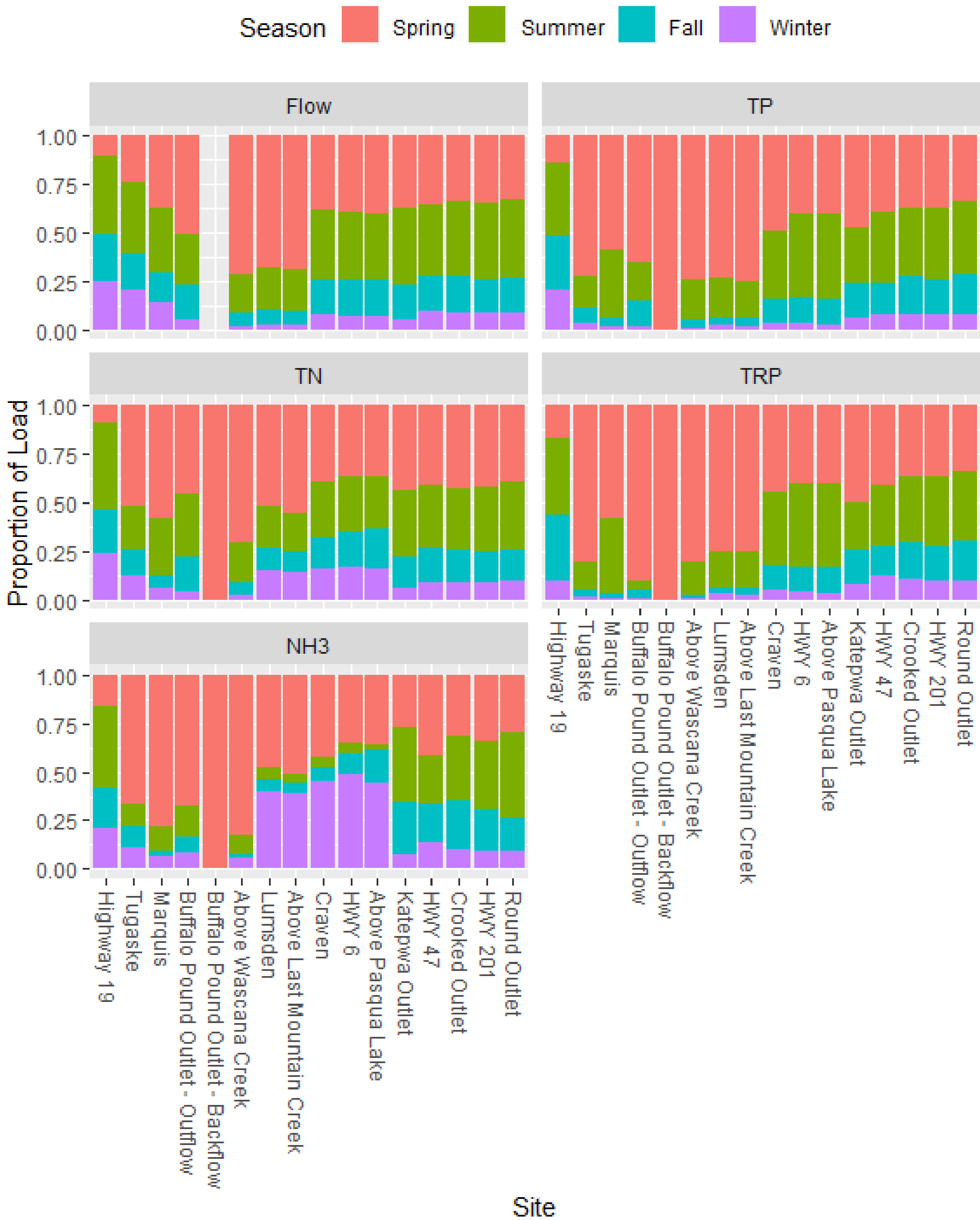


Figure 94: Proportion of total load at each mainstem site split by season. Sites are arranged along the x-axis from upstream to downstream. Buffalo Pound outlet was split into outflow and backflow periods. Seasons were divided as: Spring: March - May, Summer: June - August, Fall: September - November, Winter: December - February.

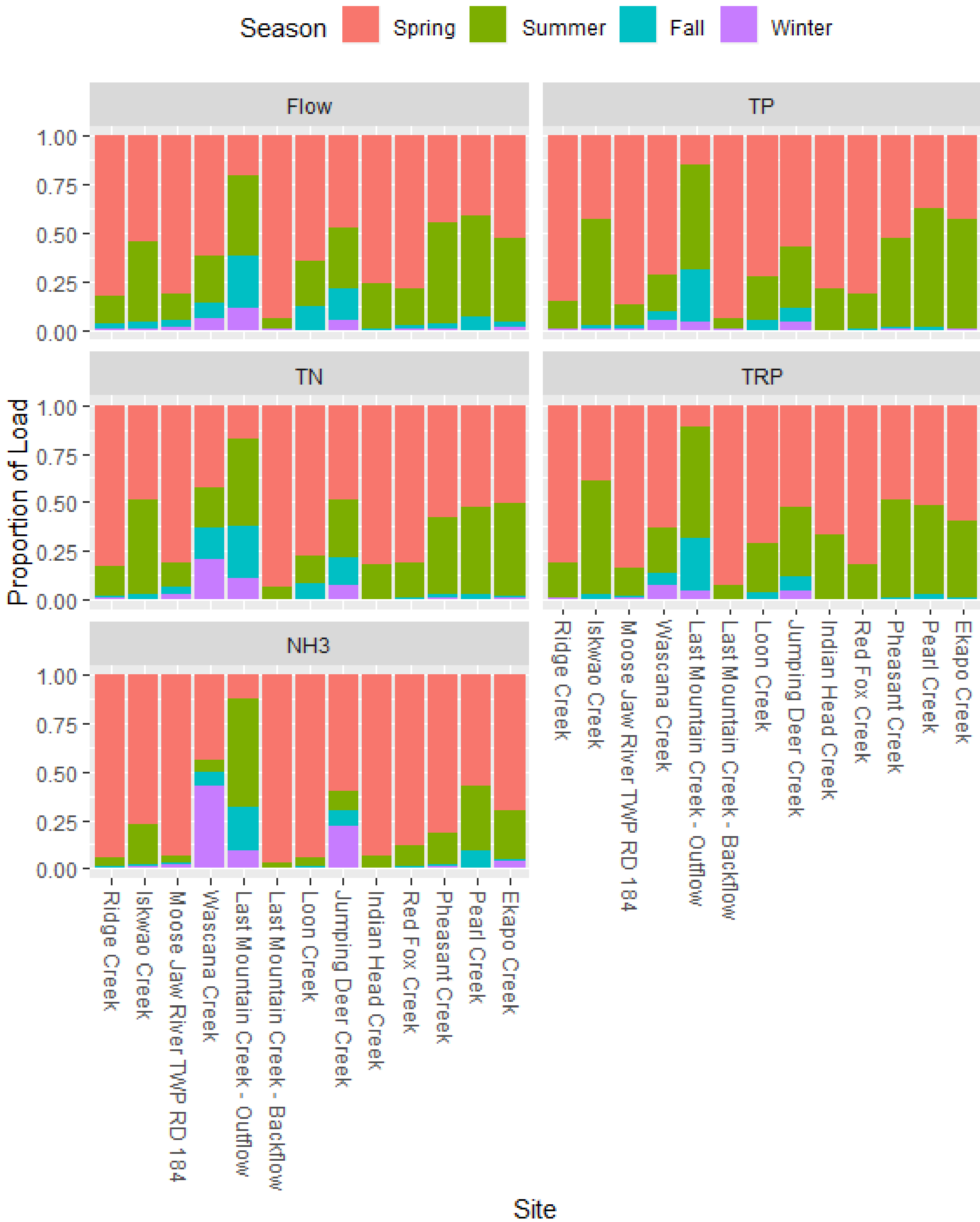


Figure 95: Proportion of total load at each tributary site split by season. Sites are arranged along the x-axis from upstream to downstream. Last Mountain Creek was split into outflow and backflow periods. Seasons were divided as: Spring: March - May, Summer: June - August, Fall: September - November, Winter: December - February.

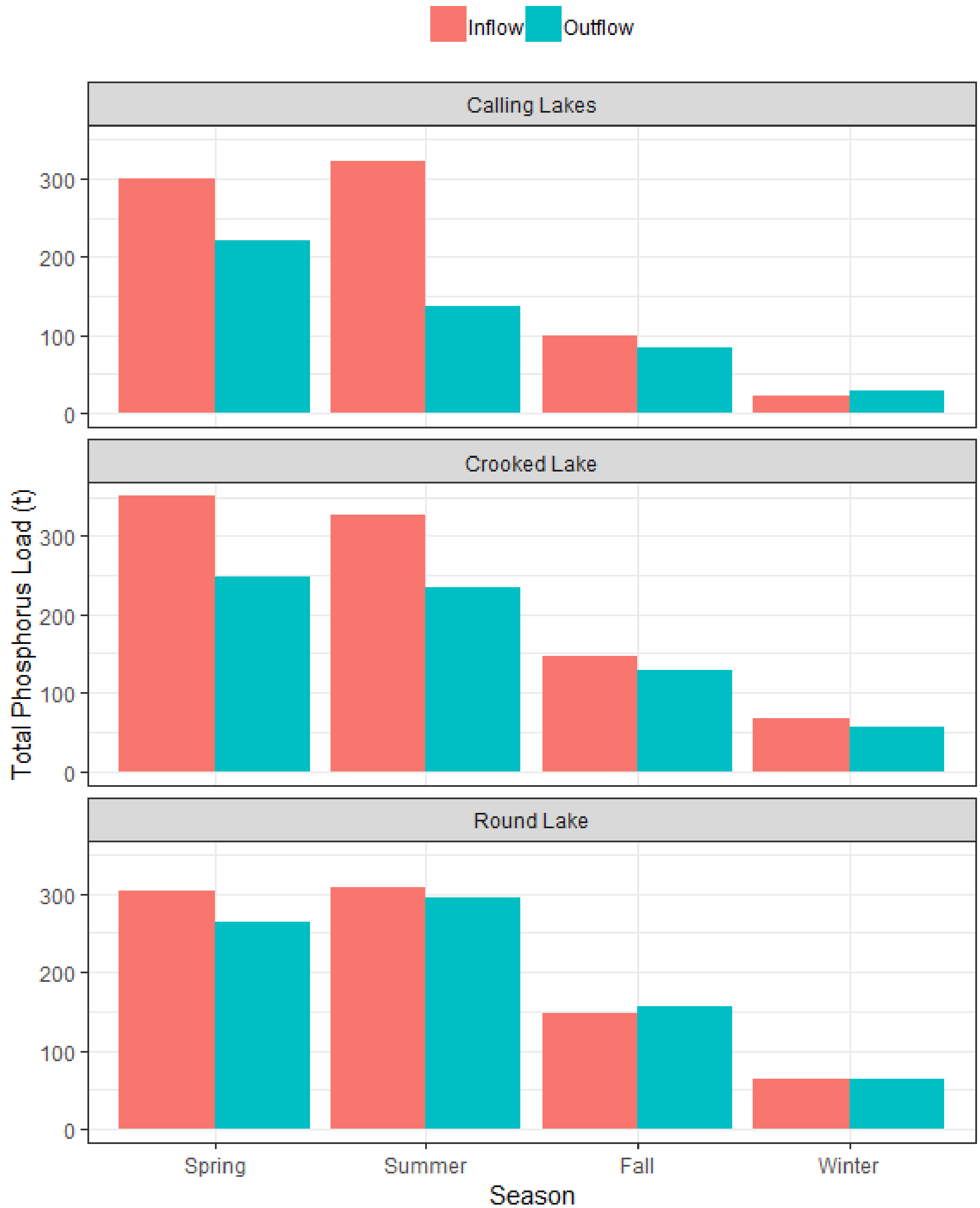


Figure 96: Total Phosphorus loading for inflows and outflows to the Calling Lakes (Pasqua, Echo, Mission, Katepwa), Crooked Lake, and Round Lake, split by season. Seasons were divided as: Spring: March - May, Summer: June - August, Fall: September - November, Winter: December - February.

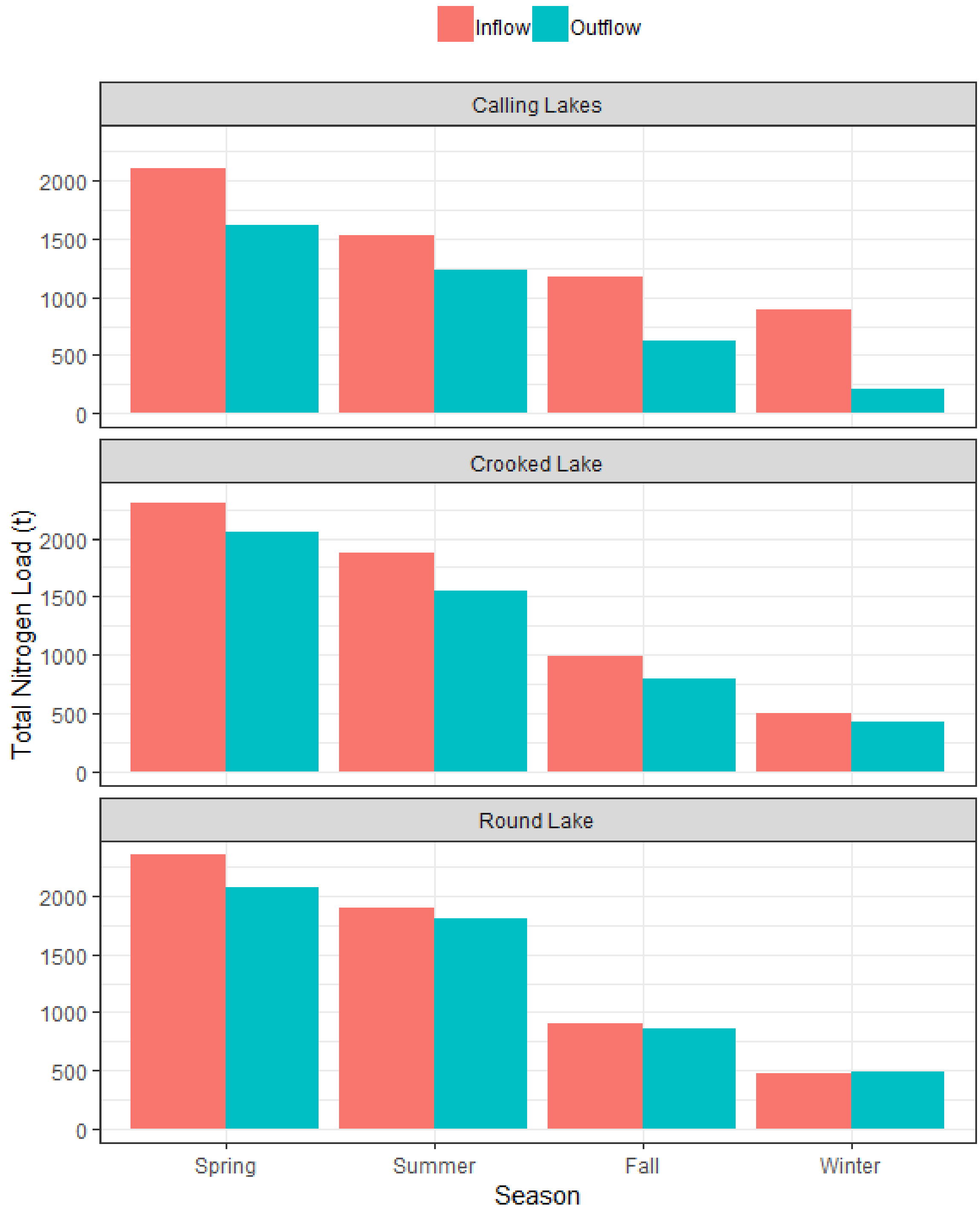


Figure 97: Total nitrogen loading for inflows and outflows to the Calling Lakes (Pasqua, Echo, Mission, Katepwa), Crooked Lake, and Round Lake, split by season. Seasons were divided as: Spring: March - May, Summer: June - August, Fall: September - November, Winter: December - February.

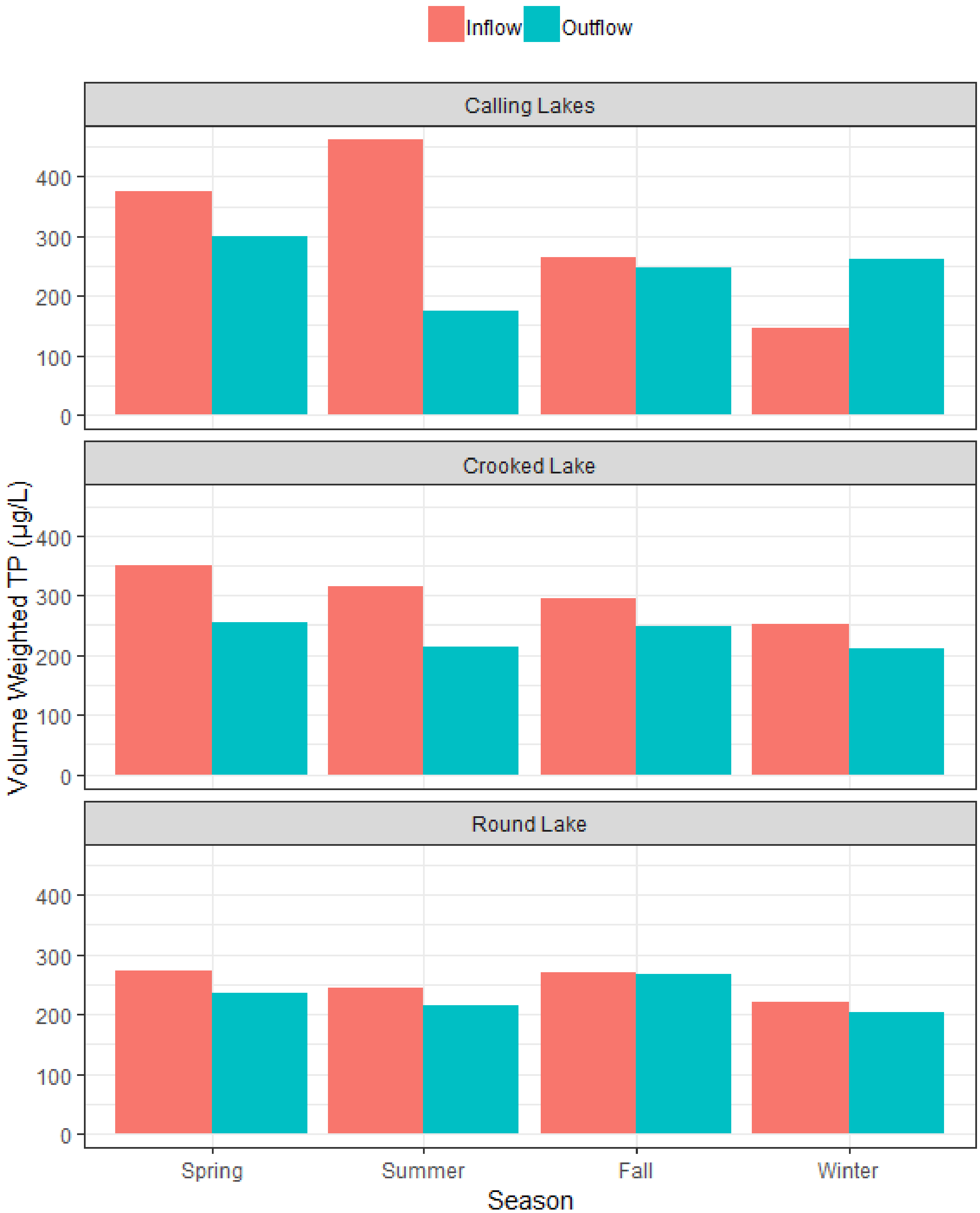


Figure 98: Volume-weighted total phosphorus concentrations in inflows and outflows to the Calling Lakes (Pasqua, Echo, Mission, Katepwa), Crooked Lake, and Round Lake, split by season. Seasons were divided as: Spring: March - May, Summer: June - August, Fall: September - November, Winter: December - February.

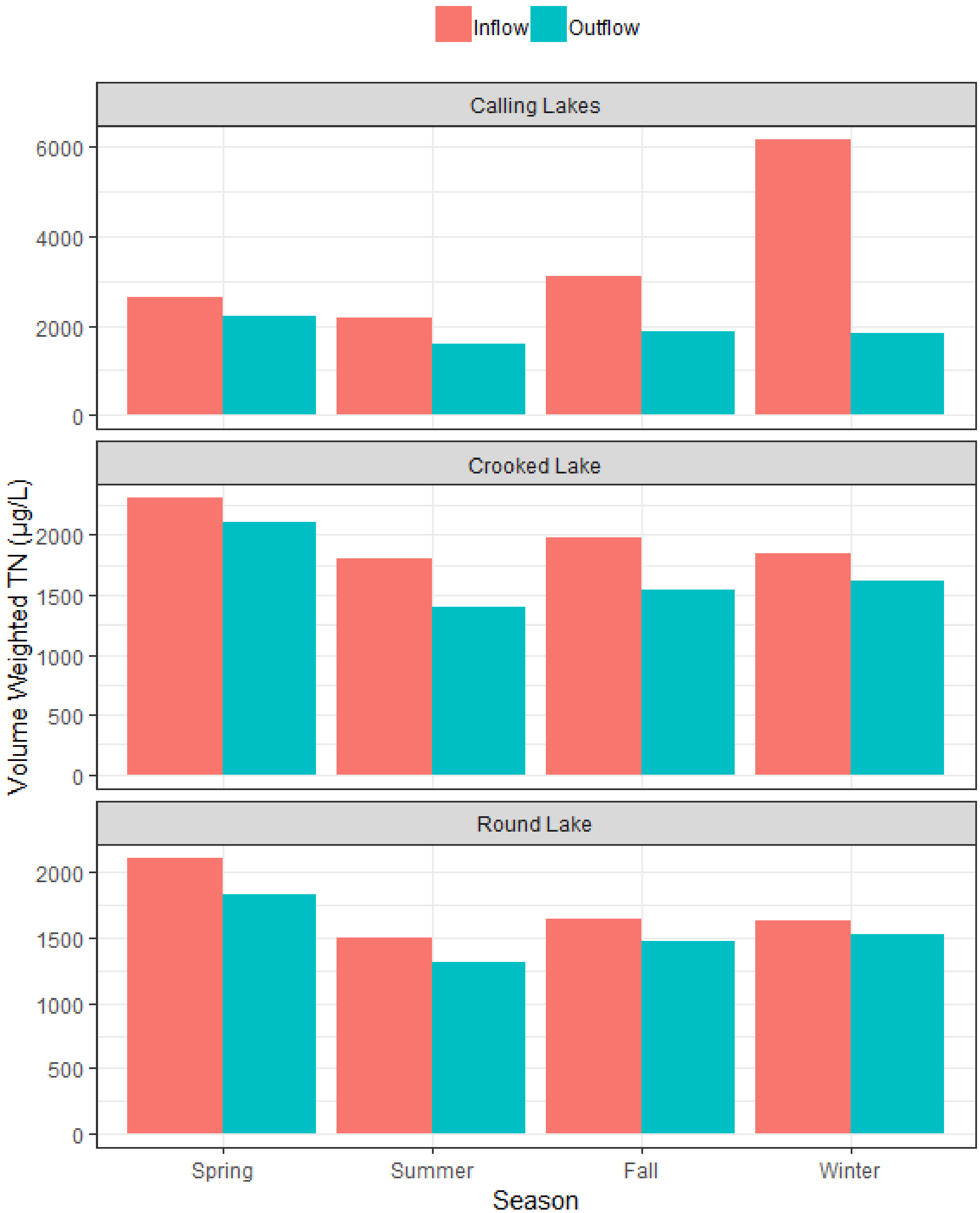


Figure 99: Volume-weighted total nitrogen concentrations in inflows and outflows to the Calling Lakes (Pasqua, Echo, Mission, Katepwa), Crooked Lake, and Round Lake, split by season. Seasons were divided as: Spring: March - May, Summer: June - August, Fall: September - November, Winter: December - February.

Tables

Table 1: Study site names, locations, and gauging station numbers where applicable. Gauging station numbers are those used by the Water Survey of Canada. * Loon Creek was sampled further upstream in 2013, at 50.8338, -104.3247

Site Name	Latitude	Longitude	Gauging Station
Qu'Appelle River at Highway 19	50.9848	-106.415	05JG006
Qu'Appelle River at Tugaske	50.9817	-106.2365	
Qu'Appelle River at Marquis	50.7673	-105.7247	
Buffalo Pound Lake outlet	50.5723	-105.3315	
Qu'Appelle River above Wascana Creek	50.6349	-104.9397	
Qu'Appelle River at Lumsden	50.6502	-104.8667	05JF001
Qu'Appelle River above Last Mountain Creek	50.6909	-104.8126	
Qu'Appelle River below Craven Dam	50.7063	-104.8	05JK002
Qu'Appelle River at Highway 6	50.8046	-104.5882	
Qu'Appelle River above Pasqua Lake	50.7875	-104.2825	05JK007
Katepwa Lake outlet	50.6604	-103.6006	
Qu'Appelle River at Highway 47	50.6421	-102.8467	
Crooked Lake outlet	50.5839	-102.6453	
Qu'Appelle River at Highway 201	50.5404	-102.5226	
Round Lake outlet	50.5255	-102.3102	
Ridge Creek	50.9503	-106.3295	05JG013
Iskwao Creek	50.9217	-106.0447	
Moose Jaw River at Highway 301	50.4003	-105.4086	05JE006
Moose Jaw River at Township Road 184	50.5576	-105.288	
Wascana Creek	50.6357	-104.9095	05JF005
Last Mountain Creek	50.7067	-104.8431	
Loon Creek *	50.8011	-104.3525	
Jumping Deer Creek	50.9199	-103.9008	05JK004
Indian Head Creek	50.6419	-103.5936	
Red Fox Creek	50.5981	-103.5656	
Pheasant Creek	50.734	-103.3291	05JL005
Pearl Creek	50.6506	-102.8507	
Ekapo Creek	50.5301	-102.7099	05JM010

Table 2: Basic hydrological measures for gauged sites in the Qu'Appelle watershed for the study years 2013-2015. Calculations were made using March 1 as the beginning of the year. * indicates sites with seasonal gauging stations, generally operating March 1 to October 31. For seasonal stations, calculations were made with the available data. It is likely that flows during the ungauged period were near zero.

Site	Year	Annual Discharge (hm3)	Peak Discharge (m3/s)	Runoff (mm)	Minimum 7-day Average Discharge (m3/s)	Days With No Flow
Highway 19	2013	74	9.3		0.041	0
Highway 19	2014	42	8.1		0.019	0
Highway 19	2015	61	8.5		0.013	0
Lumsden	2013	360	192	51.8	0.834	0
Lumsden	2014	378	83.9	54.3	1.13	0
Lumsden	2015	377	117	54.2	0.725	0
Craven	2013	401	96.4	38.6	0.258	0
Craven	2014	725	67.2	69.7	0.135	0
Craven	2015	640	67.2	61.5	4.56	0
Above Pasqua Lake	2013	424	83.3	38.2	0.948	0
Above Pasqua Lake	2014	863	69	77.7	1.14	0
Above Pasqua Lake	2015	733	89.5	66	3.98	0
Welby	2013	721	146	42.2	3.11	0
Welby	2014	1725	454	100.9	3.03	0
Welby	2015	1029	114	60.2	7.98	0
Ridge Creek*	2013	4	10.6	22.7	0	3
Ridge Creek*	2014	13	21.5	70.1	0.003	0
Ridge Creek*	2015	11	11.7	56.8	0.001	0

Site	Year	Annual Discharge (hm3)	Peak Discharge (m3/s)	Runoff (mm)	Minimum 7-day Average Discharge (m3/s)	Days With No Flow
Moose Jaw River	2013	236	203	67.9	0.004	0
Moose Jaw River	2014	132	38.1	38.1	0.005	0
Moose Jaw River	2015	169	126	48.7	0	14
Wascana Creek	2013	115	65.6	66.1	0.052	0
Wascana Creek	2014	118	57	67.9	0.229	0
Wascana Creek	2015	140	48.8	80.3	0.182	0
Jumping Deer Creek*	2013	5	2.7	28.2	0	97
Jumping Deer Creek*	2014	26	15	150.8	0	38
Jumping Deer Creek*	2015	23	12.2	136.6	0	10
Pheasant Creek*	2013	19	22.2	56.2	0.001	0
Pheasant Creek*	2014	93	67.9	269	0	9
Pheasant Creek*	2015	30	15.9	86.7	0	29
Ekapo Creek*	2013	35	25.7	79	0	42
Ekapo Creek*	2014	96	61.1	218.7	0	26
Ekapo Creek*	2015	24	14.9	53.6	0.03	0

Table 3: Basic hydrological variables for gauging stations in the Qu'Appelle watershed. For stations with gauges with year-round operation, only years with complete annual records were used. Calculations were made using March 1 as the beginning of the year. * indicates sites with seasonal gauging stations, generally operating March 1 to October 31. For seasonal stations, calculations were made with the available data. It is likely that flows during the ungauged period were near zero.

Site	Gross Drainage Area (km2)	Effective Drainage Area (km2)	Years of Record	Mean Annual Discharge (hm3)	Mean Peak Discharge (m3/s)	Mean Runoff (mm)	7Q10 (m3/s)	Mean Days with no Flow
Highway 19			1959-2015	78	7.3		0	33.3
Lumsden	17500	6950	1968-2015	230	74.5	33.2	0.342	0
Craven	32900	10400	1955-2015	205	31.3	19.7	0.025	0.3
Above Pasqua Lake	36500	11100	1970-2015	247	36.2	22.2	0.083	0.1
Welby	50900	17100	1975-2015	411	70.2	24	0.077	3
Ridge Creek*	460	188	1970-2015	5	7.9	25.6	0	39.9
Moose Jaw River	9230	3470	1973-2015	90	55.2	25.8	0	24.1
Wascana Creek	3850	1740	1973-2015	78	33.5	45.1	0.024	0
Jumping Deer Creek*	1680	170	1941-2015	3	3.1	18.6	0	81.4
Pheasant Creek*	1150	345	1947-2015	11	11.1	32.1	0	117.2
Ekapo Creek*	1100	441	1969-2015	18	12.4	40.2	0	52.9

Table 4: Total nutrient loading at Qu'Appelle River and tributary sites from March 1, 2013 to February 29, 2016. Loads were calculated using the midpoint method. For Last Mountain Creek, a negative load indicates net loading towards Last Mountain Lake, rather than towards the Qu'Appelle River.

Site	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 + NO2 Load (t)	NH3 Load (t)	TSS Load (t)	Discharge
Highway 19	2.6	99	0.6	30	3.1	798	177
Ridge Creek	13.3	69	7.3	8	6.1	1738	28
Tugaske	23.5	205	10.2	32	13.1	7601	219
Iskwao Creek	23.8	95	19.3	6	5	221	39
Marquis	83	460	43.7	48	23.4	29087	304
Buffalo Pound outlet	-0.3	152	-1.6	-5	-3	-4835	163
Buffalo Pound outlet - Outflow	23.3	263	8.7	15	8	3529	208
Buffalo Pound outlet - Backflow	23.6	110	10.3	21	11	8364	45
Moose Jaw River at Highway 301	282.1	1310	155	279	94.2	88000	537
Moose Jaw River at TWP RD 184	343.4	1547	126.1	255	112	111627	551
Above Wascana Creek	296.5	1472	152	177	66.7	96887	744
Wascana Creek	262.9	3541	115	1126	1610	112345	373
Lumsden	550.4	4745	267.6	1289	1424	211579	1114
Above Last Mountain Creek	549.6	4912	269.5	1269	1413	227453	1181
Last Mountain Creek	5.8	250	25.5	-188	-166	-49993	584
Last Mountain Creek - Outflow	182.8	1252	112.1	10	35.7	20335	915
Last Mountain Creek - Backflow	177	1002	86.6	198	201.7	70328	331
Craven	575.3	5110	288.8	990	1274	171822	1765

Site	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 + NO2 Load (t)	NH3 Load (t)	TSS Load (t)	Discharge
Highway 6	596.6	4825	311.4	855	1116	220021	1824
Loon Creek	18.3	121	12.5	31	15.4	2014	38
Above Pasqua Lake	742.9	5699	382.4	1030	1345	244564	2019
Jumping Deer Creek	15.4	147	9.8	9	12.5	1670	74
Katepwa outlet	468.6	3675	322.8	724	333.7	20750	1961
Indian Head Creek	47.5	206	20	61	17.5	28819	53
Red Fox Creek	18.8	91	9.4	20	3.2	15594	37
Pheasant Creek	96.3	551	68.9	98	44	9731	212
Pearl Creek	84	461	36.4	99	31.4	33101	163
Highway 47	891.4	5668	468	1098	318.5	304254	2810
Crooked outlet	667.7	4834	492	941	332.3	35963	2861
Ekapo Creek	90.3	422	38.2	47	20.5	44723	166
Highway 201	822.2	5630	545.7	982	381.8	133943	3214
Round outlet	781.7	5236	581.6	812	324.9	30094	3408

Table 5: Volume-weighted nutrient concentrations for the Qu'Appelle River and tributary sites from March 1, 2013 through February 29, 2016. For Last Mountain Creek, a negative concentration indicates net loading towards Last Mountain Lake rather than towards the Qu'Appelle River.

Site	TP (μg/L)	TN (μg/L)	TRP (μg/L)	NO3 + NO2 (μg/L)	NH3 (μg/L)	TSS (mg/L)
Highway 19	15	559	4	172	17	4
Ridge Creek	475	2469	262	275	216	62
Tugaske	107	937	47	146	60	35
Iskwao Creek	614	2441	498	165	130	6
Marquis	274	1516	144	157	77	96
Buffalo Pound outlet	-2	938	-10	-33	-18	-30
Buffalo Pound outlet - Outflow	112	1265	42	73	39	17
Buffalo Pound outlet - Backflow	525	2450	228	457	245	186
Moose Jaw River at Highway 301	525	2440	289	519	175	164
Moose Jaw River at TWP RD 184	623	2806	229	463	203	203
Above Wascana Creek	398	1977	204	238	90	130
Wascana Creek	705	9496	308	3020	4317	301
Lumsden	494	4258	240	1157	1278	190
Above Last Mountain Creek	465	4158	228	1074	1196	193
Last Mountain Creek	10	428	44	-321	-284	-86
Last Mountain Creek - Outflow	200	1368	123	11	39	22
Last Mountain Creek - Backflow	535	3029	262	598	610	213
Craven	326	2894	164	561	722	97
Highway 6	327	2646	171	469	612	121
Loon Creek	480	3176	327	813	404	53
Above Pasqua Lake	368	2823	189	510	666	121
Jumping Deer Creek	210	2000	133	125	170	23

Site	TP (μg/L)	TN (μg/L)	TRP (μg/L)	NO3 + NO2 (μg/L)	NH3 (μg/L)	TSS (mg/L)
Katepwa outlet	239	1874	165	369	170	11
Indian Head Creek	888	3860	375	1140	327	539
Red Fox Creek	505	2461	252	532	86	420
Pheasant Creek	455	2603	325	463	208	46
Pearl Creek	517	2838	224	607	193	204
Highway 47	317	2017	167	391	113	108
Crooked outlet	233	1690	172	329	116	13
Ekapo Creek	545	2543	230	281	124	270
Highway 201	256	1752	170	306	119	42
Round outlet	229	1537	171	238	95	9

Table 6: Nutrient loading at Qu'Appelle River and tributary sites split by study year. Study years use the period March 1 - February 28/29 as a year. Loads were calculated using the midpoint method. For Last Mountain Creek, a negative load indicates net loading towards Last Mountain Lake, rather than towards the Qu'Appelle River.

Site	Study Year	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 + NO2 Load (t)	NH3 Load (t)	TSS Load (t)	Discharge
Highway 19	2013	1.1	49	0.4	16.2	1.3	388.9	73.6
Highway 19	2014	0.7	24.7	0.1	10.4	0.6	206.8	42.4
Highway 19	2015	0.9	25.6	0.2	3.8	1.1	202.3	61.4
Ridge Creek	2013	1.5	10.1	0.6	1.5	0.8	328	4.3
Ridge Creek	2014	6.4	30.1	3.2	2.7	2.4	1096	13.2
Ridge Creek	2015	5.4	28.9	3.5	3.5	2.9	314.3	10.5
Tugaske	2013	3.1	49.1	1.1	12.9	2.7	1596	79.9
Tugaske	2014	10.4	83.1	3.7	11.3	4.7	4038	62
Tugaske	2015	10.1	73.1	5.4	7.7	5.7	1967	77.3
Iskwao Creek	2013	0.8	7	0.4	0.1	0.2	28.7	3.7
Iskwao Creek	2014	18.1	66.6	15.3	3.7	2	138.9	26.2
Iskwao Creek	2015	5	21.1	3.6	2.6	2.8	53.2	8.8
Marquis	2013	7.1	69.6	2.2	8.3	2.3	5036	88.9
Marquis	2014	45.4	233.1	23.6	21.1	9.8	15115	106.1
Marquis	2015	30.6	157.6	17.9	18.3	11.2	8936	108.6
Buffalo Pound outlet	2013	-14	-33.4	-5.4	-8.4	-4.8	-6766	14.6
Buffalo Pound outlet	2014	9.1	121.5	1.5	3.9	2.6	2004	91.1
Buffalo Pound outlet	2015	4.5	64.4	2.3	-0.9	-0.8	-73.7	56.8
Buffalo Pound outlet - Outflow	2013	3.9	45.5	1.9	5.4	2.3	673	49.3
Buffalo Pound outlet - Outflow	2014	9.1	121.5	1.5	3.9	2.6	2004	91.1

Site	Study Year	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 + NO2 Load (t)	NH3 Load (t)	TSS Load (t)	Discharge
Buffalo Pound outlet - Outflow	2015	10.2	95.6	5.2	5.9	3.2	851	67.2
Buffalo Pound outlet - Backflow	2013	17.9	79	7.3	13.8	7.1	7439	34.6
Buffalo Pound outlet - Backflow	2015	5.7	31.2	2.9	6.7	4	924.6	10.3
Moose Jaw River at Highway 301	2013	121.2	480.5	60.9	91.8	37.4	57220	235.7
Moose Jaw River at Highway 301	2014	71	370.2	44.4	101.9	16.4	12710	132.1
Moose Jaw River at Highway 301	2015	89.9	459.4	49.7	85	40.5	18070	169.1
Moose Jaw River at TWP RD 184	2013	161.8	651.1	42.8	82.8	52.2	70199	241.9
Moose Jaw River at TWP RD 184	2014	74.2	381.2	37.7	89.9	15.8	16498	135.6
Moose Jaw River at TWP RD 184	2015	107.4	514.2	45.5	82.6	44.1	24930	173.8
Above Wascana Creek	2013	89.8	354.1	55.2	49.1	13.8	29284	245.2
Above Wascana Creek	2014	109.1	588.9	46.2	46.9	19.8	39255	260.5

Site	Study Year	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 + NO2 Load (t)	NH3 Load (t)	TSS Load (t)	Discharge
Above Wascana Creek	2015	97.6	528.7	50.5	81	33.1	28349	238.6
Wascana Creek	2013	65.8	1011	32.1	313.6	475.8	36204	115
Wascana Creek	2014	89.1	1220	39.2	388.3	585.4	32981	118.1
Wascana Creek	2015	108	1311	43.6	424.5	548.9	43160	139.8
Lumsden	2013	152.5	1266	93.3	336.8	399.7	64078	359.7
Lumsden	2014	191.7	1764	82.1	454.1	567.1	71626	377.7
Lumsden	2015	206.2	1715	92.2	498.4	457.6	75876	377
Above Last Mountain Creek	2013	144.1	1297	88.7	335.7	406.4	77899	373.5
Above Last Mountain Creek	2014	189.2	1827	82.2	434.1	547.1	70789	402.6
Above Last Mountain Creek	2015	216.2	1788	98.5	499.3	459.5	78765	405.3
Last Mountain Creek	2013	-13.9	-69.7	-4.8	-56.4	-46.8	-15926	27.9
Last Mountain Creek	2014	25.8	241	28.5	-48.4	-62.4	-16565	321.9
Last Mountain Creek	2015	-6.1	78.5	1.8	-82.8	-56.8	-17502	234.4
Last Mountain Creek - Outflow	2013	38.3	210.1	25.1	2.3	6.1	4910	147.8
Last Mountain	2014	76.3	550.5	47.5	5.2	10	7708	408

Site	Study Year	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 + NO2 Load (t)	NH3 Load (t)	TSS Load (t)	Discharge
Creek - Outflow								
Last Mountain Creek - Outflow	2015	68.3	491.1	39.5	2.7	19.6	7718	359.1
Last Mountain Creek - Backflow	2013	52.2	279.8	29.9	58.8	52.9	20836	120
Last Mountain Creek - Backflow	2014	50.5	309.5	19	53.6	72.5	24273	86.1
Last Mountain Creek - Backflow	2015	74.4	412.6	37.7	85.5	76.4	25220	124.7
Craven	2013	127.4	1132	75.6	265.6	294.7	51240	401.3
Craven	2014	227.9	1967	111.6	336.9	458.8	57324	724.5
Craven	2015	220	2011	101.6	387.2	520.7	63258	639.6
Highway 6	2013	141	1143	70.2	223.3	322.4	76327	403
Highway 6	2014	251.5	1913	133.3	253.7	423.2	79440	759
Highway 6	2015	204.1	1768	107.9	378.2	370.9	64254	661.6
Loon Creek	2013	5.5	35.6	3.7	11.5	3.5	533.3	11
Loon Creek	2014	7.6	52.8	5.3	12.7	6.5	671.7	16.8
Loon Creek	2015	5.2	32.9	3.5	6.8	5.4	809	10.4
Above Pasqua Lake	2013	163.5	1404	88.2	296.9	491.7	50715	423.8
Above Pasqua Lake	2014	335	2276	171.8	322.3	486.3	120664	862.6
Above Pasqua Lake	2015	244.4	2019	122.4	410.3	367.2	73185	732.6
Jumping Deer Creek	2013	0.9	14.2	0.5	2.5	1.3	86.6	6.6
Jumping Deer Creek	2014	7.5	71.7	5	2.1	5.2	598.1	35.1

Site	Study Year	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 + NO2 Load (t)	NH3 Load (t)	TSS Load (t)	Discharge
Jumping Deer Creek	2015	7.1	61.2	4.2	4.6	6.1	985.7	31.8
Katepwa outlet	2013	141.1	1046	104.3	248.4	90.9	11375	550.2
Katepwa outlet	2014	189.4	1497	123	206.7	163.3	5740	796.8
Katepwa outlet	2015	138.2	1131	95.5	269.1	79.6	3635	614.1
Indian Head Creek	2013	19.7	74.8	4.4	28.6	5.6	12396	18.7
Indian Head Creek	2014	16.2	69.2	10	13.3	4.3	9797	19.5
Indian Head Creek	2015	11.6	62.3	5.6	19	7.6	6626	15.3
Red Fox Creek	2013	2.8	21.5	3.3	4	0.5	4374	12.3
Red Fox Creek	2014	9.2	35.7	3.8	5.6	1.4	6307	14.7
Red Fox Creek	2015	6.8	34.2	2.2	10.2	1.3	4914	10.1
Pheasant Creek	2013	16.6	128.3	10.3	48	13.5	2086	28.9
Pheasant Creek	2014	59.3	305.8	44.9	29	19.4	4505	138.3
Pheasant Creek	2015	20.5	117	13.7	21.1	11.1	3140	44.5
Pearl Creek	2013	13	153.6	7.7	64.5	13.1	2827	46.3
Pearl Creek	2014	62.1	263.5	23.6	22.1	12.5	27408	100.6
Pearl Creek	2015	9	44.3	5.1	12	5.8	2866	15.6
Highway 47	2013	200.1	1302	100.1	342.8	82.7	70843	612.7
Highway 47	2014	422.2	2557	230.2	395.5	133.4	114514	1300
Highway 47	2015	269.1	1810	137.7	359.6	102.4	118897	897.5
Crooked outlet	2013	172.7	1272	132.6	356.9	90.1	12907	644.3
Crooked outlet	2014	305.6	2114	223.8	286.2	162	12403	1325

Site	Study Year	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 + NO2 Load (t)	NH3 Load (t)	TSS Load (t)	Discharge
Crooked outlet	2015	189.4	1449	135.6	298	80.2	10653	891.6
Ekapo Creek	2013	11.7	91.2	7.1	20.8	3.2	2384	37.3
Ekapo Creek	2014	67.4	271.5	24	17.7	11.5	38811	103.2
Ekapo Creek	2015	11.2	58.8	7	8.1	5.8	3528	25.3
Highway 201	2013	205.1	1441	139.3	342.1	97.5	33846	759.7
Highway 201	2014	387.4	2516	263.9	328.1	191.7	52879	1490
Highway 201	2015	229.7	1673	142.4	312.2	92.7	47218	964.6
Round outlet	2013	208.7	1323	161.3	232.1	82.9	9621	836
Round outlet	2014	357	2301	267.8	286.6	158.2	12259	1560
Round outlet	2015	216.1	1612	152.5	293.2	83.8	8215	1012

Table 7: Volume-weighted nutrient concentrations for the Qu'Appelle River and tributary sites split by study year. Study years use the period March 1 - February 28/29 as a year. For Last Mountain Creek, negative concentrations indicate net loading to Last Mountain Lake, rather than the Qu'Appelle River.

Site	Study Year	TP (μg/L)	TN (μg/L)	TRP (μg/L)	NO3 + NO2 (μg/L)	NH3 (μg/L)	TSS (mg/L)
Highway 19	2013	14	665	6	221	18	5
Highway 19	2014	15	582	2	245	14	5
Highway 19	2015	15	417	2	62	19	3
Ridge Creek	2013	341	2374	149	340	189	77
Ridge Creek	2014	485	2284	239	208	180	83
Ridge Creek	2015	516	2740	336	331	273	30
Tugaske	2013	38	614	14	161	33	20
Tugaske	2014	168	1341	60	183	76	65
Tugaske	2015	130	946	70	100	74	25
Iskwao Creek	2013	207	1878	105	29	60	8
Iskwao Creek	2014	689	2536	584	141	78	5
Iskwao Creek	2015	565	2395	409	294	313	6
Marquis	2013	80	783	24	94	26	57
Marquis	2014	428	2196	223	199	93	142
Marquis	2015	281	1451	165	169	103	82
Buffalo Pound outlet	2013	-957	-2286	-368	-575	-328	-462
Buffalo Pound outlet	2014	100	1334	17	43	28	22
Buffalo Pound outlet	2015	80	1133	40	-15	-13	-1
Buffalo Pound outlet - Outflow	2013	80	924	39	110	46	14
Buffalo Pound outlet - Outflow	2014	100	1334	17	43	28	22
Buffalo Pound outlet - Outflow	2015	152	1423	77	87	47	13
Buffalo Pound outlet - Backflow	2013	518	2280	212	400	204	215

Site	Study Year	TP (µg/L)	TN (µg/L)	TRP (µg/L)	NO3 + NO2 (µg/L)	NH3 (µg/L)	TSS (mg/L)
Buffalo Pound outlet - Backflow	2015	548	3017	283	651	382	89
Moose Jaw River at Highway 301	2013	514	2038	258	389	158	243
Moose Jaw River at Highway 301	2014	537	2802	336	771	124	96
Moose Jaw River at Highway 301	2015	532	2717	294	503	239	107
Moose Jaw River at TWP RD 184	2013	669	2692	177	342	216	290
Moose Jaw River at TWP RD 184	2014	548	2813	278	663	116	122
Moose Jaw River at TWP RD 184	2015	618	2959	262	476	254	143
Above Wascana Creek	2013	366	1444	225	200	56	119
Above Wascana Creek	2014	419	2261	178	180	76	151
Above Wascana Creek	2015	409	2216	212	339	139	119
Wascana Creek	2013	572	8787	279	2726	4137	315
Wascana Creek	2014	754	10323	332	3287	4956	279
Wascana Creek	2015	773	9380	312	3036	3927	309
Lumsden	2013	424	3519	259	936	1111	178
Lumsden	2014	507	4671	217	1202	1501	190
Lumsden	2015	547	4549	245	1322	1214	201
Above Last Mountain Creek	2013	386	3473	238	899	1088	209
Above Last Mountain Creek	2014	470	4539	204	1078	1359	176

Site	Study Year	TP (μg/L)	TN (μg/L)	TRP (μg/L)	NO3 + NO2 (μg/L)	NH3 (μg/L)	TSS (mg/L)
Above Last Mountain Creek	2015	534	4411	243	1232	1134	194
Last Mountain Creek	2013	-499	-2501	-172	-2026	-1678	-572
Last Mountain Creek	2014	80	749	89	-150	-194	-51
Last Mountain Creek	2015	-26	335	8	-353	-242	-75
Last Mountain Creek - Outflow	2013	259	1421	170	16	41	33
Last Mountain Creek - Outflow	2014	187	1349	116	13	25	19
Last Mountain Creek - Outflow	2015	190	1368	110	8	55	21
Last Mountain Creek - Backflow	2013	435	2332	249	490	441	174
Last Mountain Creek - Backflow	2014	587	3595	221	622	842	282
Last Mountain Creek - Backflow	2015	596	3308	302	686	612	202
Craven	2013	318	2819	188	662	734	128
Craven	2014	315	2715	154	465	633	79
Craven	2015	344	3144	159	605	814	99
Highway 6	2013	350	2837	174	554	800	189
Highway 6	2014	331	2521	176	334	558	105
Highway 6	2015	308	2673	163	572	561	97
Loon Creek	2013	506	3250	342	1052	320	49
Loon Creek	2014	451	3144	314	755	386	40
Loon Creek	2015	500	3150	332	655	519	78
Above Pasqua Lake	2013	386	3314	208	701	1160	120
Above Pasqua Lake	2014	388	2638	199	374	564	140

Site	Study Year	TP (μg/L)	TN (μg/L)	TRP (μg/L)	NO3 + NO2 (μg/L)	NH3 (μg/L)	TSS (mg/L)
Above Pasqua Lake	2015	334	2756	167	560	501	100
Jumping Deer Creek	2013	139	2155	78	374	196	13
Jumping Deer Creek	2014	213	2041	144	61	147	17
Jumping Deer Creek	2015	222	1924	133	143	191	31
Katepwa outlet	2013	256	1901	190	451	165	21
Katepwa outlet	2014	238	1879	154	259	205	7
Katepwa outlet	2015	225	1842	155	438	130	6
Indian Head Creek	2013	1055	4006	234	1532	302	664
Indian Head Creek	2014	832	3550	516	685	219	503
Indian Head Creek	2015	756	4077	366	1242	496	433
Red Fox Creek	2013	224	1743	267	322	38	355
Red Fox Creek	2014	627	2433	262	380	95	430
Red Fox Creek	2015	670	3373	220	1007	132	484
Pheasant Creek	2013	575	4442	357	1660	467	72
Pheasant Creek	2014	429	2212	325	210	140	33
Pheasant Creek	2015	460	2626	307	474	249	70
Pearl Creek	2013	280	3315	166	1393	282	61
Pearl Creek	2014	617	2620	234	220	124	273
Pearl Creek	2015	572	2828	328	766	369	183
Highway 47	2013	327	2124	163	559	135	116
Highway 47	2014	325	1967	177	304	103	88
Highway 47	2015	300	2017	153	401	114	132
Crooked outlet	2013	268	1974	206	554	140	20
Crooked outlet	2014	231	1596	169	216	122	9
Crooked outlet	2015	212	1625	152	334	90	12
Ekapo Creek	2013	314	2446	192	557	87	64
Ekapo Creek	2014	653	2631	233	171	111	376
Ekapo Creek	2015	442	2325	278	321	229	139

Site	Study Year	TP (μg/L)	TN (μg/L)	TRP (μg/L)	NO3 + NO2 (μg/L)	NH3 (μg/L)	TSS (mg/L)
Highway 201	2013	270	1897	183	450	128	45
Highway 201	2014	260	1689	177	220	129	35
Highway 201	2015	238	1734	148	324	96	49
Round outlet	2013	250	1583	193	278	99	12
Round outlet	2014	229	1475	172	184	101	8
Round outlet	2015	214	1593	151	290	83	8

Table 8: Nutrient loading at each site determined using the midpoint, Beale and Loadest methods. For TRP and NO3 + NO2 at Marquis, the Loadest model failed to converge. * Loadest model diagnostics suggested a poor model.

Site	Method	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 + NO2 Load (t)	NH3 Load (t)	TSS Load (t)
Highway 19	Midpoint	2.6	99.2	0.6	30.5	3.1	798
Highway 19	Beale	2.7	89.9	0.7	29.8	3	945.9
Highway 19	Loadest	2.9	93.4	0.7 *	45.2 *	3.2	871
Ridge Creek	Midpoint	13.3	69.1	7.3	7.7	6.1	1738
Ridge Creek	Beale	14.4	66.1	7.1	8.5	6.8	2374
Ridge Creek	Loadest	17 *	70.1	10.5 *	12.6 *	7	1931
Tugaske	Midpoint	23.5	205.4	10.2	31.9	13.1	7601
Tugaske	Beale	39.5	283.8	16	36.2	21.2	13950
Tugaske	Loadest	23.9 *	209.5	14.2 *	59.9 *	13.8	8367 *
Iskwao Creek	Midpoint	23.8	94.6	19.3	6.4	5	220.8
Iskwao Creek	Beale	21.9	90.8	17.2	10.2	6	273.1
Iskwao Creek	Loadest	25.7	89.1	21.3	50.8 *	5.2	221.2
Marquis	Midpoint	83	460.3	43.7	47.8	23.4	29090
Marquis	Beale	95.8	486.7	45.4	55.5	26.8	36540
Marquis	Loadest	98.8	457.3			24.8	35800
Buffalo Pound outlet	Midpoint	-0.3	152.4	-1.6	-5.4	-3	-4835
Buffalo Pound outlet	Beale	0.5	158.7	-1.7	-7.6	-4.4	-4323
Buffalo Pound outlet - Outflow	Midpoint	23.3	262.6	8.7	15.2	8	3529
Buffalo Pound outlet - Outflow	Beale	24.3	271.9	8.8	14.2	7.1	3710
Buffalo Pound outlet - Backflow	Midpoint	23.6	110.2	10.3	20.6	11	8364
Buffalo Pound outlet - Backflow	Beale	23.8	113.2	10.5	21.7	11.5	8032

Site	Method	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 + NO2 Load (t)	NH3 Load (t)	TSS Load (t)
Moose Jaw River at Highway 301	Midpoint	282.1	1310.1	155	278.6	94.2	88000
Moose Jaw River at Highway 301	Beale	286.6	1320	151.7	246.3	103	90120
Moose Jaw River at Highway 301	Loadest	326.8	1239.6	181.3	730.4 *	96.6	148000 *
Moose Jaw River at TWP RD 184	Midpoint	343.4	1546.5	126.1	255.3	112	111600
Moose Jaw River at TWP RD 184	Beale	363.2	1564	122.9	231.5	124	125300
Moose Jaw River at TWP RD 184	Loadest	364.1	1409.8	233.5 *	1509.2 *	96.1	155800 *
Above Wascana Creek	Midpoint	296.5	1471.8	152	176.9	66.7	96890
Above Wascana Creek	Beale	306.5	1520	161.2	188.1	76.4	98970
Above Wascana Creek	Loadest	336	1522.1	161	390.9 *	65.5	119200
Wascana Creek	Midpoint	262.9	3541.4	115	1126.3	1610.1	112300
Wascana Creek	Beale	291.5	2942.1	113.5	934	1148.3	134500
Wascana Creek	Loadest	276.8	3217	124.3	1524.9 *	2316.6 *	145400
Lumsden	Midpoint	550.4	4744.7	267.6	1289.3	1424.3	211600
Lumsden	Beale	577	4329	276.5	1217.8	1044.3	229700
Lumsden	Loadest	591.2	4779.5	298.3	1364.9	2538.8 *	216100
Above Last Mountain Creek	Midpoint	549.6	4912	269.5	1269.1	1413	227500
Above Last Mountain Creek	Beale	576.9	4469.7	277.4	1202.4	1028.2	250000

Site	Method	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 + NO2 Load (t)	NH3 Load (t)	TSS Load (t)
Above Last Mountain Creek	Loadest	578.9	4865.9	294.4	1365.9	2129.2 *	224700
Last Mountain Creek	Midpoint	5.8	249.8	25.5	-187.7	-166	-49990
Last Mountain Creek	Beale	1.7	226.9	23.7	-204.6	-161.5	-51960
Last Mountain Creek - Outflow	Midpoint	182.8	1251.7	112.1	10.2	35.7	20340
Last Mountain Creek - Outflow	Beale	188.3	1260.1	114.1	9.2	37.4	21200
Last Mountain Creek - Backflow	Midpoint	177	1001.9	86.6	197.9	201.7	70330
Last Mountain Creek - Backflow	Beale	186.5	1033.2	90.4	213.8	198.9	73150
Craven	Midpoint	575.3	5109.8	288.8	989.7	1274.3	171800
Craven	Beale	632.4	5008.2	305.5	1013.8	1045.7	203800
Craven	Loadest	616.3	5198.7	300.8	1124.1	1367.5 *	198000 *
Highway 6	Midpoint	596.6	4824.7	311.4	855.1	1116.5	220000
Highway 6	Beale	615.4	4592	312.4	835.7	842.7	238900
Highway 6	Loadest	625.1	4917.6	313.8	948.7	1375.8 *	244100
Loon Creek	Midpoint	18.3	121.3	12.5	31	15.4	2014
Loon Creek	Beale	19.9	142.2	12.9	42.8	20.1	2534
Loon Creek	Loadest	19.6	121.1	13.5	210.7 *	14.7 *	2668
Above Pasqua Lake	Midpoint	742.9	5698.8	382.4	1029.5	1345.2	244600
Above Pasqua Lake	Beale	780.4	5374.1	390.1	995.2	948.8	271100
Above Pasqua Lake	Loadest	783.8	5777.6	390.8	1494.8 *	1504.9 *	269100

Site	Method	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 + NO2 Load (t)	NH3 Load (t)	TSS Load (t)
Jumping Deer Creek	Midpoint	15.4	147.1	9.8	9.2	12.5	1670
Jumping Deer Creek	Beale	17.2	150.6	10.6	11	12.7	1979
Jumping Deer Creek	Loadest	16.9	150	11.2	14.8	12.6	1759
Katepwa outlet	Midpoint	468.6	3674.5	322.8	724.2	333.7	20750
Katepwa outlet	Beale	480.5	3756.4	329.7	784.7	328.3	24780
Katepwa outlet	Loadest	483.3	3711.3	335.5	1051.7 *	347.9 *	24100
Indian Head Creek	Midpoint	47.5	206.2	20	60.9	17.5	28820
Indian Head Creek	Beale	58.3	228.8	20.5	77.9	21.3	36350
Indian Head Creek	Loadest	48.6	198	22.9	86.5	18.5	36160
Red Fox Creek	Midpoint	18.8	91.4	9.4	19.8	3.2	15590
Red Fox Creek	Beale	21.5	100.5	8.2	20.1	3.4	16740
Red Fox Creek	Loadest	19.9	88.3	14.6 *	18.2	2.9	17380
Pheasant Creek	Midpoint	96.3	551.1	68.9	98.1	44	9731
Pheasant Creek	Beale	102.5	577.9	73.6	110.1	53.2	10820
Pheasant Creek	Loadest	121.5	607.6	89.9 *	234 *	46.6	17380 *
Pearl Creek	Midpoint	84	461.3	36.4	98.7	31.4	33100
Pearl Creek	Beale	107.3	491.2	39.9	81.4	27.8	51940
Pearl Creek	Loadest	68.4	412.6	36.7	76.7	30.4	17430 *
Highway 47	Midpoint	891.4	5668.4	468	1097.9	318.5	304300
Highway 47	Beale	911.4	5795.7	485.5	1158.9	323	317900
Highway 47	Loadest	901.2	5709.9	464.1	2508.6 *	317.4	330800
Crooked outlet	Midpoint	667.7	4833.9	492	941.1	332.3	35960
Crooked outlet	Beale	677.7	4869.2	501	965.3	337.9	38680
Crooked outlet	Loadest	688.8	4808	512.7	1239.5 *	326	37480
Ekapo Creek	Midpoint	90.3	421.5	38.2	46.6	20.5	44720
Ekapo Creek	Beale	104.3	449.1	43.2	49	25.5	55160

Site	Method	TP Load (t)	TN Load (t)	TRP Load (t)	NO3 + NO2 Load (t)	NH3 Load (t)	TSS Load (t)
Ekapo Creek	Loadest	126.2 *	426.5	58.6 *	56.7 *	21	53800
Highway 201	Midpoint	822.2	5630.5	545.7	982.4	381.8	133900
Highway 201	Beale	851.9	5792.9	568	1038.7	406.5	149800
Highway 201	Loadest	863.1	5713.7	570.8	1208.9 *	386.1	157000 *
Round outlet	Midpoint	781.7	5236.4	581.6	811.9	324.9	30090
Round outlet	Beale	841.1	5282.9	593.6	866.6	333.1	32760
Round outlet	Loadest	873.5	5289.4	624.4	1162.2 *	342 *	34980

Table 9: Total phosphorus and total nitrogen loading from the Regina WWTP to Wascana Creek. Estimated loads with upgrades are an estimate of what loads might have been during our study if recent upgrades had already been done. They were calculated using effluent discharge volumes from 2013-2015, but average monthly effluent concentrations from July 2017 - June 2018.

Study Year	TP Load (t)	TN Load (t)	Estimated TP Load with Upgrades (t)	Estimated TN Load with Upgrades (t)
2013	21.47	939.8	14.52	274.9
2014	24.56	994.7	15.58	290.6
2015	23.2	1026	14.42	271.1
Totals	69.23	2960	44.52	836.6

Table 10: Nutrient loads for the Qu'Appelle River at Welby for 1975 - 2015. Loads were calculated using the midpoint method from monthly data from the Prairie Provinces Water Board.

Study Year	TP Load (t)	TN Load (t)	SRP Load (t)	NO3 + NO2 Load (t)	NH3 Load (t)	Discharge (hm3)
1975	221.8			143.7		698.2
1976	218.8			171.3		831.6
1977	14.51			5.351	3.466	69.33
1978	20.6			9.723	4.152	83.04
1979	89.17			156.2	18.91	378.1
1980	27.25			12.18	5.061	101.2
1981	16.06		9.631	6.37	3.143	62.86
1982	80.4		34.92	16.93	15.3	279.9
1983	81.37		42.3	38.55	21.46	329
1984	14.04		9.263	6.517	5.96	68.15
1985	58.57		28.02	45.84	18.22	244.2
1986	25.73		12.71	22.69	9.576	139
1987	13.74		6.661	3.986	3.28	76.99
1988	3.357		0.9556	0.5366	0.6215	19.49
1989	12.4		7.967	10.47	4.094	67.24
1990	41.2		14.17	14.91	10.16	163.2
1991	37.69		21.2	4.135	7.205	163.8
1992	32.22		12.98	8.132	10.72	164.5
1993	23.24		9.425	4.925	6.984	161.8
1994	78.93	512.6	25.89	23.57	18.97	428.7
1995	87.46	764.9	36.18	217.1	34.93	449.6
1996	130.8	1002	52.64	114	49.69	718.8
1997	97.09	765.8	51.87	71.41	27.92	595.6
1998	27.53	219.3	11.34	26.31	7.745	191.9
1999	151.5	918.8	81.36	100.4	35.35	688.8
2000	15.67	148.3	6.165	10.53	7.698	155.3
2001	70.05	515.7	25.22	105.8	37.58	331.9
2002	15.24	129.9	4.858	14.3	6.749	89.84
2003	60.79	389.5	19.72	48.96	24.53	281.3
2004	40.61	229.8	18.67	18.22	11.22	193
2005	132.6	773.3	55.16	55.77	36	451.9

Study Year	TP Load (t)	TN Load (t)	SRP Load (t)	NO3 + NO2 Load (t)	NH3 Load (t)	Discharge (hm3)
2006	113.9	600.5	44.13	59.91	26.39	425.9
2007	92.54	534.3	33.96	91.51	23.29	429.5
2008	22.02	165.4	8.037	10.33	5.442	123
2009	63.41	321.2	23.61	21.84	17.02	197
2010	187.6	1163	114.6	105.9	45.14	811.6
2011	566.8	3360	301.4	397.3	170	2262
2012	140.2	999.4	52.14	174.5	33.22	480.9
2013	159.8	1702	70.73	328.9	37.08	721.7
2014	430.1	2471	213.5	291.4	116.8	1725
2015	246.9	1471	104.2	215.1	129.1	1041

Table 11: Volume-weighted nutrient concentrations for the Qu'Appelle River at Welby for 1975 - 2015. Loads were calculated using the midpoint method from monthly data from the Prairie Provinces Water Board.

Study Year	TP (μg/L)	TN (μg/L)	SRP (μg/L)	NO3 + NO2 (μg/L)	NH3 (μg/L)
1975	317.7			205.8	
1976	263.1			206	
1977	209.3			77.18	50
1978	248			117.1	50
1979	235.8			413.1	50
1980	269.3			120.3	50
1981	255.5		153.2	101.3	50
1982	287.3		124.8	60.48	54.68
1983	247.3		128.6	117.2	65.23
1984	206		135.9	95.64	87.46
1985	239.8		114.7	187.7	74.61
1986	185.1		91.39	163.2	68.87
1987	178.4		86.52	51.77	42.6
1988	172.2		49.03	27.53	31.88
1989	184.4		118.5	155.6	60.88
1990	252.4		86.82	91.33	62.21
1991	230.1		129.5	25.25	43.99
1992	195.8		78.87	49.43	65.16
1993	143.7		58.27	30.44	43.18
1994	184.1	1196	60.38	54.98	44.24
1995	194.5	1701	80.47	482.9	77.69
1996	182	1393	73.24	158.6	69.12
1997	163	1286	87.08	119.9	46.88
1998	143.4	1143	59.06	137.1	40.35
1999	220	1334	118.1	145.8	51.32
2000	100.9	954.9	39.71	67.8	49.58
2001	211.1	1554	75.99	318.7	113.2
2002	169.7	1446	54.07	159.2	75.12
2003	216.1	1385	70.09	174.1	87.19
2004	210.4	1191	96.75	94.38	58.13
2005	293.4	1711	122.1	123.4	79.67
2006	267.4	1410	103.6	140.7	61.97

Study Year	TP (μg/L)	TN (μg/L)	SRP (μg/L)	NO3 + NO2 (μg/L)	NH3 (μg/L)
2007	215.4	1244	79.06	213.1	54.22
2008	179	1345	65.37	84	44.26
2009	321.9	1630	119.9	110.9	86.38
2010	231.2	1433	141.2	130.5	55.62
2011	250.5	1485	133.2	175.6	75.13
2012	291.5	2078	108.4	362.8	69.08
2013	221.4	2358	98	455.7	51.38
2014	249.4	1433	123.8	169	67.75
2015	237.2	1413	100.1	206.6	124

Table 12: Summary of selected annual phosphorus loads and volume-weighted concentrations from Cross (1978), Munro (1986a), and Munro (1986b). Site names have been changed from the original publications to better compare with our study. In Cross (1978), loads for tributary sites are presented as exports (mg/m2). These were converted to loads (t) using the effective drainage areas in Cross (1978). Volume-weighted concentrations were calculated using flow volumes supplied in the studies if available, or with flow data from the Water Survey of Canada. Where no data is presented for volume-weighted concentrations, flow data were unavailable. For some sites, flow data was not complete in each year. In these cases, volume-weighted concentrations were calculated for the years where full flow data were available. Years in parentheses indicate which years volume-weighted concentrations are calculated for if different from total load calculations. For Munro (1986b), loads for Apr 1980-Jun 1983 are totals over the whole study period.

Study	Years	Site	Mean P Load (t)	Mean Volume-weighted P (μg/L)
Cross	1970-1976	Buffalo Pound Outflow	12 (4-21)	
Cross	1970-1976	Moose Jaw River	100 (28-180)	1274 (485-4848)
Cross	1970-1976	Above Wascana Creek	113 (16-239)	
Cross	1970-1976 (1973-1976)	Wascana Creek	234 (98-492)	2901 (1771-4633)
Cross	1970-1976	Lumsden	211 (141-273)	991 (251-1802)
Cross	1970-1976	Craven	167 (107-281)	733 (266-1376)
Cross	1970, 1971	Loon Creek	3 (1-4)	
Cross	1970-1976 (1971-1976)	Above Pasqua Lake	129 (53-177)	484 (247-698)
Cross	1970-1972, 1974-1976	Jumping Deer Creek	1 (0-3)	298 (54-481)
Cross	1970-1976	Katepwa outlet	140 (48-210)	471 (278-677)
Cross	1970-1972, 1974-1976	Indian Head Creek	2 (0-6)	
Cross	1970-1972, 1975-1976	Pheasant Creek	5 (2-9)	327 (260-365)
Cross	1970-1976	Highway 47	161 (24-288)	

Study	Years	Site	Mean P Load (t)	Mean Volume-weighted P (μg/L)
Cross	1970-1976	Crooked outlet	128 (17-236)	299 (223-369)
Cross	1970-1972, 1975	Ekapo Creek	3 (2-8)	238 (173-304)
Cross	1970-1976	Highway 201	136 (20-249)	
Cross	1970-1976	Round outlet	95 (20-172)	221 (181-271)
Munro a	1971-1976	Above Wascana Creek	59 (20-103)	379 (103-498)
Munro a	1971-1976	Wascana Creek	133 (93-180)	2278 (504-6047)
Munro a	1972-1976	Lumsden	165 (148-196)	946 (217-1892)
Munro a	1971, 1974-1976	Craven	159 (126-207)	413 (272-665)
Munro a	1974-1976	Above Pasqua Lake	173 (146-204)	349 (270-461)
Munro a	1977-1981	Above Wascana Creek	43 (20-104)	604 (307-962)
Munro a	1977-1982	Wascana Creek	28 (11-50)	615 (321-1041)
Munro a	1977-1982	Lumsden	85 (46-184)	607 (344-889)
Munro a	1977-1981	Craven	36 (17-104)	423 (330-512)
Munro a	1977-1982	Above Pasqua Lake	44 (21-76)	509 (339-866)
Munro b	1981	Above Pasqua Lake	24	447
Munro b	1982	Above Pasqua Lake	60	294
Munro b	Apr 1980-Jun 1983	Above Pasqua Lake	135	312
Munro b	1981	Katepwa outlet	17	358
Munro b	1982	Katepwa outlet	94	442
Munro b	Apr 1980-Jun 1983	Katepwa outlet	178	393

Table 13: Summary of N loading data from Munro (1986b). Loads for Apr 1980 - Jun 1983 are totals over the whole study period.

Site	Year	TN Load (t)	Volume-weighted N (μg/L)
Above Pasqua Lake	1981	292	5330
Above Pasqua Lake	1982	470	2320
Above Pasqua Lake	April 1980 - June 1983	1244	2877
Katepwa outlet	1981	51	1061
Katepwa outlet	1982	213	1001
Katepwa outlet	April 1980 - June 1983	467	1031

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Appendix A

Hydrology for the Qu'Appelle Mass Balance Water Quality Study

Hydrology for the Qu'Appelle Mass Balance Water Quality Study

DRAFT REPORT

Version 02282018

Hydrology Services Unit

Prepared by

Cesar Perez-Valdivia

Contents

Objective

The objective of this study is to provide daily flow estimates for ungauged tributaries and locations within the main stem of the Qu'Appelle River as well inflows and outflows from the Qu'Appelle Lakes. The daily time series were created by using recorded flows, water levels, area capacity curves and operating records of the different structures in the Qu'Appelle River and by applying statistical methods, effective drainage area ratios, and mass balance and continuity equations.

1. Upper Qu'Appelle - Upstream of Buffalo Pound Lake

1.1 Iskwao Creek Flow Estimation

Iskwao Creek was one of the two creeks of the Upper Qu'Appelle watershed for which hydrometric data was collected previously. The station, Iskwao Creek near Craik (05JG014), was operated from 1972 to 2011 providing valuable hydrological information for the northern part of the Upper Qu'Appelle watershed. This long period of record, 40 years, allowed the development of statistical relationships with other hydrometric data collected in nearby watersheds. Strong statistical relationships made possible the development of linear or non-linear multiple regression models to estimate flows in the Creek after the station was discontinued.

Statistical relationships in the Upper Qu'Appelle watershed were initially explored by A. Nazemi in 2013 in order to estimate the ungauged contribution of the watershed to Buffalo Pound Lake. At the time Nazemi developed a non-linear regression model to estimate the ungauged contribution into Buffalo Pound Lake and linear regression models to estimate flows at Iskwao Creek hydrometric station. In order to develop the regression models, Nazemi separated the year into a cold and a warm season. The cold season was defined from November to March while the warm season was defined from April to October. The two different seasons resulted in two different regression models written as function of Ridge Creek flows. The cold season model, that in practicality applies only for the month of March because hydrometric stations are operated from March 1st to October 31st, and the warm season are defined by equations 1.1 and 1.2.

$$\text{Iskwao}_{ck} = 0.3112 * \text{Ridge}_{ck}^{\,0.4537} \qquad \text{(equation 1.1)}$$

$$\text{Iskawo}_{ck} = 0.4957 * \text{Ridge}_{ck} + 0.1185 \qquad \text{(equation 1.2)}$$

The warm season model has a conditional that if flows at Ridge Creek are zero flows at Iskwao Creek should be zero ignoring the intercept in the equation.

To validate and complement the equations proposed by Nazemi, additional multiple linear regression models were developed and tested using other hydrometric data recorded in nearby watersheds. Preliminary, correlation analyses between Iskwao Creek and Lewis, Brighwater Creek, and Arm River hydrometric stations were carried out to assess the strength of the relationship (Table 1). The results of the correlation analyses suggested that

Lewis Creek had the highest correlation with Iskwao flows followed by Brightwater Creek flows (non-parametric correlation). In general, Ridge Creek flows resulted in the smallest correlation coefficient, however, the hydrometric station was further considered in the multiple linear regression models because of its location within the Upper Qu'Appelle Watershed. Based on the results of the correlation analyses Lewis and Ridge Creek were used to develop the multiple linear regression models. A total of 17 additional regression models were developed using these stations as predictors (Table 1. 2). The models were developed over different time periods to account for the different hydrological conditions. In addition to the models presented in table 1.2, a couple of MLR models using Ridge Creek, Brightwater, and Arm River as predictors were developed over the 1972-2011 period. Statistically, these two models performed better than the model developed using Lewis and Ridge Creek flows (R^2 of 0.73 vs 0.70); however, when analyzing the flow estimates for the 2013-2016 period these models underestimated flows, in particular for 2014.

Table 1.1: Daily Correlation for the period 1972-2011

	Kendall Correlation				Pearson Correlation				Spearman Correlation			
	Ridge	**Lewis**	**Bright**	**Arm**	**Ridge**	**Lewis**	**Bright**	**Arm**	**Ridge**	**Lewis**	**Bright**	**Arm**
Iskwao Creek	0.52	0.65	0.60	0.56	0.71	0.71	0.73	0.76	0.64	0.70	0.66	0.65

The multiple linear regression model has the following form:

$$Iskwao_Q = a + b * Ridge_Q + c * Lewis_Q \qquad \text{(equation 1.3)}$$

Where *b* and *c* are the regression coefficients for Ridge and Lewis creek and *a* is the intercept. Table 3 summarizes the regression coefficients for all the models and provides the coefficient of the determination (R^2).

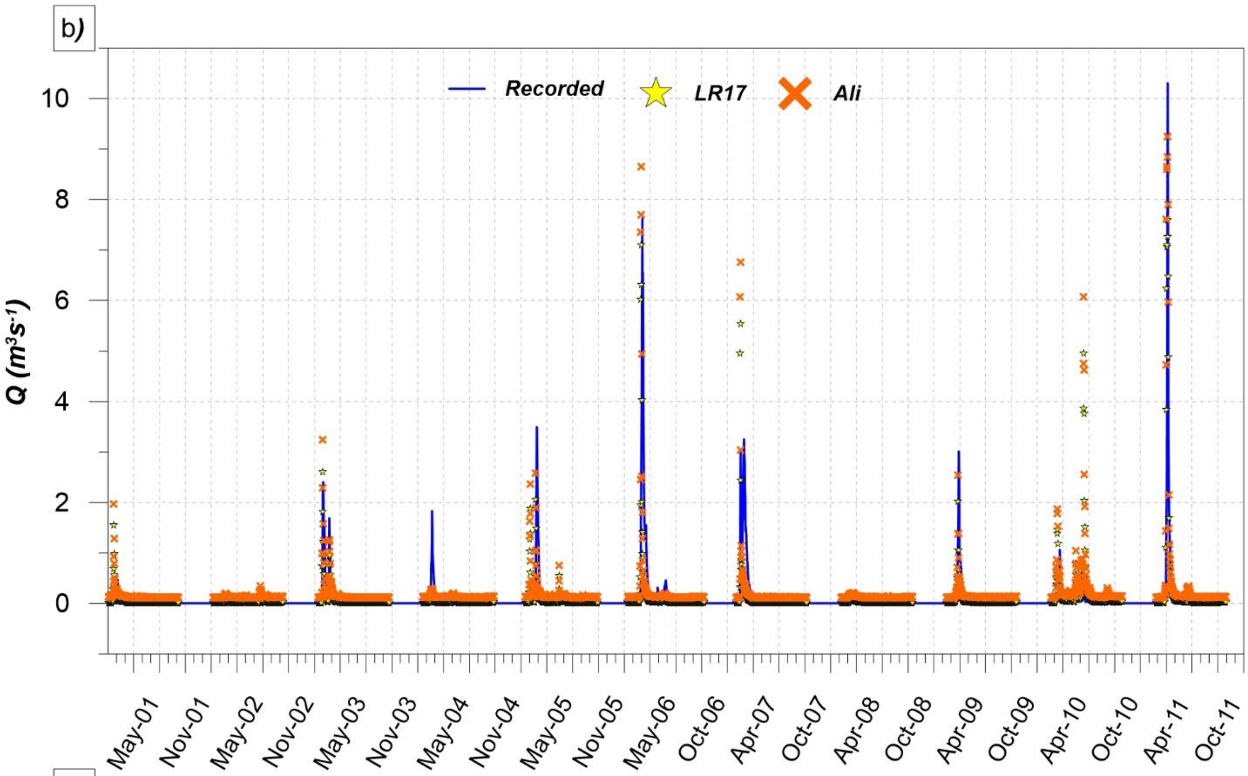
Table 1.2: Regression coefficients for the linear regression models

Regression	*a*	*Ridge Creek*	*Lewis Creek*	*Period*	R^2
Ali1*	0.118500	0.495700	----	1972-2011	0.51
Ali2*	0.118500	0.495700		1972-1992	0.63
LR1**	-0.009877	0.092144	0.653400	2001-2011	0.78
LR2	0.063933	0.284324	-----	2001-2011	0.41
LR3	-0.007375	----	0.757053	2001-2011	0.75
LR4	0.009011	0.140686	0.587773	1991-2011	0.72
LR5	0.058080	0.228626	----	1991-2011	0.42
LR6	0.026337	----	0.748242	1991-2011	0.59
LR7	0.007213	0.150245	0.624238	1981-2011	0.72
LR8	0.044332	0.244944	----	1981-2011	0.43
LR9	0.022629	----	0.809044	1981-2011	0.58
LR10*	-0.003798	0.219316	0.646982	1972-2011	0.70
LR11	0.032698	0.313655	----	1972-2011	0.51
LR12	0.017858	----	0.935501	1972-2011	0.50
LR13	-0.010749	0.320990	0.758317	1972-1992	0.77
LR14	0.010403	0.426633	----	1972-1992	0.63
LR15	0.014220	----	1.267800	1972-1992	0.50
LR16	-0.007680	0.305880	0.758179	1972-1995	0.76
LR17**	0.012012	0.411937	----	1972-1995	0.62
LR18	0.015995	----	1.259348	1972-1995	0.50

*Note that the open water season equation proposed by Nazemi was used for all year round in the estimation of the R^2.

Three linear regression models (LR1, LR10, and LR17) were selected to estimate flows for Iskwao Creek. These modes explain 78, 70, and 62 % of the observed variance in the recorded Iskwao Creek flows. The LR1 regression model was developed over a shorter period of time (2001-2011) to account for the most recent hydrological conditions. On the other hand, LR10 was developed over the common time period (1972-2011) to provide a more robust hydrological relationship while LR17 was developed over the 1972-1995 to reproduce the work carried out by Nazemi. Comparing this model to the model developed by Nazemi, both models provided similar results in terms of the coefficient of determination (0.62 vs 0.63), although Nazemi's model was evaluated over the 1972-1992 period. The two models have a positive intercept, however the intercept in Nazemi's equation is an order of magnitude greater and does not necessarily represent the hydrological conditions in the Iskwao Creek watershed. There is not always flow in Iskwao Creek when the flow at Ridge Creek is zero and this is the reason to impose the arbitrary condition that when flows at Ridge Creek are zero flows at Iskwao Creek should be zero.

Figure 1.1 illustrates recorded and simulated flows at Iskwao Creek for the period 2001-2011 by the three regression models.



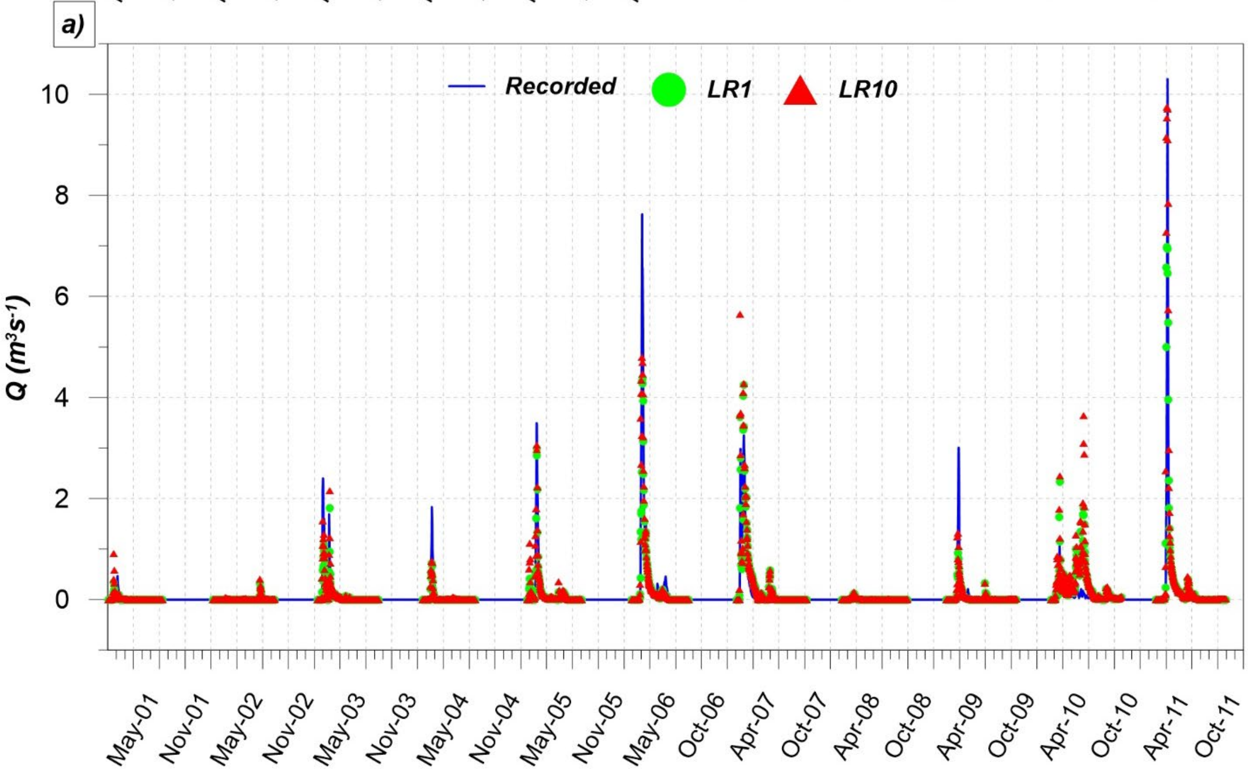


Figure 1.1: Observed and estimated flows for Iskwao Creek for the period 2001-2011.

Overall, the LR1 model underestimated peak flows for most years and captured the timing of the summer runoff but not its magnitude, which was in general overestimated (2007, 2010). The LR10 model estimated greater peak flows than LR17 and did overall better (with a greater R^2) but also failed estimating the magnitude of the summer events which was driven by the greater influence that flows from Lewis Creek have in the equation. The LR17 model did a better job estimating spring peaks than the two other models, however, peak flows were overestimated in 2001, 2007 and 2010. The model did poorly replicating flows during 2004 (year below normal) and summer runoff of 2006. On the other hand, summer runoff during 2010 was overestimated. The model defined by Nazemi (Ali model) provides greater peaks than LR17 (due to larger regression coefficients) and had the same limitations (i.e. no capturing flows during 2004 and overestimating summer runoff during 2010).

Even though all the models reproduced relatively "well" flows at Iskwao Creek (in terms of R^2) they were limited by the predictors used in the regression models. The use of Ridge Creek as predictor, which headwaters are southern of the Qu'Appelle River, resulted in spikier hydrographs. On the other hand, the use of Lewis Creek, which is in a nearby watershed northern of the Upper Qu'Appelle, produced a wider/ fatter hydrograph than Iskwao Creek particularly during summer runoff.

The regression models that used only one predictor resulted in smaller R^2 values than the models developed over a long period of time using two predictors. Although, there were periods of time in which the one predictor regression model resulted in better statistics. Then, when applying the model, it is assumed that the hydrological conditions are very similar as the hydrological conditions for which the model was developed, which is not necessarily true.

Finally, the LR10 model was considered to provide the best flow estimates for Iskwao Creek independently of the time period that was being forecasted (based on the statistical results). The coefficient of determination of this model was 0.70, which was not the highest provided in table 1.2 but accounts for a hydrological relationship of over 40 years. In addition, the results of this model are supported by field observations (Figure 1.2). Figure 2 illustrates images of Iskwao and Ridge Creek at the sampling location (July 7, 2014) and the estimated flows at Iskwao Creek (hydrometric station) by the four regression models. The image of Iskwao Creek suggests flows above normal (flows out of bank) during this period while the picture of Ridge Creek shows little water that day. Note that normal (return period of two years) flows for Iskwao and Ridge Creek are 4.5 and 5.2 m^3/s respectively.

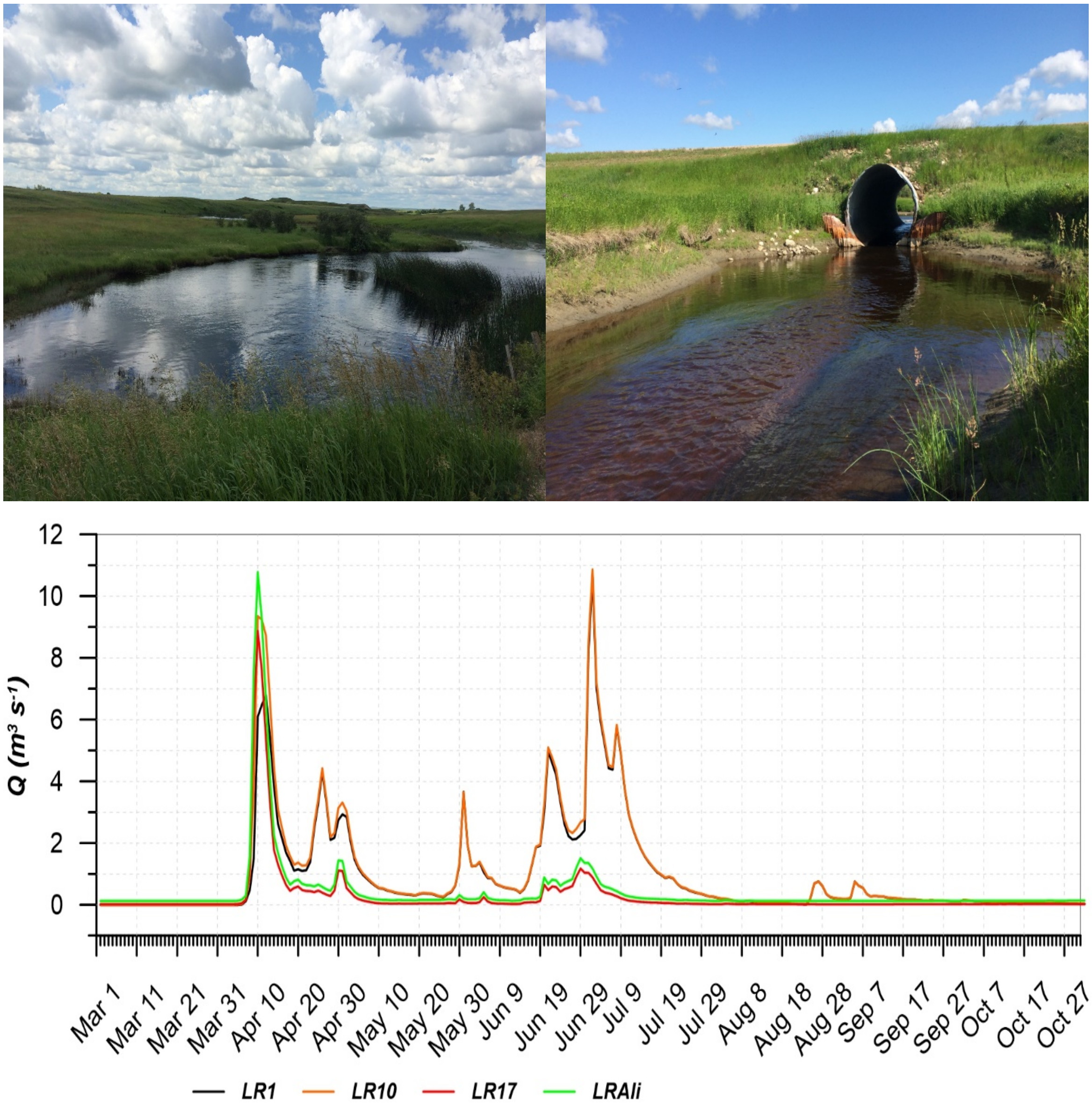


Figure 1.2: top) Iskwao Creek (left) and Ridge Creek (Right) on July 7, 2014. Bottom) Estimated flows for 2014 based on the different MLR models.

Figure 1.3 illustrates estimated flows for Iskwao Creek at the hydrometric station and the sampling location for the period 2013-2016.

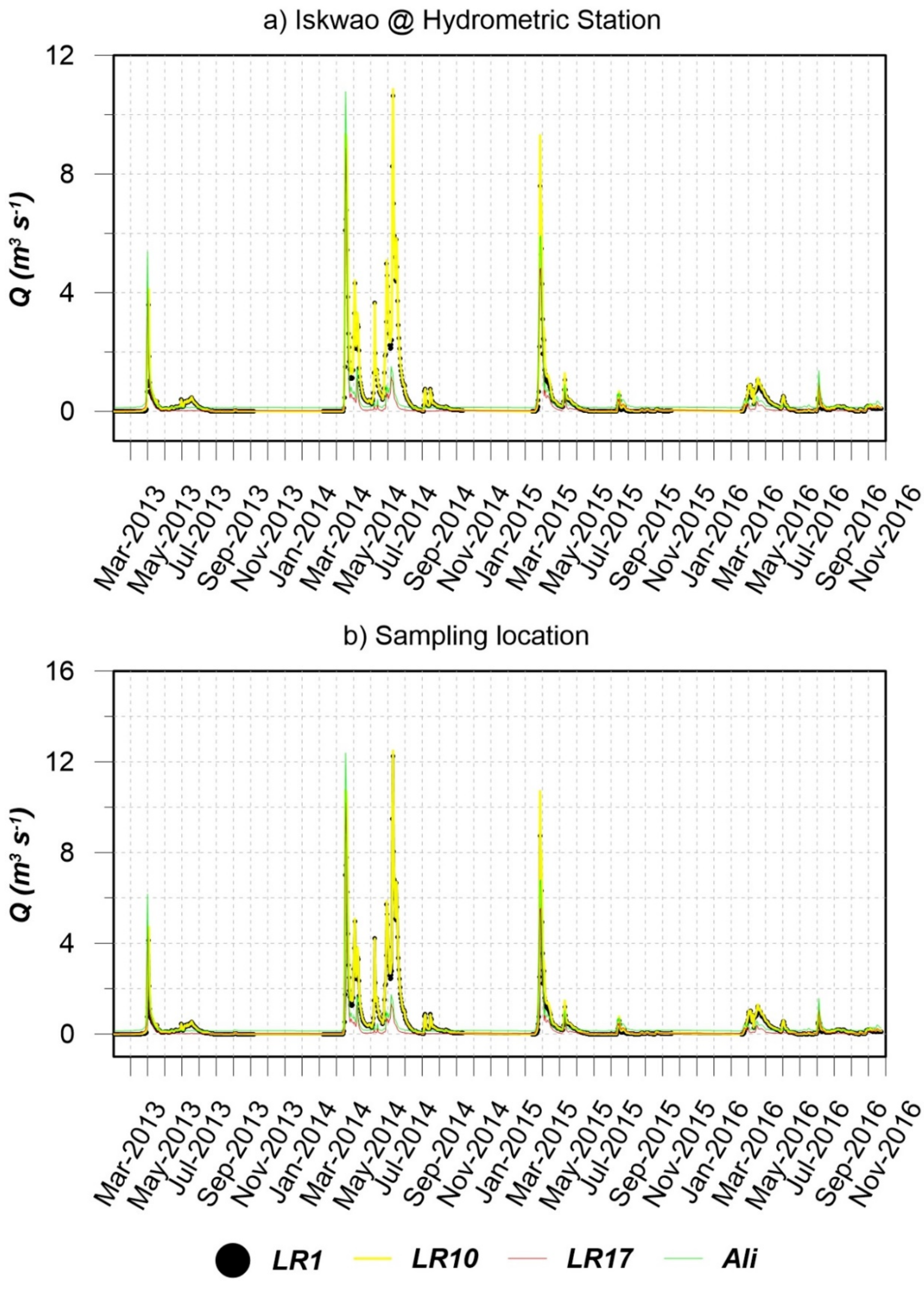


Figure 1.3: Estimated flows at Iskwao Creek near Craik hydrometric station (a) and estimated flows at the sampling location (b). Note that the effective drainage area to the sampling location is 15% greater than that the EDA to the hydrometric station.

1.2 **Qu'Appelle River above Buffalo Pound Lake (05JG004) and Ungauged Flows**

Hydrometric data at Qu'Appelle River above Buffalo Pound Lake hydrometric station (05JG004) was recorded from 1935 to 1995. Initially the data was recorded manually during the open water season and just in 1968 the data became continuous at daily time steps. Water Survey of Canada discontinued the station in 1995 but was reactivated in June 2015 by the Water Security Agency. The Qu'Appelle River at this location has an estimated effective drainage area of 996 km^2. Only 35% of the effective drainage area to the hydrometric station is gauged. Ridge Creek (05JG013) and Iskwao Creek (05JG014) are the two other hydrometric stations that recorded data in the watershed until 2011 and currently Ridge Creek is the only active hydrometric station.

Table 1.3: summarizes effective and gross drainage are of the upper Qu'Appelle watershed.

Hydrometric Station (ID)	EDA (km^2)	GDA (km^2)
Ridge Creek (05JG013)	233	460
Iskwao Creek (05JG014)	114	370
Lewis Creek (05JH005)	143	464
Qu'Appelle River above BPL (05JG004)	996	2,666

In addition to natural runoff, the Qu'Appelle River above Buffalo Pound (05JG004) hydrometric station records data from the Elbow Diversion Canal (05JG006), therefore, flows at this station can be represented by the following equation.

$$Q_{05JG004} = Q_{Ungauged} + Q_{05JG013} + Q_{05JG014} + Q_{05JG006} \qquad \text{(equation 1.4)}$$

Then ungauged flows above Buffalo Pound Lake can be defined as the recorded flows at the Qu'Appelle River above BPL (05JG004) minus recorded flows from Ridge Creek (05JG013), Iskwao Creek (05JG014), and the Elbow diversion (05JG006) which is represented by the following equation.

$$Q_{Ungauged} = Q_{05JG004} - Q_{05JG013} - Q_{05JG014} - Q_{05JG006} \qquad \text{(equation 1.5)}$$

These stations recorded data for a common period of time of 24 years (1972-1995). The equation 1.5 provides positive and negative values throughout the year. Negative values (Figure 1.4) might be the result of water going into storage or being lost in the system before reaching Qu'Appelle River above Buffalo Pound Lake hydrometric station. Figure 1.4 illustrates ungauged flows for 1972-1995.

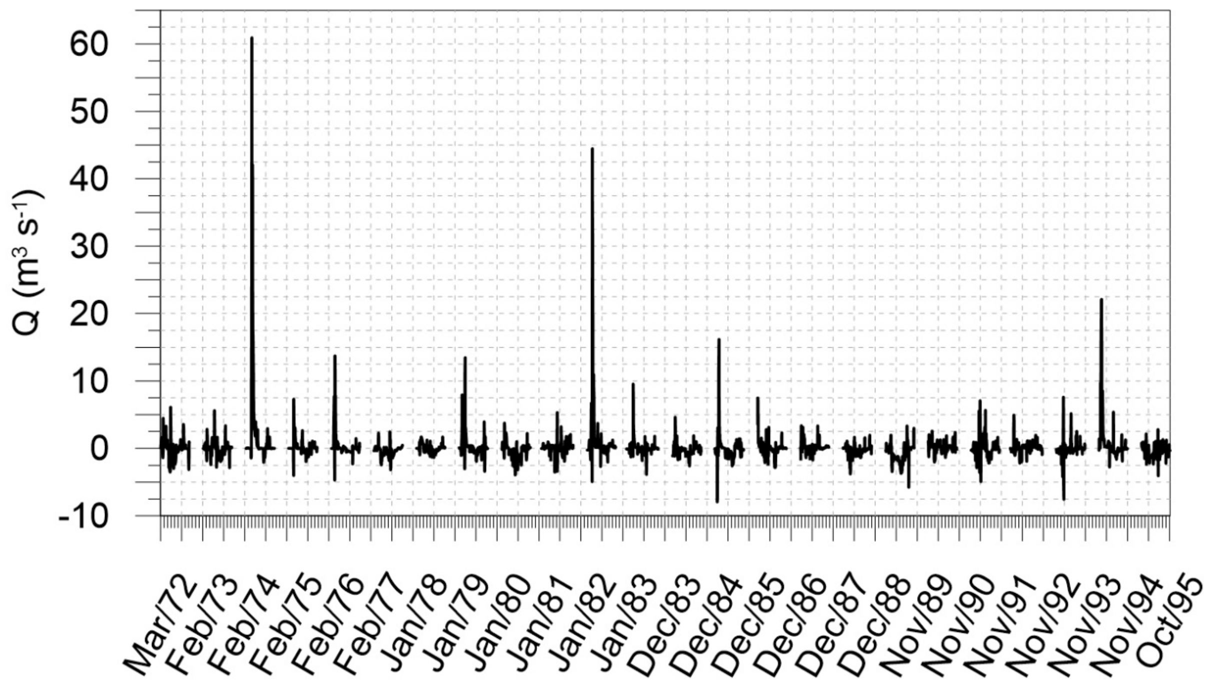


Figure 1.4: Ungauged contribution to the Qu'Appelle River above Buffalo Pound (05JG004) for the period 1972-1995.

The ungauged flow estimates calculated above were used to define five multiple linear regression models. As with the MLR models for Iskwao Creek, ungauged flows were defined as function of Ridge and Lewis Creek for the period 1972-1995. The regression coefficients are summarized in table 1.5. The five models explain between 0.35 and 0.50 of the variance of the ungauged flows. The largest coefficient of determination was obtained with the model that used Ridge and Lewis Creek as predictors and considered only positive flows (uLR4).

In addition, the non-linear regression model to estimate the ungauged flows of the Upper Qu'Appelle watershed proposed by Nazemi was assessed over the 1971-1992 period. The coefficient of determination of this equation was similar to the linear regression equations developed using Ridge Creek as predictor (uLR2; table 1.5). On the other hand, Nazemi's equation was also outperformed by the equations that used Ridge and Lewis Creek as predictors (Table 1.5).

Table 1.4: MLR coefficients for the ungauged flows. * Only positive values of the ungauged flows were used to define the regression model.

MLR	*a*	*Iskwao Coeff.*	*Ridge Coeff.*	*Lewis Coeff.*	*Coeff. of Determination (R^2)*
uLR1	-0.06056	2.33341	----	----	0.42
uLR2	-0.05478	----	1.10386	----	0.35
uLR3*	0.25844		1.13106	----	0.42
uLR4*	0.21321		0.86742	1.88534	0.50

uLR5	-0.10808		0.82014	2.03052	0.42
uAli	-0.05958*Ridge^2 + 2.77*Ridge -0.1463				0.35

In addition to assessing the performance of the linear regression models for estimating ungauged flows above BPL, the hydrometric data recorded at the station was reconstructed using equation 1.4 and compared to the recorded data over the period 2015-2016 (Figure 1.5). Figure 1.5 illustrates estimated and observed ungauged plus Iskwao flows (a) and the reconstructed flows at the hydrometric station (b). Overall, the models presented small differences in the flow estimation among them.

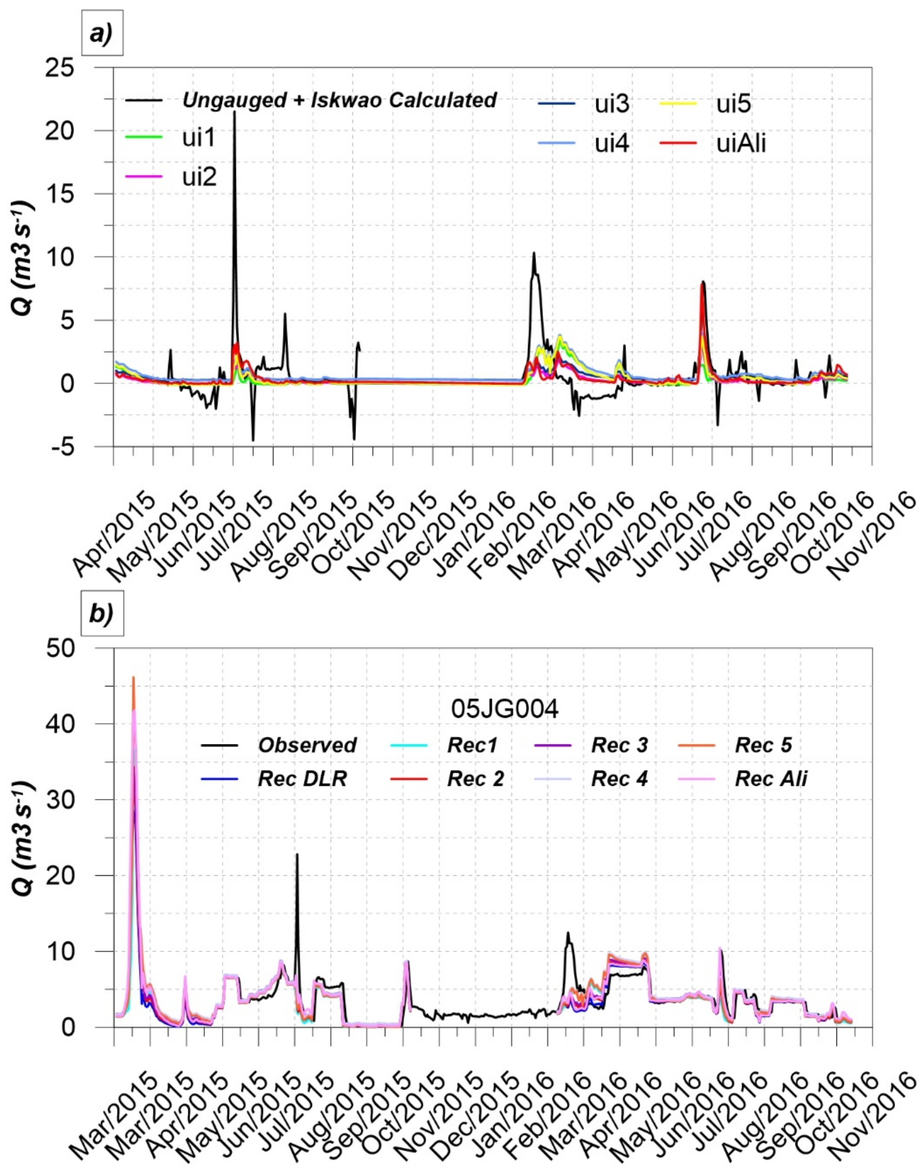


Figure 1.5: a) Recorded and estimated Ungauged plus Iskwao flows at Qu'Appelle River above Buffalo Pound Lake. b) Recorded and reconstructed flows at Qu'Appelle River above Buffalo Pound Lake from March 2015 to October 2016.

The goodness of the estimate was evaluated according to the coefficient of determination between the reconstructed time series and the observed data (Table 1.5). In general, all the models with the exception of Rec DLR model, which was based on a linear regression of the flows recorded at Qu'Appelle River above Buffalo Pound Lake (05JG004), perform well. Their coefficient of determination ranges between 0.83 and 0.86 and this high coefficient is mostly due to that during this period of time the only unknown was the ungauged flows. On the other hand, the performance of the models decreased over the 2015-2016 period considerably. This is likely because during this period the regression models used two variables that were derived from other hydrometric stations, increasing the uncertainty in the prediction. The coefficient of determination over this period ranges between 0.46 and 0.53.

Table 1.5: Summarizes the reconstructed time series and the coefficient of determination for each one of the reconstructed models.

Reconstruction 05JG004	Equation used (2015-2016)	R^2 (1972-1995)	R^2 (2015-2016)
Rec1	uLR1 + 05JG0013 +05JG14LR1 + 05JG006	0.86	0.46
Rec2	uLR2 + 05JG013 + 05JG014LR10 + 05JG006	0.84	0.49
Rec 3	uLR3 + 05JG013 + 05JG014LR10 + 05JG006	0.85	0.49
Rec 4	uLR4 + 05JG013 + 05JG014LR17 + 05JG006	0.86	0.49
Rec 5	uLR5 + 05JG013 + 05JG014LR17 + 05JG006	0.85	0.49
Rec Ali*	uAli + 05JG013 + 05JG014Ali + 05JG006	0.83	0.53
Rec AliMod	uAli + 05JG013 + 05JG014LR10 + 05JG006	--	0.53
Rec DLR**	-0.04674 + 2.50844*05JG013 + 05JG006	0.7	0.48
** extracted the releases from Qu'Appelle dam estimating a natural flow.			

Note that for the period 1972-1995 the model used the recorded flows at Iskawao Creek.

The reconstructed models did not capture two significant runoff events over the evaluation period. The models predicted low flows during a summer event that occurred in late July 2015 and also underestimated flows during the spring runoff of 2016 (Figure 5b). The recorded peak flow during the summer event was ~ 23 m^3/s while the models predicted just over 4 m^3/s.

The results summarized in table 1.5 also suggest that the models for the Qu'Appelle River above Buffalo Pound Lake are more sensitive to the ungauged flow estimation than the Iskwao flow estimation, which is consistent with the drainage areas ratios. The models presented little variation in the coefficient of determination when the same linear regression to estimate ungauged flows was used. On the other hand, the non-linear regression proposed by Nazemi provided a better coefficient of determination over the evaluation period (2015-2016) despite its slightly lower value over the development period. The comparison of the two reconstructions using the non-linear regression for the ungauged flow suggested that there is little variability of the flows due to the Iskwao flow estimate (2015-2016). Even though the models were evaluated over a short period of time, in comparison to their development period, the results provided above are considered acceptable and the non-linear relationship proposed by Nazemi will be used to estimate ungauged flows of the upper Qu'Appelle watershed. The estimated ungauged flows and flows recorded at Ridge Creek for the period 2013-2016 are illustrated in Figure 6.

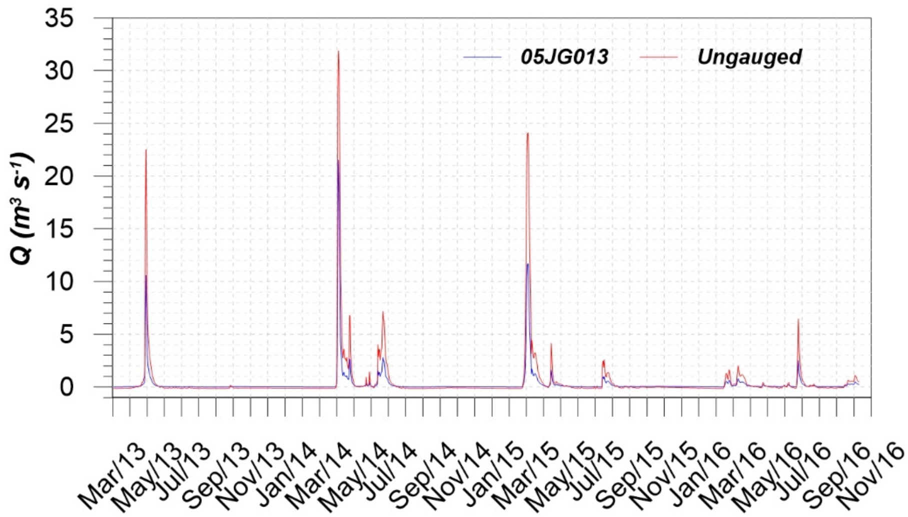


Figure 1.6: Ungauged flow estimation for the upper Qu'Appelle watershed and Ridge Creek flows.

All the reconstructed flows of the Qu'Appelle River above Buffalo Pound Lake are illustrated in figure 1.7. The largest discrepancies presented by the regression models tended to occur during the summer events (i.e. Figure 1.7a, July 2014). Figure 1.7b illustrates the two selected flow reconstruction (Rec Ali and Rec AliMod). As mentioned earlier, these two estimations did not present large discrepancies over the evaluation period, which was likely because the models were evaluated only over two years. However, when comparing the two models over a longer period of time (i.e. 2013-2016; Figure 1.7b) some discrepancies were observed, particularly during the summer of 2014. The differences in the flow estimation are mostly driven by the Iskwao flow estimation.

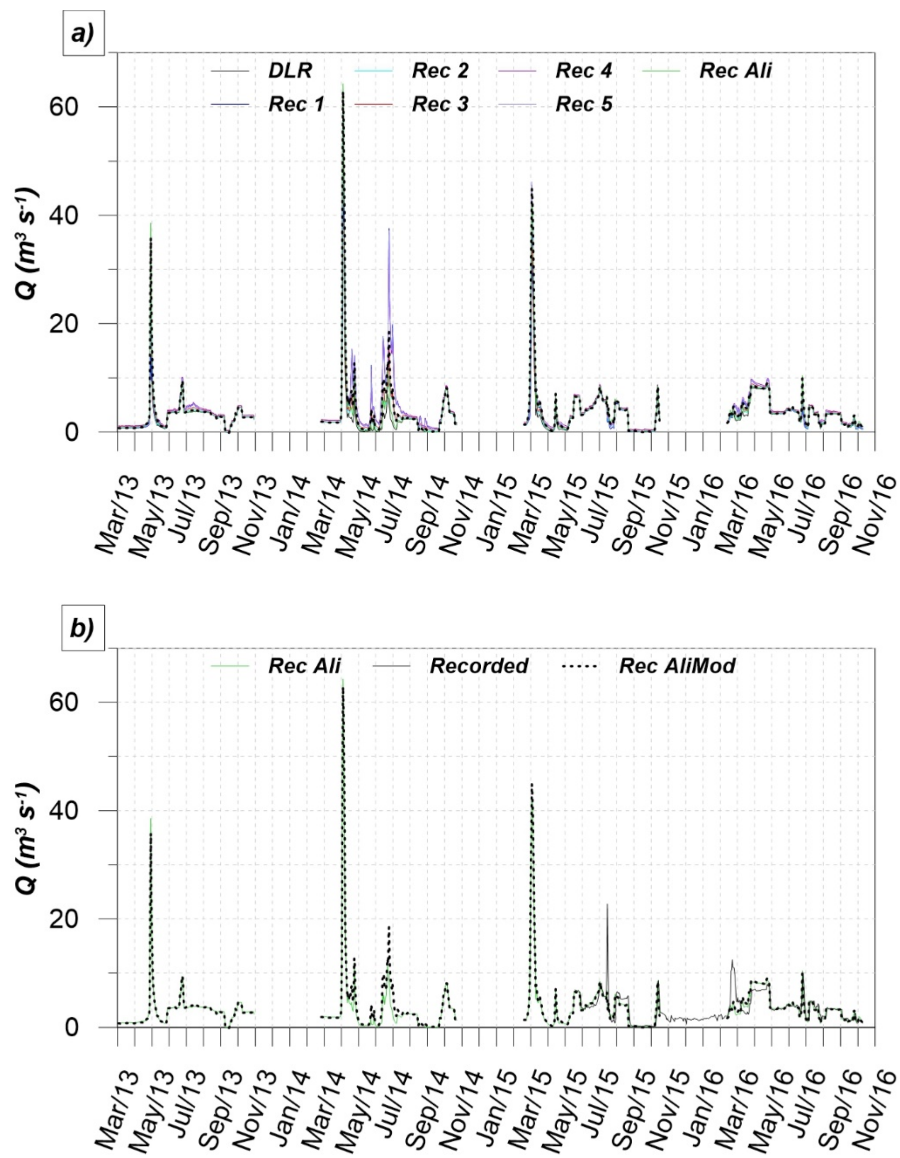


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Figure 1.7: a) Reconstructed flows at Qu'Appelle River above Buffalo Pound Lake (Hydrometric station 05JG004). B) Selected reconstruction based on coefficient of determination (R^2).

Finally, figure 1.8 shows the two reconstructed time series and the "completed" estimated time series for the Qu'Appelle River above Buffalo Pound Lake. The resulting time series is a combination of the estimated flows by the regression model (March to October) over the period 2013-2015 plus recorded flows over the wintertime (Nov-Feb) at the Elbow Canal Diversion and finally the recorded flows from June 2015 to October 2016.

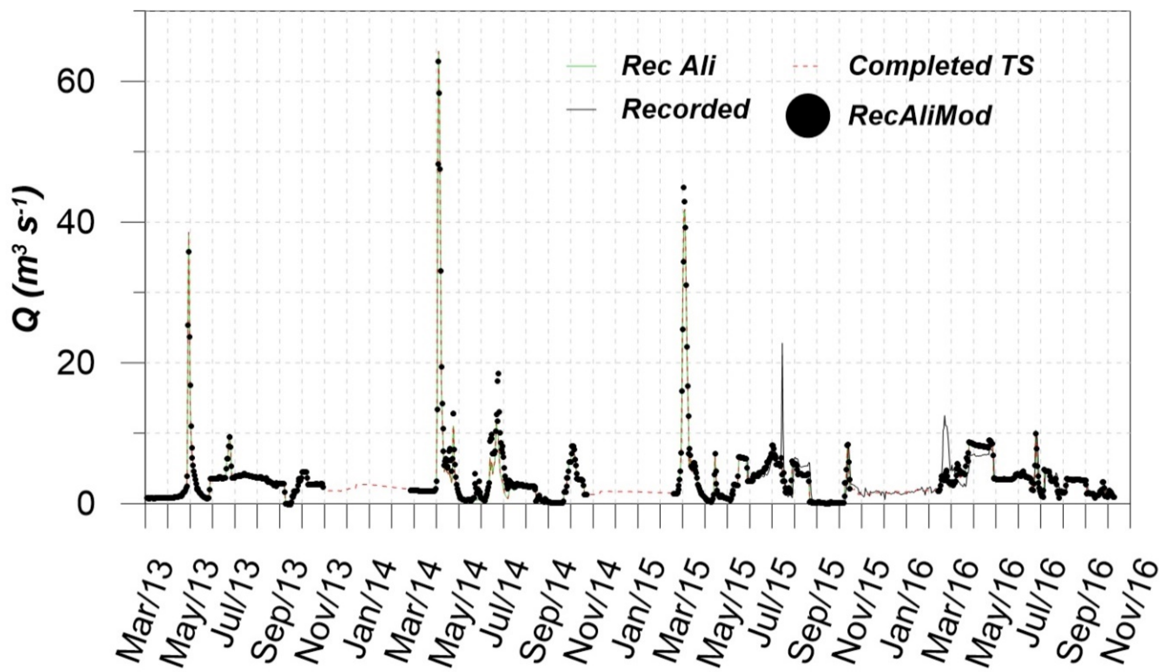


Figure 1.8: Estimated and recorded flows at Qu'Appelle River above Buffalo Pound Lake hydrometric station (05JG004). The final time series are formed by the reconstructed flows and observed records.

The analyses provided here did not take into consideration travel times when developing linear regression equations. In reality, it will probably take a day or two for the flows recorded at Ridge Creek to appear at the Qu'Appelle River above Buffalo Pound Lake hydrometric station and maybe less for the flows recorded at Iskwao Creek. The travel times can also be taken into consideration by the development of a lagged model.

*1.3 **Qu'Appelle River at Tugaske***

Flows of the Qu'Appelle River at Tugaske is the sum of the flows of Ridge Creek, Elbow Diversion, and flows from the ungauged part of the watershed (Equation 1.6). The effective drainage area to the sampling location at the Tugaske crossing is estimated to be 352 km^2 from which 119 km^2 are ungauged. This estimation assumes that the Deer Run Creek does not cross Highway # 627 and enters the Qu'Appelle River on the upstream side of the Tugaske crossing. Table 1.6 summarizes the drainage areas for the different creeks in the Upper Qu'Appelle watershed.

Table 1.6.: Effective drainage areas

Stream	Drainage Area (km^2)
Ridge Creek	233
Ungauged Qu'Appelle	54.3

Deer Run Creek	65
Total	352.3
Ungauged Area	119.3

$Q_{Tugaske} = Q_{Ridge} + Q_{Elbow} + Q_{unTugaske}$ (equation 1.6)

$Q_{unTugaske} = (Area_{UnTugaske}/Area_{UnWatershed}) * Q_{UnWatershed}$ (equation 1.7)

Where $Area_{unWatershed} = 490\ km^2$

Flows at Ridge Creek and Elbow Canal Diversion for the period 2013-2016 are known while the ungauged flows for the Upper Qu'Appelle watershed were estimated in the previous section. Therefore, flows of the Qu'Appelle River at Tugaske were calculated by applying equations 1.6 and 1.7 (Figure 9).

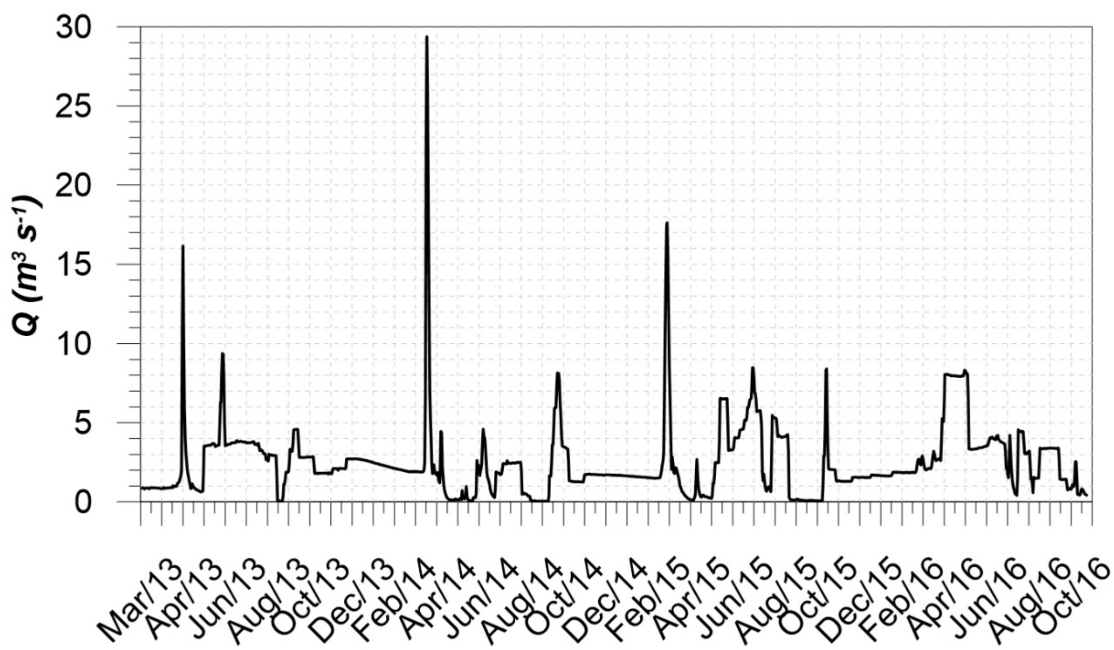


Figure 1.9: Estimated flows at Qu'Appelle River at Tugaske from March 2013 to October 2016.

1.4 **Qu'Appelle River at Marquis**

The Qu'Appelle River at Marquis sampling location is only a few kilometers downstream of the Qu'Appelle River above Buffalo Pound Lake hydrometric station. Therefore, the flows for this station are divided into two periods. The first period is from March 2013 to May 2015, for this period the estimated flows are the result of adding the flows from the MLR model (calculated in the previous section) and flows from the ungauged area between the sampling location and the hydrometric station. The second period is from June 2015 to October 2016 and was obtained by adding the recorded flows at Qu'Appelle River above Buffalo Pound Lake (05JG004) and the additional ungauged flows between the two locations.

$Q_{2013\text{-}15} = Q_{MLR} + Q_{UnMarquis\ 2013\text{-}15}$ (equation 1.8)

Where:

Q_{MLR} was estimated in the previous section.

$Q_{2015\text{-}16} = Q_{05JG004} + Q_{UnMarquis\ 2015\text{-}16}$ (equation 1.9)

Expressing ungauged flows at Marquis as function of the drainage areas we obtain equation 1.10. The additional contributing drainage area between the Qu'Appelle River above Bufallo Pund Lake and Marquis is 42 km^2.

$Q_{UnMarquis} = (Area_{UnMarquis} / Area_{UnWatershed}) * Q_{Ungauged\ Watershed}$ (equation 1.10)

Where: $Area_{unWatershed} = 490\ km^2$

Figure 1.10 illustrates the estimated flows of the Qu'Appelle River at Marquis for the period 2013-2016.

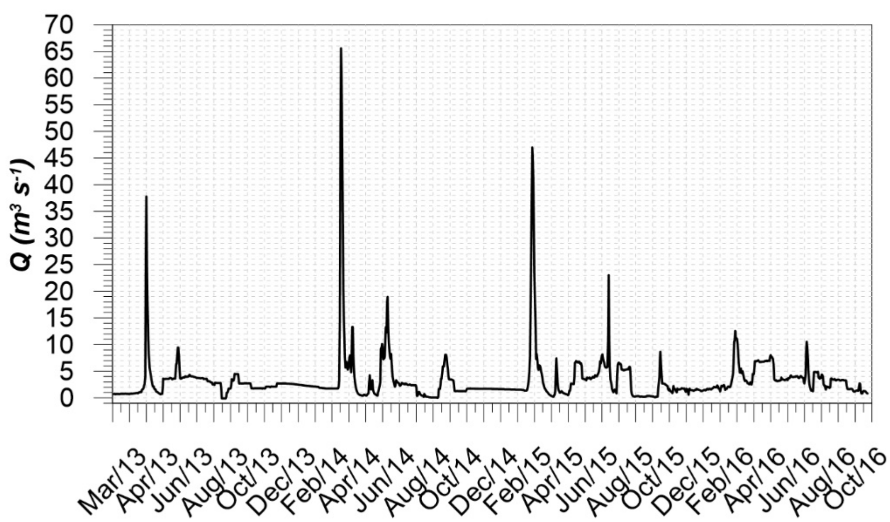


Figure 1.10: Qu'Appelle River at Marquis 2013-2016.

2 *Buffalo Pound Lake, Outflows and Backwater Estimates*

2.1 ***Background***

Buffalo Pound Lake experiences backwater flows from the Moose Jaw River when flows exceed 50-60 m3/s. The water enters the lake through the fish passage and overtopping the radial gates (gates are closed during the backwater period). Until 1994 the amount of backwater into the lake was more or less quantifiable because flows were recorded in the Moose Jaw River and in the Qu'Appelle River (hydrometric station 05JG007) just downstream of the confluence. Currently flows in the Moose Jaw River continue to be recorded a few kilometers upstream of the confluence (Moose Jaw River near Burdick, 05JE006). Therefore, assuming that there is little to zero flow contribution between these two stations, backwater flows into Buffalo Pound Lake can be estimated as the difference of flows at the two hydrometric stations whenever flows at Moose Jaw River (05JE006) are greater than the flows at the Qu'Appelle River (05JG007; equation 2.1). Backwater flows are expected to occur until Buffalo Pound lake peaks. Figure 2.1 illustrates the historical recorded flows at the two hydrometric stations and water levels at Buffalo Pound for the period 1972-1994.

Backwater to Buffalo Pound is defined by equation 2.1:

$$BW_{BP} = Q_{05FE006} - Q_{05JG007} \quad \text{if} \quad Q_{05FE006} >= Q_{05JG007} \quad \text{(equation 2.1)}$$

Historical records suggest that there were 7 years (1974, 1975, 1976, 1979, 1982, 1983, and 1994) in which backwater into Buffalo Pound Lake occurred during the 1972-1994 period.

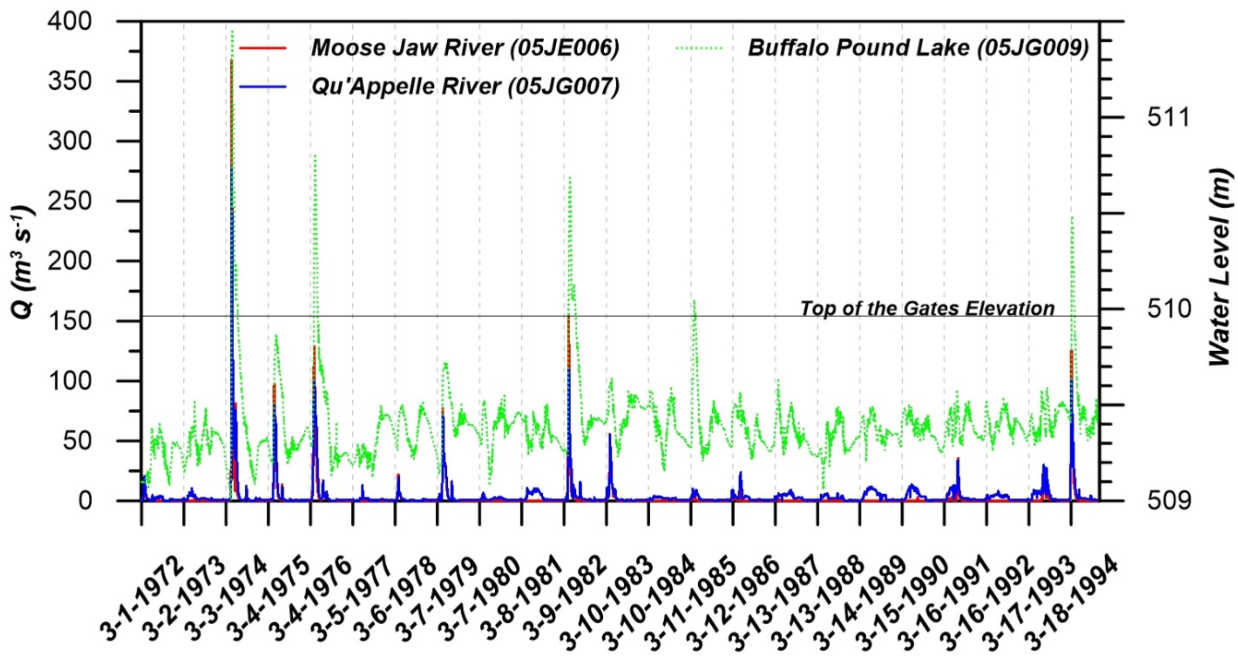


Figure 2.1: Historical Moose Jaw and Qu'Appelle River flows and water levels of Buffalo Pound Lake for the period 1972-1994.

2.2 **Backwater Models into Buffalo Pound Lake**

Multiple Linear regression models were also used to estimate the relationship between backwater flows, Moose Jaw River flows and the Lake Level of Buffalo Pound for the period 1972-1994.

The models follow the form

$$BW_{BP} = a + b * Q_{05FE006} + c * Q_{05JG09e} \qquad \text{(equation 2.2)}$$

Where:

$Q_{05FE006}$ is the recorded flow at the Moose Jaw River and $Q_{05JG09e}$ is the recorded water level at Buffalo Pound (05JG009) minus 509.85 m, which is the top of the radial gates. In order to account for the effect of the lake on back flows only positive values were used. The intercept is defined by a, and b and c are the regression coefficients of the model.

Following the general multiple linear regression (MLR) equation, four MLR models were defined using recorded flows and water levels for the 1972-1994 period.

Regression 1: The first MLR model was defined using the observed records for the three hydrometric stations. The main assumption of this model is that ignores the variable *time*. In other words, backwater to Buffalo Pound Lake for the day ***i*** is function of the flow recorded at 05JE006 and the Lake level during the day ***i***.

Regression 2: The MLR model 2 aimed to take into consideration the variable "***time***". The backwater model used the previous day flow and water level to estimate back flows into the lake. (Assuming a lag of 1 day)

Regression 3: This model also takes into consideration the previous day flow and water level. The difference of this model is that uses an average of two days to define the model. The advantage of using the average over the 1-day lag is that minimizes the impact of the hydrometric errors in the backwater computation.

Regression 4: The MLR model 4 was defined by using the same concepts as the Regression 3 model but the coefficients for this model were estimated using only spring runoff months.

The regression coefficients for the four fitted models to estimate backwater flow into Buffalo Pound Lake are summarized in table 2.1. These models explain between 63 and 70% of the variance of the backwater flow estimate. Overall, the models simulated better backwater flows for years in which the flows of the Moose Jaw River exceeded 100 m^3/s (1974, 1976, 1982, and 1994). On the other hand, all the models overestimated the backwater volume for years in which the Moose Jaw River flow was between 50 and 100 m^3/s (1975, 1979, and 1983).

Table 2.1: Multiple linear regression models and their respective coefficients.

MLR	Coefficients			R^2_{adj}
	a*	***b***	***c***	
Regression 1	-0.1496	0.24311	-14.4804	0.63
Regression 2	-0.14541	0.176298	-7.82662	0.67
Regression 3	-0.12852	0.219643	-12.6379	0.69
Regression 4	-0.24607	0.226011	-13.1037	0.70

*For the purpose of this analysis, only the positive values obtained from the regression analysis were used.

Statistically the best performing models are Regression 3 and Regression 4 that explain ~70% of the variance providing a greater degree of confidence on their estimate. Although, the level of confidence decreases when flows in the Moose Jaw River are less than 100 m^3/s.

Figure 2.2 illustrates the backwater estimates from the four regression models with the actual backwater calculation while table 2.2 summarizes the monthly ratios of estimated to observed back water for the seven years in which backwater flows occurred.

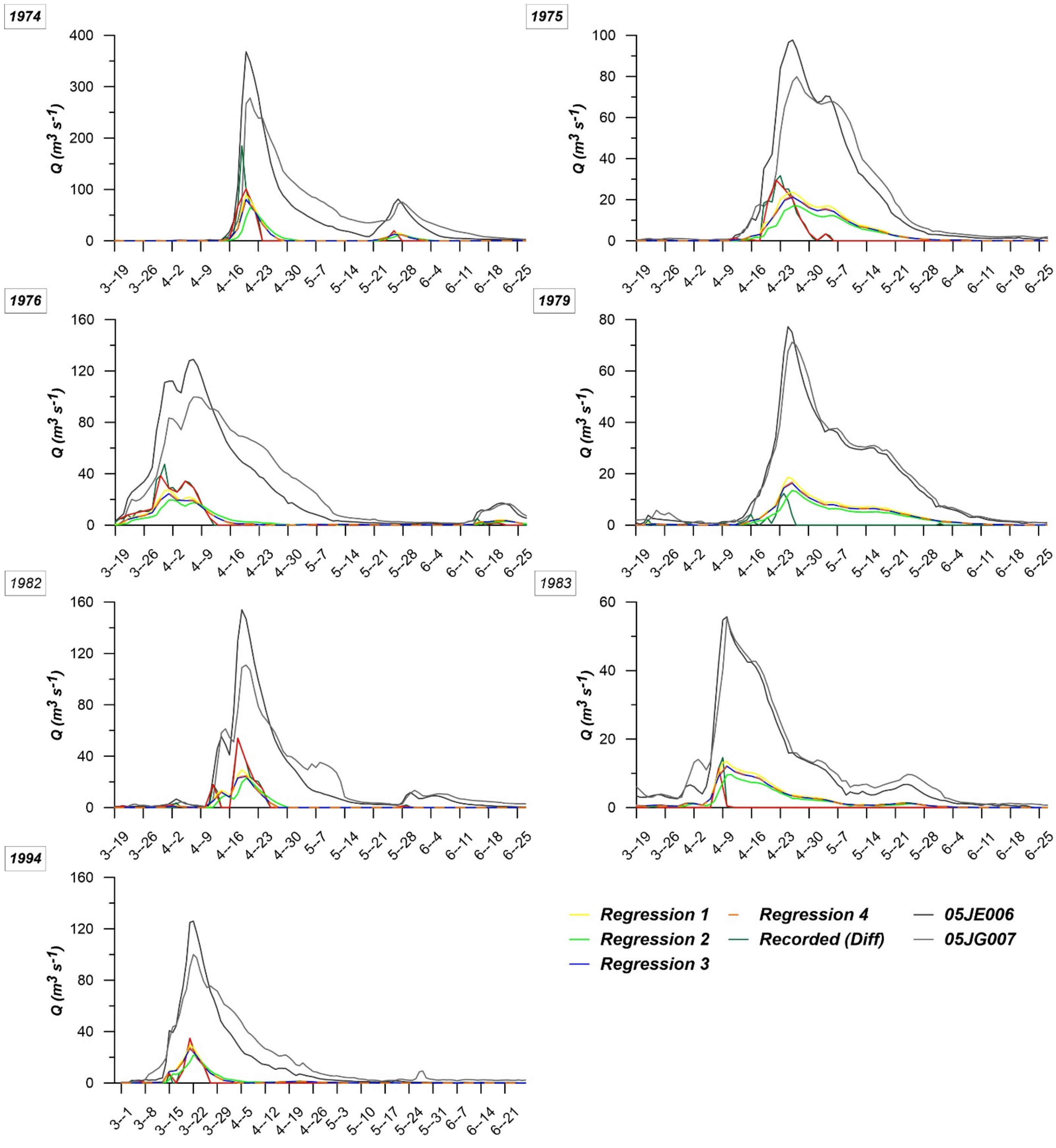


Figure 2.2: Backwater flow estimation in Buffalo Pound Lake for the period 2013-2016

Table 2.2: Mean monthly flow ratio observed backwater to simulate by the regression model.

	Regression Model 1			Regression Model 2			Regression Model 3			Regression Model 4		
Year	Mar	Apr	May	Mar	Apr	May	Mar	Apr	May	Mar	Apr	May
1974		1.18			0.94			1.11			1.08	
1975		1.02	0.04		1.12	0.09		1.05	0.04		1.03	0.04
1976	1.64	1.13		1.37	1.20		1.75	1.19		1.72	1.18	
1979		0.36			0.15			0.40			0.40	
1982		1.25			1.34			1.41			1.39	
1983		0.17			0.09			0.14			0.13	
1994	0.70			0.77			0.77			0.70		

Based on the coefficient of determination and the monthly volume ratios provided in table 2.2 the Regression Model 4 was considered to provide the best estimate of backwater into Buffalo Pound Lake.

Additionally, the backwater flow estimates obtained by the Regression Model 4 were also compared to the estimate inflow volume to the lake during 2013. The estimated backwater flow volume into Buffalo Pound Lake during the spring runoff of 2013 was more or less estimated by calculating the difference in the lake volume pre and post high flows of the Moose Jaw River. In other words, the lake level on April 26, 2013 was 509.061 m and flows of the Moose Jaw River were 36 m^3/s. The lake peaked on May 12, 2013 at 510.22 m while the flows of the Moose Jaw River receded to 61 m^3/s. Therefore, the inflow volume based on the area-elevation-capacity curve of the lake during this period of time was ~ 35,000 dam^3 while the regression model estimated a backwater volume of ~ 34,600 dam^3. However, the model might be overestimating the total volume because it is very likely that there were also inflows from the Upper Qu'Appelle. Similarly, the total inflow volume during the backwater period of 2015 was near ~30,000 dam^3, however, flows in the Moose Jaw River were smaller than during 2013 which resulted in a smaller volume of backwater into Buffalo Pound Lake. The backwater volume during 2015 was estimated to be ~10,400 dam^3.

2.3 **Outflows from Buffalo Pound Lake**

The outflows from the lake were estimated according the existing operation log. It was assumed that there were no outflows from the lake during the backwater period. For the periods in which the operation log did not provide flow information the water level and the outflow rating curve were used to estimate the lake outflows. Figure 2.3 illustrates the estimated outflows from Buffalo Pound Lake as well calculated backwater flows and water levels for the period 2013-2016.

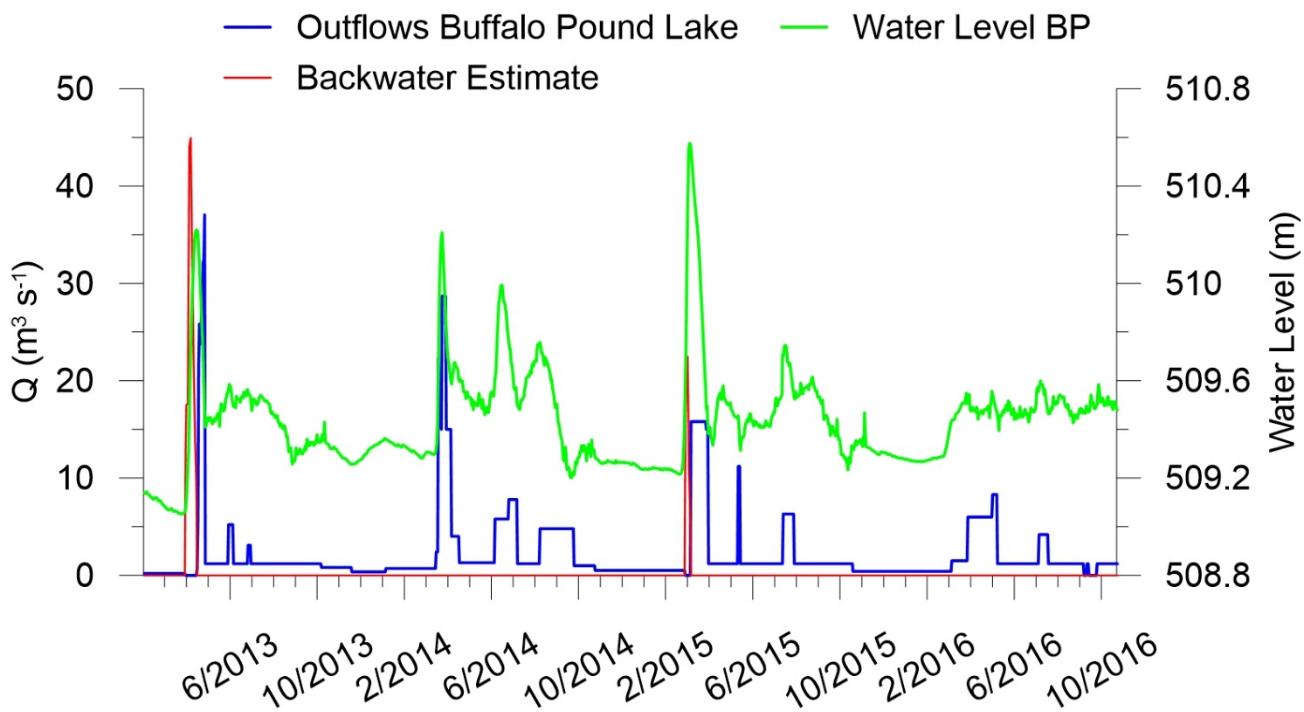


Figure 2.3: Outflows and backwater estimate from Buffalo Pound Lake for the period 2013-2016.

3 *Lumsden Craven Area*

3.1 Qu'Appelle River Upstream of Wascana Creek Confluence (Q_{uWas})

This sampling location is located only a couple of kilometers upstream of the confluence of the Qu'Appelle River and Wascana Creek. There is only one major tributary (Wascana Creek, 05JF005) between this sampling location and the Qu'Appelle River at Lumsden hydrometric station (05JF001). Therefore, flows at this sampling location can be estimated as the recorded flows at Lumsden minus the Wascana Creek (05JF005) flows (equation 3.1)

$$Q_{uWas} = Q_{05JF001} - Q_{05JF005} \qquad \text{(equation 3.1)}$$

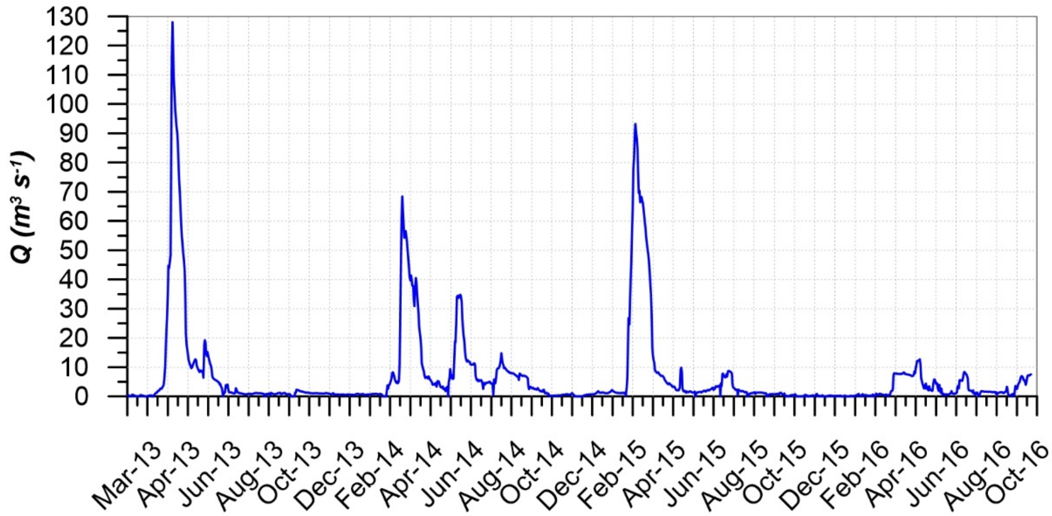


Figure 3.1: Estimated flows for Qu'Appelle River upstream of the Wascana Creek confluence.

3.2 Qu'Appelle River Upstream Lumsden (Q_{uLum})

Flows at this location are considered to be the same as the recorded flows at the Qu'Appelle River at Lumsden hydrometric station (Figure 3.2).

$$Q_{uLum} = Q_{05JF001} \qquad \text{(equation 3.2)}$$

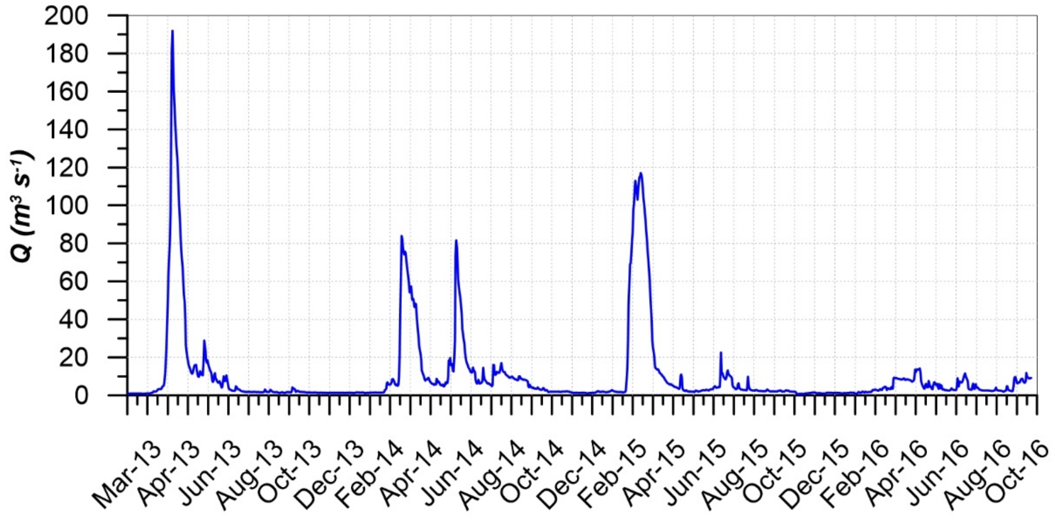


Figure 3.2: Estimated daily flows of the Qu'Appelle River upstream Lumsden.

3.3 Qu'Appelle River Upstream of Last Mountain Lake Confluence (Q_{uLas})

Flows of the Qu'Appelle River upstream of the confluence with Last Mountain Creek are the result of the recorded flows at Lumsden plus the gauged flows from Boggy Creek and ungauged flows from the drainage area between the hydrometric stations and the sampling location.

The hydrometric station in Boggy Creek is located a few kilometers upstream of the confluence with an estimated effective drainage area of 234 km^2. The ungauged drainage area between the two station and the sampling location is estimated to be 231 km^2. Therefore, the additional ungauged contribution was estimated using recorded flows at Boggy Creek and drainage area ratios. The main assumption was that the ungauged and Boggy Creek drainage areas have a similar hydrological response.

Daily flows of the Qu'Appelle River upstream of Last Mountain Lake were calculated according to equation 3.3.

$Q_{uLas} = Q_{05JF001} + (Area_{ungauged}/Area_{Boggy}) * Q_{05JF006} + Q_{05JF006}$ (equation 3.3)

Where:

$Area_{ungauged}$ = 231 km^2 and $Area_{Boggy}$ = 234 km^2.

Finally, estimated daily flows of the Qu'Apppelle River upstream Last Mountain Lake confluence are illustrated in figure 3.3

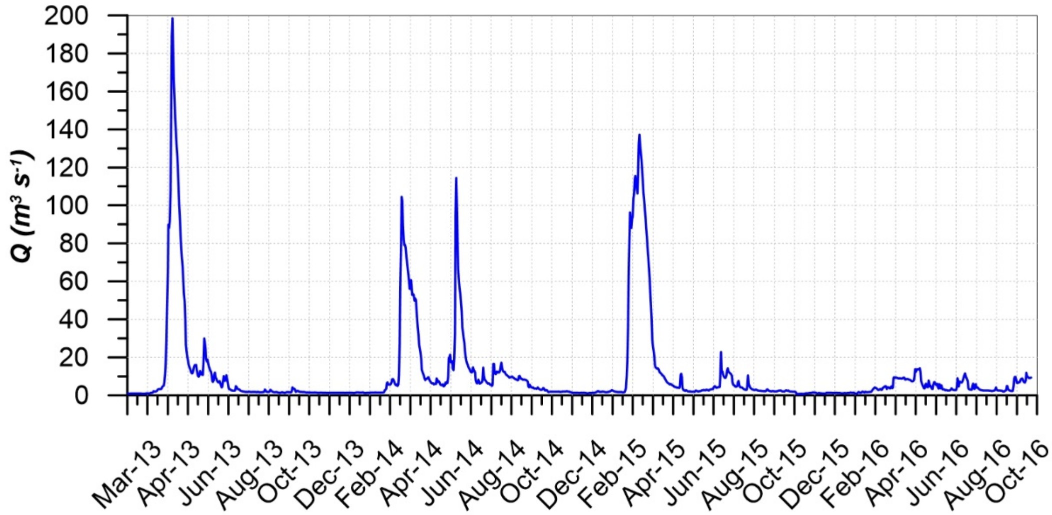


Figure 3.3: Daily flows of the Qu'Appelle River upstream of Last Mountain Lake confluence.

3.4 Last Mountain Lake Channel (Q_{LML})

Flows in the Last Mountain Lake Channel are the result of the recorded flows at the Qu'Appelle River below Craven Dam (05JK002) minus the flows of the Qu'Appelle River upstream of Last Mountain Lake confluence.

$$Q_{LML} = Q_{uLas} - Q_{05JK002} \qquad \text{(equation 3.4)}$$

The equation above results in positive and negative values. Positive values indicate that the flows are inflows from Last Mountain Lake while negative values indicate that the flows are outflows into Last Mountain Lake (Figure 3.4).

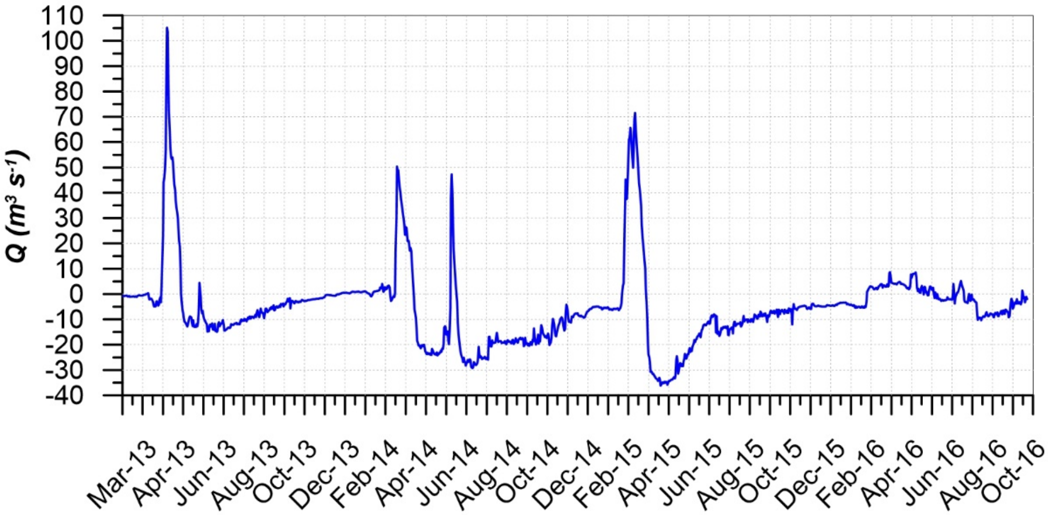


Figure 3.4: Daily flow estimate of Last Mountain Lake channel.

3.5 Loon Creek

Loon Creek flows used to be recorded at Loon Creek near Markinch hydrometric station (05JK006), however, the station was operational for a period of 11 years only (1944-1954). Unfortunately, this short record does not overlap with other records from stations nearby which makes impossible to attempt the development of empirical relationships. On the other hand, hydrometric data was collected at the sampling location from April to October of 2014.

The 2014 data was used to carry out correlation analyses with nearby hydrometric stations. The results of these analyses suggested that recorded flows at Echo creek during 2014 are significantly correlated (r = 0.84) with the recorded Loon Creek flows. This significant correlation was used to develop a linear regression model using Echo Creek flows as predictor of Loon Creek flows (equation 3.5)

$$Q_{Loon} = 0.3884 + 0.37516 * Q_{Echo} \quad \text{(equation 3.5)}$$

The intercept of the equation above is 0.3884 suggesting that whenever the flows at Echo Creek are zero flows at Loon Creek are 0.38 m^3/s. This is not always the case and a conservative assumption would be that whenever the flows at Echo Creek are zero the flows at Loon Creek should be zero. Figure 3.5 illustrates the recorded and estimated flows of Loon Creek for the period 2013-2016. The figure illustrates the flows calculated using equation 3.5 therefore, flows should be adjusted considering the field observation or just assuming a flow of zero when flows in Echo Creek are zero.

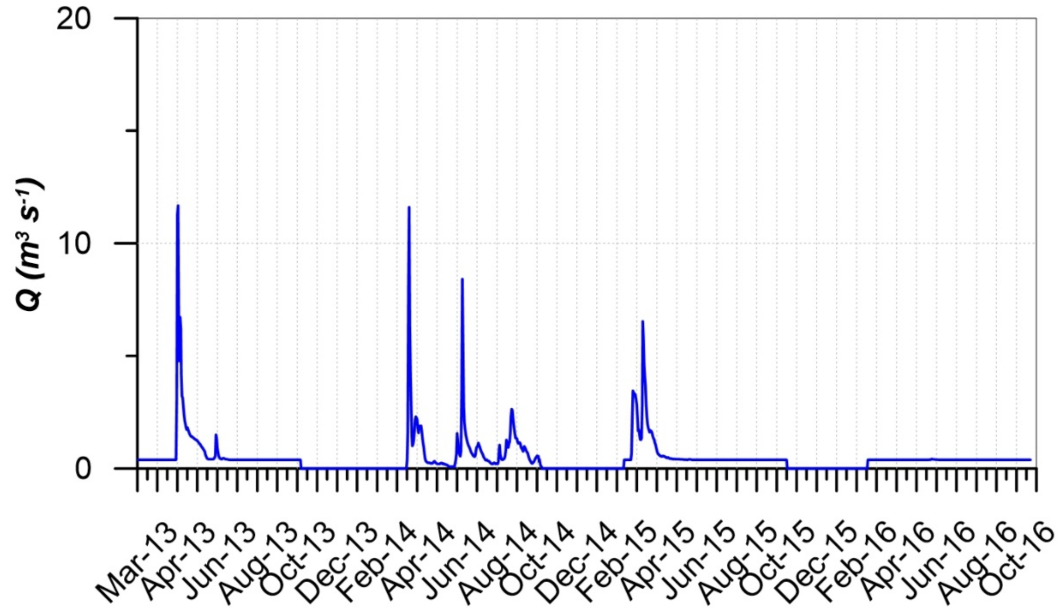


Figure 3.5: Estimated flows for Loon Creek at the sampling location for the period 2013-2016.

3.6 Qu'Appelle River at Highway # 6

This sampling location is located between the Qu'Appelle River at Craven and Qu'Appelle River below Loon Creek hydrometric stations. The Qu'Appelle River below Loon Creek hydrometric station records flows from Loon Creek as well. The additional effective drainage area to this station is 436 km^2, including Loon Creek. The effective drainage area between the two stations that contributes directly to the Qu'Appelle system is 320 km^2 (the effective drainage area of Loon Creek is 216 km^2), however, the additional contributing area to the Qu'Appelle River at Highway #6 is only 90 km^2.

Therefore, flows at Qu'Appelle River at Highway # 6 can be estimated as the recorded flows below the Craven structure plus the flows from the additional contributing drainage area to the sampling location (90 km^2).

Flows recorded at Qu'Appelle River below Loon Creek are equal to the flows recorded at Craven plus the flows from the ungagged area between the hydrometric stations plus the flows from Loon Creek (equation 3.6).

$$Q_{QuALoon\,(t)} = Q_{Cra\,(t-3)} + Q_{unQuA\,(t)} + Q_{Lcrk\,(t)} \qquad \text{(equation 3.6)}$$

Since the flows at Loon Creek were estimated previously the only unknown in the equation is the flow from the ungauged drainage area in the main stem, therefore:

$$Q_{unQuA\,(t)} = Q_{QuALoon\,(t)} - Q_{Cra\,(t-3)} - Q_{Lcrk\,(t)} \quad \text{(equation 3.7)}$$

$$Q_{QHwy6\,(t)} = Q_{Cra\,(t-1)} + (Area_{Hwy\,6} / Area_{UnQuA}) * Q_{unQuA\,(t)} \quad \text{(equation 3.8)}$$

Where:

$Area_{Hwy\,6} = 90\ km^2$ and $Area_{UnQuA} = 320\ km^2$ and t in days

The equation above assume a travel time of three days between the two stations (based on cross-correlation) and the travel time from Craven to Highway # 6 was assumed to be 1 day.

Daily flow estimates of the Qu'Appelle River at Highway # 6 are illustrated in figure 3.6 as well as recorded flows of the Qu'Appelle River below Craven and Loon Creeks.

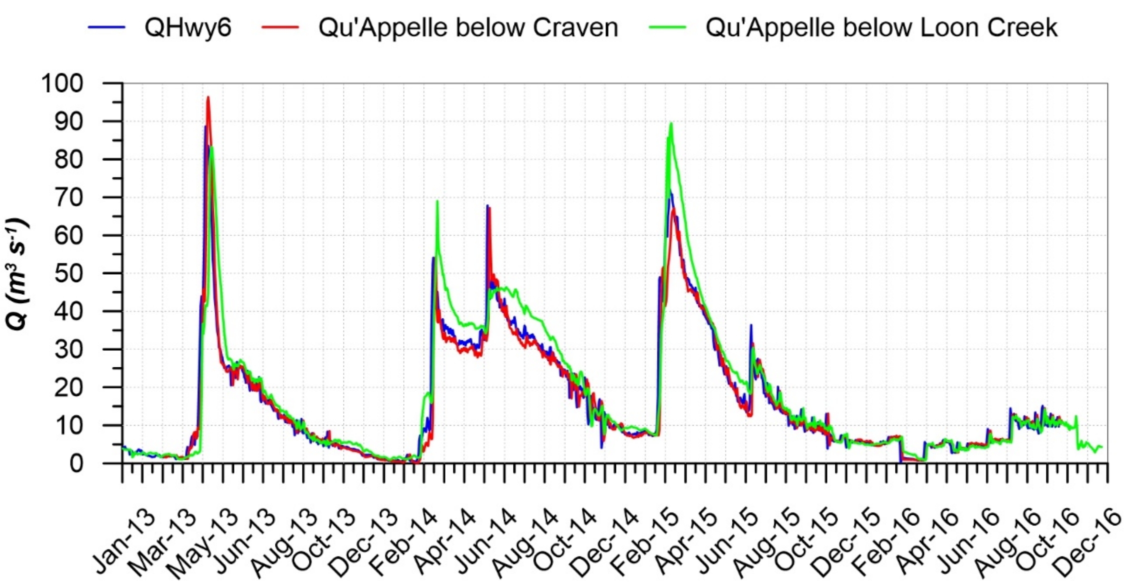


Figure 3.6: Estimated flows of the Qu'Appelle River at Highway #6 (blue) and recorded flows of the Qu'Appelle River below Craven and Loon Creek. No lags were applied to the time series in the figure.

4. Qu'Appelle Lake and Tributaries

4.1 Katepwa Lake Outflows

Outflows from Katepwa Lake were initially estimated using the recorded water levels, the existing operating logs, and the outflow rating curve for the weir, the radial and sluice gates, and the fish passage.

Outflows through the radial gates for the different settings were estimated using the set of curves illustrated in figure 4.1 while figure 4.2 illustrates the previous and modified outflow rating curve for the weir.

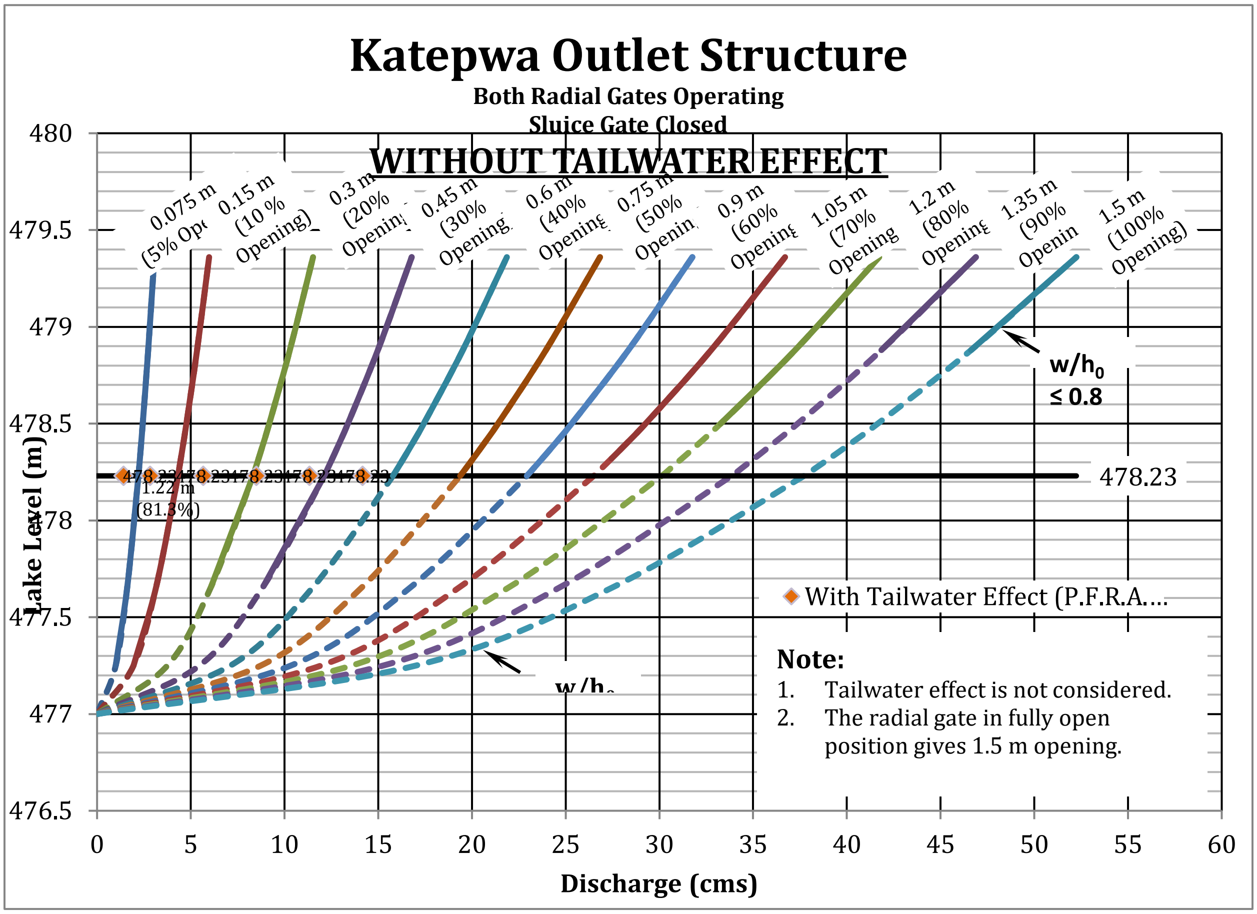


Figure 4.1: Outlet rating curve for different opening settings.

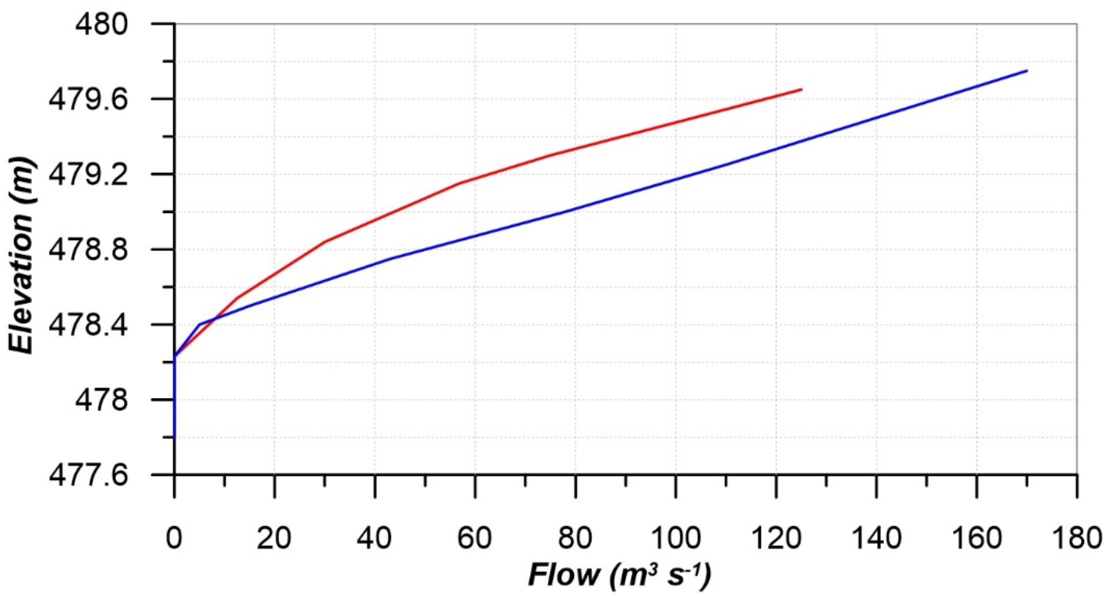


Figure 4.2: Previous (red) and modified (blue) outflow rating curve for the Weir (Katepwa Lake).

In order to verify the estimated outflows, the Qu'Appelle River inflow time series to the lakes was calculated and compared to the recorded flows of Qu'Appelle River below Loon Creek hydrometric station (05JK008). The Qu'Appelle inflows were calculated by reverse routing the outflows derived from initial outflow rating curve and subtracting the local flow contribution to the lakes. The reverse routing approach assumed the following:

a) Pasqua and Echo Lakes were combined into one Lake; therefore, their surface areas and volume capacities were also combined.
b) The historical recorded water levels of Echo Lake represents the historical water levels of the combined lake.
c) The ungauged contribution to this combined Lake (Q_{UnE}) is function of the drainage areas.
d) Mission and Katepwa Lakes were also combined into one lake.
e) The historical recorded water levels of Katepwa Lake represents the historical water levels of this combined lake.
f) The ungauged contribution (Q_{UnK}) is function of the drainage areas.
g) Upstream inflows to Katepwa Lake are equal to Echo Lake outflows.
h) Net evaporation is calculated and the gross evaporation at Regina weather station minus precipitation recorded at the Indian Head weather station.

The most recent area-capacity curves for each lake were combined to create the surface areas and capacities of the two combined lakes and are illustrated in figure 4.3.

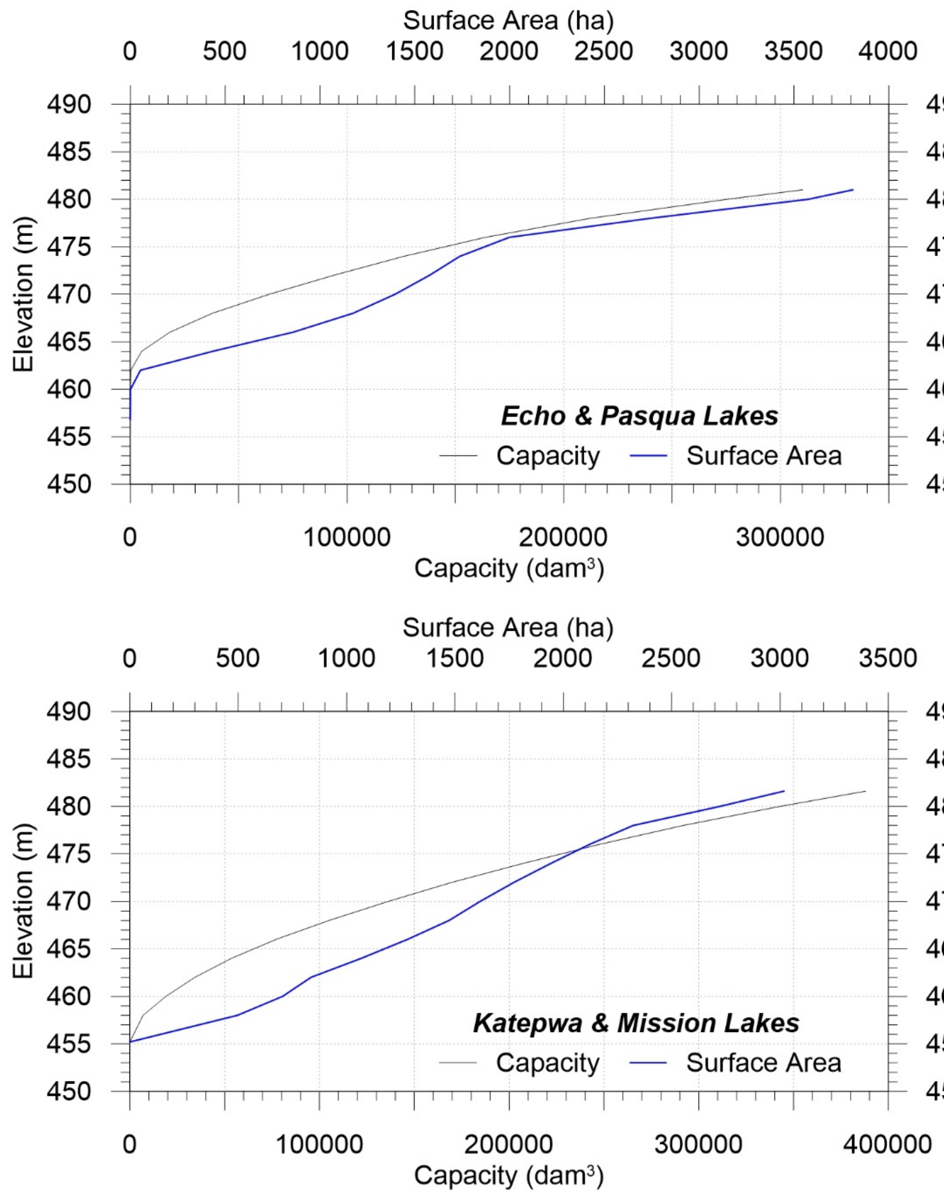


Figure 4.3: Combined surface area and capacities. Top) Echo and Pasqua Lake. Bottom) Mission and Katepwa Lake.

Additionally, the existing operating logs and outflow rating curve for Echo Lake were used to reconstruct the lake outflows. These flows were used to verify the Mission-Katepwa Lake reverse routing (upstream inflows to Mission-Katepwa Lake should be equal to the outflows from Echo Lake). The two time series were not expected to match perfectly each other, however, their comparison provides valuable information of the reliability of the outflow rating curve used for the Katepwa weir. An acceptable inflow calculation will suggest that the two time series follow a similar pattern within a reasonable range considering the uncertainty in the estimation of Echo Lake outflows and the uncertainty associated to the inflow calculation to Mission and Katepwa Lakes. The uncertainty in the estimation of Echo

Lake outflows is mainly associated to the outflow rating curve. Lake outflows are function of the water levels of Echo Lake but also function of the water levels of Mission Lake. On the other hand, the uncertainty in the upstream inflow calculation to Mission and Katepwa Lakes is due to the estimation of the ungauged contribution in terms of volume and timing as well the calculation of the net evaporation (summer precipitation is spatially variable).

Net inflows to the combined Mission and Katepwa Lakes were calculated using the following equations:

$DS_{MK\,(i)} = Q_{inMK\,(i)} - Q_{outMK\,(i)}$ (equation 4.1)

$Q_{inMK\,(i)} = Q_{Echo\ Ck\,(i)} + Q_{Qu'Appelle\ Upstream\,(i)} + Q_{UnMK\,(i)}$ (equation 4.2)

$Q_{outMK\,(i)} = Q_{Outflows\ Katepwa\,(i)} + Q_{NetEvapMK\,(i)}$ (equation 4.3)

Where: DS_{MK} = Change in storage in the combined lake Mission-Katepwa

$Q_{Echo\ Ck}$ = Echo Creek Recorded flows

$Q_{Qu'Appelle\ Upstream}$ = Qu'Appelle River flows (Echo Lake outflows)

$Q_{NetEvap\ MK}$ = Net outflows/inflows due to evaporation/ precipitation from/to the Lakes

$Q_{UnMK} = (Area_{UnK} / Area_{Echo\ Ck}) * Q_{Echo\ Ck}$ (equation 4.4)

Where: $Area_{UnK} = 303\ km^2$

$Area_{Echo\ Ck} = 253\ km^2$

Reordering equation 4.2:

$$Q_{Qu'Appelle\ Upstream\,(i)} = Q_{inMK\,(i)} - Q_{Echo\ Ck\,(i)} - Q_{UnMK\,(i)}$$

Similarly, the daily water balance for Pasqua-Echo Lakes and the upstream inflow calculation are described by the following equations:

$DS_{PE\,(i)} = Q_{inPE\,(i)} - Q_{outPE\,(i)}$ (equation 4.5)

$Q_{inPE\,(i)} = Q_{Qu'Appelle\ River\ Loon\,(i)} + Q_{Jumping\ Deer\,(i)} + Q_{UnPE\,(i)}$ (equation 4.6)

$Q_{UnPE\,(i)} = (Area_{UnPE} / Area_{Echo\ Creek}) * Q_{Echo\ Ck\,(i)}$ (equation 4.7)

Where:

Area $_{UnPE}$ = 249 km^2

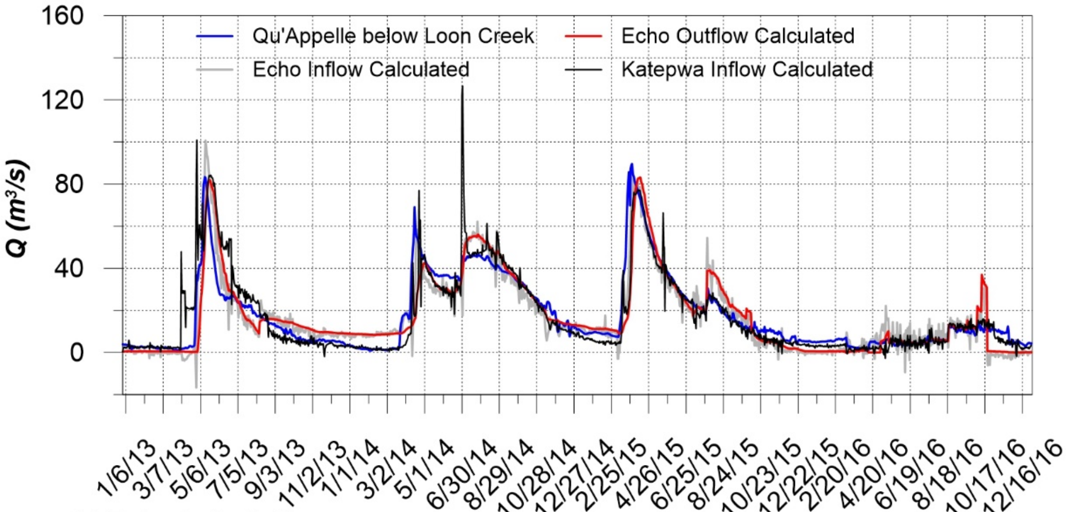
$$Q_{outPE\ (i)} = Q_{Outflows\ Echo\ (i)} + Q_{NetEvap\ PE\ (i)} \qquad \text{(equation 4.8)}$$

Where: $Q_{Outflows\ Echo} = Q_{Qu'Appelle\ Upstream}$

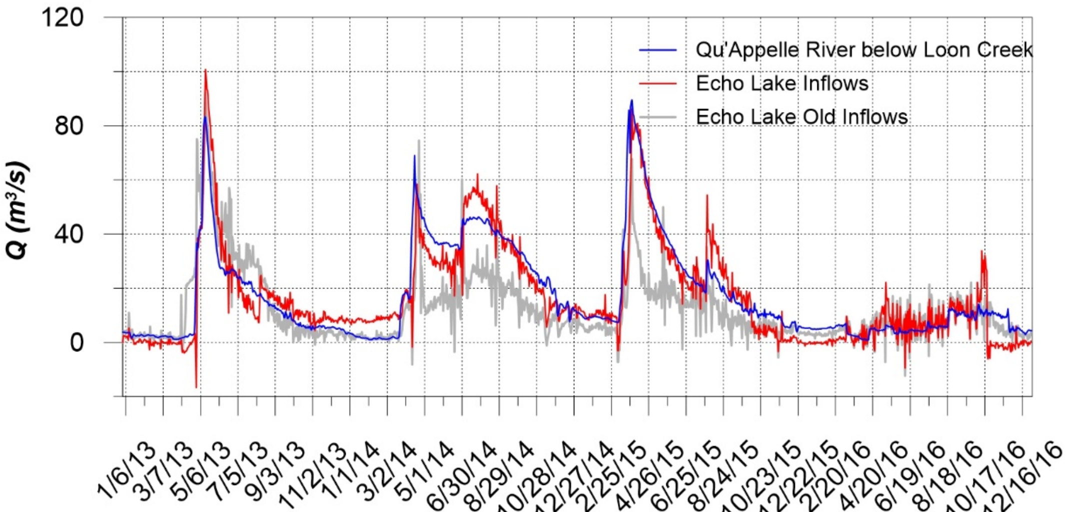
Results of the reverse routing are presented in Figure 4.4. Figure 4.4a illustrates the final calculated Mission-Katepwa inflows, recorded levels of the Qu'Appelle River below Loon Creek, the estimated Pasqua-Echo Lake (based on the rating curves and operating logs), and the calculated upstream inflows obtained by reverse routing the estimated outflows. Overall, the calculated upstream inflows to Mission-Katepwa Lake are relatively close the Echo Lake outflows derived from the operating logs and the modified outflow rating curves. Although, outflows during the summer and fall of 2013 and 2014 tend to be greater than the calculated inflows.

On the other hand, the overall results of the reverse routing approach are summarized in Figure 4.4b. The figure illustrates recorded flows of the Qu'Appelle River below Loon Creek and the estimated Qu'Appelle inflows to Pasqua and Echo Lakes using the previous and modified ouflows rating curve of Katepwa Lake weir. The calculated inflows using the modified version of the curve tracks closer to the recorded flows of the Qu'Appelle River below Loon Creek than the inflows calculated with the previous version of the curve. Finally, Figure 4.4c illustrates the Katepwa Lake outflows and the recorded flows of the Qu'Appelle River below Loon Creek and the recorded flows of the Qu'Appelle River at Hyde. In terms of magnitude, Katepwa Lake outflows are comparable to the recorded flows below Loon Creek while the shape and the magnitude of the recorded flows at Hyde are consistent with the hydrograph shape and magnitude of the Katepwa Lake outflows.

a) Echo Lake Inflows-Outflows



b) Echo Lake Inflows



c) Katepwa Lake Outflows

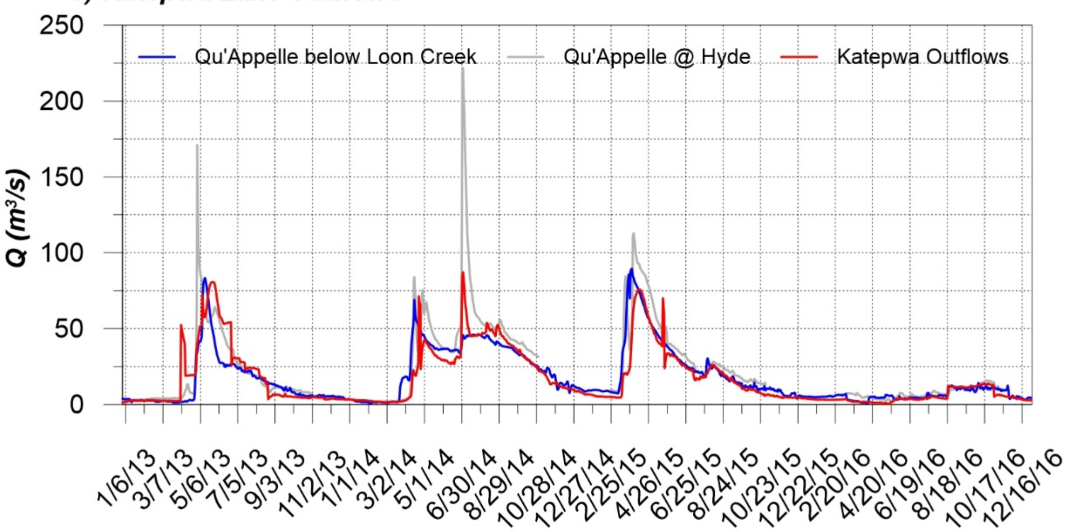


Figure 4.4: a) Estimated Katepwa Lake inflows from the Qu'Appelle River, estimated outflows of Echo lakes based on the operating logs and outflows curves and Qu'Appelle inflows to Pasqua and Echo calculated by reverse routing the estimated outflows. b) Inflows to Pasqua and Echo Lake using the two different outflow rating curves of Katepwa Lake. c) Recorded flows at Qu'Appelle River below Loon Creek and at Hyde hydrometric stations and final outflows of Katewpa Lake.

4.2 Pheasant Creek

Pheasant Creek flows at the hydrometric (05JL005) station were obtained previously by the water quality unit. However, there is another sampling location within the Creek near the confluence with the Qu'Appelle River. To estimate the flows of Pheasant Creek at the confluence, recorded flows at the hydrometric station should be adjusted using the drainage are ratio. The additional drainage area between the hydrometric station and the confluence is 108 km^2. The effective drainage area to the Pheasant Creek hydrometric station is 221 km^2. Therefore, flows at the sampling location near the confluence should be adjusted using a factor of 1.49.

4.3 Crooked Lake

Around Crooked Lake there are three sampling water quality locations, Pearl Creek, Qu'Appelle River at Highway #47, and at the outflow of the Lake.

Flows are recorded in the Qu'Appelle River just upstream of Crooked Lake. During most years, these flows (Qu'Appelle River at Hyde) can be considered inflows to the Lake. However, during low frequency runoff events a significant runoff contribution from Pearl Creek and the local drainage area is expected.

During above normal hydrological conditions inflows to the Lake can be estimated by using the recorded water levels, the outlet rating curve, and the area capacity curve as described by equation 4.9.

$$Ds_{(t)} = Q_{in(t)} - Q_{Out(t)} \quad \text{(equation 4.9)}$$

Where:

DS is the change in storage and Q_{in} and Q_{out} are inflows and outflows to the lake at time t. Note that the Q_{in} is the net inflow and includes the net evaporation outflow.

In order to account for the impact of the large precipitation event that took place during the summer of 2014, daily precipitation and evaporation records estimated at Broadview weather station were used for the water balance (equation 4.9).

Outflows from Crooked Lake were estimated according to the operating log and the different outlet rating curves for the structure. The hydraulic structure of Crooked Lake is formed by 9 bays and 12 stoplogs. Therefore, the structure operation consists in removing/adding logs from/to the different bays to obtain the desire outflow.

The operating log of the structure for the 2013-2016 period was used to determine the different stoplogs configurations and calculate the outflows from the lake under the different operations. A total of 13 operations on the structure were carried out during this period of time, due to the different stoplogs configuration each operation resulted in a different outlet rating curve. Table 4.1 below summarizes the outlet rating curves for 12 of the 13 operations carried out during this period of time.

Table 4.1: Outflow rating curve for the different structure operation during 2013-2016.

Elev. (m)	*C1 (m^3/s)*	*C2 (m^3/s)*	*C3 (m^3/s)*	*C4 (m^3/s)*	*C5 (m^3/s)*	*C6 (m^3/s)*	*C8 (m^3/s)*	*C9 (m^3/s)*	*C10 (m^3/s)*	*C11 (m^3/s)*	*C12 (m^3/s)*	*C13 (m^3/s)*
450.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
451	0.4	0.2	0.2	0.2	0.4	4.8	0.0	0.0	0.0	0.0	0.0	0.4
451.2	4.0	2.7	2.0	2.7	4.0	8.8	1.0	0.0	0.0	0.0	1.3	3.9
451.5	13.0	8.7	6.5	8.7	13.0	17.5	4.9	0.4	0.4	0.7	5.8	14.0
451.8	25.0	16.8	14.1	17.9	27.8	29.1	13	5.1	7.1	9.2	15.5	28.8
452	36.0	25.7	23.2	27.7	40.1	38.7	22.7	12.6	15.7	18.6	25.6	41.3
452.3	56.0	43.5	40.8	46.2	61.6	57.6	40.7	28.4	32.6	36.2	44.3	62.9
452.5	71.3	57.4	54.7	60.6	77.7	72.4	54.8	41.1	46.0	50.0	58.8	79.1
453	115.0	98.4	95.4	102.5	123.0	115.0	96.0	79.4	85.5	90.5	100.0	124.8

The table above does not summarize the outlet rating curve when the structure is wide open. This operation occurs when above normal runoff conditions are forecasted. The "historical" wide open outflow rating curve for Crooked Lake is illustrated in figure 4.5 and was initially used to calculate inflows to the lake. However, when using this curve to estimate inflows into the lake, the reverse routing resulted in smaller inflows than the flows recorded at the Qu'Appelle River at Hyde hydrometric station. This suggested a potential error either in the development of the curve or in the recorded flows. Additionally, a new outflow rating curve was proposed by Klohn Crippen Berger (KCB) in the Crooked Lake Outlet Structure Replacement report (2017), however, this curve did not present significant differences than that historical curve and the reverse routing resulted in the same issues described above.

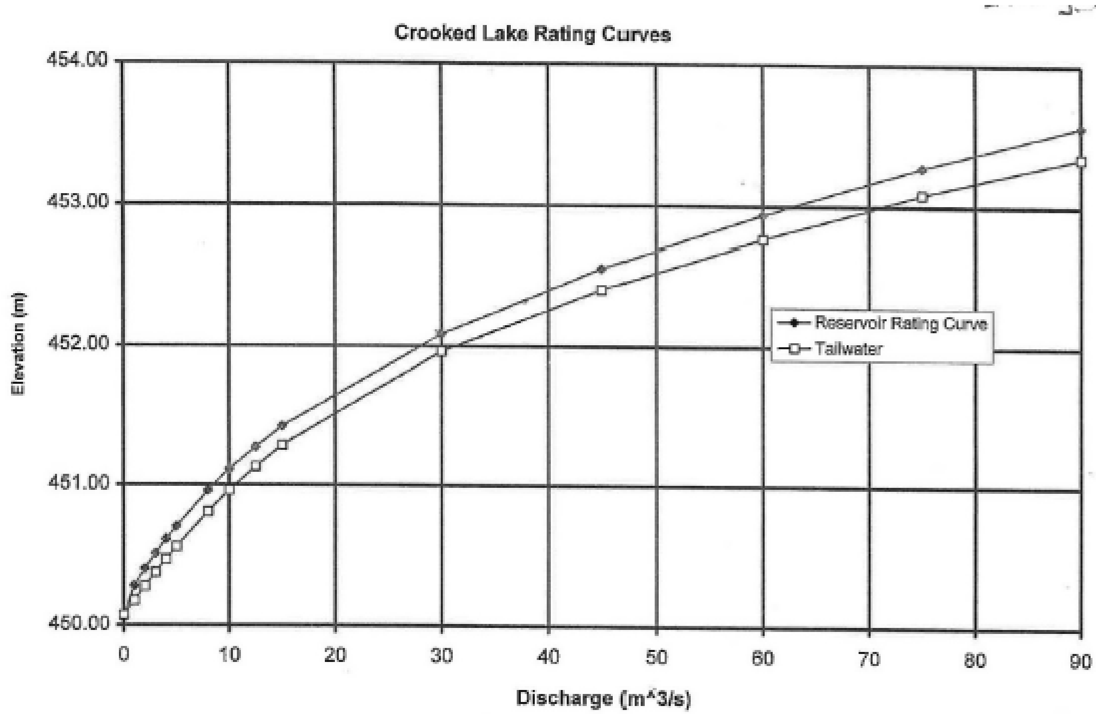


Figure 4.5: Historical Crooked Lake rating curve, structure wide open.

To proceed with the reverse routing and obtain a reliable inflow estimation, it was assumed that the potential error was with the outflow rating curve for wide open conditions. Thus, the main assumption was that the inflows to Crooked Lake cannot be smaller than the recorded flows of the Qu'Appelle River at Hyde hydrometric station (due to the short distance between the hydrometric station and the lake). These assumptions resulted in an adjusted version of the outlet rating curve for wide open conditions as illustrated in figure 4.6.

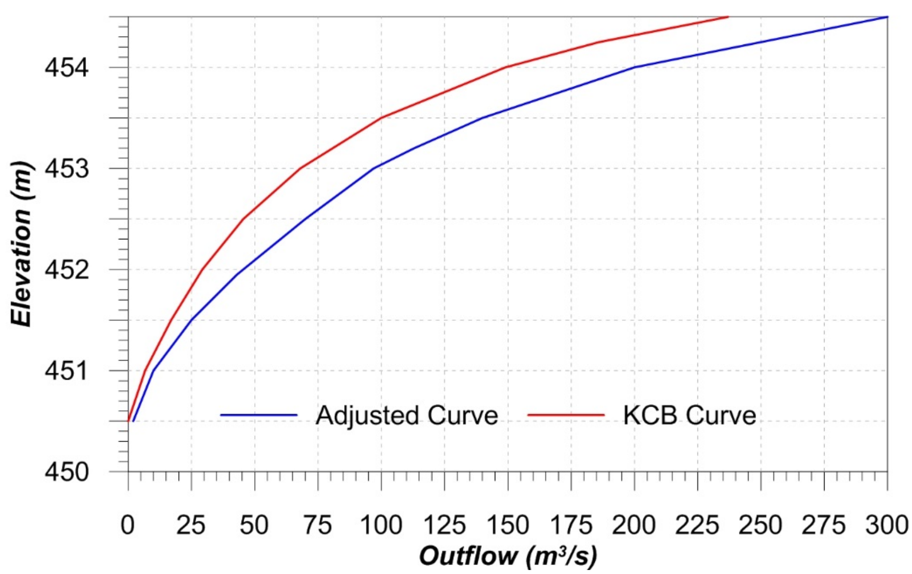


Figure 4.6: Outlet rating curve provided by KCB and adjusted rating curve (structure wide open).

Figure 4.7a illustrates the recorded water levels, estimated outflows, and calculated inflows by the reverse routing. The estimated inflows calculated using the adjusted outlet rating curve are also compared to the recorded flows at Hyde (Figure 4.7b). The difference in peak flows is due to the additional contribution from Pearl Creek and the local drainage area, particularly during the 2014 summer runoff event.

In addition, inflows to Crooked Lake can also be expressed according to equation 4.10.

$$Q_{in} = Q_{05JM013} + Q_{Pearl\ Creek} + Q_{Ungauged} \qquad \text{(equation 4.10)}$$

Where:

Q_{in}: inflows to the lake estimated by using equation 4.9

$Q_{05JM013}$: Flows recorded at Qu'Appelle River at Hyde

$Q_{Ungauged}$: Ungauged flows

Then ungauged flows can be obtained from Equation 4.11 where the only unknown are Pearl Creek flows.

$$Q_{Ungauged} = Q_{in} - Q_{Pearl\ Creek} - Q_{05JM013} \qquad \text{(equation 4.11)}$$

However, the ungauged flows, the ungauged drainage area, and the Pearl Creek drainage area are already known. Therefore, Pearl Creek flows can be estimated using drainage area rations as expressed in equation 4.12.

$$Q_{Pearl\ Creek} = (Area_{Pearl} / A_{Ungauged}) * Q_{Ungauged} \qquad \text{(equation 4.12)}$$

Using the same principle, flows of the Qu'Appelle River at Highway #47 can be expressed as function of the drainage areas.

$$Q_{H47} = (Area_{H47} / Area_{Ungauged}) * Q_{Ungauged} + Q_{05JM013} \qquad \text{(equation 4.13)}$$

The local (ungauged) effective drainage area to Crooked Lake was defined as the area below the Qu'Appelle River at Hyde hydrometric station and the lake. This ungauged area was estimated to be 272 km^2 from which 139 km^2 correspond to Pearl Creek. The sampling location, Qu'Appelle River at Highway #47, is a few kilometers downstream of the hydrometric station and has local drainage area of 16 km^2.

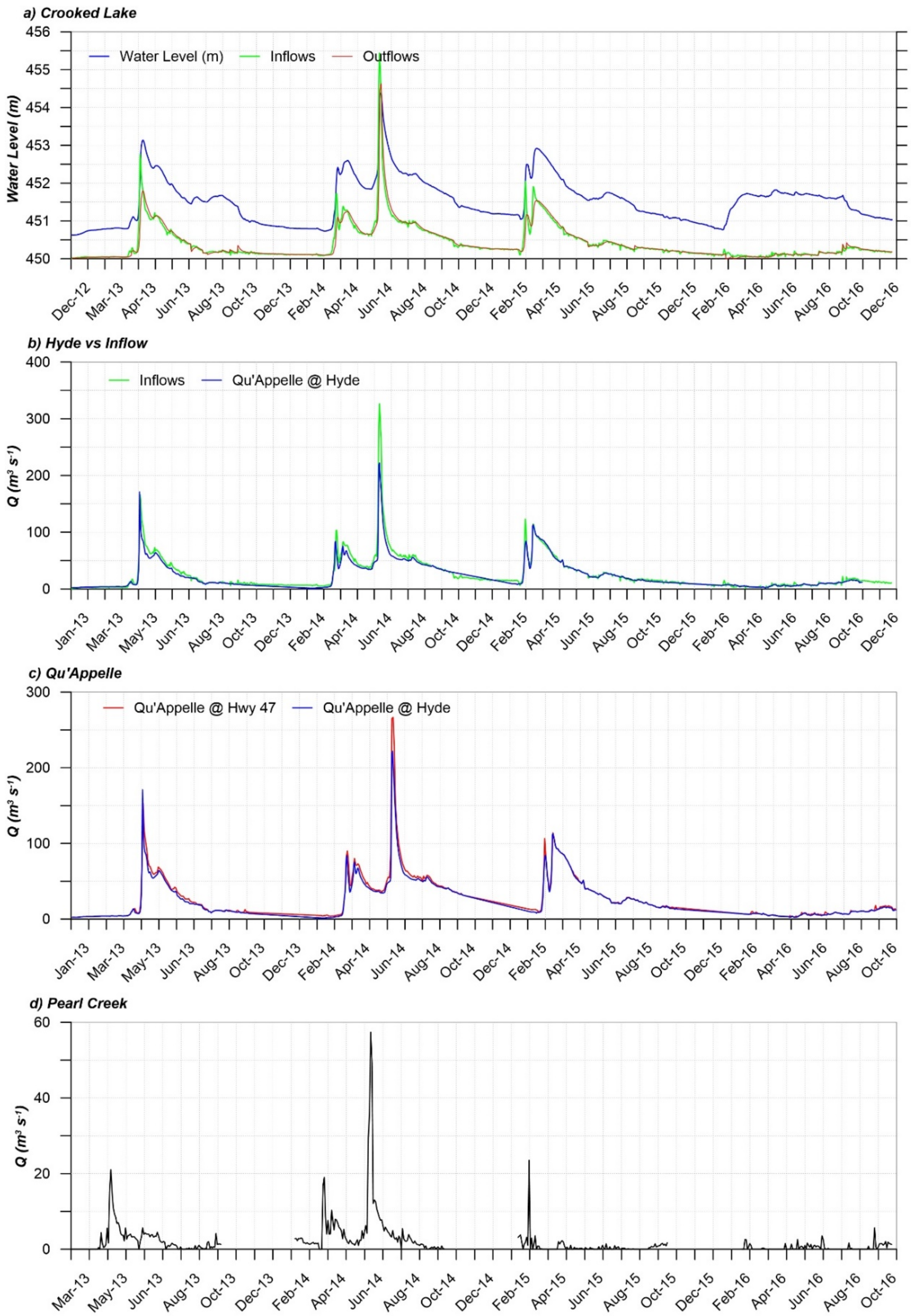


Figure 4.7: a) Crooked Lake levels and estimated inflows and outflows for the period 2013-2016. b) Estimated inflows and recorded flows at Qu'Appelle River at Hyde hydrometric

station. c) Estimated flows at of the Qu'Appelle River at Highway #47 and recorded flows at Hyde. d) Estimated Pearl Creek flows.

4.5 Round Lake Outflows

No operation records were available for the structure; therefore, outflows of Round Lake were estimated using the wide-open outlet rating curve for the existing structure. As with the outflow rating curve for Crooked Lake, there were some historical curves and one that was developed more recently using a HEC-RAS model. Figure 4.8 illustrates the different outflow rating curve for Round Lake.

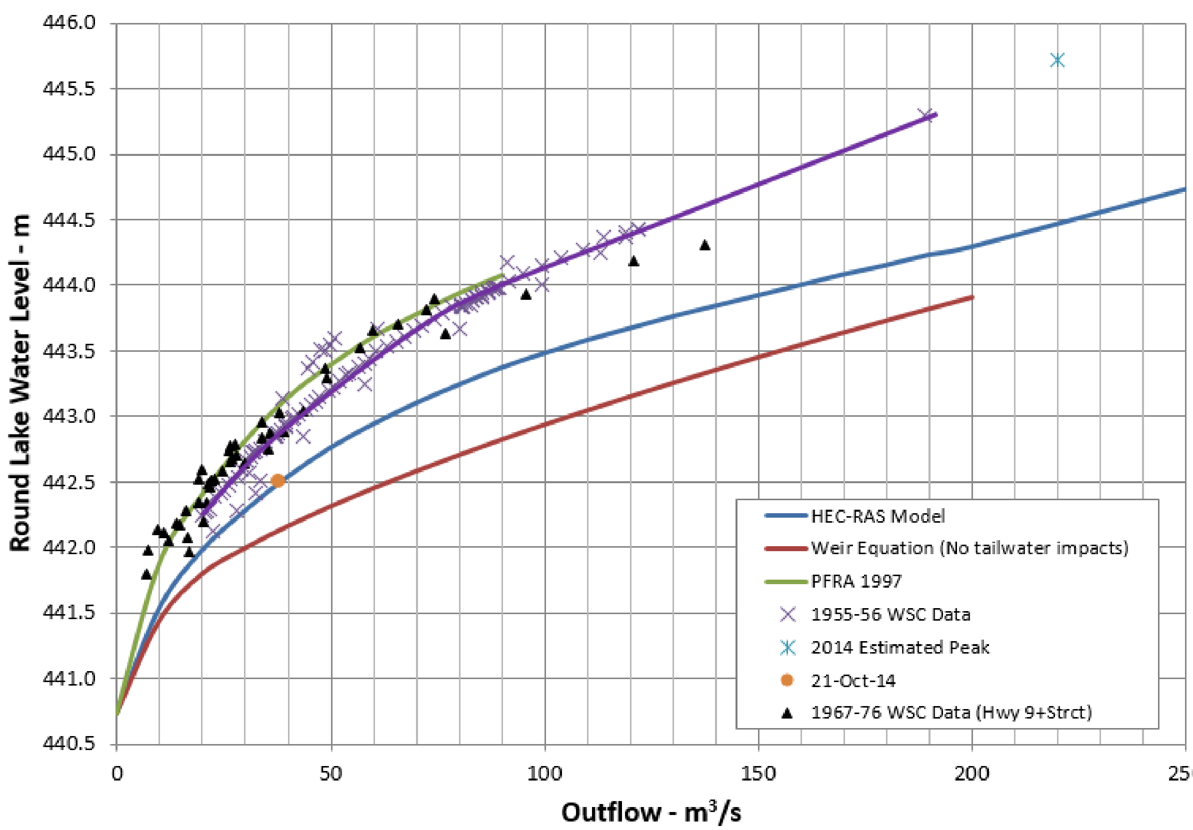


Figure 4.8: Historical and the HEC-RAS outflow rating curve for Round Lake (source: H:\Basin Operations\F_HYD\HYD\PROJECTS\5-QU'APPELLE RIVER\5-2 QU'APPELLE RIVER\Round Lake\Outlet Hydraulics\Round Lake Rating Curves.xlsx).

Even though the development of the historical rating curve considered observed flows, these curves are over 50 years old and might not represent the existing hydraulic conditions. On the other hand, the outflow curve obtained from the HEC-RAS model diverges significantly from the historical curves when the water level in the lake exceeds 442.5 m. In order to verify the performance of the different outlet rating curves a simple assumption was made, inflows to Round Lake cannot be smaller than the sum of the Crooked Lake outflows and the flows from Ekapo Creek. Unfortunately, the inflows calculated using the historical outflow rating curve were smaller than the sum of Crooked Lake outflows and Ekapo Creek flows (Figure 4.9a), therefore, the most recent curve (HEC-RAS curve; Figure 4.10) was used to calculate inflows into the Lake. Using the curve developed using the hydraulic model resulted in inflows that were greater than the sum of the Crooked Lake outflows and the flows from Ekapo Creek, satisfying the previous hypothesis (Figure 4.9b).

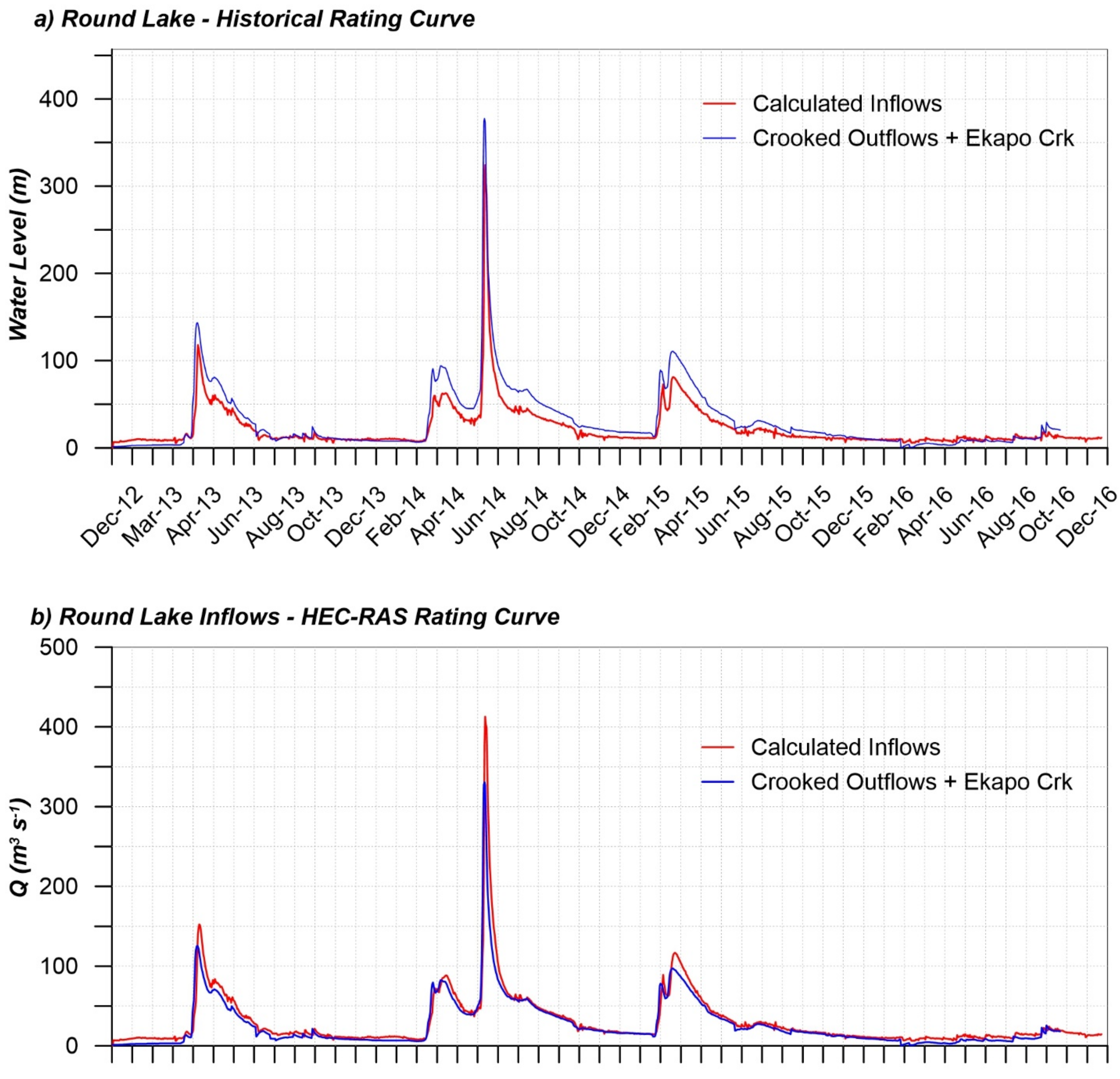


Figure 4.9: a) Calculated inflows into Round Lake using the historical outflow rating curve. b) Calculated inflows into Round Lake using the latest outlet rating curve (HEC-RAS).

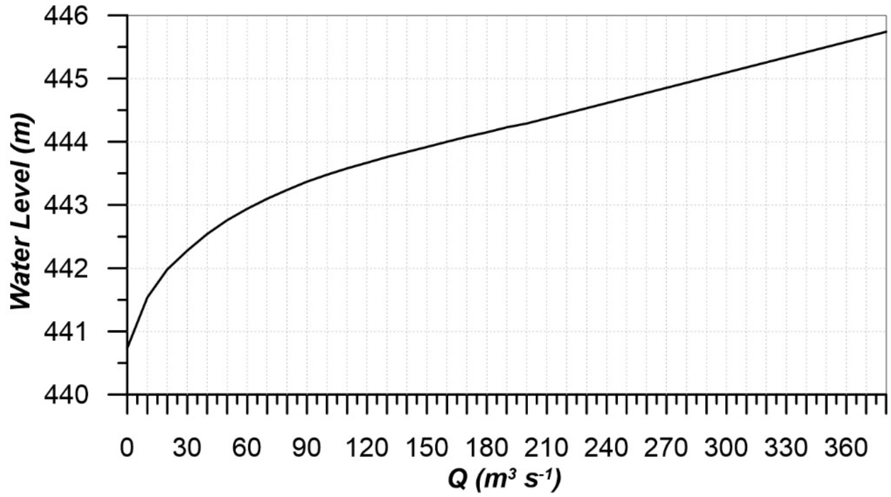


Figure 4.10: Outlet Rating Curve based on HEC-RAS model (extended).

Recorded water levels, outflows, and estimated inflows to Round Lake are illustrated in Figure 4.11. The outflows of the lake were also compared to the flows recorded at the Qu'Appelle River near Welby hydrometric station (Figure 4.11c). In general, recorded flows at the Qu'Appelle River near Welby hydrometric station are greater than the outflows from Round Lake, which is expected due to the additional contributing drainage area between the lake and the hydrometric station.

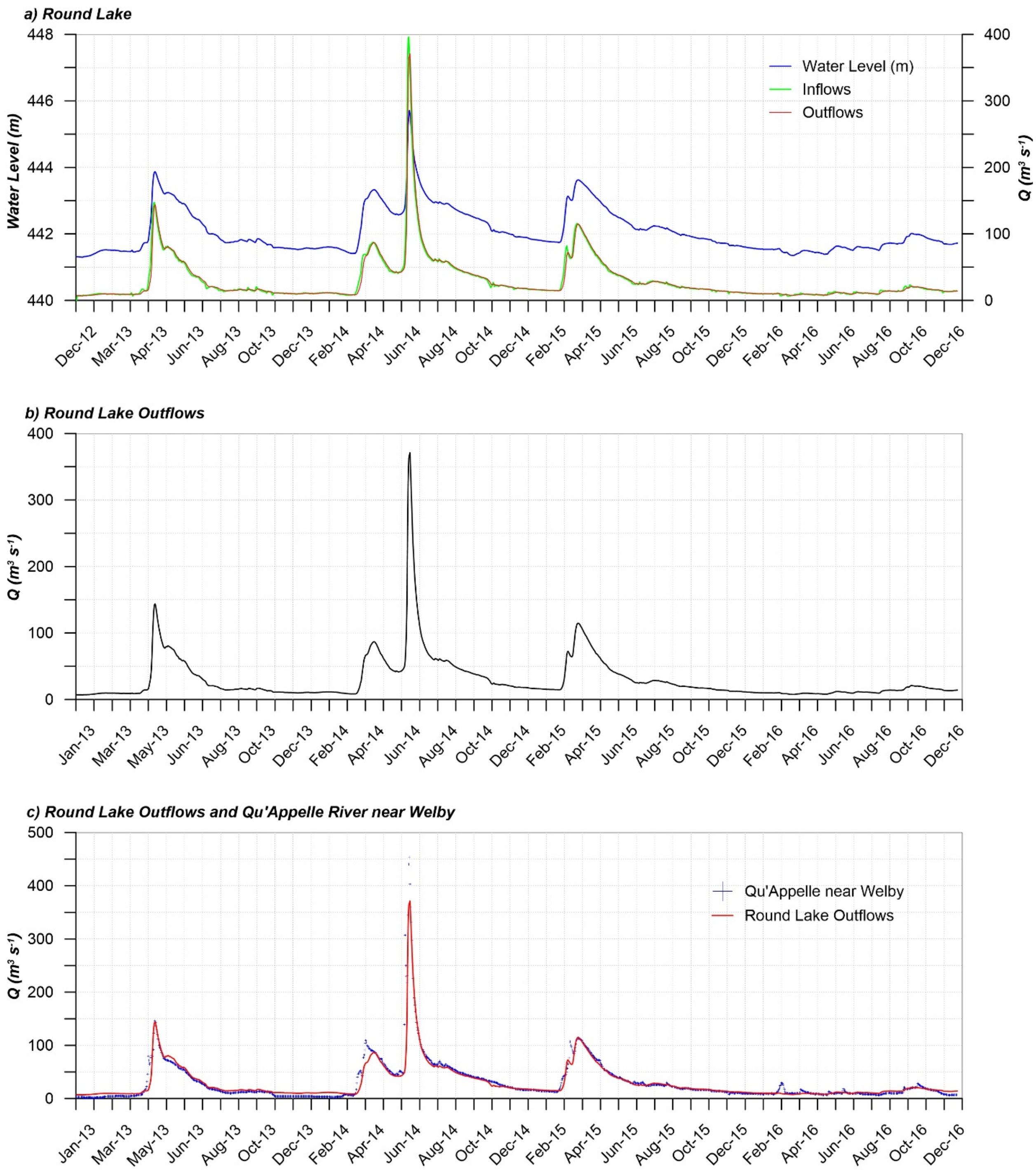


Figure 4.11: a) Round Lake water levels and estimated inflows and outflows. b) Outflows from Round Lake. c) Comparison of outflows from the Lake and recorded flows at the Qu'Appelle River near Welby hydrometric station.

4.6 Qu'Appelle River at Highway #201

The methodology used to estimate flows of the Qu'Appelle River at Highway #201 is the same that was used to estimate the flows at Highway #41. Inflows to Round Lake can also be expressed according to equation 4.14, which is the sum of the Crooked Lake outflows, flows from Ekapo Creek, and the flows from the ungauged drainage area.

$$Q_{inR} = Q_{Out\ Crooked} + Q_{05JM010} + Q_{Ungauged} \qquad \text{(equation 4.14)}$$

Inflows to the lake were estimated previously by the reverse routing, therefore the only unknown in the equation is the ungauged flows ($Q_{Ungauged}$). Then the ungauged flows are equal to the inflows to the lake minus Crooked Lake outflows minus the Ekapo Creek flows (Equation 4.15).

$$Q_{Ungauged} = Q_{inR} - Q_{Out\ Crooked} - Q_{05JM010} \qquad \text{(equation 4.15)}$$

The ungauged contributing drainage area (EDA) is also known and by using drainage area ratios, the ungauged flow portion to Highway #201 was estimated. Finally, flows of the Qu'Appelle River at Highway #201 can be calculated following equation 4.16.

$$Q_{Hwy\ 201} = Q_{Out\ Crooked} + Q_{05JM010} + (Area_{Hwy\ 201} / Area_{Ungauged}) * Q_{Ungauged}$$
(equation 4.16)

Where:

$A_{Hwy201} = 107\ km^2$, $Area_{Ungauged} = 211\ km^2$

Finally, estimated flows of the Qu'Appelle River at Highway #201 are illustrated in figure 4.12.

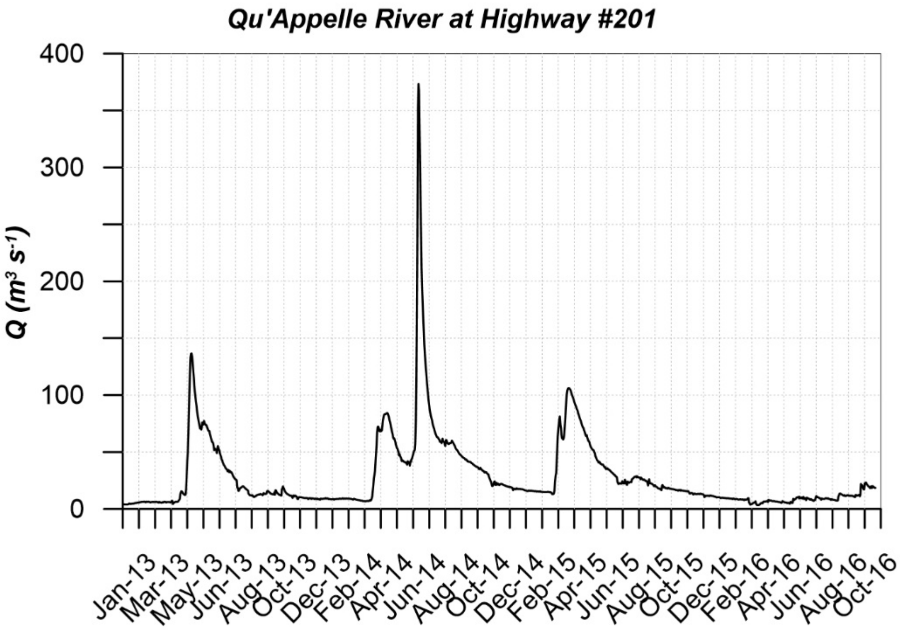


Figure 4.12: Estimate flows of the Qu'Appelle River at Highway #201.

5 Data Files

Table 5.1 summarizes the name of the electronic files attached to this report that contain the time series required to carry out the water quality study of the Qu'Appelle River Basin.

Table 5.1: File names of the electronic time series.

#	File	Description
1	Iskwao at the WQ Sampling Location.xlsx	Estimated daily flows for the Iskwao Creek at the sampling location for 2013-2016
2	QuAppelle at Marquis final.xlsx	Estimated daily flows for the Qu'Appelle River at Marquis for the period 2013-2016
3	QuAppelle at Tugaske final.xlsx	Estimated daily flows for the Qu'Appelle River at Tugaske for the period 2013-2016
4	Outflows BPL & BW vf.xlsx	Daily outflows from Buffalo Pound Lake and Back water estimate into the Lake for the period 2013-2016
5	Quwasv2.csv	Estimated daily flows of the Qu'Appelle River upstream the Wascana Creek confluence for the period 2013-2016
6	Qulumv2.csv	Estimated daily flows of the Qu'Appelle River upstream Lumsden 2013-2016
7	Qlmlv2.csv	Estimated daily flows of the Last Mountain Lake channel for the period 2013-2016
8	Qulasv2.csv	Estimated daily flows of the Qu'Appelle River upstream of Last Mountain Lake for the period 2013-2016
9	Loonv12042017.csv	Estimated daily flows for Loon Creek for the period 2013-2016
10	QHwy6v12052017.csv	Estimated daily flows of the Qu'Appelle River at Highway #6 for the period 2013-2016
11	Katepwa Qoutv2.csv	Estimated daily outflows from Katepwa Lake 2013-2016
12	Pearl Creek Filled.csv	Estimated daily flows for Pearl Creek, the Qu'Appelle River at Highway #47 and the Qu'Appelle River at Hyde
13	Crooked Lake Outflows.xlsx	Estimated daily outflows from Crooked Lake (2013-2016)
14	Round Lake Outflows.xlsx	Estimated daily flows of the Qu'Appelle river at Highway #201 and Round Lake Outflows (2013-2016)

Appendix A

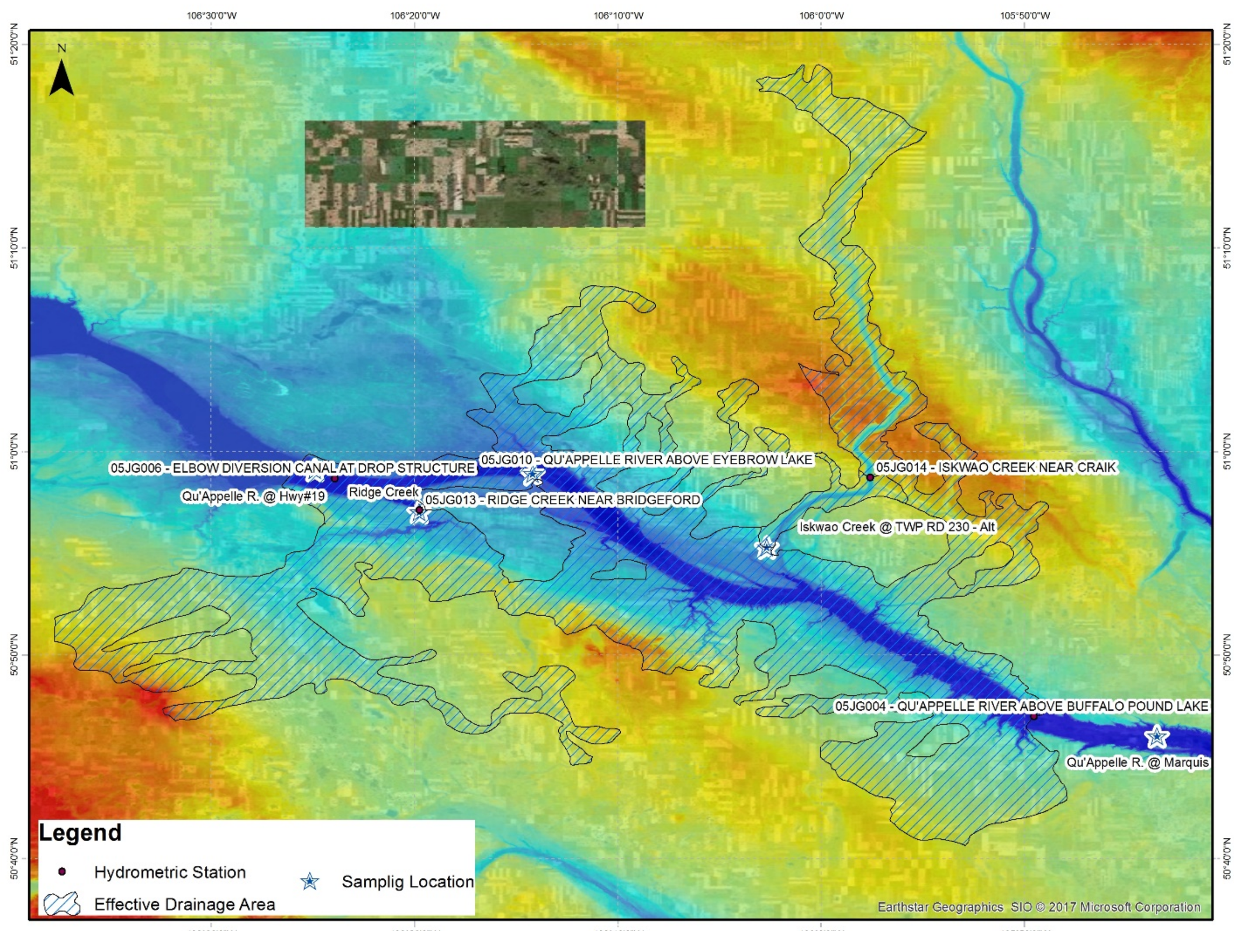


Figure A1: Effective drainage area of the upper Qu'Appelle Watershed and water quality sampling location.

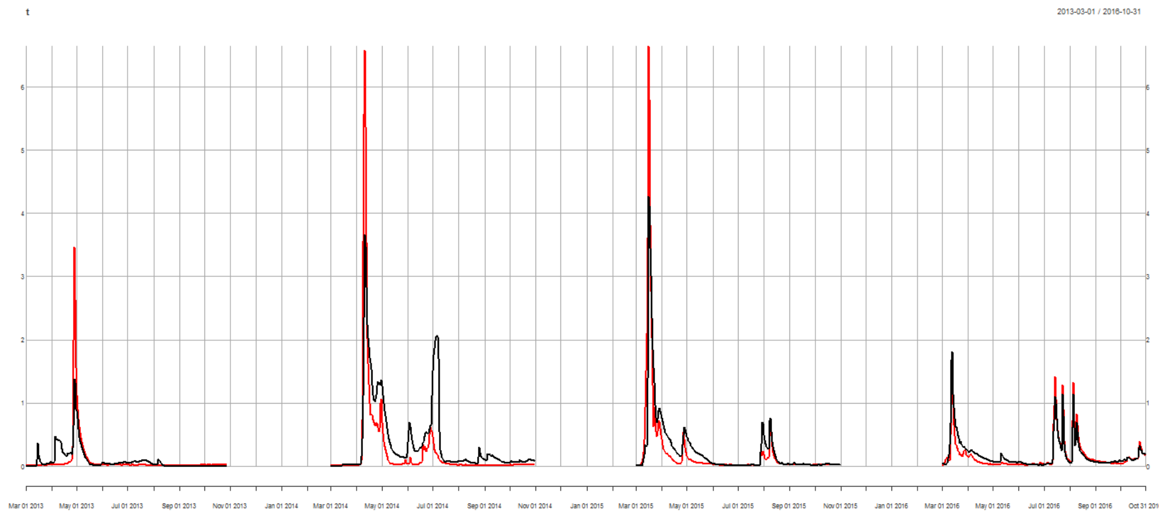


Figure A2: Multiple Linear Regression models for Iskwao Creek using Arm River, Ridge, and Brightwater Creek as predictors. Black line is model A and red line is model B.

A) Iskwao <- -0.007024 + 0.131786 * Arm + 0.141756 * Bright --- R2 = 0.7295 period 1972-2011
B) Iskwao <- 0.013361 + 0.215702 * Ridge + 0.16153 * Bright --- R2 = 0.726 period 1972-2011