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Hydrological and seasonal controls of phosphorus in Northern Great Plains agricultural streams

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Core Ideas

- Coherent seasonal patterns in stream phosphorus point to regional drivers
- Discharge is not the primary driver of total phosphorus dynamics in Prairie streams
- Stream phosphorus concentrations peak with snowmelt and in mid-summer
- Coherence with conductivity and temperature suggest drivers vary by season

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Abstract

Controls on nutrient transport in cold, low relief agricultural regions vary dramatically among seasons. The spring snowmelt is often the dominant runoff and nutrient loading event of the year. However, climate change may increase the proportion of runoff occurring with rainfall and there is an urgent need to understand seasonal controls on nutrient transport in order to understand how patterns may change in the future. In this study, we assess patterns and drivers of total phosphorus (TP) dynamics in eight streams draining agriculturally-dominated watersheds, located in southern Manitoba, Canada. Data from three years of monitoring revealed highly coherent patterns of TP concentrations in streams, with pronounced peaks in the spring and mid-summer across the region. This coherent pattern was in spite of considerable interannual variability in the magnitude and timing of discharge; in particular, a major storm event occurred in summer 2014, which resulted in more discharge than the preceding spring melt. Concentration-discharge model fits were generally poor or not significant, suggesting that runoff generation is not the primary driver of TP dynamics in the majority of streams. Seasonal patterns of conductivity and stream temperature suggest mechanisms controlling TP vary by season; a spring TP concentration maximum may be related to surface runoff over frozen soils while the summer TP maximum may be related to temperature-driven biogeochemical processes, which are not well-represented in current conceptual or predictive models. These findings suggest that controls on stream TP concentrations are dynamic through the year, and responses to increases in dormant and non-dormant season temperatures may depend on seasonally-variable processes.

1.0 Introduction

Phosphorus (P) is a limiting nutrient in agricultural systems as well as freshwater ecosystems (McCullough et al., 2012; Schindler, 2012). Excess P increases algae blooms and stimulates

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plant growth, which increases respiration and decomposition which consumes oxygen and creates anoxic environments (eutrophication) (Schindler et al., 2012). Transport of P from watersheds to surface waters is promoted by human activities including agricultural practices such as fertilizer use, irrigation, wetland drainage, land conversion, and soil erosion (Carpenter et al., 1998; Bennett et al., 2012). Spatial patterns of soil P can vary considerably across landscapes, and depend on factors such as management practices and landform (Wilson et al., 2016). Wetlands generally act as long-term P sinks on the landscape, however P retention varies depending on soil texture and short-term hydrological fluctuations (Haque et al., 2018). Natural wetlands demonstrate P sink behavior compared with drained wetlands (Haque et al., 2018) and the loss of small wetlands due to land conversion for agriculture or other land uses promotes P loading to downstream waters. (Cheng and Basu, 2017). Intensive agriculture also influences watershed hydrology and runoff patterns, generally homogenizing runoff regimes and linking nutrient export and hydrological dynamics (Basu et al., 2011), although these patterns are not always generalizable to snowmelt-dominated regions (Ali et al., 2017). A robust understanding of the interplay between hydrological and biogeochemical controls on P mobility and transport is necessary for managing landscapes to protect water quality (Sharpley et al., 1999).

There remain major gaps in our understanding of nutrient transport in cold, low relief agricultural regions such as the Northern Great Plains. The hydrology of this region is dominated by cold regions processes (Pomeroy et al., 2007); and the spring snowmelt is usually the biggest hydrological event of the year, accounting for a large proportion of both annual water and nutrient export (Corriveau et al., 2011; Costa et al., 2017). Historically, rates of evapotranspiration in the summer coupled with low precipitation volumes have resulted in relatively small contributions of growing season events to runoff in prairie streams (Shook and

Pomeroy, 2012). However, in the past five decades, there has been a documented increase in the proportion of precipitation falling as rain and the number of multi-day summer rainstorms, concurrent with a decrease in snowmelt runoff (Shook and Pomeroy, 2012; Dumanski et al., 2015). Large rainfall events can result in changes to runoff pathways and dramatic nutrient export, as seen in the 2014 extreme rainfall event in the Assiniboine watershed (Wilson et al., in review). As winters warm and snowpacks decrease, the importance of summer hydrological processes in these seasonally snow-covered regions will increase. Coupled with the ongoing landuse change in this region, changes in the temperature and precipitation regimes can result in dramatic changes to runoff patterns (Dumanski et al., 2015; Mahmood et al., 2017), which will in turn influence P export (Wilson et al., in review). Thus, understanding how controls on nutrient transport vary seasonally is critical for predicting future changes to P dynamics in this region.

A typical method for investigating hydrological controls on chemical behavior in watersheds is via inspection of concentration-discharge (c-Q) relationships (Basu et al., 2010, 2011; Ali et al., 2017). However, recent studies in this region have demonstrated that these models often have a poor fit in many prairie watersheds, particularly those with steep slopes, ineffective natural drainage and/or anthropogenic drainage modification (Ali et al., 2017). This may be due to the high level of spatial and temporal heterogeneity in landscape sources of P and runoff (Corriveau et al., 2013; Wilson et al., 2016). In many regions, intensive agriculture is associated with invariant P concentrations across runoff conditions, due to large legacy stores of the nutrient from years of fertilization (Basu et al., 2010; Sharpley et al., 2013). However, in contrast with other regions, work from the Northern Great Plains suggests that seasonal patterns of P concentrations can exhibit much more variability compared with patterns of runoff, both among catchments and from year-to-year (Rattan et al., 2017). Recent work from Ali et al., (2017)

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suggests that on the Canadian Prairies, fill and spill runoff generation during wet years and seasonal changes to soil infiltration during dry years leads to variable sources of P being mobilized across the landscape and thus non-chemostatic behavior. Furthermore, the spatial organization of agricultural development may influence both the magnitude (Yates et al., 2014) and timing (Rattan et al., 2017) of stream P concentrations. This combination of threshold-driven hydrological behavior, heterogeneous spatial patterns of P sources on the landscape and extreme seasonality result in complex and dynamic controls on stream P concentrations.

The objective of our study was to examine temporal and spatial patterns P concentrations in streams in watersheds on the Northern Great Plains. Specifically, we used sub-weekly stream chemistry samples and continuous discharge data from eight streams for three years to test the hypothesis that controls on stream TP concentrations are regionally coherent and vary among seasons.

2.0 Methods

2.1 Study Area

This study examined eight catchments located in the Assiniboine and Red River watersheds in southwestern Manitoba (Figure 1). The climate in southwestern Manitoba is continental and annually has a wide range in temperature, with an average daily temperature of 19.2 °C in July and -16.5°C in January. Average daily temperatures are above zero between the months of April and October, and these months are consistent with the open-water season observed during the years of this study. The precipitation for the open-water season averages 366 mm total, while the winter averages 96 mm total (climate data based on record from 1980-2010 for Brandon, MB and retrieved from http://climate.weather.gc.ca/). These sites are located within the Aspen

Parkland and Lake Manitoba Plain ecoregions; in the past, the landscape was covered with grasslands, deciduous forests and wetlands (Smith et al., 1998), but in the present day, the majority of land is used for agriculture, and there is no significant urban development within these catchments (Table 1). Soils in the study region were formed on gently undulating or kettled calcareous glacial till. Two of the study catchments, LHOROD and RLNGR, encompass parts of Riding Mountain National Park, and thus have significant forest cover and some intact natural wetlands (Table 1).

2.2 Stream Chemistry and Discharge Samples

Water samples were taken as frequently as every few days to every few weeks from March to November 2013-2015. The frequency of sampling varied by site, year and open-water season; see Table 1 for the exact number of water samples from each site, as well as the acronym for each site name. A well-mixed part of the stream was sampled using twice-rinsed polycarbonate bottles. Samples were transported in a cooler frozen until analysis. A sulfuric acid/persulfate digestion of samples was performed prior to colourimetric analysis to determine TP concentration with the ascorbic acid method. It is worth noting that total dissolved phosphorus was highly correlated with TP, and the dissolved fraction made up a high percentage of the TP concentration in all samples, consistent with other work done in the region (McCullough et al., 2012; Liu et al., 2013; Untereiner et al., 2015), and therefore all data analysis was done with TP concentrations only. Water temperature at three sites (LHOROD, OR, RLNGR) was measured at the time of sample collection using a hand held thermometer placed in stream near the middle of the water column. Higher resolution temperature data was also collected at 2 sites (WCE, WCW) with pressure transducers (Onset HOBO U20-001-04) placed on the stream bottom. For six of eight streams studied sampling locations were at Water Survey of Canada (WSC)

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hydrometric monitoring sites so discharge data was obtained from the WSC hydrometric database (www.wsc.ec.gc.ca). For two sites (Willow Creek East and Willow Creek West) discharge was calculated based on stage rating curves developed over three years using flow measurements collected with a hand held velocity meter and half hourly depth measurements by a pressure transducer (Onset HOBO U20-001-04). Resulting rating curves had a high level of accuracy ($r^2 > 0.98$ at each site). More detailed methods on the calculation of streamflow at these two sites are included in Wilson et al. (in review)

2.3 Characterization of watersheds

Soil characteristics (% sand and % clay at the 0-15 cm depths) in each watershed were quantified using the 90m resolution Gridded Soil Landscapes of Canada data product from the Canadian Soil Information Service (Macdonald and Kloosterman, 1984) that has been generated in support of the GlobalSoilMap initiative. Land cover (% forest, % wetland and % annual cropland) within each watershed was classified based on the 2006 edition of Land Use / Land Cover Landsat TM Maps from the Province of Manitoba Remote Sensing Centre. Effective drainage area was calculated from data from the Prairie Farm Rehabilitation Administration and is representative of average runoff conditions (based on a two year return period) for the Canadian prairie provinces beginning in the 1970s based on surface topography, density of the natural stream network, number and size of wetlands and consultation with local residents. Average slope, minimum and maximum elevation were calculated from a digital elevation model (90 m resolution) derived from Shuttle Radar Topography Mission (SRTM) data.

2.4 Statistical Analyses

Two types of models, power law models (Equation 1) and hydrograph separation models (Equation 2, Equation 3), were fit to the TP-Q data for each study catchment, following Ali et al., (2017). The power law model equation was fit as:

$c = aQ^b$ [Equation 1]

where c is TP concentration, Q is discharge, a is the intercept parameter and b is the slope parameter; and the hydrograph separation model was fit as

When $Q < ThresQ$: $c = C_g$ [Equation 2]

Otherwise: $c = C_g + C_r$ [Equation 3]

where Q is discharge, ThresQ is the breakpoint, c is TP concentration, C_g is the TP concentration at baseflow and $C_g + C_r$ is the solute concentration when both baseflow and runoff contribute to streamflow. The same model fitting process was applied to the conductivity-Q data.The residuals of the best model fit of the TP-Q, as determined by the goodness of fit (r^2) were calculated as the difference between the observed and modelled values. For sites where model fit was poor (r^2<0.2), residuals were calculated from a horizontal line with a y value of the mean concentration. Hydrograph separation models were fit using the segmented package (Muggeo, 2015) to identify ThresQ, and the lm function to fit Equation 2 and Equation 3. In order to determine if the c-Q relationships were driven by seasonal differences, the data were divided by season, using visual inspection of the hydrograph to identify the end of the spring melt period, and the model fitting exercise was repeated using just the spring data and just the summer data.

The day of year for each of the three study years was normalized to start on the first day of the spring melt for each catchment, indicated by when discharge started increasing in the spring,

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termed Days Since Melt (DSM). The catchment-specific residuals of the TP-Q models were then modelled against DSM, using three types of models: a linear model, a segmented regression model with one breakpoint and a segmented regression model with two breakpoints. Segmented regression models were fit using the segmented package (Muggeo, 2015). Briefly, the breakpoints were estimated using a bootstrap restarting algorithm which identifies local optima where the linear relation changes (Wood, 2001). Goodness of fit (r^2) was calculated for all three models at a significance level of α=0.05; r^2 values exceeding 0.2, 0.4, 0.6, and 0.8 were interpreted as fair, reasonable, good, and very good model fits, respectively (Ali et al., 2017).

For sites with significant breakpoint models, the data were divided into three time periods: Period 1 (from the onset of melt to first breakpoint); Period 2 (from the first breakpoint to the second breakpoint); and Period 3 (from the second breakpoint to the end of the record). Catchment-specific linear regression models between the residuals of the conductivity-discharge relationship and DSM, as well as stream temperature and DSM were fit for each of the three periods. All statistical analyses were performed in R (R Core Team, 2017).

3.0 Results

3.1 Seasonal patterns of phosphorus and discharge

Discharge in the study streams followed a predictable seasonal pattern with a peak in the spring associated with the spring snowmelt and a period of low flow during the summer and fall, interrupted by peaks associated with rainstorms (Figure 2a). There was considerable interannual variability in the magnitude and timing of storm peaks; in particular, a major storm event occurred in early summer 2014, which in several streams resulted in more discharge than the preceding spring melt (Wilson et al., in review). There was also a strong seasonal pattern in total phosphorus (TP) concentrations across the eight study streams, with the highest concentrations observed at the onset of spring melt and one or more peaks observed during the summer and fall (Figure 2b). There was considerable variation among sites in the median and range of TP concentrations; the predominantly forested sites (RLNGR and LHOROD) had relatively low TP concentrations, while the sites dominated by annual cropland (BOYR, LASER, LASEC, OR, WCE, WCW) had relatively high TP concentrations.

3.2 Concentration-discharge relationships

The goodness of fit (r^2) of models predicting TP from discharge ranged from not significant to 0.47. Of the eight sites, the power law model produced the best fit at two sites (WCW and WCE), the hydrograph separation model produced the best fit at two site (BOYR and LASEC) and no model producing a fair model fit ($r^2 > 0.2$) could be fit to the other four sites (Table 2; Figure 3). The results were consistent when considering only the summer season, with the power law producing the best fit at WCW and WCE, the hydrograph separation model producing the best fit at BOYR and LASEC and the other four sites remaining with no fair model fit (Table 2). Using only the spring data resulted in somewhat different patterns of model fit. Two streams (LHOROD and RLNGR) had reasonable, negative relationships between TP and discharge using the power law model, while LASER, LASEC and WCW had reasonable, positive relationships using the power law model (Table 2).

3.3 Temporal patterns and drivers of stream phosphorus

Significant segmented regression models were fit between the normalized Days Since Melt (DSM) and the residuals of the TP-discharge relationship at all sites except for BOYR and LASEC, the two sites with the hydrograph separation TP-discharge models (Figure 4). For the

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remaining sites, there were two significant breakpoints, which were remarkably synchronous in time (breakpoint 1 ranging from day 35 to 43; breakpoint 2 ranging from day 60 to 122) (Table 3). These breakpoints also correspond with temporal patterns in conductivity and stream temperature (Table 4). During the first period (i.e. before the first breakpoint), the residuals of the conductivity-discharge relationship increased significantly from the onset of melt to the first breakpoint at three sites (OR, WCE and WCW). After the first breakpoint, the patterns in conductivity residuals were not coherent among sites. Temperature increased significantly during the first period at three sites (LHOROD, WCE and WCW), and decreased significantly during the final period (i.e. after the second breakpoint) at all sites (Table 4).

4.0 Discussion

Streams across southern Manitoba exhibit a strikingly coherent seasonal pattern of P dynamics. Concentrations peak with the onset of snowmelt and decline through the spring, and generally rise to a second, usually smaller peak again in the summer (Figure 2b). Examining the relationships between TP and discharge at individual sites revealed generally poor model fits (Figure 3), consistent with other work in the Canadian Prairies demonstrating that controls on P dynamics in this region that are independent of discharge (Ali et al., 2017). Indeed, the residuals of the c-Q relationships were also temporally coherent across sites, with peaks in early spring and mid-summer (Figure 4). Seasonal patterns of conductivity residuals and stream temperature were also synchronous with TP patterns. Conductivity residuals increased from the onset of melt through to the first breakpoint (Figure 5), while stream temperatures consistently were at their maxima concurrent with the second breakpoint (Figure 6). Taken together, these results suggest that the mechanisms controlling patterns of stream TP concentration may vary by season.

4.1 Concentration-discharge relationships

There were three distinct groups of catchments based on the model fits to the TP-discharge relationships: at 2 catchments, hydrograph separation models produced the best fits, at 3 catchments, power law models produced the best fit and at the remaining 4 catchments, no models produced a reasonable model fit (Figure 3). Ali et al., (2017) found that c-Q model fits were poorest in watersheds with complex drainage patterns, such as higher slopes, high proportion of noncontributing areas or poorly drained soils. The four catchments with no model fit, LHOROD, OR, RLNGR, and LASER are lower gradient with higher proportions of existing (LHOROD, OR, RLNGR) ineffective drainage and more poorly defined contributing area. LHOROD, OR, and RLNGR are located on the northwestern side of the study area and have large areas with depressional or "pothole" wetlands. As a result, these three catchments have the highest proportion of poorly-drained wetlands of the sites used in the study. LASER is located in the Red River Valley and has been extensively drained to support agriculture, but continues to experience flooding / ponding issues on agricultural land during wet seasons (McCullough et al., 2012). Also, LHOROD and RLNGR encompass parts of Riding Mountain National Park, leading to considerable forest cover, lower rates of soil disturbance and fertilizer input, as well as the lowest median and peak TP concentrations of the study sites. These two sites have the smallest proportion of annual cropland, and therefore human modification of drainage is much less in these catchments (Table 1). When considering only the spring data, these two sites with considerable forest cover had negative c-Q relationships (Table 2), suggesting again that the sources of P within these watersheds are perhaps different. Negative c-Q relationships suggest source limited systems (Moatar et al., 2017), which is consistent with low P soils in forested areas.

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The hydrograph separation model, where concentrations increase with increasing discharge only above a threshold flow value, suggests that runoff generation is the primary driver of solute dynamics, since baseflow concentrations are relatively flat (O'Connor et al. 1976). This suggests that watersheds that exhibit this relationship are likely transport-limited, as the P is only mobilized in high concentrations from landscape source areas when discharge is above a given threshold (Ali et al., 2017). The two catchments where hydrograph separation models produced the best fit (BOYR and LASEC) are of higher slope and span the Pembina Escarpment, which overlies permeable parent material. These watersheds tend to exhibit higher water yield and groundwater influence that results in the presence of baseflow. The threshold at which concentration increases are observed at these sites may indicate a shift from groundwater driven base flow to soil water and overland flow during runoff events. As described in Ali et al., (2017) those watersheds with naturally effective drainage exhibited c-Q relationships with the highest predictive ability. WCE and WCW are both naturally effectively drained and were fit with the power-law (linear) c-Q model because no significant c-Q threshold was observed. These two catchments differ from BOYR and LASEC in that a clear indication of a threshold shift in water chemistry was not observed and may indicate that surface water inputs alone are the primary driver of c-Q in well drained watersheds without significant groundwater influence.

4.2 Temporal patterns and drivers of stream phosphorus

The seasonal pattern of TP dynamics is consistent across catchments of varying sizes and landscape characteristics (Figure 2b). This is particularly evident when examining the time series of residuals of the TP-Q relationship (Figure 4). Examining the residuals of the concentration-discharge relationship allows us to identify patterns in the concentration data independent of the effect of discharge (Renwick et al., 2018). Positive residuals indicate that the

TP concentrations are higher than would be predicted from the TP-Q relationship, and negative residuals indicate the concentrations are lower than would be predicted. Therefore, the coherent peaks in TP-Q residuals observed in the summer are indicative of a seasonal pattern of TP concentrations independent of peaks driven by summer storms. The two streams where this coherent pattern is not observed (BOYR and LASEC) are the two streams where a hydrograph separation model best fit the TP-Q data. In these catchments, the higher TP concentrations are highly correlated to increases in discharge, meaning that, as detailed above, runoff generation resulting in mobilization of phosphorus from the landscape is the dominant control on stream TP concentrations. However, for the other streams in this study, discharge is not the dominant control on TP. The coherence of the peak dates suggests that regional scale drivers that affect availability and mobility of TP may be responsible for these patterns.

The pattern of decreasing TP concentrations through the snowmelt period is consistent with modelling work done by Costa et al. (2017) on nitrate (NO_3) dynamics through snowmelt. In that paper, the authors suggest that high NO_3 concentrations in snow and surface flow, resulting from nutrient rich plant residues left on the field in the fall, result in very high concentrations in the initial snowmelt, but as the melt progresses and soils thaw, runoff becomes dominated by throughflow, and NO_3 concentrations decrease. The same argument could be true for TP, which is also known to desorb from surface soils or leach from vegetation, and residue left on fields over the winter, and can be released from during freeze-thaw cycles in the late fall (Tiessen et al., 2010; Liu et al., 2013; Elliott, 2013; Whitfield et al., 2019). In this study, as in others in this region, the majority of TP is in the dissolved form. Erosion of particulate P is typically not a major source of P export in this landscape where the topography is flat and much of the runoff occurs during the spring when soils are frozen (Salvano et al., 2009; Liu et al., 2014). This

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flowpath-switching mechanism to explain the spring TP patterns is also supported by the conductivity data. Melting snow and surface runoff will have lower conductivity than water passing through ion-rich deeper soil layers, and so an inverse relationship with TP would be consistent with a change in flowpaths.

The coherent summer peaks in stream TP concentrations are not easily explained by hydrological patterns or point source inputs, as has been suggested in other studies (Corriveau et al., 2013; Rattan et al., 2017). However, conductivity trends differ from TP trends in the later spring and summer, indicating that a flowpath-based mechanism is unlikely to explain the coherent summer peaks (Figure 5). The coherence of the peak concentrations across catchments and seasons is not compatible with rainfall-driven export of TP from the landscape to the stream, given the lack of coherence in the timing of storms. It is notable that the TP dynamics from 2014 are coherent with the other study years, given that 2014 featured an extreme rainfall-runoff event in summer, resulting in high TP export (Wilson et al., in review). This suggests that the patterns observed in this dataset are robust even under years with variable hydrological regimes. Other studies have suggested that seasonal release from sewage lagoons results in summer peaks in stream TP (Carlson et al., 2013; Rattan et al., 2017), however in the present study, the summer patterns of TP are observed across a range of watersheds, most of which are sparsely populated and have little or no sewage input. This summer pattern, however, is coherent with the seasonal peak in stream temperature (Figure 6), with the peak in the overprediction of TP relative to Q occuring at the same point in the season as the peak stream temperature. This suggests that biogeochemical processes, controlled by temperature may be responsible for this regional coherence.

Stream temperature will control many aquatic and soil processes that result in the removal, transformation and release of P within a stream (Withers and Jarvie, 2008). These processes include physical and chemical mechanisms such as dissolution and desorption reactions which release bound P from soil and stream sediments (Fox, 1989), and biological mechanisms including the assimilation and release of P in periphyton and phytoplankton (Dodds, 2003), decomposition of both allochthonous and autochthonous organic matter (Pusch et al., 1998) and uptake and decay of macrophytes (Carpenter and Lodge, 1986). During summer in the study streams, adjacent riparian areas and wetlands, and in catchment soils the water movement tends to be slow between runoff events while biological productivity tends to be high. These conditions may leading to stagnant conditions which promote anoxia, particularly in lower gradient environments and could result in release of P, particularly given the geological setting of the streams (Orihel et al., 2017). Recent work has demonstrated that with rising temperatures, the metabolic balance of streams shifts to higher rates of respiration compared with production, promoting low oxygen conditions and potentially creating favourable conditions for P release from sediments (Song et al., 2018). Any of these mechanisms could be a plausible explanation for why TP concentrations (independent of discharge) decline during the late summer and early fall. Given the strong association between the observed patterns in TP and stream temperature, future work in this region should examine the possible in-stream and in-soil mechanisms behind this pattern.

4.3 Implications and future research directions

Like many regions across North America, the Northern Great Plains is experiencing declining snowpacks, earlier snowmelts, longer growing seasons and changes in precipitation patterns during the growing season (Shook and Pomeroy 2012). The frequency, intensity and length of growing season rainfall have all increased in the last several decades (Shook and Pomeroy, 2012; Szeto et al., 2015; Dumanski et al., 2015). Hydrological processes and pathways of runoff

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associated with summer rainfall in this region are fundamentally different from those which predominate during spring snowmelt. For instance, surface depressional storage may regulate runoff during spring melt, but if a large summer rainfall event occurs on saturated soils, the surface storage may be at capacity and thus not predictive of runoff volume or pathways (Wilson et al., in review). This study documents consistent seasonal patterns of high stream TP concentrations during the growing season. Combined with the changes to precipitation and runoff patterns, these results suggest an increasing need for management strategies which account for growing season dynamics in order to mitigate excess TP export across the Northern Great Plains.

5.0 Conclusions

Understanding the controls on P mobility and transport in agricultural landscapes is critical for informing management decisions to protect water quality. There has been widespread interest in understanding snowmelt dynamics, as this is the dominant hydrological event of the year in northern regions, and often transports the majority of nutrients (Costa et al., 2017). Recent studies have acknowledged that controls on P loading from landscapes vary seasonally (Corriveau et al., 2011; Rattan et al., 2017). The results of this study suggest that controls on stream P concentrations are not consistent among seasons, and that there are regionally consistent patterns in stream P independent of hydrological controls. While spring P dynamics are well-correlated with discharge and flowpath metrics, growing season P concentrations exhibit coherent seasonal peaks across years and catchments, independent of flow dynamics. Cold, agricultural regions, including the Northern Great Plains, are getting warmer, with smaller snowpacks and longer summer droughts where streams are hydrologically disconnected from the watershed (Schindler and Donahue, 2006). Investigating growing season stream P dynamics in this landscape is critical for understanding the full picture of P cycling in these regions and for making informed decisions about water quality management.

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Table 1. Site characteristics. Numbers in each year refer to the total number of total phosphorus samples collected.

Site Name	Site Acronym	2013	2014	2015	Effective Drainage Area (%)	Wetland (%)	Annual Cropland (%)	Forest (%)	Sand (%)	Clay (%)	Minimum elevation (masl)	Maximum elevation (masl)	Average slope (%)
Roseisle Creek	BOYR	34	34	24	90.59	0.80	70.53	12.8	2.82	0.27	302	514	2.18
Little Saskatchewan near Horod	LHOROD	39	43	14	65.84	13.44	5.14	55.6	8.47	0.00	558	725	1.96
La Salle River near Elie	LASER	54	85	20	100.00	0.08	83.10	2.73	0.02	80.4	237	265	0.69
Elm Creek Channel	LASEC	27	27	19	49.78	0.18	40.03	25.1	36.45	34.6	244	306	0.99
Oak River	OR	16	70	62	23.65	10.42	57.71	5.29	0.38	0.00	459	679	1.15
Rolling River new Erickson	RLNGR	31	43	15	88.78	11.03	8.51	56.6	3.99	5.56	550	755	2.78
Willow Creek East Branch	WCE	89	112	59	98.43	1.69	74.97	1.93	0.00	1.58	376	474	1.27
Willow Creek West Branch	WCW	92	126	71	65.41	3.52	72.82	3.98	0.00	3.88	377	474	1.08

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Table 2: Fits of models predicting total phosphorus concentration from discharge. The power law model is described in Equation 1 and the hydrograph separation model is described in Equations 2 and 3. ThresQ is the breakpoint ln-transformed discharge. NA indicates that no breakpoint could be located using the model fitting algorithm, and therefore no model could be fit.

	Power law model		Hydrograph separation model		
All seasons					
Site	p value	r^2	p value	r^2	ThresQ
BOYR	<0.01	0.08	<0.01	0.34	-0.36
LASER	0.04	0.03	0.01	0.05	-2.20
LASEC	<0.01	0.34	<0.01	0.46	-1.05
LHOROD	0.32		0.27		
OR	0.12		0.06		
RLNGR	0.83		0.35		
WCE	<0.01	0.33	<0.01	0.14	0.38
WCW	<0.01	0.47	<0.01	0.30	-0.61
Spring					
Site	p value	r^2	p value	r^2	ThresQ
BOYR	0.32		0.07		
LASER	<0.01	0.32	NA		
LASEC	<0.01	0.55	0.02		
LHOROD	<0.01	0.30	0.72		
OR	0.35		0.15		
RLNGR	0.02	0.25	0.05		
WCE	0.44		0.31		
WCW	<0.01	0.36	NA		
Summer					
Site	p value	r^2	p value	r^2	ThresQ
BOYR	0.17		<0.01	0.23	-0.36
LASER	0.01	0.05	<0.01	0.09	-2.18
LASEC	<0.01	0.23	<0.01	0.35	-4.73
LHOROD	0.96		0.91		
OR	0.08		0.16		
RLNGR	0.29		0.10		
WCE	<0.01	0.23	0.22		
WCW	<0.01	0.48	<0.01	0.32	-0.79

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Table 3: Fits of models predicting the residuals of the total phosphorus-concentration model from Days Since Melt.

	Linear regression model		Segmented model (one breakpoint (BP))			Segmented model (two breakpoints (BP))			
Site	p value	r^2	p value	r^2	BP 1 (Days Since Melt)	p value	r^2	BP 1(Days Since Melt)	BP 2 (Days Since Melt)
BOYR	0.55		0.11			0.07			
LASER	0.01	0.04	<0.01	0.13	105.86	<0.01	0.46	40.75	58.09
LASEC	0.60		0.59			0.11			
LHOROD	0.35		<0.01	0.23	27.10	<0.01	0.32	43.17	86.05
OR	0.30		0.05			<0.01	0.56	37.09	122.33
RLNGR	0.03	0.05	0.02	0.17	36.36	<0.01	0.38	43.09	70.50
WCE	<0.01	0.05	<0.01	0.26	26.03	<0.01	0.48	35.32	78.13
WCW	0.02	0.02	<0.01	0.33	27.63	<0.01	0.49	36.12	90.96

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Table 4: Linear regression relationships between days since melt and residuals of the conductivity-discharge relationship and water temperature, respectively.

		Conductivity			Water temperature		
	Site	p value	r^2	slope	p value	r^2	slope
	LASER	0.35					
	LHOROD	0.72			0.00	0.38	8.15
Period 1	OR	0.04	0.12	0.01	0.27		
Onset of melt to first breakpoint	RLNGR	0.06			0.11		
	WCE	0.00	0.24	0.01	0.00	0.93	12.39
	WCW	0.00	0.32	0.02	0.03	0.73	9.88
	LASER	0.01	0.20	0.02			
	LHOROD	0.10			0.00	0.43	46.37
Period 2	OR	0.00	0.22	0.02	0.32		
1st breakpoint to 2nd breakpoint	RLNGR	0.55			0.91		
	WCE	0.67			0.07		
	WCW	0.24			0.01	0.70	64.76
	LASER	0.09					
	LHOROD	0.95			0.00	0.34	-32.59
Period 3	OR	0.00	0.19	-0.02	0.01	0.83	-27.40
2nd breakpoint to end of record	RLNGR	0.40			0.00	0.41	-45.72
	WCE	0.00	0.07	0.02	0.00	0.80	-68.79
	WCW	0.01	0.06	-0.03	0.01	0.68	-46.50

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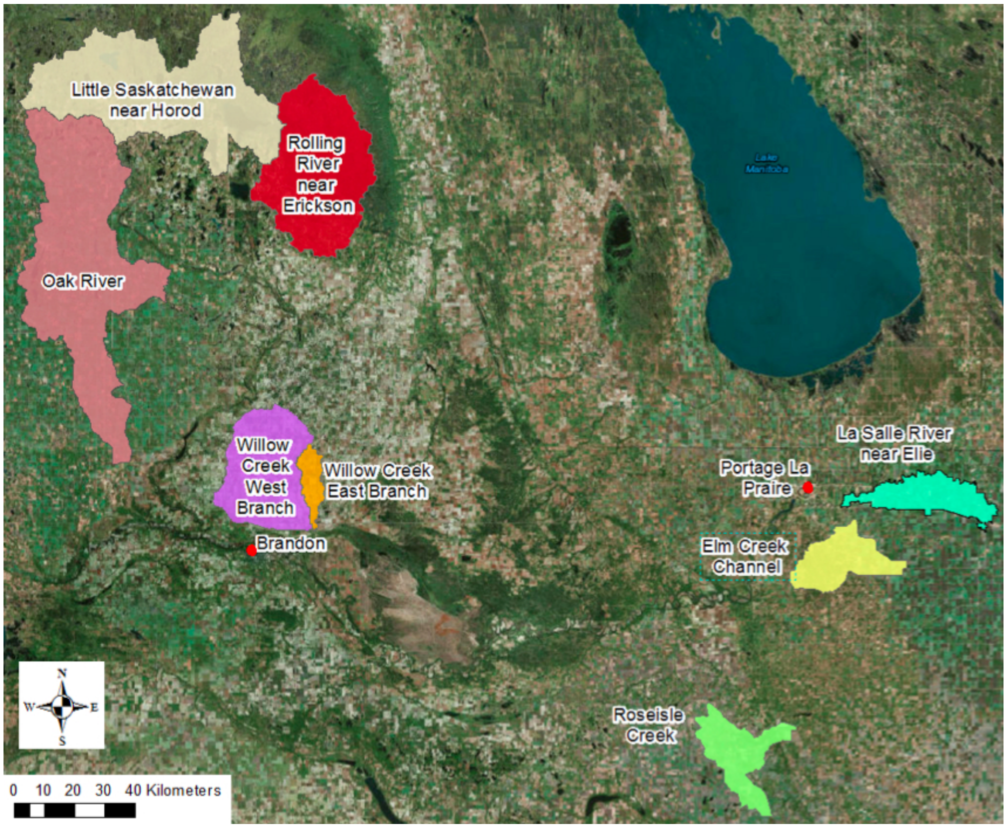

Fig. 1. Eight sub-catchment study sites in southwestern Manitoba. Data obtained from Agriculture and Agri-food Canada.

300x247mm (72 x 72 DPI)

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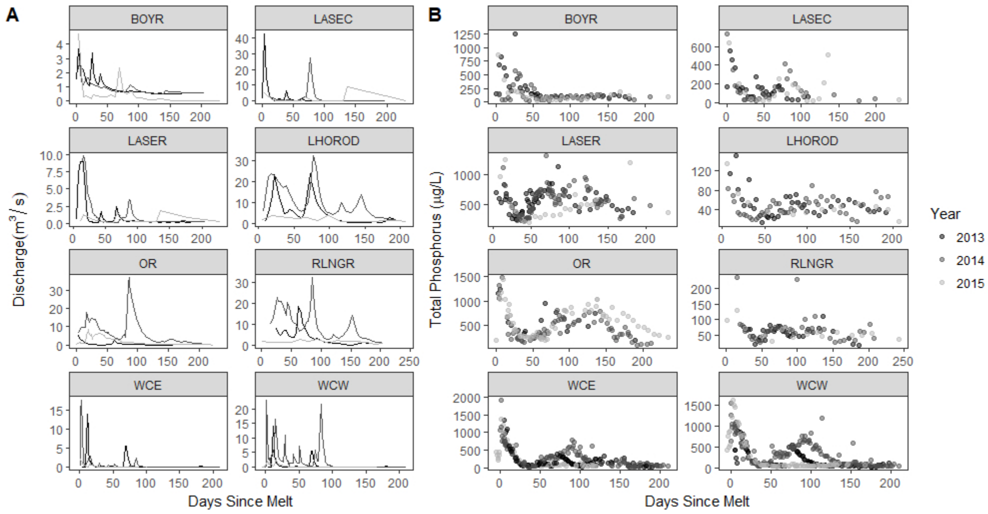

Fig 2. Seasonal patterns of a) discharge and b) total phosphorus concentration in eight streams for three years. The x axis is standardized such that day zero is the day of peak discharge during the spring melt period.

264x137mm (96 x 96 DPI)

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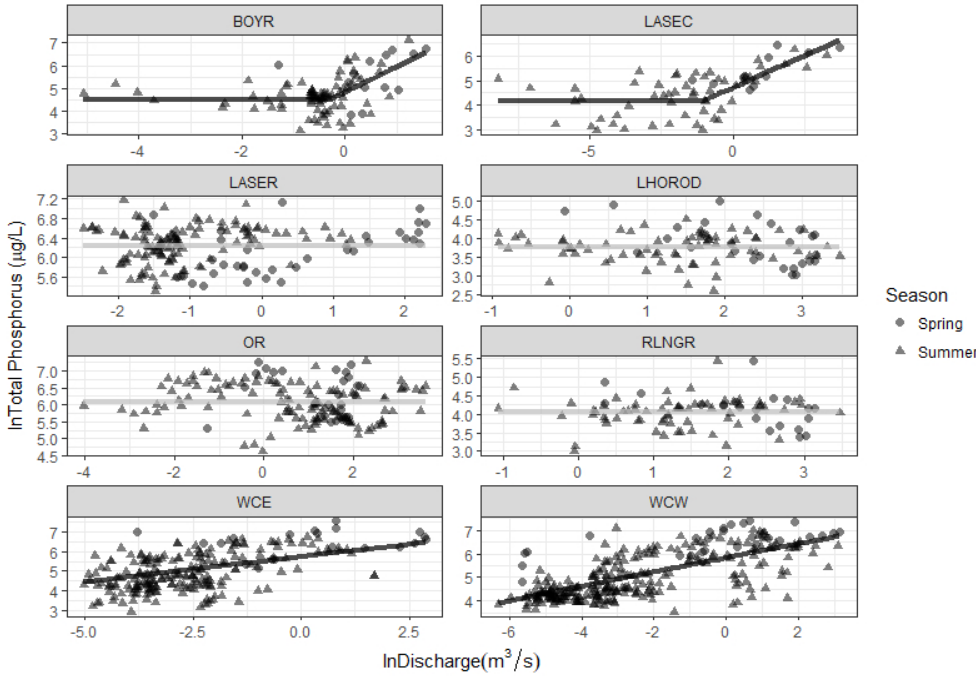

Fig 3. Relationships between total phosphorus concentration and discharge at eight streams in southern Manitoba. Data were collected in three years (2013, 2014, 2015). Solid black lines indicate significant model fits. Solid grey lines indicate mean concentrations where no reasonable model fit was possible.

211x146mm (96 x 96 DPI)

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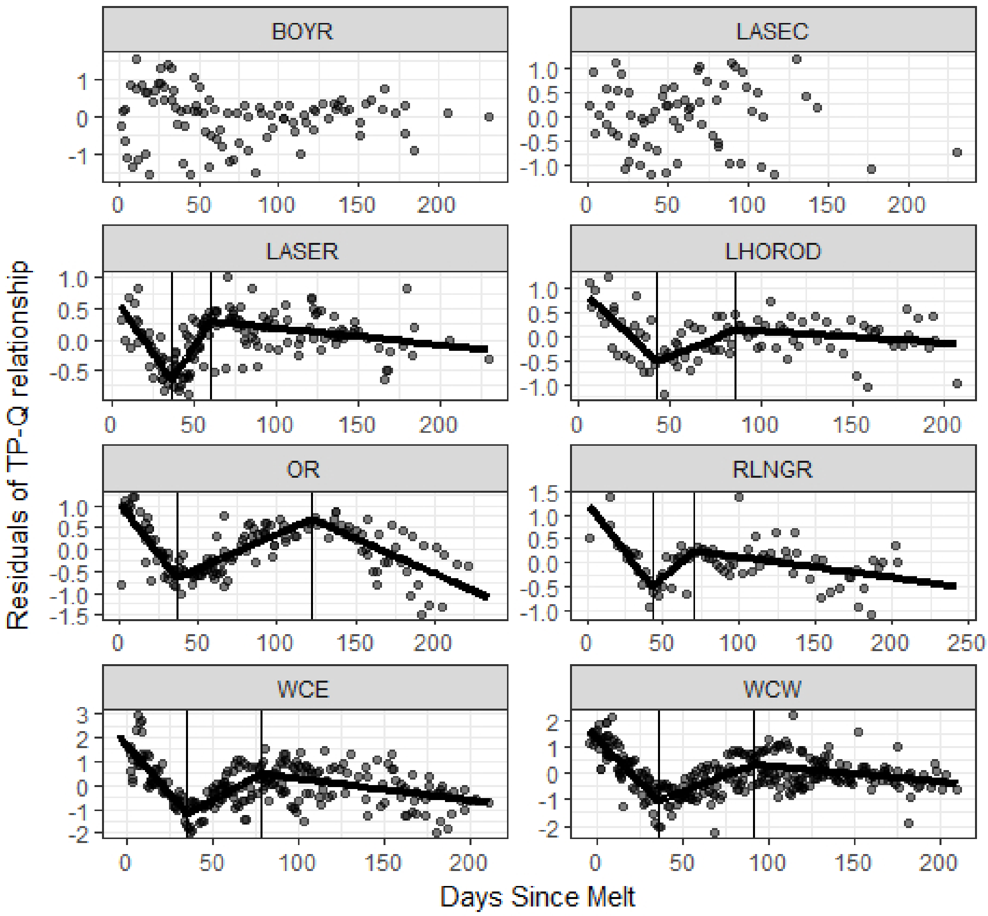

Fig 4. Time series of the residuals of the total phosphorus-discharge relationship. Solid lines indicate significant piece-wise regression models. Vertical lines indicate the breakpoints identified in the model.

141x132mm (96 x 96 DPI)

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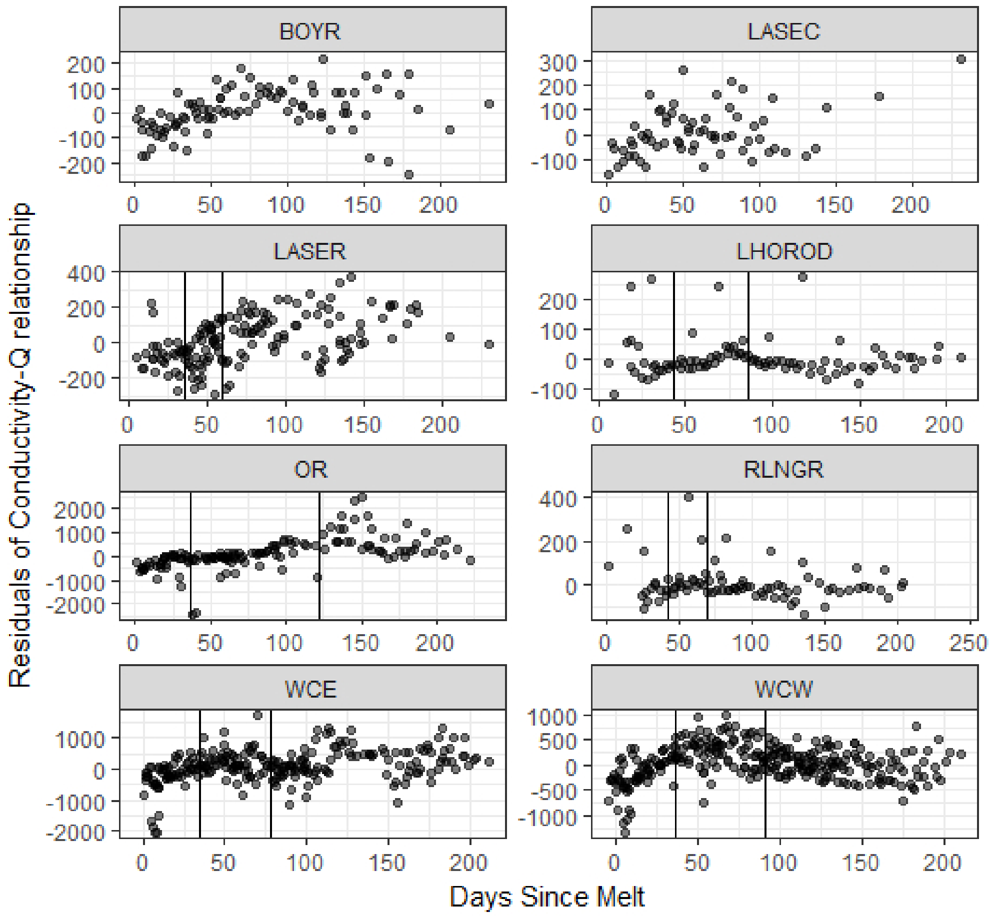

Fig. 5 Time series of the residuals of the conductivity-discharge relationship. The vertical lines are breakpoints identified from the TP time series analysis.

141x132mm (96 x 96 DPI)

J. Environ. Qual. Accepted Paper, posted 02/26/2019. doi:10.2134/jeq2018.07.0281

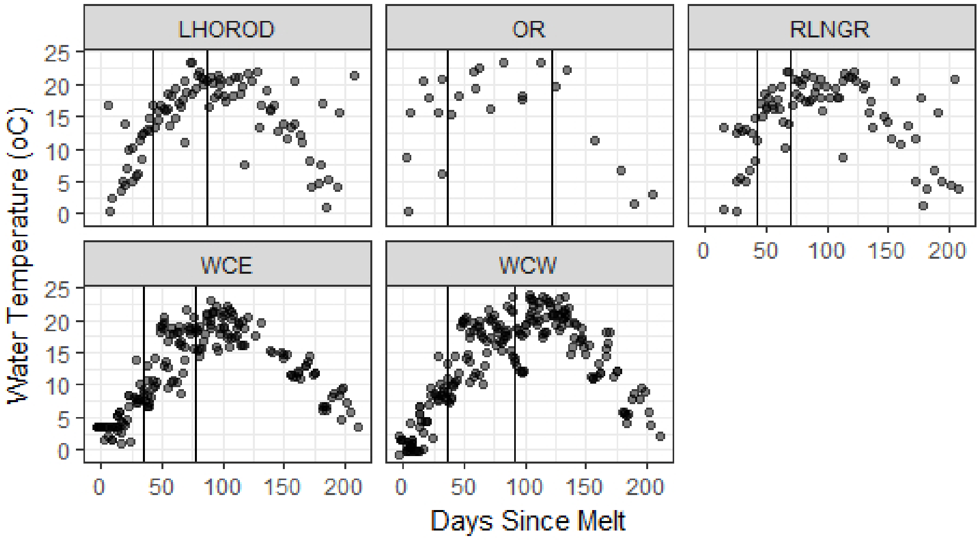

Fig. 6 Time series of water temperature. The vertical lines are breakpoints identified from the TP time series analysis.

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