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Critical Factors Affecting Field-Scale Losses of Nitrogen and Phosphorus in Spring Snowmelt Runoff in the Canadian Prairies

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A long-term, field-scale study in southern Manitoba, Canada, was used to identify the critical factors controlling yearly transport of nitrogen (N) and phosphorus (P) by snowmelt runoff. Flow monitoring and water sampling for total and dissolved N and P were performed at the edge of field. The flow-weighted mean concentrations and loads of N and P for the early (the first half of yearly total volume of snowmelt runoff), late (the second half of yearly total volume of snowmelt runoff), and yearly snowmelt runoff were calculated as response variables. A data set of management practices, weather variables, and hydrologic variables was generated and used as predictor variables. Partial least squares regression analysis indicated that critical factors affecting the water chemistry of snowmelt runoff depended on the water quality variable and stage of runoff. Management practices within each year, such as nitrogen application rate, number of tillage passes, and residue burial ratio, were critical factors for flow-weighted mean concentration of N, but not for P concentration or nutrient loads. However, the most important factors controlling nutrient concentrations and loads were those related to the volume of runoff, including snow water equivalent, flow rate, and runoff duration. The critical factors identified for field-scale yearly snowmelt losses provide the basis for modeling of nutrient losses in southern Manitoba and potentially throughout areas with similar climate in the northern Great Plains region, and will aid in the design of effective practices to reduce agricultural nonpoint nutrient pollution in downstream waters.

Nitrogen (N) and phosphorus (P) in agricultural land have the potential to be transported to streams and lakes (Moog and Whiting, 2002; Buda et al., 2009; Tiessen et al., 2010; Li et al., 2011), potentially causing eutrophication and jeopardizing aquatic ecosystems. For example, as the 10th largest freshwater lake in the world with an area of 24,500 km^2, Lake Winnipeg in Manitoba, Canada, has experienced increased frequency and severity of algal blooms in the past decade because of the enrichment of N and P (Lake Winnipeg Stewardship Board, 2006). Among all sources of N and P, agricultural activities have been identified as one of the important sources responsible for the deterioration of the water quality in Lake Winnipeg (Lake Winnipeg Stewardship Board, 2006). However, although nutrient loadings in streams have been related to agricultural intensity, the specific activities responsible for the impact have not been identified (Corriveau et al., 2011; Yates et al., 2012).

Agricultural N and P enter freshwater systems mainly through runoff. Spring snowmelt runoff, which represents approximately 80% of annual runoff in the northern Great Plains (Nicholaichuk, 1967; Hansen et al., 2000; Glozier et al., 2006), is important for N and P exports to aquatic ecosystems (Bourne et al., 2002). Many factors individually or interactively affect N and P losses from agricultural land. They can be grouped into management factors that affect soil properties, and hydrological and weather factors that determine the nature of snowmelt runoff events.

Management practices that add nutrients or maintain high levels of soil nutrients have been reported to increase N and P in runoff by increasing the available nutrient source (Hansen et al., 2002; Moog and Whiting, 2002; Little et al., 2007; Buda et al., 2009; Salvano et al., 2009). The transport of N and P in watersheds has also been shown to be impacted by management practices such as tillage and crop choice that can affect

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Abbreviations: AvFlow, average flow rate; CumRain, cumulative rainfall; CumSnow, cumulative snowfall; DegDay, degree day during the runoff period; DurR, duration of runoff; FWMCTN, flow-weighted mean concentration of total nitrogen; FWMCTP, flow-weighted mean concentration of total phosphorus; LTN, load of total nitrogen; LTP, load of total phosphorus; NApp, nitrogen application rate; PApp, phosphorus application rate; PkFlow, peak flow rate; PLS, partial least squares analysis; SWE, snow water equivalent; Tmax, maximum temperature during snowmelt runoff events; VIP, variable importance of projection; VolR, volume of runoff.

antecedent soil moisture (Jamieson et al., 2003; Christopher et al., 2008). Fang and Pomeroy (2007) found that low antecedent soil moisture decreased snowmelt runoff, whereas the volume of runoff (VolR) resulting from snowmelt increased when the preceding fall soil moisture was high (Suzuki et al., 2005).

Hydrologic and weather factors were also highly linked to the water chemistry in runoff and affected nutrient loss (Tisseuil et al., 2008; Townsend-Small et al., 2011; Shrestha et al., 2012). Among factors affecting water quality, VolR was widely accepted by many researchers to be the main factor controlling N and P (Moog and Whiting, 2002; Turgeon and Courchesne, 2008; Salvano et al., 2009; Sui et al., 2010; Iida et al., 2011). Cockburn and Lamoureux (2008) reported that volume and intensity of snowmelt runoff were important controls on sediment yield and consequent P losses. Runoff volume is highly dependent on the snow water equivalent (SWE) of the snowpack (Suzuki et al., 2005; Cockburn and Lamoureux, 2008) and snowmelt infiltration into frozen soil (Su et al., 2011) that is in turn controlled by snow depth and variation of snow depths that affect the degree of soil freezing (Su et al., 2011) and fall soil moisture content discussed previously. Severe soil freezing resulting from shallow snow depth has also been shown to increase root mortality and subsequent nutrient losses during spring snowmelt runoff (Han et al., 2010; Su et al., 2011). In a watershed study in eastern Canada, rainfall during snowmelt was reported to be another important factor influencing nutrient loss (Su et al., 2011).

Nutrient losses are not constant during snowmelt, and significant temporal variability has been observed within snowmelt runoff events. In a cold climate, the first flush of snowmelt runoff is considered to be the most critical event for nutrient export (Han et al., 2010). Studies have shown that concentrations of N and P were generally greater during the initial stage of snowmelt than averages for the entire snowmelt (Corriveau et al., 2011; Townsend-Small et al., 2011). Temporal variability has also been observed in physical factors during snowmelt as Forbes and Lamoureux (2005) reported that daily discharge from snowmelt was initially highly correlated with temperature, but the relationship became weaker late in snowmelt. This temporal variability within a snowmelt runoff suggests that the factors controlling N and P losses in runoff vary during the snowmelt process. Consequently, the division of yearly total snowmelt runoff into early and late phases should enhance the understanding of the controls on nutrient transport.

In watershed studies, the complex relationships between water quality and multiple controlling factors are difficult to analyze using multiple regression techniques. A large number of variables is required to characterize the controls on water quality (Macrae et al., 2010), and interactions between explanatory factors weaken relationships between water chemistry and any single predictor variable (McNamara et al., 2008). Even when long-term data are available, the number of explanatory variables often exceeds the number of observations in watershed studies, presenting a challenge to the use of multiple regression analysis to select important controlling factors, particularly when multicolinearity exists (Neter et al., 1996). Partial least squares (PLS) analysis is more powerful for these types of data because it does not require variables to be independent and does not overfit even when the explanatory variables exceed the observations (Carrascal et al., 2009). The technique has been successfully used by Zvomuya et al. (2008) to identify important soil quality indicators from 19 predictor variables in a long-term field study, and in a watershed study by Lopez et al. (2008), who identified that percent barren area and stream density were the key factors controlling P export.

To our knowledge, no study has been conducted to identify the critical factors controlling nutrient exports by snowmelt runoff. In this study we used a long-term data set collected from a 4-ha agricultural, field-scale watershed that had been under the same management regime for 17 yr to generate explanatory factors that described tillage, weather, and hydrologic variables and used PLS analysis to determine the critical factors for yearly snowmelt runoff losses of N and P. Within this general objective we aimed to determine if the critical factors were different for (i) N and P, (ii) concentrations and loads, and (iii) early (the first half of yearly total volume of snowmelt runoff) and late (the second half of yearly total volume of snowmelt runoff) runoff.

Materials and Methods

Watershed Description

The study site is located in the South Tobacco Creek Watershed, southern Manitoba, Canada (49°20′ N, 98°22′ W) (Fig. 1). The site is the conventional tillage watershed within a pair of conventional and conservation tillage watersheds. Since the establishment of the study in 1993, the conventional tillage watershed has remained under conventional tillage practices. A detailed site description has been reported by Tiessen et al. (2010). Briefly, soils in the watershed are classified as Dark Gray Chernozems (Mollisols) with slopes of approximately 5%. The climate is subhumid continental and characterized by cold, long winters. The long-term mean annual temperature is approximately 3°C and the annual precipitation is approximately 550 mm with 25 to 30% of precipitation occurring as snowfall (Environment Canada, 2012). Cropping sequence, tillage operations, fertilizer application rates, and snowmelt runoff period during the study period, 1993 to 2010, are given in Table 1. The normal field management practices were performed by the landowner.

Data Collection

Surface snowmelt runoff has been monitored at the study site since 1994. Each year, snow accumulated from October or November through March and then melted in March and/or April (Table 1) on soil that was usually frozen. The snowmelt runoff events were typically composed of diurnal patterns, with most runoff occurring during daylight hours. In some years, snowmelt occurred as two or more events due to periods of cold weather, which interrupted melting; however, the interruptions were generally short and had little impact on subsequent runoff. Therefore, separate runoff events within a year were treated as a single snowmelt runoff event, resulting in a total of 16 yearly snowmelt runoff events from the 17-yr study because there was no snowmelt runoff in 2000. Runoff that occurred at the end of April was excluded if field notes indicated that the event was mainly caused by rain. In addition, each yearly snowmelt runoff event was split into two halves: “early” (the first half of yearly

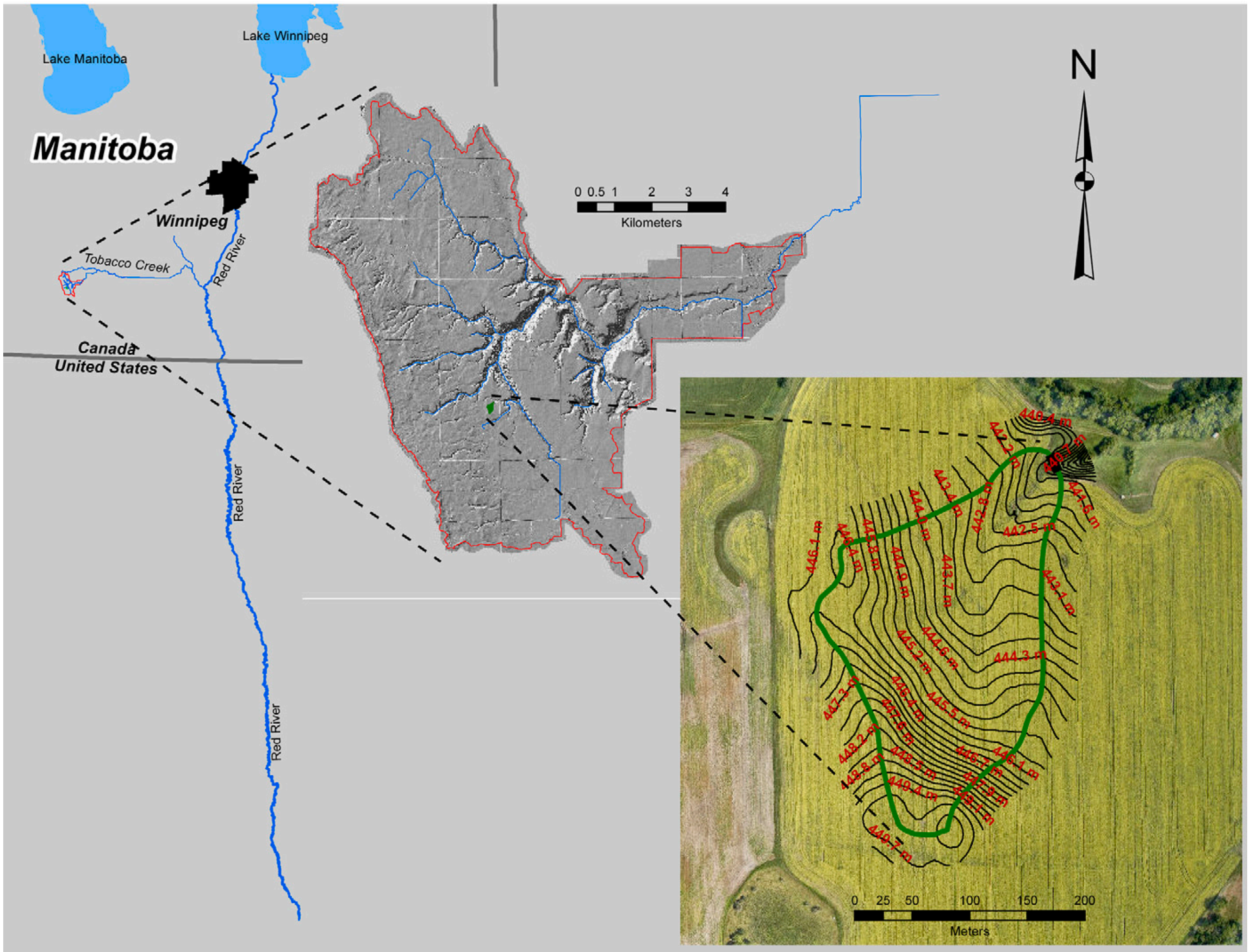

Fig. 1. Map of the study watershed under long-term conventional tillage.

total volume of runoff) and "late" (the second half of yearly total volume of runoff) runoff solely based on VolR.

Runoff was monitored at the outlet of the watershed using a V-notched weir and an ultrasonic depth instrument (SR50, Campbell Scientific) connected to a data logger (CR10X0, Campbell Scientific) by monitoring the depth of flow over the weir and the flow rate was calculated. The depth of water passing over the weir was recorded at 5-min intervals. Runoff volume was calculated for each interval and was summed to give VolR, which was expressed as runoff yield (volume per unit of watershed area). Average flow rate (AvFlow) was calculated as the flow volume per unit of flow time. Peak flow rate (PkFlow) was the maximum flow rate in the hydrographs. The start and end times of each snowmelt runoff event were recorded and the cumulative duration of flow was expressed as duration of runoff (DurR).

An auto-sampler (800SL; Sigma, Medina, NY) was programmed to sample water at the v-notched weir during runoff events. Water samples were generally collected during the rising limb, at the peak, and during the falling limb of each diurnal runoff cycle, and were supplemented by occasional grab samples. The number of water samples each year ranged from 3 to >20. The concentrations of total N, total dissolved N, total P, and total dissolved P were determined using standard colorimetric methods as described by Tiessen et al. (2010). The nutrient concentrations were linearly interpolated between water samplings in a given runoff event. Total nutrient loads were calculated as the product of the 5-min flow volumes (m^3) and actual or interpolated nutrient concentrations (mg L^{-1}) and summed for the given time period of the early, late, and yearly snowmelt runoff. The flow-weighted mean concentrations of nutrients were calculated by dividing the total load by total runoff volume.

Since 1997, soil samples have been collected in the fall after harvest and sent to Agvise Laboratories (Northwood, ND) for nitrate N and Olsen-P analyses using standard methods. Commercial N fertilizer was applied in the spring and/or fall of the previous year, and yearly N application rate (NApp) is reported in Table 1. All P fertilizer was applied in the spring, and P application rate (PApp) is also reported in Table 1. The parameters of tillage intensity and residue burial ratio were derived from the Revised Universal Soil Loss Equation, version 2 (USDA, 2008) according to the specific tillage implement and crop for each year (Table 1). In addition, the number of tillage passes each year was recorded. If two passes occurred in 1 yr, the cumulative tillage intensity and residue burial ratio were estimated as the sum of the individual effects, with an assumption that the second tillage implement only affected the remaining portion of soil unaffected by the first pass. Crops were

Table 1. Summary of crop, tillage implement, number of tillage passes, nitrogen and phosphorus application rates, tillage intensity (TillInt), residue burial ratio (RBR), and date of snowmelt runoff during the study period.

Year	Crop	Fall tillage implement (no. tillage passes)†	N application rate		P application rate	Tillage index for each tillage pass‡		Date of snowmelt runoff	
			Spring	Fall	Spring	TillInt	RBR	Beginning	Ending
			kg ha^{-1}	kg ha^{-1}	kg ha^{-1}				
1993	Flax (*Linum usitatissimum* L.)	No tillage (0)	0	0	0	0	0		
1994	Wheat (*Triticum aestivum* L.)	(HDC) (2)	100	0	14	0.85	0.4	4 March	14 March
1995	Canola (*Brassica napus* L.)	Light-duty cultivator (2)	95	0	15	0.4	0.325	16 March	15 April
1996	Wheat	Light-duty cultivator (2)	62	0	12	0.4	0.35	12 March	11 April
1997	Flax	HDC (1)	56	0	0	0.85	0.35	1 April	18 April
1998	Flax	HDC (2) + harrow (2)	67	67	0	0.85 + 0.5	0.35 + 0.275	25 March	1 April
1999	Wheat	HDC (1) + anhydrous rig (1)	11	67	15	0.85 + 0.8	0.4 + 0.2	18 March	April 7
2000	Canola	HDC (1)	11	0	17	0.85	0.35	–§	–
2001	Oat (*Avena sativa* L.)	HDC (1)	56	0	15	0.85	0.4	21 March	19 April
2002	Flax	HDC (1) + harrow (1)	56	0	0	0.85 + 0.5	0.35 + 0.275	27 March	29 March
2003	Wheat	HDC (1)	73	0	12	0.85	0.4	15 March	7 April
2004	Canola	HDC (1)	90	0	17	0.85	0.35	25 March	3 April
2005	Barley (*Hordeum vulgare* L.)	HDC (1) + harrow (1)	67	0	0	0.85 + 0.5	0.4 + 0.3	30 March	5 April
2006	Canola	HDC (1)	78	0	5	0.85	0.35	31 March	11 April
2007	Wheat	HDC (2)	90	95	5	0.85	0.4	19 March	26 March
2008	Canola	HDC (1)	13	0	5	0.85	0.35	30 March	3 April
2009	Wheat	HDC (1)	90	0	5	0.85	0.4	22 March	15 April
2010								14 March	3 April

† HDC, heavy-duty cultivator. Tillage depths are 12.7, 10.2, 7.6, and 10.2 cm for HDC, light-duty cultivator, harrow, and anhydrous rig operation, respectively. The tillage speed is 6.4 km h^{-1} for harrowing and 8.0 km h^{-1} for other operations.

‡ Tillage index was derived from Revised Universal Soil Loss Equation, version 2 (USDA, 2008).

§ No snowmelt runoff in 2000.

harvested by the producer, and crop yields were estimated and expressed as Mg ha^{-1}.

On-site rainfall was monitored from March to October using a tipping-bucket rain gauge. Rainfall data from November to the following February were obtained from a nearby Environment Canada weather station (Miami Thiessen, 49°22′ N, 98°17′ W). Snowfall data were obtained from the same Environment Canada weather station. Cumulative rainfall (CumRain) was assumed to be the sum of rainfall from the first snowfall in the previous fall to the end of snowmelt runoff in the following spring (or to the end of the early runoff for the early runoff calculation). Cumulative snowfall (CumSnow) was calculated as the sum of snowfall during the same period as for CumRain.

The on-site ambient air temperature was monitored at hourly intervals. During each spring snowmelt runoff period, a degree day (DegDay) above a base temperature of 0°C was computed using the hourly temperature rather than the daily maximum and minimum temperatures. The advantage of using hourly temperature is that each positive temperature peak contributes to the degree day. By contrast, some positive temperature peaks are ignored when using daily temperature if the daily positive maximum temperature is lower than the absolute value of daily negative minimum temperature.

The prerunoff degree day was defined as a period from 1 February to the beginning of spring snowmelt runoff (or to the beginning of the late runoff for the late runoff event). The hourly maximum temperature (Tmax) during the snowmelt runoff events was also chosen as a predictor variable. In addition, the precipitation in previous October was calculated and used as an indicator of antecedent soil moisture.

In anticipation of snowmelt runoff, a snow survey was conducted each year in March as described by Tiessen et al. (2010). During each snow survey, 12 snow depths were measured and snow density was determined by weighing snow samples of a known volume. The coefficient variation of snow depths was calculated as a ratio of the standard deviation to the mean of snow depths and was used to describe the overall variability of snow depths in a given year. Snow water equivalent was calculated as the product of snow depth and density.

Statistical Analyses

Partial Least Squares Regression Analysis

To identify important factors affecting response variables, PLS analysis was conducted using Proc PLS in SAS (SAS Institute Inc., 2008). There were 18 predictor variables and four response variables collected in this study. The predictor variables include six management factors, eight weather factors, and four hydrologic factors (Table 2). The four response variables consisted of flow-weighted mean concentration of total N (FWMCTN), flow-weighted mean concentration of total P (FWMCTP), load of total N (LTN), and load of total P (LTP) (Table 3). Each variable was checked for normality before fitting the PLS model, and data were either log transformed or square-root transformed if the assumption of normality was violated.

Table 2. Variability of predictor variables in the early, late, and yearly total snowmelt runoff during the study period from the fall of 1993 to 2010.

Category	Variable†	*n*‡	Early snowmelt runoff				Late snowmelt runoff				Yearly snowmelt runoff			
			Min.	Max.	Mean	CV	Min.	Max.	Mean	CV	Min.	Max.	Mean	CV
						%				%				%
Management	NApp (kg ha^{-1})	16	0	184.8	72.9	63	Same as the early runoff				Same as the early runoff			
	PApp (kg ha^{-1})	16	0	17.1	8.1	79								
	TillPass	16	0	4.0	1.4	57								
	RBR	16	0	0.8	0.4	40								
	TillInt	16	0	0.99	0.8	50								
	Yield (Mg ha^{-1})	16	1.1	3.6	2.3	35								
Weather	CumRain (mm)	16	4.4	63.1	27.6	74	4.4	67.0	31.6	67	4.4	67.0	31.6	67
	CumSnow (mm)	16	78.8	195.4	134.0	24	91.9	206.6	144.6	23	91.9	206.6	144.6	23
	PDegDay (°C)	16	0	7.9	3.0	80	2.2	18.7	10.0	48	0	7.9	3.0	80
	DegDay (°C)	16	0.6	15.3	6.9	52	3.5	48.8	20.0	62	5.4	60.9	26.9	57
	Tmax (°C)	16	2.4	9.9	7.0	29	6.7	19.1	13.4	27	8.7	19.1	13.5	24
	PPO (mm)	16	14.0	150.1	47.3	69	Same as the early runoff				Same as the early runoff			
	CVSD	16	0.2	1.3	0.6	67								
	SWE (mm)	16	5.9	93.9	58.5	49								
Hydrology	AvFlow (L s^{-1})	16	0.1	11.2	4.9	73	0.1	11.0	3.6	78	0.1	9.1	3.9	72
	PkFlow (L s^{-1})	16	0.3	110.3	32.4	99	0.2	76.0	26.9	82	0.3	110.3	35.8	89
	DurR (h)	16	11.0	133.0	57.9	64	22.0	210.5	79.8	66	33.7	343.5	137.8	60
	VolR (m^3 ha^{-1})	16	3.6	679.4	249.8	82	3.2	678.8	249.6	82	6.9	1358.0	499.3	82

† AvFlow, average flow rate; CumRain, cumulative rainfall; CumSnow, cumulative snowfall; CVSD, coefficient of variation of snow depths; DegDay, degree day during the runoff period; DurR, duration of runoff; NApp, nitrogen application rate; PApp, phosphorus application rate; PDegDay, pre-runoff degree day from 1 February to the start of snowmelt runoff; PkFlow, peak flow rate; PPO, precipitation in previous October; RBR, residue burial ratio; SWE, snow water equivalent; TillInt, tillage intensity; TillPass, number of tillage passes; Tmax, maximum temperature during snowmelt runoff events; and VolR, volume of runoff.

‡ Because there was no snowmelt runoff in 2000, the number of observations was 16 for the 17-yr study.

The variation and ranges of the variables we examined were quite different (Tables 2 and 3); therefore, the data were centered and scaled to have mean 0 and standard deviation 1 before fitting to the PLS model. Scatter plots of X-score vs. Y-score and X-scores against each other were plotted to view the strength of the relationship and the irregular patterns in the data.

For each response variable, three separate PLS analyses corresponding to the early, late, and yearly snowmelt runoff were performed. For LTN and LTP, the dependence on VolR likely reflects its direct influence as a component in the load calculation; however, for FWMCN and FWMCP, the relationship with VolR is indirect and represents the dilution of available nutrients. Consequently, the PLS analysis was performed with all 18 predictor variables (including VolR) for FWMCTN and FWMCTP, but with 17 predictor variables (excluding VolR) for LTN and LTP. In PLS analysis, PLS latent variables are generated to explain most of variations in predictor and response variables. The number of PLS latent variables was first determined by cross validation so that the model minimized the predicted residual sum of squares. In PLS analysis, extracting too many PLS latent variables can cause overfitting problems. A CVTEST option was added to test if there was a significant difference in predicted residual sum of squares when using a fewer number of PLS latent variables than recommended by cross validation. Fewer PLS latent variables were selected if there was no significant difference. Therefore, the number of PLS latent variables for each analysis was determined by cross validation along with the CVTEST option.

Variable importance of projection (VIP) values describe the relative contribution of the predictor variables to the PLS latent variables. Variables with values of VIP larger than 0.8 are considered to be factors that significantly influence the variation of the response variable (Wold, 1995). Preliminary PLS analyses indicated that there were many predictor variables having a VIP

Table 3. Variability of response variables in the early, late, and yearly total snowmelt runoff during the study period from 1993 to 2010.

Response variable†	*n*‡	Early snowmelt runoff				Late snowmelt runoff				Yearly snowmelt runoff			
		Min.	Max.	Mean§	CV	Min.	Max.	Mean	CV	Min.	Max.	Mean	CV
					%				%				%
FWMCTN (mg L^{-1})	15	2.03	15.42	8.14	56	2.03	18.04	7.18	69	2.35	16.72	7.74	58
FWMCTP (mg L^{-1})	16	0.17	1.84	0.52	69	0.18	1.38	0.51	51	0.20	1.45	0.53	63
LTN (kg ha^{-1})	15	0.02	5.94	1.61	96	0.04	3.13	1.14	82	0.06	8.76	2.81	84
LTP (kg ha^{-1})	16	0.004	0.24	0.09	73	0.004	0.28	0.12	67	0.01	0.51	0.22	73

† FWMCTN, flow-weighted mean concentration of total nitrogen; FWMCTP, flow-weighted mean concentration of total phosphorus; LTN, load of total nitrogen; and LTP, load of total phosphorus.

‡ Because there was no snowmelt runoff in 2000 and nitrogen concentration in 2007 was missing, the number of observations was 15 for N response variables and 16 for P response variables during the 17-yr study.

§ For FWMCTP and LTP, median rather than mean is reported since the normality distribution was violated.

value >0.8. To refine the important factors, we define variables having VIP value >1.2 as critical factors.

Simple Regression Analysis

To describe the relationship between a response variable and the corresponding critical factor with the greatest VIP value, simple linear regression analyses were conducted using Proc REG (SAS Institute Inc., 2008). When the most critical factor was the same for the early and late runoff for a given response variable and the linear relationship was significant, intercepts and slopes of the two linear functions were compared using a nested regression with incremental parameters model (Bates and Watts, 1988). Model assumptions (normal distribution and constant variance of the error terms) were verified by examining the residuals.

Analysis of Variance

The response variables were compared between the early and late runoff using paired-t analysis (SAS Institute Inc., 2008). Before data analysis, the statistical assumption of normality distribution was tested. The FWMCTN and LTN data passed the normality test after transformations; however, the FWMCTP and LTP data failed. Consequently, the FWMCTP and LTP data were analyzed using nonparametric analysis (signed rank test), and medians rather than means were reported due to the degree of skewness. Because of the large degree of variability associated with a field study of this nature, the significance level (P) was set at 0.1.

Results

Descriptive Results

During the 17-yr experimental period, the least variation was for CumSnow in the yearly snowmelt runoff (CV = 23%) and the largest variation was for PkFlow in the early snowmelt runoff (CV = 99%) (Table 2). The application rates for N and P fertilizers were based on soil test recommendations and varied among years (CV = 63% for NApp and 79% for PApp). The DegDay and Tmax in the late runoff were 190% and 90% greater than those in the early runoff, respectively. Snow survey before the beginning of snowmelt indicated that the variation of snow depths differed among years with a CV ranging from 20 to 130%. Snow water equivalent varied by nearly a factor of 16 with a range from 5.9 to 93.9 mm (CV = 49%). The hydrologic variables partially reflected the variation of weather parameters and differed substantially among years. For example, in the yearly snowmelt runoff events, the peak flow rate ranged from 0.3 to 110.3 L s^{-1} with a CV of 89% and the VolR ranged from 6.9 to 1358 m^3 ha^{-1} with a CV of 82%. Average flow rate and PkFlow were 36 and 20% greater in the early runoff than in the late runoff, respectively. In contrast, DurR was 27% shorter in the early runoff.

Among the response variables, more variation was associated with loads than with concentrations (Table 3). For example, the FWMCTN had a CV of 58% compared to 84% for LTN in the yearly snowmelt runoff. Total nutrients were strongly correlated with the corresponding total dissolved nutrients (data not shown), with correlation coefficients ranging from 0.94 to 0.99. The percentage of dissolved nutrient relative to the total nutrient was slightly greater in the early runoff than in the late runoff. In the yearly snowmelt runoff, 91% of TN and 73% of TP were in dissolved forms. However, only total N and P are reported in this study as total N and P are normally used in surface water quality guidelines.

Volume of Runoff

The PLS results presented in Table 4 include the predictor variable VolR in the FWMCN and FWMCP analysis but exclude it from the analysis of LTN and LTP. Including VolR as a predictor variable had little effect on the proportion of the variability in LTN and LTP explained by the PLS latent variables (data not shown). When VolR was included as a predictor variable, VolR was identified as the most important factor affecting LTN and LTP (data not shown). A PLS analysis using VolR as a response variable indicated that 80 to 82% of its variability, depending on stages of runoff, could be explained using the other hydrological and weather variables (data not shown). Four critical variables (AvFlow, SWE, CumRain, and DegDay) for VolR were common to early, late, and yearly snowmelt runoff in this analysis.

Flow-weighted Mean Concentration of Total Nitrogen

The two-latent-variable PLS model performed well, accounting for 97% of the variability in FWMCTN for the early snowmelt runoff with the first PLS latent variable explaining 91% of the variability (Table 4). In comparison, the one-latent-variable PLS model explained 74% of variability for the late snowmelt runoff and 71% for the yearly snowmelt runoff. Thirteen variables for the early runoff, 12 for the late runoff, and 9 for the yearly snowmelt runoff contributed to the variability of FWMCTN significantly, as indicated by the VIP values >0.8 (Table 4). The most important variable was NApp for the early runoff, SWE for the late runoff, and AvFlow for the yearly snowmelt runoff. Simple linear regression analyses indicated that all three most critical predictor variables had significant linear relationships with FWMCTN (Fig. 2).

Nine variables, common to the early, late, and yearly snowmelt runoff periods, had VIP >0.8 and were significant factors affecting FWMCTN (Table 4). From the 18 predictor variables, four (NApp, AvFlow, CumSnow, and prerunoff degree day) were critical factors (VIP >1.2) for FWMCTN for the early snowmelt runoff, whereas seven variables (NApp, AvFlow, SWE, VolR, number of tillage passes, residue burial ratio, and variation of snow depths) were critical factors for late and yearly snowmelt runoff events. Among these critical factors, NApp, number of tillage passes, residue burial ratio, and variation of snow depths had positive effects on FWMCTN, whereas AvFlow and VolR had negative effects on FWMCTN (Table 4). Four variables (DurR, PApp, tillage intensity, and precipitation in previous October) were not significantly related to FWMCTN (VIP <0.8).

Flow-weighted Mean Concentration of Total Phosphorus

The one-latent-variable PLS model performed reasonably well, representing 68, 70, and 67% of the variability in FWMCTP for the early, late, and yearly snowmelt runoff, respectively (Table 4). Ten variables for the early runoff, 13 for the late runoff, and 10 for the yearly snowmelt runoff had significant contributions to the FWMCTP (Table 4). Snow water equivalent was the most important factor controlling the variability of FWMCTP for the early, late, and yearly snowmelt runoff. Simple linear regression analyses indicated that the linear relationship between SWE and FWMCTP was significant (Fig. 2). As the most important factor controlling FWMCTP for the early and late runoff, SWE had similar effects on FWMCTP for both periods ($P = 0.762$ for intercept comparison; $P = 0.683$ for slope comparison).

Table 4. Variable importance for projection (VIP) and regression coefficient (RC) for flow-weighted mean concentration of total nitrogen (FWMCTN), flow-weighted mean concentration of total phosphorus (FWMCTP), load of total nitrogen (LTN), and load of total phosphorus (LTP) in the early, late, and yearly total snowmelt runoff.

Variable†	Early snowmelt runoff		Late snowmelt runoff		Yearly snowmelt runoff		Early snowmelt runoff		Late snowmelt runoff		Yearly snowmelt runoff	
	VIP	RC	VIP	RC	VIP	RC	VIP	RC	VIP	RC	VIP	RC
	FWMCTN						FWMCTP					
NApp	1.41	0.28	1.21	0.10	1.50	0.13	0.57	−0.05	1.18	−0.30	0.60	−0.05
PApp	0.80	−0.18	0.22	0.02	0.12	−0.01	0.49	0.04	0.79	0.14	0.51	0.04
TillPass	1.11	0.20	1.26	0.11	1.34	0.11	0.05	−0.01	0.66	−0.10	0.10	−0.01
RBR	0.96	0.16	1.20	0.10	1.25	0.11	0.42	−0.04	0.96	−0.16	0.53	−0.05
TillInt	0.50	−0.06	0.63	0.05	0.47	0.04	1.00	−0.09	1.15	−0.24	1.05	−0.09
Yield	0.88	0.20	0.18	−0.02	0.19	0.02	0.51	−0.05	0.79	−0.19	0.65	−0.06
CumRain	1.03	0.09	0.87	−0.07	0.78	−0.07	1.14	−0.10	0.97	−0.02	1.15	−0.10
CumSnow	1.30	0.18	0.80	−0.07	0.51	−0.04	1.20	−0.11	0.97	−0.03	0.91	−0.08
DegDay	0.89	−0.13	0.91	−0.08	0.99	−0.08	1.10	−0.10	1.01	0.07	1.12	−0.10
PDegDay	1.30	0.30	0.72	−0.06	0.70	0.06	0.38	−0.04	0.84	−0.17	0.41	−0.04
Tmax	0.47	−0.03	0.88	−0.07	0.52	−0.04	0.45	0.04	1.03	−0.06	0.75	−0.07
PPO	0.70	−0.16	0.52	−0.04	0.59	−0.05	1.38	−0.13	0.96	−0.03	1.28	−0.11
CVSD	0.96	0.10	1.36	0.11	1.32	0.11	0.61	0.06	0.74	0.11	0.72	0.06
SWE	1.01	0.04	1.52	−0.13	1.23	−0.10	1.62	−0.15	1.43	−0.36	1.67	−0.15
AvFlow	1.29	−0.21	1.37	−0.11	1.64	−0.14	1.16	−0.11	1.15	−0.25	1.37	−0.12
PkFlow	1.06	−0.10	1.01	−0.08	1.08	−0.09	1.29	−0.12	0.93	0.02	0.98	−0.09
DurR	0.70	0.04	0.69	−0.06	0.61	−0.05	1.11	−0.10	0.79	−0.01	1.00	−0.09
VolR	1.01	−0.08	1.32	−0.11	1.31	−0.11	1.60	−0.15	1.29	−0.10	1.64	−0.14
#PLS	2 (4)‡		1 (2)		1 (2)		1 (2)		1 (4)		1 (3)	
PV	91 (97)§		74 (82)		71 (84)		68 (83)		70 (90)		67 (86)	
	LTN						LTP					
NApp	0.73	0.08	0.15	−0.01	0.19	−0.02	0.96	−0.08	0.82	−0.08	0.83	−0.08
PApp	0.32	0.08	0.32	0.03	0.13	0.01	0.73	0.06	0.53	0.05	0.59	0.06
TillPass	0.68	0.10	0.23	−0.02	0.26	−0.02	0.57	−0.05	0.68	−0.06	0.60	−0.06
RBR	0.70	0.04	0.05	0.01	0.10	−0.01	0.61	−0.05	0.49	−0.05	0.51	−0.05
TillInt	0.60	0.01	0.53	0.04	0.20	0.02	0.34	−0.03	0.05	0.01	0.12	−0.01
Yield	0.74	0.18	0.59	0.05	0.81	0.07	0.51	0.04	0.24	0.02	0.34	0.03
CumRain	1.43	0.26	1.97	0.16	1.74	0.16	1.41	0.12	1.52	0.14	1.45	0.14
CumSnow	1.47	0.23	1.14	0.09	1.35	0.12	1.51	0.13	1.08	0.10	1.22	0.12
DegDay	0.98	−0.06	1.33	0.11	1.15	0.10	1.14	0.10	1.70	0.16	1.55	0.15
PDegDay	0.85	0.27	0.63	0.05	0.17	0.02	0.01	0.01	0.84	0.08	0.15	−0.01
Tmax	0.49	−0.01	1.11	0.09	1.42	0.13	0.55	0.05	1.24	0.11	1.34	0.13
PPO	0.52	−0.04	0.24	0.02	0.19	0.02	0.05	0.01	0.25	0.02	0.15	0.01
CVSD	1.08	−0.20	0.94	−0.07	1.13	−0.10	0.96	−0.08	0.76	−0.07	0.80	−0.08
SWE	1.55	0.28	1.34	0.11	1.55	0.14	1.37	0.11	1.12	0.10	1.16	0.11
AvFlow	1.09	−0.08	0.80	0.06	0.88	0.08	1.05	0.09	0.75	0.07	1.06	0.10
PkFlow	1.18	0.03	1.15	0.09	1.00	0.09	1.43	0.12	1.18	0.11	1.22	0.12
DurR	1.41	0.31	1.70	0.13	1.57	0.14	1.63	0.14	1.68	0.16	1.66	0.16
#PLS	3 (4)		1 (1)		1 (1)		1 (1)		1 (1)		1 (1)	
PV	94 (98)		54 (54)		69 (69)		60 (60)		75 (75)		79 (79)	

† AvFlow, average flow rate; CumRain, cumulative rainfall; CumSnow, cumulative snowfall; CVSD, coefficient of variation of snow depths; DegDay, degree day during the runoff period; DurR, duration of runoff; NApp, nitrogen application rate; PApp, phosphorus application rate; PDegDay, pre-runoff degree day from 1 February to the start of snowmelt runoff; PkFlow, peak flow rate; #PLS, number of partial least squares analysis (PLS) factors; PPO, precipitation in previous October; PV, percentage of variation in response variable explained by PLS factors; RBR, residue burial ratio; SWE, snow water equivalent; TillInt, tillage intensity; TillPass, number of tillage passes; Tmax, maximum temperature during snowmelt runoff events; and VolR, volume of runoff.

‡ Number of PLS factors determined by cross validation along with CVTEST option (number of PLS factors determined by cross validation).

§ Percentage of variation explained by the first PLS factor (percentage of variation explained by the first two PLS factors).

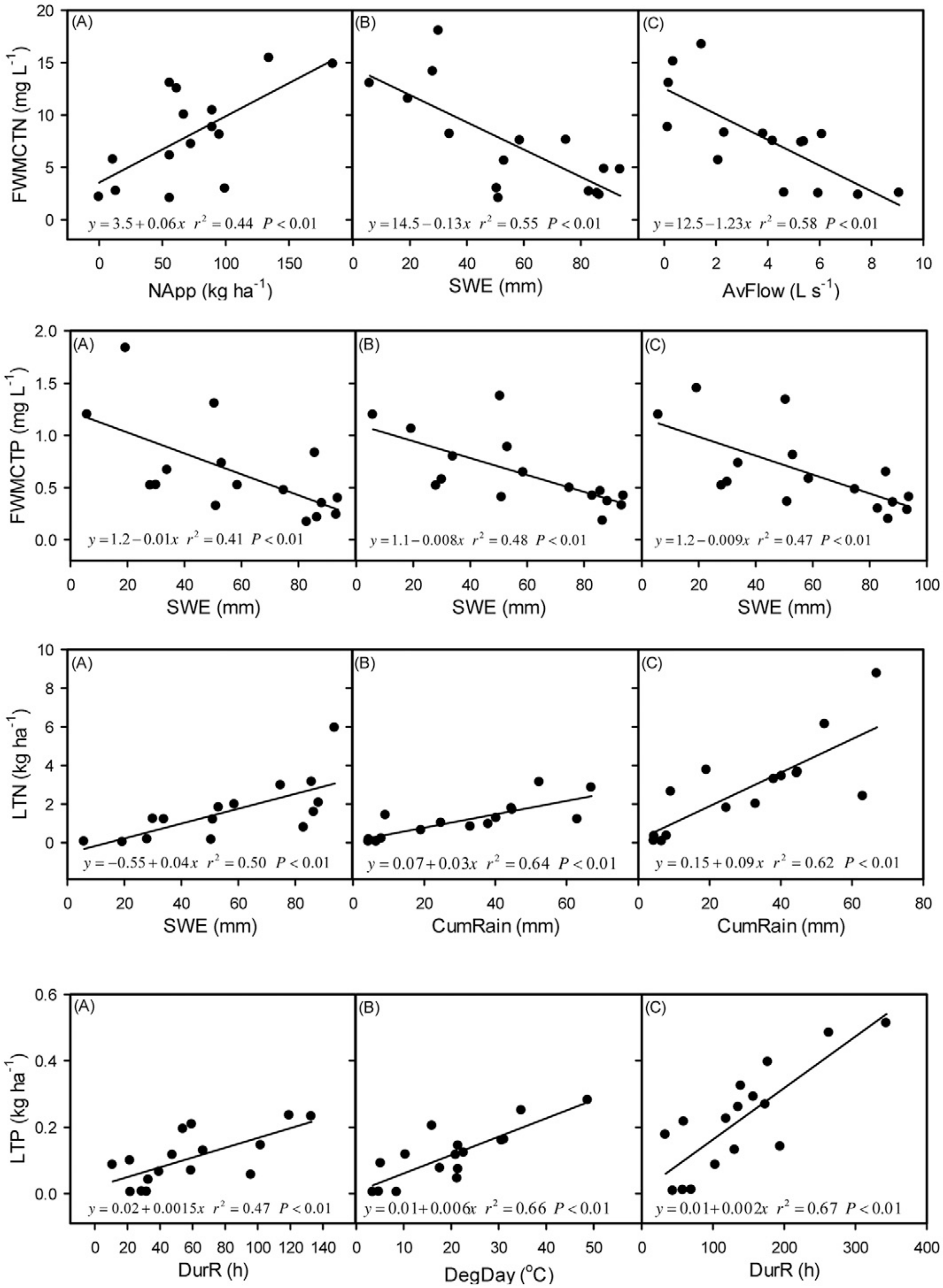

Fig. 2. Linear relationships between response variables and the most important, corresponding predictor variables in the (A) early, (B) late, and (C) yearly total snowmelt runoff periods. AvFlow, average flow rate; CumRain, cumulative rainfall; DegDay, degree day during the runoff period; DurR, duration of runoff; FWMCTN, flow-weighted mean concentration of total nitrogen; FWMCTP, flow-weighted mean concentration of total phosphorus; LTN, load of total nitrogen; LTP, load of total phosphorus; NApp, nitrogen application rate; SWE, snow water equivalent.

Nine variables, common to the yearly, early, and late runoff periods, were significant factors (VIP >0.8) affecting FWMCTP. Five of these variables (PkFlow, SWE, VolR, CumSnow, and precipitation in previous October) were the critical factors (VIP >1.2) for FWMCTP for the early runoff, two variables (SWE and VolR) for the late runoff, and four variables (AvFlow, SWE, VolR, and precipitation in previous October) for the yearly snowmelt runoff event. Nearly all of these critical factors, except for PkFlow, had negative effects on FWMCTP (Table 4). Four variables (PApp, crop yield, number of tillage passes, and variation of snow depths) were not significantly related to FWMCTP (VIP <0.8).

Load of Total Nitrogen

The three-latent-variable PLS model performed well, accounting for 94% of the variability in LTN for the early snowmelt runoff (Table 4). The one-latent-variable PLS model explained 54% of variability for the late runoff and 69% for the yearly snowmelt runoff. Nine variables for the early runoff, 9 for the late runoff, and 10 for the yearly snowmelt runoff contributed to the LTN significantly (VIP >0.8; Table 4). Among these significant factors, SWE was the most important for LTN in the early snowmelt runoff and CumRain was the most important for late and yearly snowmelt runoff. The LTN in the early, late, and yearly snowmelt runoff events was linearly related to the corresponding, most important predictor factors (Fig. 2).

Eight variables, common to the yearly, early, and late runoff periods, were significant factors (VIP >0.8) affecting LTN. Four variables (DurR, SWE, CumRain, and CumSnow) were the critical factors (VIP >1.2) for LTN for the early runoff, four variables (DegDay, DurR, SWE, and CumRain) for the late runoff, and five variables (DurR, SWE, Tmax, CumRain, and CumSnow) for the yearly snowmelt runoff. These critical factors had positive effects on LTN (Table 4). Six variables (NApp, PApp, number of tillage passes, precipitation in previous October, residue burial ratio, and tillage intensity) were not significantly related to LTN (VIP <0.8).

Load of Total Phosphorus

Performance of the one-latent-variable PLS model for LTP was best for yearly snowmelt runoff, explaining 79% of the variability (Table 4). The one-latent-variable PLS model accounted for 60% of the variability for the early snowmelt runoff and 75% for the late snowmelt runoff (Table 4). Nine variables for the early runoff, 9 for the late runoff, and 10 for the yearly snowmelt runoff had significant (VIP >0.8) contribution to variability in LTP (Table 4). Duration of runoff was the most important factor for the early and yearly snowmelt runoff, and DegDay was the most important factor for the late snowmelt runoff. These three most important factors were linearly related to LTP (Fig. 2).

Seven variables common to the yearly, early, and late runoff periods were significant factors (VIP >0.8) affecting LTP. Five variables (DurR, PkFlow, SWE, CumRain, and CumSnow) for the early snowmelt runoff, four variables (DegDay, DurR, Tmax, and CumRain) for late snowmelt runoff, and six variables (DurR, DegDay, CumRain, Tmax, CumSnow, and PkFlow) for the yearly snowmelt runoff were critical factors (VIP >1.2). These critical factors positively affected LTP (Table 4). Six variables (PApp, crop yield, number of tillage passes, precipitation in previous October, residue burial ratio, and tillage intensity) were not significantly related to LTP (VIP <0.8).

Difference in Response Variables between the Early and Late Runoff

Of the four response variables, only LTP was significantly different ($P = 0.07$) between the early and late runoff, with 33% more LTP in late runoff.

Discussion

Critical Hydrologic Factors

The large variation of VolR in the present study was similar to the previous findings by Fang and Pomeroy (2007), who reported that the discharge resulting from snowmelt on the Canadian prairies was highly unstable due to variations in weather among runoff events. Since VolR is closely related to nutrient loads as demonstrated by the mathematical relationship between nutrient load and VolR, VolR was excluded for the PLS analyses for LTN and LTP. For FWMCTN and FWMCTP, VolR was identified as one of the top three factors along with AvFlow and PkFlow, particularly for FWMCTP. The negative effect of VolR on FWMCTN and FWMCTP was likely due to the effects of dilution with an assumption of fixed rate of mobilization (Keller et al., 2008; Iida et al., 2011). Even though VolR was excluded for the PLS analysis for LTN and LTP, the importance of VolR on LTN and LTP should not be ignored. For reference, VolR was the most important factor affecting LTN and LTP when VolR was included as one of the predictor variables (data not shown). Therefore, VolR was considered to be one of the most important factors controlling N and P transport in snowmelt runoff. This is well supported by numerous studies demonstrating that VolR was the main factor affecting water chemistry in snowmelt runoff (e.g., Jamieson et al., 2003; Salvano et al., 2009; Shrestha et al., 2012).

In addition to VolR, the two flow-rate variables, AvFlow and PkFlow, were important factors for all examined response variables. Compared with the late stage of snowmelt runoff, the severely frozen soil and/or the presence of a superficial ice sheet during the early stage of runoff restricted infiltration of snowmelt water, resulting in significantly ($P = 0.09$) greater flow rate during the early snowmelt runoff period. In addition, the deeper snowpack during the early runoff may also have contributed to the greater flow rate in the early runoff. Peak flow rate in the early runoff had the greatest variability (CV = 99%) among all examined variables. Because of the large variability, there was no statistical difference in PkFlow for the two periods of runoff ($P = 0.39$), even though the numerical average for PkFlow in the early runoff was 20% greater than in the later runoff.

Together with VolR, DurR determines the intensity of runoff. The significantly ($P = 0.03$) longer DurR in the later runoff could be attributed to the lower flow rate. The positive relationship between DurR and nutrient loads (Table 4) suggested greater nutrient losses under the longer duration circumstances (i.e., the later runoff). Export of nutrients by runoff can originate from nutrients stored in snowpack, plant residues, and labile reserves in the surface soil. The longer DurR increased the period of contact between plant residues and runoff water, which allowed more nutrients to be released from the plant residues and increased total nutrient export. The nutrients remaining in the snowpack after the first flush was a minor factor in determining the loads of nutrients in northern Michigan (Stottlemyer and Toczydlowski, 1999). In comparison, a large nutrient pool in soil is an important source of nutrients, particularly at the late stage of snowmelt when the effective depth of interaction between soil and runoff increases. The longer snowmelt duration in the late runoff, as indicated by the greater DurR, increased the chances of the water–soil contact due to the reduced snowpack cover and accelerated the process of soil thawing. This increased soil–runoff contact might contribute to the large nutrient losses, partially explaining the significantly greater LTP in the late runoff.

Nutrient loss by runoff is a hydrochemical process; however, the same hydrologic predictor variable could have more important effects on one response variable than the others. For example, during the yearly snowmelt runoff, AvFlow was the most important variable for N concentration, whereas the effect of AvFlow on N load was relatively smaller, suggesting practices in reducing nutrient losses in runoff should be specific to the element of interest. Overall, all four tested hydrologic variables were interrelated to each other, and VolR was the most important factor affecting N and P in snowmelt runoff. In realistic farming management practices, VolR is difficult to manage; however, control structures that hold water on the landscape could reduce VolR and N and P losses to the downstream water systems.

Critical Weather Factors

The results demonstrated that CumSnow was one of the important factors affecting N and P in runoff for the early and late snowmelt runoff, but had a greater effect on the former period. The importance of the snowfall at the beginning stage of snowmelt runoff is consistent with previous studies. For example, Oberts (2003) reported that during the snowmelt runoff, the concentration of solute decreased with the progress of snowmelt. Han et al. (2010) also concluded that the first flush of snowmelt runoff was considered the most critical event in nutrient export. The importance of CumSnow was related to the proportion of precipitation. Averaged for the 17-yr study period from the first snow in the previous fall to the end of snowmelt runoff in the following spring, snowfall accounted for approximately 82% of the total winter precipitation, providing the majority of runoff water.

In addition to CumSnow, CumRain is one of the most important water sources for snowmelt runoff in the present study, accounting for 47% of SWE by the time of snow survey. We found that CumRain was an important factor for FWMCTN and FWMCTP and a critical factor for LTN and LTP. Particularly, CumRain was the most important factor for LTN in the yearly snowmelt runoff. The importance of CumRain in N and P export was related to the large proportions of rainfall in total precipitation and the accelerated snowmelt caused by rainfall. During the yearly snowmelt runoff period, rainfall accounted for 49% of total precipitation, providing considerable amount of water for runoff. Energy in the raindrops and reduced snow albedo caused by rain on snow can accelerate the snowmelt process. As well, rain on the bare, thawed surface soil during the late stage of snowmelt runoff, together with raindrop splash effects, could trigger soil erosion (Su et al., 2011). The relatively larger percentage of particulate nutrients in the late snowmelt runoff suggested the occurrence of slight soil erosion during the late stage of runoff. Since particulate P was bound to soil particles, the slight soil erosion may have contributed to the significant increase in total P losses in the late runoff. Similarly, Su et al. (2011) concluded that a large amount of rainfall during snowmelt was the most important weather factor influencing P losses. In addition, increased P losses in the late runoff may also have been due to increases in the effective depth of interaction between runoff and soil as the soil thawed, allowing more interaction between meltwater, soil particles, and plant residues.

Snow can be unevenly distributed due to redistribution by wind and topographic conditions. Snow depths on the field in any given year varied in the present watershed study and more snow accumulated in places with lower elevation. The variation of snow depths as indicated by coefficient of variation of snow depths was an important factor for FWMCTN during the early snowmelt runoff and a critical factor for FWMCTN during the late and yearly snowmelt runoff events (Table 4). The positive effects of variation of snow depths on FWMCTN could be due to the increased N mineralization caused by unevenly distributed snow depths during snow seasons. Judd et al. (2011) found that a deep snowpack insulated soils from the cold air and allowed biological N transformation in the winter. In addition, Han et al. (2010) reported that shallow snow cover on soil increased the severity of soil freezing and hence root mortality, which released nutrients for transport in spring snowmelt runoff. Consequently, the varying snow depths probably increased soil mineral N (at the end of snowmelt runoff) and positively affected FWMCTN. Contrary to the positive effect on FWMNTN, variation of snow depths had a negative effect on LTN. This was likely attributed to the reduced VolR due to unevenly distributed snow. Uneven insulation by the snowpack would result in areas of unfrozen surface soil, which would increase water infiltration. Su et al. (2011) reported that soil status (frozen vs. unfrozen soil in the 0- to 5-cm layer) was one of the two most important factors affecting nutrient exports during snowmelt runoff because unfrozen soil increased meltwater infiltration and decreased VolR. Similarly, Cockburn and Lamoureux (2008) reported that the varying snow cover modified the volume and intensity of runoff and then nutrient export.

Among all examined weather predictor variables, SWE was identified to be the most important with VIP values consistently larger than 1.0. The importance of SWE is related to its effects on VolR and nutrient export (Suzuki et al., 2005; Cockburn and Lamoureux, 2008). The snowpack not only provides a source of water but also supplies nutrients. In the present study, measurements of N and P concentrations in the snowpack began in 2004. From 2004 to 2010, the N concentration in snowpack averaged 1.11 mg L^{-1} and P concentration averaged 0.09 mg L^{-1}. According to the SWE and corresponding nutrient concentration, we estimated that nutrients in the precipitation were equivalent to approximately 23% of total N export and 24% of total P export. This relatively large quantity of nutrients in precipitation may contribute to the importance of SWE in N and P export for snowmelt runoff. In addition, we found that per unit increase in SWE could increase LTN export by 0.039 kg N ha^{-1} in the early runoff. The negative effect of SWE on FWMCTN and FWCTP in runoff was likely due to a dilution effect. This dilution effect would be expected under conditions of our study where most of the lost nutrients were in dissolved forms.

An indicator of antecedent soil moisture, precipitation in previous October, was one of the important drivers for FWMCTP. Similarly, Jamieson et al. (2003) reported the importance of antecedent soil moisture content in P losses in snowmelt runoff, with less P loss under drier conditions. In the current study, FWMCTP was primarily controlled by SWE and VolR. Snow water equivalent and VolR were strongly correlated ($r^2 = 0.73$) and SWE determined VolR to a great extent, suggesting FWMCTP was mainly controlled by discharge. Soil moisture was reported to be an important factor affecting discharge during snowmelt (Jamieson et al., 2003; Fang and Pomeroy, 2007). On the Canadian prairies, Fang and Pomeroy (2007) reported that snowmelt runoff decreased dramatically with low soil moisture due to substantial infiltration into unsaturated frozen soil. Therefore, the effect of precipitation in previous October on FWMCTP is closely related to water infiltration and VolR. The negative relationship between precipitation in previous October and FWMCTP was likely due to the dilution effects by higher VolR from the higher precipitation.

Temperature determines the start point of snowmelt runoff to a great extent. The temperature-based variable, DegDay, was an important factor for all examined response variables. This is supported by numerous findings indicating that DegDay is a key temperature index parameter in modeling snowmelt process (Singh et al., 2000; Li and Williams, 2008). Another temperature variable, Tmax, was not important for the early runoff for any of the response variables; however, Tmax was an important or critical factor during the late runoff. Similarly, DegDay had a larger effect for the late runoff than for the early runoff. At the beginning of snowmelt, the field was covered by snow and the effect of temperature is mainly on snow alone. As snowmelt progresses, the snow cover becomes thinner and the temperature gradually affects soil nutrient transformations such as dissolution, desorption, and mineralization. Also, as mentioned before, the effects of these processes will also be greater as the effective depth of interaction between runoff water and soil increases during thawing. Nutrients from soils and plant residues represent most of the total nutrient export in the current study and in other studies (Stottlemyer and Toczydlowski, 1999; Townsend-Small et al., 2011). The temperature effect on soil in the late runoff explained why Tmax and DegDay had larger effects during the late runoff than during the early runoff. Cockburn and Lamoureux (2008) reported that snowpack depth in combination with thermal conditions determined the volume and intensity of snowmelt runoff. The intensified snowmelt caused by high Tmax and DegDay in our study likely resulted in high PkFlow, and potentially increased soil erosion later in runoff. This, along with the effect of thawing on the depth of interaction between runoff and soil, might explain the positive relationship between LTP and the temperature indices, Tmax and DegDay.

Weather factors affected N and P exports in snowmelt runoff through different processes. For instance, CumSnow and CumRain affected nutrient exports presumably by providing water and nutrient sources. In comparison, the temperature indices, along with CumRain, affected nutrient exports probably by governing snowmelt patterns and runoff intensity. The difference in weather factors between the early and late snowmelt runoff might also modify nutrient export in the late runoff compared with the early runoff. Overall, SWE was identified as the most important weather factor controlling N and P transports in snowmelt runoff.

Critical Management Practices

Our results indicate that NApp was a critical factor controlling FWMCTN with a positive effect (Table 4). Similarly, a positive correlation between fertilizer N rate and stream N concentration was reported in a large-scale watershed study (Tisseuil et al., 2008). Although NApp contributed significantly to the variation in FWMCTN, NApp had no effect on LTN. In the same study region, however, Corriveau et al. (2011) reported significant effects of N usage on differences in LTN among watersheds. The study by Corriveau et al. (2011) was conducted on larger watersheds and excessive N applications in some of the watersheds could have resulted in the response of LTN. The LTN appears to be less responsive to N application rates determined by soil testing as in our single-site study.

Phosphorus application rate was not an important factor for either FWMCTP or LTP at any stage of snowmelt runoff. However, in other studies, P rates have been reported to be an important control on transport of P in surface runoff (Moog and Whiting, 2002; Buda et al., 2009), particularly when P applications are recent (Hart et al., 2004). In our study, P application rates were modest and all P application occurred in the spring of the previous year, more than 10 mo and one crop before runoff. Also, unlike applied fertilizer N, which remains highly soluble, applied fertilizer P is stabilized in soil by precipitation and adsorption reactions, making it relatively resistant to mobilization in the dissolved form. In addition, the majority of spring snowmelt runoff occurred on partially frozen soil, resulting in small amounts of soil erosion and small losses of particulate P. The reduced water erosion, the soil-P buffering capacity, and the timing and modest rates of P application are probably the reasons for the absence of a PApp effect on P in the runoff in this study. The study by Corriveau et al. (2011) also failed to find a relationship between fertilizer application and P transport.

To test if soil N and P were driving factors for N and P in snowmelt runoff, a data set starting in 1997 rather than in 1993, but including soil N and P as predictor variables, was analyzed using PLS method. The results indicated that neither soil N nor P was a factor driving N or P in runoff from this field, since the VIP values of soil N and P were smaller than 0.8 (data not shown). The majority of snowmelt runoff occurred on frozen soil in the study region and soil–runoff interaction would be minimal, weakening soil effects on N and P export. In contrast, Little et al. (2007) reported soil test P was linearly related with FWMCTP in a watershed study in Alberta. The Alberta study was conducted at multiple sites, including sites with extremely high soil test P, which provided a large variation of soil nutrients (e.g., <10 to up to 500 mg kg^{-1} of soil test P) to which water quality variables could respond. In contrast, the current study spanned >10 yr but was limited to one site. In our study, soil test P ranged from 7 to 23 mg kg^{-1} with a CV of 33%. These values for soil test P are not nearly as great as those for the study by Little et al. (2007) and, in fact, Little et al. (2007) found no significant relationship between runoff P and soil test P when they considered only the sites that had soil test P values <50 mg kg^{-1}. Similarly, the range in soil test N values was also relatively narrow, varying from 7.3 to 17.3 mg kg^{-1} with a CV of 28%. Therefore, compared with hydrologic and weather data, soil N and P were very stable on the site where fertilizer N and P were applied based on soil test recommendations. The consistency of soil N and P during the study period might explain why soil test N or P were not important compared to the highly variable weather and hydrologic factors.

The FWMCTN and FWMCTP in runoff responded to the number of tillage passes differently. The number of tillage passes was one of the critical factors for FWMCTN, but the least important factor for FWMCTP. Tillage operations break soil aggregates and accelerate N release from soil organic matter, thus affecting nutrient concentrations in runoff. In addition, more tillage passes were likely associated with greater weed populations; consequently, the more tillage passes, the more weed biomass and crop residues were buried. The mineralization of the buried plant biomass can also release nutrients. The released inorganic N from soil aggregates and plant residues would be available for transport in snowmelt. Consequently, the number of tillage passes had a positive, significant effect on FWMCTN. The response of P to the number of tillage passes was different than for N. Phosphorus losses are often closely associated with soil erosion since P is tightly bound to soil particles. However, on the Canadian prairies, spring snowmelt runoff occurs mainly on frozen soil (Little et al., 2007), resulting in low rates of erosion. Similarly, soil erosion was not severe at our study site, explaining the lack of response of P to the number of tillage passes. Another source of P in snowmelt runoff is release on freezing from actively growing plant material (Elliott, 2013). Weed control by fall tillage would eliminate this source and reduce P available to interact with runoff and hence reduce FWMCTP.

Tillage-related variables (number of tillage passes, tillage intensity, and residue burial ratio) were not important factors, neither for LTN nor LTP. However, a previous study at the same site demonstrated that contrasting tillage systems (conventional vs. conservation tillage) substantially modified N and P exports during snowmelt runoff (Tiessen et al., 2010). Compared with the contrasting tillage systems, the current study was conducted only in the conventional tillage system and any tillage interaction was not able to be tested. Therefore, the relatively consistent annual tillage operations could explain why tillage had no effect on LTN or LTP.

Compared with hydrologic and weather factors, the range of management practices for this field was much narrower during the 17-yr experimental period and may explain why management practices were less important in controlling N and P losses in snowmelt runoff. As a result, among the management variables, only NApp and the number of tillage passes were identified as critical factors, and only for the concentration of N in snowmelt runoff.

Conclusions

The results for our 17-yr field-scale watershed study indicated that the driving factors for annual changes in FWMCTN, FWMCTP, LTN, and LTP were different, suggesting the effective practices in water quality protection for a given field need to be specific to the nutrient element of interest. Since N application rate and number of tillage passes were critical factors having a positive effect on FWMCTN, reducing N application rate and number of tillage passes may assist in decreasing FMWCTN. In comparison, SWE and VolR were the top two driving factors negatively affecting FWMCTP due to a dilution effect. Compared with FWMCTN and FWMCTP, the DurR had a larger effect on LTN and LTP. The driving factors were also different for the early snowmelt runoff compared with the later snowmelt runoff, and significantly more LTP was lost in the later runoff, probably because of the increasing depth of interaction between runoff and soil and slight soil erosion. Volume of runoff was identified as one of the top three factors, together with average and peak flow rates, affecting nutrient concentration, and is a critical factor for nutrient load because of the relationship between nutrient load and VolR. For the yearly total snowmelt runoff, degree day, SWE, AvFlow, and PkFlow were identified as important factors controlling all examined response variables. When considering all response variables during different stages of runoff, SWE was the most important factor (VIP >1.0) among all 17 predictor variables (excluding VolR). The identification of critical factors controlling N and P in snowmelt runoff from this field-scale watershed will aid in the design of effective practices to reduce agricultural nonpoint nutrient pollution in downstream waters.

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