Journal of Environmental Quality
SPECIAL SECTION
AGRICULTURAL WATER QUALITY IN COLD ENVIRONMENTS

Seasonal Variation in Sediment and Phosphorus Yields in Four Wisconsin Agricultural Watersheds

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Abstract

Agricultural water quality projects in two distinct topographic regions in Wisconsin collected 5 to 10 yr of continuous stream discharge, suspended sediment (SS), total P (TP), and total dissolved P (TDP) in four watersheds (2100–5000 ha) from 2006 to 2016. Previous agricultural nonpoint SS and TP reduction efforts in two of these watersheds documented cold versus warm season differences in water quality response. The goal of this study was to identify seasonal partitioning of SS, TP, and TDP in storm event loads to inform stream water quality protection efforts. We used National Weather Service Coop Observer frost depth reports to identify dates when watershed soils were frozen. By comparing daily mean event discharge for dates relative to frost, we identified a 32-d post-frost high-discharge "thaw" period. Combined, the frozen and thaw periods contributed about half of the annual SS and TP runoff event loads, ranging from 47 to 63% for SS and from 45 to 51% for TP. The proportion of runoff event TDP during this time was even higher, 62 to 79%, with the majority during thaw. Watershed average volumetric runoff coefficients (event flow/precipitation and snowmelt) were two to four times higher during the freeze and the thaw compared with the rest of the year. To reduce total stream loads in regions with similar climates to Wisconsin, this study indicates that using management practices that curb sediment and P delivery to streams in the winter and early spring may be as important as those designed for nonfrozen conditions.

Core Ideas

- About half of stream event suspended sediment and total P loads were during frost and thaw.
- A majority of annual event total dissolved P loading was during thaw.
- Watershed average runoff coefficients were higher in frost and thaw.

J. Environ. Qual. 48:950–958 (2019)
doi:10.2134/jeq2019.03.0134
Supplemental material is available online for this article.
Received 23 Mar. 2019.
Accepted 3 June 2019.
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In Wisconsin, as in other states in the US Upper Midwest, soils typically freeze for 3 to 4 mo in the winter (Hahn, 2017). Most of the runoff and total phosphorus (TP) loads from agricultural fields can be from snowmelt and rainfall on frozen soils, depending on field conditions and weather (Komiskey et al., 2011; Stuntebeck et al., 2011; Good et al., 2012). Efforts to curb TP losses from winter runoff in northern US states have often focused on manure management and restrictions on manure application to frozen and snow-covered soils (Fallow et al., 2007; Williams et al., 2011; Liu et al., 2018) rather than on soil conservation. Suspended sediment (SS) loads from cropland-derived runoff over frozen and thawing soils are typically low compared with storm events when the soil is not frozen, whereas total dissolved P (TDP) loads may be comparatively high (Panuska et al., 2008; Stuntebeck et al., 2011). Measured SS and TP loads in Wisconsin's rural streams can be greater in the nongrowing season (November–April) than in the growing season, with the highest loadings in the months associated with the spring thaw (Danz et al., 2010). The 6-mo November through April period often designated as the nongrowing season includes a month or more before the soil is frozen and additionally some time post-thaw. Length and timing of soil frost throughout Wisconsin vary from year to year (Hahn, 2017), and studies have not typically delineated stream yields by frozen and nonfrozen periods.

This report summarizes monitoring data on year-round sediment and P loads for four agricultural watersheds (Fig. 1) collected for paired watershed projects (Ertman, 2017; Carvin et al., 2018). Research in one of the watershed pairs suggested a frozen versus nonfrozen seasonal difference in SS load response to conservation practice implementation (Carvin et al., 2018). An earlier conservation project in one of the other watersheds also indicated a seasonal (vegetative versus nonvegetative) difference in response to watershed-wide efforts to reduce stream storm loads of SS and TP (Corsi et al., 2005).

Given the contrasting seasonal results from the two studies, we seek to understand seasonal differences in stream loading to inform agricultural watershed SS and TP reduction efforts. Our objective is to use the continuous stream monitoring data from the four watersheds, coupled with the projects'

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Abbreviations: MRCC, Midwestern Regional Climate Center; NWIS, National Water Information System; NWS, National Weather Service; SS, suspended sediment; TDP, total dissolved phosphorus; TP, total phosphorus.

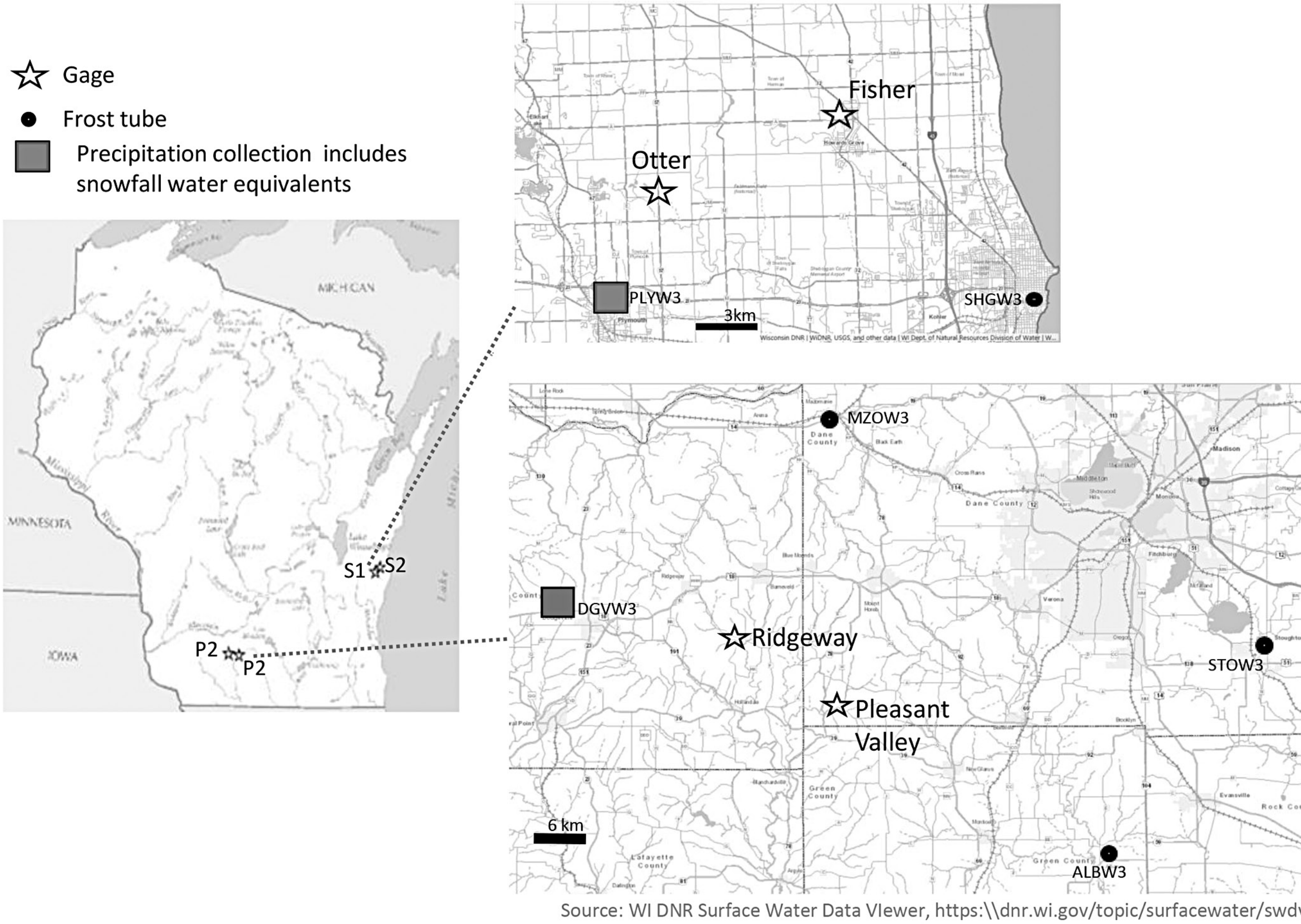

Fig. 1. Location of study watershed gages, frost depth recordings, and precipitation collection sites in Wisconsin.

agricultural land inventories to compare stream discharge, SS, TP, and TDP yields when the soil is frozen and thawing with those for the nonfrozen seasons.

Materials and Methods

Study Watersheds

The first two study watersheds, Pleasant Valley (P1) and Ridgeway (P2), are in the unglaciated region of Wisconsin in the Pecatonica River basin and have been previously described (Carvin et al., 2018). The second set of watersheds, Otter Creek (S1) and Fisher Creek (S2), are in the previously glaciated region of Wisconsin in the Sheboygan River basin. All four watersheds had a combination of beef, dairy, and cash grain farms, with similar grain and forage crop rotations. Compared with the Pecatonica watersheds, P1 and P2, the Sheboygan watersheds, S1 and S2, are smaller and less steep, with a greater percentage of land in cropland and soils with a greater clay content (Table 1). The Sheboygan watersheds also have more poorly drained areas, as evidenced by each having 6% of their land in wetlands compared with <1% for the Pecatonica watersheds.

Stream Water Quality Monitoring and Hydrograph Separation

The USGS installed streamflow-gaging and water-quality monitoring stations at the outlets of P1 (USGS Station 05432927) and P2 (USGS Station 05432695) in fall 2006 and at the outlets of S1 (USGS Station 040857005) and S2 (USGS Station 040854592) in summer 2011. Gaging, sampling, and analysis protocols are described in Carvin et al. (2018) for year-round water sample collection during low-flow periods (baseflow) and during rain-on-snow, snowmelt, and rain events from October 2006 through September 2016 in P1 and P2 and from October 2011 through September 2016 in S1 and S2. Streamflow (discharge), SS, and TP samples were collected for the entire monitoring periods for all watersheds. In P1 and P2, TDP samples were not collected during events until October 2009. In S1 and S2, TDP was collected at all SS and TP sampling times, except it is not available for S2 for the year ending in September 2016.

Calculation of daily mean discharge and loads for SS, TP, and TDP were described in Carvin et al. (2018). Daily mean loads and concentrations are available to the public through the USGS National Water Information System (NWIS; USGS, 2018). We used the USGS Hydrograph Separation Program (HYSEP; Sloto and Crouse, 1996) fixed-interval method to identify the baseflow components of stream loads. We then calculated storm and snowmelt runoff event loads by subtracting the baseflow component from the stream total load. Event discharge was also calculated as total discharge minus baseflow. We calculated flow-weighted stream SS, TP, and TDP concentrations for each watershed for the frozen soil, thaw, and nonfrozen seasons by summing mean daily discharge multiplied by the mean daily concentration for all the days in the season and then dividing by the sum of mean daily discharge for the season.

Identifying the Frozen Soil Period

Soil frost-in and frost-out dates were derived from frost depth measurements recorded in the National Weather Service (NWS) Coop Observer Reports (Hahn, 2017; NWS, 2018; Fig. 1). Measurements are made twice weekly in grassy sites with NWS frost depth gages monitored by volunteers. The primary site used for P1 and P2 was Stoughton (STOW3), as it was the closest site with the most complete record, and frost dates were crosschecked using the measurements at Mazomanie (MZOW3) and Albany (ALBW3) when available. The measurement location used for S1 and S2 was Sheboygan (SHGW3), and we confirmed frost dates with measurements in neighboring counties (not shown in Fig. 1). We define frost-in as the first date with recorded frost depth >2.5 cm that continued for more than 1 wk. Frost-out was the first date with no recorded frost depth without refreezing in consecutive weeks. Frost depths varied from site to site across Wisconsin even at similar latitudes. The sites themselves are not close enough together to determine how much variability we could expect within a watershed. Given the pattern of frost-in and frost-out across the closest sites to the study watersheds, we consider these frost dates to be generally accurate within 10 d (i.e., frost was likely to be completely in or out of the watershed within a window including 10 d prior to and 10 d after our designated frost-in or frost-out date). The annual frost-in and frost-out dates were identified for 2006 to 2016 for P1 and P2 and 2011 to 2016 for S1 and S2.

Calculating Water Available for Runoff and Runoff Coefficients

Daily precipitation (rain plus snow water equivalent), snowfall depth, snow depth on ground, and mean temperature data were obtained from the closest sites with continuous snowfall records in the Midwestern Regional Climate Center (MRCC) database: Dodgeville (NWSLI DGVW3) for P1 and P2, and Plymouth (NWSLI PLYW3) for S1 and S2 (MRCC, 2018). For P1 and P2, USGS published onsite daily rainfall but not snow water equivalent for October 2006 through September 2011 (NWIS; USGS, 2018). Onsite precipitation is not available for S1 and S2. Whenever onsite rainfall records were unavailable, we used daily rainfall records from the same MRCC sites used for snowfall records. When snow was present, we calculated daily volumes of water released from snowmelt or rain on snow using a variation of the degree day method (USDA-NRCS, 2004) with a degree day coefficient for melt of 0.59 cm $°C^{-1}$ d^{-1} and a snow water-holding capacity of 0.07 cm cm^{-1} snow. We calculated seasonal average watershed volumetric runoff coefficients for three seasons (frozen soil, thaw, and nonfrozen) by dividing the sum of daily event discharge in a season by the sum of daily rainfall and snow water release in that season.

Results and Discussion

Seasonal Distribution of Suspended Sediment and Phosphorus Yields

Mean daily rainfall and snow water release and stream SS, TP, and TDP yields for each watershed are in Fig. 2. All watersheds had runoff event-related peaks in mean daily SS and TP yields in March through April. In P1 and S2, the late winter–early spring period included the largest peaks in mean yields for both TP and SS. In P2, TP yields peaked in March, but SS yields reached higher daily means in the summer (July and August). In S1, there was a peak in both TP and SS resulting from 6 cm of rainfall over 3 d in mid-December in 2015, when the soil was not yet frozen; S2 also had high SS and TP yields for this storm, but not to the same extent. In general, TDP yields peaked with TP in all watersheds, but the peaks were not as pronounced, with TDP constituting a lower proportion of TP when TP yields were highest (Fig. 2).

Storm and Snowmelt Event Flows

All four streams are groundwater fed with perennial baseflow, although P1 and P2 have a larger proportion of the total streamflow from baseflow than S1 and S2 because of abundant

Table 1. Land use in study watersheds and selected watershed characteristics (Ertman, 2017; USGS, 2017; Carvin et al., 2018; C. Ertman, Sheboygan County Land Conservation Department, written communication, 2018; USDA-NRCS, 2018).

Characteristic	P1	P2	S1	S2
Area (ha)	4977	4923	2121	2467
Land use type (% total area)				
Cropland	34	34	58	65
Pasture	8	11	1	1
Woodlands	28	27	10	11
Grassland	25	24	13	9
Wetlands	<1	<1	6	6
Other (residential, transportation)	5	5	12	8
Watershed characteristics				
Mean annual precipitation (mm)	891	908	876	824
Mean annual snowfall water equivalent (mm)†	62	67	80	79
Soil surface texture	Silt loam	Silt loam	Silt loam, clay loam, loam, silty clay	Silt loam, clay loam, sandy loam, silty clay loam, loam, silty clay
Avg. cropland slope range (%)	6–12	6–12	2–6	2–6
Poorly drained soils‡ (%)	6	5	19	33
Cropland avg. soil-test P (Bray P1, mg kg^{-1})	41	37	37	25

† This is a subset of mean annual precipitation and was estimated as mean snowfall depth divided by 14 as per Stuntebeck et al. (2011).

‡ Soils mapped as somewhat poorly, poorly, or very poorly drained.

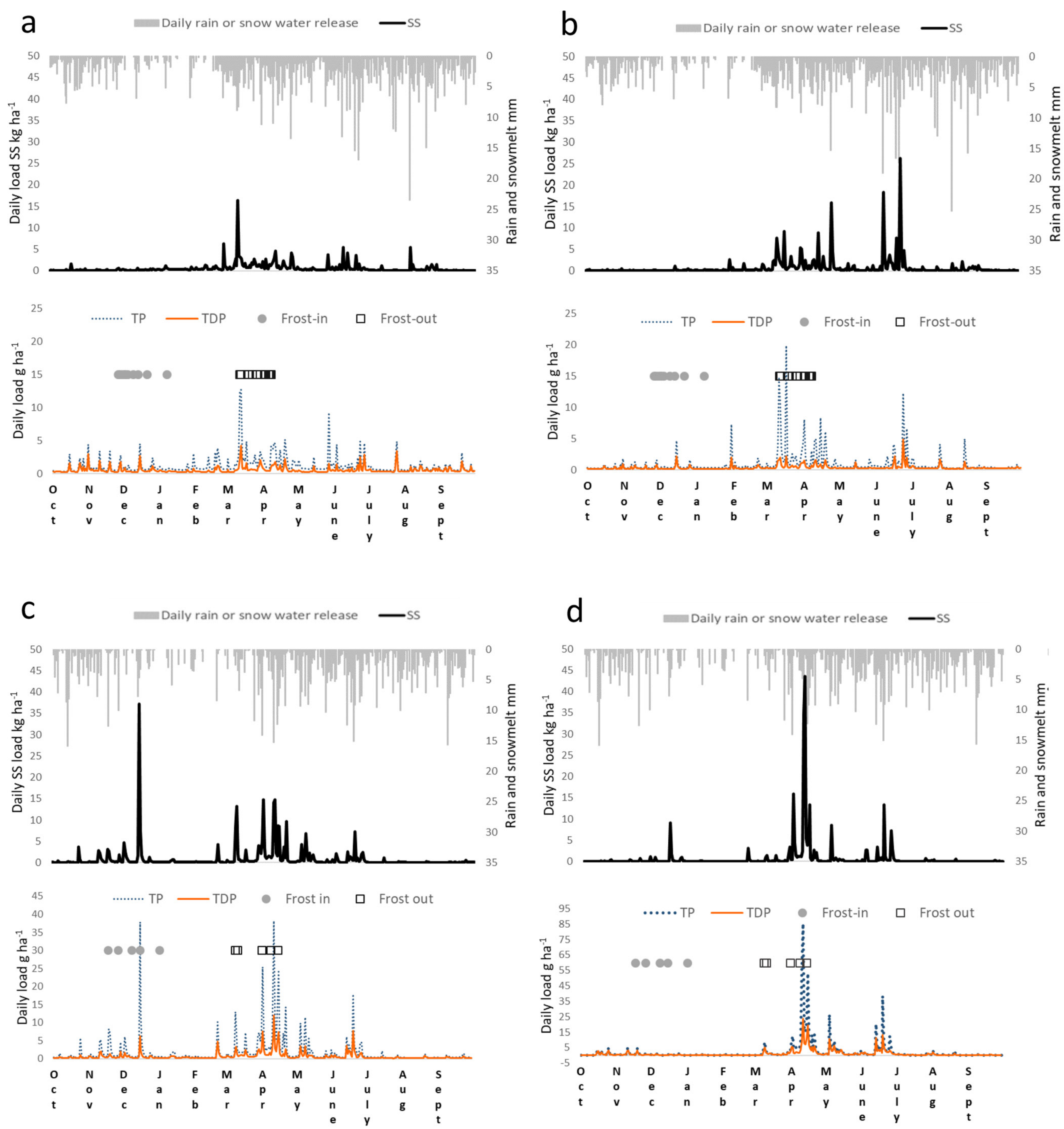

Fig. 2. Mean daily rain or snow water release, suspended sediment (SS), total P (TP), and total dissolved P (TDP) yields for four watersheds: (a) P1, October 2006 through September 2016 (TP and TDP start October 2009), (b) P2, October 2006 through September 2016 (TP and TDP start October 2009), (c) S1, October 2011 through September 2016, and (d) S2, October 2011 through September 2016 (TP and TDP through September 2015). Symbols mark frost-in and frost-out dates for each monitoring year. Note the differences in scale on the axis for the TP and TDP loads between Panels a–b, c, and d.

springs in Driftless Area watersheds (WDNR, 2013). Logically, effects of field-based management practices on stream SS and TP are most likely to be observed during event flows resulting from rain, rain on snow, or snowmelt runoff. Averaged over all years of daily streamflow records, event flow was the minority of discharge for all watersheds, ranging from 10 to 16% for P1 and P2 to 26 to 38% for S1 and S2 (Table 2). In contrast, the majority (60– 81%) of SS was transported in events rather than baseflow, and event TP loads were half or more of total loads for all watersheds. Higher event versus baseflow loads of SS and TP in these watersheds is consistent with the findings of Danz et al. (2010) for similarly sized watersheds in the same regions. Event TDP loads were 40 to 52% of total TDP loads.

Compared with P1 and P2, S1 and S2 had two to four times more total discharge in event flow (Table 2). This reflects the higher clay content of soils and the greater proportion of wetland and poorly drained areas in S2 and S1 (Table 1). Single tile lines draining wet areas or waterways are located in an estimated

Table 2. Events as a percentage of total for stream discharge and suspended sediment (SS), total P (TP), and total dissolved P (TDP) loads for four watersheds.

Watershed	Events			
	Discharge	SS	TP	TDP
	% total			
P1†	10	60	50	41
P2†	16	77	57	40
S1‡	26	75	61	52
S2§	38	81	61	51

† Discharge, SS, and TP from October 2006–September 2016. TDP October 2009–September 2016.

‡ October 2011–September 2016.

§ Same as above for S1, except TDP through September 2015.

30% of the fields in S1 and 60% in S2 (C. Ertman, Sheboygan County Land Conservation Department, written communication, 2018). These lines may enhance routing of surface flow to the stream by draining areas where runoff collects.

Examination of mean daily event discharge further demonstrates hydrologic differences between the pairs of watersheds (Fig. 3). The daily event discharge shows similar seasonal patterns for the watersheds within a pair, but the pairs are notably different from each other. Mean daily event discharge was greater in the late spring, summer, and early fall than in the late winter and early spring in P1 and P2 (Fig. 3a). In contrast, event discharge peaked in April in S1 and S2, with comparatively lower discharge rates in the summer and very low rates in the fall (Fig. 3b). One cause of this difference in event discharge patterns is climatic, as there is less annual precipitation and more precipitation as snowfall in S1 and S2 (Table 1). The August spikes in P1 and P2 resulted from record-setting rains of 460 mm over the month of August 2007.

Frozen Soil and the Thaw Transition Periods

Average soil frost-in period for P1 and P2 for the winters from December 2006 through April 2016 was 110 d, with a minimum of 75 d in 2015–2016 and a maximum of 130 d in 2008–2009. Frost-in dates ranged from 26 November to 7 January and frost-out ranged from 11 March to 6 April in P1 and P2 (Fig. 2a and 2b). The average duration of frozen soil for S1 and S2 for the winters of 2011–2012 through 2015–2016 was 110 d. The shortest frost-in period was 70 d in 2015–2016, and the longest was 139 d in 2013–2014. Frost-in occurred as early as 17 November and as late as 31 December, whereas frost-out dates also varied by more than a month, from 8 March to 14 April (Fig. 2c and 2d).

To relate the peaks observed in discharge in late winter and early spring to frost conditions, we plotted mean daily event discharge by days relative to the frost-out date for all available discharge data. We identified a high-event transition period lasting ∼22 d from frost-out (Supplemental Fig. S1 and further explanation in the supplemental data). We designated these 22 d plus the 10 d prior to the frost-out day (to account for the uncertainty in the frost-out date) as the transition "thaw" period. Thaw, thus defined, was 9% of the days of each year. We categorized all events from the frost-in date to the start of thaw as frozen; the length of this season varied from year to year. Events during the frozen period resulted from midwinter warm periods usually involving rain on snow or frozen ground. Events during the thaw were caused both by snowmelt and by rain on snow or bare ground. More than one-third of event discharge in S1 and S2 occurred during thaw, whereas in P1 and P2, thaw accounted for <20% of event flow (Table 3).

Seasonal Runoff Coefficients

Seasonal watershed average volumetric runoff coefficients (sum of daily event flow for season/sum of daily rainfall or snow water release for season) are useful for distinguishing seasonal patterns in runoff versus infiltration. In all watersheds, runoff coefficients were two to four times higher during freeze and thaw compared with the rest of the year (Table 3), consistent with minimal evapotranspiration and comparatively low drainage rates December through March in this region (Twine et al., 2004). Runoff coefficients for the more poorly drained S1 and S2 were at least double those for P1 and P2 in all seasons, likely a result of poorer drainage (Table 2). Drainage affects both nonfrozen and frozen soil infiltration. Frozen soil infiltration rates are lower with increasing soil ice content, and the wetter the soil is when freezing, the lower the permeability (Lundberg et al.,

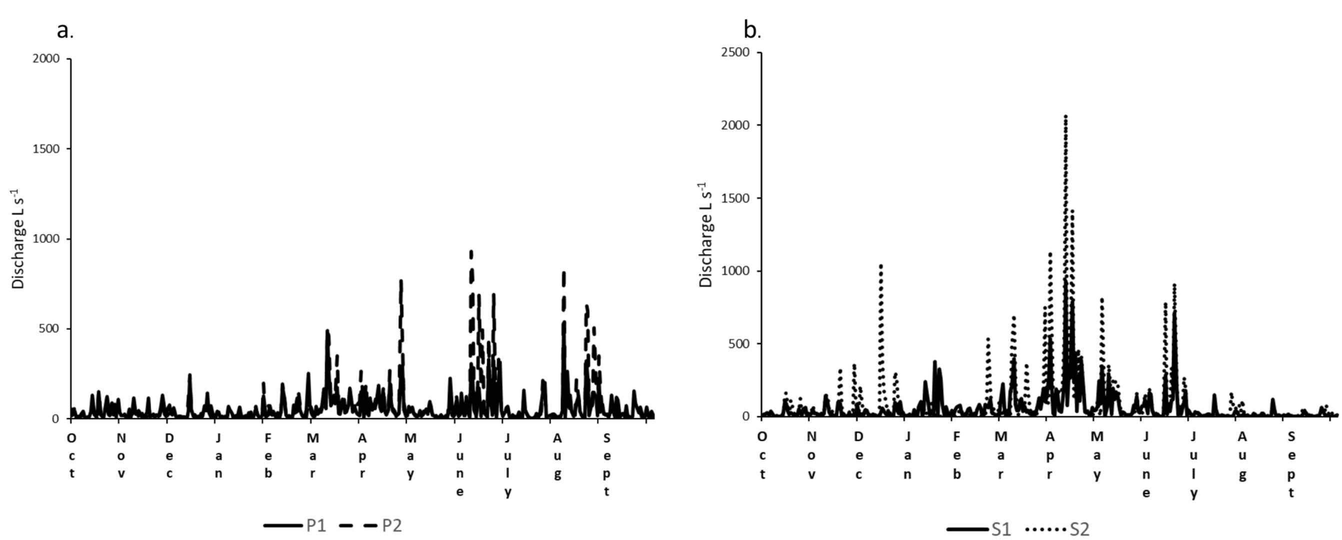

Fig. 3. Average mean daily event flow discharge for the four study watersheds: (a) P1 and P2, October 2006 to September 2016, and (b) S1 and S2, October 2011 to September 2016.

2016; Mohammed et. al., 2018). Macropores allow infiltration in unsaturated frozen soils but can become blocked when infiltrating snowmelt refreezes in freeze–thaw cycles (Mohammed et al., 2018). Possibly the higher thaw runoff coefficients in S1 and S2 compared with frost are a result of saturation of both matrix and macropore flow channels. In addition to drainage, the higher proportions of cropland compared with woodlands and grasslands likely contribute to lower infiltration rates in all seasons (Mishra et al., 2010; Xu et al., 2013; Lundberg et al., 2016).

With the exception of the frozen and thaw seasons for S1 and S2, these "lumped" seasonal runoff coefficients are generally lower than watershed runoff coefficients calculated using median or average event runoff coefficients (Dhakal et al., 2012). In contrast, seasonal runoff coefficients from individual agricultural fields in Wisconsin calculated using the same method were similar or lower, with median values of 0.04, <0.01, 0.01, and 0.25 for spring, summer, fall and winter, respectively (Good et al., 2012). In addition to representing increased P transport potential due to increased runoff flow volume, higher runoff coefficients lead to an increase in runoff P concentrations when soluble-P-containing materials like manure or fertilizer are on the soil surface (Vadas et al., 2019).

Seasonal Distribution of Event-Related Suspended Sediment and Phosphorus

Seasonal distributions of event SS, TP, and TDP yields were similar to those for event flows except that the proportions of total yields during thaw were always larger than the proportion of total discharge during thaw (Fig. 4). This is because flow-weighted concentrations of SS, TP, and TDP are higher during thaw than during other seasons (Table 4). The percentages of SS and TP event yields in the frozen period were small compared with thaw except for in P1 (Fig. 4b and 4c). The higher frozen period SS in P1 is primarily a result of rainstorms in February and March 2009, both with >3 cm of rain with no snow cover and fluctuating temperature conditions similar to thaw. The proportion of total SS that occurred during the thaw period alone ranged from 24% for P1 to 61% for S2, and when combined, the frozen and thaw periods accounted for 47 (P2) to 63% (S2) of SS yields (Fig. 4b). Similarly, TP yields during frozen soil and thaw combined ranged from 45 (P1) to 51% (P2 and S2) of the total (Fig. 4c). Median daily event loads were generally higher during the thaw relative to frozen soil and nonfrozen periods for both SS and TP, yet all watersheds had high load outliers (defined as exceeding the third quartile by 1.5× the difference between the first and third quartiles) for event SS, event TP, or both (Supplemental Fig. S2). This is consistent with observations that high loading events commonly dominate total event SS and TP for similarly sized watersheds in the same topographic settings in Wisconsin (Danz et al., 2010).

Across all watersheds, the majority of event TDP yields occurred during thaw, ranging from 52 (S1) to 62% (P1) (Fig. 4d). Frozen soil and thaw periods combined accounted for 62 (S1) to 79% (P1) of TDP yields. The overall proportion of event TP as TDP was 27% in P1, 20% in P2, 31% in S1, and 38% in S2, with these proportions trending lower when the soil was not frozen. Thus, most TP in event flow was in a particulate rather than dissolved form. In stream flow, TP was primarily particulate during thaw in all watersheds, but the dominant form of P varied between watersheds in the other seasons (Table 4). It is noteworthy that S2 had the highest overall and thaw TP and TDP event yields and stream concentrations (Fig. 4c and 4d, Table 4) but had the lowest mean soil test P (Table 1). It is also interesting that agricultural land use inventories in these watersheds showed no winter manure applications or livestock access to streams, whereas both of these were present in P1 and P2 (Carvin et al., 2018; C. Ertman, Sheboygan County Land Conservation Department, written communication, 2018).

In these four watersheds, roughly half of event SS and TP yields are associated with frozen soil and thaw periods. In the Upper Midwest, erosion control for SS and sediment-bound P has typically focused on rainfall runoff from unfrozen soil. These results suggest that conservation efforts to reduce event SS and TP yields would benefit from the development of management practices designed to reduce or mitigate the effects of runoff from snowmelt and rain on frozen and thawing soil. Practices that promote infiltration when the soil is frozen or thawing, however, may be inconsistent or in conflict with the goals of other management practices applied during the nonfrozen period. For example, whereas no-till is widely used to reduce soil erosion and related stream SS concentrations, fall tillage on the contour has the potential to decrease snowmelt runoff and related SS, TP, and TDP compared with no-till (Stock et al., 2019). On the other hand, some practices such as vegetated buffers designed to promote infiltration during the growing season may not perform well under frozen conditions (Kieta et al., 2018).

One important source of both stream SS and sediment-bound P that may be more prevalent with freezing and thawing is channel erosion (Lamba et al., 2015; Inamdar et al., 2018). Newly thawed bank soils are particularly susceptible to erosion and failure (Gatto, 1995). Comparatively high runoff from frozen and thawing soils (Table 3) could increase entrainment of loose eroding bank sediment and enhance hydraulic erosion in streams and concentrated flow channels. Practices that protect stream banks and eroding channels may be of particular benefit in areas with seasonally frozen soil.

Comparatively high thaw-period stream TP concentrations in the study watersheds are primarily sediment-bound P. In the low-relief landscapes of the Canadian Prairies, annual stream TP concentrations also peak with snowmelt or rain on

Table 3. Seasonal distribution of event discharge and watershed-wide runoff coefficients for four agricultural watersheds.

Watershed	Flow monitoring period	Proportion of event discharge			Runoff coefficient		
		Frozen	Thaw	Nonfrozen	Frozen	Thaw	Nonfrozen
		%					
P1	Oct. 2006–Sept. 2016	22	14	64	0.07	0.04	0.03
P2	Oct. 2006–Sept. 2016	18	19	63	0.07	0.06	0.04
S1	Oct. 2011–Sept. 2016	13	37	50	0.14	0.23	0.06
S2	Oct. 2011–Sept. 2016	10	39	51	0.15	0.34	0.09

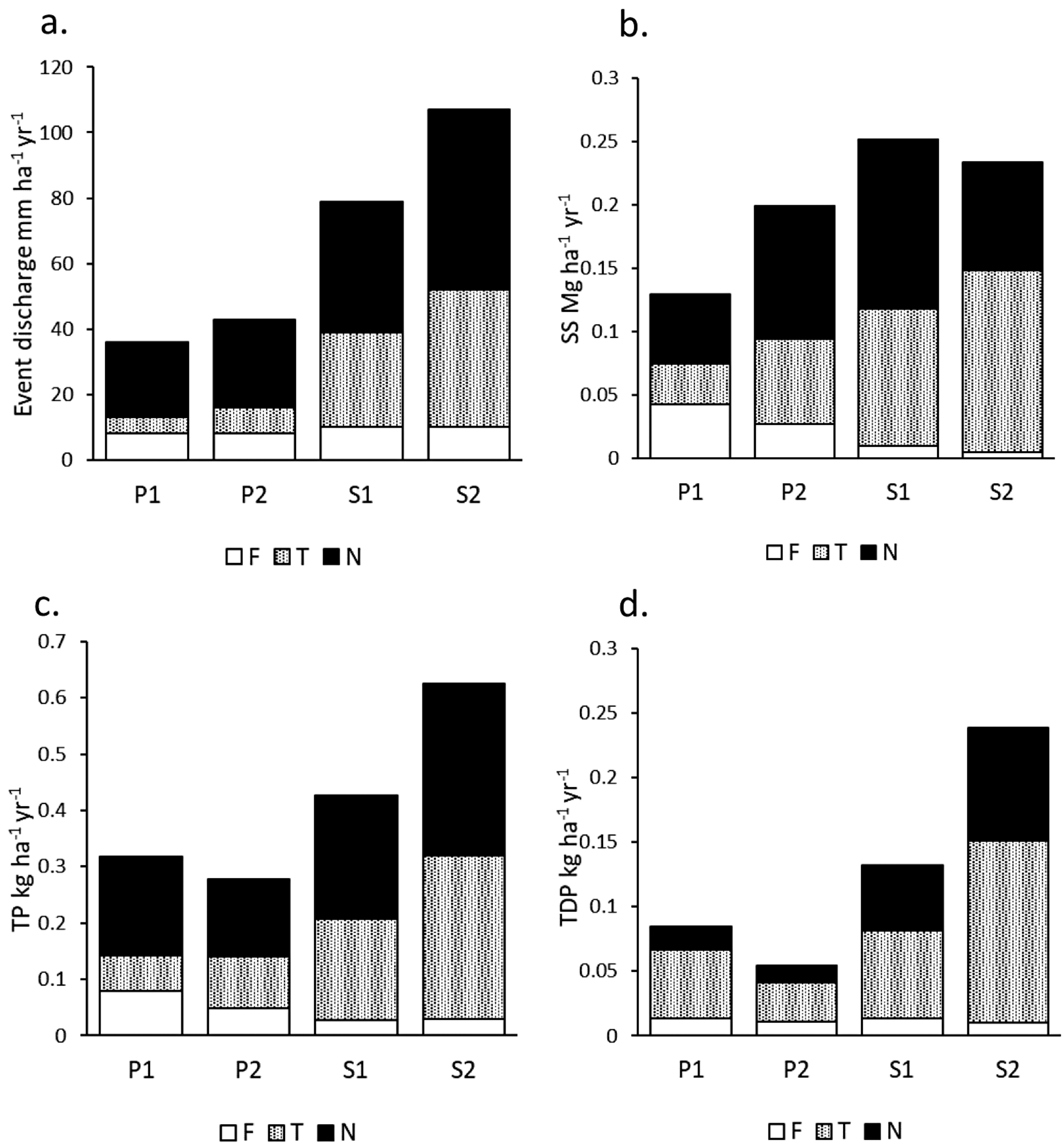

Fig. 4. Mean annual event discharge and yields at outlets of four watersheds while the soil is frozen (F), during the 10 d prior to and 22 d after soil is completely thawed (T), and the remainder of the year (N): (a) event discharge, (b) suspended sediment (SS), (c) total P (TP), and (d) total dissolved P (TDP). In P1 and P2, event discharge, SS, and TP were monitored October 2006 to September 2016; TDP was monitored October 2009 to September 2016. In S1 and S2, all discharge and yields were monitored October 2011 to September 2016, except S2 TDP ended September 2015.

Table 4. Flow-weighted mean (FWM), minimum, and maximum daily mean stream suspended sediment (SS), total P (TP), and total dissolved P (TDP) concentrations by season for four watersheds.

Watershed	Monitoring period†	Season	SS			TP			TDP			TDP/TP
			FWM	Min.	Max.	FWM	Min.	Max.	FWM	Min.	Max.	
			mg L^{-1}									
P1	Oct. 2009–Sept. 2016	Frozen	68	6	2490	0.13	0.04	1.10	0.04	0.02	0.33	0.33
		Thaw	85	6	421	0.20	0.05	0.79	0.08	0.02	0.50	0.37
		Nonfrozen	22	2	427	0.10	0.03	0.77	0.05	0.01	0.51	0.49
P2	Oct. 2009–Sept. 2016	Frozen	23	5	825	0.11	0.04	1.12	0.04	0.02	0.51	0.40
		Thaw	71	8	1680	0.22	0.05	1.59	0.07	0.02	0.22	0.30
		Nonfrozen	10	2	1430	0.09	0.03	0.54	0.05	0.01	0.32	0.51
S1	Oct. 2011–Sept. 2016	Frozen	29	3	319	0.10	0.04	0.62	0.05	0.03	0.26	0.52
		Thaw	125	2	942	0.26	0.04	1.15	0.09	0.01	0.22	0.37
		Nonfrozen	104	2	1810	0.17	0.03	1.88	0.08	0.01	0.36	0.45
S2	Oct. 2011–Sept. 2015	Frozen	6	2	67	0.14	0.03	0.47	0.09	0.03	0.47	0.68
		Thaw	142	2	979	0.38	0.03	1.35	0.16	0.03	1.35	0.43
		Nonfrozen	72	2	433	0.36	0.07	1.10	0.22	0.07	1.10	0.62

† Only years with all three concentrations (i.e. not missing TDP) are included.

snow; however, most of this P is in dissolved form (Corriveau et al., 2011; Casson et al., 2019). In eight Manitoba catchments monitored over 3 yr, TP concentrations were at their maximum (0.6–2 mg L^{-1}) at the beginning of spring melt and decreased over the melt period as the dominant flow path switched from direct surface runoff to through flow (Casson et al., 2019). In Ontario headwater watersheds, maximum TP concentrations measured over a year occurred in rain-on-snow events (≤0.47 mg L^{-1}), regardless of watershed dominant land use (agriculture or wetland–woodlands) and with a wide range of TP to TDP ratios (Miles et al., 2013). The seasonality of peak stream TP concentrations is very different in a tile-drained landscape with a less intense frost season in central Ohio; there, the highest TP concentrations are in summer when flows are lowest (Ford et al., 2018). For example, in a 389-ha watershed, winter (January–March) flow-weighted mean TP concentrations (0.11 mg L^{-1}) were significantly less than those in spring (0.26 mg L^{-1}), summer (0.34 mg L^{-1}), and fall (0.17 mg L^{-1}) (King et al., 2015). Although TP in stream flow in this landscape is primarily dissolved P, Ford et al. (2018) postulated that a greater contribution of sediment P in higher flow conditions in winter and spring was a result of eroding stream channels.

Conclusion

Runoff events when the soil was frozen and during the thaw period contributed 30 to 50% of the discharge and close to half or more of the average annual event loads of SS, TP, and TDP in four agricultural watersheds in previously glaciated and unglaciated regions of Wisconsin. Although flow regimes for these four watersheds varied, all had frozen soil and thaw average runoff coefficients that were at least twice those for the nonfrozen part of the year. Finding ways to reduce runoff volume from snowmelt and rain on frozen soil and prevent flow-channel erosion are promising avenues for watershed conservation efforts to reduce stream SS, TP, and TDP in regions with seasonally frozen soil.

Supplemental Material

Supplemental materials include "Appendix I. Identifying the High Discharge Period Following Frost-Out in Four Wisconsin Watersheds" and "Appendix II. Mean Daily Suspended Sediment and Phosphorus Event Load Distributions."

Conflict of Interest

The authors have no conflicts of interest in relation to publication of this article.

Acknowledgments

The Nature Conservancy, USDA National Integrated Water Quality Program (Award 2009-51140-06049), and USGS Cooperative Matching Fund provided funding. The manuscript benefited from anonymous reviewers selected by the journal and Matthew Komiskey (USGS).

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