Phosphorus losses in surface and subsurface runoff from a snowmelt event on an agricultural field in Quebec

A. Jamieson, C.A. Madramootoo and P. Enright

Brace Centre for Water Resources Management, Ste-Anne-de-Bellevue, Quebec, Canada H9X 3V9

Jamieson, A., Madramootoo, C.A. and Engright, P. 2003. **Phosphorus losses in surface and subsurface runoff from a snowmelt event on an agricultural field in Quebec**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **45**: 1.1-1.7. Phosphorus concentrations exceed water quality guidelines in most of the major rivers in southeastern Quebec. The problem is particularly important in the Pike River, which drains into the Missiquoi Bay of Lake Champlain. Elevated phosphorus concentrations can lead to a reduction in the palatability of drinking water, a decrease in diversity of aquatic life, and loss of recreational opportunities. These problems have been observed in the Bay. An agricultural field in southeastern Quebec was instrumented to measure and evaluate the partitioning of phosphorus between surface runoff and subsurface drainage, year round. The snowmelt event was the dominant surface and subsurface event for the 2000/2001 water year. The 2000/2001 water year was unusually dry, which resulted in a limited number of surface and subsurface runoff events. The annual depth of surface runoff at one site was 87.5 mm. The estimated depth of subsurface runoff of the snowmelt event was 93.7 mm. Subsurface drainage flow was 51.7% of the total volume of runoff from the field during the snowmelt event. The total phosphorus load in surface runoff for the spring snowmelt was 166.4 g/ha. The estimated total phosphorus load in subsurface drainage for the spring snowmelt was 98.2 g/ha. The estimated subsurface total phosphorus load accounted for 37.1% of the total loads during the snowmelt. Therefore, the subsurface drains proved to be a significant pathway for phosphorus.

La teneur en phosphore des eaux de la plupart des rivières du sud-est du Québec excède celle établié dans les critères de qualité de l'eau de surface. Ce problème est particulièrement important pour la Rivière aux Brochets, qui se déverse dans la Baie Missiquoi du Lac Champlain, au sud-est du Québec. Une teneur élevée de phosphore dans l'eau peut en réduire la palatabilité, enrayer son utilisation ludique et y réduire la biocénose aquatique. Tous ces problèmes on été notés dans la Baie. Un champs agricole au sud-est du Québec, furent instrumentés afin de mesurer et d'évaluer, tout au long de l'année, le partage du phosphore entre le ruissellement et le l'écoulement hypodermique par voie du système de drainage souterrain. La fonte des neiges fut le principal évènement de l'année hydrologique 2000/2001, autant en surface que par voie souterraine. L'année hydrologique 2000/2001 fut particulièrement sèche, et donc d'un nombre restreint d'évènements de ruissellement et d'écoulement hypodermique. Au cours de l'année le ruissellement à une site totalisa 87.5 mm, dont seulement 0.2 mm furent entregistrés après la fonte des neiges. L'écoulement hypodermique provenant de la fonte des neiges fut de 93 mm, soit 51.7% du volume total perdu du champ lors de la fonte. La charge totale en phosphore des eaux de ruissellement lors de la fonte des neiges fut de 166.4 g/ha, tandis que celle estimée pour les eaux d'écoulement hypodermique fut de 98.2 g/ha, soit 37.1% de la charge totale. Les drains souterrains furent donc une importante voie de cheminement pour les pertes de phosphore.

INTRODUCTION

Anthropogenic non-point source pollution has contributed to the rapid acceleration of eutrophication in some Quebec rivers. Recent improvements to municipal wastewater treatment plants combined with a conscious effort from the industry sector to reduce their waste disposal have both decreased the amount of phosphorus (P) inputs to rivers from point sources (Bolinder et al. 2000). Non-point sources are now recognized to be the main contributors of P to rivers in Quebec (Ministry of Environment of Quebec 1999).

In the past, agricultural communities were self-sufficient in that their entire feed and waste disposal were produced locally and recycled within the community (Sharpley et al. 1993). The subsequent increase in population has led to a greater demand of food worldwide, which has resulted in a greater demand for farms to produce. To attain the required efficiency, farms have moved away from being small and self-sufficient to large industries dependent on external inputs. Furthermore, often the land base has not kept pace with the increase in the number of animal units on the farm. As a result, manure is over applied on the land, which has lead to elevated P levels. In fairness, many of these farms were permitted under law to apply manure to the land based only upon the nitrogen (N) requirements of the crop. For swine and poultry producers, this led to over application of P. The move from small to large-scale production and the trend to specialization are what has resulted in the current pollution problem. In Quebec, these large animal production units have been identified as sources for phosphorus contaminated water (Bolinder et. al. 2000).

Previous research has focused on best management practices to reduce the transport of P to surface waters via surface erosion and runoff. The installation of subsurface drainage systems is one such practice in that it helps reduce soil erosion from agricultural fields by improving infiltration and preventing soil saturation (Culley et al. 1983). A saturated soil is more susceptible to surface runoff, which is responsible for the detachment and transport of sediment from agricultural fields. A reduction in soil erosion meant a reduction in the particulate P leaving the field, and the excess water would filter through the soil and leave the drains P free. However, with continuous addition of P inputs to the soil, the water leaving the drains is no longer considered P free. In Quebec, the P leaving the fields via drains has been a growing concern, especially in the lowlands of the St. Lawrence River. Beauchemin et al. (1998) recorded high total phosphorus (TP) concentrations in the drainage water of 27 tile-drained soils. The TP concentrations ranged from 0.01 to 1.17 mg/L. In 1994, 14 out of 27 sites exceeded the Quebec water quality standard of 0.03 mg of TP/L and in 1995, 6 out of the 25 sites exceeded this same standard.

In Quebec, as elsewhere, the potential P losses that may occur via tile drains is a topic of keen interest. However, very little data exist on annual loads in tile drains. This paper reports on some preliminary results from a field site in Southern Quebec, which was installed to measure concentration and loads in surface runoff and tile drainage waters.

MATERIALS and METHODS

Site description

The project was initiated in 2000 at a field site located near Bedford, Quebec. Bedford is 70 km southeast of Montreal and is situated within the Pike River watershed. Bedford, located in one of the warmer regions of Quebec, has an average annual temperature of 6.8°C and a subsequent frost-free period of 155 days. The Pike River has an arc shape, which begins in the state of Vermont, drains throughout Quebec, and exits into the Missiquoi Bay, which is the Quebec portion of Lake Champlain. The Pike River, which is roughly 58 km long and drains an area of 629 km^2, has an average annual discharge rate of 6.5 m^3/s. The watershed area that lies in Quebec is 530 km^2.

The field site resides within the Pike River watershed and has moderate soils P and P saturation levels. The average soil P level for the site was 140 kg of P/ha and the percent of P saturation was 7%; this is considered moderate. The site consisted of a mixture of a Bedford sandy clay loam and a St. Sebastien shaly loam. The soil nutrient levels were determined by a study that was carried out in 1998 by the Institute de Recherche et Developpement en Agroenvironnement (IRDA) (unpublished data).

The data collected encompassed the water year, October 1, 2000 to September 30, 2001. Over this period, inorganic fertilizer was applied to the site three times, once during seeding on May 2, 2001 and again on May 16, 2001 and June 1, 2001. The nutrient ratio of the first fertilizer was 18.5-18.5-22.5 and it was applied at a rate of 150 kg/ha. The application was banded together with the seed during planting. The second fertilizer application was at a rate of 180 kg/ha with nutrient ratio of 46-0-0. The third application was at rate of 150 kg/ha with a nutrient ratio of 46-0-0. Both the second and third applications were broadcast.

The field drains at an average slope of 1% towards the surface outlet point, which is in close proximity to the subsurface drain outlet. The subsurface and surface drainage areas for the Gagnon site were 7.8 and 10.2 ha, respectively. The subsurface drainage systems consist of 110 mm diameter laterals with a 210 mm diameter outlet.

Surface runoff instrumentation

To measure the volume of surface runoff from the field, an HS flume was designed and installed. To size the flume, the Soil Conservation Service (SCS) method was used with a one in 5-yr storm (Schwab et al.1993). The SCS curve number was selected to reflect the soil type and the current field practices. Other parameters such as slope and length of slope were determined with drainage and topography maps. The SCS method resulted in a 0.6- m HS flume. The flume is rated for 0 to 0.31 m^3/s, and was equipped with a stilling well. The depth of water in the stilling well was measured with a submersible pressure transducer, which determines the water pressure that is then converted to a depth of water. An ultrasonic sensor was also installed at the site to give an additional measurement of runoff depth. The ultrasonic sensor was centered above the flume floor, which gave an accurate representation of the flow through the flume. To ensure that all water during an event was channeled from the edges of the field to the flume, soil and plywood berms were constructed along the downstream edge of the field. The first part of the berm consisted of soil that was built up to a height of 0.61 m and extended roughly 3 m on either side of the flume. The other part of the berm comprised plywood and polyethylene sheeting. The plywood was an extension of the flume walls and continued out parallel to the edge of the field. The polyethylene plastic was stapled to the plywood. The plastic was buried 150 mm under the ground to prevent any seepage under the berm.

Tile drainage runoff instrumentation

A Global Water Insertion Flow meter (IF-200; Global Water Instrumentation Inc, Gold River, CA) was inserted near the end of the collector to measure the flow in the tile drains. The IF-200 is a propeller flow meter with a 50.8 mm threaded insertion fitting.

Agricultural drain flow does not always fill the entire pipe. To attain full pipe flow for all rates of drain outflow, a U-section of pipe was installed (Fig. 1). To allow for smooth flow through the measurement section, the bottom of the U-section (Fig. 1) where the flow meter resides had to be straight and at least 15 times the diameter of pipe in length. In this case, the diameter of the pipe was 152 mm. Therefore the entire length of the flow meter section had to be at least 2.3 m long. Furthermore, the section before the flow meter had to be two-thirds the distance of the entire section. The remainder of the U-section (Fig. 1) consists of two sets of 22° elbows (schedule 35). Each elbow was separated by a 0.61-m section of schedule 35 PVC pipe. The 0.61-m section allowed for a 76.2 mm clearance from the bottom of the existing drainage system to the top of the new modified section. It is important to note that after the minimum required distance for the flow meter was respected the drain was then raised back to its original slope. For maintenance, a manhole 0.915 m in diameter was inserted into the soil just above the flow meter.

The site was equipped with a Campbell Scientific 21X Datalogger (Campbell Scientific, Inc., Edmonton, AB). It was programmed to monitor all sensors on a 5-second interval and calculate the rate of surface and subsurface discharge. The discharge was averaged, and the rainfall was totaled over a 15 minute interval and recorded. Temperature and radiation data were averaged and recorded hourly. The datalogger tabulated flow and activated both the surface and subsurface runoff samplers according to a specified sampling strategy. The sites are 100 km from the Macdonald Campus; therefore, a phone line was installed at each site so that they could be monitored remotely. During the winter the site was checked bi-monthly to monitor temperature in the enclosure. This was particularly important since most of the equipment installed is sensitive to

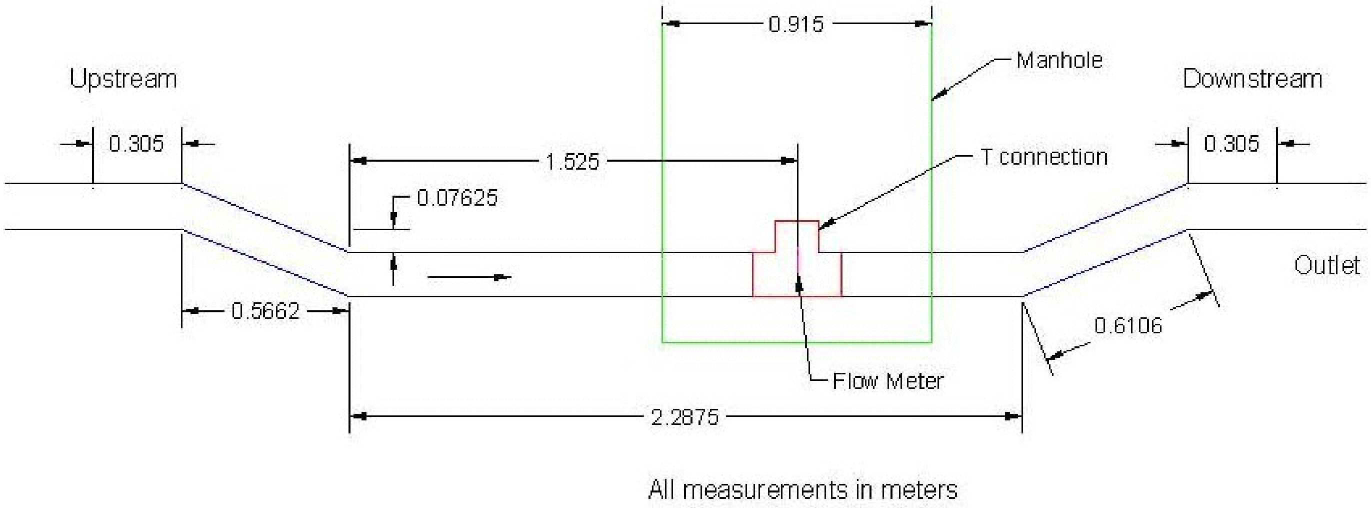

Fig. 1. Subsurface flow measurements.

freezing temperatures. The data were collected and processed once a week and then transferred into a spreadsheet. The site was also equipped with a spark gap unit installed between the sensors and the datalogger to filter out any electrical noise from all the equipment. The spark gap unit also protects the water sampler from electrical surges.

Water quality analysis

The surface runoff samples were discrete samples. The purpose of using discrete samples for surface runoff was to examine variations in phosphorus concentrations throughout a storm event. To accurately represent all types of storm events, a geometrical increasing sampling strategy was used, similar to that proposed by Tremwel et al. (1996). An American Sigma (800SL; American Sigma Inc., Loveland, CO) surface sampler was used at each site. The sampler has a carousel with 24 one-litre bottles. Two 1-L samples were taken each time the sampler was activated. The intake tube was suspended above the center of the flume to sample low flows and at the same time avoid sediment build up at the bottom of the flume. Since a sampler resided at each site year round, an enclosure was built at each site to protect each sampler from the harsh environment. Each enclosure was 2.14 x 1.22 m in size, well insulated, and equipped with a baseboard heater to keep the inside temperature above 15°C during the winter.

The subsurface samples were flow-weighted composite samples. Composite samplers were cost effective and were not as large as discrete samplers. Furthermore, large variations of phosphorus levels during an event were not expected in the subsurface samples. The WS300 Global Water sampler has a threshold value of 1 mm of runoff over the entire subsurface drainage area. Each sample taken was 250 mL. The bottle could have held up to 7.57 L of water, making for a total of 30 samples that could have been taken in one event. Similar to the surface samplers, at each site an enclosure was built to house the WS300. Each enclosure was 0.76 x 0.76 m, well insulated, and equipped with a 75 W light bulb to keep the inside temperatures above 15°C. Each enclosure was placed on top of the constructed manhole mentioned above. An access port was installed just downstream from the IF200 flow meter on the 152-mm PVC subsurface drain outlet pipe to collect subsurface samples.

From each surface runoff sample, a 500-mL subsample was collected from the 1-L bottle in the carousel. For subsurface runoff samples, a 500-mL subsample was collected from the 7.5-L bottle. All samples were placed in a cooler and shipped to the IRDA for analysis. Each bottle was rinsed with acid and de-ionized water at the IRDA lab to ensure no contamination. The samples were analyzed for the following parameters: pH, suspended material (SS), TP, total dissolved phosphorus (TDP), orthophosphates (Ortho-P), P, potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), ammonia (NH_4), and nitrate (NO_3). Particulate phosphorus (PP) was calculated as the difference between TP and TDP. For budgetary reasons, bioavaliable P was only measured during large storm events.

Meteorological data acquisition

The instrumentation was installed in the summer of 2000 and became operational for the water year 2000-2001 i.e. between October 1, 2000 and September 30, 2001. To monitor weather conditions, the site was equipped with a rain gauge, air temperature sensors, and thermocouples for the stilling wells, subsurface wells, subsurface enclosure, and surface enclosure. Data were also obtained from the Quebec Ministry of Environment (MENV), Philipsburg station, located approximately 9 km south of the site.

Snow sampling was performed on February 8 and March 20, 2001. The sampling points were equally spaced 60 m apart along a row and the adjacent rows were separated 60 m from each other. Using a snow core sampler, the depth of the snow pack was recorded at each point and a core of snow was placed in a 2-L plastic ziplock bag. The bags were later weighed and the estimated average water equivalency depth (EAWED) for the field was calculated. To calculate the EAWED, the specific density of the snow was determined by dividing the mass of the snow sampled by the volume of snow sampled. The volume of snow was calculated by multiplying the snow core sampler's cross sectional area by the recorded snow pack depth. The EAWED in centimeters was then determined by multiplying the average specific density by the average snow pack depth.

Table 1. Hydrometeorology of the three rainfall events.

Date of storm	Rainfall (mm)	Rainfall intensity (mm/h)	Runoff volume (mm/ha)	Percent of annual surface runoff
2000-11-26	19.6	2.61	0.10	0.11
2001-05-19	27.7	2.77	0.08	0.09
2001-08-31	17.4	23.20	0.04	0.05

RESULTS and DISCUSSION

According to the Philipsburg weather station, rainfall data for 2000-2001 was 21% lower than the long-term average, based on 29 years of record. As a result of the drier than usual conditions, only four surface runoff events were sampled. The dominant surface runoff event at the site was the 2001 spring snowmelt. The IF200 subsurface flow meters failed, which resulted in missing measured tile drainage flows in late November 2000, early December 2000, and the 2001 spring snowmelt.

Surface and subsurface runoff

There was only one large surface runoff event, that being the spring snowmelt, which lasted from April 8 to 11, 2001. The snowmelt accounted for 99.8 % of the total surface runoff for the whole water year. The other three surface runoff events (November 26, 2000, May 22, 2001, and August 31, 2001) were considered to be small. The depth of runoff that exited the field during the snowmelt event was 87.3 mm. The depth of water discharged by November 2000, May 2001, and August 2001 storms were 0.10, 0.08, and 0.04 mm, respectively (Table 1).

The average equivalent depth of water of the snowpack calculated on March 20, 2001 was 312 mm. On March 22 and 23, 2001, a sizable storm deposited 400 mm of wet heavy snow. Snow sampling for 6 random points showed that snow coverage was very uniform, given the relatively flat nature of the field, and there being no obstructions. The equivalent depth of water was 82 mm. For reference, Dorval, which is situated approximately 85 km from the site, recorded a water equivalency of 63.8 mm for the same two days. No other significant snowstorms occurred between March 23, 2001 and snowmelt (April 8, 2001). The estimated average water equivalency depth (EAWED) was calculated by summing the EAWEDs of March 20 and 23 then subtracting a reported sublimation rate. Fassnacht et al. (1999) reported a sublimation rate of 1 mm/d for Southern Ontario. This value was within the range of 0.029 to 1.642 mm/d and 0.668 to 1.219 mm/d as reported by Williams (1959) and Martinelli (1960). For estimation purposes, a sublimation rate of 1 mm/d was used. The EAWED prior to the snowmelt was 181 mm. Knowing the EAWED and the amount of surface runoff, the subsurface runoff during the snowmelt was determined from Eq. 1.

$$\mathrm{Pr} + \mathrm{EAWED} = \mathrm{SRO} + \mathrm{SSRO} + \mathrm{DS} + \mathrm{ET} + \Delta \mathrm{S} \quad (1)$$

where:

Pr = precipitation (mm),
EAWED = estimated average water equivalency depth (mm),
SRO = surface runoff (mm),
SSRO = subsurface runoff (mm),
DS = deep seepage (mm),
ET = evapotranspiration (mm), and
ΔS = change in soil moisture (mm).

During the snowmelt event there was no precipitation, therefore the only input to the drainage system was the water equivalency of the snow pack on the field. The parameters DS, ET, and ΔS are all assumed to be zero. It is reasonable to assume that during the 4-day event very little water was lost to deep seepage and to the atmosphere. Furthermore, it is reasonable to assume that the field was at or near field capacity during the first snowmelt event. Therefore, the difference in soil moisture between the first snowfall in December and the snowmelt event is negligible compared to the values of EAWED and SRO. The estimated depth of runoff through the tile drains during the snowmelt event was 93.7 mm. If we combine the total depth of surface runoff for the water year with the depth of subsurface drainage runoff from the snowmelt, the result is 164.8 mm. Despite the missed subsurface drainage events, this is considerably low for a region where the average annual precipitation is 1171 mm.

Sediment and P in surface runoff

The suspended sediment (SS) concentrations were 36, 28, and 157 fold higher for the May, November, and August events, respectively, than the snowmelt event (Table 2). Two of the

Table 2. SS, TP, and ortho-P concentrations and losses in surface runoff from three small rainfall events compared with the same concentrations for the snowmelt.

Event	SS		TP		Ortho-P	
	Concentration (mg/L)	Load (kg/ha)	Concentration (mg/L)	Load (g/ha)	Concentration (mg/L)	Load (g/ha)
Spring snowmelt	86	75.30	0.19	166.36	0.06	57.34
Novenber 2000	1946	1.96	2.62	2.65	0.08	0.09
May 2001	2500	2.05	2.50	2.05	0.31	0.25
August 2001	11,000	4.66	2.20	0.93	0.42	0.18
Total		83.95		172.00		57.86

Table 3. Average TP, SS, and ortho-P concentrations of the subsurface samples taken on November 29 and December 8, 2000 and those taken prior and during the snowmelt event.

	SS (mg/L)	TP (mg/L)	Ortho-P (mg/L)
2000-11-29	0.05	0.09	0.04
2000-12-08	0.06	0.02	0.04
Winter*	2.00	0.021	0.01
Snowmelt**	33.40	0.11	0.04

* Average concentrations of subsurface samples between March 5 and April 2, 2001 (n=33)

** Average concentrations of subsurface samples between April 9 and April 17, 2001 (n=10)

rainfall runoff events occurred when the soil was bare, therefore making it easier to detach and transport sediment. Interestingly enough, the August event produced the largest sediment concentration, however in August the crop cover would be the greatest hence reducing the raindrop impact (Table 2). The most probable reason for the SS concentration differences within the rainfall events was the difference in their respective rainfall intensities (Table 1). The greater the rainfall intensity, the higher the potential for detachment of soil particles as result of raindrop impact. Culley et al. (1983) reported similar SS concentrations for surface runoff generated by snowmelt and rainfall. They also observed that the higher sediment concentrations from the rainfall events lead to larger particulate phosphorus (PP) concentrations and therefore larger total phosphorus (TP) concentrations. The TP concentrations of the rainfall events nearly doubled those of the snowmelt event. A similar trend was observed at the site; higher sediment concentrations resulted in higher TP concentrations for the rainfall events (Table 2). The TP concentrations of the November, May, and August events increased by 14, 15, and 12 fold, respectively, over the spring snowmelt concentrations (Table 2). The May and August events had significantly higher ortho-P concentrations than those of the November and spring snowmelt event (Table 2). The lower ortho-P concentrations for spring snowmelt may be a result of dilution from the snow pack. Furthermore, colder temperatures slow down mineralization of P and hence prevent the release of P to surface waters (Sallade and Sims 1997). Gaynor and Findlay (1995) observed similar variations in ortho-P concentrations between the summer and winter months.

The total P losses for the water year were 172 g/ha (Table 2). The decreases in TP losses are a result of the drier than usual conditions observed at the site. In England, Catt et al. (1998) reported annual TP losses ranging from 2.42 to 32.76 kg ha^{-1} y^{-1} from a loamy clay soil in rotation, an increase of 13 fold between a dry and wet year. The total ortho-P losses at the site were 57.9 g/ha (Table 2) again lower than previous studies, such as Gaynor and Findlay (1995) who reported annual ortho P losses of 155, 222, and 152 g ha^{-1} y^{-1} for 1988, 1989, and 1990, respectively. Gaynor and Findlay (1995) found that ortho-P losses appear to be less affected by dry or wet conditions. The lower ortho-P losses may be a result of low soil P levels in the A horizon. Despite the higher TP and ortho-P concentrations found during the rainfall events, the snowfall was the dominant event in terms of P pollution. The snowmelt event represented 96.7 and 99.1% of the total loads for TP and ortho-P, respectively. Culley et al. (1983) had similar results during the dry year of their study. In 1980, they observed that the spring snowmelt represented 65% of the total runoff for the year. As a result, the TP loads from the snowmelt represented 51% of the total load for the whole year, despite a lower TP concentration. Despite the significantly lower SS concentrations found in the snowmelt event, the total SS lost was much greater than the SS lost in the rainfall events. The snowmelt represented 89.7 % of the total SS lost for the water year. The raindrop impact of the rainfall events had a more dramatic effect on the SS concentration than the SS loads.

Sediment and P in subsurface runoff

During the late fall of 2000, there was visible subsurface drain flow at the site. Unfortunately, it was not recorded by the flow meter, and therefore is considered to be missing data. However, on November 29, 2000 and December 8, 2000, spot drain flow measurements were made at the outlet. The estimated drain flow was 1.85 and 1 L/s for November 29 and December 8, 2000, respectively. These flow rates, assuming they remained constant for the day, translate into runoff volumes of 1.6 and 0.86 mm/d for November 29 and December 8, 2000, respectively. These amounts were significantly lower than those observed during snowmelt. The snowmelt event had an estimated volume of 93.7 mm/ha, which is significantly higher than the two fall events. Furthermore, the TP, SS, and ortho-P concentrations are small compared to the TP, SS, and ortho-P concentrations found during the snowmelt event (Table 3). Therefore, with the smaller drainage runoff and lower concentration data, it is reasonable to assume that these two fall events, which were missed, would not dramatically effect the overall TP, SS, and ortho-P losses for the water year.

At snowmelt, the drains began to flow full (15 mm/d) on April 8, 2001 and continued to flow full until April 12, 2001. By April 17, 2001 both drains had significantly slowed down and were flowing at an extremely low rate (less than 1 mm/d). The monthly average rainfall for the Philipsburg weather station was 87.4 mm, and for this year the Philipsburg weather station only recorded 10.2 mm. Since soils are normally at field capacity after snowmelt, any subsequent rainfall would give rise to additional subsurface drainage. However, during April 2001 there was no rainfall after snowmelt, and as such, there was no subsequent drain flow. Therefore all samples taken between April 8 and 17 are representative of the snowmelt event.

There is no water quality standard in Quebec for TP concentrations in tile drains. However, Quebec does have a water quality standard for TP in surface water, which is 0.03 mg of TP/L. The samples taken during the snowmelt event exceeded the Quebec water quality standard at the site (Fig. 2). There was a difference in the average SS concentration before the snowmelt and the average SS concentration during the snowmelt (Table 3). The SS concentrations during snowmelt were 16.7 times the SS concentrations prior to snowmelt. The higher SS concentration during snowmelt resulted in a 9.6 fold increase in PP concentrations. The soil at the site is a hard cracking clay, therefore aiding preferential flow of nutrient rich

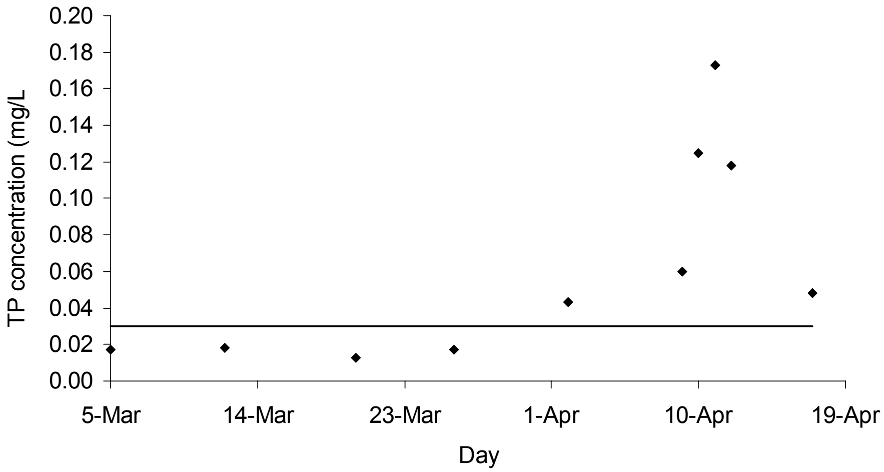

Fig. 2. Total phosphorus concentrations of surface runoff prior and during the snowmelt event. Horizontal solid line represents the Quebec water quality standard for surface water.

surface water to reach the drains faster and more frequent (Gaynor and Findlay 1995). Furthermore, preferential flow may cause interior erosion and colloidal transport of P from the surface layer to the subsurface drains (Magid et al. 1999). Ortho-P concentrations also increased dramatically during the snowmelt period. These data are consistent with the literature, whereby TP concentrations in subsurface runoff are governed by the dissolved P forms (Hooda et al. 1999; Beachemin et al. 1998; Gaynor and Findlay 1995; Heckrath et al. 1995; Culley et al. 1983). Despite the lack of concrete flow data from the drain effluent, a trend similar to that of other studies emerged. The drains were flowing at full capacity for 4 days during the snowmelt. Presumably the drains began to flow at full capacity late April 8 or early April 9, and this coincided with the first manually pulsed samples. The samples taken on April 9 show a substantial increase in concentration for all P forms. As the snowmelt proceeded, the P concentrations began to taper off, despite the continuous high drain effluent. Dils and Heathwaite (1998) observed within a rainfall runoff event a similar trend for TP and TDP forms in tile drainage effluent, whereby an initial peak in concentration was followed by a recession, despite the continuous discharge rate.

Table 4 summarizes the P losses among its different constituents and also between surface and subsurface runoff. The estimated subsurface TP losses were 98.2 g/ha, which is much lower than the subsurface TP losses reported by Catt et al. (1998), Gaynor and Findlay (1995), Culley et al. (1983), and Bolton et al. (1970). The dry conditions and unmeasured subsurface runoff events attribute to the lower TP losses observed. Dry years have an impact on the amount of nutrient losses from a field. Catt et al. (1998) reported a three fold increase in TP losses between a dry and wet year. The total TP losses for the snowmelt event were 264.6 g/ha. Despite the lower subsurface losses, the overall contribution of the drains during the event is significant. In a similar study conducted in Minnesota, Zhao et al. (2001) observed very little contribution from the drains for the overall TP losses for a single event in spring. Zhao et al.(2001), reported that during the rainfall induced event, the TP losses from the drains only accounted for 2.6% of the total TP losses for the event. The TP losses in the drains at the site accounted for 37.1% of the total TP losses during the snowmelt event, which is significantly higher than the Zhao et al. (2001) report. The difference may be a result of the partitioning of runoff volume. For Zhao et al. (2001), the subsurface volume represented 36.6% percent of the total runoff volume, whereas the subsurface volume at the site for the snowmelt event represented 51.8% of the total runoff volume.

CONCLUSIONS

The 2001 snowmelt event accounted for 99.8% of the total surface runoff for the water year. The depth of surface runoff from this snowmelt event was 87.3 mm. Due to malfunctions of the subsurface flow meter, it was impossible to obtain good subsurface runoff data. The depth of runoff that exited the drains during the spring snowmelt based on a water balance calculation was estimated to be 93.7 mm. The total runoff that exited the site via surface and tile drainage flow was 181.2 mm.

The surface runoff suspended sediment concentrations for the November 26, 2000, May 19, 2001, and August 31, 2001 events were 36, 28, and 154 times, respectively, the average suspended sediment concentration of the 2001 snowmelt. The snowmelt generated greater sediment losses. The suspended sediment loads for the 2001 snowmelt were 75.3 kg/ha, which were 38, 37, and 16 times the suspended sediment loads for the November 26, 2000, May 19, 2001, and August 31, 2001 events, respectively.

The surface runoff total phosphorus concentrations for the November 26, 2000, May 19, 2001, and August 31, 2001 events were 14, 15, and 12 times, respectively, the average total phosphorus concentrations of the 2001 snowmelt. Despite the higher total phosphorus concentrations in the small surface runoff events, the snowmelt produced greater total phosphorus losses. The total phosphorus load for the 2001 snowmelt event was 0.166 kg/ha. The three other surface events represented only 3.3% of

Table 4. Surface, subsurface, and combined losses of SS, TP, and ortho-P for the 2001 snowmelt event.

	SS		TP		Ortho-P	
	Loss (kg/ha)	Percent of total	Loss (g/ha)	Percent of total	Loss (g/ha)	Percent of total
Surface	75.27	70.63	166.4	62.88	57.34	62.45
Subsurface	31.30	29.37	98.2	37.12	34.48	37.55
Total	106.6		264.6		91.82	

the total phosphorus load for the entire water year. Therefore, the snowmelt event proved to be the more significant event in terms of P pollution.

The average TP and ortho-P concentrations from the tile drains were 45 and 44% lower, respectively, than the average TP concentrations for surface runoff. The subsurface drains yielded an average of 0.1048 mg of TP/L for the snowmelt event, which is well over the water quality standard (0.03 mg of TP/L) set by the Quebec government.

The estimated tile drainage volume allowed for the partitioning of phosphorus to be analysed for the snowmelt event. The TP and ortho-P losses from the drains were 37.1 and 37.6%, respectively, of the total TP and ortho-P losses for the event. The tile drains represented approximately one-third of the TP losses for the water year. This indicates that tile drains are significant pathways for phosphorus during snowmelt events.

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