Snowmelt and its role in the hydrologic and nutrient budgets of prairie streams

Julie Corriveau, Patricia A. Chambers, Adam G. Yates and Joseph M. Culp

ABSTRACT

Small watersheds in the Canadian Prairies are characterized by seasonally disconnected hydrologic networks whereby stream channels are hydrologically connected during snowmelt but have disconnected reaches throughout the remainder of the year. Snowmelt is the most significant hydrological event in the Canadian Prairies, yet few studies have investigated the role of snowmelt in the nutrient budget of prairie streams. We quantified hydrologic and nutrient dynamics during snowmelt for ten agricultural subwatersheds distributed along a gradient of human activity in the Red River Valley, Canada, to evaluate the timing of nitrogen (N) and phosphorus (P) export. Elevated concentrations of total P (TP) and total N (TN) were observed during the snowmelt peak, with maximum concentrations reaching 3.23 mg TP L^{-1} and 18.50 mg TN L^{-1}. Dissolved P and N dominated the total nutrient pool throughout snowmelt, likely due to reduced erosion and sediment transport resulting from the combination of the flat topography, frozen soil and stream banks, and gradual snow cover melt. Significant correlations were observed between snowmelt N load ($r = 0.91$; $p < 0.05$) and both agricultural land cover and fertilizer usage, with a weaker correlation between snowmelt P load ($r = 0.81$; $p < 0.05$) and agricultural area. Our results showed that snowmelt plays a key role in nutrient export to prairie aquatic ecosystems and this may have serious impacts on downstream ecosystems. Land use management practices need to consider the snowmelt period to control nutrient loads to Lake Winnipeg and other waterbodies in the Great Plains.

Key words | Canadian Prairies, export, nitrogen, nutrients, phosphorus, snowmelt, streams

Julie Corriveau (corresponding author)
Patricia A. Chambers
Adam G. Yates
Environment Canada,
867 Lakeshore Rd,
P.O. Box 5050,
Burlington,
Ontario,
Canada L7R 4A6
E-mail: *Julie.Corriveau@ec.gc.ca*

Joseph M. Culp
Environment Canada and Canadian Rivers Institute,
10 Bailey Dr.,
P.O. Box 4400,
Fredericton,
New Brunswick,
Canada E3B 5A3

INTRODUCTION

Prairie streams and rivers represent a dwindling resource of unpolluted freshwater in North America (Dodds *et al.* 2008). They are also critical components of the Great Plains ecosystem, providing a hydrological connection between the terrestrial grasslands and downstream rivers and lakes. This connection governs the timing and magnitude of nutrient export to downstream ecosystems. However, much of the Canadian and USA Great Plains ecosystem has been fundamentally altered by conversion to agricultural and urban land cover. These land-use changes, as well as stream manipulations (e.g. channelization; riparian and instream vegetation removal), have increased nutrient export to aquatic ecosystems, contributing to eutrophication of prairie lakes, toxic algal blooms and loss of sensitive species (Wiley *et al.* 1990; Hall *et al.* 1999; Bourne *et al.* 2002; Dodds *et al.* 2008).

doi: 10.2166/wst.2011.676

In Canada, deterioration of water quality in Lake Winnipeg, the tenth-largest (24,514 km^2) freshwater lake on Earth, has raised concerns about the role of point versus non-point sources in contributing to eutrophication of Great Plains waterbodies. Preliminary estimates of TN and TP loads from Lake Winnipeg tributaries have clearly identified the Red River as a major contributor of nutrients to Lake Winnipeg (Bourne *et al.* 2002), with 27.1 and 41.4% of the Red River TP and TN contribution, respectively, derived from point sources, notably the city of Winnipeg and other municipal and industrial effluents. The Canadian portion of the Red River watershed encompasses 12,900 km^2 and is characterized by a wide range of human activities, making it difficult to ascribe the portion of the nutrient load derived from agricultural versus urban sources. Typical of prairie watersheds, the Red River watershed features a nearly flat topography dissected by small wetlands and channelized streams and rivers, many of which have been altered as a result of intensive drainage for agriculture. This landscape, combined with the continental semi-arid climate of the Canadian Prairies, results in hydrological disconnects along stream networks. During snowmelt, stream channels are hydrologically connected (and, depending upon snowpack depth and rate of snowmelt, may flood extensively), whereas for the remainder of the year all streams except mainstem rivers have disconnected reaches as a result of low or no flows caused by high temperatures, limited precipitation, and increased evaporation (summer and fall) or frozen channels (winter). Snowmelt is therefore the most significant runoff event in the Canadian Prairies, contributing >80% of the annual runoff volume (Granger *et al.* 1984; Glozier *et al.* 2006; Little *et al.* 2007). Hence, hydrological connectivity of subwatersheds during snowmelt may exert a strong influence on annual nutrient exports to the Red River, and ultimately to Lake Winnipeg.

The goal of our study was to quantify hydrologic and nutrient dynamics in prairie streams in the Red River watershed of Manitoba, Canada during snowmelt. Specifically, we quantified nutrient export during snowmelt from 10 subwatersheds representing a gradient of human activity, and evaluated the timing of nutrient export from subwatersheds to the Red River main tributaries. An improved scientific understanding of the contribution of headwater streams to nutrient export during snowmelt is essential for designing land use management practices to control nutrient loads to Lake Winnipeg.

MATERIAL AND METHODS

Study area

The Red River Valley of south-western Manitoba is dominated by agricultural land used for grain, oilseed and livestock production. As part of a larger continuing study on nutrient losses from prairie watersheds, water quantity and quality were monitored throughout snowmelt at the outlet of ten subwatersheds distributed along a gradient of agricultural land cover in the Red River Valley (Table 1; Figure 3).

Hydrology and chemistry

Stream discharge at all sites was estimated using an indirect approach. A pressure transducer logger (HOBO, Onset Computer Corporation, MA) was deployed in each stream from October 2009 to May 2010 for water level and temperature measurements at 30-min intervals. For all sites, reference water level was measured at logger deployment and retrieval. Atmospheric pressure and temperature were also monitored at four of the ten sites to correct the raw water level data and obtain net water level at all sampling sites. Daily net water levels were then related to the product of daily discharge, measured at stations located within 50 km of each of our sampling sites, and the drainage-area ratio between the sampling site and the discharge station. Daily provisional discharge data were obtained from Water Survey of Canada (WSC; www.wateroffice.ec.gc.ca.). Daily discharge for each site was predicted from net water level using a power or a polynomial relation. For all

Table 1 | Sites, stream names, watershed area, outlet coordinates and nearest hydrometric gauge from Water Survey of Canada (WSC)

Site	Stream	Area (km^2)	Longitude	Latitude	WSC station
WBLS-1	West Branch La Salle River	64.54	−97.7752	49.9308	05OG008
ECC-2	Elm Creek Channel	602.24	−97.7779	49.8125	05OG005
TC-3	Tobacco Creek	350.94	−98.0018	49.4032	05OF024
BC-4	Buffalo Creek	626.28	−97.5499	49.1766	05OC019
DC-5	Deadhorse Creek	180.36	−98.0017	49.2368	05OC016
GC-7	Graham Creek	183.55	−97.9306	49.3564	05OF024
HD-8	Hespeler Drain	217.54	−97.8861	49.1677	05OC016
SC-9	Shannon Creek	279.39	−98.0016	49.2744	05OF014
ER-10	Elm River	105.32	−98.0101	49.9124	05OG008
BCD-11	Big Coulee Drain	83.69	−97.3792	49.6947	05OG001

10 sites, predicted discharge was significantly correlated with observed discharge ($0.734 < r < 0.971$; $p < 0.05$; $n > 10$ for each site). Grab water samples from a depth of approximately 20 cm were taken daily at all sites during the rising limb and peak of the snowmelt hydrograph and weekly during the falling limb, with a total of 10–15 samples collected per site between March 13 and April 25 2010. All water samples were collected in high density polyethylene bottles, stored at 4 °C in a cooler and transported to Environment Canada's National Laboratory for Environmental Testing in Saskatoon (SK). Samples from all sites were analyzed for TN and TP; dissolved N (TDN) and P (TDP) were analysed at four sites. TN and TDN were determined colorimetrically as nitrite after automated cadmium reduction of nitrate to nitrite (Eaton *et al*. 2005). TP and TDP were determined colorimetrically as orthophosphate using stannous chloride (Eaton *et al*. 2005). Analyses for TDN and TDP were performed on filtered sub-samples (<0.45 μm). Daily site concentrations were estimated by interpolating between sampling days; load (L) for a given snowmelt period was the sum of the daily loads of that period.

Land use

Detailed information on data sources and calculations used to estimate land cover, fertilizer usage and population served by wastewater lagoons are given in Yates *et al*. (2011). In brief, watershed boundaries were delineated using ArcGIS 9.3 (ESRI 2008) extension Arc Hydro 1.4 (ESRI 2010) based on a 30 m digital-elevation model and a 1:50,000 stream network. Information on application of synthetic fertilizers was summarized from records of application maintained by the Manitoba Agricultural Services Corporation (www.mmpp.com/mmpp.nsf/mmpp_publications.html). Wastewater lagoon information (location, receiving water, and population served) was obtained from Manitoba Conservation (http://www.gov.mb.ca/conservation).

RESULTS AND DISCUSSION

Temporal variation in nutrient export during snowmelt

Stream discharge and nutrient export during snowmelt varied both within (i.e. temporal variation) and among (i.e. spatial variation) the 10 study streams. In 2010, snowmelt initially started in mid-March, about two weeks earlier than normal. Although snowmelt hydrographs varied among sampling sites (Figure 1), a general pattern was observed with a main snowmelt (March 13 to 29) followed by a secondary snowmelt (March 30 to April 10) and a post-snowmelt period (April 11 to 25). As demonstrated by Glozier *et al*. (2006), the timing of snowmelt in south Manitoba is subject to great inter-annual variation, depending on weather.

For most sampling sites, discharge peaked during the main snowmelt period and coincided with visible runoff from flooded fields adjacent to the streams. This overland flow likely generated significant nutrient-enriched runoff to streams due to prolonged water contact with soil. Air temperature dropped below 0 °C after March 19, reducing and/or stopping snowmelt processes and inducing discharge recession. A subsequent temperature increase induced a second melt from March 30 to April 10, during which 19.8 mm of rain fell on April 2nd. The rising limb and discharge peak were less than during the main snowmelt because most of the water from melted snow had already drained to the streams. The post-snowmelt period was characterized by a recession limb reaching base flow discharge at all sites. Although data are not yet available for the remainder of 2010, our results to date are consistent with findings of others that snowmelt in the Canadian Prairies is the most significant hydrological time period. In fact, a study of streams in southern Manitoba reported that snowmelt may account for 56–95% of annual flow (Glozier *et al*. 2006).

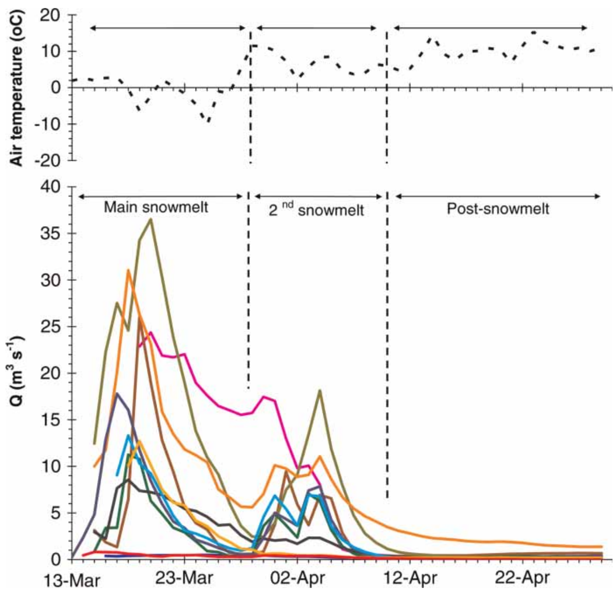

Figure 1 | Mean daily air temperature from Environment Canada weather station located at Morden (south Manitoba) and hydrograph showing the change in discharge (*Q*) through snowmelt for all sites.

Concentrations of P and N at all sites varied greatly through the snowmelt and post-snowmelt periods, with an average for the 10 sites ranging from 0.343–0.864 mg L^{-1} TP and 3.85–7.84 mg L^{-1} TN. In general, TP and TN concentrations were greater during the main snowmelt and lower during post-snowmelt discharge recession (Figure 2).

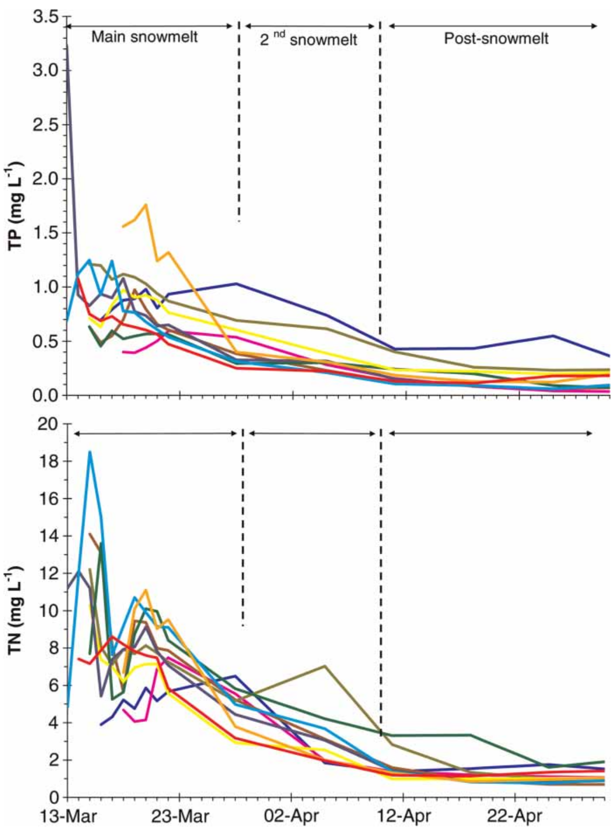

Figure 2 | Concentrations of TP and TN during different phases of snowmelt 2010.

Discharge was generally correlated with TP ($0.37 < r < 0.97$; $p < 0.05$) and TN ($0.52 < r < 0.94$; $p < 0.05$) concentrations, although the strength of the associations varied among sites. For the four sites where water samples were analysed for dissolved nutrients, dissolved forms comprised 81.7–87.2% TP and 94.0–95.7% TN (median values), indicating that dissolved forms dominated snowmelt. These observations agree with other studies on prairie streams or field runoff that reported high proportions of dissolved nutrients throughout snowmelt (Glozier *et al.* 2006; Sheppard *et al.* 2006; Little *et al.* 2007; Tiessen *et al.* 2010). The combination of flat topography, frozen soil and stream banks, and a gradual melt appears to considerably reduce erosion and sediment transport during snowmelt (Glozier *et al.* 2006; Tiessen *et al.* 2010).

Based on our grab samples analyses, nutrient loads from the subwatersheds ranged from 456–28,308 kg TP and 3738–228,406 kg TN (Table 2). The main snowmelt period (March 13–29) contributed the majority of nutrients (64.3–97.8% TP; 71.4–97.4% TN) compared to only 0–5.1% TP and 0–3.2% TN for post-snowmelt (April 11–25). Export from our 10 subwatersheds varied from 5.4–101.8 kg TP km^{-2} and 59.5–731.3 kg TN km^{-2} (Table 2).

Similar snowmelt export coefficients have been reported for South Tobacco Creek in southern Manitoba, with values ranging from 36–91 kg TP km^{-2} and 133–307 kg TN km^{-2} (Glozier *et al.* 2006). By comparison, other studies of Prairie

Table 2 | Loads of total phosphorus and nitrogen for all subwatersheds during different phases of snowmelt 2010

Site	Phosphorus Main SN (kg)	2nd SN (kg)	Post-SN (kg)	Total (kg P km^{-2})	Nitrogen Main SN (kg)	2nd SN (kg)	Post-SN (kg)	Total (kg N km^{-2})
WBLS-1	467	223	37	11.3	2,817	896	124	59.5
ECC-2	9,636	2,809	30	20.7	109,848	25,536	356	225.4
TC-3	6,137	976	72	20.5	71,365	13,280	822	243.5
BC-4	23,679	4,497	131	45.2	181,223	46,372	810	364.9
DC-5	2,383	864	59	18.3	36,727	13,703	1,021	285.3
GC-7	14,724	3,270	687	101.8	112,244	18,825	3,154	731.3
HD-8	6,858	1,068	30	36.6	62,365	11,576	321	341.4
SC-9	4,146	884	2	18.0	51,054	14,852	27	236.0
ER-10	7,714	132	46	75.2	49,316	1,014	316	482.3
BCD-11	381	68	6	5.4	4,300	695	59	60.2

SN = Snowmelt.

Table 3 | Land use cover, fertilizer application and wastewater lagoon (WWL) information for the ten subwatersheds

Site	Land use (%) Agriculture	Deciduous forest	Grassland	Fertilizer Land fertilized (%)	P (kg ha^{-1})	N (kg ha^{-1})	WWL[a] (pop. km^{-2})
WBLS-1	82.5	1.5	6.2	73.6	26.9	65.7	2.32
ECC-2	54.7	13.7	22.6	31.3	10.8	28.0	1.06
TC-3	70.3	13.4	11.3	68.9	18.0	61.3	1.88
BC-4	82.6	4	5.9	71.3	17.7	42.4	0.91
DC-5	69.4	7.7	13.3	55.1	12.4	38.9	0
GC-7	81.6	4	7.8	58	16.7	50.1	0
HD-8	66.2	7.6	15.6	49.2	16.2	44.1	0
SC-9	65.4	10.4	14.9	62.4	17.3	52.0	0.89
ER-10	57.1	15.5	12.3	48.9	17.8	36.9	0
BCD-11	88.3	0.8	3.8	76	24.1	71.3	0

[a]Population served by wastewater lagoons by km^2.

rivers have reported much lower nutrient export: 1.73 kg km^{-2} TP during snowmelt for a small tributary of the Assiniboine River, Manitoba (Neil 1992); 0.464 kg TP and 1.334 kg TN km^{-2} during spring high flows, which includes snowmelt, for the Souris River, Manitoba (Chacko 1986); and 1.329–10.237 kg km^{-2} TP annually for five Canadian Prairie streams (Fortin & Gurney 1998). Although several studies have investigated the ecological relevance of nutrient export in the Great Plain ecosystem (Tate 1990; Chambers *et al.* 2005; Dodds & Oakes 2006; Dodds *et al.* 2008; Banner *et al.* 2009), only a few studies have highlighted the role of snowmelt in delivering nutrients to downstream ecosystems.

Human activity gradient and nutrient export

Analysis of human activity in our 10 subwatersheds showed that agriculture was the dominant land cover in all basins, covering 55–88% of the area (Table 3). Fertilizer was applied to 31–76% of the watershed areas at rates of

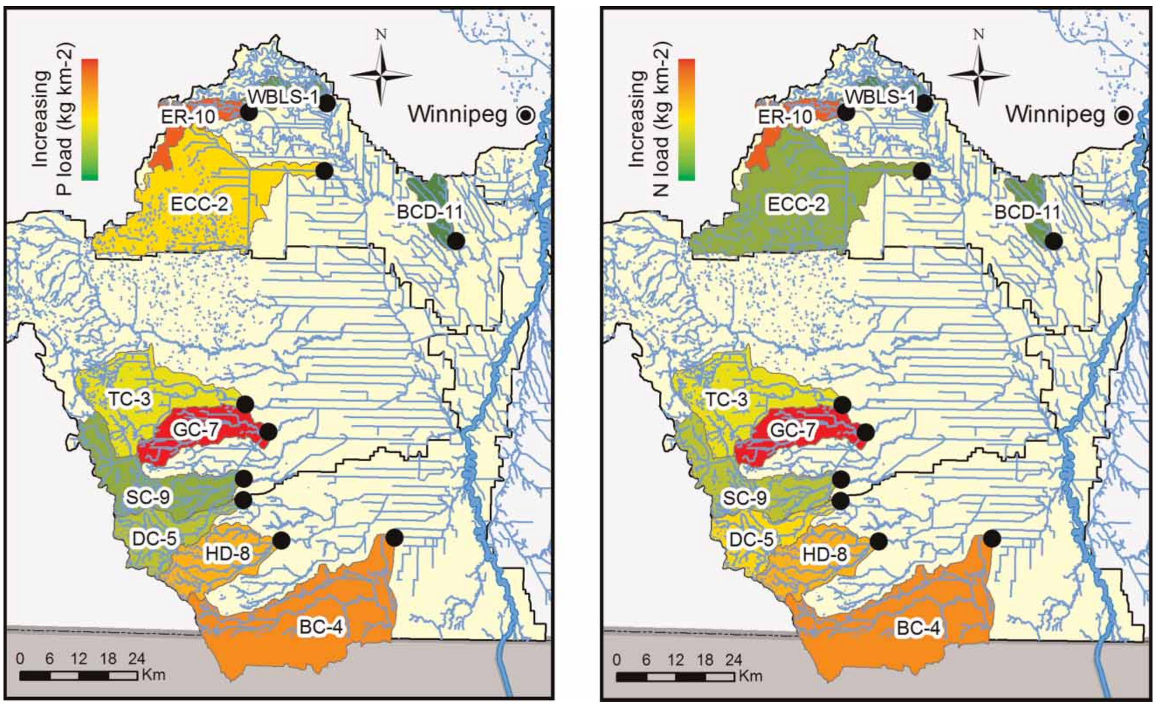

Figure 3 | Gradient of total phosphorus (left) and nitrogen (right) loads normalized to watershed area for snowmelt 2010 in south-western Manitoba.

11–27 kg P ha^{-1} and 28–71 kg N ha^{-1}. The density of people served by wastewater lagoons (WWL) was fairly low for the 10 watersheds, indicating that WWLs are unlikely to be a dominant factor influencing snowmelt loads (Table 3).

Comparison of nutrient export from our subwatersheds with measures of human activity showed that snowmelt N was better correlated with land use than was snowmelt P. Snowmelt TN was strongly correlated with both agricultural land cover ($r = 0.91$; $p < 0.05$) and the estimated quantity of N fertilizer applied in the watershed ($r = 0.8$; $p < 0.05$); snowmelt TP was only correlated with agricultural land cover ($r = 0.81$; $p < 0.05$). The stronger relationships between land use and TN as compared to TP are surprising given that snowmelt TP and TN loads were correlated ($r = 0.97$; $p < 0.05$), resulting in similar gradients in TP and TN export for all but two subwatersheds (Figure 3). Nevertheless, our findings agree with other prairie studies that demonstrate stronger relationships for annual N concentration and/or load, as compared to P, with land use (Little *et al.* 2003; Dodds & Oakes 2006). In contrast, Banner *et al.* (2009) found a strong relationship ($R^2 = 0.79$) between annual median TP concentration and riparian land use along Prairie streams. However, TN data were not presented to assess whether N or P was better predicted by land cover. Observations that streams and ponds in southern Manitoba often have high nutrient values (Pip 2005) and that agricultural activities were the major source of N and P to southern Manitoba streams (Bourne *et al.* 2002) also attest to the important role of agriculture as a nutrient source to prairie surface waters.

CONCLUSION

Snowmelt is the most significant time period in the hydrologic cycle for streams and rivers in the Canadian Prairies. Although the contribution of snowmelt to annual water budgets has been examined for prairie watercourses, few investigations have been conducted on stream nutrient export during snowmelt. Characterization of nutrient loads in 10 subwatersheds in the Red River Valley of south-western Manitoba, Canada showed that concentrations of TP and TN varied considerably through the snowmelt and post-snowmelt periods, with concentrations typically greater during the snowmelt peak and lower during post-snowmelt discharge recession. Much (>80%) of the TP and TN exported was in the dissolved phase, thus posing significant eutrophication risk to proximal and downstream ecosystems. Nutrient export was correlated with agricultural land cover in the watershed; this observation and results from other studies in the region suggest that agricultural activities are a dominant source of nutrients to southern Manitoba streams. Our results suggest that an improved scientific understanding of the contribution of snowmelt to the nutrient budget of prairie aquatic ecosystems is essential for designing land use management practices to control nutrient loads to Lake Winnipeg and other waterbodies in the Great Plains.

REFERENCES

Banner, E. B. K., Stahl, A. J. & Dodds, W. K. 2009 Stream discharge and riparian land use influence in-stream concentrations and loads of phosphorus from Central Plains watersheds. *Environ. Manage.* **44**, 552–565.

Bourne, W. K., Armstrong, N. & Jones, G. 2002 A Preliminary Estimate of Total Nitrogen and Total Phosphorus Loadings to Streams in Manitoba, Canada. Water Quality Management Section, Manitoba Conservation, Report No. 2002–04, Winnipeg.

Chacko, V. T. 1986 *Nutrient Characteristics of the Souris River at Coulter, Manitoba, During Low Flow Years*. Water Quality Branch, Inland Waters Directorate, Environment Canada, Regina, SK.

Chambers, D. K., Arruda, J. A. & Jaywardhana, A. A. 2005 A synoptic water quality survey of the Spring River and its tributaries. *T. Kansas Acad. Sci.* **108**, 47–56.

Dodds, W. K. & Oakes, R. M. 2006 Controls on nutrients across a prairie stream watershed: land use and riparian cover effects. *Environ. Manage.* **37**, 634–646.

Dodds, W. K., Gido, K., Whiles, M. R., Fritz, K. M. & Matthews, W. J. 2008 Life on the edge: the ecology of Great Plains Prairies Streams. *BioScience* **54**, 205–215.

Eaton, A. D., Clesceri, L. S., Rice, E. W. & Greenberg, A. E. 2005 *Standard Methods for the Examination of Water and Wastewater*. 21st edition, American Public Health Association, Washington, DC.

Fortin, R. & Gurney, S. 1998 Phosphorus Loading to the Shellmouth Reservoir. Government of Manitoba, Manitoba, Canada.

Glozier, N. E., Elliott, J. A., Holliday, B., Yarotski, J. & Harker, B. 2006 *Water Quality Characteristics and Trends in a Small Agricultural Watershed: South Tobacco Creek, Manitoba, 1992–2001*. Environment Canada, Ottawa.

Granger, R. J., Gray, D. M. & Dyck, G. E. 1984 Snowmelt infiltration to frozen Prairie soils. *Can. J. Earth. Sci.* **21**, 669–677.

Hall, R. I., Leavitt, P. R., Quinlan, R., Dixit, A. S. & Smol, J. P. 1999 Effects of agriculture, urbanization, and climate on water quality in the northern Great Plains. *Limnol. Oceangr.* **44**, 739–756.

Little, J. L., Nolan, S. C., Casson, J. P. & Olson, B. M. 2007 Relationships between soil and runoff phosphorus in small Alberta watersheds. *J. Environ. Qual.* **36**, 1289–1300.

Little, J. L., Saffran, K. A. & Fent, L. 2003 Land use and water quality relationships in the lower Bow River watershed, Alberta, Canada. *Water Qual. Res. J. Canada* **38**, 563–584.

Neil, P. W. 1992 Estimating total phosphorus in a small prairie tributary. Thesis, Faculty of Graduate Studies and Research. University of Regina, Regina, Saskatchewan.

Pip, E. 2005 Surface water quality in Manitoba with respect to six chemical parameters, water body and sediment type and land use. *Aquat. Ecosyst. Manage.* **8**, 195–207.

Sheppard, S. C., Sheppard, M. I., Long, J., Sanipelli, B. & Tait, J. 2006 Runoff phosphorus retention in vegetated field margins on flat landscapes. *Can. J. Soil Sci.* **86**, 871–884.

Tate, C. M. 1990 Patterns and controls of nitrogen in tallgrass prairie streams. *Ecology* **71**, 2007–2018.

Tiessen, K. H. D., Elliott, J. A., Yarotski, J., Lobb, D. A., Flaten, D. N. & Glozier, N. E. 2010 Conventional and conservation tillage: influence on season runoff, sediment and nutrient losses in the Canadian Prairies. *J. Environ. Qual.* **39**, 964–980.

Wiley, M. J., Osborne, L. L. & Larimore, R. W. 1990 Longitudinal structure of an agricultural Prairie River System and its relationship to current stream ecosystems theory. *Can. J. Fish. Aquat. Sci.* **47**, 373–384.

Yates, A. G., Culp, J. M. & Chambers, P. A. 2011 Estimating nutrient production from human activities in subcatchments of the Red River, Manitoba. *J. Great Lakes Res.* (in press).

First received 6 January 2011; accepted in revised form 5 May 2011