Lower Souris Watershed Committee

Moosomin Lake Watershed, SK
Land Use and Water Quality

UNIVERSITY OF SASKATCHEWAN
Global Institute for Water Security
USASK.CA/WATER

MOOSOMIN LAKE WATERSHED, SK
LAND USE AND WATER QUALITY

JENNIFER ROSTE & HELEN BAULCH
GLOBAL INSTITUTE FOR WATER SECURITY
UNIVERSITY OF SASKATCHEWAN

FOR

LOWER SOURIS WATERSHED COMMITTEE

Date: June 7, 2019.

EXECUTIVE SUMMARY

In this report, we assessed the current nutrient loads to Moosomin Lake and the potential impact of various Beneficial Management Practices (BMPs) in the Moosomin Lake watershed. There was limited, yet sufficient, monitoring in the Moosomin Lake watershed to determine that loads to the lake are significant. The lake does retain some of the load and there is some evidence of the sediments becoming a source of P in the late summer. The lake flushes frequently in spring, on average seven times by the end of June (ranging 0 to 28 times, 2007 to 2017) and then stagnates during the later summer season with greater than 75% of the annual flow volume to the lake having passed by end of June, and negligible flow occurring over winter. The impact of nutrient mitigation activities in the watershed are expected to translate strongly to the water quality in the lake, although within a shallow reservoir with a relatively large drainage area, nutrient sources in the sediments, and soils may lead to lags before water quality benefits are fully realized. Land sourced nutrient loads to the lake from the effective drainage area (EDA) range broadly 0.05-4.6 kg/ha for total nitrogen, TN (mean 1.0 kg/ha) and 0.02-0.7 kg/ha for total phosphorus, TP (mean 0.2 kg/ha). These values are similar to those found in other agricultural Canadian prairie watersheds facing similar challenges related to water quality. Control of nutrient loads to streams and the lake in this watershed could, in time, result in lower nutrient levels in the lake and with continued management potentially mitigate the occurrence of cyanobacterial blooms.

To prioritize actions to control nutrient loads to the streams and lake, we assessed the potential benefit of seven BMPs: fertilizer nutrient management; relocation of manure spreading to non-contributing drainage areas (NCDA) of the watershed; wetland restoration; management of cattle wintering sites; riparian grazing management; conversion of fallow fields to minimum tilled annual crops; and conversion of annual crops to perennial forage crops. We first constrained the export coefficients (ECs) in the Canadian prairie literature to values meaningful in Moosomin Lake watershed and used these values to quantify the contribution to the total load estimated for the various land uses in the watershed. There is limited research on Beneficial Management Practice efficacy in the prairies and anticipated variation in BMP efficacy even within this watershed; as such, this exercise is intended as a screening-level assessment to understand and prioritize potential management changes, with recognition that next steps to more fully understand how to manage watershed nutrient exports should involve process-based model assessment, discussions with landowners, and ultimately should consider an adaptive management approach where monitoring is used to inform practice and policy.

There are multiple important outcomes from this exercise. The reduction to the size of the EDA associated with wetland restoration efforts has much potential to reduce P and N loads in-streams with more water retained on the land. Specific site conditions and placement of a wetland in the watershed will dictate the impact any particular wetland restoration project may have. We also emphasize that current evidence suggests extant drainage in the catchment has contributed to elevated nutrient loads in the catchment, and the potential water quality impacts of further drainage should be carefully considered given the apparent magnitude of drainage impacts, and difficulty in restoring or replacing nutrient retention function of wetland ecosystems. Relocation of cattle wintering sites away from streams (or using holding ponds for effluent) is expected to have relative quick and quantifiable impacts on P and N downstream. Managers can be very strategic about which sites to target for relocation or holding pond installation. This exercise also reinforces the importance of fertilizer nutrient management. The magnitude of mineral fertilizer application is very large, but BMPs associated with nutrient management are under-studied in the region. Liu et al. (2019a) suggest that there are reductions to P in runoff with reduced fertilizer application rates without compromising yields, hence we emphasize the importance of managing fertilizer application rates. Managing the excreta and structural damage resulting from livestock access to streams is expected to be worthwhile, and important especially where lakeshore grazing is unrestricted. Actual grazed extent of riparian zones and lakeshore could be better interpreted by managers in the watershed to fully assess the potential of this BMP and target its application in the watershed. Finally, relocation of manure spreading is expected to have relatively small effects as it affects a relatively small number of hectares of the watershed. In terms of the potential to reduce to P loading, in erosion prone areas consideration should be given to converting the fallow and annual crops to perennials.

There are significant uncertainties in these data and analyses. As such, caution is required when applying the results of this work to future policy and research decisions. The results presented here should be used for

qualitative ranking of priorities to achieve benefit, but not for quantitative prediction of future change, as the magnitude of change, and timescale of change cannot be reliably anticipated. Monitoring and evaluation of the efficacy of BMP implementation in nutrient reduction is crucial to ensuring success in this landscape, and must account for the timescale over which benefits can be anticipated.

Table 1. **BMP Prioritization**. The recommended prioritization of BMPs for the Moosomin Lake watershed is summarized below. The uncertainty associated with the various aspects of assessing the BMP performance is also evaluated on a scale of low - med(ium) - high: *Source*—variability to the assessed current land use contribution to P and N loads to Moosomin Lake; *Benefit*—variability in the assessed magnitude of the reduction to nutrient exports (benefit) using the BMP; and *ECs*—variability of the BMP and land use nutrient ECs in the literature.

BMP	**Rationale & Uncertainty**
High	
Relocate livestock wintering sites situated < 200m from streams	*Rationale*: Wintering sites or corrals near streams and lakeshores are obvious sources of P and N. These sources are readily transported once deposited in or by streams. Livestock site inventories indicate these sites are a significant source of P and N in the watershed. Benefits from mitigation are expected to be substantive; but yet we present moderate variability in the potential benefit as the livestock site impacts were based on an area ratio of census data (at the RM scale) and not on inventories of animals at each identified intensive feeding site and the ECs taken from corral studies varied widely per NU which resulted in a large range in assessed benefit for this BMP. *Uncertainty Assessment*: Source (low), Benefit (med), ECs (high)
Restoration of wetlands	*Rationale*: We assessed the impacts of drainage by quantifying the increase in EDA resulting from past drainage activities in the watershed. There is moderate uncertainty in the assessment of drainage extent as the wetland inventory doesn't capture well the extent of drainage that resulted in the present day EDA (source), moderate uncertainty in the range of potential benefit of restoring drained wetlands based on the key assumption of re-establishing previous NCDA to reduce both discharge volumes and nutrient loads to the lake, and low uncertainty in the land use export coefficients applied to assess TP and TN reductions. *Uncertainty Assessment*: Source (med), Benefit (med), ECs (low)
Fertilizer Management	*Rationale*: A majority of the land in the watershed is subject to fertilization; and this is a substantive source of P and N in runoff. Consistent practice of the 4R's Right Source @ Right Rate, Right Time, Right Place®(Canadian 4R Research Network, 2018) are argued to reduce concentrations in runoff from cropped fields. Here we used the reduced fertilization rates achievable with automatic section control and GPS coupled with research on Manitoba crops to quantify a potential benefit to nutrient management practices. There is limited research that quantifies the relationship between reduced fertilizer application and nutrient reductions in runoff; yet there is enough to confer confidence that nutrient management in catchment hotspots and on cropland, in general will reduce P and N losses from fields. *Uncertainty Assessment*: Source (low), Benefit (med), ECs (high)
Moderate	
Riparian Grazing Restriction	*Rationale*: There is structural damage to streambeds and physical deposition of urine and dung that occur with lakeshore and riparian grazing; both sources of P and N that can be eliminated with this BMP. There is limited supporting literature to quantify this benefit and the variability in ECs is relatively high. *Uncertainty Assessment*: Source (low), Benefit (med), ECs (high)
Relocating Manure applied lands	*Rationale*: There is not a large area of the watershed EDA that is subject to manure application, but the benefit of relocation is fairly certain and efforts to do this where appropriate are recommended. *Uncertainty Assessment*: Source (med), Benefit (low), ECs (high)
Fallow to minimum till crop conversion	*Rationale*: This BMP requires a site specific assessment of soil erosion. There is a benefit to conversion to minimum till crops and this should be capitalized on where it is appropriate to so. *Uncertainty Assessment*: Source (high), Benefit (low), ECs (high)
Low Priority to No Benefit	
Conversion of annual crops to perennial crops	*Rationale*: The uncertainty with the potential of this BMP to reduce P really makes this BMP slightly problematic in the prairies where runoff over frozen soils leads to large dissolved P fractions during the major runoff event of the year. Observations of total P and dissolved P in the watershed indicate that there are erosive processes occurring in the watershed; these areas of high erosion potential might be considered for conversion to perennial crops with the aim of reducing nutrients in runoff. *Uncertainty Assessment*: Source (low), Benefit (high), ECs (high)

Contents

Acknowledgements 7
1. Background 9
2. Moosomin Lake Water Quantity and Quality 11
 2.1. Discharge Records 11
 2.2. Water Quality Records 12
 2.3. Phosphorus and Nitrogen Loads into the Lake 19
 2.4. Discussion 21
3. Predicting Land Based Phosphorus and Nitrogen Exports 23
 3.1. Moosomin Lake Watershed Land Use 23
 3.2. Selecting the Moosomin Lake Watershed Export Coefficients 28
4. Assessing BMP Performance 33
 4.1. The BMPs 33
 4.2. BMP Performance 41
5. Discussions 43
6. Management and Monitoring 45
 6.1. Next Steps 46
Appendix A. Hydrochemistry Data 47
Appendix B. Land use and Export Coefficients Data 57
 B.1. Export Coefficients - selection 63
References 71

Acknowledgements

There were many people who contributed to the makings of this report. Staff at the Saskatchewan Water Security Agency spent many hours brainstorming and providing data and background to those data. Etienne Shupena-Soulodre, Saul Marin, and John-Mark Davies were our primary contacts, but there were others as well. John-Mark provided thoughtful feedback throughout and Etienne encouraged alternate view points. The Lower Souris Watershed Committee provided feedback and Jane Elliott at Environment and Climate Change Canada provided insights to address some of the LSWC questions. And, Daniel Phalen, the technician at the LSWC office spent countless hours analyzing and interpreting geospatial data and producing images. The views and opinions expressed in this report remain those of the authors; although these views have been broadened and challenged through our collaboration with you. Thank-you all. We look forward to working with you again. Funding was provided for this research by the Saskatchewan Water Security Agency.

1. Background

Moosomin Lake is a constructed reservoir 10 km long and narrow; less than 0.5 km wide at its widest point (Saskatchewan Watershed Authority, 2007). The reservoir was established and managed by the Prairie Farm Rehabilitation Administration (PFRA) in the 1950s and today the man-made lake is used for recreation (swimming, boating, fishing, etc...), irrigation and flow control on the Pipestone Creek (Lower Souris River Watershed Committee). The reservoir is situated on the Pipestone Creek at the confluence of the Little Pipestone Creek and the Pipestone Creek. The gross drainage area (GDA) of the Moosomin Lake watershed is approximately 3,405 km^2 with and a modern day estimated effective drainage area (EDA) of 1,676 km^2 (49%)[1]. Activities in the watershed are largely agricultural with crop land comprising 72% of the GDA (78% of the EDA). Crop cover in the watershed was calculated using the Centre for Agroclimate Geomatics and Earth Observation Science and Technology Branch (2017) land satellite imagery analyses.

Table 2. **Land Use in the Moosomin Lake Watershed**.

Drainage Area	Crop Land	Urban	Natural Grassland	Forest	Wetland	Other
GDA	71.9%	2.1%	0.5%	14.3%	9.5%	1.7%
EDA	77.5%	2.0%	0.8%	11.0%	7.6%	1.1%

The Lower Souris Watershed Committee (LSWC), with funding from the Saskatchewan Water Security Agency (WSA), retained the Global Institute for Water Security to assess the current nutrient loading to Moosomin Lake and the potential for future reductions to these loadings with modifications to the agricultural practices in the region. There is a paucity of recent data on water quality in the reservoir complicating any real assessment of its current health. Based on desired outcomes and data availability, this study is comprised of two primary steps: 1) To provide history on water quality records in the reservoir, assess current loadings based on available data, and speculate on the impact of the current nutrient loadings to the reservoir, and 2) To apply land use and available export coefficients for the Canadian prairies to estimate potential nutrient reductions to the streams (and ultimately Moosomin Lake) with the implementation of select agricultural management practices.

There have been a few hydrochemistry investigations on the subject of land use and hydrology in the reservoir watershed. Two thirds of the watershed area was the subject of a land use hydrology study for a drainage impact modelling assessment by Perez-Valdivia et al. (2017). The nutrient sources and land use have been studied in detail in the past by Goodbrand et al. (2010) and Roste and Baulch (2017) for specific subbasins[2] of the Pipestone (an estimated 6% areal coverage of the reservoir watershed). Also, water quality in the Pipestone creeks and an unnamed creek, as it relates to river taxonomic inventory was studied in 2006 by Phillips et al. (2008). Our present investigation is the first to compile the current state of knowledge regarding nutrient sources (phosphorus and nitrogen) in the Moosomin Lake watershed and apply known land use and nutrient

[1]This modern day drainage area assessment was performed by the Lower Souris Watershed Committee in an effort to reflect the impacts of current drainage levels in the watershed. The alternative is to use the drainage areas assessed by the PFRA in the 1970s (Martin, 2001) and updated most recently in 2008 according to Perez-Valdivia et al. (2017). In conversation with the WSA there are several reasons that require a modification to the PFRA delineated EDA. The PFRA didn't include the Kipling marsh which drains several rural municipalities and has a constructed ditch. This constructed ditch and its drainage area should be included in the modified drainage area. Also, on the north side of the basin near Wapella/Whitewood there are remnants of post glacial creeks and these do run although not originally included in the EDA; but included in the modified drainage area (Shupena-Soulodre, 2019)

[2]These studies used eleven Gross Experimental Drainages (GEDs) of which six (GED21, 28, 29, 33, 38, and 40) are fully within the reservoir watershed with an approximate 6% areal coverage. They have a relatively high resolution water quality and land use data set.

export relationships on the Canadian prairies to guide agricultural management practices in the region based on estimates of potential phosphorus and nitrogen abatement.

2. Moosomin Lake Water Quantity and Quality

2.1. **Discharge Records.** The main tributaries to the lake are the Pipestone Creek and the Little Pipestone Creek. There a few unnamed creeks feeding the lake as well. The Pipestone Creek is actively monitored by the Water Survey of Canada, Environment and Climate Change Canada with a record extending back to 1960 (Water Survey of Canada, 05NE003). This station is located about 10 kms upstream of the reservoir.

The stream record for the hydrometric station 05NE003 is used as the reference station to estimate the streamflow downstream at Moosomin Lake and for the Little Pipestone Creek at Moosomin Lake. This was done based on calculated monthly average flows for the monitored months March through October[3] at the reference station and the EDAs for each station. These estimates were provided by the WSA for use in this project[4]. The annual discharge volumes discretized by month for 05NE003, Pipestone Creek and Little Pipestone Creek at the reservoir are shown in Figure 1 for the years 2007 - 2017 which coincide with the years for which there are some existing chemistry data for these streams.

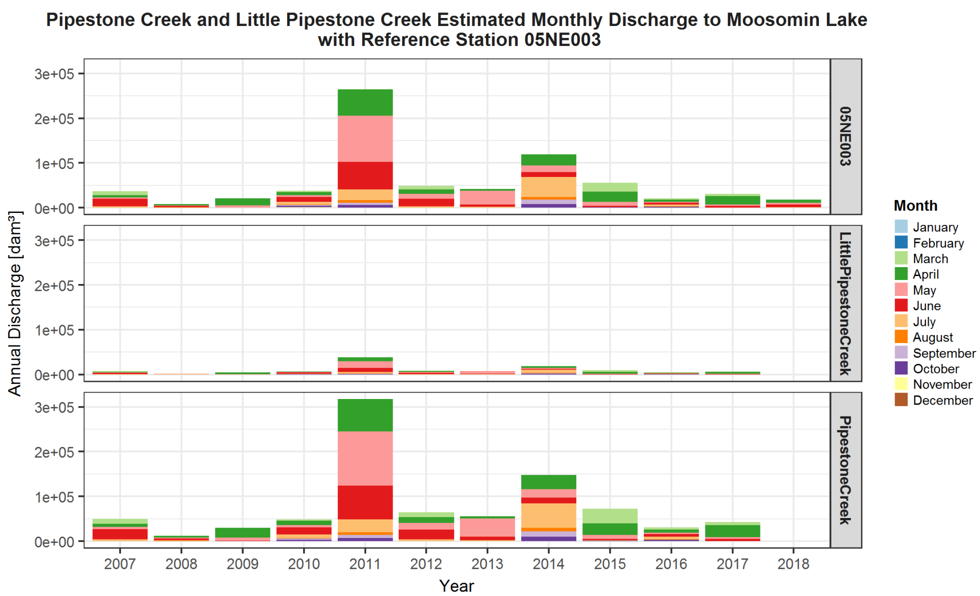


FIGURE 1. **Monthly Creek Discharge Volumes 2007 to 2018**. Discharge volumes for the Pipestone Creek and Little Pipestone Creek were calculated based on an area ratio (EDA, GDA ratios) transfer of streamflow record from the Water Survey of Canada station 05NE003. Tabular values for these data are provided in Table A.1. Figure A.1 illustrates the full streamflow record at 05NE003.

[3]Correspondence with the WSA indicates that although there is some groundwater contribution to flows in the Pipestone Creek during wetter years; negligible flow over the winter months for 2007 − 2017 is a reasonable assumption (Marin and Siba, 2019)

[4]WSA notes: "Annual volumes were transferred using contributing area ratio between the reference station and the location of interest. Note that the basic assumption here is that the runoff index per unit area is uniform. The EDA and the GDA were taken into account as follows: Volumes of water with return periods equal to or less than 1:2 year were transferred using the EDA; for volumes of water with return periods larger than 1:2 year, the contributing area for the reference station and for the selected location were estimated by assuming a gradual transition from the EDA to the GDA. The assumption was that for 1:2 year the EDA will be the contributing area, while for the 1:500 year event the GDA will be the contributing area. For return periods between 2 year and 500 year, an interpolation following a log scale for the return periods is used for estimating the contributing area; and the estimated annual flow volumes are transformed into monthly mean flows following the mean monthly flow distribution in the reference station". (Marin, 2019a)

The Pipestone Creek and Little Pipestone Creeks are the primary sources of water flowing into Moosomin Lake. There exist some unnamed streams and ephemeral drainages to the reservoir of unquantified, but relatively small flow contribution to the lake. To aid with assessing loads and function of Moosomin Lake, the WSA performed a water balance[5] to estimate annual discharge from the lake. The annual discharge volumes from the lake are shown in Figure 2 for the years of 2007 – 2017 (see also Table A.1).

The mean annual inflow (2007 - 2017) from Pipestone is an estimated 79,404 dam^3 and from Little Pipestone 10,674 dam^3 for an annual average total 90,078 dam^3 (range 15,000 dam^3 - 356,000 dam^3). This number is an under estimate of actual discharge into the lake as it accounts for discharge from about 90% of the entire EDA. Active storage in the reservoir is 10,844 dam^3 indicating that the active water supply[6] in the reservoir can be refreshed multiple times annually. The shallow depth and brief residence time also indicate that the water quality in the influent creeks is of importance in defining lake water quality. Since 2007, apparent in Figure 2, by the end of June the estimated discharge from Moosomin Lake indicates that there was a sufficient volume to refresh the reservoir more than once, and on average 7 times with a range from 0 to 28 times (median 4-5 times). In all years since 2007, 75% of the annual discharge had passed by end the end of June (Figure 3). This remaining 25% of discharge is in most years, insufficient to refresh the reservoir.

2.2. **Water Quality Records.**

Moosomin Lake. Moosomin Lake is a shallow polymictic lake with an average depth of 4.5 m and a maximum depth of 7.9 m (Saskatchewan Watershed Authority, 2005). The full supply level storage volume is 11,155 dam^3 of which 311 dam^3 is dead storage (Saskatchewan Watershed Authority, 2005; Lower Souris River Watershed Committee). To increase the lake's winter oxygen levels a mechanical aeration system has been, although it is not currently operated (for more on aeration refer to discussion in Section 2.4).

Historically, water quality sampling was performed on the lake in all years 2003 - 2006 (inclusive) to assess the water quality in the reservoir with respect to recreational use. Sampling locations included mid-lake, shoreline stations, and a station near Pipestone Creek inflow (Saskatchewan Watershed Authority, 2005, 2007). The reservoir water quality was assessed as fair to poor according to the established Water Quality Index used by the WSA (Saskatchewan Watershed Authority, 2005, 2007). Coincidental with these assessments was the taxonomic inventory performed in four

[5]Water balance hydrology notes from the WSA: "Lake evaporation was estimated using the monthly gross evaporation values calculated from climate records at Broadview, SK climate station. This station is located about 60 km northwest from Moosomin Lake. Precipitation on the Lake was based on the historical records from Moosomin, SK climate station. Missing values at this station were filled with records from the Elkhorn, SK climate station. Inflow to the Lake was estimated by transferring historical annual water volumes from Pipestone Creek above Moosomin Lake (05NA003) hydrometric station. The drainage area to the lake was as estimated at its outlet. Water Levels from the lake were as recorded at Moosomin Lake near Moosomin (05NA002) hydrometric station. The water balance was done for the period March 1987 to October 2017. No values were estimated for the November to February periods. Discharge simulation results were compared with flow recorded at Pipestone Creek near Moosomin (05NE001) hydrometric station. The purpose of this comparison was to validate the water balance. Monthly historical records at 05NE001 compared acceptably with simulated values for the period 1987 to 1994. Most of the simulated values were a little higher than the recorded values at 05NE001 hydrometric station and there is room for improvement in the estimate. The EDA associated to the lake was as in the PFRA drainage area delineation. This area is about 1070 km^2. I did a sensitivity analysis to this area by reducing it in about 3%. Following the EDA reduction, results also compared acceptably with historical records for the period 1987 to 1994, but most of the simulated values were a little smaller than the recorded values at 05NE001 hydrometric station. Also, the bias for the spring high flows was much larger. The relationship between results and the EDA was expected since the inflow to the lake was estimated by transferring flows from 05NE003 hydrometric station by using area ratio." (Marin, 2019b)

[6]Active volume is the full supply level storage less dead storage; dead storage being the volume not able to be drained by gravity (i.e. streamflow).

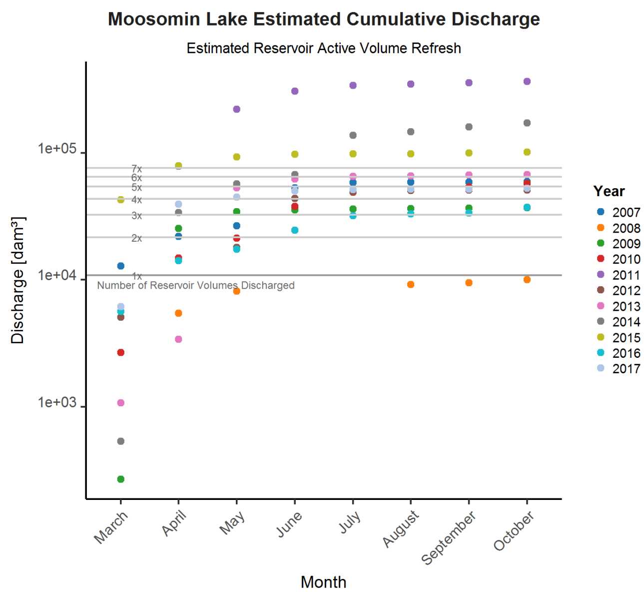


FIGURE 2. **Cumulative Discharge from Moosomin Lake**. The discharge volume is shown on a log scale for clarity.

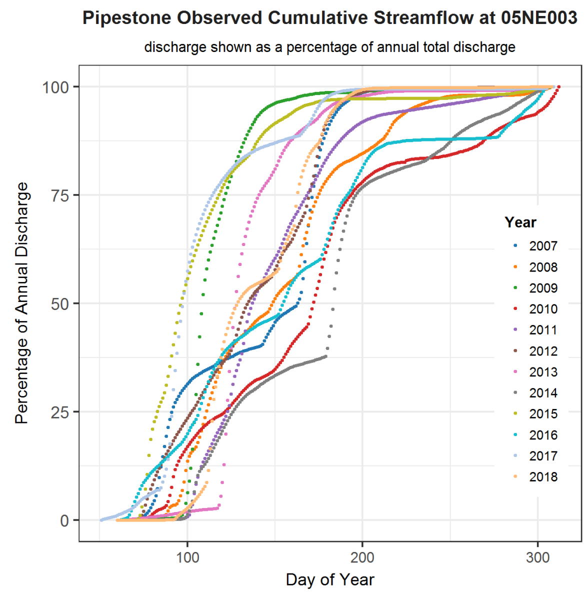


FIGURE 3. **Cumulative Discharge at 05NE003**.

creek locations upstream and one downstream of Moosomin Lake by Phillips et al. (2008). Phillips et al. (2008) used a Modified Hilsenhoff Biotic Index to assess pollution levels in the Pipestone Creek and found the water quality in the creek to be poor and indicative of significant organic pollution. The source of the pollution was not established but the authors speculated that there are many potential sources of organic pollution in the watershed including, but not limited to, agricultural chemicals, sewage lagoon leakage, and cattle corrals. Since the publication of this work, additional research on the use of metrics such as the Hilsenhoff Biotic Index that have been developed elsewhere in North America suggests that they may not directly measure organic pollution in rivers and streams such as the Pipestone Creek (Phillips, 2017). The macroinvertebrate communities of Southern Saskatchewan in particular have communities that reflect high tolerance values (from Barbour et al. (1999)) regardless of human activities in many cases (Phillips, 2017), and other metrics may be applied to the Pipestone Creek in the future which will clarify the sources of stress on ecosystem health here[7].

TABLE 3. **Total phosphorus trigger ranges for Canadian lakes and rivers**. This table is taken from Canadian Council of Ministers of the Environment (2004, Table 1) and presents the levels at which phosphorus levels might trigger further investigation subject to the specific ecosystem and established natural levels in that region or system.

Trophic Status	Canadian Trigger Ranges Total Phosphorus [mg/l]
Ultra-oligotrophic	< 0.004
Oligotrophic	0.004 – 0.010
Mesotrophic	0.010 – 0.020
Meso-eutrophic	0.020 – 0.035
Eutrophic	0.035 – 0.100
Hyper-eutrophic	> 0.100

[7]These final two sentences providing an update on the use of the Hilsenhoff Biotic Index in Pipestone Creek were provided by Iain Phillips at the WSA as a comment on his original report Phillips et al. (2008) and subsequent Ph.D. research (Phillips, 2017).

The 2003 - 2006 water sampling records for the reservoir provide an average concentration of 0.2 mg/L for total phosphorus (TP) and 2.0 mg/L for total nitrogen (TN) with some change year to year as shown in Figure 4. The concentrations for phosphorus are in the range of a hyper-eutrophic system using the established lake trophic status indicators for phosphorus provided in the Canadian Water Quality Guidelines for the Protection of Aquatic Life (Canadian Council of Ministers of the Environment, 2004) in Table 3. Similar to the discussion below, NO_x as N is low to below detection in most samples and, as a result, total Kjeldahl nitogen (TKN) is representative of TN. The TN:TP mass ratios observed in the reservoir in the sample years, ranged 5:1 to 18:1, with a mean of 11:1 (Figure 5).

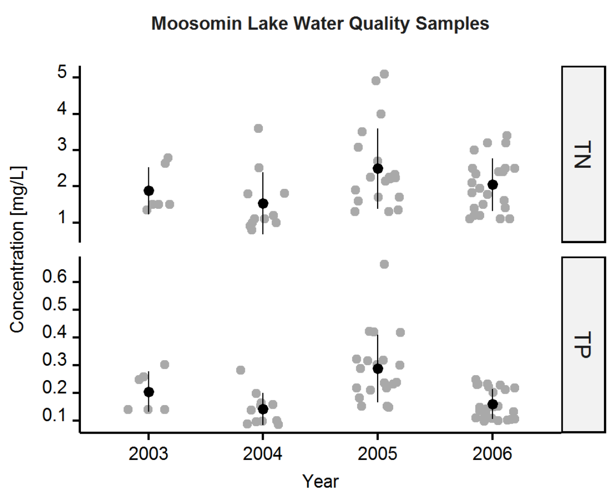


FIGURE 4. **Moosomin Lake TP and TN Historical Water Quality**. These plots are a summarization of the all samples taken by the WSA for all locations (shoreline, near creek, mid-lake surface and bottom). A more detailed presentation of these data are provided in Saskatchewan Watershed Authority (2005, 2007).

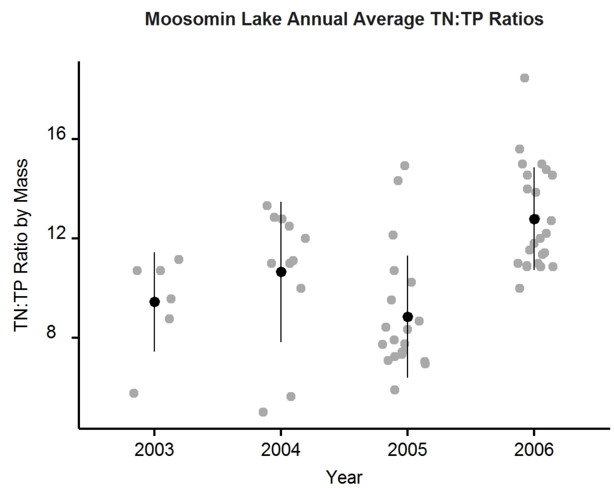


FIGURE 5. **Moosomin Lake TN:TP Ratios Historical Record**. These mass ratios are calculated from the data points in Figure 4 and are a summarization of the all the samples taken by the WSA for all locations (shoreline, near creek, mid-lake surface and bottom).

Pipestone and Little Pipestone. The WSA executed several water quality sampling programs in the lake watershed. One of the more thorough water quality records in the watershed is at the Water Survey of Canada hydrometric station 05NE003 called PSC-152. The PSC-152 water quality record of grab samples is available for 2007 to present. Just downstream of Pipestone Reservoir (approximately 80 kilometers upstream of 05NE003) the WSA established a temporary hydrometric station in 2008 to 2010 to coincide with water chemistry sampling at PSC-71. Along this same reach of the Pipestone Creek additional chemistry samples were taken between PSC-71 and PSC-152 at locations PSC-104 and PSC-126. The location numbers reference stream distance in kilometers and PSC refers to PipeStone Creek. The chemistry at PSC-182 is 30 kilometres downstream of PSC-152 and, actually, located just after Moosomin Dam. Figure 6 illustrates these site locations in the watershed. This chemistry record is used here to estimate the actual load of phosphorus and nitrogen entering the reservoir annually.

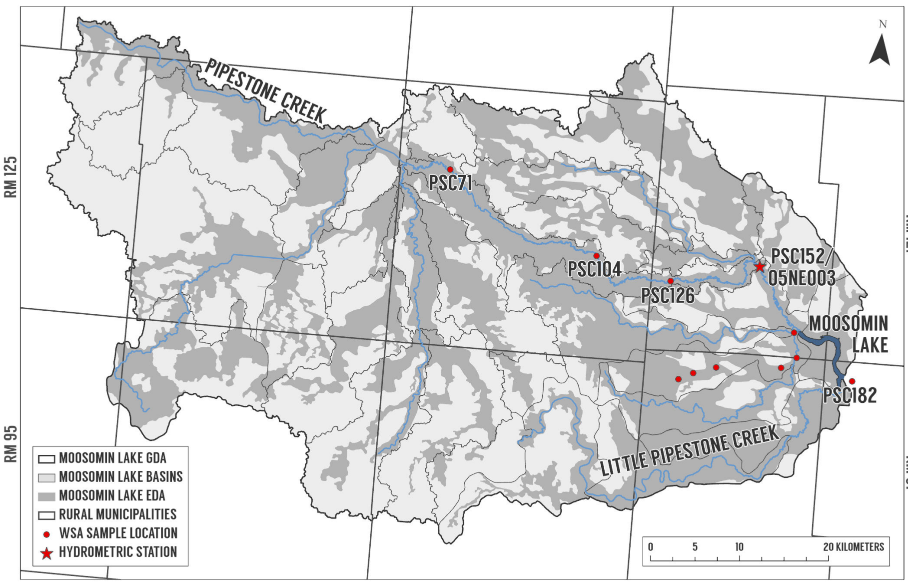


Figure 6. **Site Map of the Moosomin Lake Watershed**. Image credit: Daniel Phalen, LSWC

The PSC-152 water quality data set is plotted against the flow time series from 05NE003 in Figures A.4 to A.7. Censored data, those data below the instrument detection limit, were filled with a random value between 0 and the detection limit; missing data were filled by linear interpolation and represented by the green points in Figures A.4 to A.7. The shortage of available TN data points is evident here as well as in Figure A.2 where other chemistry samples were quantified for availability. The relationship between TKN and TN in these data has a mean ratio of 0.96 for PSC-152 (Figure A.8). And, the fraction of dissolved P (DP) in the TP observations is about 60% with some seasonal change to this ratio (Figure A.3).

Boxplots for DP, TP and TKN illustrate data availability and mean concentration values for each month at Station PSC-152 (Figures 8 to 12). Evident in these data is the fact that there does exist some seasonality (i.e. higher concentrations during snowmelt runoff and late summer) to the observed chemistry concentrations, a flow-concentration relationship may exist but statistical rigour is required to assess this (Figures 7 to and 11) (although not observable on a log-scale Figures A.9a to A.9c), and the concentrations appear to increase over time (Figure 13) as do the flows (Figure 13.

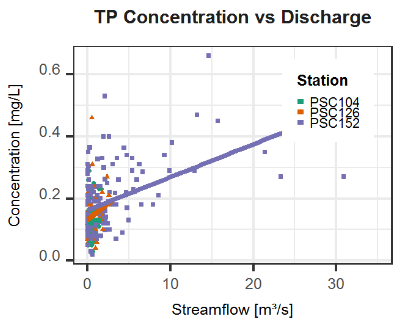


FIGURE 7. **TP Concentration vs Discharge on Pipestone Creek**. The coloured lines show a the best fit linear regression model through the data points; colours represent the different stations.

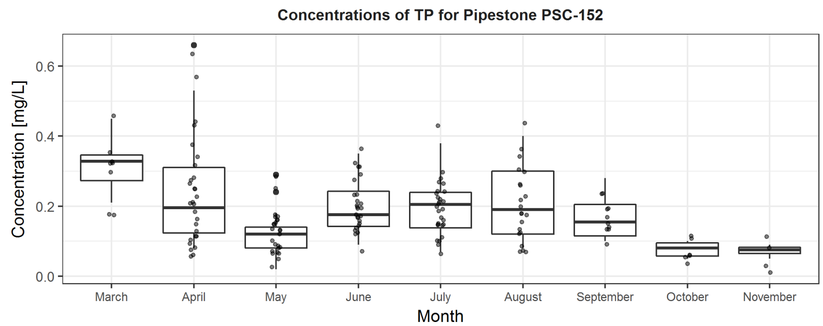


FIGURE 8. **Average Monthly TP Concentrations on Pipestone Creek PSC-152**. Boxplots illustrate the mean and inter-quartile range and whiskers (95th percentile) for collected chemistry data at PSC-152.

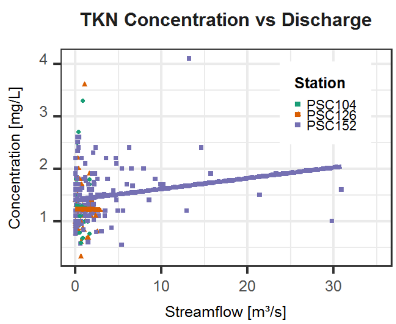


FIGURE 9. **TKN Concentration vs Discharge on Pipestone Creek**. The coloured lines show a the best fit linear regression model through the data points; colours represent the different stations.

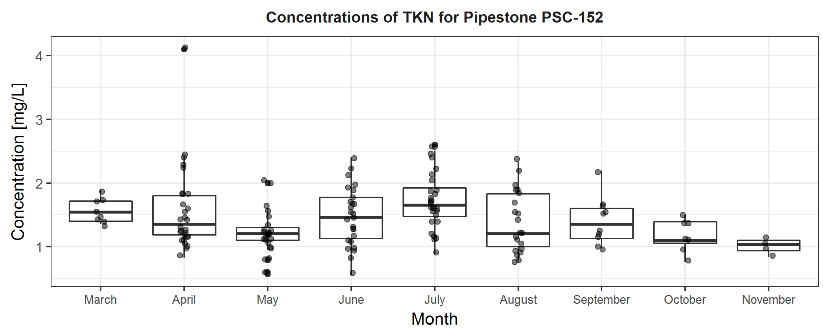


FIGURE 10. **Average Monthly TKN Concentrations on Pipestone Creek PSC-152**. Boxplots illustrate the mean and inter-quartile range and whiskers (95th percentile) for collected chemistry data at PSC-152.

The mean concentrations of TKN and TP at PSC-152 on Pipestone Creek, over the 2007 - 2018 time period, were 1.5 mg/L TKN and 0.2 mg/L TP with mean concentrations (2003 - 2006) of 2.0 mg/L TN in Moosomin Lake and 0.2 mg/L of TP (reported above). Downstream of the dam, at PSC-182 there are two years of data, 2009 and 2010. The paired samples taken in 2009 and 2010 for PSC-152 upstream and PSC-182 downstream of Moosomin Dam are plotted in Figure 14. The plots indicate that concentrations are reduced for TP and TKN after Moosomin Dam except in the late summer / early fall at the same time chlorophyll-*a* and organic carbon in the lake peak as discussed in Section 2.4 (see also Figures A.10 to A.13). The calculated mean concentrations for the paired samples taken in 2009 and 2010 for PSC-152 are 1.3 mg/L TN and 0.19 mg/L TP and for PSC-182 are 1.2 mg/L TN and 0.13 mg/L TP.

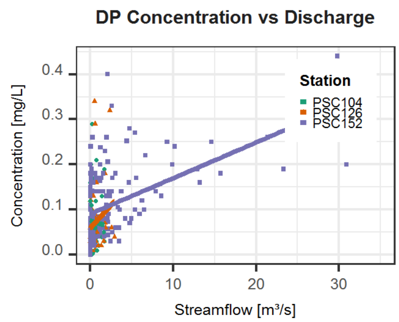


FIGURE 11. **DP Concentration vs Discharge on Pipestone Creek**. The coloured lines show a the best fit linear regression model through the data points; colours represent the different stations.

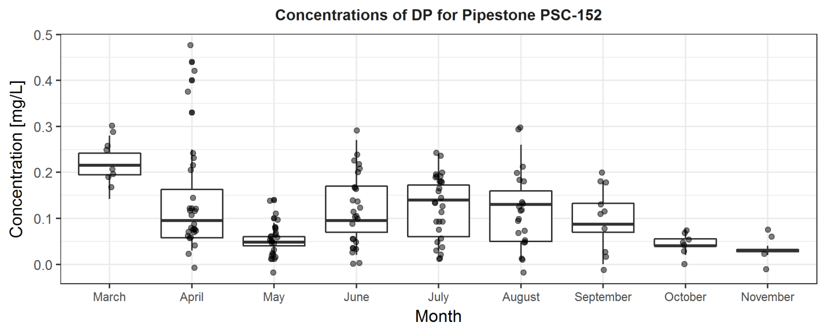


FIGURE 12. **Average Monthly DP Concentrations on Pipestone Creek PSC-152**. Boxplots illustrate the mean and interquartile range and whiskers (95^{th} percentile) for collected chemistry data at PSC-152.

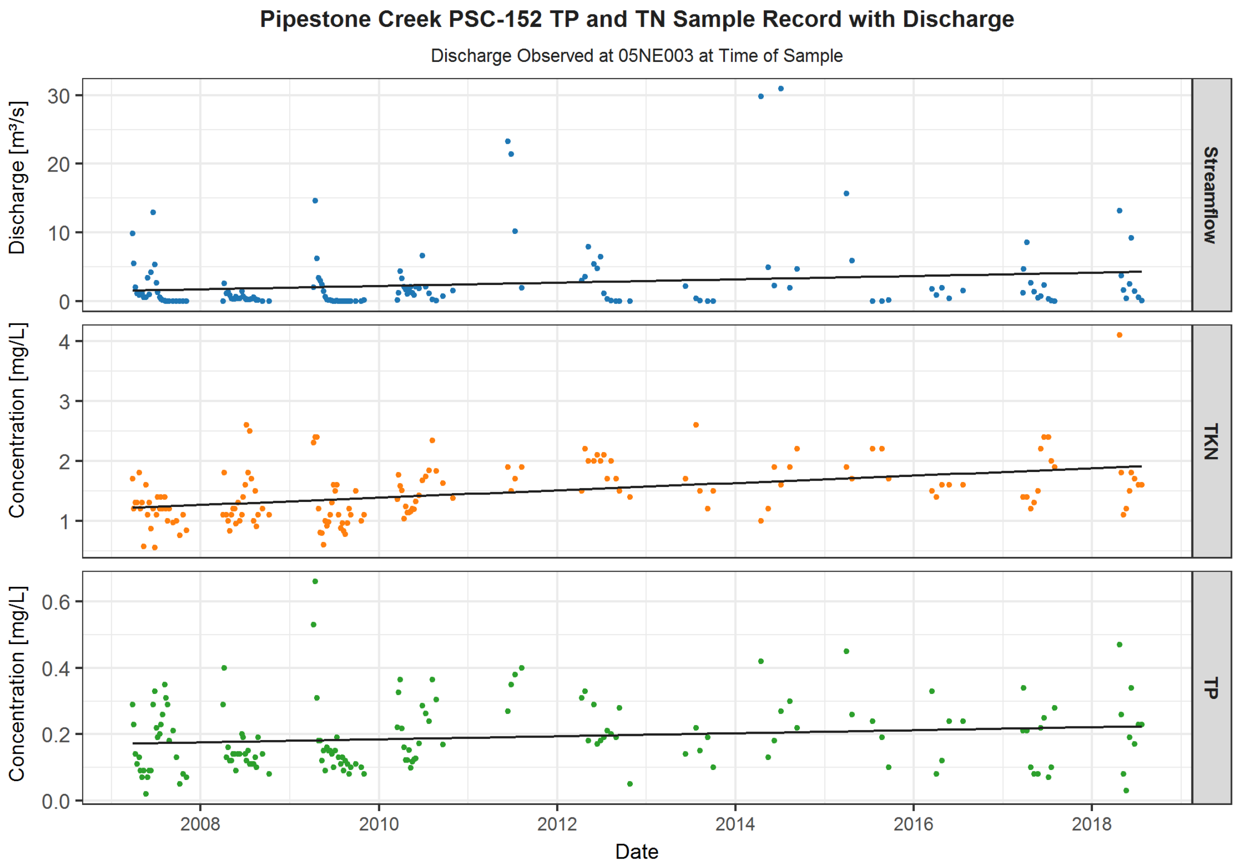


FIGURE 13. **Time Series of Observed TP and TKN Concentrations in Pipestone Creek at PSC-152**. These concentration data appear to be increasing at PSC-152 over the 11 years of the sample record. The time trend of these seasonally patterned, autocorrelated data is upward for both TKN (slope of the trend: 0.0036), TP (slope of the trend: 0.00015), and observed streamflow (slope of trend:0.015) using a time series linear regression model for autocorrelated data (Hyndman et al., 2019). Further statistical rigour is recommended to gain confidence in these initial assessments and to clarify the flow-concentration relationship.

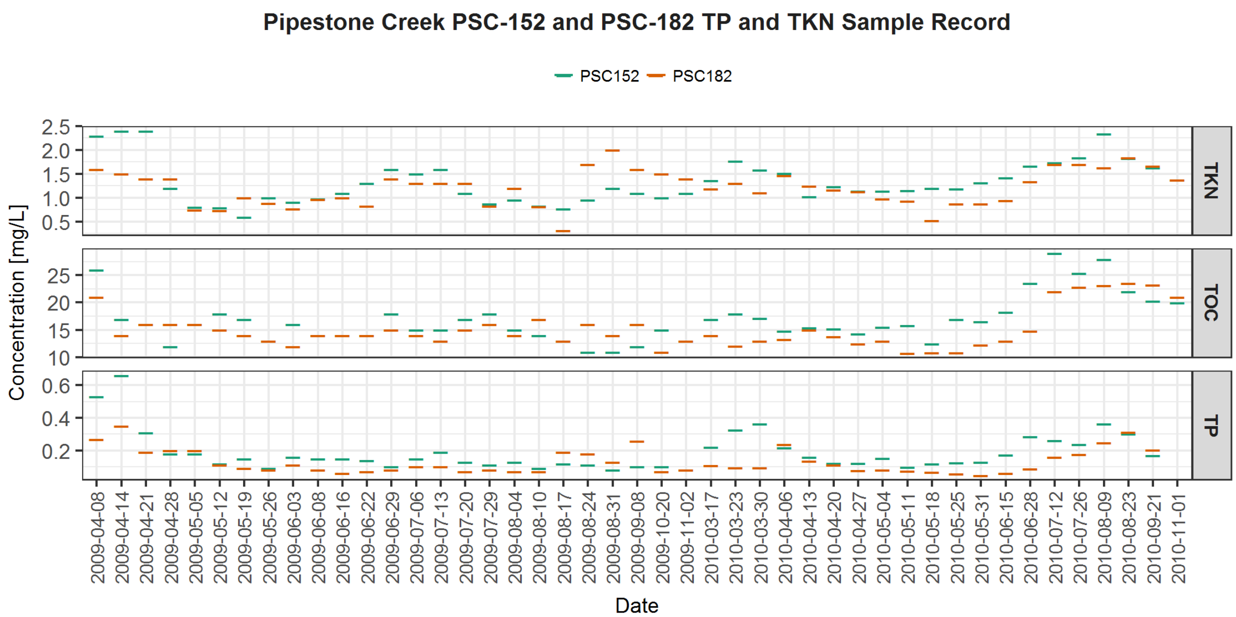


FIGURE 14. **PSC-152 and PSC-182 TP, TKN and TOC Data**. This plot pairs each sample taken at PSC-152 (upstream of Moosomin Lake) with PSC-182 (after the Moosomin Dam). It is evident here that for most of the year (except late summer / early fall) that concentrations are lower after the dam.

2.3. **Phosphorus and Nitrogen Loads into the Lake.** Annual loads of TN and TP observed in the Pipestone Creek were tabulated at PSC-152 using two methods: 1) using daily streamflows and daily concentrations interpolated, using linear interpolation between sample points, from the (less frequent than daily) chemistry observations (dark blue in Figure 16) and 2) using the monthly streamflow estimations provided by the WSA and a calculated flow weighted mean concentration (FWMC) based on the set of observed chemistry concentrations and flows for each month (light blue in Figure 16). These two methods were employed to provide validation for the load estimates and both methods did, indeed, produce similar estimates. These loads estimated for PSC-152 were then transferred to Moosomin Lake proportional to the monthly discharge volumes for both Pipestone Creek and the Little Pipestone Creek at Moosomin Lake.

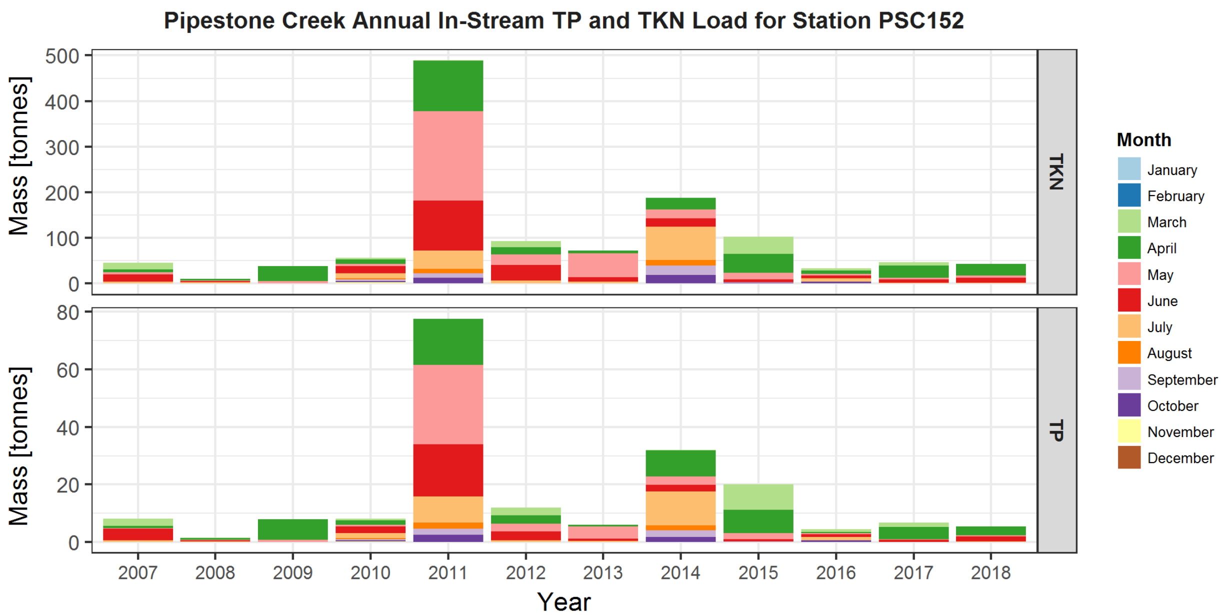


Figure 15. **Tabulated TKN and TP Loads at PSC152.**

The next phase of this project is to estimate the sources of these loads and the potential reduction to these loads were land management changes made in the region. The total loads tabulated for each of the years 2007 to 2017 have some point contributions; primarily municipal lagoons in the Moosomin Lake watershed. Over the 2007 to 2017 time frame the municipal contributions to loading ranged from $0.02 - 14\%$ for TN and $0.04 - 12\%$ for TP with an average 1.7 tonnes of TN and 0.2 tonnes of TP discharged annually to the streams. In the subsequent discussion of loads from the Pipestone and Little Pipestone Creek, these municipal contributions to the loads have been subtracted, in an attempt to isolate loads to sources that are diffuse in the watershed and likely agriculture related.

The ranges of annual TN and TP loads per unit area to the lake, referred to as export coefficients, for 2007 to 2017 are $0.05 - 2.0$ kg/ha for TN and $0.01 - 0.3$ for TP for the GDA and $0.1 - 4.6$ kg/ha for TN (mean 1.0 kg/ha TN) and $0.02 - 0.7$ kg/ha for TP (mean 0.2 kg/ha TP) for the EDA. The wet year of 2011 data extends the range of coefficients dramatically (Figure 17). These calculated ranges of export coefficients for the Moosomin Lake watershed are plotted in comparison to the export coefficients in a few other regions on the Canadian prairies in Figure 18. The Qu'Appelle watershed shown is a 55,700 km^2 study area with coefficients for the $2013 - 2016$ study period (Roste and Baulch, 2018); some of the eleven Pipestone GEDs are situated within the Moosomin Lake watershed (noted previously), drainages range $4.1 - 8.0$ km^2 and the coefficients

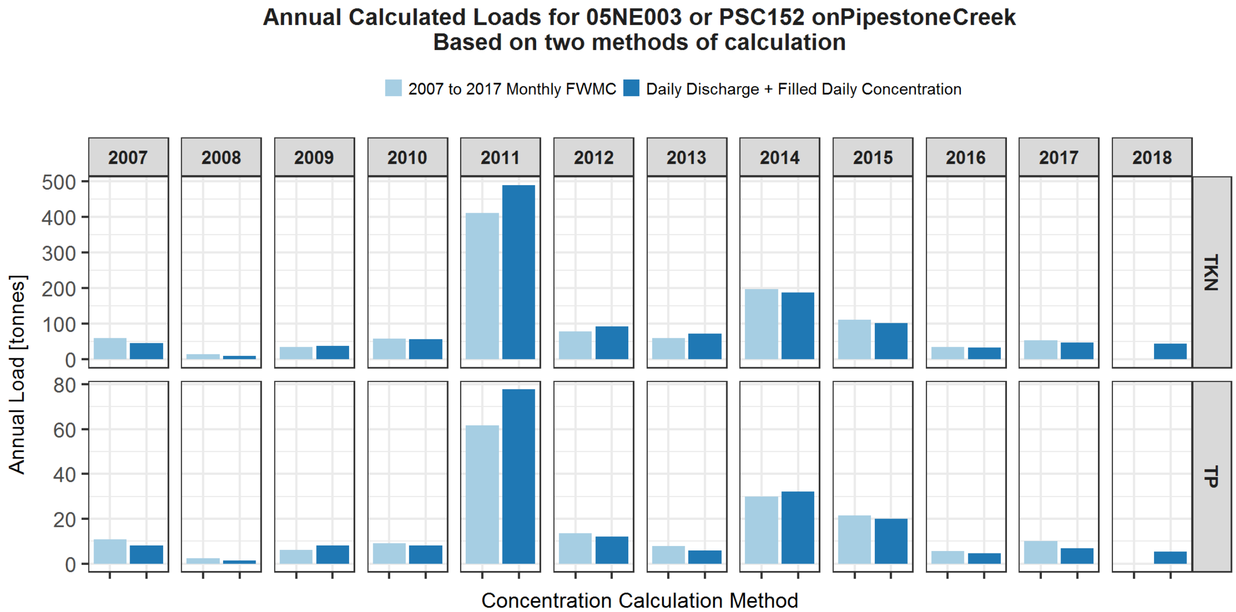


FIGURE 16. **Estimated TKN and TP Loads at PSC152 Using Two Methods.**

are for monitoring results during the period of 2007 - 2009 (Goodbrand et al., 2010; Roste and Baulch, 2017). The Southern Manitoba export coefficients are for the years 2010, 2013, and 2014 for eleven subwatersheds in the Red River valley ranging 65 - 626 km^2 (Rattan et al., 2016).

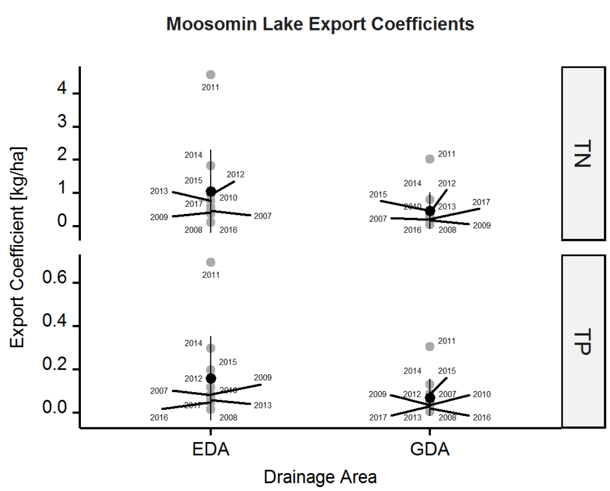


FIGURE 17. **Calculated Export Coefficients for Moosomin Lake Watershed.** Export coefficients for the Gross Drainage Area and Effective Drainage Area of the Moosomin Lake Watershed for the years 2007 - 2017.

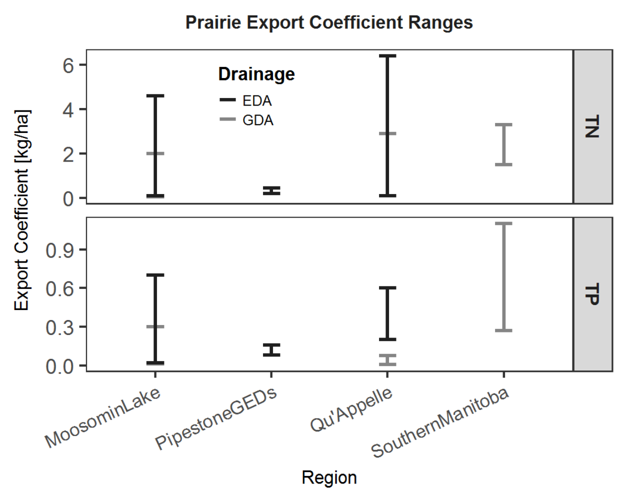


FIGURE 18. **Calculated Export Coefficients for Prairie Watersheds.** A regional comparison of export coefficients for the Canadian prairies. Ranges in light grey bars indicate GDA export coefficients and those in dark grey, the EDA export coefficients. See text for details of catchment size and monitoring periods.

2.4. **Discussion.** Moosomin Lake receives high concentrations of TP and TN from the Pipestone Creek and Little Pipestone Creek as well as the surrounding lands adjacent to the lake. This contributes to a substantial nutrient load with an average annual surface loading rate to Moosomin Lake for phosphorus of 6.1 t/km^2/yr and nitrogen of 44.1 t/km^2/yr based on measured flows and chemistry from 2007-2017.[8] The actual chemistry and health of the lake have not been assessed since 2006. At that time, dissolved oxygen levels in the lake decreased substantively over winter[9] but were otherwise $6 - 15$ mg/L, the calculated mass ratios of TN:TP averaged 11:1 (Section 2.2), Secchi disk reading were the smallest and chlorophyll-a was highest in late July and August[10] (Saskatchewan Watershed Authority, 2005, 2007). Also, data in Figure A.3 suggest that particulate P transport, while lower than dissolved P, is an important nutrient source. Erosion from fields, or streambanks may therefore be important nutrient sources in the catchment.

Calculated TN and TP loads from the concentrations and streamflow data in the Pipestone Creek available 2007−present day average, 7:1 for TN:TP by mass[11] in Pipestone Creek. The land sourced exports of N and P in the Moosomin Lake watershed are comparable to those from other Canadian prairie watersheds, such as those in southern Manitoba and the Qu'Appelle in Saskatchewan, where P and N levels have been (adversely) impacting fresh waters and are in need of management (Figure 18). Moosomin lake could potentially benefit from reductions to N and P loads, with P often thought of by limnologists as the most important nutrient to control to help manage nuisance algal biomass. Managers need to understand the challenges posed by the setting of Moosomin Lake and what can be realistically achieved. Inflows to the lake, as with other southern prairie waterbodies, have high concentrations of inflowing nutrients (hyper-eutrophic levels) that result in increased risk of nuisance algal bloom formation. And, it is known that agricultural activities increase the amount of nutrients in streams. Understanding the relative contribution from agricultural activities and the anticipated effect on waterbodies resulting from reducing these inputs, for example through implementation of BMPs, is needed when developing watershed management strategies.

Winter aeration can be an approach to help reduce the risk of winter fish kills. Aeration may also have broader water quality benefits. However, field assessments on aeration in well mixed reservoirs have shown that aeration does not improve reservoir trophic status (assessed in terms of dissolved oxygen, phosphorus, nitrogen, Secchi disk and chlorophyll-a levels) (Siwek, 2018; Kuha et al., 2016), but it may potentially increase the TN:TP ratio as there is some indication that hypolimnion aeration may encourage precipitation and sedimentation of P (Siwek, 2018), and help reduce the recycling of P from sediments. Within relatively large, shallow reservoirs such as this the benefits of aeration for nutrient retention may be somewhat limited. However, aeration can help reduce acute risks, such as the risk of winter fish kills associated with low oxygen. Also, if oxygenation can be maintained at the sediment-water interface, this can help enhance sediment-associated P retention, and reduce the risk of P mobilization from sediments (also termed 'internal phosphorus loading'). However, ensuring adequate aeration for a large sediment area such as this,

[8] For comparison, the loading rates to a few eutrophic and hyper-eutrophic lakes in Saskatchewan: Buffalo Pound (5.7 t/km^2/yr TN, 1.1 t/km^2/yr TP), Crooked Lake (126 t/km^2/yr TN, 20 t/km^2/yr TP), and Round Lake (175 t/km^2/yr TN, 25 t/km^2/yr TP). Influent load estimates are in-stream only (i.e. direct overland contributions to load not included) and as estimated by the WSA for the years of 2013-2015. Travers Lake is a hyper-eutrophic lake in Alberta and Morales-Marin et al. (2017) estimated loads in-stream to the lake, which yield surface loading rates of 3.7 t/km^2/yr TN, 0.8 t/km^2/yr TP. Lake Winnipeg in 1999-2007 experienced loads of 3.8 t/km^2/yr TN, 0.3 t/km^2/yr TP (Levesque and Page, 2011).

[9] Late winter early spring dissolved oxygen levels were observed to be 2.9-5.7 mg/L at the 3.5 to 4 m depth (Saskatchewan Watershed Authority, 2005, 2007)

[10] Smallest Secchi disk readings were $0.6 - 0.7$ m and, highest chlorophyll-a readings were 100-178 μg/L (Saskatchewan Watershed Authority, 2005, 2007).

[11] We evaluated this relationship in a couple locations, at 05NE003 55.6 tonnes of TN:8.4 tonnes of TP (6.6:1) and as predicted for the entire watershed in Section 3.2, 95.2 tonnes of TN:14.2 tonnes of TP (6.7:1).

is very challenging. Using current aeration equipment may have some nutrient retention benefit for the reservoir (and can definitely help avoid winter fish kills); however extending aeration efforts may not be merited at this time. Other options, such as direct chemical amendment could be considered, but again are challenging in lakes such as this with shallow depths, and large watersheds (Baulch et al., 2018), and rapid flushing rates. Overall, reducing the external load of phosphorus (and nitrogen) to the lake (point and non-point source) is considered a more fruitful investment than aeration (Kuha et al., 2016; Nygrén et al., 2017); so although water quality improvements are likely achievable, the lake may always be eutrophic. (Baulch et al., 2018).

3. Predicting Land Based Phosphorus and Nitrogen Exports

3.1. **Moosomin Lake Watershed Land Use.** Calculating nutrient exports from land sources to receiving streams and lakes is challenging. Most watersheds are not sufficiently monitored to alleviate the need for assumptions and the application of data from from other (hopefully similar) regions; and Moosomin Lake watershed is no exception. In the previous sections, we took inventory of the available chemistry and discharge data in the Moosomin Lake watershed and using the best available data (the data at Pipestone Creek upstream of lake, the co-located PSC-152 for water quality at the hydrometric station 05NE003) estimated the current nutrient loads to the lake for the years 2007 to 2017 (inclusive). And, here we investigate agricultural Beneficial Management Practices (BMPs) that may reduce the export of land sourced nutrients to the influent streams and the lake. There are three important questions that managers should answer in order to plan appropriately: 1) What are the achievable reductions with the application of BMPs?; 2) If these reductions to nutrient loadings are achieved, what is the expected lake response?; and 3) Based on the predicted change in lake condition and goals of managers, what is the overall value of the BMPs?. This section is designed to address the first question and Section 6 speaks to the use of adaptive management to address the subsequent two points. Here, we proceed to work through the steps performed in the assessment of the potential performance of seven BMPs thought likely to be beneficial (Section 4): fertilizer management, relocation of manure applied lands, annual crop to perennial forage conversion, fallow to minimum till annuals conversion, the restoration of wetlands, relocation of winter feeding sites, and restricted grazing access to lakeshore and riparian zones. In the discussion to follow, the beneficial nature of any one BMP is determined by the predicted reduction to current nutrient exports from the area of land within the EDA associated with the BMP. The reductions are quantified in units of mass whereas the export coefficients (ECs) are units of mass per unit area typically, kg/ha. The subsequent BMP assessment follows these steps:

(1) Identify the land use practices and tabulate the land area allocated to each land use in the watershed (Section 3.1).
(2) Aggregate export coefficients in the Canadian prairie for these land uses. (Section 3.2, Tables B.1-B.3)
(3) Predict land sourced nutrient exports to Moosomin Lake based on land use in the effective drainage area or EDA of the watershed and established ECs in the literature[12]. (Section 3.2, Table 6)
(4) Simulate a change in land use practice to one of the seven chosen BMPs by applying the ECs associated with the BMP to the land area allocated to the BMP. (Sections 4.1 and 4.2, Table 8)
(5) Evaluate BMP performance based on the predicted change to land sourced nutrient exports. (Section 5, Table 9)

Multiple sources of data were utilized to establish the current land use in the Moosomin Lake watershed (Figure 23):

Cropland, Urban, Barren, Exposed and Water Covered Areas. The Centre for Agroclimate Geomatics and Earth Observation Science and Technology Branch (2017) imagery analyses were used to establish crop types as wells as urban, barren, exposed, forested, and water areas. Crop types provided by the inventory are binned as grassland/prairies, pasture/forages, land too wet to be seeded, fallow, barley, oats, rye, winter wheat, spring wheat, corn, canola/rapeseed, flaxseed, soybeans, peas, lentils and canary seed.

[12]The mean nutrient loads from 2007 through 2017 were used as the target predicted value. This was with the years of 2011 and 2014 removed as these were very high flow years that would most definitely include runoff and in the case of 2011, ponding, in normally noncontributing drainage areas (NCDA) of the GDA.

Wetland Area. The area designated as wetland in the Centre for Agroclimate Geomatics and Earth Observation Science and Technology Branch (2017) landsat imagery was less than that designated as wetland by the inter-agency wetland inventory. The land area in crops was adjusted to reflect this change to make sure the all land areas summed to (and did not exceed) the total EDA and GDA[13]. The Canadian Wetland Inventory (Saskatchewan Watershed Security Agency et al.; Boychuk et al., 2014) defines multiple wetland area types: constructed, intact, partly drained, farmed, and fully drained. For the purposes of this analysis current wetland area is the tally of constructed and intact wetlands. Drained wetland area is comprised of partly drained and fully drained. Farmed wetlands have the capacity to retain water (temporarily ponded during and after a runoff event, or more consistently under wet conditions) and can be regularly farmed and are defined by Boychuk et al. (2014) as areas where "The soil surface has been mechanically or physically altered for production of crops, but hydrophytes will become re-established if farming is discontinued". This wetland inventory is a work-in-progress and is not necessarily reflective of extant drainage in the Moosomin Lake Watershed; updating the inventory for this 3400 sq.km. watershed to accurately represent current conditions is a large task outside the scope of this project. In *Restoration of Wetlands* under Section 4.1 we use the modified EDA as a proxy for estimating the extant drainage in the watershed.

Table 4. **Wetland Area Designation in Moosomin Lake Watershed**. Wetland area fractions of the watershed area are based on those designated in the interagency wetland inventory (Saskatchewan Watershed Security Agency et al.; Boychuk et al., 2014). Areas in the GDA that are designated as 'drained' are likely ditched and actually draining to streams. The drained areas of the GDA comprise 0.3% (9.3 km^2 of 3405 km^2) of the total watershed area based on completely + partly drained = $0.042 + 0.23 = 0.3\%$.

Wetland Designation	GDA	EDA
Completely Drained	0.042%	0.07%
Constructed	0.07%	0.07%
Farmed	0.6%	0.6%
Intact	9.4%	7.4%
Partly Drained	0.23%	0.3%

Livestock grazing and wintering, and manure spreading. The numbers of livestock (cows, sheep, and horses[14]) and area of land with manure spread in the watershed were both established based on Canadian agricultural census data for the RMs in the watershed (Statistics Canada, 2016). The numbers in the watershed, subwatersheds, and basins were determined based on the fraction of area of the RM within the EDA. Animals are not uniformly distributed throughout the watershed nor are manured lands evenly distributed; but it is a method of approximation based on available data. To further place livestock in the EDA vs GDA, the livestock counts were weighted by the percentage of corrals located in each drainage area. The livestock were converted to nutrient units (NU). A nutrient unit is defined as "the number of animals that will produce the amount of nutrients that give the fertilizer replacement value of the lower of 43 kilograms of nitrogen or 55 kilograms of phosphate as nutrient" (Ontario Ministry of Agriculture Food and Rural Affairs,

[13]Typically wetlands are drained to service the growing of crops, therefore any land area designated as wetland that was over and above that identified by Centre for Agroclimate Geomatics and Earth Observation Science and Technology Branch (2017) was subtracted by the land identified as land in crops, in this case the land allocated as forages were de-rated in land area. The actual area designated as wetland in the EDA is 4.1% (5.2% in the GDA) in the landsat imagery and 7.6% (8.2% with farmed included) as constructed and intact wetlands in the Canadian Wetland Inventory (9.4% of GDA 10% (with farmed wetlands included) of the GDA).

[14]Sheep and horses were provided from Statistics Canada (2006) data.

2007)[15]. The number of corrals or livestock wintering sites was inventoried by the LSWC staff and each livestock site in the EDA was provided with a drainage path length from corral to stream, and size assessment (Figures 19 and 20). Examples of the large, medium, small corral sizes are provided illustratively in Figure B.1.

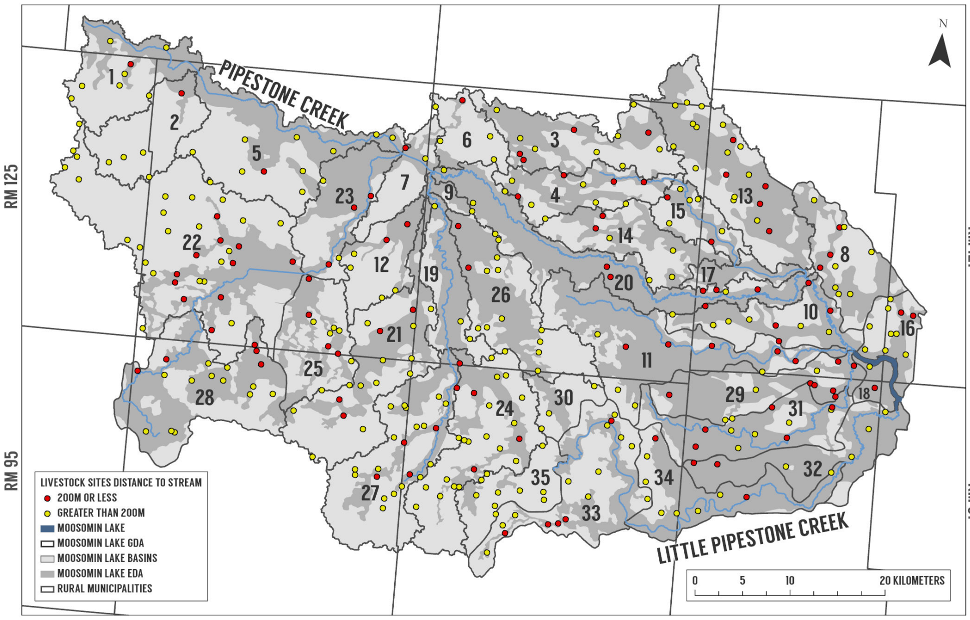


FIGURE 19. **Livestock Sites Proximity to Stream**. This geospatial analysis performed by the LSWC staff located the livestock sites and the length of each site's drainage route to stream. Livestock sites are indicated by the coloured circles. The basin numbers are discussed in Section 3.2 and presented in Figure 22.

[15]The more familiar term used has been animal unit (AU) where the animals are equalized in terms of grazing impact. For reference, one dairy cow (small-frame, 800-1000 lbs, milking or dry, such as Jerseys) or beef cow (includes unweaned calf and replacements) are each one nutrient unit; which for purposes of this research is equal to the animal unit definition used in the corral studies (one - 455 kg (1000 lb) cow).

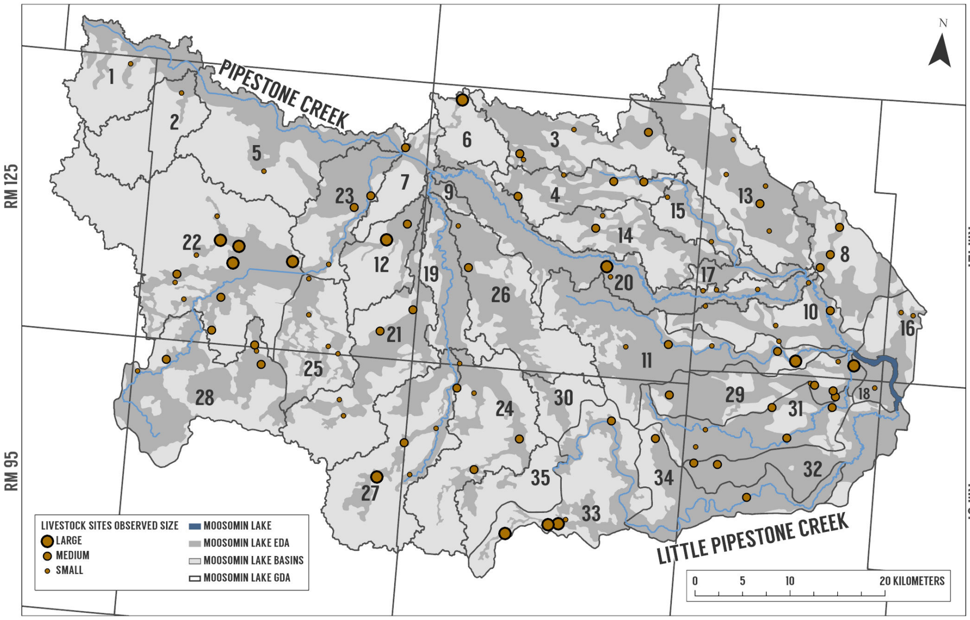


Figure 20. **Livestock Sites Size Assessment**. The size of each identified livestock site is indicated by the size of the circle (refer to Figure B.1 for an illustration of these livestock site sizes). The sites within 200m of a stream are shown here; although all 295 sites were assessed. The basin numbers are discussed in Section 3.2 and presented in Figure 22. Image credit: Daniel Phalen, LSWC

Lakeshore and riparian grazing. The distance of riparian zone and lakeshore adjacent to pasture land was assessed by the LSWC staff and provided for use in this study (Figure 21). Lineal meters of riparian grazing were quantified using GIS analyses and data interpretation. This exercise didn't distinguish those areas that may already be fenced off to livestock, or account for areas of land identified in the GIS layers as grassland (other land use category) that may support livestock grazing. All told, in discussions with the LSWC staff, the estimated meters of riparian and lakeshore access in the Moosomin Lake watershed are potentially under estimated. Application of these results, as with application of any others in this report, requires careful consideration of the current land use practices in the watershed.

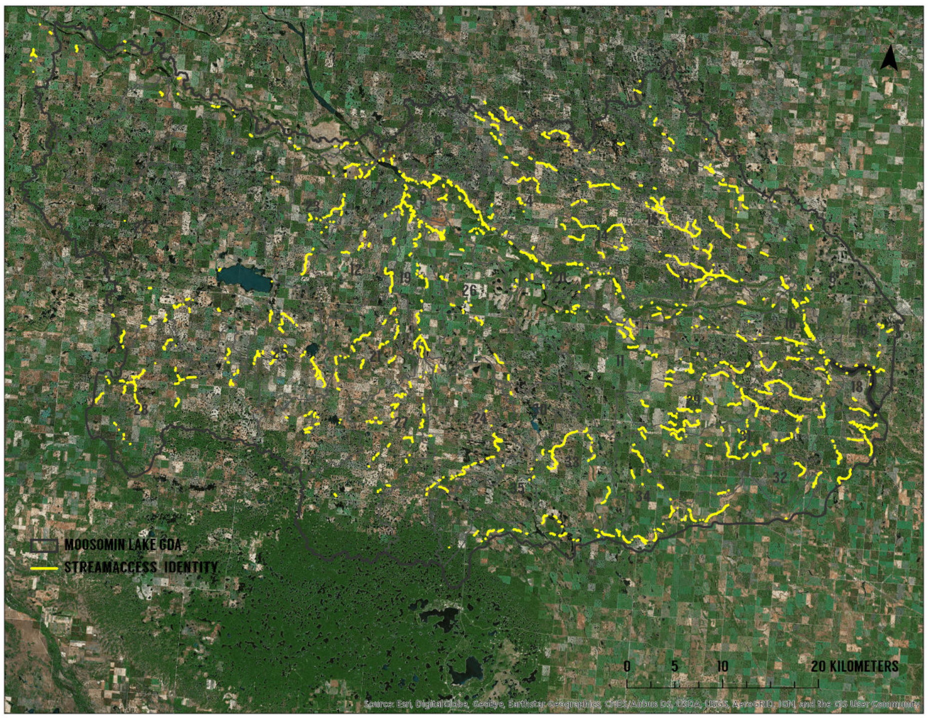


FIGURE 21. **Assessed grazing access to streams and lakes**. The image shown indicates (yellow) the length of streams and lakeshore identified with grazing access. Image credit: Daniel Phalen, LSWC

3.2. **Selecting the Moosomin Lake Watershed Export Coefficients.** An aggregated list of land use ECs for the Canadian prairie has been developed in previous work by the authors for the Qu'Appelle Watershed Stewards and Research and Monitoring Committee (summarized, presented and updated in Tables B.1-B.3). The exact values selected from the ranges provided in those tables are shown alongside the corresponding land use for the Moosomin Lake watershed in Table 6. ECs in the literature are developed from different scales of experimental and observational data. These scales are noted in the EC tables. Edge-of-field scale water quality data will often be elevated over that observed at the watershed scale. Some export coefficient models will use a scaling factor by various names to account for differences in scale for the coefficients applied in the model. We refer the reader to the land retention factor in Liu et al. (2019b), the land-to-water delivery factor in SPARROW (Schwarz et al., 2006, Part 1), the nutrient delivery ratio used by Yang et al. (2008) as examples and Alberta Agriculture and Rural Development (2014, Section 7.2.2) for a general discussion on water quality measurements and scale. In our assessment here, we recognize that edge-of-field export coefficients and laboratory scale data likely elevate some of the data applied here. As a result, the significance of N and P contributed from edge-of-field data such as manured spread land, fallow crops, and corrals may be disproportionately high. This may also apply to the 'forest' land use. The export coefficient for forest, although at the watershed scale, seems elevated but is reflective of the available data. In addition, no explicit nutrient retention is accounted for in this exercise (i.e. that offered by transport overland in ditches, streams, ponds); but we rely simply on watershed scale export coefficient data to represent some, but not all of this retention. There is also a response lag in terms of hydrological routing and that resulting from legacy nutrients that impacts the assessment of edge-of-field nutrient response with watershed scale nutrient response. These uncertainties, though important, do not bias final outcomes as this step serves simply to tune the export coefficients to the Moosomin Lake watershed, and these 'selected' ECs need to be applied in the context for which they are used here and are not necessarily broadly applicable or comparable elsewhere.

To estimate the loads of phosphorus and nitrogen to Moosomin Lake from its watershed, the loads calculated for each of the Little Pipestone Creek and Pipestone Creek were summed and divided by 0.9 (see footnote to Table 5). These two creeks are not the only sources of inflow (and TP and TN) to Moosomin Lake, but comprise the vast majority of it, 90% by contributing area. The selected export coefficients (Table 6) were applied to the area in the watershed dedicated to each land use to predict the total loading to Moosomin Lake from the EDA. Before predicting the loads for the entire watershed, the loads were predicted for the subwatershed named 05NE003, shown in Figure 22, (where the ECCC hydrometric station and WSA PSC-152 sample location are co-located). Once the predicted TP and TN loads were reasonably close to the target mean loading for the years of 2007 to 2017 at 05NE003 (Table A.2) the same ECs were used to predict the loads to Moosomin Lake from the entire EDA for the watershed[16]. The observed TN and TP and the predicted TN and TP loads for the various component watersheds are tabulated in Table 5.

The selection process for each land use EC involved some trial and error (Section B.1). Initial parameterizations used median values for the different land uses; however, this led to substantive overestimation of nutrient exports at the watershed scale. As a result, EC's were lowered, leading to stronger model fit. Uncertainty in ECs (Table 6) is a substantive source of uncertainty in

[16]The large flow years of 2011 and 2014 were removed from the calculation of the target mean TP and TN loads as these discharge volumes would definitely have involved contributions from areas that are normally non contributing, referred to as the non contributing drainage area (NCDA). As an exercise though, the export coefficients used to predict the mean flows at 05NE003 based on EDA were applied to the watershed GDA (this includes the areas that are normally noncontributing) to see if they provide a close approximation of the observed 2011 and 2014 nutrient loads. As shown in Table 5, they under-predicted the observed loads by approximately 65% for those years (see discussion).

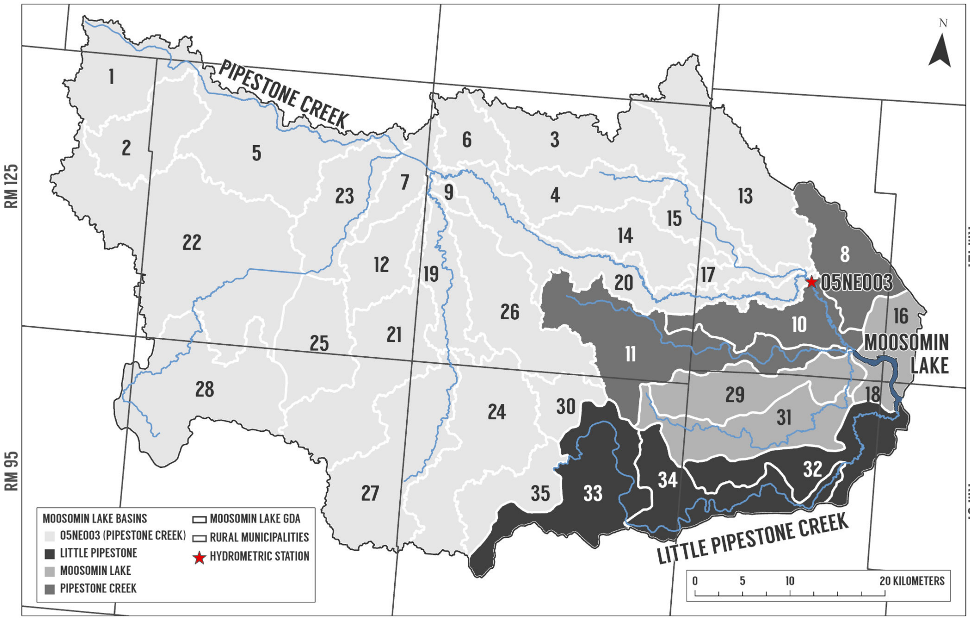


FIGURE 22. **Subwatersheds and Basins of the Moosomin Lake Watershed**. This image shows the subdivision of the watershed into 35 basins. Basins are shaded to indicate which subwatershed they belong to. The location 05NE003 on Pipestone Creek is where the hydrometric and chemistry stations are co-located. Export coefficients together with the land uses and areas in the 05NE003 subwatershed were used to predict P and N loads observed at 05NE003 (Table 5) and ultimately predict loads to the reservoir from the entire watershed. Image credit: Daniel Phalen, LSWC

TABLE 5. **Predicted Nutrient Exports in the Moosomin Lake Watershed and Subwatersheds**. The loads predicted at each of the subwatershed locations are such that subwatershed 05NE003 contributes to the Pipestone Creek subwatershed; and Little Pipestone Creek + Pipestone Creek + Moosomin Lake all together comprise the Moosomin Lake Watershed. Refer to Figure 22.

Nutrient	SubWatershed	Observed Exports tonnes	Predicted Exports tonnes	Drainage Area sq.km.	Percent Difference - Predicted Exports vs Observed 2007-2017 Max	2007-2017 Mean	2007-2017 Min
TN	05NE003	55.6	55.6	987	-46%	0.5%	431%
TP	05NE003	8.4	8.5	987	-58%	1.4%	471%
TN	LittlePipestoneCreek	11.0	11.6	214	-38%	6%	343%
TP	LittlePipestoneCreek	1.7	1.7	214	-53%	3.9%	365%
TN	PipestoneCreek	75.1	74.1	1288	-45%	-1.3%	370%
TP	PipestoneCreek	11.3	11.1	1288	-58%	-1.7%	399%
TN	MoosominLakeWatershed	95.6 *	95.2	1676	-44%	-0.4%	366%
TP	MoosominLakeWatershed	14.4 *	14.2	1676	-57%	-1.3%	393%
					2011,2014 Max	2011,2014 Mean	2011,2014 Min
TN	05NE003	489.8	119.3	2337	-76%	-65%	-36%
TP	05NE003	77.6	18.8	2337	-76%	-66%	-41%

* Estimated as (Little Pipestone Creek + Pipestone Creek)/0.9. The Moosomin Lake subwatershed comprises 10% of the watershed area and therefore Little Pipestone Creek and Pipestone Creek are estimated to comprise 90% of the observed nutrient exports for Moosomin Lake Watershed.

this exercise, and we will revisit the handling of uncertainty in our discussion of management recommendations (Section 5).

These predicted loads for the Moosomin Lake watershed are comprised of various land use categories. The watershed composition by area is illustrated in Figure 23 and the contribution of each land use category to the predicted TP and TN exports is shown in the adjacent Figure 24. To reiterate, these land sourced exports to Moosomin Lake are predicted based on the use of the applied export coefficients shown in Table 6. The predicted loads at 05NE003 are within 0.5% of the target mean observed loads for TN and 1.4% of the target mean observed load for TP. For the high flow years of 2011 and 2014 the same export coefficients under predict observed loads by approximately 65% for both nutrients (Table 5). This under prediction highlights one of the challenges of export coefficients to capture nutrient exports in catchments subject to highly variable runoff volumes. During wet years such as 2011 and 2014, activation of the NCDA, saturated soils, and extensive ponding would be some of the factors expected to increase the typical export coefficients.

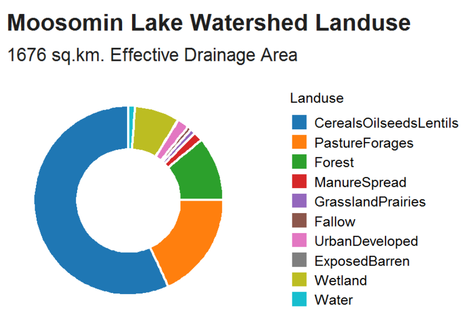


Figure 23. **Moosomin Lake Watershed by Land Use Category**. The are two additional land use categories not shown here as they don't comprise an area, these are Corrals and Riparian Grazing. In the watershed effective drainage area there are 25,229 NUs (animals quantified in terms of nutrients units) and 373,100 linear meters of identified riparian areas through pasture land.

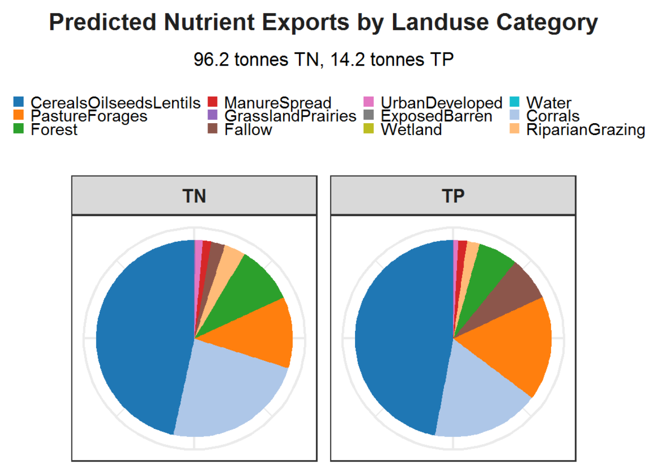


Figure 24. **Predicted Nutrient Exports attributed to each Land Use Category**.

The EDA for Moosomin Lake watershed includes all 35 subbasins (referred to subsequently as basins) shown in Figure 22. The 35 basins are a hybrid of those defined by Perez-Valdivia et al. (2012) and the work of the LSWC for this assessment. The division of the watershed into these 35 basins allows managers to assess spatially where the largest contribution of nutrients originates in the watershed. This will aid with selecting monitoring and BMP implementation strategies. Average export coefficients and total exports for each of the 35 basins are presented in Tables B.5 and B.6. For TN, the export coefficients range 0.37 to 0.71 with basins 10, 2, and 8 ranked with highest export of TN per unit area. For TP, the export coefficients range 0.05 to 0.13 with basins 1, 12, and 26 on the high end.

TABLE 6. **Export Coefficients for the Moosomin Lake Watershed Land Use**. The range of export coefficients found in the Canadian prairies are shown beside the selected EC for each land use. For more information on these land use export coefficients and others refer to Tables B.1 and B.2, the work of Roste and Baulch (2018), and Liu et al. (2019b).

		TN Export Coefficients			TP Export Coefficients		
Land use	**Area** [ha]	**Selected** [kg/ha]	**Range** [kg/ha]	**Load** [kg]	**Selected** [kg]	**Range** [kg/ha]	**Load** [kg]
Cereals,Oilseeds,Lentils	95,304	0.48	0.21 – 0.8	45,746	0.07	0.07 – 0.29	6,671
Pasture, (perennial) Forages	30,495	0.2	0 – 3.11	6,099	0.08	0 – 0.52	2,440
Fallow	1,208	3.5*[17]	1/2 of 3.6 – 16	4,228	0.85	1/2 of 1.7 – 7.8	1,027
Manure Spread land	2,689	0.9*	1/2 of 0.25 – 2.5	2,420	0.075	1/2 of 0.15 – 0.49	202
Grassland and Prairies	1,405	0.15	0.04 – 0.18	211	0.01	0.01 – 0.06	14
Forest[18]	18,425	0.5	0.5 – 2.7	9,213	0.05	0.05 – 0.18	921
Urban and Developed	3,328	0.35	0.35 – 5.5	1,165	0.03	0.03 – 1.25	100
Exposed or Barren[19]	73	0.4	0.4 – 11.05	29	0.036	0.005 – 0.37	3
	[NU]	[kg/NU]	[kg/NU]	[kg]	[kg/NU]	[kg/NU]	[kg]
Corrals	25,229 NU	0.9	0.1 – 4.8	22,706	0.1	0.015 – 1.4	2,523
	[m]	[kg·/ha]	[-]	[kg]	[kg·/ha]	[-]	[kg]
Riparian Grazing	- 373,100 m	1.5 kg/ha · 60m 90	1 – 7.13 kg/ha 40 – 80 m corridor	3,358	0.2 kg/ha · 40m 8	0.2 – 1.42 kg/ha 40 – 80 m corridor	298
Total Load				**95,175**			**14,199**
Observed Load[20]				**95,600**			**14,500**

[17] These * values stand out as potentially high. They were selected from an adjusted range as discussed in the text; but further work and research could be done to investigate these (all) values and possibly tweak the EC selection used here. As a side exercise, many iterations were used to investigate ECs; with the outcome that the final recommendations were not impacted. This exercise merely informs the BMP assessment process so that reasonable values are applied and that has been accomplished.

[18] Forest includes woodland and shrublands. This value is also thought to be quite high but it is taken from the available EC data in Table B.1. Further investigative action to determine how reflective these Alberta based EC data are of the environmental conditions and forest in Moosomin Lake watershed was not taken, as it has no impact on the outcomes of study other than to likely over estimate the contributions of P and N from forest to the overall nutrient load in the watershed.

[19] The EC for barren and exposed land was calculated based on a runoff ratio of 0.5 x atmospheric deposition rates of P and N. These are provided in Table B.1.

[20] This is the average estimated load based on flow and chemistry observations for the years of 2007-2017 (2011 and 2014 excluded). Table A.2 tabulates the estimated loads at Pipestone and Little Pipestone.

4. Assessing BMP Performance

4.1. **The BMPs.** In Section 3, the land use composition was established and nutrient loads to Moosomin Lake predicted using a selection of ECs found in the Canadian prairie. Establishing these current EC values for the watershed constrained the values of ECs to be used for the BMP assessment. This step is intended to guide the process toward outcomes that are meaningful for this particular watershed. The seven selected BMPs are presented and discussed in the following paragraphs. After discussion of the BMPs and their associated reductions (Table 8), their potentials in the Moosomin Lake watershed are presented.

Precision Farming / Nutrient (fertilizer) Management. To manage the input of fertilizers on cropland, there are several BMPs that might be considered. It is important to note that with this BMP, we are looking for a way to reduce P and N fertilizer inputs to the land, how this achieved (whether a technology is required to do this or whether agronomic recommendations for fertilization rates need to be modified) is really not the point. The point is that sustained reductions in P fertilization rates below agronomic recommendations without compromising yields but reducing P in runoff may be achievable. Here, we look to technologies to provide a quantifiable reduction to fertilizer inputs, in order that we may estimate a benefit for this practice in the Moosomin Lake watershed. Now, precision farming offers variable rate application of fertilizer, for example. The efficiencies related to precision farming are not easily isolated or quantified (as they vary) in terms of reductions in P and N application (increased fertilization application can also be the case in precision agriculture) and economics rather than improved water quality are the benchmark. However, using section control and GPS for farming practices such as seeding have been reported in the literature to result in a minimum 9% reduction in spatial overlap (Kaivosoja and Linkolehto, 2016) for one seeding/fertilization technology and therefore, the same reduction in P and N application during fertilization using that implement. Higher values in Saskatchewan have been reported, anecdotally, of 20% reduction in inputs (for product advertising in The Western Producer) (Raine, 2009). Bourgeault Industries Limited (2015) cited a potential 7% reduction in overlap using their technology. Section control and GPS are not new technologies and many farmers will have adopted this practice by now and the uniformly shaped fields benefit less from its use. To be cautious of over estimation, we assumed automatic section control and GPS are used on half of the fertilized land or that this land wouldn't gain from its use, therefore 1/2 of the reported reduction range yielding, $3.5\% - 10\%$ is applied here. To approximate the reduction in fertilizer loss with runoff with this reduction to fertilizer application, we refer to the work of Liu et al. (2019a), who found a $26 - 28\%$ reduction in fertilizer P inputs resulted in a $42 - 52\%$ reduction in P concentrations at the edge-of-field during a nine year paired field study in South Tobacco Creek, Manitoba. This equates to a $1 : 1.74\%$ P input:loss ratio [21]. Nitrogen data are lacking, therefore, we applied the modelling work of Morales-Marin et al. (2017, Figure 12)[22] which indicates that 1:1.2 ratio in N load reductions compared to those achieved for P with a 20% reduction in fertilizer application in the South Saskatchewan River Basin, and equates to a N input to loss ratio of $1 : 1.45\%$.

Relocation of Manure Applied Lands. Solid cattle manure is applied to lands in the Moosomin Lake watershed. The BMP of relocating manure applied lands involves assessing the reduction to TP and TN in runoff if all manured lands in the EDA were relocated outside of the EDA. This further assumes that the relocated nutrients are not translocated from the non-contributing fields in atypically wet periods — which is an important area where future work is needed. Runoff coefficients for unamended and manure spread fields are taken from the work of King (2015) and King et al.

[21] 27%(P input reduction) : 47%(reduction in P loss)

[22] Refer to Figure 12 Morales-Marin et al. (2017). At a 20% reduction in fertilizer inputs to 'hotspots' in the watershed the authors found a 1:1.2 ratio for TN:TP reductions to exports.

(2017) shown in Table B.3. These coefficients are used to estimate the range in benefit available with relocation of manure spreading: the benefit of relocation of manure spreading practices was calculated as the difference between nutrient export coefficients in manured (incorporated or unincorporated) fields and the coefficients in unamended fields. This worked out to a reduction of 0.17 – 1.1 kg/ha of TN and 0.12 – 0.36 kg/ha of TP based on these laboratory data which will likely exaggerate the difference on a watershed scale and, as with fallow crops (discussed below) the values are reduced by half to 0.09 – 0.55 kg/ha of TN and 0.06 – 0.18 kg/ha of TP.

Annual Crop to Perennial Forage Conversion. All else being equal, soils with perennial cover types, when compared to soils with annual crops, tend to show increased infiltration once the soil macropores have developed and therefore reduced discharge volumes during runoff events and potentially reduced nutrient exports (Baulch et al., 2019). The plot scale studies by Hargrave (1992) in Manitoba show a difference in wheat and alfalfa crop cover type nutrient exports of 5.8 kg/ha TN and 3.1 kg/ha TP. This difference is likely pronounced due to the small scale of the study. The land use and water quality data in Pipestone Creek, SK showed that discharge was also negatively correlated to the extent of permanent cover[23] on the landscape (Roste and Baulch, 2017), whereas this decrease in runoff was not observed by Liu et al. (2014). The difference observed in the watershed scale GED data between permanent cover and cropland varied 0.17 – 0.62 kg/ha TN and 0.07 – 0.23 kg/ha TP. There are also studies that indicate the desired reduction in nutrient exports with conversion to perennial crops may not be achievable at all, as P is shown to increase with conversion to forages without the added contributions from grazing and there is no change observed for N (Liu et al., 2014). Where erosion of soils in an issue, planting to perennials can be beneficial to P, but where P is primarily in the dissolved form (such as during a prairie snowmelt) perennials may serve to increase P in runoff. Selective application of this BMP is required. For the purposes of this assessment here, we simulated a conversion of 20% of the land in cereal crops to perennial forage crops with BMP export coefficients for converted land of 0-0.28 kg/ha TN and −0.05-0.07 kg/ha TP. The range in benefit for TN starts at 0 to reflect the observation of no change by Liu et al. (2014) and for the upper end we applied the difference in ECs used for annuals and perennials of 0.28 kg/ha based on ECs set for this watershed (Table 6). For TP, the negative -0.5 kg/ha low end of the range is a somewhat arbitrary value used to emphasize that occasions arise where perennials will increase P in runoff. The low end (0.07 kg/ha) of the GED data was used as the upper limit of the range for P reduction.

Fallow Crop to Minimum Till Crop Conversion. The practice of summer fallow on agriculture lands is a traditional method to control weeds, disease, and pests in addition to providing some water conservation in the soils. The practice has been largely replaced with chemical fallow, direct seeding, and/or pesticides and herbicides. In this watershed (Figure 23) there is a relatively small portion of land in the watershed that is left to summer fallow[24]. The practice of summer fallow leaves the soil susceptible to erosion by wind and water runoff; and therefore prone to more nutrient loss during runoff events. There is a field scale Saskatchewan study (Nicholaichuk and Read, 1978) and plot scale Manitoba study (Hargrave, 1992) where we were able to compare export coefficients for fallow fields and wheat crops (refer to Table B.1). The difference in runoff from the 9% sloping Manitoba studies is large with a range of 1.9 – 19.8 kg/ha TN and 2.3 – 5.9 kg/ha TP with conversion from fallow to wheat. This difference is larger than that from the 1 – 4% sloped larger field scale plots near Swift Current, SK: 3.1 kg/ha TN and 1.2 kg/ha TP with conversion from fallow to wheat, where the lesser sloped soils would be less prone to erosion during runoff. The ECs

[23]Permanent cover defined as pasture, hayland, and woodland (in that order of prevalence). There are livestock grazing of similar densities on both the permanent and cropland (stubble grazing) cover types.

[24]Discussions with the LSWC at our meeting on March 18, 2019 indicate that even the small portion of land designated as fallow is an over estimate.

selected for fallow land in Section 3.2 were 3.5 kg/ha TN and 0.85 kg/ha TP based values selected from a range reduced by 1/2 as these are field and plot scale data. Here for BMP assessment, we reduce the range of the potential benefit by 1/2 to 0.95 – 9.9 kg/ha TN and 0.6 – 3.0 kg/ha TP as these too are field and plot scale data, and therefore to adjust for this we divided by 2 as a 2x scale factor to account for field to watershed differences in ECs is not uncommon and, as an example, was applied by Yang et al. (2008) over the entire Broughton's Creek watershed to account for in-stream retention of nutrients. The selected EC values for annual crops were 0.48 kg/ha TN and 0.07 kg/ha TP. Subtracting these ECs from the fallow land ECs yields a difference of 3.0 kg/ha TN and 0.78 kg/ha TP. We use these values as the upper limit of the benefit for the conversion of fallow crops with the lower limits as set above, and apply 0.95 – 3.0 kg/ha TN and 0.6 – 0.78 kg/ha TP reduction to estimate the benefits of conversion of 75% of fallowed land (to minimum till wheat) in the EDA. The concerns expressed by the LSWC that the land area in fallow is over estimated should be noted when evaluating this benefit.

Restoration of Wetlands. On the Canadian prairies, land used for agriculture is often drained to gain efficiencies in crop production. This drainage increases the EDA through hydrologic connectivity which has coincided with deteriorated water quality and increased streamflow discharges (Baulch et al., 2019). Re-establishing or restoring these wetlands on the landscape may provide several benefits such as flood management, wildlife habitat, and nutrient retention (Pattison-Williams et al., 2018). The actual impact that the restoration of any one wetland may have in a watershed is site specific. Nutrient retention is one potential benefit of wetland restoration, and the focus of our exercise here. Wetland restoration has been shown to increase P and N concentrations in-stream under some conditions (Zhang et al., 2017; Kinsman-Costello et al., 2016, 2014) and field studies have also shown that the soils from drained wetlands can be hotspots for P on the landscape (Badiou et al., 2018). It requires approximately 10 years in the Canadian prairie before a restored wetland will provide equivalent ecosystem services to that of a permanent unmodified wetland (Bortolotti et al., 2016). Ultimately, retaining water on the landscape in wetlands is expected to retain nutrients because the hydrologic benefits of reducing peak and annual flows will have a direct effect on nutrient loads. Care should be taken, though, to ensure that farmed wetlands which are restored are managed appropriately, to avoid nutrient re-release and transport downstream. Our assumptions in the subsequent discussions are based on either restoration of wetlands or the use of other practices such as gating to cease flows and reduce the size of the EDA and so mitigate the streamflow and nutrient impacts of historic wetland drainage.

There are several modelling studies applying the Cold Regions Hydrological Modelling (CHRM) platform (Pomeroy et al., 2007) with or without the Wetland DEM (Digital Elevation Model) Ponding Model (WDPM) (Shook et al., 2013), or the Soil Water Assessment Tool(SWAT) (Yang et al., 2007)) to look at the changes to annual streamflow volumes that may occur with wetland drainage and restoration and fewer that further attempt to estimate the predicted change to annual P and N loads in-stream. Table B.4 highlights these modelling studies performed on the Canadian prairie. The Smith Creek and Vermilion models found that antecedent hydrological conditions (i.e. soil moisture and ponded volume) affect the ability of wetlands to impact streamflow from the basin (Pomeroy et al., 2012, 2014). For example, all else being equal, if the watershed was dry, the wetlands would reduce streamflow discharges more than if the watershed was wet, as under dry conditions a landscape and wetlands would have the ability to store more water during the precipitation event. Under flooded conditions, there would be little retention of rainfall or snowmelt (akin to pouring more water into an overfull tub). Siting of the wetland in the landscape affects the amount of impact that a particular restored wetland can have and those lower in the drainage path (intercepting more drainage area) are able to affect more change to nutrient exports and runoff volumes (Hansen et al., 2018; Yang et al., 2012; Pomeroy et al., 2014, 2012). Baulch et al. (2019)

summarize relevant prairie research and expected outcomes from wetland restoration, drainage, and options for drainage mitigation.

To understand the potential effects of wetland restoration on flows and consequent effects on nutrient loads in this study, we look to the hydrological modelling work done in a portion of the basin (e.g., Perez-Valdivia et al. (2017)) focused on understanding potential future drainage effects. The model study in Pipestone Creek watershed (Table B.4) was based on the drainage area of the Pipestone Creek at the hydrometric station 05NE003, a subwatershed comprising 66% of the Moosomin Lake watershed. The SWAT model was set up and applied in the river basin and several drainage scenarios run. For each increase in NCDA drained (15%, 30%, 50%), Perez-Valdivia et al. (2017) re-defined the EDA of the basin to estimate the change (increase) in annual volume of water discharged at 05NE003 on the Pipestone Creek. Refer to Figure 25 where we plotted the model results for the three drainage scenarios presented by Perez-Valdivia et al. (2017) (Figure B.2 shows the relationship with the (0,0) data point included). The results are nearly perfectly linear when plotted against the EDA, which is one of the primary considerations when transferring flows from a gauged to an ungauged watershed. We also applied the modelled increase in EDA for each scenario to ECs for annual and perennial crops land use, to estimate the average annual increases of N and P in nutrient loads that might occur in the Pipestone when the new EDA is fully active in runoff events. Based on this method of calculation the increases to nutrient loads are slightly less than the predicted increases to streamflow (Table 7). Regardless, the magnitude of increases suggests that drainage is a major contributor to elevated nutrient loads. This is important in considering further drainage works in the catchment.

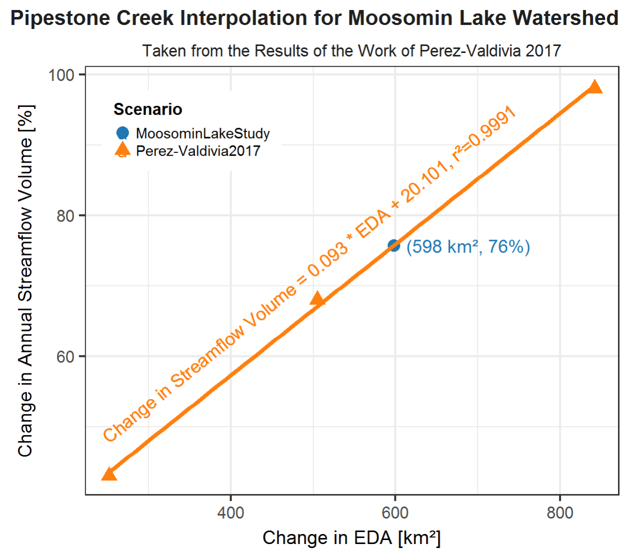


FIGURE 25. **Linear Model from Pipestone Creek Drainage Study**. The annual change in flow volumes with increased drainage predicted by Perez-Valdivia et al. (2017) for the Pipestone Creek watershed plots linearly against the respective EDA associated with each incremental drainage scenario (orange triangles). This linear relationship was used to estimate the change in annual flow volumes that might be achievable were Moosomin Lake watershed EDA restored to the pre-drainage ratio of 0.32, a reduction of 598 km^2 (blue circle) from its current 0.49 EDA/GDA ratio. Figure B.2 illustrates this relationship with the (0,0) data point.

Now let's look at how much the EDA has been increased in the Moosomin Lake watershed with extant drainage. Extant drainage was estimated at 0.3-0.9% of watershed area based on the wetland inventory (Saskatchewan Watershed Security Agency et al., partly drained, completely drained, farmed) as shown in Table 4 increasing the EDA/GDA ratio from 0.32 to 0.49 (Table 7). The PFRA EDA was determined in the 1970s before drainage efforts really ramped up so we are considering that area as a 'pre-drainage EDA' benchmark for the purposes of this study. We compare the PFRA EDA ('pre-drainage') to the modified EDA developed for this study (see discussion in Section 1 and Figure B.4). Drainage is estimated to have decreased the NCDA by 26% or 59,893 ha. The EDA is a not a static value as it is based on the expected 1:2 year hydrological response and this response is determined by antecedent hydrological conditions and landscape connectivity, precipitation, climate, and the geophysical conditions of the landscape, to name a few factors, and therefore the EDA can change for any runoff event. It is a simplification of hydrological processes to assume a static EDA; but it is common to transfer flows based on the EDA and estimated increases to the EDA during wet years. Here, we assume a static EDA as this is adequate assumption to quantify change for a high-level screening assessment such as this.

We perform similar math as we did with the work of Perez-Valdivia et al. (2017) discussed above and presented in Table 7 to determine that full restoration could potentially reduce nutrient loads to Moosomin Lake by 26% for TN and 32% for TP with the 59,893 ha increase in the EDA. Pipestone Creek being nested in Moosomin Lake Watershed and comprising the majority of it by area, therefore, is hydrologically similar for use in predicting changes in streamflow with changes in EDA as done by Perez-Valdivia et al. (2017). The linear model generated from the modelled flow response as performed by Perez-Valdivia et al. (2017) for the years 2007-2009 by Perez-Valdivia et al. (2017) as plotted in Figure 25 was, therefore, applied to the change in EDA estimated to have resulted from the drainage activities in Moosomin Lake watershed. This suggests that drainage may have increased flows to the lake by an average 76% annually. In the future, modelling efforts to calculate changes in annual load using a dynamic EDA and modelled flow response based on specific wetland restoration scenarios would remove some of the uncertainty in this assessment.

Table 7. **Applying Pipestone Drainage Creek Study to Moosomin Lake Watershed.** This table summarizes the results of the Perez-Valdivia et al. (2017) SWAT model drainage study in Pipestone Creek. The nutrient loads are calculated based on the area added to the EDA and the export coefficients (0.40 kg/ha TN and 0.07 kg/ha TP, area weighted averages for perennial and annual crops). The shaded grey areas are the baseline scenarios used in the modelling study and our current study. Figure 25 illustrates the linear model resulting from the Perez-Valdivia et al. (2017) results and its application to the data point (blue) relating to our study, enabling an estimate of the change in annual flow volume of 76% that may occur with full restoration of extant drainage.

Watershed	Scenario Δ NCDA	Δ EDA	$\frac{EDA}{GDA}$	Δ Annual Streamflow	Δ Annual Nutrient Load Δ TN[25]	Δ TP[26]	Source
Pipestone Creek	status quo	-	0.25		55.9 tonnes	8.3 tonnes	*streamflow:*
2,242 km^2 GDA	↓ 15%	+252 km^2	0.36	↑ 43%	↑ 18%	↑ 21%	Perez-Valdivia et al. (2017)
	↓ 30%	+505 km^2	0.47	↑ 68%	↑ 36%	↑ 43%	*nutrients:*
	↓ 50%	+842 km^2	0.62	↑ 98%	↑ 60%	↑ 71%	calculated using ECs
Moosomin Lake	status quo	-	0.49		96.2 tonnes	14.2 tonnes	*streamflow:*
3,405 km^2 GDA	↓ 26%	-598 km^2	0.32	↓ 76%	↓ 26%	↓ 32%	Interpolation (Figure 25) *nutrients:*
	alternate[27]	-286 km^2	0.4	↓ 47%	↓ 12%	↓ 15%	calculated using ECs

The effects of wetland drainage and restoration on nutrient loading remain an area of high scientific uncertainty. Despite this, we conclude that 1) drainage can contribute to increased flows and nutrient loads, and 2) wetland restoration may only partially compensate for the full effects of drainage (as the benefits of wetlands are myriad, see Pattison-Williams et al. (2018); Calhoun et al. (2017); Zamberletti et al. (2018), and restoration efforts may simply not be timely or effective in re-creating all aspects of the historical wetlands). Hydrological research in this basin, and other prairie sites suggests that substantive increase in flows can result from drainage. The magnitude of flow changes will depend on factors including current climatic conditions, antecedent hydrological conditions (affecting the storage capacity in the watershed), and catchment structure. Ongoing research at University of Saskatchewan is aimed at helping better understand the type of drainage-flow responses that can result across different climatic conditions and basin structures, and should

[25]The change in TN exports is calculated for each scenario by: $\frac{\Delta\text{EDAx EC}_{\text{TN}}}{\text{estimated tonnes TN exported in the status quo}}$. For example 25,200 ha x 0.40 kg/ha /55.9 tonnes = 18%

[26]The change in TP exports is calculated for each scenario by: $\frac{\Delta\text{EDAx EC}_{\text{TP}}}{\text{estimated tonnes TP exported in the status quo}}$. For example 25,200 ha x 0.07 kg/ha /8.32 tonnes = 21%

[27]This alternate scenario illustrates the estimated potential in restoration benefits of wetlands given the current EDA is actually 286 km^2 larger than the historic EDA rather than the 598 km^2 estimated for this assessment.

help reduce uncertainty in assessments such as this in the future. The relationship between concentrations and discharge is not well defined, the flow-concentration relationship in these data could be rigorously investigated, modelling studies in Table B.4 imply that concentrations will not be reduced in step with discharge reductions, and of course there is the potential for increased P and N losses from previously drained wetlands discussed above. We also ran an *alternate* scenario in Table 7 to demonstrate that even if the current EDA is over-estimated by double and that the EDA/GDA is really 0.4, the benefits estimated for wetland restoration would still be substantial. It is difficult to say how much of the wetland capacity may be restored, so we estimated 50% and leave it to managers to adjust this according to set targets. In addition, the SWAT models in Table B.4 predict that nutrient benefits range 37-76% of the predicted reduction in annual flow volume; whereas, for Moosomin Lake the nutrient retention benefit with restoration is $34 - 42\%$ of the predicted 47-76% reduction in annual flow volumes. Nutrient retention for Moosomin Lake is conservatively estimated here. We will use the *alternate* scenario as the lower bound for this BMP and estimate $12 - 26\%$ of TN and $15 - 32\%$ of TP loading decrease for the potential benefit for restoration in this watershed based on a change from the current EDA/GDA ratio of 0.49 to 0.32.

Relocation of Winter Feeding Sites. The intent of including this BMP, is to assess the benefit of modifying grazing practices to reduce losses of P and N to streams. There are various ways that this can be achieved, such as by providing holding ponds at intensive feeding sites or relocating sites to the NCDA. Here we use relocation of intensive feeding sites near streams as a proxy for any method that achieves the desired outcome of diverting runoff from winter feeding sites from entering streams. Intensive grazing practices of penning cattle in corrals and winter bale grazing (WBG) concentrate the urine and dung from cattle in a localized area with a tendency for this nutrient source to runoff to streams particularly in the spring during snowmelt. Research has shown that the nutrient loss per animal as nutrient units (NUs) wintered using WBG is very similar to the nutrient loss per NU wintered in corrals (Chen et al., 2017). Therefore, for the relocation of winter feeding sites BMP we used the available corral study data presented in Table B.2. The impact of this BMP is quantified by simulating the relocation of all corrals within 200 m of a stream to the NCDA. This was achieved by using the fraction of corrals relocated and multiplying that by the NUs for that basin to determine how many NUs would be relocated. This number of NUs was multiplied by the coefficients, 0.1-1.0 kg/ha TN and 0.015-0.06 kg/NU, shown in Table 8. In answer to questions regarding extensive grazing practices and their efficacy we note that lower animal densities in extensive feeding sites can be beneficial when carefully placed while uneven distribution of nutrients, increased need of tillage and spring clean up on these sites can pose challenges to controlling nutrient runoff. Therefore, structural controls to intensive winter feeding sites, such as holding ponds, may be easier to control nutrient runoff from (Elliott, 2019).

Restricted Grazing Access to Riparian Zones. Livestock grazing on fields with streams and lakes often involves unlimited streambank access (Cooke and Prepas, 1998) and can allow for unmitigated surface transport of P and N to streams and, ultimately, lakes via structural damage to the streambank, cattle trails (Miller et al., 2017), and stream-side deposits of feces and urine. Lakeshore grazing causes the same structural damage as riparian grazing, but without the potential for any retention of nutrient en route to the lake which can be very problematic — entirely unmitigated deposit and surface transport of P and N to the lake and structural damage to the shore. The LSWC used geospatial tools to determine that there are an estimated 373 km of grazed streambank in the Moosomin Lake watershed (Figure 21, Section 3.1). The results of the streambank fencing study performed by Miller et al. (2010a) and presented in Table B.2 were used here to investigate the potential impact of restricted riparian access on P and N exports. The reduction in TN and TP load observed by Miller et al. (2010a), during dry years rather than wet years, as there was no change was apparent during wet years, was applied to the selected grazed pasture export coefficients from Majeau Creek, AB (Table B.1, $1.0-7.13$ kg/ha TN and $0.20-1.42$ kg/ha TP). Lineal meters of streams and lakeshore passing through grazed pasture land are used to assess this BMP, therefore, the benefit was required in units of kg $\cdot$ m/ha and the width of the exclusion fencing ($40-80$m as used in the study by Miller et al. (2010a)) was applied to create and reduction of $40-570$ kg·m/ha TN and $8-114$ kg·m/ha TP (Table 8), with a reduced range to make sense with these data of $40-110$ kg·m/ha TN and $8-24$ kg·m/ha TP adopted here.

Residue Management and Soil Organic Matter (SOM). [28]The practice of leaving crop residues on the fields can be beneficial to soil moisture, nutrient stores, and fertility. Residue material that is young, growing and high in moisture content can be a significant source of nutrients (and a concern for P) in runoff, so weed and perennial crop management practices need to be considered here whereas cereal stubble and straw that is typically lower in water content and senesced before winter is not such a concern. Residues and stubble resulting from reduced tillage practices have prevented displacement of blowing snow during the winter and soil in summer, and generally retained moisture on the fields, although as mentioned in, *Annual Crop to Perennial Forage Conversion*, there are variable results on whether the practice actually decreases snowmelt runoff. These no-till benefits need to be balanced with considerations for management of weeds and the placement of perennial grasses (as buffers or otherwise) and how they will impact nutrients in snowmelt runoff events (particularly). Residue management options exist such as baling, incorporation, and grazing residues. Baling of annual crop residues removes organic matter and nutrients from fields; this nutrient loss is replaced with fertilizers whereas the loss of organic material is not. Incorporation of residues, retains the organics and nutrients both, but requires tillage and tillage can result in greater losses of nutrients and soils during runoff events. Grazing retains these nutrients (conversion to excreta P and N) and organics and avoids tillage; but adds the further challenge of making sure the grazing locations are away from water drainage paths (especially important for winter grazing and runoff considerations over frozen soils in spring) and that nutrient sources are distributed in the fields. There are structural benefits to increasing the organic material in soils but these benefits of SOM need to be weighed against the increased source of P and N to runoff. This is especially important if the nutrients in soil become stratified in surface layers. Increasing soil infiltration and SOM would be optimum in terms of soil health and susceptibility to nutrient loss. The take home message here is that the handling of residues and SOM on cropland is site specific: the goal is to manage soils to optimize infiltration (minimize runoff) and maintain SOM and nutrient stores; or alternatively, avoid unincorporated nutrient sources (excreta, residues, added fertilizers) in locations and times known to be runoff prone. For further discussion on application of the various soil and water management BMPs in the Canadian prairie, we refer the reader to Baulch et al. (2019).

[28]Foundation for this discussion taken from and edited by Elliott (2019, personal correspondence). Questions relating to residue management and SOM were raised by the LSWC on 18 March; and we sought further insights from an expert.

Table 8. **BMP Export Coefficients for Moosomin Lake Assessment**. The typical range of export coefficients found for these BMPs in the Canadian prairies are shown along with a selected range for the potential BMP when applied to the respective area in the Moosomin Lake EDA. The selected range often has a reduced upper range as a result of the EC used to predict the target mean observed loads in the watershed (Section 3).

		Total Nitrogen Export Coefficients			Total Phosphorus Export Coefficients		
BMP	**Area** of EDA	**Typical Range**	**Selected Range**	**Estimated Reduction**	**Typical Range**	**Selected Range**	**Estimated Reduction**
	[ha]	[kg/ha]	[kg/ha]	[kg]	[kg/ha]	[kg/ha]	[kg]
fertilizer management	95,304	0.011 – 0.12	0.011 – 0.068[29]	1,016 – 6,633	0.0043 – 0.090	0.0043 – 0.014[30]	406 – 1,327
annual crop to perennial conversion	20% of 49,766	0 – 0.62	0 – 0.28	0 – 2,789	−0.05 – 0.23	−0.05 – 0.07	−498 – 698
fallow to annuals conversion	75% of 1,208	0.95 – 9.9	0.95 – 3.0	861 – 2,736	0.3 – 3.0	0.6 – 0.78	544 – 707
relocation of manure applied lands	2,689	0.17 – 1.1	0.085 – 0.55	229 – 1,479	0.12 – 0.36	0.06 – 0.18	161 – 584
	[–]	[%]	[%]	[kg]	[%]	[%]	[kg]
restoration of wetlands	50% of 59,893 ha[31]	12 – 26%[32] of 95,175 kg TN	12 – 26%[33]	5,711 – 12,745	15 – 32%[34] of 14,199 kg TP	15 – 32%[35]	1,065 – 2,272
	[NU]	[kg/NU]	[kg/NU]	[kg]	[kg/NU]	[kg/NU]	[kg]
relocation of winter feeding sites[36]	12,795	0.1 – 4.8	0.1 – 0.9	1,280 – 11,516	0.015 – 1.4	0.015 – 0.1	191 – 1,280
	[m]	[kg·/ha]	[-]	[kg]	[kg·/ha]	[-]	[kg]
riparian grazing restriction	- 373,100 m	1 – 7.13 kg/ha 40 – 80 m corridor 40 – 570 kg · m/ha	40 – 110 kg · m/ha	1,493 – 4,104	0.2 – 1.42 kg/ha 40 – 80 m corridor 8 – 114 kg · m/ha	8 – 24 kg · m/ha	299 – 896

[29] The reductions here are calculated using the 3.5 – 10% reduction in inputs using ACS with GPS, and the 1:1.45 input to loss ratio. This equates to a 5.1 – 14.5% reduction to the current export coefficients on fertilized land. These numbers are applied to the range 0.21 – 0.48 kg/ha TN.

[30] The reductions here are calculated using the 3.5 – 10% reduction in inputs using ACS with GPS, and the 1:1.74 input to loss ratio. This equates to a 6.1 – 17.4% reduction to the current export coefficients on fertilized land. These numbers are applied to the range 0.07 – 0.08 kg/ha TP.

[31] This is the estimated increase to the EDA attributed to drainage in the watershed. The wetland inventory provided 0.3-0.9% of watershed area as drained wetlands; as discussed this inventory requires updating. The assessment here, then, proceeds using the change in EDA to estimate wetland restoration potential.

[32] Calculated in Table 7

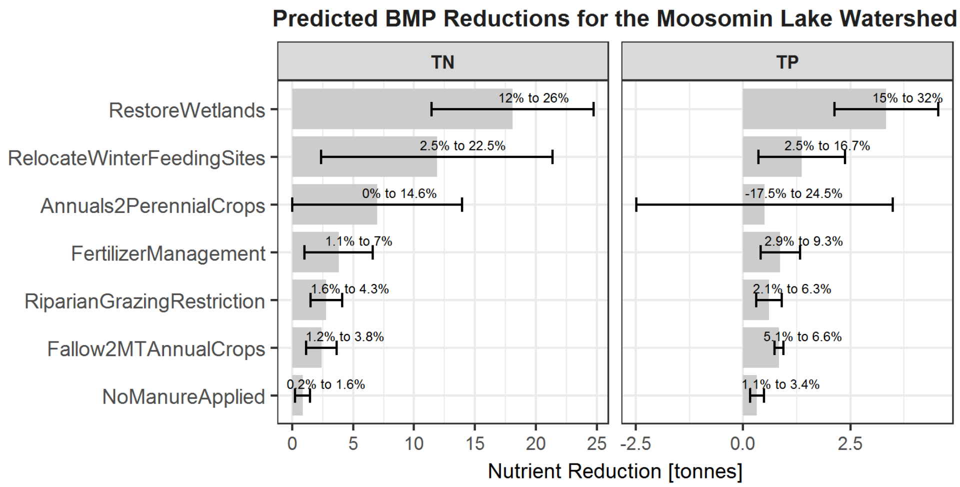
[33] Wetland restoration impacts reduce the total load to the lake. For example, 26% x 95,175 kg TN ≈ 24,745 kg, and assuming 50% restoration would imply 0.5 x 26% x 95,175 kg TN ≈ 12,745 kg.

[34] Calculated in Table 7

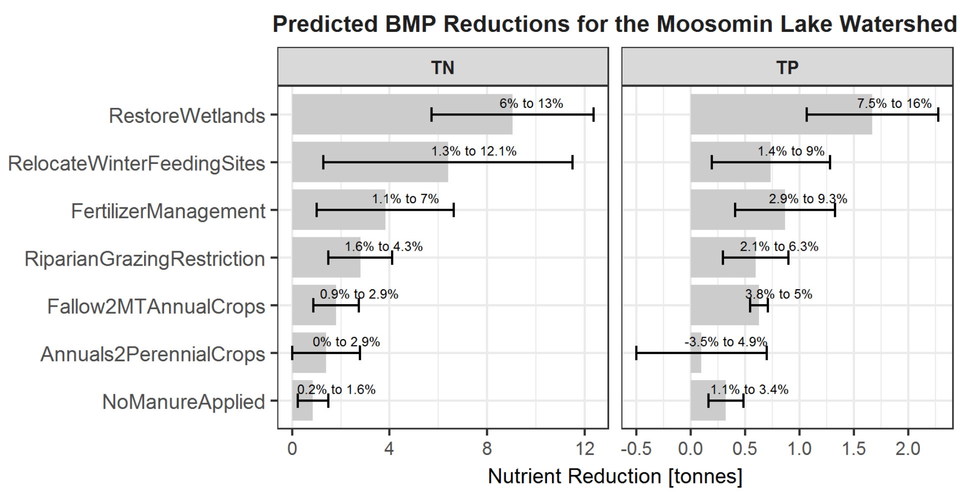
[35] Wetland restoration impacts reduce the total load to the lake. For example, 32% x 14,199 kg TN ≈ 4,544 kg and 50% restoration would achieve half this reduction.

[36] Relocating all corrals with 200m of a stream equates to moving a total of 102 corrals of a total 295 from the various basins in the watershed. All basins with corrals have at least one within 200m, basin 22 has 10 corrals with the 200m. The fraction of corrals to be moved from each basin is accounted for by relocating livestock NUs.

4.2. **BMP Performance.** Individual BMP performance assessment is based on the results plotted in Figure 26 and reported in Table 8. Before we interpret these results, review the results as presented in Figures B.5-B.6 as they may provide more perspective.



(A) BMP Performance with 100% adoption for each practice (all wetlands restored, all annual crops converted to perennials, all fallow crops seeded, all cattle wintering sites relocated or effluent diverted, all riparian grazing restricted, all manure spreading relocated to NCDA, and nutrient management practiced on all lands where it currently is not practiced or there is no benefit to do so (an estimated 1/2 the seeded land)).



(B) BMP Performance with prescribed adoption limits for some BMPs: 20% of annuals converted to perennials, all intensive feeding sites with 200m of streams relocated, 75% of fallow crops converted to minimum till annuals, and 50% of the wetland capacity restored.

Figure 26. **BMP Performance for Moosomin Lake**. The total reduction potential for each of the BMPs is illustrated with the bars, the minimum and maximum estimated range of benefit are represented with the error bars, and the percentages are the percentage of the total predicted export of nutrient from the Moosomin Lake watershed EDA that could potentially be eliminated by implementing the BMP. The top, Figure 26a shows the BMPs with full adoption and the bottom, Figure 26b compares the BMPs with limited adoption for some BMPs.

These results indicate that reductions to TN and TP loading may be best achievable with wetland restoration, the relocation of winter feeding sites, and fertilizer management. Each of these BMPs has a large range of potential efficacy. Fertilized lands, intensive grazing sites, and historic drainage all have large contributions to nutrient exports from the watershed for N and/or P. Our assessment suggests that wetland drainage has had a major impact on nutrient export. Fallow conversion benefits, although likely over-estimated, are site-specific. The widespread adoption of the chemical fallow and zero till cropping practices that leave vegetation in the field during runoff and blowing snow events has changed the prairie landscapes and soils. If fallowing practices in these catchments can be altered, there are gains, beyond reduced losses of P and N to erosion, that include higher soil moisture, reduced tillage implement passes, and economics to name a few. Both reduced tillage and fallow cropping practices involve increased chemical application, which has its own set of implications in watersheds. Point being, the impacts of on farm decisions, as in other decisions, tend to be multi-faceted.

Another view on these data is to look at the performance of each BMP in the 35 basins and select BMPs spatially from the estimated minimum reduction potentials for each BMP by basin as shown in Figures B.7-B.8. For example, basin 26 stands out for fallow to crop conversion potential, basis 20, 29, and 31 for possible riparian grazing restrictions, and basins 11, 20, 22 and 29 have a likelihood of high reductions with the relocation of their winter livestock feeding sites. Refer to basin 29 in Figure 20 and note the large site near both Moosomin Lake and a major tributary. Figure 19 highlights (red) all the livestock wintering sites within 200m of streams and Figure 20 indicates the assessed size of each of these near-to-stream sites. The minimum estimated benefit of relocation of winter feeding sites is about 1.3% and 1.4% of the total exports for both N and P, respectively. Managers and policy makers can be very strategic about which sites to target. Recall, that census livestock numbers were distributed equally among wintering sites (corrals) in this assessment and therefore, benefits of the relocating the larger sites could be more specifically assessed based on actual livestock counts. This assessment did not include an inventory of holding ponds for livestock sites. Holding ponds are means to retain P and N from livestock pens for later removal outside of the EDA.

5. Discussions

There are levels of uncertainty in all these data and assessed outcomes; but past experiences in nutrient management suggest an adaptive management approach, where the best available information is accessed, synthesized and analyzed to initiate on-ground management action. Monitoring of actions will increase understanding of what is effective and build management knowledge. This is preferable to waiting for more definitive scientific results because ecosystems are complex so waiting could result in prolonged inaction plus the process of adaptive management itself will meaningfully direct science and understanding. Table 9 summarizes the authors' interpretation of this assessment and recommendations for how BMPs should be prioritized for the watershed.

Strategic re-establishment of wetlands in the landscape can help reduce nutrient loads in runoff to streams in this watershed; there has been substantial drainage and increase in the EDA for the watershed. This has resulted in unmitigated transport of runoff to streams, increasing both streamflow and nutrients loads to Moosomin Lake. It is recommended that existing wetlands and the ecosystem services that they offer be maintained in this watershed; and if drainage must occur options to mitigate potential P and N loss should be given due consideration (Baulch et al., 2019). Our assessment does suggest that extant drainage in the catchment has contributed to elevated nutrient export; however restoration will not necessarily reverse these effects i.e. the original hydrology, geochemistry, and biology of wetlands may not may or may not be returned to the historic state given the extent of changes to the landscape that has occurred with wetland drainage, even if full restoration was possible. Thoughtful restoration based on available science is recommended. Nutrient (fertilizer) management deserves renewed attention. New work (Liu et al., 2019a) suggests that reduced P runoff can be achieved relatively rapidly, without sacrificing crop yields. Automated section control likewise can help reduce overlap, and unnecessary costs as one option for nutrient management. Moving winter feeding sites (or managing the runoff and effluent from these sites) restricting grazing, and relocating manure spreading to outside the EDA are all likely to reduce P and N losses to runoff, and literature results suggest these may be relatively rapid. While shifting from fallow to minimum till annual crops may also have benefits, assessment of specific sites is merited to better understand erosion risk and other factors which affect both nutrient export, but also other agronomic considerations.

Table 9. **BMP Prioritization**. The recommended prioritization of BMPs for the Moosomin Lake watershed is summarized below. The uncertainty associated with the various aspects of assessing the BMP performance is also evaluated on a scale of low - med(ium) - high: *Source*—variability to the assessed current land use contribution to P and N loads to Moosomin Lake; *Benefit*—variability in the assessed magnitude of the reduction to nutrient exports (benefit) using the BMP; and export coefficients or *ECs*—variability of the BMP and land use nutrient export coefficients in the literature.

BMP	**Rationale & Uncertainty**
High	
Relocate livestock wintering sites situated < 200m from streams	*Rationale*: Wintering sites or corrals near streams and lakeshores are obvious sources of P and N. These sources are readily transported once deposited in or by streams. Livestock site inventories indicate these sites are a significant source of P and N in the watershed. Benefits from mitigation are expected to be substantive; but yet we present moderate variability in the potential benefit as the livestock site impacts were based on an area ratio of census data (at the RM scale) and not on inventories of animals at each identified intensive feeding site and the ECs taken from corral studies varied widely per NU which resulted in a large range in assessed benefit for this BMP. *Uncertainty Assessment*: Source (low), Benefit (med), ECs (high)
Restoration of wetlands	*Rationale*: We assessed the impacts of drainage by quantifying the increase in EDA resulting from past drainage activities in the watershed. There is moderate uncertainty in the assessment of drainage extent as the wetland inventory doesn't capture well the extent of drainage that resulted in the present day EDA (source), moderate uncertainty in the range of potential benefit of restoring drained wetlands based on the key assumption of re-establishing previous NCDA to reduce both discharge volumes and nutrient loads to the lake, and low uncertainty in the land use export coefficients applied to assess TP and TN reductions. *Uncertainty Assessment*: Source (med), Benefit (med), ECs (low)
Fertilizer Management	*Rationale*: A majority of the land in the watershed is subject to fertilization; and this is a substantive source of P and N in runoff. Consistent practice of the 4R's Right Source @ Right Rate, Right Time, Right Place®(Canadian 4R Research Network, 2018) are argued to reduce concentrations in runoff from cropped fields. Here we used the reduced fertilization rates achievable with automatic section control and GPS coupled with research on Manitoba crops to quantify a potential benefit to nutrient management practices. There is limited research that quantifies the relationship between reduced fertilizer application and nutrient reductions in runoff; yet there is enough to confer confidence that nutrient management in catchment hotspots and on cropland, in general will reduce P and N losses from fields. *Uncertainty Assessment*: Source (low), Benefit (med), ECs (high)
Moderate	
Riparian Grazing Restriction	*Rationale*: There is structural damage to streambeds and physical deposition of urine and dung that occur with lakeshore and riparian grazing; both sources of P and N that can be eliminated with this BMP. There is limited supporting literature to quantify this benefit and the variability in ECs is relatively high. *Uncertainty Assessment*: Source (low), Benefit (med), ECs (high)
Relocating Manure applied lands	*Rationale*: There is not a large area of the watershed EDA that is subject to manure application, but the benefit of relocation is fairly certain and efforts to do this where appropriate are recommended. *Uncertainty Assessment*: Source (med), Benefit (low), ECs (high)
Fallow to minimum till crop conversion	*Rationale*: This BMP requires a site specific assessment of soil erosion. There is a benefit to conversion to minimum till crops and this should be capitalized on where it is appropriate to so. *Uncertainty Assessment*: Source (high), Benefit (low), ECs (high)
Low Priority to No Benefit	
Conversion of annual crops to perennial crops	*Rationale*: The uncertainty with the potential of this BMP to reduce P really makes this BMP slightly problematic in the prairies where runoff over frozen soils leads to large dissolved P fractions during the major runoff event of the year. Observations of total P and dissolved P in the watershed indicate that there are erosive processes occurring in the watershed; these areas of high erosion potential might be considered for conversion to perennial crops with the aim of reducing nutrients in runoff. *Uncertainty Assessment*: Source (low), Benefit (high), ECs (high)

6. Management and Monitoring

The uncertainty in this assessment is substantial as is the complexity of the system we are assessing. Despite this, the need to make operational decisions to manage nutrients and water in the Moosomin Lake watershed is necessary, and policy must advance. Where policy decisions must be made in the absence of scientific certainty, an adaptive management approach is frequently recommended. This would mean that parallel with plans to implement BMPs, a plan to monitor BMP efficacy would be established, and a commitment made to revisiting practices based on findings of the monitoring program. Chik et al. (2017) state clearly the tenets of Adaptive Management.

> An Adaptive Management approach...
> (1) Makes the most reasonable management choices for a given scale or setting based on current knowledge and understanding,
> (2) Predicts conditions that will result from those management actions,
> (3) Monitors how the system actually behaves over time relative to the expectations, and
> (4) Modifies actions as needed in response to what is actually observed.
>
> Chik et al. (2017)

While watershed managers seek understanding at the scale of medium- to large-scale watersheds such as Moosomin Lake watershed, it can be challenging to measure and attribute impacts at these scales due to landscape heterogeneity and inter-annual variation in climate, along with lags in observing benefits (e.g., due to nutrient legacies), and factors such as in-stream processing. Therefore, where possible monitoring close to the source is recommended.

While recommendations for a full monitoring program are beyond the scope of this report, we suggest the following—

To understand watershed nutrient transport and BMP efficacy:

- Higher inter-annual variation in flows and loads is common in the prairies, and exemplified here. This high variation, combined with potential lags in response before benefits of BMP implementation can be seen suggest that a monitoring program must be planned over the medium-long term (> 5 year) if BMP-related benefits are the target of study, even then it may not be possible to detect and attribute change in water quality and loads based on BMPs. Monitoring efforts can be targeted to the periods most important to accurately estimating loads. High flow events are important to capture; therefore these are times for high frequency monitoring. In some regions (and at some scales) snowmelt shows low concentration variability; however, that is not the case in the data examined here, suggesting that thorough sampling is required in rainfall runoff and snowmelt runoff periods.
- Monitoring at the main inflow to the reservoir is the most critical site for understanding changing nutrient loads and their importance. Using the same, or similar sites through time (and near hydrometric stations) helps ensure data integrity.
- If BMPs are implemented and monitoring is targeted at understanding their efficacy, then the smallest spatial scale (often field-scale) can be the most effective scale to attribute impacts. Paired design (control, BMP implementation sites) may be most effective.
- See also Culp and Wheater (2016) available online at http://cwn-rce.ca/ for additional recommendations.

To understand reservoir water quality changes:

- Monitoring in the lake should reflect the goals and address the questions that managers have and these recommendations should be considered with that in mind.

- There are numerous options, many of which are expensive or require specialized equipment. Key factors of management concern include the clarity of the water column – which can be measured very simply and easily using a Secchi disk from a boat. In addition, some programs have developed citizen-science approaches to bloom monitoring using photography, that could be used to track bloom conditions across years. Finally, detailed chemical sampling may not be realistic, however sampling in spring (after freshet, prior to the bloom) will help in understanding nutrient conditions within the lake. New relatively inexpensive ($<$ \$1500) oxygen sensors can also be deployed to assess the risk (or duration) of low oxygen conditions in the reservoir bottom waters, which can be a consequence of blooms, but can also contribute to extended blooms, due to potential for enhanced internal nutrient regeneration from the sediments with low oxygen conditions.
- Establishing a photographic diary of the lake to track algal abundance can be helpful. Photos taken of the same location on the lake, by drones or from a fixed location, offer valuable temporal data and complement sampling records.
- Of note as well, are potential health risks associated with cyanobacterial blooms. If summer monitoring is undertaken, assessment of appropriate safety practices is advised (such as avoiding skin contact). It may also be advisable to consider posting sites to warn of cyanobacterial bloom risk, or consider testing for bloom toxicity when blooms are apparent in summer. Bloom toxicity is very challenging to predict, and can change rapidly, hence a precautionary approach to minimize risk is widely recommended.

We remind the reader, again, that there are significant uncertainties in these data and analyses. As such, caution is required when applying the results of this work to future policy and research decisions. The results presented here should be used for qualitative ranking of priorities to achieve benefit, but not for quantitative prediction of future change, as the magnitude of change, and timescale of change cannot be reliably anticipated without more detailed analyses and specific data (i.e. soil test P). Monitoring and evaluation of the efficacy of BMP implementation in nutrient reduction is crucial to ensuring success in this landscape, and must account for the timescale over which benefits can be anticipated.

6.1. **Next Steps.** In this report, we have evaluated the nutrient loads to Moosomin Lake and the potential of BMPs to reduce this agricultural sourced nutrient loading to Moosomin Lake. This report is intended as a high level screening tool for BMP actions in the watershed and should serve to assist and empower managers to continue with an active management plan for the Moosomin Lake watershed. A plan of action to reduce nutrient loads to Moosomin Lake based on an adaptive management approach should include the following major steps, although not necessarily in the sequence noted below:

- take action and implement selected BMPs in the watershed in an effort to reduce P and N losses to streams and lakes;
- decide on and implement a monitoring plan for the watershed;
- assess the likely lake response;
- determine the water quality objectives for the lake that the managers would like to achieve;
- evaluate BMP performance based on monitored and desired outcomes for the watershed and lake;
- revise action plan as necessary

The sequence with which to progress with these steps, and effort dedicated to each will depend on realities of time, and budget, although early action on nutrient management is highly recommended.

Appendix A. Hydrochemistry Data

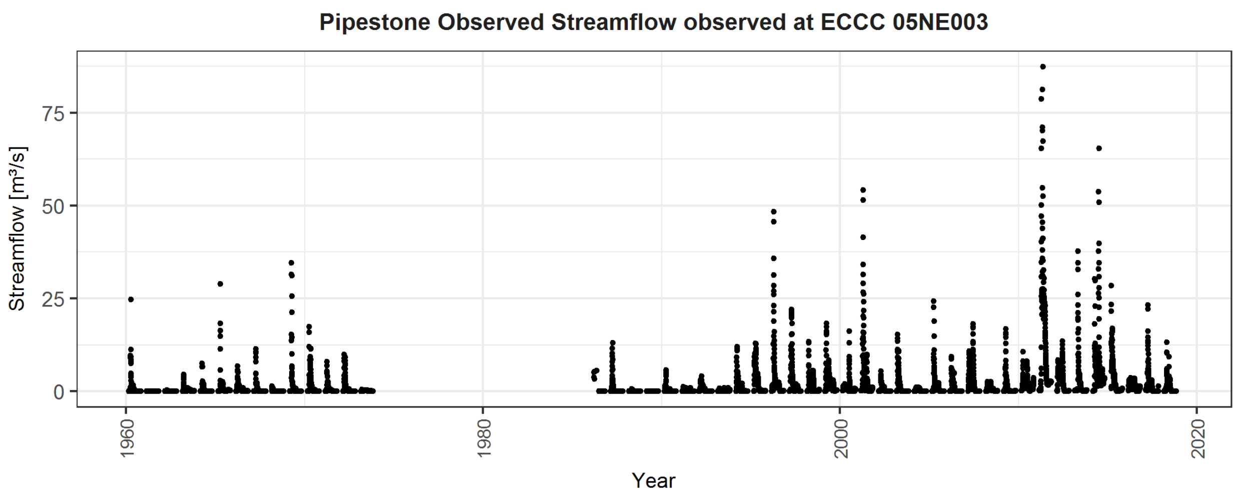


FIGURE A.1. **Daily Observed Streamflow at Water Survey of Canada Station 05NE003 (Pipestone Creek above Moosomin Lake)**.

TABLE A.1. **Annual Discharge Volumes for Pipestone Creek and Little Pipestone Creek at Moosomin Lake and 05NE003**. Figure 1 shows the monthly discharge volumes as a component of these annual discharge volumes at each location. 2018 value for 05NE003 are based on provisional flow values.

Year	05NE003 [dam^3]	at Moosomin Lake Pipestone [dam^3]	at Moosomin Lake Little Pipestone [dam^3]	Moosomin Lake Outflow [dam^3]
2007	37 156	50 250	7 363	59 607
2008	8 423	12 566	2 083	9 996
2009	20 740	29 847	4 727	37 152
2010	35 856	48 633	7 154	57 603
2011	264 565	317749	38 686	365 005
2012	49 361	64 831	9 121	50 820
2013	42 050	56 087	8 064	67 340
2014	119 394	147 791	18 966	172 437
2015	55 529	72 263	10 031	101 174
2016	21 458	30 734	4 840	37 221
2017	31 078	42 687	6 384	52 531
2018	17 934	-	-	-

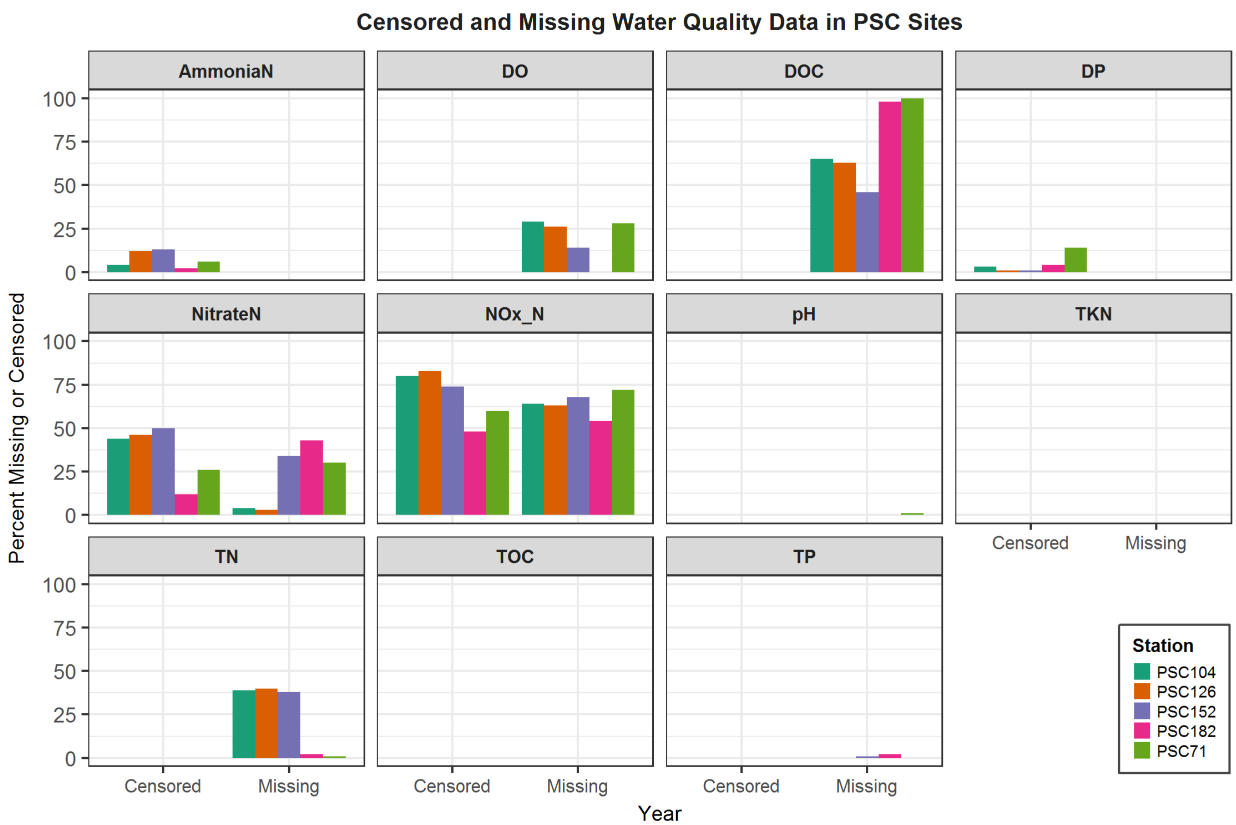


FIGURE A.2. **Censored and Missing Water Quality Data**. This is a selected subset of the available chemistry data in the Moosomin Lake watershed. Missing data is the percentage of unmatched chemistry samples. Censored data percentage reflects the number of available data points that were below the sample detection limit. TKN, TP and DP are some of the most complete data sets.

TABLE A.2. **Annual Nutrient Loads for PSC-152, Pipestone Creek, Little Pipestone Creek**. The annual TP and TKN estimates for PSC-152 used the daily time series data from 05NE003 and the filled chemistry observation data set at PSC-152. Estimates for loadings at Pipestone Creek and Little Pipestone Creek were generated by transferring the loads at PSC-152 to Pipestone at Moosomin Lake and Little Pipestone at Moosomin Lake proportional to the estimated annual discharge at each location.

	Total Kjeldahl Nitrogen			Total Phosphorus		
		at Moosomin Lake			at Moosomin Lake	
Year	**PSC-152** [tonnes]	**Pipestone** [tonnes]	**Little Pipestone** [tonnes]	**PSC-152** [tonnes]	**Pipestone** [tonnes]	**Little Pipestone** [tonnes]
2007	45	62	9	8	11	2
2008	11	16	3	1	2	0.4
2009	39	55	9	8	12	2
2010	57	77	11	8	11	2
2011	490	588	72	78	93	11
2012	93	122	17	12	16	2
2013	73	97	14	6	8	1
2014	188	232	30	32	4	5
2015	103	134	19	20	26	4
2016	34	48	8	5	7	1
2017	47	65	10	7	9	1
2018	43	-	-	-	-	-

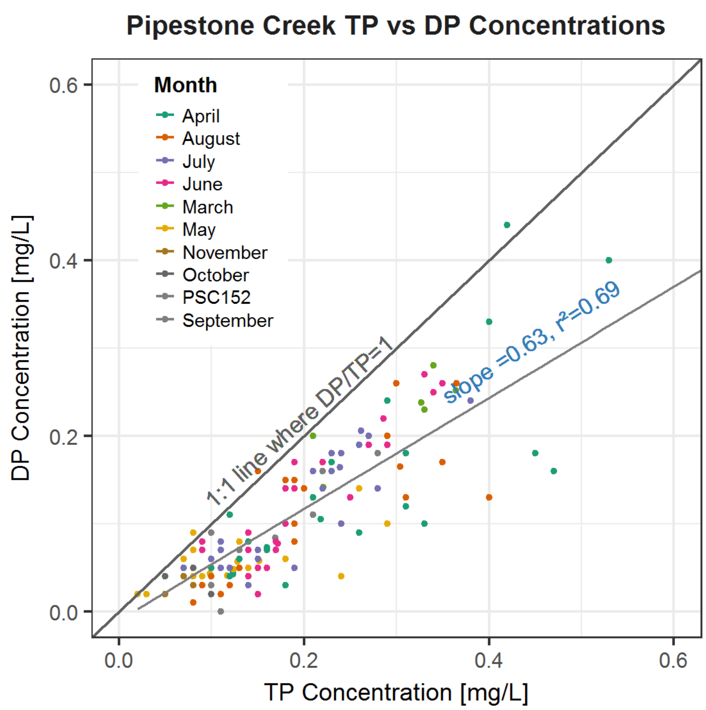


FIGURE A.3. **DP vs TP Concentration Relationship (PSC-152)**. Dissolved P is plotted against TP here. Frequently, prairie runoff, at the field and small catchment scale, is characterized by a large fraction (> 90%) of the total P runoff comprised of DP. Here, the relationship in Pipestone Creek is shown to be about 60% DP.

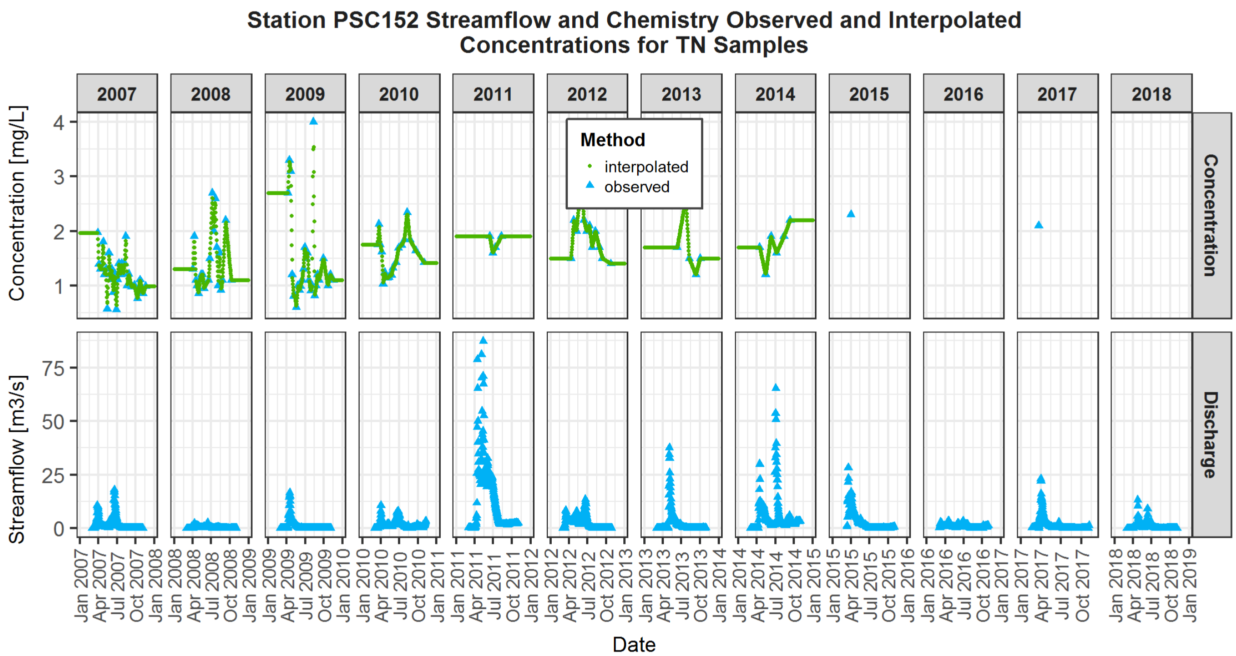


FIGURE A.4. **PSC-152 / 05NE003 Discharge and TN Concentration Data**. This plot illustrates the observed chemistry data, interpolated fill, and original discharge time series for TN.

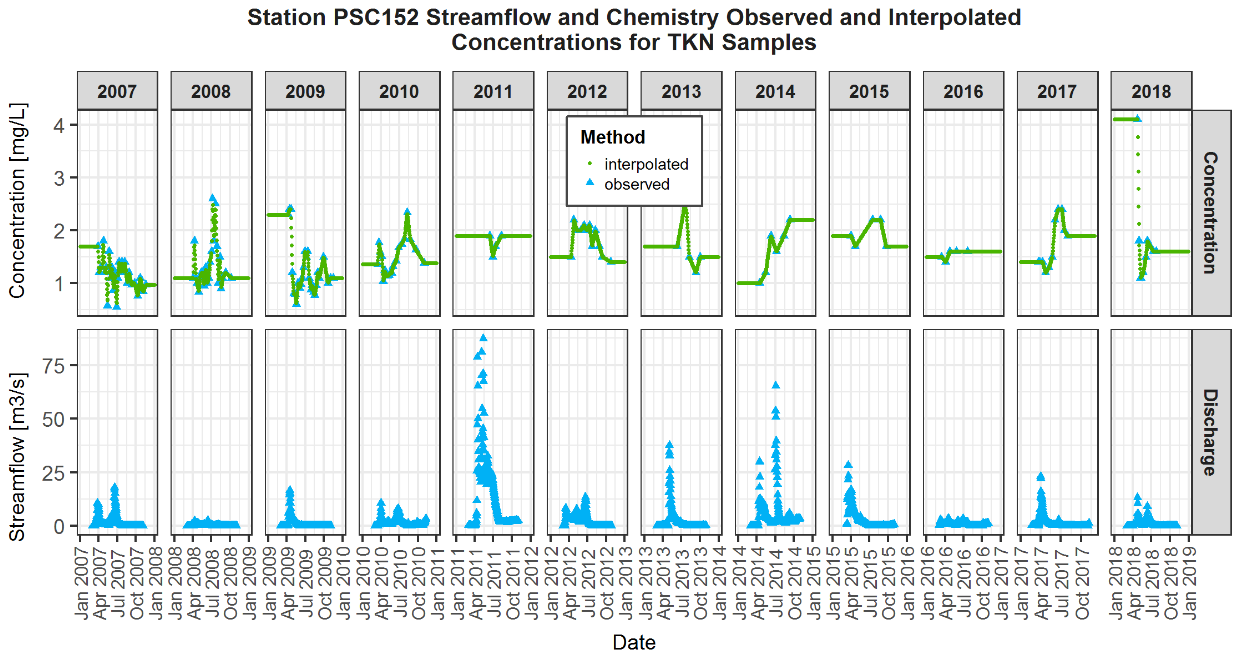


FIGURE A.5. **PSC-152 / 05NE003 Discharge and TKN Concentration Data**. This plot illustrates the observed chemistry data, interpolated fill, and original discharge time series for TKN.

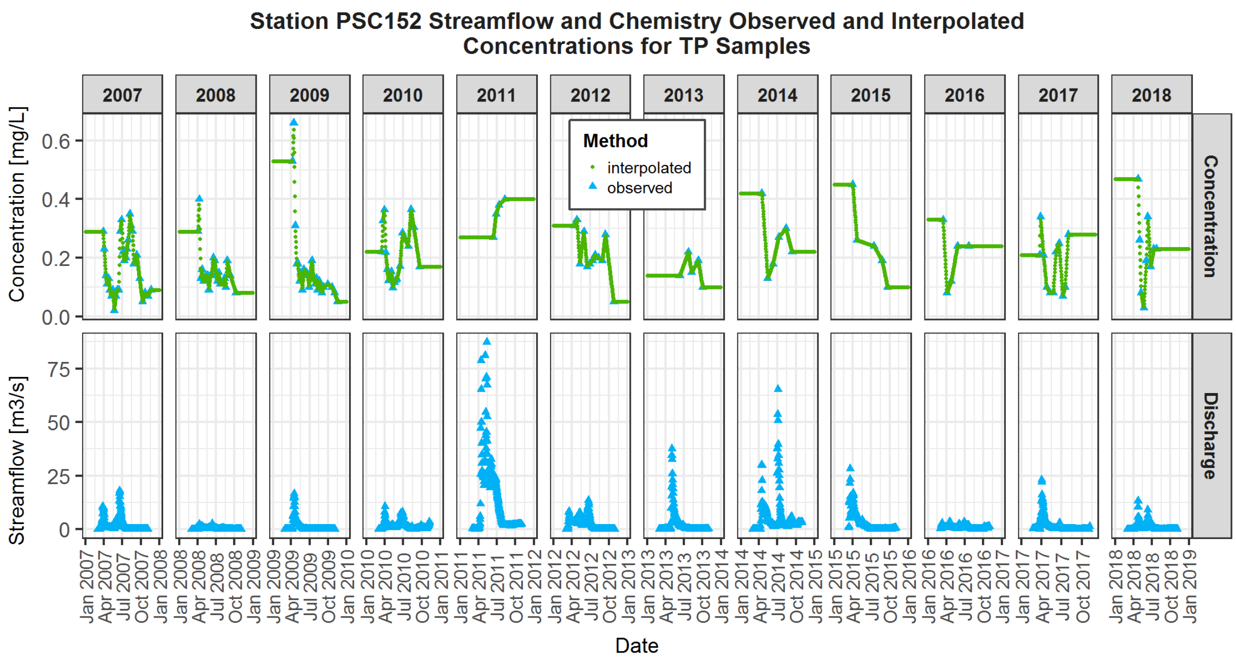


FIGURE A.6. **PSC-152 / 05NE003 Discharge and TP Concentration Data**. This plot illustrates the observed chemistry data, interpolated fill, and original discharge time series for TP.

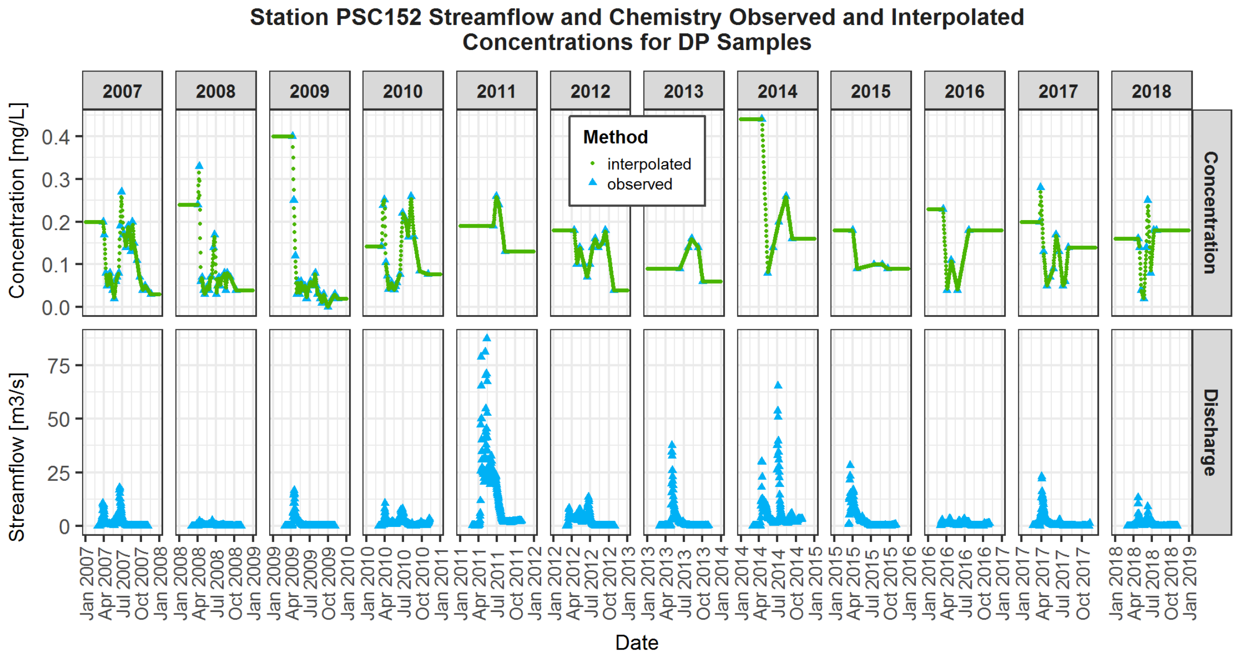


FIGURE A.7. **PSC-152 / 05NE003 Discharge and DP Concentration Data**. This plot illustrates the observed chemistry data, interpolated fill, and original discharge time series for DP.

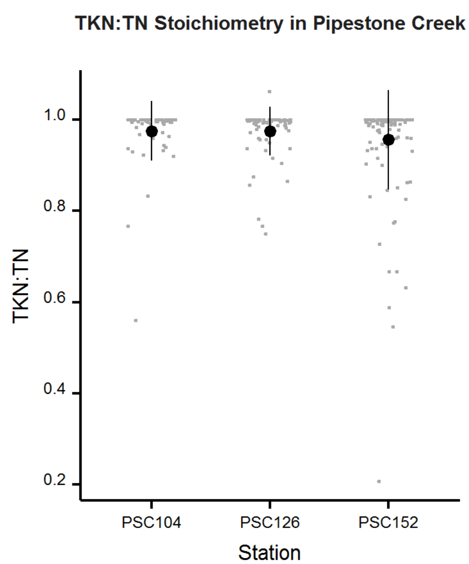
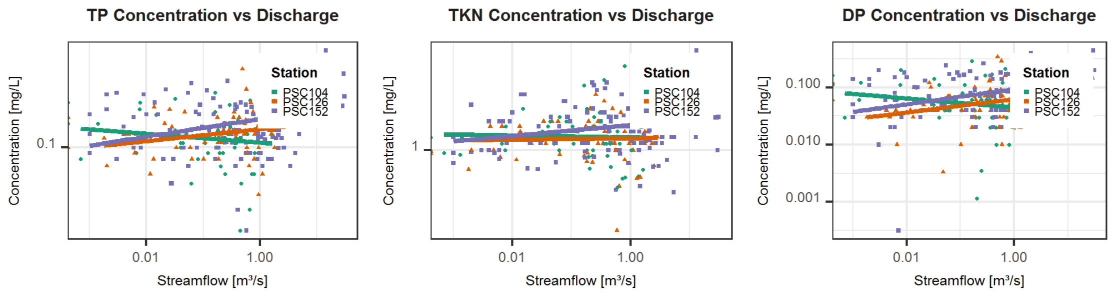


FIGURE A.8. **TKN:TN Stoichiometry in Pipestone Creek**. These plots show the scatter of data and the similarity in the TKN:TN mass ratio relationships among sample locations.



(A) TP (logscale) (B) TKN (logscale) (C) DP (logscale)

FIGURE A.9. **Flow concentration plots for DP, TP, and TKN in Pipestone Creek.**

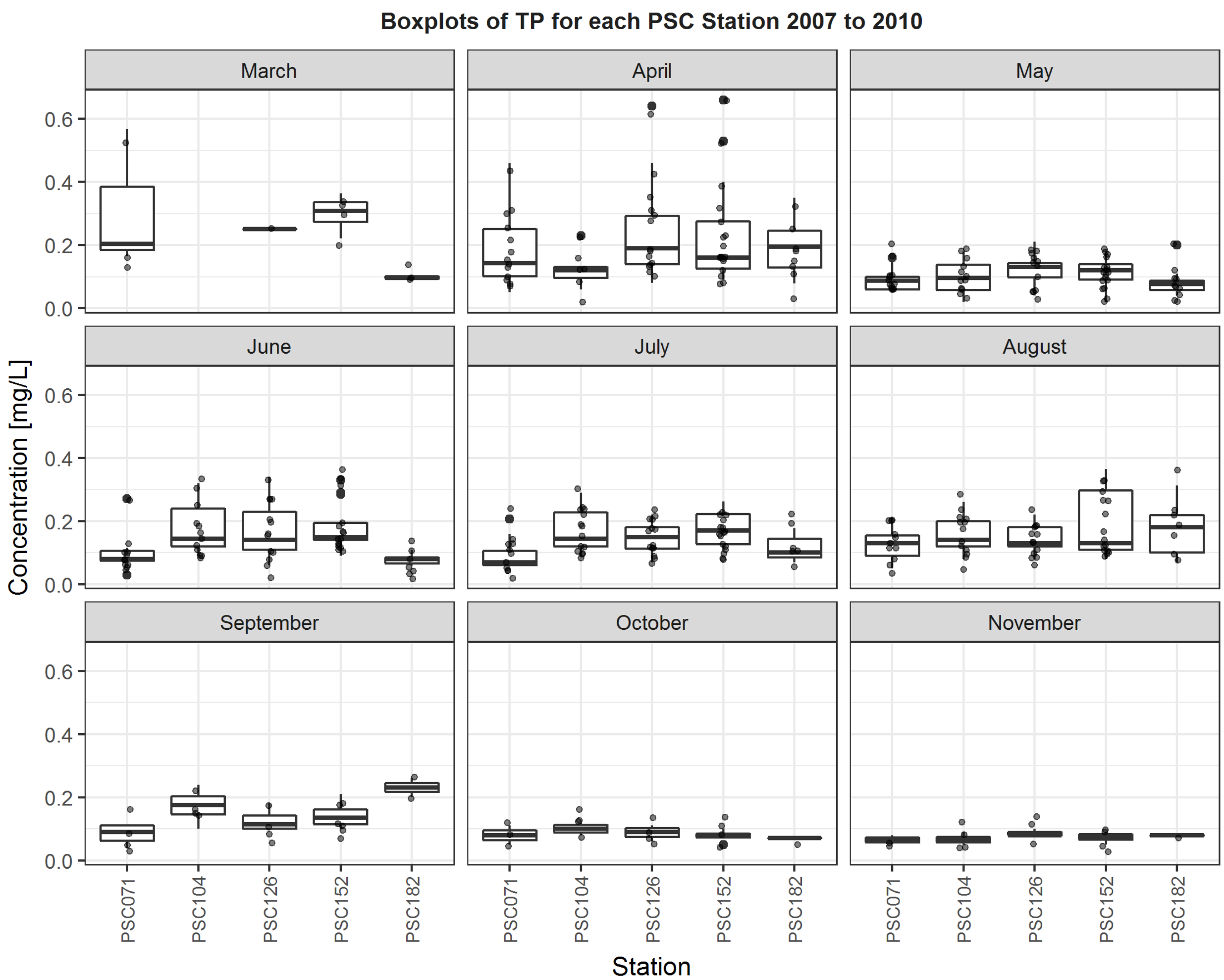


FIGURE A.10. **Mean Monthly Concentrations for TP 2007-2010**.

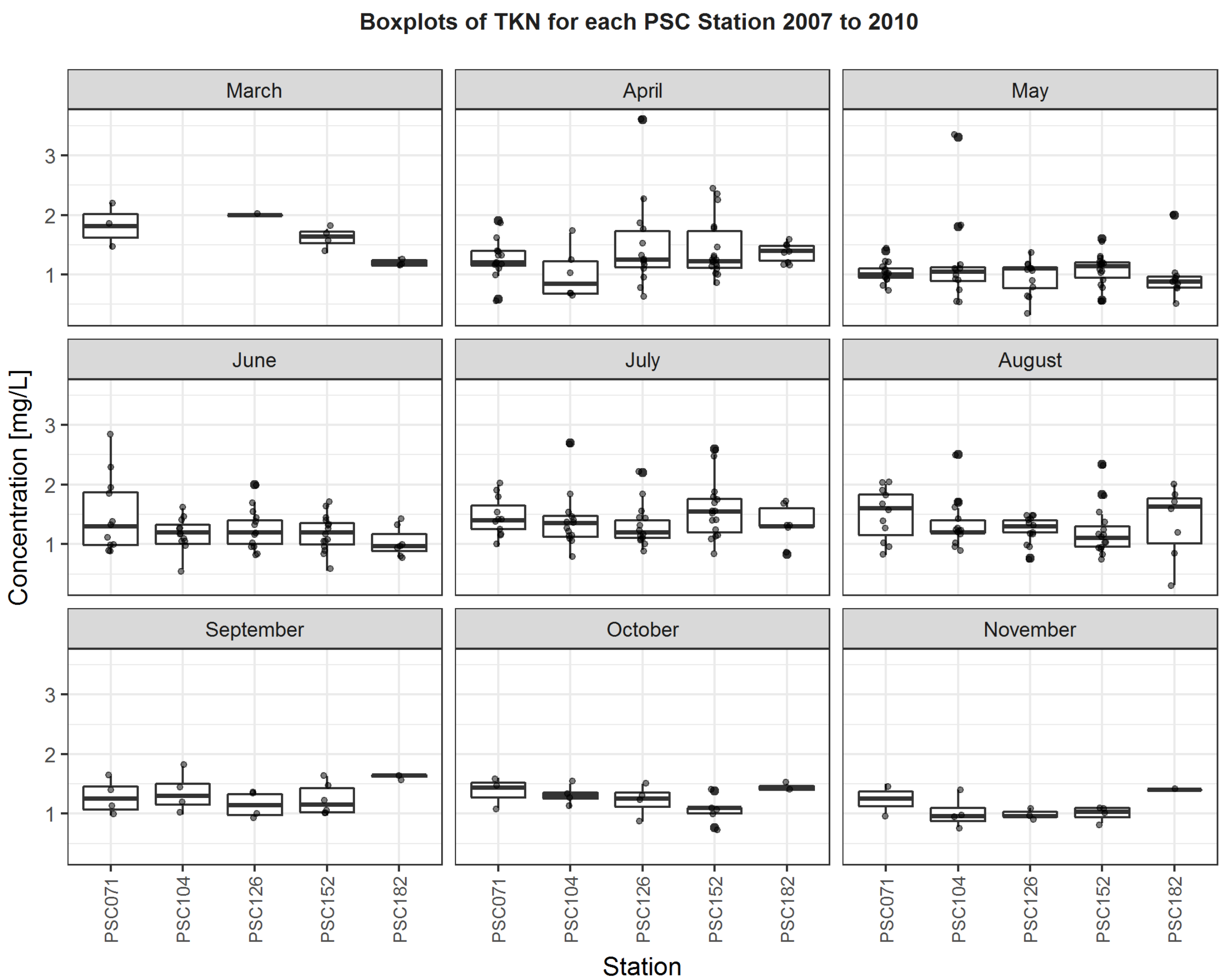


FIGURE A.11. **Mean Monthly Concentrations for TKN 2007-2010**.

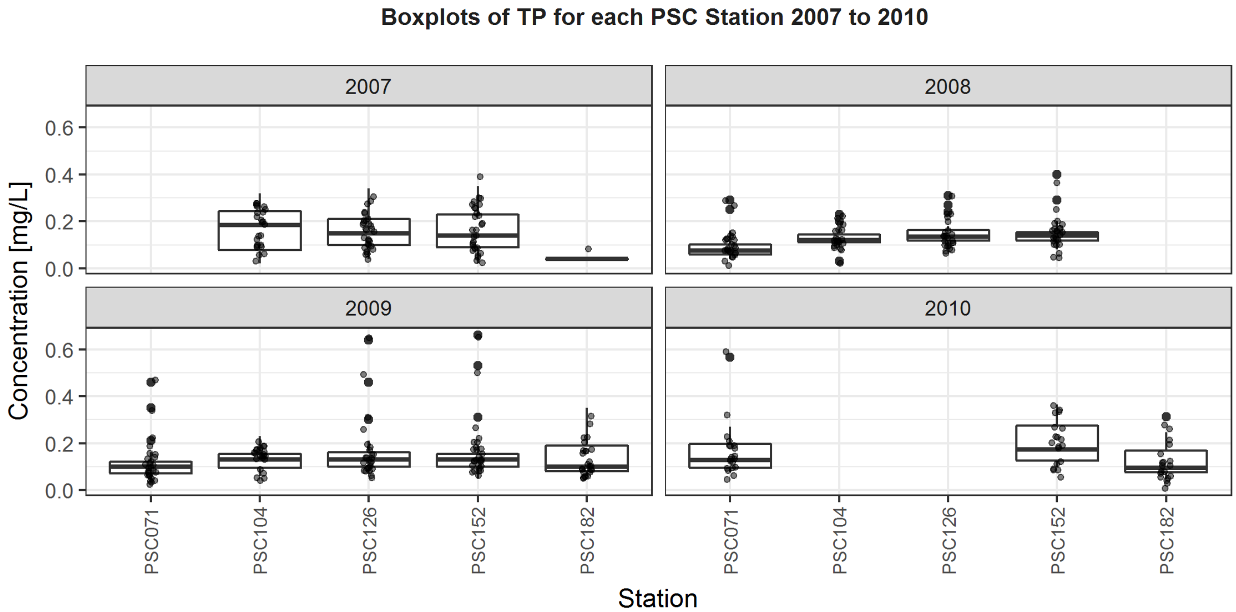


FIGURE A.12. **Mean Annual Concentrations for TP 2007-2010.**

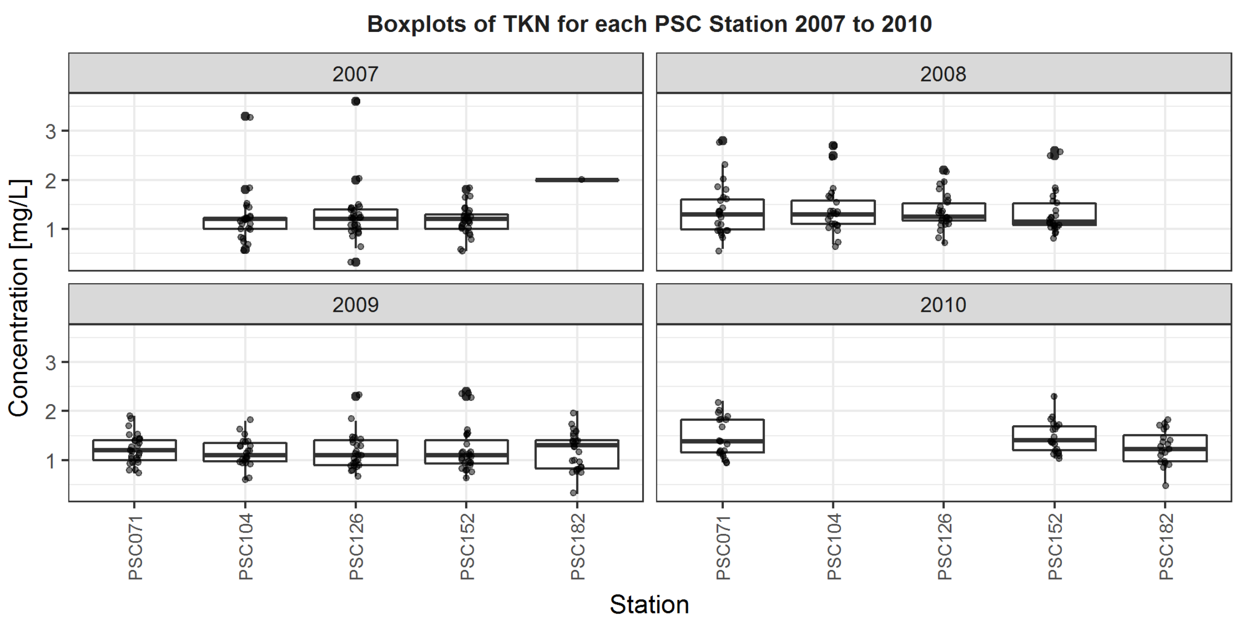


FIGURE A.13. **Mean Annual Concentrations for TKN 2007-2010.**

Figure B.1. **Corral Size Selection Examples**. These images are all at the same 1:4000 scale to illustrate the difference between large, medium, and small intensive livestock site sizes. Image credit: Daniel Phalen, LSWC

Table B.1. **Export Coefficients for Agricultural Crops on the Canadian Prairies**.

land cover	TN [kg/ha]	TP [kg/ha]	scale, description	season, years	source
60 – 85% cropland	0.21 – 0.80	0.08 – 0.29	eleven, 407 – 7985 ha subwatersheds livestock density: 0.1 – 3.7 AU/ha	3 yrs, all-year 2007 – 2009	Roste and Baulch (2017) Pipestone Creek SK
70 – 95% permanent cover[37]	0.04 – 0.18	0.01 – 0.06	eleven, 407 – 7985 ha subwatersheds livestock density: 0.7 – 4.1 AU/ha	3 yrs, all-year 2007 – 2009	Roste and Baulch (2017) Pipestone Creek SK
60 – 92% cropland	1.4 – 3.7, wet 0.27 – 3.6, dry	0.14 – 1.2, wet 0.05 – 1.9, dry	eleven, 65 – 626 km^2 watersheds livestock density: 0.1 – 0.2 NU/ha	3 yrs, all-year, wet & dry 2010, 2013, 2014	Rattan et al. (2016) Red River Valley, MB[38]
80% cropland	–	0.12 – 0.14	one, 3.8 km^2 subwatersheds	summer(wetter), spring+summer (wet) 2 yrs: 1994, 1995	Cooke and Prepas (1998) Baptiste Lake AB
34% cropland 25 head of cattle	–	0.57, 0.34	one, 6.6 km^2 subwatersheds, 2 yrs	summer(wetter), spring+summer (wet) 2 yrs: 1994, 1995	Cooke and Prepas (1998) Baptiste Lake AB[39]
34% cropland 100 head of cattle	–	0.82, 0.57	one, 6.6 km^2 subwatersheds, 2 yrs	summer(wetter), spring+summer (wet) 2 yrs: 1994, 1995	Cooke and Prepas (1998) Baptiste Lake AB
forested	–	0.23, 0.07	two, 57 – 60 km^2 subwatersheds	summer(wetter), spring+summer (wet) 2 yrs: 1994, 1995	Cooke and Prepas (1998) Baptiste Lake, AB
agriculture	IQR[40]: 1.5 – 9.8 $\mu = 4.0$	IQR: 0.2 – 1.3 $\mu = 0.6$	many watersheds, < 1 to $> 10,000$ ha	all year	Nguyen (2006, Figures 5&11) great plains, mostly AB
forested, native veg.	IQR: 0.5 – 2.7 $\mu = 1.2$	IQR: 0.05 – 0.18 $\mu = 0.2$	many watersheds, < 1 to $> 10,000$ ha	all year	Nguyen (2006, Figures 5&11) great plains, mostly AB
perennials	3.11	0.52	5, 4 – 13 ha fields	8 yrs, spring melt, wet 2005 – 2012	Liu et al. (2014) South Tobacco Creek MB
annual crop	2.89	0.20	5, 4 – 13 ha fields	8 yrs, spring melt, wet 2005 – 2012	Liu et al. (2014) South Tobacco Creek MB
annuals to perennial conversion	no change	↑ 0.32 or (160%)	five, 4 – 13 ha fields, 1 – 4% slope	8 yrs, spring melt, wet 2005 – 2012	Liu et al. (2014) South Tobacco Creek MB
summer fallow	3.6	1.7	four, 4 – 5 ha fields, 1 – 4% slope	spring melt, wet, 6 yrs 1970 – 1975	Nicholaichuk and Read (1978) Swift Current SK
spring wheat	0.52	0.48	four, 4 – 5 ha fields, 1 – 4% slope	spring melt, wet, 6 yrs 1970 – 1975	Nicholaichuk and Read (1978) Swift Current SK
fallow to wheat conversion[41]	↓ 3.1	↓ 1.2	four, 4 – 5 ha fields, 1 – 4% slope	spring melt, wet, 6 yrs 1970 – 1975	Nicholaichuk and Read (1978) Swift Current SK
grazed pasture	1.0 – 7.13	0.20 – 1.42	ten, 39 – 10,127 ha subwatersheds 0.067 livestock/ha	spring melt, summer Mar 14 - Jun 11, 1981	Mitchell & Hamilton (1982) Majeau Creek AB [42]
grazed pasture[43]	IQR= 2.5 – 8.0 $\mu = 5.1$	IQR= 0.3 – 1.9 $\mu = 0.85$	18,371 km^2 watershed	1993 hydrologic year	MDEQ (2001) Flathead Lake watershed, MT
alfalfa[44]	0.0 – 1.8 $\mu = 0.53$	0.0 – 0.5 $\mu = 0.2$	five, 0.1 ha plots at 4 sites, 9% slope	3 yrs, summer 1988 – 1990	Hargrave (1992), MB
fallow[45]	7.2 – 23.9 $\mu = 16$	5.4 – 10.9 $\mu = 7.8$	five, 0.1 ha plots at 4 sites, 9% slope	3 yrs, summer 1988 – 1990	Hargrave (1992), MB
wheat[46]	4.1 – 10.1 $\mu = 6.7, n = 5$	1.3 – 8.3 $\mu = 3.4, n = 5$	five, 0.1 ha plots at 4 sites, 9% slope	3 yrs, summer 1988 – 1990	Hargrave (1992), MB
fallow to wheat conversion[47]	↓ 1.9 – 19.8 $\mu =\downarrow 9.0, n = 5$	↓ 2.3 – 5.9 $\mu =\downarrow 3.6$, $n = 5$	five, 0.1 ha plots at 4 sites, 9% slope	3 yrs, summer 1988 – 1990	Hargrave (1992), MB
wheat to alfalfa conversion[48]	↓ 2.1 – 9.8 $\mu =\downarrow 5.8$	↓ 0.8 – 8.3 $\mu =\downarrow 3.1$	five, 0.1 ha plots at 4 sites, 9% slope	3 yrs, summer 1988 – 1990	Hargrave (1992), MB
atmospheric deposition	0.8-22.1	0.01-0.74	western Canada	year round	Chambers et al. (2001) Köchy and Wilson (2001)

[37] Permanent cover includes pasture, woodland, and hayland. Pasture >> hay land >> woodland. Refer to Goodbrand et al. (2010).
[38] Five watersheds had sewage discharges from populated areas.
[39] This watershed had two cattle operations, one- 100 head of cattle and one- 25 head of cattle. The study had one sample site located above the 100 head of cattle. The cattle were wintered near the streambank with unlimited access for grazing and water.
[40] IQR, interquartile range
[41] The values for conversion from fallow to wheat are not provided by Nicholaichuk and Read (1978), these are calculated values.
[42] Mitchell and Hamilton (1982) suggest using phosphorus export coefficients: 0.5 kg/ha for grazed catchments and 0.2 kg/ha for mixed forest / light agricultural.
[43] Taken from boxplots in Figures 4-5 and 4-6. Data for these figures were taken from 1993 data analyzed by Stanford et al. (2001).
[44] This study showed a difference in the heavy clay losses vs loams,sandy, and/or clayey soils. Alfalfa on heavy clay averaged 0.8 kg/ha TN and 0.3 kg/ha TP.
[45] For the heavy clay site, 162 kg/ha TN and 72 kg/ha TP were the observed losses.
[46] For the heavy clay site, 100 kg/ha TN and 41 kg/ha TP were the observed losses.
[47] The values for conversion from fallow to wheat are not provided by Hargrave (1992), but were calculated.
[48] The values for conversion from wheat to alfalfa (annual to perennial) are not provided by Hargrave (1992), but were calculated. The data includes both minimum and conventional till (CT) wheat. Removing CT changes the average for TN to 5.3 kg/ha (n=3) and increases the average for TP to 3.7 kg/ha (n=3).

TABLE B.2. **Export Coefficients for Livestock Land Use on the Canadian Prairies**.

land use	TN [kg/NU]	TP [kg/NU]	scale, description	season, years	source
corrals	0.10 – 28 mean 4.8, n=15	0.015 – 1.34 mean 0.42, n=15	considered field scale (corrals, on site holding ponds)	winter, 2006-2014	provided by Jane Elliott, ECCC
corrals	0.62 – 4.3 mean 2.5, n=2	0.25 – 1.42 mean 0.83, n=2	field scale (corrals, on site holding ponds)	winter, 2014	Saskatchewan, 2014
land use	**TN** $[\frac{kg \cdot m}{ha}]$	**TP** $[\frac{kg \cdot m}{ha}]$	**scale, description**	**season, years**	**source**
riparian grazing	40 – 570	80 – 114	ten, 39 – 10,127 ha sub-watersheds	spring melt	Table Mitchell and Hamilton (1982) Majeau Creek, AB cited in Table B.1) 40m–80m riparian corridor
riparian restriction	↓ 21 – 52%[49]	↓ 32 – 43%[50]	Lower Little Bow, AB (watershed)	2005 – 2007	Miller et al. (2010a)

[49] observed change in some dry years, no change in TN load exports observed in wet years
[50] observed change in some dry years, no change in TP load exports observed in wet years

Table B.3. **Export Coefficients and Abatement Potential for Manure Fertilized Fields in the Prairie**.

Practice[51]	TN [kg/ha]	TP [kg/ha]	scale	season	Source
control[52]	0.08 – 1.4 NO_3–N	0.03 – 0.13 SRP	laboratory bucket study	3 yrs: 2007 – 2009 spring snowmelt	King (2015); King et al. (2017), SK
manure applied	0.25 – 2.5 NO_3–N	0.15 – 0.49 SRP	laboratory bucket study[53]	3 yrs: 2007 – 2009 spring snowmelt	King (2015), SK
manured to unamended field conversion[54]	↓ 0.055 – 1.1 TN	↓ 0.12 – 0.36 TP	laboratory bucket study	3 yrs: 2007 – 2009 spring snowmelt	King (2015), SK
liquid hog manure	no change	↓ 0.01 – 0.04[55]	laboratory bucket study	12 years: 1997 – 2009 spring snowmelt	King (2015)
Abatement potentials for fields converted from manured amended to unamended fields:					
incorporated manure	↓ 39 – 74%	↓ 76 – 87%	eight,2 – 248 ha fields, 1 – 8%	3 yrs: 2003 – 2005 spring (dry,dry,dry), summer(dry,average,average)	Little et al. (2007)[56], AB Casson et al. (2008)[57], 7 sites in AB
unincorporated manure	↓ 87 – 91%	↓ 96 – 99%	eight,2 – 248 ha fields, 1 – 8%	3 yrs: 2003 – 2005 spring (dry,dry,dry), summer(dry,average,average)	Little et al. (2007) Casson et al. (2008), 7 sites in AB
incorporated manure	↓ 0 – 44%	↓ 0 – 39% [58]	6m x 10m plots	3 yrs: 2005 – 2007 summer (rainfall simulated)	Miller et al. (2010b), Lethbridge AB[59]

[51] All manure refers to solid cattle manure, except were it states, liquid hog manure.
[52] no ammendments
[53] This was a laboratory study to simulate spring runoff conditions on SK black chernozemic soils; manure application rates 150 – 213 kg/ha TP and 180 – 561 kg/ha of TN with 60 tonnes/ha of manure spread. Runoff over both frozen and thawing soil slabs was simulated; with runoff over thawing soils producing more nutrient export (as a results of increased soil water interaction). Authors found no evidence of a difference in P and N exports with different manure incorporation methods.
[54] Most of runoff at field scale (and smaller) is dissolved (most particulate as you scale up the watershed), therefore SRP would comprise most of the TP in the King (2015) experiments. For TN, we have assumed that NO_3–N would be the only fraction of TN to change (NH_4–N in runoff did not differ with manure amendments according to King (2015)).
[55] This is based on values taken from Figures 4.5 and 4.6 for SRP exports from frozen and thawing soil slabs. Values for the control were 0.004 & 0.017 kg/ha and for treatment were 0.041 & 0.029 kg/ha.
[56] Little et al. (2007) reported non manured fields spring runoff flow weighted mean concentration (FWMC) 0.2 – 0.86 mg/l of TP and summer FWMC 0.36 – 1.57 mg/l of TP; unincorporated manure spring FWMC 23.5 mg/l TP and manure cultivated sites runoff FWMC 0.84 – 6.63 mg/l TP. This was estimated as 76 – 87% reduction in TP runoff for incorporated manure and 96 – 99% reduction for abatement of unincorporated fall applied manure sites.
[57] Little et al. (2007) reported non manured fields spring runoff FWMC 2.32 – 13.4 mg/l of TN and summer FWMC 4.35 – 16.8 mg/l TN; unincorporated manure spring FWMC 26.6 – 105.9 mg/l of TN and manure cultivated sites runoff FWMC 3.80 – 50.7 mg/l TN. Estimated this as 39 – 74% reduction in TP runoff for incorporated manure and 87 – 91% reduction for abatement of unincorporated fall applied manure sites.
[58] First year runoff losses for P on amended strips were much higher than years 2 and 3 of the study period, first year of study was the first year of manure application to the strips. Therefore, to be conservative, the first year results were not considered here.
[59] Barley test strips, manure and mineral N applied in spring at rates from 40 – 162 kg/ha TN and 0 – 35 kg/ha TP. Reductions are based on a comparison to losses from an unamended barley control strip. TP taken from Figure 3: control exports (1-3 kg/ha/hr) treatment exports (1-4.9 kg/ha/hr) equates to 0-39% improvement for TP; TN taken from Figure 4, control exports (1.4 kg/ha/hr) and treatment exports (1.4-2.5 kg/ha) equates to 0-44% improvement for TN

TABLE B.4. **Watershed Drainage and Restoration Models**. This table provides a brief description of the Smith Creek, SK; Vermilion River, AB; and Pipestone Creek, SK watersheds used in wetland modelling simulations.

Watershed	Area	Slope	Land Use	Area of Watershed that is Wetland	Area of Watershed that is Drained Wetland	ΔStreamflow or Nutrient Load Drainage	ΔStreamflow or Nutrient Load Restoration	Model	Source
Broughton's Creek	251 km^2	~ 3.5%	73% cropland 27% other[60]	9%	2.5%	↑ 30% TP, TN	↓ 23% TP, TN	SWAT	Yang et al. (2008)
					modelled 1% drainage	↑ 15% TP, TN	↓ 10% TP, TN		
Smith Creek	393 km^2	2 – 5%	48% cropland 52% other[63]	11%	13%	↑ 55%[61]	↓ 26%[62]	CRHM WPDM[64]	Pomeroy et al. (2014) Dumanski et al. (2015)
Smith Creek	435 km^2	0 – 8%	73% cropland 27% other[67]	16%	13%	↑ 161%[65] ↑ 48% TN ↑ 145% TP	↓ 67%[66] ↓ 33% TN ↓ 54% TP	SWAT	Yang et al. (2012)
					modelled 1 – 4% drainage & restoration	↑ 16% ↑ 5% TN ↑ 11% TP	↓ 8% ↓ 4% TN ↓ 6% TP		
Vermilion River	7,860 km^2	0.6 – 3.3%	80% cropland 20% other[68]	~ 7%	~ 1%		-	CRHM	Pomeroy et al. (2012)
Vermilion Sub-basins[69]	46 – 505 km^2	–	–	5.2 – 7.6%	0.5 – 2.5%	↑ 2.5 – 13%	↓ 1 – 3.5%		
Pipestone Creek	2,242 km^2	-	44% cropland 56% other[71]	~ 11%	modelled 1.8%	↑ 43%[70]	-	SWAT	Perez-Valdivia et al. (2017)

60 other includes: rangeland, forest, wetlands, roads

61 These are total change in discharge over the 6 year modelled period, 2007-2013. Actual annual values ranged widely (0-300%) with from flood conditions (0%) to moderate to dry years (200 – 300%).

62 These are total change in discharge over the 6 year modelled period, 2007-2013. Actual annual values ranged widely (0-70%) with conditions that ranged from flood conditions to dry years.

63 other includes: native grassland, deciduous and/or coniferous forest and wetlands

64 Shook et al. (2013)

65 This is the average change in discharge for the modelled years of 1990-2009. Acutal values will range widely considering flood conditions to dry conditions.

66 This is the average change in discharge for the modelled years of 1990-2009. Acutal values will range widely considering flood conditions to dry conditions.

67 other includes: native grassland, deciduous and/or coniferous forest and wetlands

68 other includes: native grassland, deciduous and/or coniferous forest and wetlands

69 Sub-basins considered were those modelled for restoration (Pomeroy et al., 2012, Figure 41b), specifically sub-basins 6 8,13,14,15,16, and 17.

70 Perez-Valdivia et al. (2017) modelled scenarios of 15%, 30%,and 50% of drainage of the existing NCDA (which equates to 11%, 23%,and 38% of the GDA) for the years of 1997-2009. Results ranged in increased volume discharge from 65 – 138% for 50% drainage of existing wetland area, with 98% being the average change to discharge. The modelled 15% reduction equates to about 1.8% of the basin area (which is a 20% decrease in the wetland area) and produced and average increase of 43% in discharge volume annually.

71 other includes, wetland, water, range-brush, pasture, forest and residential

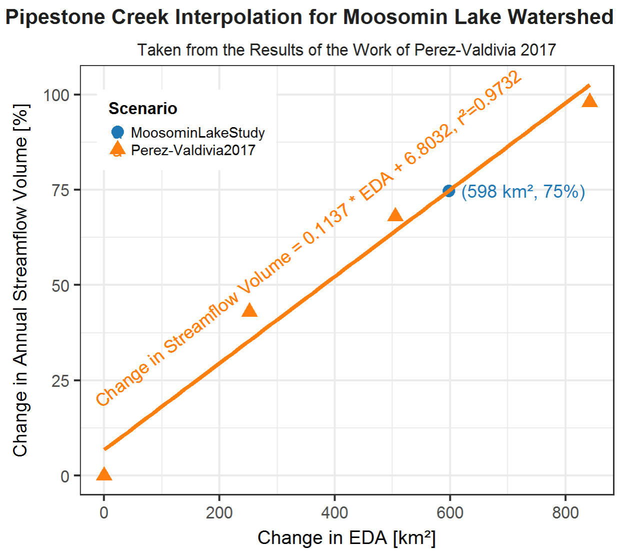


FIGURE B.2. **Linear Model from Pipestone Creek Drainage Study**. The annual change in flow volumes with increased drainage predicted by Perez-Valdivia et al. (2017) for the Pipestone Creek watershed plots linearly against the respective EDA associated with each incremental drainage scenario (orange triangles). This linear relationship was used to estimate the change in annual flow volumes that might be achievable were Moosomin Lake watershed EDA restored to the pre-drainage ratio of 0.32, a reduction of 598 km^2 (blue circle) from its current 0.49 EDA/GDA ratio. Figure 25 illustrates this without the (0,0) data point.

B.1. **Export Coefficients - selection.** The selection process for each land use EC involved some trial and error. For the first trial, all ECs were set to the median value in the range. This over predicted the observed target mean[72] loads by 137% for TN and 330% for TP.

To adjust the TP ECs and produce an estimate closer to the target mean, all ECs were moved to the lowest values in their ranges (save Pasture and Forages which was set near 0 at 0.08 which is 0.01 above the value used for Cereals,Oilseeds,Lentils). This change moved the predicted load for TP within -0.5% of the targeted observed mean value. For TN, the next step was to adjust all of the smaller scale ECs to the lower ends of their ranges (Fallow, PastureForages (used 0.20 kg/ha), ExposedBarren[73], ManureApplied (used 0.9 kg/ha), and Urban[74]). After these changes, TN was still over predicted by 71% (Figure B.3) where the contribution from the land uses Forest and Corrals comprised a large portion of the loading to the watershed. The EC for Corrals was lowered to 0.9 kg/ha from the median of 2.4 kg/ha and the EC for Forest lowered to its low range value of 0.5 kg/ha with a result of 11% over prediction of the target mean and an obvious proportional increase in the contribution of Cereals,Oilseeds,Lentils to the total load.

Now, the lab/plot/field scale ECs for ManureApplied land and Fallow were very elevated above those for the watershed scale ECs, the ranges for these EC values were, therefore, adjusted by half. Assuming a 2x scale factor to account for in-stream (and land) retention of nutrients is precedented in the work of Yang et al. (2008). This set the values for TP at 0.085 and 0.075 for Fallow and ManureApplied respectively. The values for Fallow and ManureApplied for were within the adjusted ranges and these values set at 3.5 kg/ha for Fallow land 0.9 kg/ha.

The last tweak for TP, was to adjust the Corrals EC to match field data TN:TP mass ratios in the holding ponds (these ranged 2:1 to 33:1), this raised the EC to 0.1 kg/NU for TP and put the TN:TP ratio at 9:1 rather than 60:1. The final load estimates for TP were set at 1.4% of the target mean at 05NE003.

In the final tweak for TN, we lowered the Cereals,Oilseeds,Lentils to 0.48 kg/ha (from 0.51) and riparian grazing to 90 kg·m/ha (from the median 305 kg·m/ha). This set all the ECs at the values shown in Table 6 and provides a prediction for TN within 0.5% [75].

[72]Recall that the target mean is the mean observed loads for 2007 through 2017 with the high flow years of 2011 and 2014 removed. We are predicting loads for the EDA in this exercise and those two extremely high flow years are expected to drain from a substantial portion of the GDA as well and will skew chosen EC values.

[73]The Exposed or Barren land EC was based on using 0.5 runoff ratio and atmospheric deposition rates. The low end of the atmospheric deposition rates were felt more reflective of the watershed.

[74]Although, not edge-of-field scale, these urban ECs were too high for the watershed. Actual municipal discharges from wastewater effluent have already been removed at this point. Only P and N from stormwater runoff in urban areas needs to be accounted for with this value.

[75]There are several regions termed GEDs (GEDs GED21, 28, 29, 33, 38, and 40) that are in the Moosomin Watershed and subject to a previous investigation by the authors (Roste and Baulch, 2017). These GEDs ranged in land use and had ECs ranging from $0.01 - 0.16$ for TP and $0.06 - 0.46$ for TN.

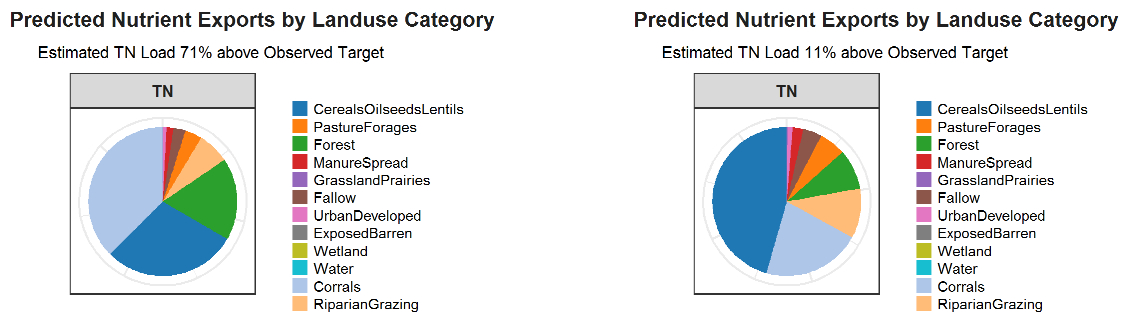


FIGURE B.3. **Predicted TN Loads by Land Use Category**. These two pie charts illustrate the change in composition of the land use contributions to total predicted load as the ECs were set for the watershed. The image on the left illustrates the composition at 71% over estimation and the one on the right 11%. For the final composition used in the BMP exercise refer to Figure 24.

TABLE B.5. **Nitrogen exports predicted for each Basin**. The export coefficient generated by calculating a nutrient load for each basin is provided alongside the total nutrient export in kilograms. These values are the summation of all the land use areas [ha] x land use EC [kg/ha]. Values are shown ranked from least to greatest basin export coefficient values.

	Nutrient	Basin	Area_km2	Exports_kgperHectare	Exports_kg
1	TN	17	18	0.38	679
2	TN	30	10	0.39	382
3	TN	15	19	0.46	895
4	TN	9	8	0.47	356
5	TN	5	73	0.48	3502
6	TN	18	15	0.50	757
7	TN	34	79	0.50	3947
8	TN	25	36	0.51	1826
9	TN	16	18	0.51	939
10	TN	23	54	0.52	2817
11	TN	27	46	0.53	2443
12	TN	3	53	0.53	2834
13	TN	28	103	0.54	5557
14	TN	21	61	0.54	3285
15	TN	31	74	0.55	4024
16	TN	4	36	0.55	1997
17	TN	32	86	0.55	4755
18	TN	29	67	0.56	3726
19	TN	22	76	0.56	4260
20	TN	13	98	0.57	5543
21	TN	20	122	0.59	7125
22	TN	33	49	0.59	2894
23	TN	14	40	0.60	2402
24	TN	24	40	0.60	2422
25	TN	19	40	0.60	2407
26	TN	11	116	0.60	6967
27	TN	35	8	0.61	473
28	TN	6	7	0.62	404
29	TN	12	20	0.65	1323
30	TN	7	11	0.65	689
31	TN	10	42	0.66	2801
32	TN	1	40	0.67	2674
33	TN	2	7	0.68	481
34	TN	8	41	0.72	2923
35	TN	26	64	0.72	4665

Table B.6. **Phosphorus exports predicted for each Basin**. The export coefficient generated by calculating a nutrient load for each basin is provided alongside the total nutrient export in kilograms. These values are the summation of all the land use areas [ha] x land use EC [kg/ha]. Values are shown ranked from least to greatest basin export coefficient values.

	Nutrient	Basin	Area_km2	Exports_kgperHectare	Exports_kg
1	TP	30	10	0.05	52
2	TP	18	15	0.05	81
3	TP	16	18	0.06	117
4	TP	9	8	0.07	52
5	TP	17	18	0.07	124
6	TP	5	73	0.07	508
7	TP	25	36	0.08	270
8	TP	32	86	0.08	656
9	TP	27	46	0.08	359
10	TP	23	54	0.08	431
11	TP	34	79	0.08	628
12	TP	13	98	0.08	790
13	TP	20	122	0.08	1002
14	TP	31	74	0.08	608
15	TP	21	61	0.08	509
16	TP	11	116	0.08	974
17	TP	35	8	0.08	66
18	TP	3	53	0.08	451
19	TP	15	19	0.08	164
20	TP	22	76	0.08	645
21	TP	28	103	0.09	875
22	TP	29	67	0.09	575
23	TP	24	40	0.09	350
24	TP	33	49	0.09	431
25	TP	6	7	0.09	58
26	TP	4	36	0.09	324
27	TP	19	40	0.09	367
28	TP	2	7	0.09	65
29	TP	10	42	0.09	387
30	TP	7	11	0.09	99
31	TP	14	40	0.09	379
32	TP	8	41	0.10	389
33	TP	1	40	0.10	381
34	TP	12	20	0.10	207
35	TP	26	64	0.13	824

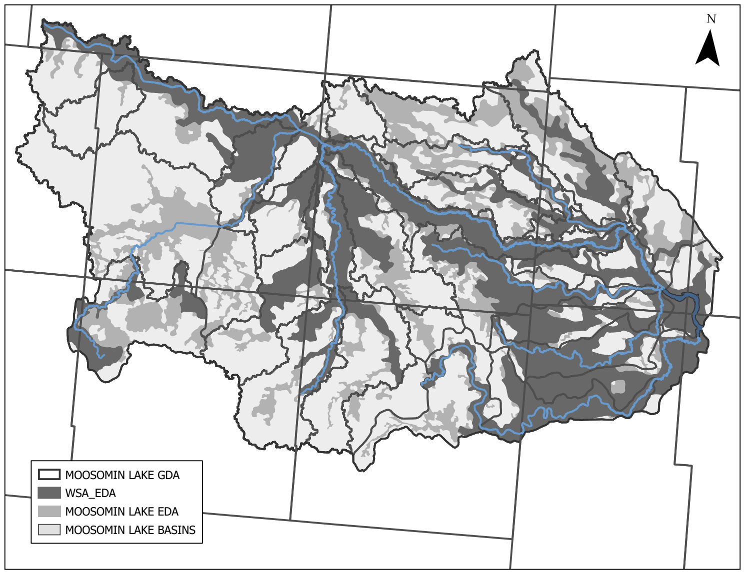


FIGURE B.4. **The Moosomin Lake Watershed EDA Extents**. This graphic highlights the difference in the effective drainage areas as provided in the PFRA data and the assessed EDA provided by the LSWC staff.

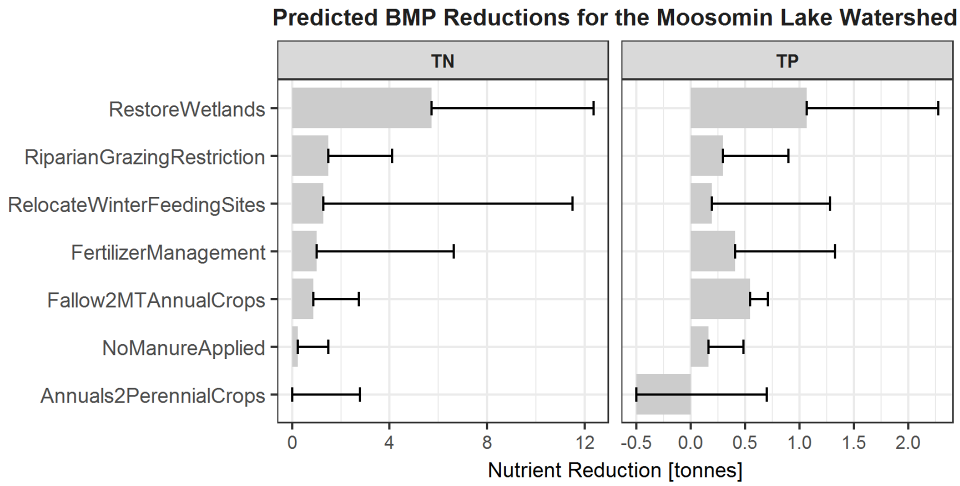


FIGURE B.5. **Minimum Predicted BMP Performance for Moosomin Lake**. The minimum reduction potential for each of the BMPs is illustrated with the bars, the minimum and maximum range of benefit are represented with the error bars.

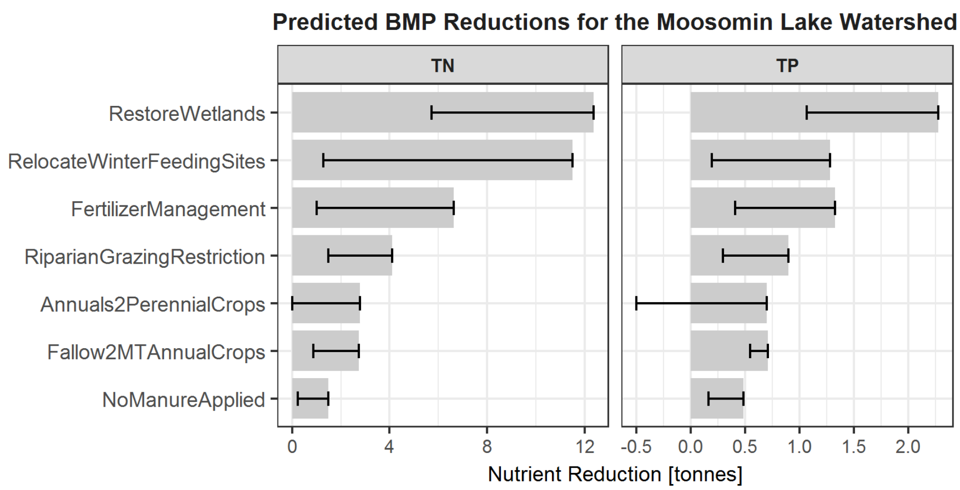


FIGURE B.6. **Maximum Predicted BMP Performance for Moosomin Lake**. The maximum reduction potential for each of the BMPs is illustrated with the bars, the minimum and maximum range of benefit are represented with the error bars.

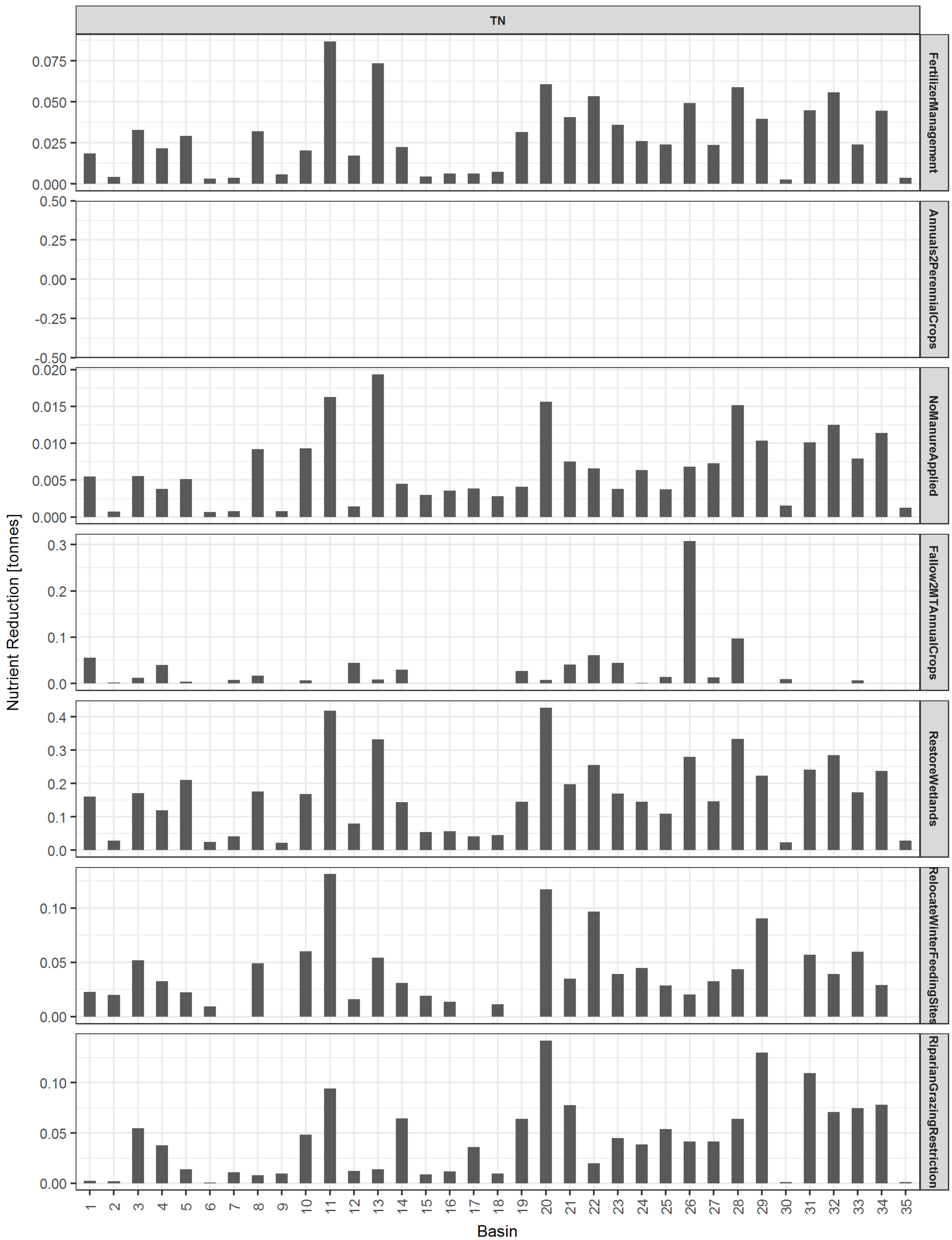


Figure B.7. **Minimum BMP Nitrogen export reductions predicted for each Basin**. Barplots of the estimated minimum potential reduction in nitrogen exports for each basin.

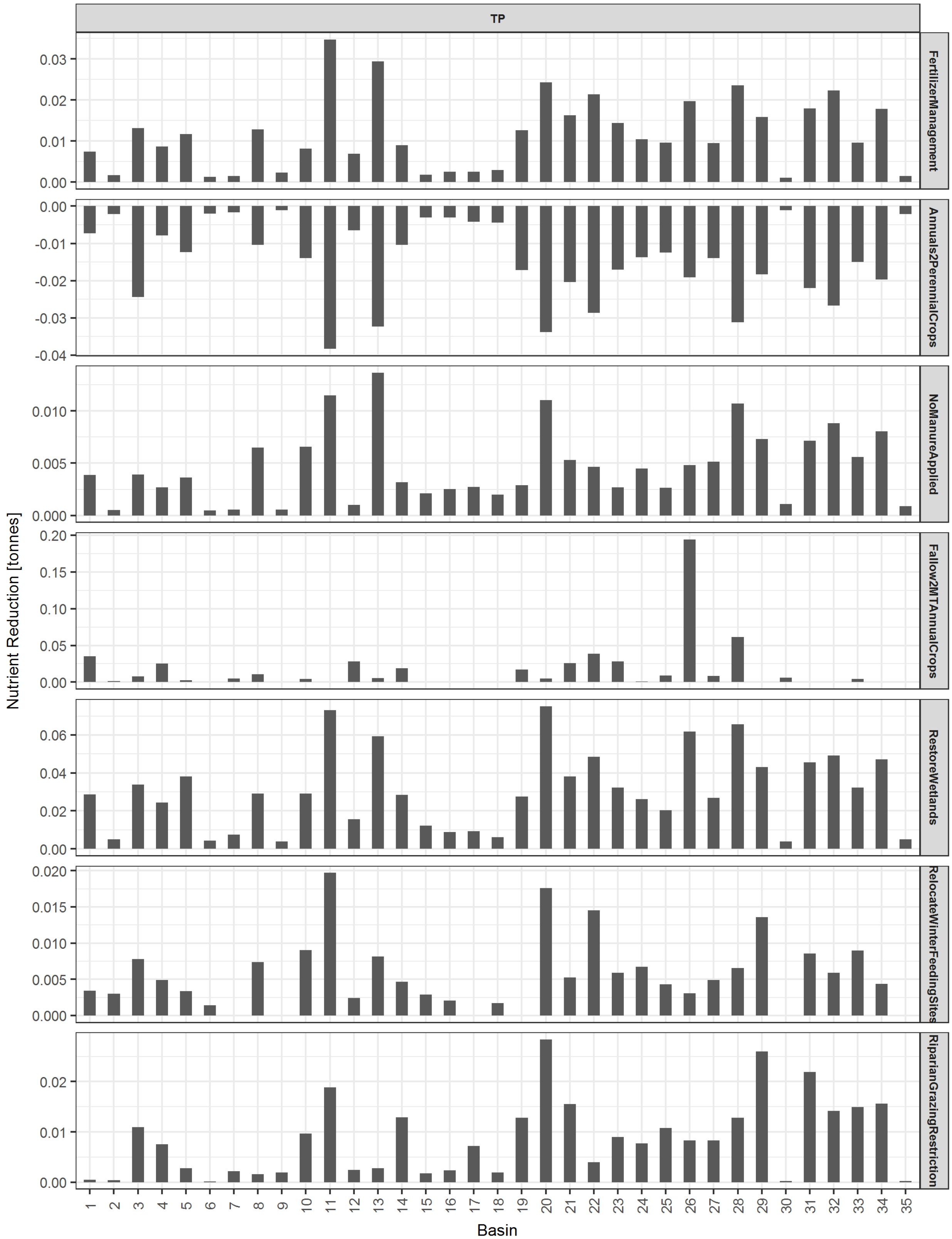


Figure B.8. **Minimum BMP Phosphorus export reductions predicted for each Basin**. Barplots of the estimated minimum potential reduction in phosphorus exports for each basin.

References

Alberta Agriculture and Rural Development (2014), Nutrient Beneficial Management Practices Evaluation Project: Volume 2 - Field Study, *Tech. rep.*, Water Quality Branch, Irrigation and Farm Water Division, Alberta Agriculture and Rural Development, Lethbridge, Alberta, Canada.

Badiou, P., B. Page, and W. Akinremi (2018), Phosphorus Retention in Intact and Drained Prairie Wetland Basins: Implications for Nutrient Export, *Journal of Environmental Quality*, (47), 902–913, doi:10.2134/jeq2017.08.0336.

Barbour, M. T., J. Gerritsen, B. D. Snyder, and J. B. Stribling (1999), Rapid Bioassessment Protocols For Use in Streams and Wadeable Rivers, Second Edition. EPA 841-B-99-002, *Tech. rep.*, U.S. Environmental Protection Agency, Office of Water, Washington, DC.

Baulch, H. M., J. J. Venkiteswaran, and J.-M. Davies (2018), The Water Quality Toolbox, *LakeLine*, *38*(3), 16–19.

Baulch, H. M., J. A. Elliott, M. R. Cordeiro, D. N. Flaten, D. A. Lobb, and H. F. Wilson (2019), Soil and water management practices: Opportunities to mitigate nutrient losses to surface waters in the Northern Great Plains, *Environmental Reviews*, *in press*.

Bortolotti, L. E., R. D. Vinebrooke, and V. L. S. T. Louis (2016), Prairie wetland communities recover at different rates following hydrological restoration, pp. 1874–1890, doi:10.1111/fwb.12822.

Bourgeault Industries Limited (2015), Auto Section Control, The ASC Advantage, *The Cutting Edge*, *Spring*, 30–35.

Boychuk, L., E. Mayer, S. Dunn, and R. Tulloch (2014), Canadian Wetland Inventory: Prairie Wetland Interpretation Guide vs2, *Tech. rep.*, Ducks Unlimited Canada Prairie Regions, Regina, SK.

Calhoun, A. J. K., D. M. Mushet, K. P. Bell, D. Boix, J. A. Fitzsimons, and F. Isselin-nondedeu (2017), Temporary wetlands: challenges and solutions to conserving a 'disappearing' ecosystem, *Biological Conservation*, *211*, 3–11, doi:10.1016/j.biocon.2016.11.024.

Canadian 4R Research Network (2018), Key Findings of the Canadian 4R Research Network Increasing Profitability and Improving, *Tech. rep.*, Fertilizer Canada.

Canadian Council of Ministers of the Environment (2004), Canadian Water Quality Guidelines for the Protection of Aquatic Life: Phosphorus: Canadian Guidance Framework for the Management of Freshwater Systems, in *Canadian Environmental Quality Guidelines*, p. 6, Winnipeg, Manitoba.

Casson, J. P., B. M. Olson, J. L. Little, and S. C. Nolan (2008), Assessment of environmental sustainability in Alberta's agri- cultural watersheds project. Volume 4. Nitrogen loss in surface runoff, *Tech. rep.*, Alberta Agriculture and Rural Development, Lethbridge, Alberta, Canada.

Centre for Agroclimate Geomatics and Earth Observation Science and Technology Branch (2017), Annual Space-Based Crop Inventory for Canada, *Tech. rep.*, Agriculture and Agri-Food Canada.

Chambers, P. A., M. Guy, E. S. Roberts, M. N. Charlton, R. Kent, C. Gagnon, G. Grove, and N. Foster (2001), Nutrients and their Impact on the Canadian Environment, *Tech. rep.*, Agriculture and Agri-Food Canada, Fisheries and Oceans Canada, Health Canada and Natural Resources Canada.

Chen, G., J. A. Elliott, D. A. Lobb, D. N. Flaten, L. Braul, and H. F. Wilson (2017), Changes in runoff chemistry and soil fertility after multiple years of cattle winter bale feeding on annual cropland on the Canadian prairies, *Agriculture, Ecosystems and Environment*, *240*, 1–13, doi:10.1016/j.agee.2017.02.003.

Chik, A. H., et al. (2017), Nutrient Management Research Insights for Decision Makers, *Tech. Rep. November*, Canadian Water Network, Waterloo, ON.

Cooke, S. E., and E. E. Prepas (1998), Stream phosphorus and nitrogen export from agricultural and forested watersheds on the Boreal Plain, *Canadian Journal of Fisheries and Aquatic Sciences*, *55*(10), 2292–2299, doi:10.1139/f98-118.

Culp, J., and H. Wheater (2016), Cumulative Effects Monitoring in the Tobacco Creek Watershed, *Tech. rep.*, Canadian Water Network.

Dumanski, S., J. W. Pomeroy, and C. J. Westbrook (2015), Hydrological regime changes in a Canadian Prairie Basin, *Hydrological Processes (special issue)*.

Elliott, J. A. (2019), Emailed dated March 27, 2019 J.Elliott, J.Roste.

Goodbrand, A., A. Lundgren, and J.-M. Davies (2010), Summary of Agricultural Land Use and Farm Management Practices for the Agricultural Land Use Study, Pipestone Creek SK, *Tech. rep.*, Saskatchewan Watershed Authority.

Hansen, A. T., C. L. Dolph, E. Foufoula-Georgiou, and J. C. Finlay (2018), Contribution of wetlands to nitrate removal at the watershed scale, *Nature Geoscience*, *11*(2), 127–132, doi:10.1038/s41561-017-0056-6.

Hargrave, A. P. (1992), Nitrogen and Phosphorus Losses in Surface Runoff due to Rainfall in Manitoba, Master of science, University of Manitoba.

Hyndman, R., et al. (2019), Forecasting Functions for Time Series and Linear Models.

Kaivosoja, J., and R. Linkolehto (2016), Spatial overlapping in crop farming works, *Agronomy Research*, *14*(1), 41–53.

King, T., J. Schoenau, and J. Elliott (2017), Relationship between Manure Management Application Practices and Phosphorus and Nitrogen Export in Snowmelt Run-off Water from a Black Chernozem Saskatchewan Soil, *Sustainable Agriculture Research*, *6*(2), 93, doi:10.5539/sar.v6n2p93.

King, T. N. (2015), Effect of solid cattle manure and liquid hog manure application on phosphorus and nitrogen in soil, run-off and leachate in Saskatchewan soils, Doctor of philosophy, University of Saskatochewan.

Kinsman-Costello, L. E., J. O. Brien, and S. K. Hamilton (2014), Re-flooding a Historically Drained Wetland Leads to Rapid Sediment Phosphorus Release, *Ecosystems*, *17*, 641–656, doi:10.1007/s10021-014-9748-6.

Kinsman-Costello, L. E., S. K. Hamilton, J. M. O. Brien, and J. T. Lennon (2016), Phosphorus release from the drying and reflooding of diverse shallow sediments, *Biogeochemistry*, *130*(1), 159–176, doi:10.1007/s10533-016-0250-4.

Köchy, M., and S. D. Wilson (2001), Nitrogen deposition and forest expansion in the northern Great Plains, *Journal of Ecology*, *89*, 807–817.

Kuha, J. K., A. H. Palomäki, J. T. Keskinen, and J. S. Karjalainen (2016), Limnologica Negligible effect of hypolimnetic oxygenation on the trophic state of Lake Jyväsjärvi, Finland, *Limnologica*, *58*, 1–6, doi:10.1016/j.limno.2016.02.001.

Levesque, L., and E. Page (2011), State of Lake Winnipeg: 1999 to 2007, *Tech. rep.*, Environment Canada and Manitoba Water Stewardship.

Little, J. L., S. C. Nolan, J. P. Casson, and B. M. Olson (2007), Relationships between soil and runoff phosphorus in small Alberta watersheds, *Journal of Environmental Quality*, *36*(5), 1289–1300, doi:10.2134/jeq2006.0502.

Liu, J., B. Ulen, G. Bergkvist, and H. Aronsson (2014), Freezing – thawing effects on phosphorus leaching from catch crops, *Nutrient Cycling in Agroecosystems*, *99*, 17–30, doi:10.1007/s10705-014-9615-z.

Liu, J., J. A. Elliott, H. Wilson, and H. M. Baulch (2019a), Impacts of Soil Phosphorus Drawdown on Snowmelt and Rainfall Runoff Water Quality, *Journal of Environmental Quality*, (accepted), 1–31.

Liu, J., J. Roste, H. Baulch, J. A. Elliott, and J.-M. Davies (2019b), Screening-level assessment of beneficial management practices in a data-limited Canadian prairie watershed, *in draft*.

Lower Souris River Watershed Committee (), Lower Souris Watershed Committee.

Marin, S. (2019a), Email dated January 18, 2019 S. Marin, J. Roste, and E. Shupena-Soulodre.

Marin, S. (2019b), Email dated March 14, 2019 S. Marin and J. Roste.

Marin, S., and D. Siba (2019), Email dated March 27, 2019 S.Marin, J.Roste, and D.Siba.

Martin, F. (2001), Addendum No. 8 to Hydrology Report #104, Agriculture and Agri-Food Canada PFRA Technical Service: Regina, SK, 109 pp. PFRA Hydrology Division, 1983. The determination of gross and effective drainage areas in the Prairie Provinces, *Tech. rep.*, PFRA Engineering Branch, Regina, SK.

MDEQ (2001), Nutrient Management Plan and Total Maximum Daily Load for Falthead Lake, Montana, *Tech. rep.*, Montana Department of Environmental Quality.

Miller, J. J., D. S. Chanasyk, T. Curtis, and W. D. Willms (2010a), Influence of Streambank Fencing on the Environmental Quality of Cattle-Excluded Pastures, *Journal of Environmental Quality*, *39*(3), 991–1000, doi:10.2134/jeq2009.0233.

Miller, J. J., D. S. Chanasyk, T. W. Curtis, and B. M. Olson (2010b), Phosphorus and nitrogen in runoff after phosphorus- or nitrogen-based manure applications, *Journal of Environmental Quality*, *40*(3), 949–958, doi:10.2134/jeq2010.0279.

Miller, J. J., T. Curtis, D. S. Chanasyk, and W. D. Willms (2017), Influence of Cattle Trails on Runoff Quantity and Quality, *Journal of Environment Quality*, *46*(2), 348, doi:10.2134/jeq2016.07.0280.

Mitchell, P., and H. Hamilton (1982), Assessment of Phosphorus Export From the Majeau Creek Watershed Lac La Nonne, *Tech. rep.*, Water Quality Control Branch, Pollution Control Division, Alberta Environment.

Morales-Marin, L., H. S. Wheater, and K. E. Lindenschmidt (2017), Assessment of nutrient loadings of a large multipurpose prairie reservoir, *Journal of Hydrology*, *550*, 166–185, doi:10.1016/j.jhydrol.2017.04.043.

Nguyen, T. T. (2006), The development and application of the export coefficient model to Alberta watersheds, with a focus on total phosphorus and total nitrogen, Master of science, Royal Roads University.

Nicholaichuk, W., and D. Read (1978), Nutrient runoff from fertilized and unfertilized fields in Western Canada, *Journal of Environmental Quality*, *7*(4), 542–544.

Nygrén, N. A., P. Tapio, and J. Horppila (2017), Will the Oxygen-Phosphorus Paradigm Persist? – Expert Views of the Future of Management and Restoration of Eutrophic Lakes, *Environmental Management*, *65*, 947–960, doi:10.1007/s00267-017-0919-z.

Ontario Ministry of Agriculture Food and Rural Affairs (2007), Nutrient Management Protocol.

Pattison-Williams, J. K., J. W. Pomeroy, P. Badiou, and S. Gabor (2018), Wetlands , Flood Control and Ecosystem Services in the Smith Creek Drainage Basin : A Case Study in Saskatchewan , Canada, *Ecological Economics*, *147*(December 2017), 36–47, doi:10.1016/j.ecolecon.2017.12.026.

Perez-Valdivia, C., D. Sauchyn, and J. Vanstone (2012), Groundwater levels and teleconnection patterns in the Canadian Prairies, *Water Resources Research*, *48*(7), n/a–n/a, doi:10.1029/2011WR010930.

Perez-Valdivia, C., B. Cade-menun, and D. W. Mcmartin (2017), Hydrological modeling of the pipestone creek watershed using the Soil Water Assessment Tool (SWAT): Assessing impacts of wetland drainage on hydrology, *Journal of Hydrology: Regional Studies*, *14*(September), 109–129, doi:10.1016/j.ejrh.2017.10.004.

Phillips, I. D. (2017), Biological Tools for Water Security in the Northern Great Plains, Doctor of philosophy, University of Saskatchewan.

Phillips, I. D., D. Parker, and G. McMaster (2008), Aquatic invertebrate fauna of a northern prairie stream: range extensions and water quality characteristics., *Western North American Naturalist*, *68*(2), 173–185, doi:10.3398/1527-0904(2008)68[173:AIFOAN]2.0.CO;2.

Pomeroy, J., X. Fang, K. Shook, C. Westbrook, and T. Brown (2012), Informing the Vermilion River Watershed Plan through Application of the Cold Regions Hydrological Model Platform Centre for Hydrology Report No . 12 Informing the Vermilion River Watershed Plan through Application of the Cold Regions Hydrological Model Pl, *Tech. Rep. 12*, Centre for Hydrology, University of Saskatchewan, Saskatoon, SK, Canada.

Pomeroy, J. W., D. M. Gray, T. Brown, N. R. Hedstrom, W. L. Quinton, R. J. Granger, and S. K. Carey (2007), The cold regions hydrological model: a platform for basing process representation and model structure on physical evidence, *Hydrological*, *21*(19), 2650–2667, doi:10.1002/hyp.

Pomeroy, J. W., K. Shook, X. Fang, S. Dumanski, C. Westbrook, and T. Brown (2014), Improving and Testing the Prairie Hydrological Model at Smith Creek Research Basin, (14), 102.

Raine, M. (2009), Once is enough: Seed Hawk's Sectional Control Technology drill cuts off seed and fertilizer when overlapping is about to begin, *The Western Producer*, *June 11.*(http://www.producer.com/2009/06/once-is-enough-seed-hawks-sectional-control-technology-drill-cuts-off-seed-and-fertilizer-when-overlapping-is-about-to-begin/).

Rattan, K., J. Corriveau, R. Brua, J. Culp, A. Yates, and P. A. Chambers (2016), Quantifying seasonal variation in total phosphorus and nitrogen from prairie streams in the Red River Basin, Manitoba Canada, *Science of the Total Environment*, *575*, 649–659, doi:10.1016/j.scitotenv.2016.09.073.

Roste, J., and H. Baulch (2017), Pipestone Creek, SK Land Use and Water Quality, *Tech. rep.*, Global Institute for Water Security, University of Saskatchewan for Saskatchewan Water Security Agency, Saskatoon, SK.

Roste, J., and H. M. Baulch (2018), Qu'Appelle Watershed , SK Land-Use and Water Quality, *Tech. rep.*, Global Institute for Water Security, University of Saskatchewan, Saskatoon SK.

Saskatchewan Watershed Authority (2005), Moosomin Reservoir Water Quality Report 2003-2004, *Tech. Rep. August.*

Saskatchewan Watershed Authority (2007), Moosomin Reservoir Water Quality Report 2005 – 2006, *Tech. rep.*

Saskatchewan Watershed Security Agency, Ducks Unlimited, Environment and Climate Change Canada, and Saskatchewan Ministry of Environment (), Canadian Wetland Inventory GIS dataset for southern Saskatchewan (those portions of coverage that are owned or co-owned by the Water Security Agency).

Schwarz, G., A. Hoos, R. Alexander, and R. Smith (2006), The SPARROW Surface Water-Quality Model Theory, Applications, and User Documentation, in *U.S. Geological Survey Techniques and Methods*, chap. Book 6, Se.

Shook, K., J. W. Pomeroy, C. Spence, and L. Boychuk (2013), Storage dynamics simulations in prairie wetland hydrology models: evaluation and parameterization, *Hydrological Processes*, *27*(13), 1875–1889, doi:10.1002/hyp.9867.

Shupena-Soulodre, E. (2019), In conversation.

Siwek, H. (2018), Trophic State and Oxygen Conditions of Waters Aerated with Pulverising Aerator: The Results from Seven Lakes in Poland, *Water*, (10), 219–229, doi:10.3390/w10020219.

Statistics Canada (2006), 2006 Census of Agriculture.

Statistics Canada (2016), 2016 Census of Agriculture.

Water Survey of Canada (), National Water Data Archive: HYDAT.

Yang, W., A. N. Rousseau, and P. Boxall (2007), An integrated economic-hydrologic modeling framework for the watershed evaluation of beneficial management practices, *Journal of Soil and Water Conservation*, *62*(6), 423–432.

Yang, W., X. Wang, S. Gabor, L. Boychuk, and P. Badiou (2008), Water Quantity and Quality Benefits from Wetland Conservation and Restoration in the Broughton 's Creek Watershed, *Tech. Rep. October 2008*, Ducks Unlimited, unnumbered report.

Yang, W., A. Bonnycastle, Y. Liu, L. Boychuk, S. Gabor, and P. Badiou (2012), Examining Water Quantity and Quality Benefits from Wetland Conservation and Restoration in the Smith Creek Watershed, *Tech. rep.*, Ducks Unlimited Canada, Oak Hammock Marsh, Manitoba, Canada.

Zamberletti, P., C. D. Michele, M. Za, F. Accatino, and I. F. Creed (2018), Connectivity among wetlands matters for vulnerable amphibian populations in wetlandscapes, *Ecological Modelling*, *384*(January), 119–127, doi:10.1016/j.ecolmodel.2018.05.008.

Zhang, Z., R. Brown, J. Bauer, and A. Bedard-Haughn (2017), Nutrient dynamics within drainage ditches under recent, medium, and long-term drainage in the Black soil zone of southeastern Saskatchewan, *Geoderma*, *289*, 66–71, doi:10.1016/j.geoderma.2016.11.027.