Evaluating phosphorus losses in surface and subsurface runoff from two agricultural fields in Quebec.

Andrew Jamieson

Department of Agricultural and Biosystems Engineering
McGill University, Montreal

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ABSTRACT

Phosphorous concentrations exceed water quality guidelines in most of the major rivers in southern Quebec. The problem is particularly acute in the Pike River, which drains into the Missisquoi Bay of Lake Champlain, in southeastern Quebec. 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. All of these problems have been observed in the Bay.

Two agricultural fields (the Marchand and Gagnon sites) located on the Pike River watershed, in southeastern Quebec were selected and equipped with instrumentation to measure and evaluate the partitioning of phosphorus between surface runoff and subsurface drainage, on a year round basis. The snowmelt event was the dominant surface and subsurface event for the 2000/2001 hydrological year. On the Marchand site surface flow data was incomplete as a result of a failure of the surface runoff flume. On both sites the IF 200 subsurface flow meters failed, which resulted in missing subsurface flow data during certain runoff events. Therefore, the majority of the comparisons made relate to the Gagnon site.

The 2000/2001 hydrological year was unusually dry, which resulted in a limited number of surface and subsurface runoff events. The annual depth of surface runoff for the Gagnon site was 87.5 mm/ha, of which only 0.2mm occurred outside the snowmelt event. The estimated depth of subsurface runoff of the snowmelt event at the Gagnon site based upon a water balance equation was 93.7 mm/ha, or 51.7% of the total volume that occurred on the Gagnon field during the snowmelt event.

The total phosphorus load in surface runoff for the spring snowmelt at the Gagnon site was 166.4 g/ha, whereas the estimated total phosphorus load in subsurface drainage was 98.2 g/ha, or 37.1% of the total load. Subsurface drains can therefore be a significant pathway for phosphorus losses.

RÉSUMÉ

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 Missisquoi 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 ont été notés dans la Baie Missisquoi.

Deux champs agricoles (les sites Marchand et Gagnon) situés sur le bassin versant de la Rivière aux Brochets, au sud-est du Québec, furent choisis et 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. Au site Marchand, les données de ruissellement furent incomplètes suite à la défaillance du canal jaugeur. Aux deux sites les débitmètres d'écoulement hypodermique IF200 défaillirent, présentant ainsi des lacunes dans les données d'écoulement hypodermique pour certains évènements. Par conséquence, la plupart des comparaisons furent faites par rapport au site Gagnon.

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 au site Gagnon totalisa 87.5 mm ha^{-1}, dont seulement 0.2 mm furent entregistrés après la fonte des neiges. L'écoulement hypodermique provenant de la fonte des neiges au site Gagnon, estimé selon le bilan hydrique, fut de 93 mm ha^{-1}, soit 51.7% du volume total perdu du champ Gagnon lors de la fonte.

La charge totale en phosphore des eaux de ruissellement lors de la fonte des neiges au site Gagnon fut de 166.4 g ha^{-1}, tandis que celle estimée pour les eaux d'écoulement hypodermique fut de 98.2 g ha^{-1}, soit 37.1% de la charge totale. Les drains souterrains furent donc une importante voie de cheminement pour les pertes de phosphore.

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AGNPS Agricultural Non-Point Source Pollution model

Al Aluminum

BAP Bioavailable phosphorus

°C Degrees Celcius

Ca Calcium

cm Centimeters

DAHP Dissolved acid-hydrolyzable phosphorus

DIS Discrete sample

DO Dissolved oxygen

DOP Dissolved organic phosphorus

DP Dissolved phosphorus

DPS Degree of phosphorus saturation

DRP Dissolved reactive phosphorus

DS Deep seepage

EAWED Estimated average water equivalency depth

ET Evapotranspiration

FP Flow proportional

ft feet

g grams

gal gallons

GPS Global positioning system

ha hectares

HPO_4^{-2} primary orthophosphates

$H_2PO_4^-$ secondary orthophosphates

hr hour

in inches

IRDA Institute de Recherche et Developpement en Agroenvironnement

K Potassium

kg Kilograms

km Kilometers

L Liters

m meters

Mg Magnesium

mg Milligrams

mL Milliliters

mm millimeters

MP Manual pumped sample

MRG Manual rain gage

N Nitrogen

Na Sodium

NH_4 Ammonia

NO_3 Nitrate

Ortho-P Orthophosphates

OM Organic matter

P Phosphorus

PP	Particulate phosphorus
ppm	Parts per million
P sat	Phosphorus saturtation
R	Coefficient of determination
s	seconds
ΔS	Change in soil moisture
SAV	Submergent aquatic vegetation
SRO	Surface runoff
SRP	Soluble reactive phosphorus
SS	Suspended sediment
SSRO	Subsurface runoff
t	Tons
TC	Time composite
TP	Total phosphorus
TDP	Total dissolved phosphorus
WEND	Watershed Ecosystem Nutrient Dynamic model
yr	year

1. INTRODUCTION

Until recently, phosphorus was largely ignored in terms of non-point source pollution in Quebec because tilled soils were believed to retain large quantities of applied phosphorus. Furthermore, nitrogen has been identified as a pollution problem due to its high mobility in soils. The majority of research and legislation therefore focused on reducing nitrogen and nitrate pollution. However recently, Quebec researchers have looked at phosphorus as the major polluter of surface waters. Research on phosphorus has largely focused on reducing the phosphorus loads in surface runoff, and ignored the contribution of drains. Recent studies in Canada, United States, Switzerland, The Netherlands and England have indicated that the drain flow may also be important.

In Quebec, the intense agricultural sector is situated southeast of Montreal in what is known as the lowlands of the St-Lawrence. This study is taking place in the Pike River (628 km^2) watershed, which is located within this intense agricultural region. Most rivers in Quebec that reside within intense agricultural areas are tributaries of the St. Lawrence. The Pike River is an international river that begins in the U.S. and drains into the Missiquoi Bay which is the Quebec portion of the Champlain Lake. Caumartin and Vincent (1994) performed an environmental assessment for the Pike River. The purpose of the study was to determine the overall quality of the Pike River and identify the sources of pollution. They concluded that the Pike River overall was in fair condition, in comparison to the larger rivers such as the Yamaska. However, increasing levels of phosphorus have degraded the quality of the water, which has raised concerns in the community. Furthermore, the Champlain Lake is a much more "sensitive" receiving body of water, than the St. Lawrence. The finger has now been pointed towards the agricultural sector, because industries in the area have all been treating their wastewater since the early 1990's. McGill University, in collaboration with le Ministère de l'Agriculture, des Pêcheries et de l'Alimentation and le Ministère de l'Environnement de Quebec started a project in 2000 with funding from FCAR/IRDA. The overall goal of the project is to validate agroenvironmental indicators and adapt them to a watershed scale to reduce phosphorus losses from agricultural fields. The project is divided into different sections, field scale, small watershed and large watershed. The first section, which pertains to this thesis, examines phosphorus losses on a field scale by measuring the amount phosphorus leaving an agricultural field via surface and subsurface runoff. Furthermore, the first section serves as a resource for field scale data, which can be used to validate the agroenvironmental indicators and computer models that will be used at both the small and large watershed scale. AGNPS and WEND models will be used for the Pike River watershed; both require the results from the field scale to be properly validated.

Hanway and Laflen (1974) concluded that P losses through the drains were not significant. At the time, the focus was on reducing P inputs from surface runoff. However, recent studies in North America and Europe have concluded that the role of tile drains can no longer be ignored (Culley et al, 1983, Gaynor and Findlay, 1995, Heckrath et al., 1995, Beauchemin et al., 1998, Dils et al., 1998, Stamm et al., 1998, Catt et al., 1998, Hooda et al., 1999). In Quebec, as elsewhere, the potential losses that may occur via tile drains is still a topic of keen interest. However, very little data exists on annual P loads in tile drain. Furthermore, the partitioning of the surface and subsurface P losses can yield to better modeling efforts and selection of best management practices. Furthermore, the snowmelt event in Quebec often accounts for a large proportion of the total surface and subsurface runoff for the year. Therefore it could prove to be a large factor in terms of P losses. A field study examining the snowmelt effect on P losses as well as on P partitioning in surface runoff and tile flow has not been previously performed in Quebec. Hence the reason for this study.

1.1 Objectives

The specific objectives of this study were to:

i. Design and install modern surface and subsurface flow instrumentation and data acquisition systems for two field sites in southeastern Quebec
ii. Evaluate yearly phosphorus surface losses from two the field sites
iii. Evaluate yearly phosphorus subsurface losses from the two field sites
iv. Undertake a preliminary examination of phosphorus partitioning in agricultural hydrology

1.2 Scope

The field component of this project was funded for two years. The first year was dedicated to designing and installing the instrumentation to measure and evaluate phosphorus losses in surface and subsurface runoff. The second year involved gathering preliminary measurements of phosphorus in surface and subsurface runoff. The data set is limited to the two field sites, which were selected. The data set is also limited to two soil types.

2. LITERATURE REVIEW

2.1 Introduction

The St Lawrence Lowlands encompass the majority of agriculture in Quebec. Most farms in this region, because of their rich soils and warm temperatures throughout the growing season, grow corn. Since corn requires an abundance of nitrogen to ensure proper growth, farmers' design their fertilizer plans based on these requirements. Most farming practices incorporate both organic and commercial fertilizers to meet nitrogen requirements. By implementing such practices farms tend to over fertilize soil in terms of phosphorus. A big misconception by farmers is that all soils are phosphorus sinks and pose no threat to groundwater pollution (Sharpley et al., 1999). The literature review will include the sources of phosphorus, the different forms of phosphorus in soil, surface water and drainage water.

2.2 Eutrophication

2.2.1 Description

In the past 30 years, surface water pollution by phosphorus has been a major concern (Sims et al., 1998). Non-point sources of surface runoff have previously been thought as the only source of phosphorus pollution (Beauchemin et al. 1998). When phosphorus enters surface waters it acts as the limiting agent for a process known as eutrophication. This process is a natural aging of lakes, but it can be accelerated by human activities. Eutrophication occurs when tiny algae decompose and remove dissolved oxygen from the water. The algae, like all plants, require nitrogen, carbon and phosphorus for growth. However, phosphorus is considered the limiting agent because both nitrogen and carbon are difficult to control due to their exchange between the atmosphere and the water (Sharpley et. al, 1999). Furthermore, nitrogen and phosphorus have different critical levels that promote algae growth in surface waters and they are 0.3 and 0.01 ppm, respectively, meaning it takes less phosphorus than nitrogen to generate algae (Daniel et al., 1994). Despite the higher critical level for phosphorus, nitrogen in certain cases may be the limiting agent, such as when the total N to total P ratio is less than 15:1 (Daniel et al., 1994). The focus remains on controlling phosphorus inputs because it is much easier to control than nitrogen inputs due to nitrogen's ability to fixate on green-blue algae (Sharpley, 1999).

2.2.2 The effects of eutrophication

The onset of eutrophication means water quality problems for both humans and the environment. The aquatic life in surface waters is affected by the decomposition of alga blooms. Decomposition results in a reduction in dissolved oxygen (DO). Hypoxic (low DO) or anoxic (no DO) can be fatal for aquatic life such as clams and worms (Boynton, 2000). The energy created by reducing DO in water result in a temperature increase, which in turn decreases the area of cooler and deeper waters, where fish and shellfish reside (Boynton, 2000). Before decomposing the algae blooms also pose a threat to the submerged aquatic vegetation (SAV) by increasing the turbidity of the water and reducing the amount of light penetrating through the water. The reduction of light has been identified as the main contributor to the decline in SAV over the past several years (Stevenson et al., 1979). The SAV plays an important role in the reproduction process of fish, as they act as a nursery and spawning areas (Stevenson et al., 1979). The reduction in habitat and spawning areas results in a reduction of fish and shellfish, which is of economic importance to fishermen situated near large bodies of fresh water (e.g. the Chesapeake Bay). Phosphorus also has implications on drinking water quality, in terms of palatability. The formation of cyanobacteria blooms periodically creates an undesirable taste (Sharpley, 2000). When these blooms die they create hepatoxins and if consumed they could prove to be fatal for livestock and humans (Sharpley, 2000).

2.3 Sources of Phosphorus

2.3.1 Natural sources of phosphorus

Surface waters can naturally cycle phosphorus via surface and groundwater flow, as well as atmospherically. Often the rates of phosphorus transport by means of aerosols or dust particles are slow in comparison to that of the surface flow (Corell, 1998). Surface flow is the primary source of transport for natural phosphorus; it is also considered to be the main source of transport for anthropogenic sources.

2.3.2 Anthropogenic sources of phosphorus

2.3.2.1 Point sources

Anthropogenic sources have always 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 industrial sector to reduce their waste disposal has decreased the amount of P inputs to rivers from point sources (Bolinder et al., 2000). Non-point sources are now the main contributors of P to rivers in Quebec (Ministere de L'Environment du Quebec 1999). A similar trend has been observed in the Chesapeake Bay area of the United States. The elimination of phosphorus detergents and improved technology of wastewater treatment plants has decreased the amount P inputs to the Chesapeake Bay from point sources by 50% since 1985 (Taylor and Pionke, 2000).

2.3.2.2 Non-point sources

In the past agricultural farming communities were self-sufficient, in that all their feed and waste disposal was produced locally and recycled within the community (Sharpley et al., 1999). 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 scale, specialized producers. While some farms have specialized in crop production, others have focused on intensive animal production. 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 led to elevated soil P levels. Many of these farms were permitted under law, which allowed for manure to be applied based only upon the 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 is in large part responsible for the current pollution problem. In Quebec, these large animal production units can be found in the lowland region of the St-Lawrence and have been identified as problem areas for phosphorus contaminated water (Bolinder et al., 2000).

Agriculture has accelerated surface water pollution by using a combination of organic fertilizer (e.g. manure) and inorganic fertilizer (e.g. commercial fertilizer). Organic fertilizers, primarily animal manure, pose short-term and long-term threats to surface waters. Application time and method of animal manure are considered have short-term P pollution effects. The greatest threat of P losses to surface waters occurs when manure is applied prior to a runoff event (Daniel et al., 1994). Until very recently, animal manures were generally applied at rates based on N requirements with no consideration for the amount of P being applied. Furthermore, the average N:P ratio in animal manure is 3:1 and the general ratio used for grain and hay crops is 8:1 (Daniel et al., 1994). The application based on N requirements over time creates a build up of P in the soil that induces P losses via both surface and subsurface runoff. Commercial P fertilizers pose only short-term effects because they are applied at rates consistent with crop needs, therefore eliminating any possible over-fertilization over time (Daniel et al., 1994). The rate, time and method of application of commercial P fertilizers determines the amount of P lost to runoff. Much like the animal manure, if a runoff event occurs soon after the application of commercial P fertilizers, it can contribute to large amounts of P losses. Furthermore, broadcast applications of commercial P fertilizers have been recorded to have on average 100 times higher concentrations of dissolved P than that of point-injected applications (Daniel et al., 1994). A growing realization of some of the problems associated with basing fertilizer recommendations upon N has resulted in changes to agricultural practices throughout much of the industrialized world. Since 1997, Quebec has established legislation which requires agricultural producers to start basing manure applications based upon the P content of the manure, soil P and percent P saturation of the soil. This will be phased in over 10 years from 2001 and 2011.

2.4 Soil Phosphorus

2.4.1 Forms of phosphorus in soil

The forms of phosphorus in soil can be loosely divided into four different categories and are based on their characteristics in soil (Coale, 2000). The four categories are, dissolved P, labile organic P, stabile organic P and inorganic P Furthermore, the quantity and distribution of each category depends on soil type and pH (Sharpley et al., 1999). Dissolved P (soil solution), which by definition refers to any P that can pass through a 0.45 micron filter. Dissolved P consists of primary and secondary orthophosphates ions ($H_2PO_4^-$ and HPO_4^{-2}) (Daniel et al., 1994). However, dissolved organic and inorganic forms of P may be present in the soil-solution P too (Sharpley and Smith, 1995). Organic forms of P comprise soil material of plant and animal origin plus all microbes that are present in the soil (Sharpley et. al, 1999). Organic P can be further divided into two categories labile and stabile. Labile organic P, is defined as all organic P that is available to the plant (Sharpley et al., 1999). Stable organic P has limited availability to plants and acts as a sink for reactive phosphorus (Coale, 2000). The final category encompasses all forms of inorganic soil P. Inorganic P consists of crystalline and amorphous phosphorus, plus phosphorus that is physically occluded or trapped inside clay aggregates (Sharpley, 1995). The availability of the inorganic P forms to the plants depends on the type and pH of the soil (Taylor and Pionke, 2000). For acidic and neutral soils aluminum and iron phosphates are present, however the aluminum phosphate is more available because of the abundance of aluminum oxides in the soil (Taylor and Pionke, 2000). For alkaline soils calcium phosphates are present due the larger quantities of calcium (Taylor and Pionke, 2000).

2.4.2 Cycling of phosphorus in soil

Plants extract phosphorus from the soil solution, and generally they require 0.3 mg/l of soil-solution P. The 0.3 mg/l of soil solution P is difficult to achieve because of the soil interactions between the dissolved P and the organic and inorganic forms of P. A balance is created in the soil between dissolved P and other forms of P, therefore any additions of P to the soil will disrupt this equilibrium (Coale, 2000). The shift in equilibrium can occur either by mineralization or immobilization. Mineralization is the process in which soil microorganisms transform the soil organic phosphorus compounds into dissolved P (Busman et al, 1998). In particular the enzyme phosphatase, which catalyzes the release of plant-available P from organic materials in the soil (Busman et al., 1998). Immobilization is the process whereby an increase in dissolved P results in an expansion in microbial population; therefore the dissolved P then becomes incorporated into organic P (Sharpley, 1999). Since soils are fertilized in order to meet dissolved P requirements, immobilization is the more common process (Coale, 2000). However, soils which have received large fertilizer applications over the years tend to become enriched, so that mineralization of the stable P will occur, which increase the P concentrations in soil solute, and create the potential for higher P losses in surface runoff and tile drainage effluent (Sharpley, 1999). The amount of dissolved P (DP) in soil is also regulated by three mechanisms, which can all be reversed (Coale, 2000). The first mechanism is the chemical precipitation of dissolved phosphorus out of the solution, and the physical sorption of dissolved phosphorus into a solid phase (Daniel et al., 1994). The second mechanism is absorption, whereby dissolved phosphorus is readily absorbed by iron, aluminum and calcium residing in the soil. The third mechanism is occlusion whereby dissolved phosphorus may be trapped inside the clay matrix of the soil. All three contribute to the removal of available P for the plant.

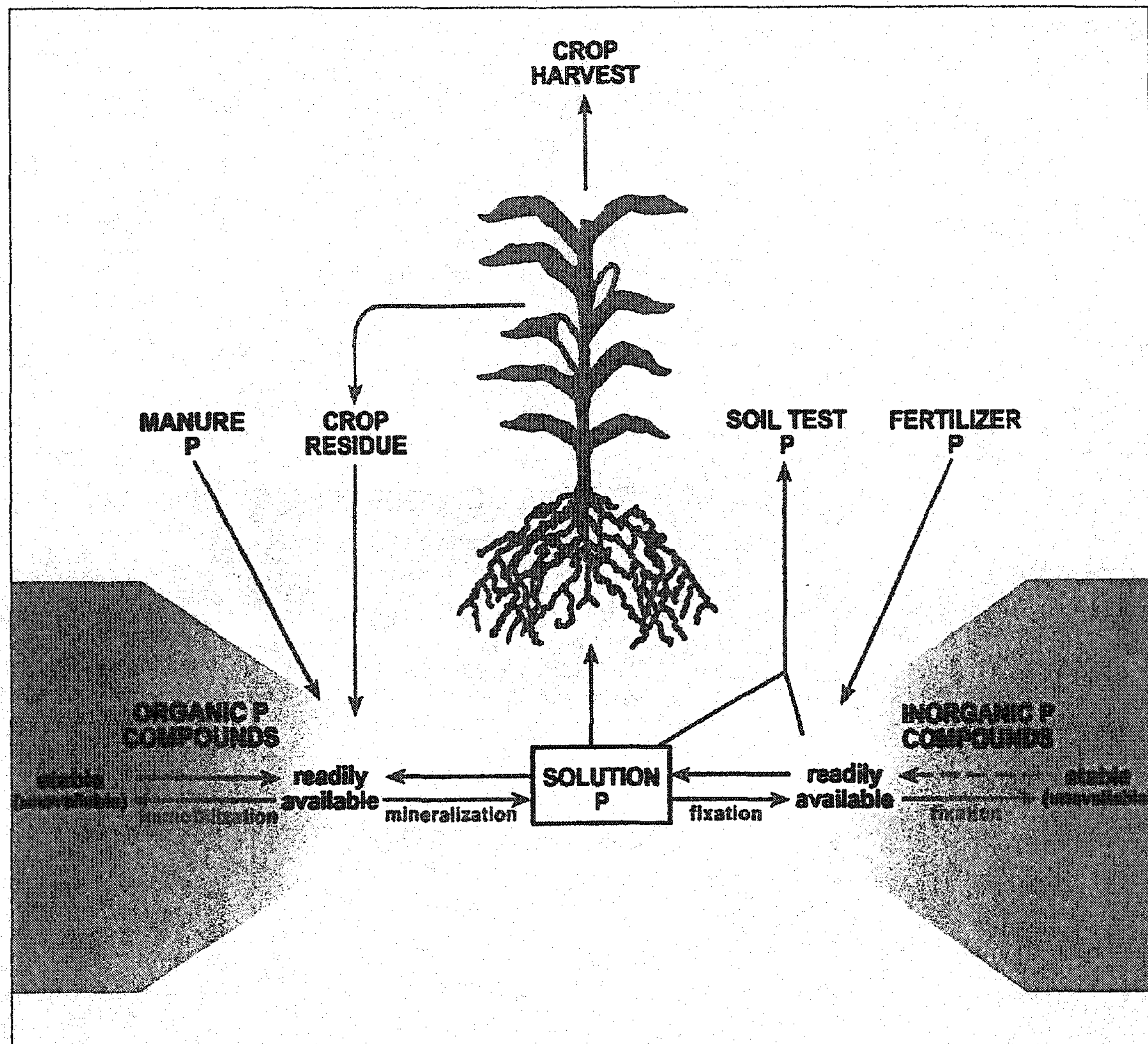

Figure 2.1 The P cycle. (Sharpley, 1999).

2.4.3 Phosphorus saturation

The general concept that soil acts as a sink for phosphorus is supported by the high sorption affinity of dissolved phosphorus to soil minerals (Gachter et al., 1998). The high absorption of P is caused by the high binding energy between soil and P (Daniel et al., 1994). However, a soil has limited sorption sites and therefore any increase in soil P above a certain soil-specific threshold results in a reduction of soil-phosphate affinity (Hooda et al., 1999). Furthermore, the high binding energy sites between soil and P decrease with increasing loading rates (Hooda et al., 1999). A decrease in soil-phosphate affinity increases the leaching ability of P once a soil has attained a certain degree of saturation (Hooda et al., 1999). The degree of phosphorus saturation (DPS) is expressed in a percent that determines the P absorption capacity of a soil (Sims, 2000). An acid ammonium oxalate solution is applied allowing the amount of ammonium oxalate P, Al and Fe to be extracted from the soil. The DPS is calculated by dividing the amount of extractable ammonium P by the sum of the extractable Al and Fe. An increase in DPS results in increased potential losses to surface runoff and leaching (Heckrath et al., 1995). The DPS has been used as a risk assessment tool for farms that pose a threat to surface waters. In the Netherlands a DPS of 25% has been set as an environmental upper limit for the protection of groundwater (Sims, 2000). Here in Quebec, critical limits of 12% to 15% have been loosely set for acidic and sandy to loamy soils in intense agricultural areas (Simard et al., 1995). These critical limits are not adequate for neutral and slightly alkaline clayey soils, because of their greater capacity to absorb P (Beauchemin and Simard, 2000). Another indicator used in Quebec is P saturation based on the Melich III extraction. The Melich III P saturation is the amount of extractable P (mg/kg) divided by the amount of extractable Al (mg/kg). In Quebec, a limit of 10% has been set to indicate which farms are vulnerable to P pollution (Giroux and Tran, 1996). Furthermore, a tentative critical limit of 20 % has been set. The results of a Melich III P test can also aid in determining the P sorption saturation level of a field. The P sorption saturation level is another helpful tool in identifying soils that are at risk of polluting P. The P sorption saturation is calculated by dividing the extractable Melich III P (mg/kg) by the sum of the P sorption maximum (mg/kg) and the extractable Melich III soil P (mg/kg). The P sorption maximum is the reciprocal of the slope of the plot of the soil solution P concentration vs the amount of P sorbed. The P sorbed is calculated as the difference between the amount of P added to the solution and the amount of P remaining in the solution. Sharpley (1997) found a significant linear relationship independent of soil type between the P sorption saturation and the amount of DP in surface runoff. No critical limits for P sorption saturation were established to identify fields that are at risk of heavy surface runoff P pollution.

2.5 Surface Runoff

2.5.1 Forms of phosphorus in surface runoff

Phosphorus can be transported via surface runoff by dissolved and particulate forms. Particulate P represents all forms of phosphorus encompassed with sediment leaving the field. Both inorganic and organic forms of P can be found in sediment. Particulate inorganic forms include P bound to clays, P occluded within soil particles and P in soil minerals (Coale, 2000). Particulate organic P can be in either labile or stable forms. The particulate labile organic forms can easily be transformed to less dynamic forms and the particulate organic stable forms are resistant to mineralization (Coale, 2000). It is important to note that the bioavailability of particulate P upon entering surface waters ranges from 10-90% (Sharpley et al., 1992). Particulate P acts as a short and long-term source of available P for aquatic life. Dissolved P consists mainly of orthophosphate, however variable amounts of dissolved organic and suspended P can be found in surface runoff (Daniel et al., 1994). The dissolved P upon entering surface waters is 100% available for aquatic plants, therefore posing a greater threat than particulate P (Sharpley et al., 1992).

2.5.2 Phosphorus transport

Both particulate and dissolved P are transported from agricultural fields, however the movement of each depends on the mechanism by which P moves through the landscape and the source of P. Mechanisms include rainfall and irrigation-induced erosion and runoff (Sharpley et al., 1993). Rainfall and irrigation induced erosion are responsible for the amount of particulate P entering surface waters. Raindrop impact and surface overflow detach and move of sediment rich in P from cultivated fields to surface waters. Particulate P generally accounts for 60-90% of total P found in surface runoff (Sharpley et al., 1992). Dissolved P in surface runoff occurs by the desorption, dissolution, and extraction of P from soil and plant material (Sharpley et al., 1993). These processes are affected by the water interaction between the rainfall or irrigation and the thin layer of surface soil (Sharpley et al., 1985). In Quebec, the spring-snowmelt event is generally the dominant hydrologic event of the year. The cold temperatures of the winter and spring freeze soil pores hence restricting the infiltration and thus increasing the amount of runoff. However, very little is known about the affects of snowmelt on the amount of P leaving agricultural fields.

The sources of P often determine which form (dissolved or particulate) will govern the P concentrations in the runoff, as well as the quantity of P lost in surface runoff. Loss of P in surface runoff is affected by the rate, time and method of application (Sharpley et al., 1993). Romkens and Nelson (1974) concluded that an increasing linear relationship exists between rate of P fertilizer and loss of P in surface runoff. Broadcast applications of P fertilizer are much more susceptible to P losses than point injection applications (Sharpley et al., 1993). Mueller et al. (1984) demonstrated using simulated rainfall that the P loss in surface runoff from a broadcast manure application was 5 times higher than that of an incorporated manure application. However, the factor producing the greatest amount of P losses in surface runoff is the time of application. Rainfall events immediately after a fertilizer application produce large quantities of both particulate and dissolved P (Daniel et al., 1994). In addition to these factors, the tillage practice affects the amount and distribution of particulate and dissolved P in surface runoff. Conventional tillage practices produce large amounts of eroded sediment, and hence large particulate P losses (90% of total P). Minimum tillage or no till practices reduce sediment, therefore decreasing the particulate P quantity from 60-90% to less than 50% of total P in surface runoff (Gaynor and Findlay, 1995). However, reducing the amount of particulate P in surface runoff results in an increase in dissolved P. For minimum or no till practices dissolved P represents 50% of total P in surface runoff (Coale, 2000). Gaynor and Findlay (1995) reported that conservation practices had reduced sediment by a factor of 2.71, however ortho-P losses had increased by a factor of 2.2. Furthermore, Zhao et al. (2001) when comparing ridge tillage systems to conventional tillage systems noticed that the ridge tillage plots recorded a 55% decrease in TP loads over the conventional tillage plots. However, those same ridge tillage plots recorded a 48% increase in soluble P loads over the conventional tillage plots. Therefore, while conservation tillage systems reduced overall TP loads compared to conventional tillage systems, they often have larger dissolved P loads than their counterpart. The ecological impact of these increases in dissolved P could be more dramatic due to the availability of the dissolved P to aquatic plants.

2.6 Subsurface Runoff

2.6.1 Forms of phosphorus in subsurface runoff.

Dissolved P is the dominant form of phosphorus in artificial tile drains. Particulate P generally represents a small fraction of the total P leaving the drains, because clay soils structurally prevent clay particles from entering the drain, and sandy silty soils are prevented from entering the drainage water, because the drain pipes are wrapped with a geotextile. However, Heckrath et al. (1995) reported large concentrations of particulate P in subsurface runoff due to soil disturbance following installation of a new drainage system. Furthermore, preferential flow has also proven to be an important pathway of particulate P in drainage water (Heathwaite et al., 2000). Dissolved P can be separated into three categories; dissolved reactive phosphorus (DRP), dissolved acid-hydrolyzable phosphorus (DAHP), and dissolved organic phosphorus (DOP). DRP is largely a measure of orthophosphates, however a small fraction of condensed phosphates could be present. DRP is often the main form of dissolved P in drainage water. However, Chardon et al. (1997) and Hooda et al. (1999) concluded that DOP could be an important form in subsurface flow from soils receiving intensive applications of livestock manure and mineral fertilizer.

2.6.2 Phosphorus leaching

The leaching of phosphorus to the tile drains and groundwater has often been ignored as a source of P pollution because of the high absorption capability of soils. However, conditions such as soil properties, climate, and agricultural practices particularly the enrichment of soil through over fertilization can create significant P losses in terms of the P enrichment of surface waters (Sims et al., 1998). The soil structure has an effect on the lateral movement of P through the soil profile, such factors as void size (numbers and distribution), the number micro and macropores and the degree of structure and aggregation control the rate of P transport (Heathwaite et al., 2000). The soil structure depends on soil type; coarse-textured soils such as deep sands that have been over-fertilized have produced significant losses of P. Furthermore, organic soils or mineral soils with a high organic matter content have been reported to encounter leaching P due to the low concentrations of oxides of Fe and Al and carbonates, which are responsible for the retention of P (Sims et al., 1998). Agricultural management practices such as continuous applications of organic and inorganic fertilizers have led to the build up of P in soils. As mentioned earlier, all soils can eventually become saturated in terms of P, creating a balanced shift of soluble P, in that the available soluble P in the soil solution increases. The excess available soluble P then filters downward through the soil profile eventually making it to the ground water. Simard et al. (1995) reported significant P leaching from agricultural soils in comparison to forested soils within a Quebec watershed. The yearly total P values for horizons A, B, and C of the forested soils were 725, 625 and 575 mg/l, respectively. The agricultural soils were divided into dairy farms and N surplus farms, where N surplus farms represent farms with an average surplus of 230 kg of N per ha per year and intensive hog farms. On the dairy farms, the N in mnaure was matched to the crop requirements, so that in effect, fields were not being over fertilized. On swine farms, the available N greatly exceeded crop requirements, so that fields were being over fertilized for N and greatly over fertilized for P. The dairy farms had yearly total P values of 1010, 675 and 650 mg/kg, for horizons A, B and C, respectively. The N surplus farms had yearly total P values 1150, 700, and 725 mg/kg for horizons A, B and C, respectively. It was concluded that the applied excess P was being leached to the lower horizons because of the P enrichment of the surface horizon. Much like surface runoff, the timing of organic and inorganic fertilizers can have an effect on the amount of P that leaches through the soil profile. Stamm et al., (1998) reported large increases of soluble reactive phosphorus (SRP) in tile drain effluent from a rainfall event that occurred two days after a fresh manure application.

Lateral flow is often not suspected as the main subsurface pathway for P. Preferential flow through macropores has played a large part in P reaching the groundwater. However, our understanding of macropore flow is limited and therefore it is often inferred as the source of P leaching without any evidence (Heathwaite et al., 2000). For example, Heckrath et al. (1995) reported that preferential flow was the cause of the high concentrations of P recorded, because the soils examined had high P absorption capabilities. In an attempt to study the effect of preferential flow, Stamm et al. (1998) inserted a blue dye tracer into two different soil profiles to observe the soil interaction. They concluded that preferential flow appears to be an efficient mechanism of P transport into tile drains. Furthermore, preferential flow may cause interior erosion and colloidal transport of P from the surface layer to the subsurface (Magid et al., 1999). The ecological impact of preferential flow could be significant because preferential flow reduces time for interaction and thus the transformation of phosphorus forms during transport (Heathewaite et al., 2000).

2.6.3 Previous studies

The installation of tile drainage systems is a common agricultural management practice in the regions of eastern Canada. Artificial drainage 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. It was believed that a reduction in soil erosion meant a reduction in the particulate P leaving the field and that the excess water would filter through the soil and leaves 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.

Eutrophication due to P loading from surface and subsurface is not just a North American problem. Europe has very intensive agricultural production without the luxury of large land bases such as North American farms. Much like North America, Europe has also in large part ignored the effect of the tile drains on P pollution until recently. Field studies on drain effluent have been performed in England, Holland, Finland, Ireland, Scotland and Switzerland.

depth were examined 0.6 m and 1m. The PP and TDP loads at 0.6m depths more than doubled those at 1m.

Gaynor and Findlay (1995) examined the effects of tillage on the P loads in the subsurface drains over a period of 3 years. Three tillage systems: conventional, ridge and no till were used. The water samples were analyzed for suspended sediment (SS) and orthophosphates (ortho-P). The 3-year mean of ortho-P loads for conventional, ridge and no till were 0.38, 0.53 and 0.87 kg of ortho-P/ha/yr, respectively. It was concluded that the larger ortho-P losses observed from conservation tillage practices were a result of altered mineralization, or reduced retention of mineralized P forms by the soil.

It should be noted that both the Culley et al. (1983) and the Gaynor and Findlay (1995) reports also included surface runoff concentrations and loads. Furthermore, both reports encountered larger concentrations of ortho-P in surface runoff than subsurface runoff. However, both Culley et al. (1983) and Gaynor and Findlay (1995) observed larger cumulative losses of ortho-P in the drains than in surface runoff. This illustrates that it is necessary to examine the overall effect (loads), in addition to the immediate effect (concentrations).

In Quebec, the P leaving the drains has been a growing concern especially in the Lowlands of the St. Lawrence. Beauchemin et al. (1998) recorded forms and concentrations of phosphorus in drainage water of twenty-seven tile-drained soils. Twenty-seven sites representing 9 different soil series were sampled above two years (1994 and 1995). In 1994 half of the soil series were sampled in the spring and the remaining were sampled in the fall. In 1995 all soil series were sampled in the fall, and two sites were not sampled because the ditch water level was over the drainage outlets. The samples were analyzed for TP, PP, TDP and DRP. DOP was assumed to be the difference between TDP and DRP. The TP concentrations are important in assessing surface water quality; the Quebec standard of TP is 0.03-mg TP/l for surface waters. The TP concentrations observed ranged from 0.01 to 1.17-mg TP/l. In 1994, 14 out of 27 sites exceeded the 0.03-mg TP/l and in 1995, 6 out of the 25 sites exceeded the 0.03-mg TP/l. It is difficult to assess the risk of P enrichment of surface waters based on these results. The limitations observed by Beauchemin et al. (1998), were the number of samples taken during the course of 2 years, and the lack of comparative data for the region. One limitation not mentioned was the concentration versus total load. High TP concentrations observed over a small amount of drainage volume might not pose as big a threat as low TP concentrations over a large amount of drainage volume. Furthermore, Beauchemin et al. (1998) used a grab sampling technique that prevented them from sampling during the snowmelt and high flows, because the water level in the ditches were above the drain outlets.

2.7 Summary

Non-point source pollution from agricultural areas has been identified as the principal source of phosphorous loads in Quebec. While it is recognized that phosphorous losses from agricultural fields is mainly a function of surface runoff and soil erosion, a limited number of studies have found that phosphorous concentrations in tile drainage effluent often exceed water quality guidelines. However, information about annual phosphorous loads and concentrations from tile drains, and it's relationship to surface runoff losses is generally not available. Difficulty in operating runoff measurement and water sampling equipment during freezing/snowmelt conditions, and obtaining reliable flow measurements in tile drain outlets, which are frequently submerged during periods of high flow, are two factors which may explain this lack of field data. Given that most of the land in intensive agricultural production in Quebec is tile drained, and that phosphorous is the dominant water quality problem, our limited understanding of the impact of tile drainage is a critical gap in knowledge. To address this gap, two agricultural fields have been equipped to measure and sample surface runoff and tile drain flow, and P in both.

3. MATERIALS AND METHODS

3.1 Site Description

3.1.1 The Pike River watershed

The project was initiated in 2000 at field sites located near Bedford, Quebec. Bedford is 70-km southeast of Montreal and is situated within the Pike River watershed (Figure 3.1). Bedford, located in one of the warmer regions of Quebec has an average annual temperature of 6.8 °C and a subsequent period of 155 frost-free days. The Pike River has an arc shape, which begins in the state of Vermont, enters southern Quebec and emptying into the Missiquoi Bay, which is the Quebec section of the Champlain Lake. The Pike River, which is roughly 58 km long and drains an area of 629 km^2 has annual average discharge rate of 6.5 m^3/s. The watershed area that lies in Quebec is 530 km^2.

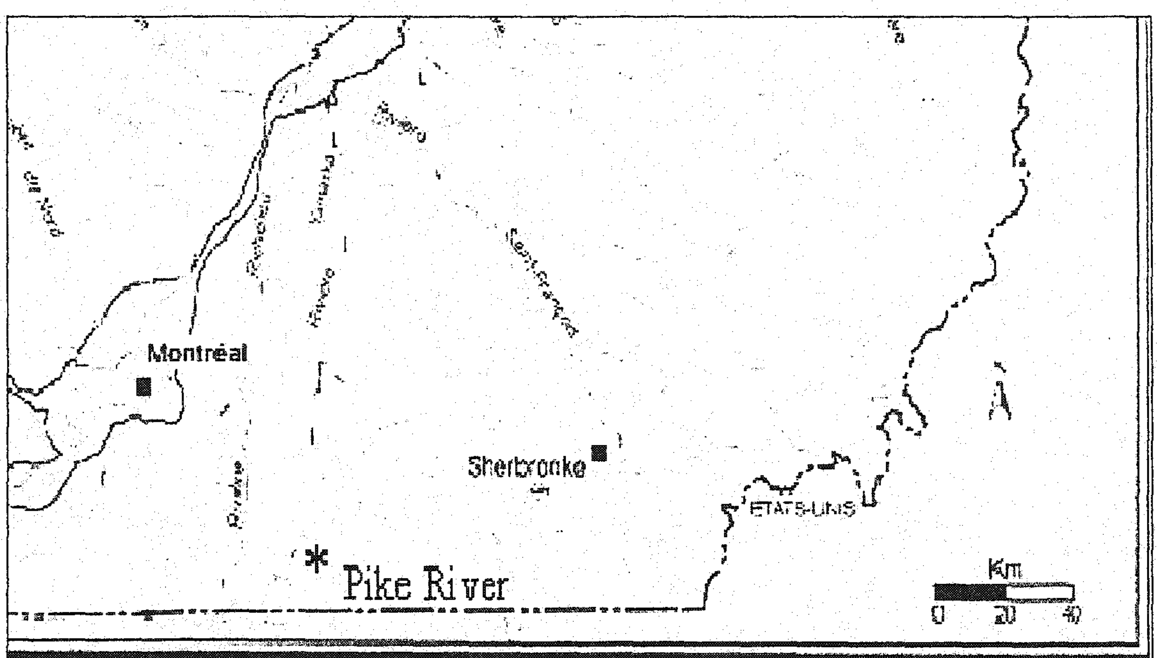

Figure 3.1 Pike River. (Modified from the Ministry of Environment of Quebec, 1999).

3.1.2 The field sites

The goal of the project was to find two farms within the Pike River watershed with soils that were high in phosphorus and percent P saturation. Furthermore, each farm had to have a different soil type and had to have an easily accessible subsurface drainage outlet close to a surface drainage outlet. The farms that were chosen met the criteria. The first farm belongs to Mr. Marchand, a dairy farmer who was situated 1 km west of Bedford. The soil P levels at Mr. Marchand's were extremely high averaging out to be 360 kg P/ha and the percent of P saturation was 23%. The soil type was a sandy loam (Rubicon). The other site belongs to Mr. Gagnon, a swine producer who was situated 4 km west of Bedford. The soil P levels at Mr. Gagnon's averaged 140 kg of P/ha and the percent of P saturation was 7%. The soil type was a mixture of two soil types, in which a Bedford sandy clay loam was surrounded by a St. Sebastien shaly loam. The soil nutrient levels for both sites were determined by a study that was carried out in 1998 by IRDA. Both sites had a visible surface outlet point located in close proximity to a subsurface drainage outlet. Although at the Gagnon sites soil P and P saturation levels were somewhat low; the surface outlet point was accessible and visible via the gullies that occurred during the previous spring snowmelt.

The data collected encompassed the water year, October 1st, 2000 to September 30th, 2001. Over this period both organic and inorganic fertilizers were applied to the Marchand farm, where as the Gagnon site, only inorganic fertilzer was applied to the field. In the fall of 2000, the Marchand field received 32t/ha of solid dairy manure and it was incorporated immediately. The Marchand farm used two inorganic fertilizer applications. The first (May 2001) had a nutrient ratio of 17-26-8 (N-P-K) and was banded during planting. The second fertilizer (June 2001) had a nutrient ratio of 34-0-15 (N-P-K), and was applied 2-4 weeks after planting. It was incorporated between rows using disks. The 17-26-8 fertilizer was applied at a rate of 191 kg/ha and the 34-0-15 fertilizer was applied at a rate of 450 kg/ha. Unlike the Marchand farm, the Gagnon farm applied inorganic fertilizer three times, once during seeding on May 2nd, 2001 and the remainder on May 16th, 2001 and June 1st, 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

(1.5ft) and 0.610m (2ft) HS flume were required for the Marchand and Gagnon sites, respectively. However, for ease in construction both were designed for a depth of 0.610m (2ft) (Figure 3.2). The HS flumes are rated for a maximum flow of $0.311 m^3/s$.

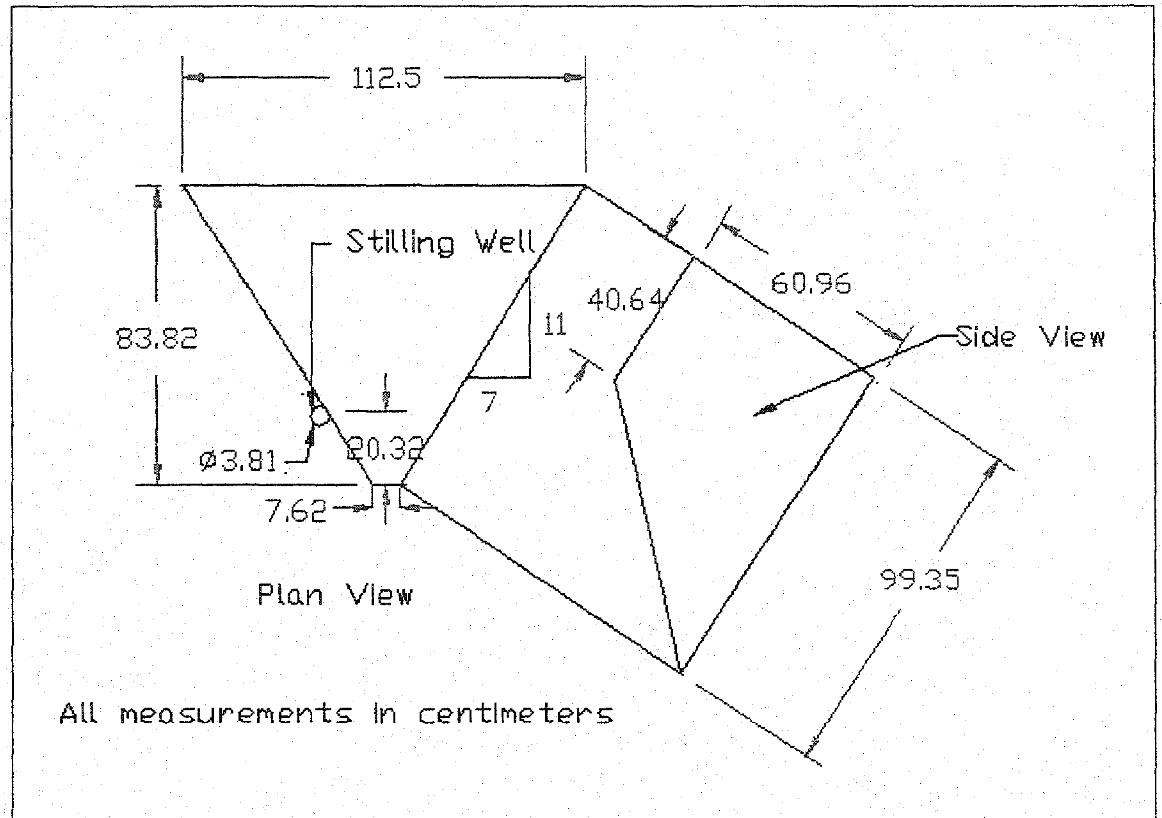

Figure 3.2 HS Flume

Each HS flume was equipped with a stilling well (Figure 3.3). The depth of water in the stilling well was measured by inserting a submersible pressure transducer. The pressure transducer determines the water pressure, and relays it as a measure of depth. One of the drawbacks of the stilling well system is that it can freeze during winter, which could result in faulty readings from the pressure transducer. Therefore, as a precautionary measure, an ultrasonic sensor was installed at each site. An ultrasonic sensor emits a sound wave that rebounds off an object and returns to its original starting point. The time at which it takes for this sound wave to return is then translated into a measurement of depth. The ultrasonic sensor was centered above the flume floor, which gave an accurate representation of the flow through the flume.

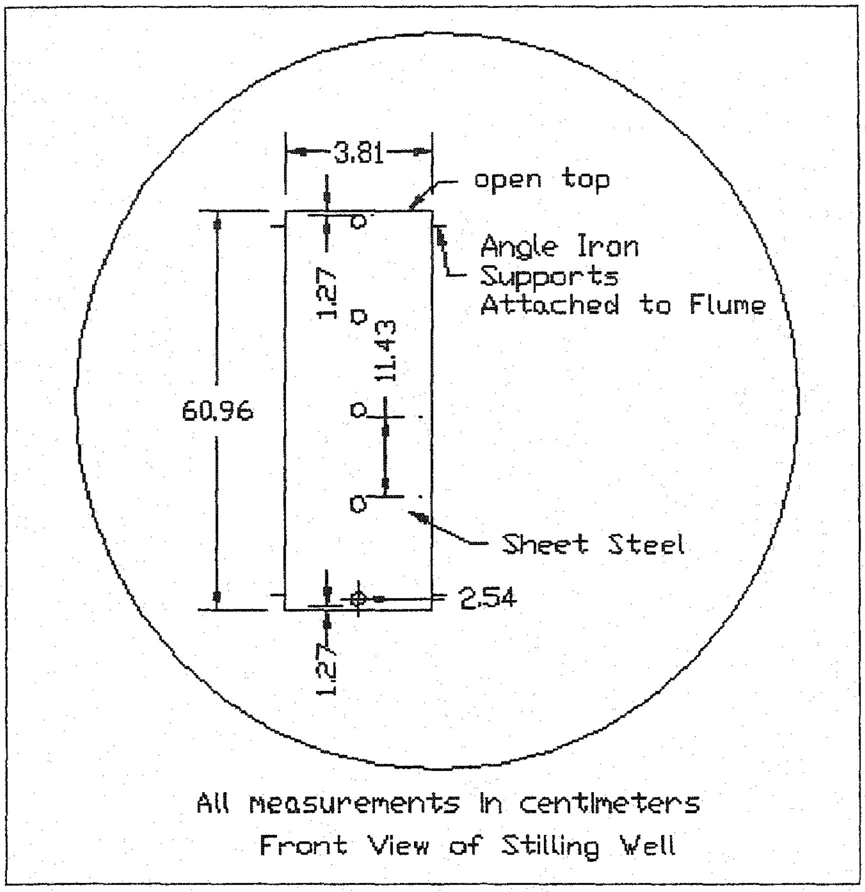

Figure 3.3 Stilling Well

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. The first part of the berm consisted of soil that was built up to a height of 0.610m (2ft) and extended roughly 3.05m (10ft) on either side of the flume. The other part of the berm comprised of plywood and polyethylene sheeting. The plywood was an extension of the flume walls and continued out parallel to the edge of the field.

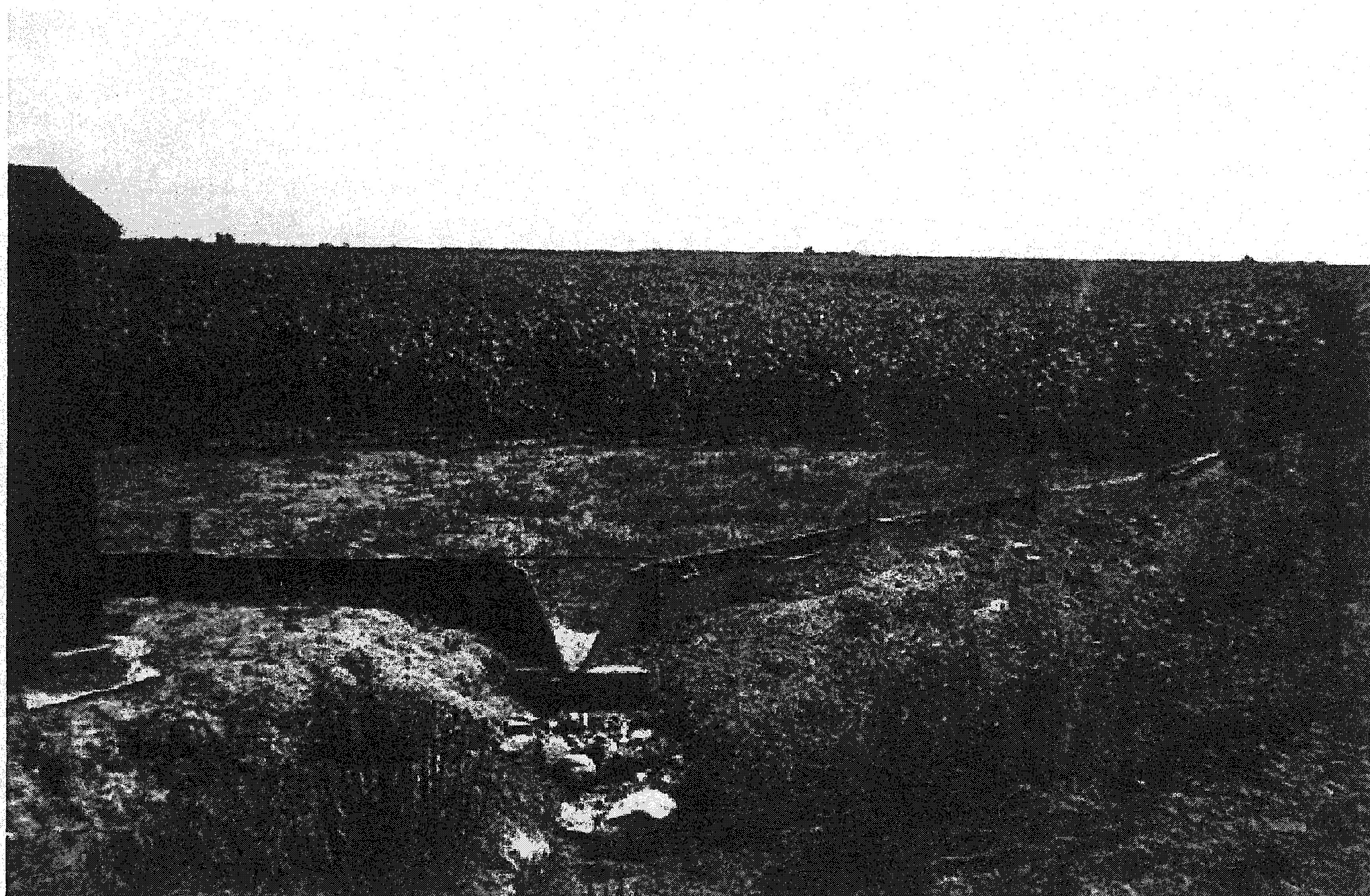

Figure 3.4 Flume and berms at Gagnon site

The plywood resided in front and extended longer than the soil section of the berm. The polyethylene sheeting was stapled to the plywood. The plastic was black to prevent weathering from the sun. Along with the face of plywood, the plastic was buried 15.24cm (6in) under the ground to prevent any seepage under the berm (Figure 3.4). The depth at which the plastic was buried was determined on site, not using a flow net calculation.

3.2.2 Tile drainage runoff

Measuring and sampling discharge in tile drain outlets in Quebec during runoff events is normally not possible, because the outlet pipes are usually submerged when the peak flow occurs. This can also lead to some backwater effects, which might reduce the performance of the drainage system. To overcome these limitations, a Global Water Insertion Flow meter (IF-200) 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 5.08cm (2in) threaded insertion fitting. The IF-200 is designed for low-pressure pipe flow.

Agricultural drain flow does not always fill the entire pipe. To attain full pipe flow, we installed a U-section of pipe, so that the center section is always flowing full (Figure 3.4). To keep the flow meter completely submersed in water, the subsurface drainage outlet was modified without disturbing the design slope of the drain.

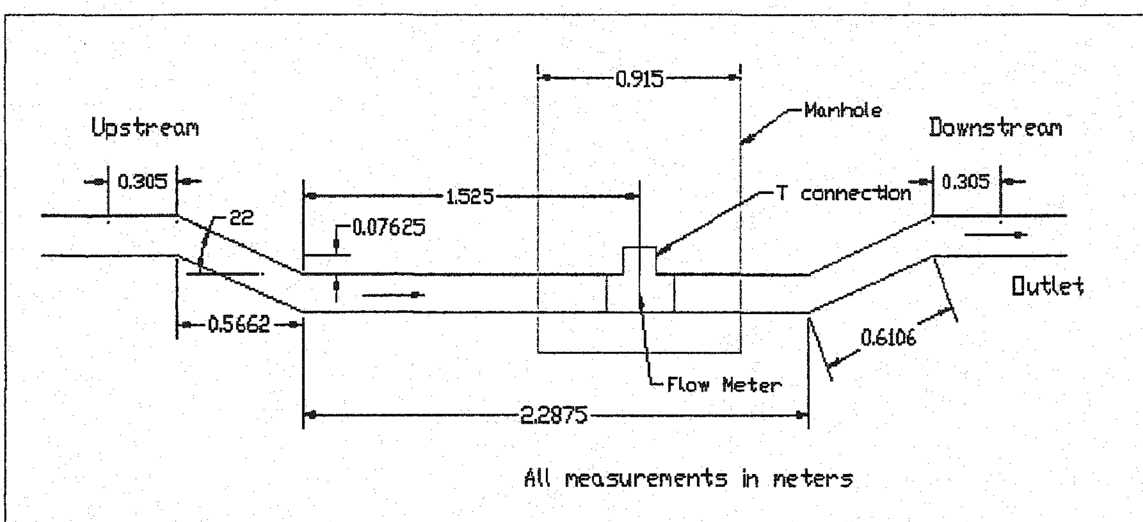

Figure 3.5 Subsurface flow measurement system

It was important to keep the design slopes, because any changes may affect system performance. To prevent this, once the drains were visible, a survey was carried out along the section of drain where the flow meter was to be inserted. To keep the flow meter completely submersed in water, the section of pipe where the flow meter resides was lowered below the existing drainage outlet. The flow meter required certain specifications for proper installation. The first requirement pertained to the 5.08cm (2in) threaded insertion fitting; a 15.24x15.24x5.08 cm schedule 40 PVC threaded T fitting was used as the insertion point of the flow meter. The other specification referred to the pipe section before and after flow meter insertion point. The flow meter section had to be straight and at least 15 times the diameter of pipe in length. In this case the diameter of the pipes were 15.24cm (6in), therefore the entire length of the flow meter section was at least 228.6cm (7.5ft) long. Furthermore, the section before the flow meter had to be 2/3 the distance of the entire section. To lower the new section below the existing drainage outlet, two sets of 22-degree elbows (schedule 35) were installed. Each elbow was separated by a 0.610m (2ft) section of schedule 35 PVC pipe. The 0.610m (2ft) section allowed for a 7.62cm (3in) 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 setting.

Assuming a constant volumetric flow rate by reducing the diameter of a pipe section decreases the velocity of the flow. Furthermore, according to Manning's equation, if the roughness coefficient (n) of the pipe is decreased the flow increases. A quick calculation, using Manning's equation, shows that a 20.32cm (8in) polyethylene tile ($n = 0.018$) has about the same carrying capacity as a 15.24cm (6in) PVC pipe ($n = 0.009$). In addition, attaching a 20.32cm (8in) PVC pipe to either a 20.32cm (8in) corrugated tubing or a 20.32cm clay tile would be difficult. Therefore, each 15.24 (6in) PVC pipe section was placed inside each 20.32 cm (8in) collector and sealed using drainage tape and expanding foam. For maintenance, a manhole 0.915m (3-ft) in diameter was inserted into the soil just above the flow meter.

3.2.3 Datalogger

Each site is equipped with a Campbell Scientific 21X Datalogger. The Datalogger is programmed to monitor all sensors on a 5 second interval and calculates the rate of discharge. The discharge is averaged, and rainfall is totaled over a 15 minute interval, and recorded. Temperature and radiation data are averaged and recorded hourly. The datalogger tabulates flow and activates both the surface and subsurface samplers, according to the specific sampling strategy. The sites are 100 km from the Macdonald Campus; therefore a phone line was installed at each site so the data could be downloaded regularly. During the winter the sites were checked regularly to monitor temperature in the manhole and housing. This was particularly important since most of the equipment is sensitive to freezing. The data was collected and processed once a week and then transferred into a spreadsheet. Each 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 sampler from any unwanted electrical surges.

3.3 Water Quality Sampling

3.3.1 Surface runoff

The surface runoff samples were flow weighted discrete samples, meaning that each sample taken for specific volume of water during an event was placed in its own bottle. The purpose of using flow weighted discrete samples for surface runoff was to examine the 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 the strategy proposed by Tremwel et al., (1996). The strategy is illustrated in Table 3.1.

Table 3.1 Geometrical Increasing Sampling Strategy

Sample Number	Geometrical Increment	Volume (mm of runoff over surface area)	Cumulative Volume (mm of runoff over surface area)
1	$0.2 * 2^{(n-1)}$ *	.2	.2
2		.4	.6
3		.8	1.4
4		1.6	3.0
5	$2 * 1.25^{(n-5)}$ *	2.0	5.0
6		2.5	7.5
7		3.13	10.63
8		3.91	14.54

* n = 1,2,3,4.....12

An American Sigma surface sampler was used at each site. The sampler has a carousel with 24 bottles each capable of holding 1 L of water. Two 1 L samples were taken each time the sampler was activated. The intake tube was suspended above the center of the flume. Furthermore, it was low enough to sample low flows and was high enough so as to avoid sediment build up at the bottom of the flume. An enclosure was built at each site to protect each sampler from the harsh environment. Each enclosure was 2.135m (7ft) x 1.22m (4ft) in size, well insulated and equipped with baseboard heater to keep the inside temperature above 15 °C during the winter. A thermocouple was placed inside each enclosure to monitor the inside temperature.

From each surface runoff sample, a 500mL subsample was collected out of the carousel 1L bottle and then placed in cooler and shipped to the IRDA lab for analysis. After every event, a clean carousel was placed in the sampler, while the old one was brought back to lab for cleaning. Each bottle was rinsed with acid and de-ionized water to ensure no contamination. The samples were analyzed for the following parameters: pH, suspended material, total phosphorus, particulate phosphorus, P, K, Ca, Mg, Na, NH_4 and NO_3. The bioavailability of phosphorus was a parameter of importance with regards to eutrophication. However, due to costs, it was only analyzed for samples where phosphorus concentrations were thought to be significant.

3.3.2 Tile drainage runoff

During large storm events or spring snowmelt, surface ditches and streams are filled with water causing subsurface outlets to be completely submerged. When the outlets are completely submerged it is impossible to take grab samples even though there is still water coming from the drains. For this reason, previous studies have not been able to take an extensive look at phosphorus in subsurface drains. To overcome this problem, an access port was installed just downstream from the IF200 flow meter on the 15.24cm PVC pipe. The intake line from the Global Water Wastewater Sampler (WS300) was installed on this access port to collect subsurface samples.

The subsurface samples were flow-weighted composite samples, meaning each subsample represents the same volume of discharge. All samples taken during an event were placed in one bottle. 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 has a threshold value of 1 mm/day of runoff over the entire subsurface drainage area. A constant incremental sampling strategy was used, meaning that at every instance the threshold was reached a sample was taken. Each sample was 250 ml. The bottle could have held up to 7.57L (2 U.S. gal.) 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 0.763 m (2.5ft) x 0.763 (2.5ft), well insulated and equipped with a 75 watt light bulb to keep the inside temperatures above 15 °C. Each enclosure was placed on top of the constructed manhole mentioned above (Figure 3.6). The intake tube was connected to a pressure tap located on the section of pipe downstream of the flow meter. A light bulb was placed in each manhole to prevent freezing of the intake tube. Thermocouples were placed in the manhole and the enclosure to monitor temperature levels.

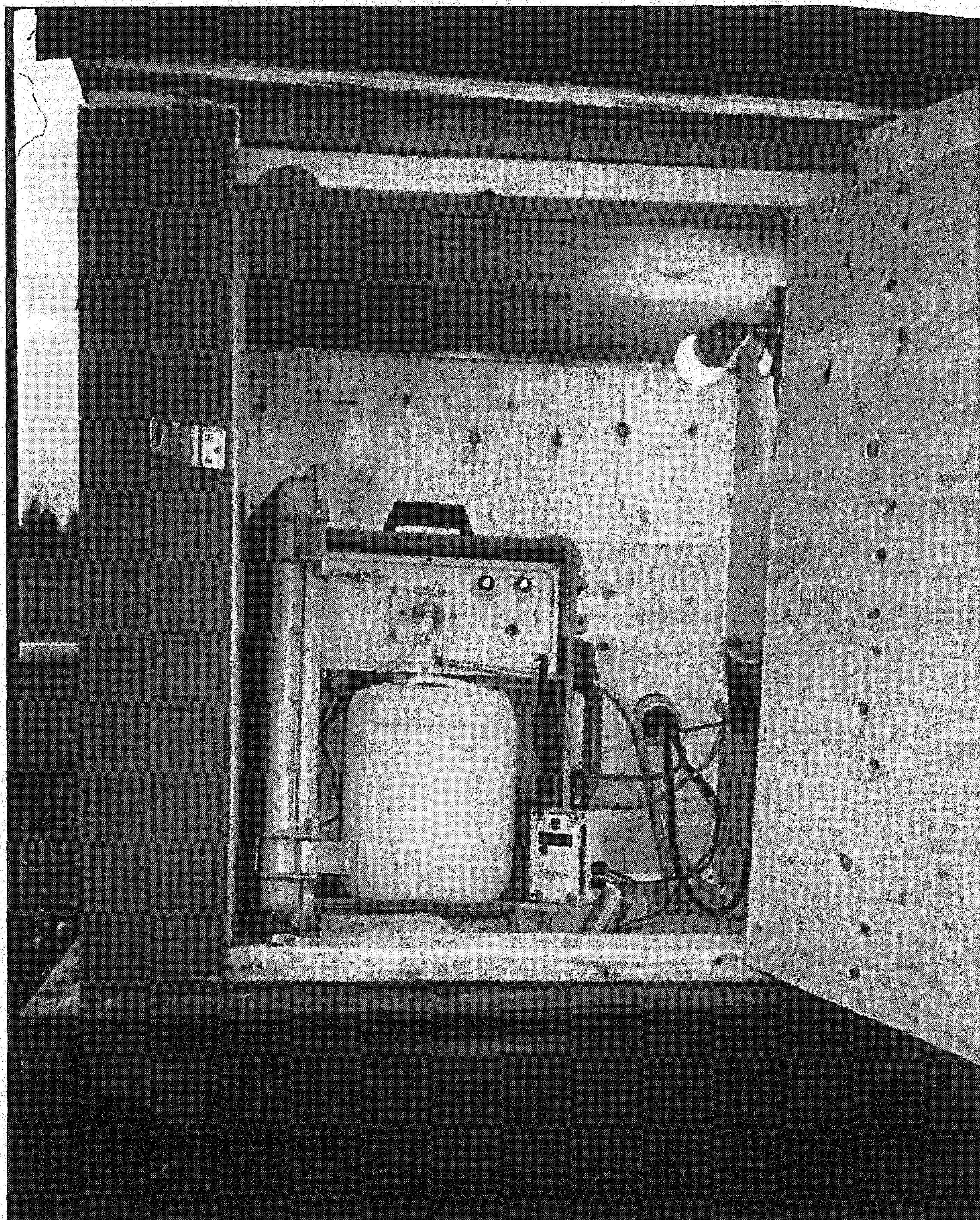

Figure 3.6 View of subsurface instrumentation at the Marchand site

After each event, a 500ml subsample was collected from the 7.57L bottle and shipped in a cooler to the IRDA lab for analysis. All bottles were rinsed with acid and de-ionized water to ensure no contamination. Each sample was analyzed for the following parameters: pH, materials in suspension, total phosphorus, ortho-phosphates, total dissolved phosphorus, suspended solids, P, K, Ca, Mg, Na, NH_4 and NO_3. For the same reasons mentioned for the surface runoff analysis, the bioavailability of phosphorus was only analyzed for large storms.

3.4 Soil Sampling

3.4.1 Sampling strategy

On July 9th, 2001, soil samples were collected on both the Marchand and Gagnon sites. An offset grid sampling strategy was used to spatially distribute the sampling points. Each point along a sampling row was spaced at 70m and the rows were spaced at 60m from each other. The purpose of the soil study was not only to determine the existing soil conditions but also observe any spatial differences within each field.

A total number of 33 and 39 samples were taken at the Marchand and Gagnon site, respectively. Each point represents a discrete sample with a depth of 20 cm. Furthermore every sampling point was given global positioning system (GPS) co-ordinates, so that the spatial variation within each field may be determined.

3.4.2 Soil analysis

3.4.2.1 Melich III extraction

The samples were dried at a temperature of 105 °C for 48 hours to remove all moisture. After the 2 days, the samples were then grounded into loose soil. Once grounded, roughly 2.5 grams of each sample was extracted and placed into a cup. Each sample was then administered 25ml of the Melich solution, then shaken for 5 minutes (Tran and Simard, 2000.). After the samples had been properly shaken, they were then filtered through a 0.45 filter. A molybdate coloring agent was then added and the filtered solution was then determined for phosphorus using colorimetry (Tran and Simard, 2000). The extracted phosphorus was recorded in mg/l and later expressed in kg/ha. The aluminum extracted by the solution was determined using atomic absorption (Tran and Simard, 2000). The amount of aluminum was recorded in mg/l, which was later expressed in mg/kg. The percent of phosphorus saturation can be calculated by dividing the soil test P concentration by the aluminum concentration.

3.4.2.2 Organic matter

To determine the organic matter of the soil the loose soil, samples were placed in a furnace at a temperature of 105 °C for 24 hours. The samples were then immediately weighed to determine the dry weight. Once weighed the samples were placed in a muffle furnace at temperature of 360 °C for 4 hours. The samples were then weighed immediately and the percent organic matter was calculated.

3.5 Meteorological Data Acquisition

To monitor weather conditions, each site was equipped with a rain gage, air temperature sensors, and thermocouples for the stilling wells, subsurface drainage wells, subsurface runoff enclosure and surface runoff enclosure. The Marchand site was also equipped with a heated rain gage and a radiation sensor.

Snow sampling was performed on February 8th and March 20th, 2001. The purpose was to determine the water equivalence of the snow pack for each site prior to snowmelt. A total of 24 and 33 snow samples were taken at the Marchand and Gagnon sites, respectively. The sampling points were equally spaced 60m apart along a row and the adjacent rows were separated 60 m from each other. Using a snow core sampler, the depth of snow pack was recorded at each point and a core of snow was placed in bag. The bags were later weighed and the estimated water equivalency depth (EAWED) was calculated. In order to calculate the EAWED the specific density of the snow must be determined first. The specific density (g/cm^3) was calculated by dividing the weight 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 was then determined by multiplying the average specific density by the average snow pack depth.

4. RESULTS AND DISCUSSION

4.1 Meteorological Data

Rainfall data was collected from October 5th, 2000 to September 30th, 2001 by six rain gages at three sites. These were: a manual rain gage at the weather station at Philipsburg, Quebec; a manual and tipping bucket gage at the Gagnon site; and a manual, unheated and heated tipping bucket at the Marchand site. Philipsburg is located 7km southwest of Bedford.

The manual rain gages were used to verify the tipping bucket data. Overall the tipping bucket rain gages over estimated the precipitation recorded by the manual rain gages by 21% and 7%, for the Marchand and Gagnon sites, respectively. For the summer months, the tipping bucket rain gages overestimated the manual rain gages more than in the spring months (Figures 4.1 and 4.2). This trend could be attributed to an increase in evapotranspiration between the spring and summer months. Another interesting point is the difference in rainfall between the two sites. The rainfall at the Marchand site was 18% and 5% higher than the Gagnon site for the tipping bucket and manual rain gages, respectively. The higher values could be a result of two factors: the spatial variability in rainfall between the two sites and the characteristics of both fields. The Gagnon field is more open and receives a greater amount of wind, therefore making it difficult for the tipping bucket and manual rain gages to trap blowing rain.

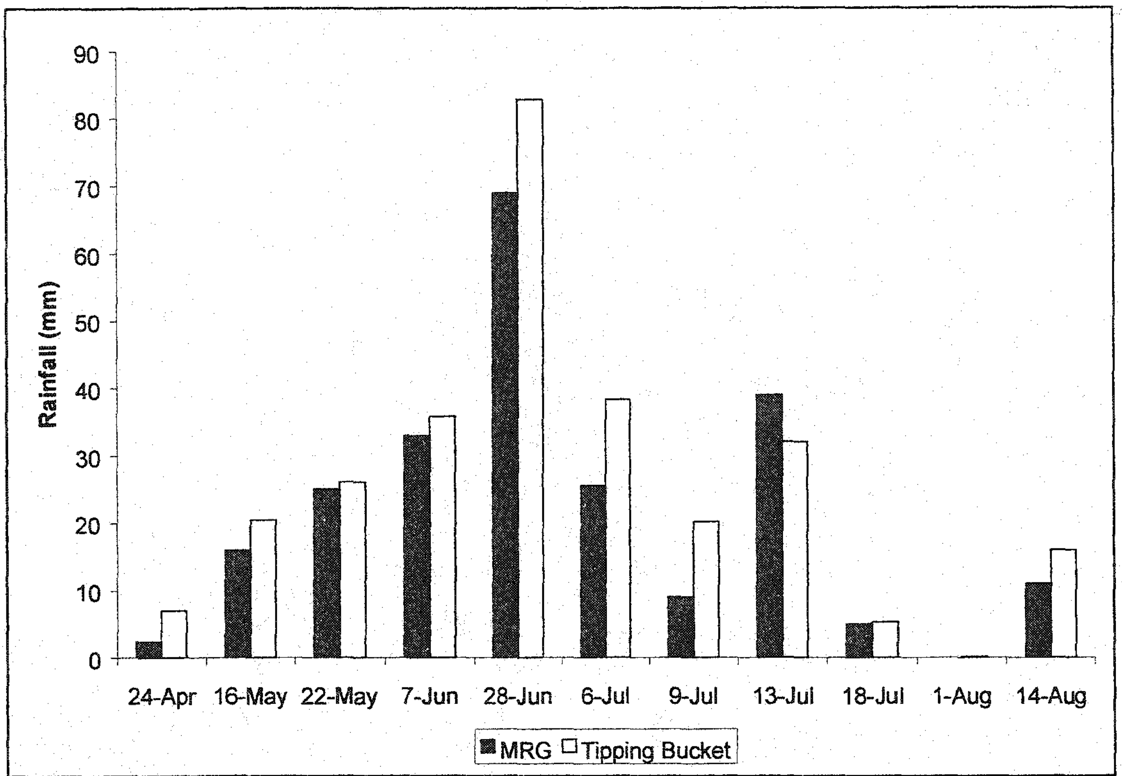

Figure 4.1 The comparison of the manual rain gage (MRG) readings and the tipping bucket rain gage readings for the Marchand site.

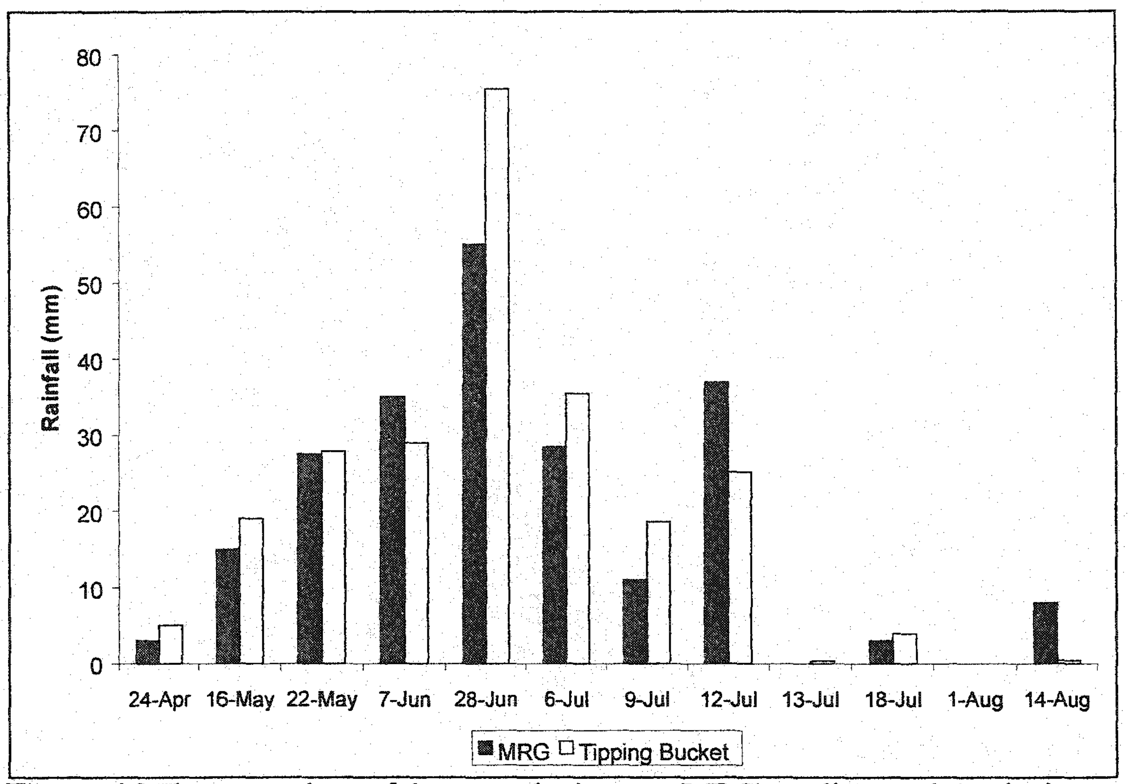

Figure 4.2 The comparison of the manual rain gage (MRG) readings and the tipping bucket rain gage readings at the Gagnon site.

The tipping bucket rain gages at both sites recorded the rainfall from the spring and summer months accurately. To ensure that the tipping buckets were recording rainfall accurately, manual rain gages were installed at both sites. Furthermore, the tipping buckets and heated rain gage were cleaned and calibrated once a month in the summer. Figure 4.3 displays the Marchand and Gagnon tipping bucket monthly totals from April to September 2001 compared with the 2001 and long term Philipsburg rainfall data for the same five months.

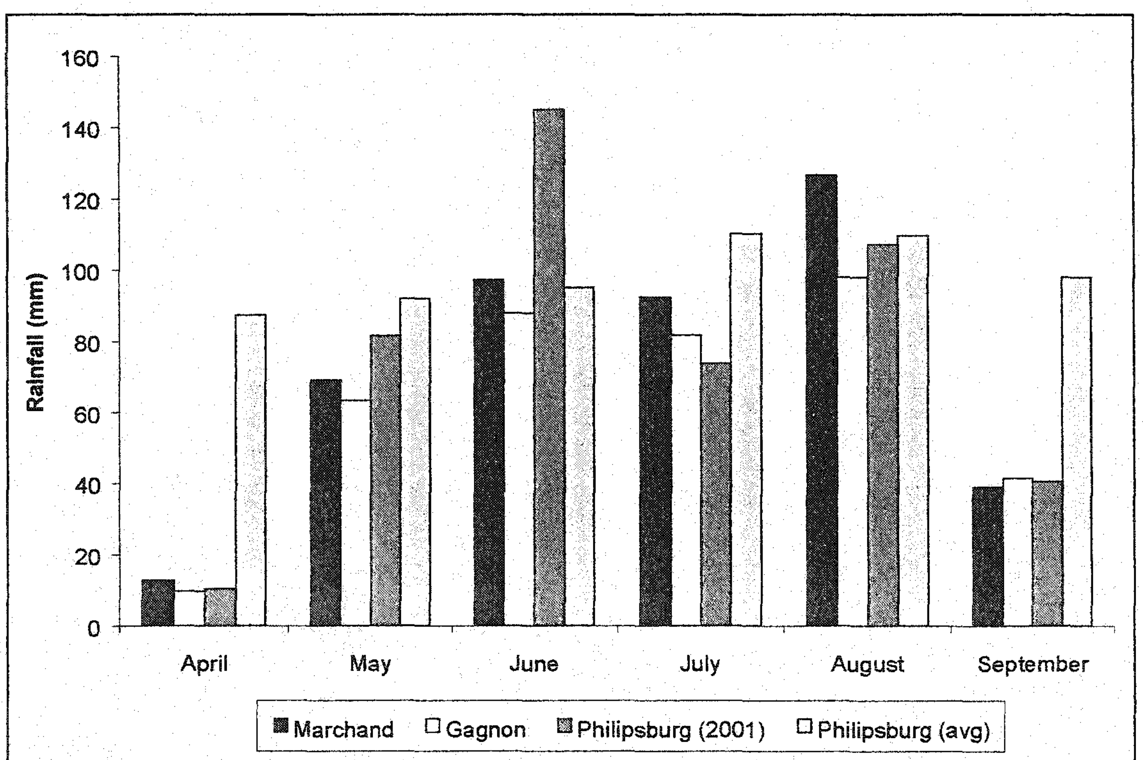

Figure 4.3 Monthly precipitation totals of both tipping bucket rain gages compared with the recorded 2001 and long term monthly precipitation totals of Philipsburg, Quebec

The monthly precipitation totals from April to September 2001, were 4.64 and 16.6% lower at the Marchand and Gagnon sites, respectively than at Philipsburg. The difference is small but there was evidence of spatial variability between the project sites and Philipsburg in the month of June. On June 22nd 2001, 68.4 mm of rainfall were recorded at the Philipsburg weather station, whereas the Marchand and Gagnon sites only recorded 26.8 mm and 24.2 mm of rainfall, respectively. The spatial difference resulted in different intensities and daily totals. Despite this isolated case, the weather conditions observed at the project sites were generally the same as those observed at the Philipsburg weather station for the water year, beginning October 1st, 2000 and ending on September 30th, 2001. Figure 4.4 is the daily rainfall between October 1st, 2000 and September 30th, 2001.

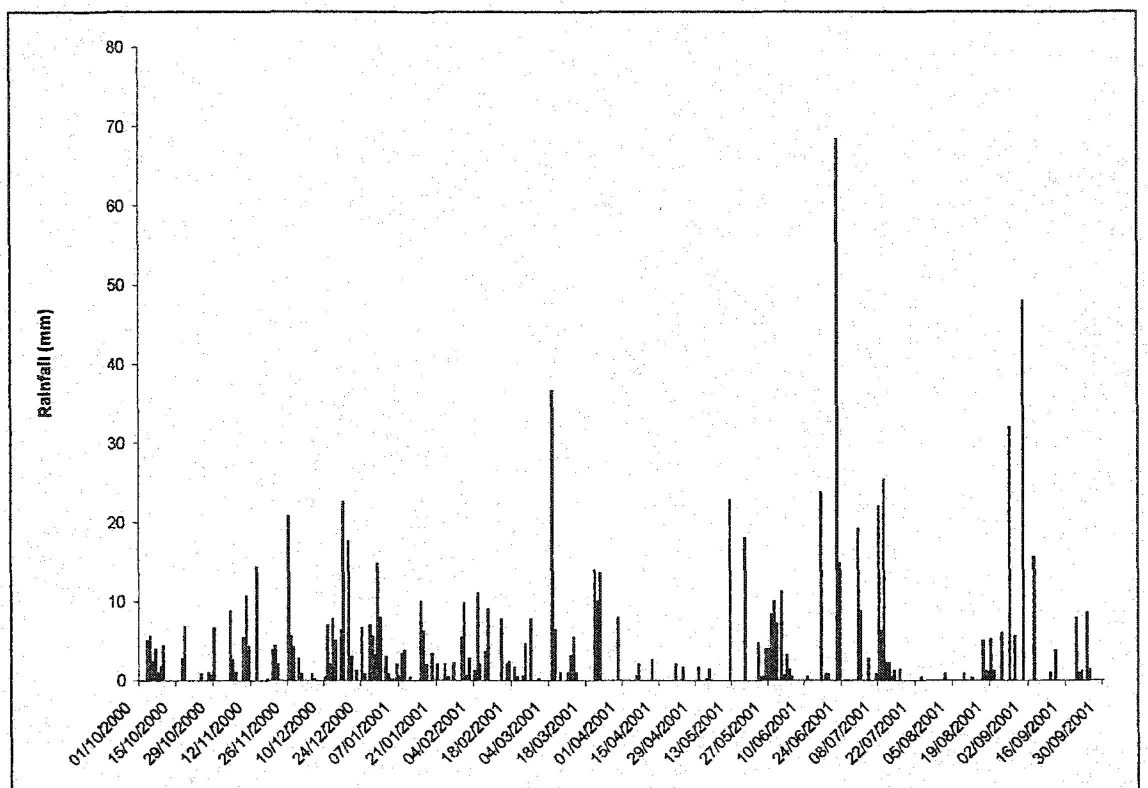

Figure 4.4 Daily rainfall from the weather station at Philipsburg, Quebec between October 1st, 2000 and September 30th, 2001.

The fall of 2000 and the spring of 2001 were drier than normal. This reduced rainfall resulted in low surface and subsurface runoff. The monthly averages for Philispsburg, Quebec were obtained to compare with the monthly precipitation totals for the water year. Table 4.1 compares the monthly rainfall averages based on 29 years of records for Philipsburg to the monthly rainfall totals of 2000-2001.

Table 4.1 The comparison of the monthly rainfall averages to the monthly rainfall totals between October 2000 and September 2001 for the town of Philipsburg, Quebec.

	Oct	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*June*	*July*	*Aug*	*Sept*
Avg (mm)	97.84	91.29	86.16	77.92	63.94	78.41	87.40	91.96	95.01	110.3	109.6	98.03
Total (mm)	42.8	90.9	120.8	57.8	57.6	100.2	10.4	81.6	145	73.8	107.1	40.6

It is evident from Table 4.1 that October 2000, April 2001 and September 2001 were below their respective monthly averages. September 2000 was also dry with a monthly total of 87 mm of rainfall. The combined precipitation total for the three autumn months of 2000 (i.e. September, October and November) was 220.7 mm, whereas the long term average monthly total precipitation for the same three months is 287.16 mm, a decrease of 23.1%. This is not an extreme decrease, however the monthly drops could explain the lack of surface runoff events. For example, October 2000 precipitation total is 59.3 % less than the long term monthly average. Dry conditions such as these limit the amount of possible runoff events; the longer the period between intense rainfall events allows the soil moisture to drop significantly below field capacity. Therefore, much larger intense rainfall events are required to generate surface and subsurface runoff. In contrast the precipitation in some of the winter months of 2000 and 2001 were higher than their respective monthly averages. The winter months consist of those months prior to snowmelt, which occurred on April 8th, 2001, i.e. December, January, February and March. The combined total precipitation for the four months were 366.6 mm, and the monthly average total for the same four months is 306.43 mm, an increase of 19.6 %. Again, this does not represent a significant increase, however the months of December and March had increases of 40.2% and 25.6 %, respectively. With the exception of 20.6 mm of rain on December 17th, 2000, all the precipitation that was recorded within the four-month winter period was snowfall. Large daily snowfalls of 17.6 and 14.8 cm were recorded at Philipsburg on December 19th and 30th, respectively. Furthermore, daily snowfalls of 36.6, 14, 10 and 13.6 cm were recorded in Philipsburg on March 5th, 21st, 22nd and 23rd, respectively. The spring months, April and May were well below the monthly averages for Philipsburg. The combined precipitation total for April and May 2001 were 92 mm, whereas the monthly average precipitation total for the same two months is 179.36 mm, a decrease of 48.7%. April 2001 contributed largely to the decrease in precipitation for the spring months. It was the driest April in 29 years of record for the Philipsburg area. This explains the lack of significant surface and subsurface events recorded in the spring months. The summer months follow a similar pattern to the fall 2000 months and spring 2001 months. The combined precipitation total for June, July and August was 325.9, in contrast to the monthly average precipitation total for the same three months which is 314.91 mm, an increase of 3.5 %. Despite the higher total, July 2001 was drier than usual with a decrease of 33.1% from its monthly average. Furthermore, there was span of 17 days where no rain fell on the Philipsburg area, a span that began on July 16th, 2001 and ended on August 2nd, 2001. According to Environment Canada web site, this was the driest summer in 54 years of record (-26.8%) for the Great Lakes region, which includes the St-Lawrence Lowlands. These dry conditions resulted in three small surface event and no significant subsurface runoff event for the entire summer of 2001.

4.2 Site Characteristics

4.2.1 Soil analysis

The top 20 cm of soil from each site was sampled on July 9th and the phosphorus present in the soil was extracted using the Mehlich III extraction. The Mehlich III extractable phosphorus concentration acts as an indicator of the amount of phosphorus that is available for plant uptake. Furthermore, the ratio between the Mehlich III extractable phosphorus concentration and the extractable aluminum concentration gives the percent of P saturation, which is an excellent environmental assessment tool for fields that are at risk of P pollution (Table 4.2). To further characterize both sites, the average percent of organic matter was determined for both surface drainage areas (Table 4.2).

The Marchand site samples ranged from 84.45 to 647.25 kg of P/ha, which demonstrates a high spatial variability in the field. The higher soil P levels were located on the north side of the field closest to the barn and the manure pile, which could be an indicator of the poor manure storage prior to the installation of the enclosed manure pit. The lower P values were located near the outlet and increased with distance from the surface and subsurface outlets. These low points correspond with some of the soils higher organic matter level. The high organic matter content may have induced mineralization of stable organic P to labile organic P, which is readily available for crop uptake and therefore removed from the soil. The P saturation varied spatially similar to the variations seen in the soil P level, which is in part due to the smaller spatial variation in aluminum concentrations. The Gagnon site samples ranged from 60.94 to 463.57 kg of P/ha. Much like the Marchand site, the Gagnon site has spatial variation in soil P level, P saturation and organic matter. However, the Gagnon site has high soil P levels situated near the surface and subsurface outlets and decreased towards the crest of the hill, in contrast to the Marchand site. Furthermore, the higher organic matter levels coincide with the higher soil P levels. This could be a result of years of soil erosion where the fertile topsoil, rich in organic material and nutrients, has slowly moved down the slope.

Table 4.2 Average P, P saturation and organic matter for both fields

Site	*Average P kg/ha*	*Average P Sat %*	*Average OM %*
Marchand	330.63	20.05	7.28
Gagnon	169.37	7.80	4.47

The Marchand site nearly doubled the Gagnon site in kg of P/ha and OM%. Furthermore, the Marchand site nearly tripled the Gagnon site in percent P saturation and surpassed the critical limit of 20% set by Quebec for fields at risk of P pollution via surface and subsurface runoff. One of the reasons for the low soil P levels at the Gagnon site is traditionally Mr. Gagnon has not over fertilized the land. He has only applied commercial fertilizer at moderate rates. Mr. Gagnon does not spread organic fertilizer on this field.

Beauchemin and Simard (2000) reported that the A horizon (0-40 cm) from 21 out 27 soil series sampled in the St Lawrence Lowlands exceeded the level of adequate fertility for corn and soyabean (53 mg of Melich III P/kg). The Marchand and Gagnon sites averaged 147.6 and 75.6 mg of Melich III P/ kg, respectively; both sites are well over the adequate fertility level for corn and soyabean.

4.3 Hydrological Events

4.3.1 Surface runoff

Four surface runoff events were recorded at the Gagnon site between October 2000 and September 2001. As mentioned earlier, the drier than average conditions caused a significant decrease in the number of surface runoff events. The events could be categorized into two sections, large and small events. The categories were based on the amount of surface runoff that was generated. There was only one large surface runoff event, that being the spring snowmelt, which lasted from April 8^{th} to April 11^{th}, 2001. The surface runoff during the spring snowmelt was recorded at both the Gagnon and Marchand site. The other three surface events (November 26^{th}, 2000, May 22^{nd}, 2001 and August 31^{st}, 2001) were considered to be small events and were only observed at the Gagnon site.

The rainfall measurements commenced on October 5^{th}, 2000 and the flow measurement and sampling equipment became functional on November 1^{st}, 2000. Based on rainfall records and visual observations, we know that no runoff events occurred in October 2000 at the Gagnon site. Therefore, the flow records represent all the surface runoff events that occurred at the Gagnon site throughout the water year i.e. October 1^{st} 2000 to September 30^{th}, 2001. The volume of water that exited the Gagnon field during the snowmelt event was 87.3 mm/ha. The volume discharged by November 2000, May 2001 and August 2001 storms were 0.10, 0.08 and 0.04 mm/ha, respectively (Table 4.3). During the water year, 87.5 mm/ha of surface runoff exited the Gagnon field, therefore the snowmelt event was the major surface runoff event of the water year. The snowmelt accounted for 99.8 % of the total surface runoff for the whole water year. For the Marchand site the only surface runoff event recorded was the snowmelt event. Therefore making 100% of the total runoff for the water year at the site.

Table 4.3 Profiles of the 3 rainfall events that occurred at the Gagnon site during the water year

Storm	*Rainfall (mm)*	*Rainfall Intensity (mm/hr)*	*Depth of Volume (mm/ha)*	*% of Annual Surface Runoff*
November 26th, 2000	19.6	2.61	.10	0.11
May 19th, 2001	27.7	2.77	0.08	0.09
August 31st, 2001	17.4	23.2	0.04	0.05

4.3.2. Spring snowmelt (April 2001)

The spring snowmelt began April 8th, 2001 and concluded on April 11th 2001. The measured depth in the flume was used, in conjunction with the rating curve for the flume, to calculate discharge every 5 seconds. These values, averaged over 15 minute intervals were used to calculate the rate of surface runoff (mm/hr). The Marchand site encountered difficulties when the water began to flow under the flume, thereby requiring minor soil berms in the field to divert the water flow through the flume. However, water eventually infiltrated under the flume and washed under the berm thus preventing surface runoff measurements. There was a period of 22 hrs whereby the water level was accurately recorded. Figures 4.5 and 4.6 illustrate the spring snowmelt flow data for both the Marchand and Gagnon sites, respectively.

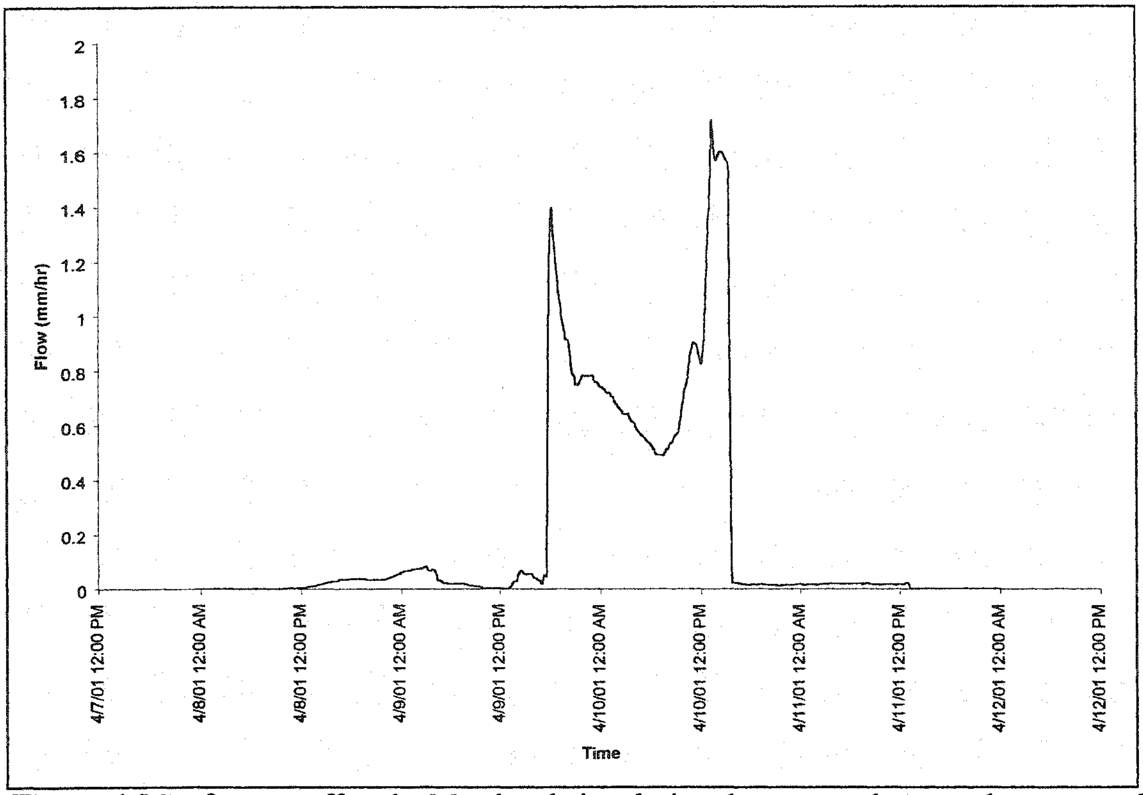

Figure 4.5 Surface runoff at the Marchand site, during the snowmelt event that occurred between April 8th and April 11th

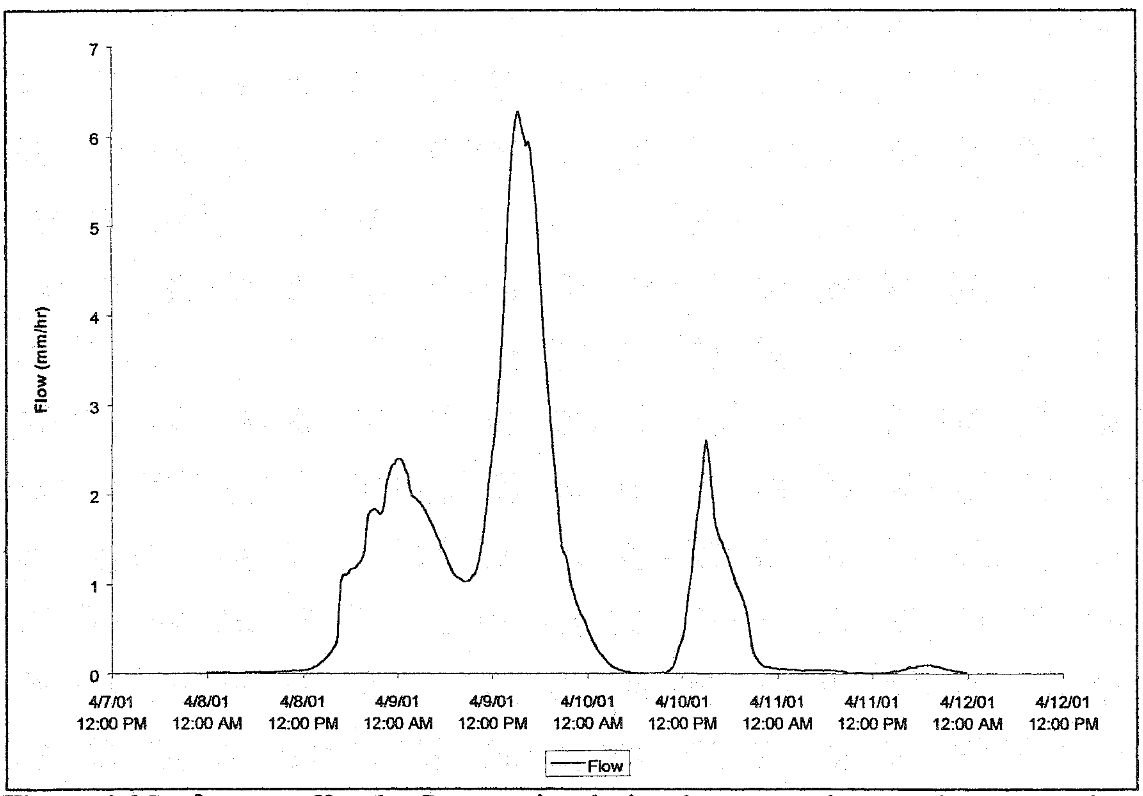

Figure 4.6 Surface runoff at the Gagnon site, during the snowmelt event that occurred between April 8th and April 11th

It is difficult to compare both sites due to the failure of measurements at the Marchand site. However some interesting observations can be deducted. The Gagnon site had the larger peak rate of 6.28 mm/hr. The higher peak is a result of better surface drainage at the Gagnon site than the Marchand site. There was visual evidence of ponding at the Marchand site, which delayed the movement of the melt water to the flume (Figure 4.7). At the Gagnon site the only ponding was immediately in front of the flume, indicating that the melt water was not delayed as it moved from its point of origin to the flume (Figure 4.8). This is more visually apparent in the Gagnon hydrograph, whereby a rapid peak and fast recession is observed (Figure 4.6). The opposite was observed at the Marchand site, resulting in a smaller and more gradual discharge rate which is illustrated by small fluctuations in the 22-hour hydrograph (Figure 4.5). Due to the failure of measurements it is difficult to conclude whether or not the peak discharge rate was accurately captured. The daily surface runoff volume for the duration of the spring snowmelt at the Gagnon site is illustrated in Table 4.3. The daily surface runoff volumes are expressed in mm/ha, and are calculated dividing the sum of the daily 15-minute volumes by the surface drainage area. The surface drainage areas for the Marchand and Gagnon sites were 6.1 and 10.2 ha, respectively.

Table 4.4 The daily surface runoff volumes for the Gagnon site during the spring snowmelt that occurred between April 8th and April 11th

Day	*Daily Surface Runoff Volume (mm/ha)*
04/08/01	12.8
04/09/01	60.0
04/10/01	13.5
04/11/01	0.9
Total	87.3

Figure 4.7 Ponding during the snowmelt event at the Marchand site

Figure 4.8 The snowmelt event at the Gagnon site

4.3.3 Subsurface runoff

During the spring snowmelt the drains were flowing at maximum capacity. Unfortunately the two IF-200 propeller meters that were installed encountered some internal damage and subsequently did not record any flow measurements throughout the entire snowmelt event. This failure was suspected earlier in the winter months and confirmed during the spring months. The flow meters were inaccessible for servicing during these months due to the high water table level, and the subsurface wells were sealed to prevent freezing. Because it was suspected that the flow meters were faulty, we undertook snow pack sampling in the winter and early spring, so that a water balance approach could be used to estimate drain flow. The dry conditions seen in the summer coupled with on going maintenance problems with the IF 200 propeller meters resulted in a lack of recorded surface drainage events during the summer months. On two days in the late autumn of 2000, spot drain flow measurements were taken during two small events at the Gagnon site. These events and their significance are further explained in section 4.4.2.1.

4.3.3.1 Snow sampling

Sampling was carried out February 8th and March 20th, 2001. A total of 24 and 33 samples were taken over the surface drainage areas of Marchand and Gagnon site, respectively. Snow depth and snow water equivalence were determined at each site. The equivalent depth of water was calculated for each point, and averaged for the field. On March 22nd and 23rd 2001, a sizable storm dumped 40cm of wet heavy snow. Snow sampling was not redone for the entire field, but a limited number of points showed that snow coverage was very uniform and the equivalent of 6.2cm of water had fallen on the Marchand site, and 8.2 cm on the Gagnon site. Dorval Airport recorded a water equivalency of 6.38cm for the same two days. Furthermore, there was very little wind during the event, therefore the deposition of snow was uniform over the entire field. No other significant snowstorms occurred between March 23rd 2001 and snowmelt (April 8th, 2001). The estimated average water equivalency depth (EAWED) was calculated by summing the EAWEDs of March 20th and March 23rd then subtracting a reported sublimation rate. Fassnacht et al. (1999) reported sublimation rates of 1mm/day for Southern Ontario. These rates coincided with ranges of sublimation rates reported by Williams (1959) and Martinelli (1960) for the same region. Williams (1959) and Martinelli (1960) reported sublimation rates of 0.029 mm/day to 1.642 mm/day and 0.668 mm/day to 1.219 mm/day, respectively. For estimation purposes a sublimation rate of 1 mm/day is sufficient to represent the conditions in Southern Quebec. Table 4.4 illustrates EAWED and snow pack depth for both sites prior to snowmelt.

Table 4.5 Estimated average water equivalency and snow pack depth at both sites.

	02/08/01		*03/20/01*		*03/23/01*			*04/08/01*
Site	Snow Depth (cm)	EAWED (cm)	Snow Depth (cm)	EAWED (cm)	Snow Depth (cm)*	EAWED (cm)*	Sublimation rate (mm/day)	Final EAWED (cm)
Mar[A]	43.3	21.0	36.5	12.5	22.9	6.2	1	17.1
Gag[B]	44.1	18.0	31.2	11.1	21.0	8.5	1	18.1

* Represents only the newly dumped snow and not the whole snow pack
A Marchand; B Gagnon

4.3.3.2 Estimated subsurface tile drainage runoff

As mentioned earlier, the IF-200 global water propeller meters did not function properly during the snowmelt event. However, due to the extensive and accurate snow sampling performed at the Gagnon and Marchand site, a simple water balance approach can be used to estimate subsurface flow. Unfortunately due to the failure of the berms at the Marchand site, the total amount of surface runoff was not recorded, so only data from the Gagnon site is considered. To estimate the subsurface runoff, a simple water budget was created (Equation 4.1).

$$P + EAWED = SRO + SSRO + DS + ET + \Delta S \quad (4.1)$$

Where		
	P	= Precipitation (mm)
	EAWED	= Estimated Average Water Equivalency Depth
	SRO	= Surface Runoff (mm)
	SSRO	= Subsurface Runoff (mm)
	DS	= Deep Seepage (mm)
	ET	= Evapotranspiration (mm)
	ΔS	= Change in Soil Moisture (mm)

During the snowmelt event at the Gagnon site there was no precipitation, therefore the only input in to the drainage system was the water equivalency of the snow pack on the field. The 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 the Gagnon field was at or near field capacity during the first snowfall and snowmelt event. Therefore, the difference in soil moisture between the first snowfall in December and the snowmelt event is negligible in terms of magnitude compared to the EAWED and SRO magnitudes.

Table 4.6 The estimated subsurface runoff for the snowmelt event at the Gagnon site

EAWED (mm/ha)	P (mm)	SRO (mm/ha)	DS (mm)	ET (mm)	ΔS (mm)	Estimated SSRO (mm/ha)
181	0	87.3	0	0	0	93.7

The estimated volume lost through the Gagnon drains during the snowmelt event was 7.1% higher then the total surface runoff Gagnon site from the 4 observed events. Unfortunately, due to the malfunctions of the IF200 flow meters it is difficult to assess the combined runoff for the water year. It can be concluded that the snowmelt event was the largest subsurface drainage event of the year. There was visual evidence of some small drainage events in the fall of 2000, however they were not recorded by the IF200. At the beginning of the 2001 summer the flow meters were replaced, but other difficulties with their relay to the datalogger caused other very small events to be missed. Once the maintenance problems were cleared up, the dry conditions set in, resulting in no subsurface events. If we combine the total depth of surface runoff for the water year with the depth of subsurface drain runoff from the snowmelt, the result is 181.2mm/ha. Despite the missed subsurface drainage events, this is considerably low for a region where the average annual precipitation is 1171.02 mm/ha.

4.4 Water Quality

4.4.1 Surface samples

For the water year a total number of 15 and 19 surface runoff samples were taken at the Marchand and Gagnon site respectively. The samples were collected by three methods: grab, manual pumped (MP), and pulsed discretely (DIS). The breakdown of the types of samples taken for each site is displayed in Table 4.7.

Table 4.7 The different type and number of surface runoff sample taken at each site

Site	*Grab*	*MP*	*DIS*
Marchand	7	3	5
Gagnon	6	3	10

All the surface runoff samples represent the snowmelt event, aside from the one discrete sample taken during each of the three rainfall events on the Gagnon site. It should be noted that the three manually pumped samples were sampled at the same time as three grab samples. The purpose was to carry out quality control (Section 4.4.1.1). These six samples were averaged together to represent a single sample in the database. It should also be noted that during the snowmelt event at the Marchand site, two grab samples were taken immediately after each other, and therefore the results were averaged to represent a single sample in the database. The sample database for the snowmelt event consists of 9 and 11 surface runoff samples for the Marchand and Gagnon sites, respectively. The discrete samples were based on a flow proportional (FP) sampling strategy as opposed to a time composite (TC) sampling strategy. Stone et al. (2000) reported no significant difference in nutrient concentration data between FP and TC strategies for stream flow. The FP strategy used was the geometrical sampling strategy proposed by Tremwel et al. (1996). This strategy enabled us to sample small, medium and large events. A constant threshold strategy would tend to under sample or miss small events and tend to over sample large events. If one was inclined to lower the threshold to incorporate the smaller events, one could run the risk of over filling the discrete sampler during large events.

The snowmelt average concentrations were calculated on a flow weighted basis, which tends to be more accurate then an overall average concentration. It should be noted that the first grab sample taken at the Marchand site was not factored into the flow weighted average because it was taken before the repairs were made to the site to reduce the leakage under the flume and to ensure proper surface flow measurements. For all the parameters measured at the Gagnon site, the flow weighted average was 10.2% higher than the overall average. At the Marchand the site, the flow weighted averages were 5.1% lower than the overall averages. The overall average concentrations at the Marchand site included the extra grab sample taken before the repairs made to the flume, which were made at 17:00 on April 9th, 2001, for this reason the overall average concentrations for all parameters were higher than the flow weighted average concentrations. The differences encountered between flow weighted and overall averages are not overwhelming. Therefore using either method to report the concentration data will not compromise any comparisons or conclusions made. For this thesis all surface runoff concentration and load data are based on flow weighted averages. The flow weighted average was calculated by first multiplying the concentration parameter of each sample in the database by its incremental volume. The incremental volume for a sample begins at the midpoint between the sample and the previous sample and ends at mid point between the sample and the next sample. The product of each sample and its incremental volume is summed and then divided by the total volume of the event to give the flow weighted average.

4.4.1.1 Quality control

A quality control on the surface samples was carried out during the spring snowmelt at both sites. The purpose of the quality control was to determine if samples taken with the automated sampler, via the intake tube located in the flume, were different than the grab samples taken at the outlet of the flume. Grab samples are the generally recognized standard in water quality work. However, due to the rapid response times on these fields, and our intention to implement a more sophisticated sampling strategy, the use of an automated discrete sampler was deemed necessary. The surface sampler was manually pulsed at the same time a grab sample was taken and then analyzed for total phosphorus (TP), total dissolved phosphorus (TDP), ortho-phosphates (Ortho-P), bioavailable (BAP) phosphorus and suspended sediment (SS); samples were taken in triplicate. There was no significant difference between manually pulsed (MP) and grab samples at the Gagnon site (Table 4.6). For the Marchand site, TP, TDP, and ortho-P in the manually pulsed samples were significantly lower than the grab samples.

Table 4.8 Quality control for manually pulsed and grab samples for both site.

Dependent Variable						
Source of Variation	TP	TDP	PP	Ortho-P	BAP	SS
Marchand						
Pulsed X Grab	*	***	--	***	--	*
Gagnon						
Pulsed X Grab	--	--	--	--	--	--

*,**,*** Denotes significant effect at $\alpha < 0.10$, 0.05, and 0.01, respectively

Therefore, samples taken with the Marchand automated sampler tend to underestimate TP, TDP, and ortho-P. The percent difference between the MP and grab samples for TP, TDP and ortho-P were 2.8, 3.5 and 3.7%, respectively (Table 4.9). Furthermore, for a significance level of 0.10 a difference in suspended solids was observed between grab and pulsed samples at the Marchand site. On average, higher sediment concentrations were found in the manual pulsed samples than the grab samples. The percent difference between the MP and grab samples was 3.3% (Table 4.9).

Table 4.9 Average concentrations for all parameters of the MP and grab samples taken at the Marchand site

Sample	*TP (mg/l)*	*TDP (mg/l)*	*PP (mg/l)*	*Ortho-P (mg/l)*	*BAP (mg/l)*	*SS (mg/l)*
MP	0.462	0.143	0.324	0.119	0.284	154
Grab	0.476	0.138	0.332	0.124	0.284	149
% Diff	2.8	3.5	2.5	3.7	0	3.3

Despite these minor differences its reasonable to assume that a grab and pulsed sample produce the same results, therefore the manually pumped, the grab and the samples taken by the auto sampler based upon the flow weighted strategy are all discrete samples. Stone et al. (2000) reported no significant differences in nutrient concentration data between grab samples and flow proportional (FP) samples for stream flow.

4.4.1.2 Flow weighted average and peak TP concentrations (snowmelt event)

The TP concentrations in surface runoff ranged from 0.193 to 0.469 mg/l and 0.052 to 0.371 mg/l for the Marchand and Gagnon sites, respectively. The flow weighted average and peak TP concentrations are illustrated in Table 4.10.

Table 4.10 The flow weighted average and peak TP concentrations for surface runoff during the 2001 snowmelt

Site	*Average TP (mg/l)*	*Peak TP (mg/l)*
Marchand	0.295	0.469
Gagnon	0.191	0.371

One must use caution in comparing the results from the two sites because of the failure at the Marchand site. The preliminary results demonstrated higher TP concentrations at the Marchand site, primarily because the samples were taken during the 22-hour functional period where flow had increased. As mentioned above, the 22-hour period could be interpreted as the peak of the snowmelt event. For the Gagnon site, the highest TP concentration appears at the end of the event, well after the peak flow rate occurred (Figure 4.10). This comes as no surprise since the beginning of the snowmelt event consists mainly of melt water. As the event proceeds the overland flow detaches the nutrient rich topsoil, hence the higher nutrient concentrations. Unfortunately, due to the problems at the Marchand site, both the beginning and end of the snowmelt event was not captured. As a result of missing the beginning and end of the event, the flow weighted TP average at the Marchand site is not a true representation of the event. Despite missing the end of the snowmelt event, where we would expect the nutrient concentrations to be higher, the Marchand site still had a higher peak than the Gagnon site. The peak TP concentrations were 0.469 mg/l and 0.371 mg/l for the Marchand and Gagnon sites, respectively. The higher TP concentrations at the Marchand site may be a reflection of higher soil P levels.

4.4.1.3 Correlating between flow and TP concentrations (snowmelt event)

There is a similarity observed on both sites as seen in Figures 4.9 and 4.10, whereby the TP concentrations appear to rise and fall with the surface flow rate. Enright et al. (1998) in a study of the St. Esprit watershed, observed the same trend in TP concentrations at the watershed outlet.

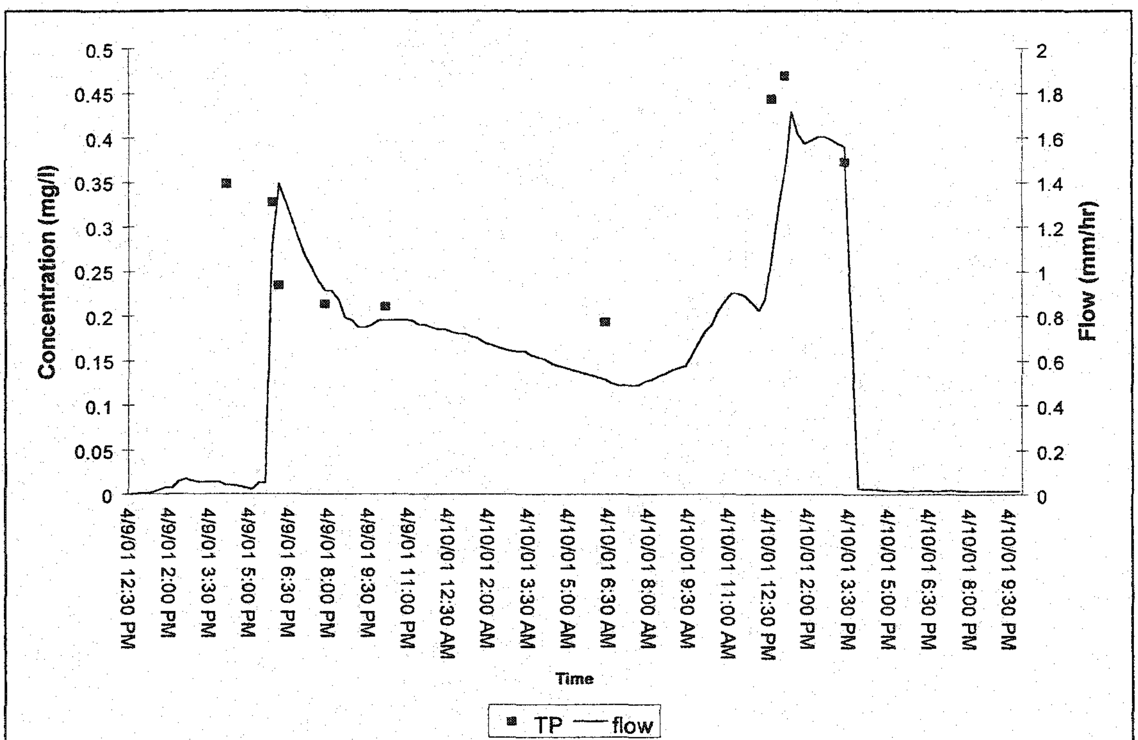

Figure 4.9 Total phosphorus concentrations and surface flow at the Marchand site during the 22-hour functional period

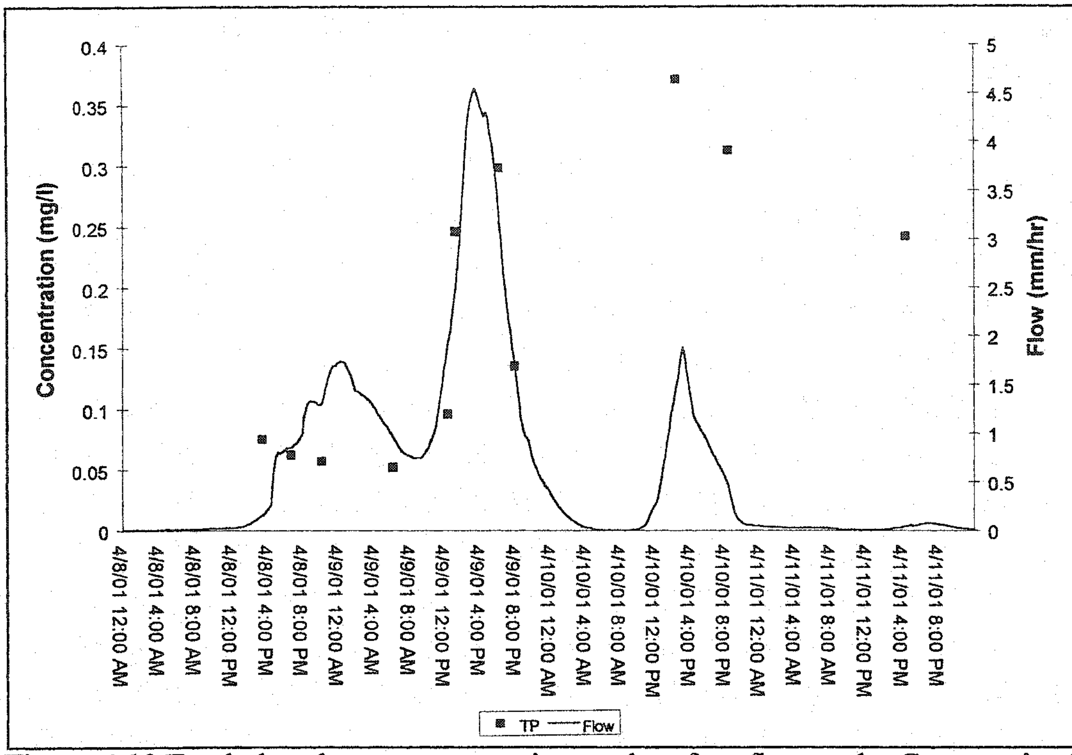

Figure 4.10 Total phosphorus concentrations and surface flow at the Gagnon site during snowmelt

A linear regression was carried out for both sites to determine whether or not there was a significant correlation between TP concentrations and surface flow rate. For the Marchand site the first grab sample was omitted since it was taken before the repairs to the flume. There was no significant correlation between TP concentrations and surface flow at both sites. The R^2 for the Marchand and Gagnon sites were 0.3962 and 0.0619, respectively. The Gagnon site was affected by the samples that were taken at the tail end of the spring snowmelt, which were high in TP concentrations.

4.4.1.4 Suspended sediment and particulate P concentrations (snowmelt event)

The suspended sediment (SS) concentrations ranged from 8 to 151 mg/l and 8 to 188 mg/l for the Marchand and Gagnon site, respectively. The particulate P concentrations ranged from 0.03 to 0.328 mg/l and 0.003 to 0.179 mg/l for the Marchand and the Gagnon site, respectively. Table 4.11 shows the flow weighted averages of SS and PP for both sites. It is important to note that all the concentration values reported for the Marchand site lie throughout the 22-hr functional period.

Table 4.11 Flow weighted averages for SS and PP at both sites for the snowmelt event

Site	*SS* (*mg/l*)	*PP* (*mg/l*)
Marchand	57.9	0.134
Gagnon	86.2	0.106

The Marchand site was the lighter soil type and more prone to erosion. The failure at the Marchand site was evidence that the soil lacked mechanical strength. Therefore a greater sediment loss would be expected. However, this proved not the case for two reasons. The SS concentrations were not sampled for the whole event. The Marchand site was not sampled at the end of the snowmelt event, which in the case of the Gagnon site proved to be significant in terms of SS concentrations. The other reason may be a result of ponding and water retention on the field (Figure 4.7). At the Gagnon site, there was no ponding on the field, and the retention time in the pool in front of the flume (Figure 4.8) was short. Quick measurements using loose debris showed a retention time of less than 1 minute, therefore making it difficult for loose sediment to be redeposited. Where as the Marchand site because of the ponding would be more susceptible to redeposition of sediment. The difference in the particulate P concentrations between both sites was greater than the SS concentrations. The Marchand flow weighted average PP concentration for the spring snowmelt event nearly doubled the flow weighted average PP concentration of the Gagnon site. The difference in PP concentrations is due to the failure of the berms and the higher P levels in the Marchand soil. The SS concentrations fluctuated based on the time of day and the flow. Figures 4.11 and 4.12 illustrate the SS concentration fluctuating with the surface runoff rate at the Marchand and Gagnon sites, respectively

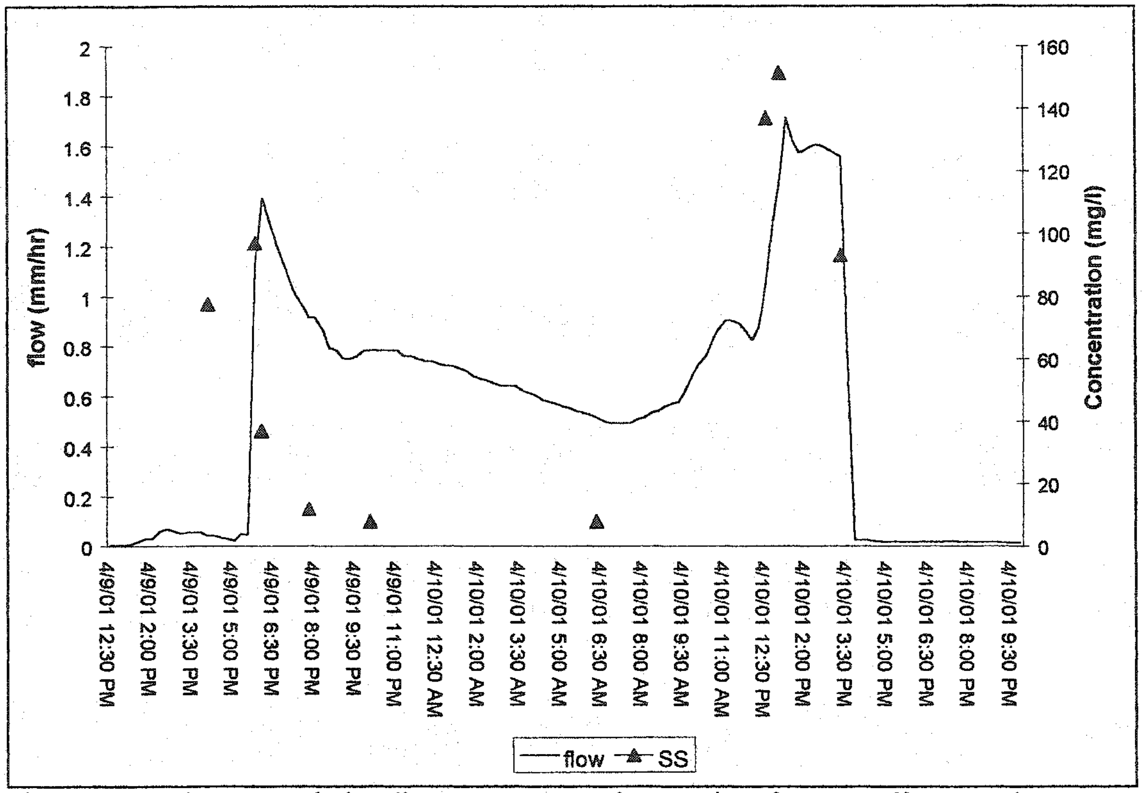

Figure 4.11 The suspended sediment concentrations and surface runoff rate at the Marchand site during the 22-hr functional period

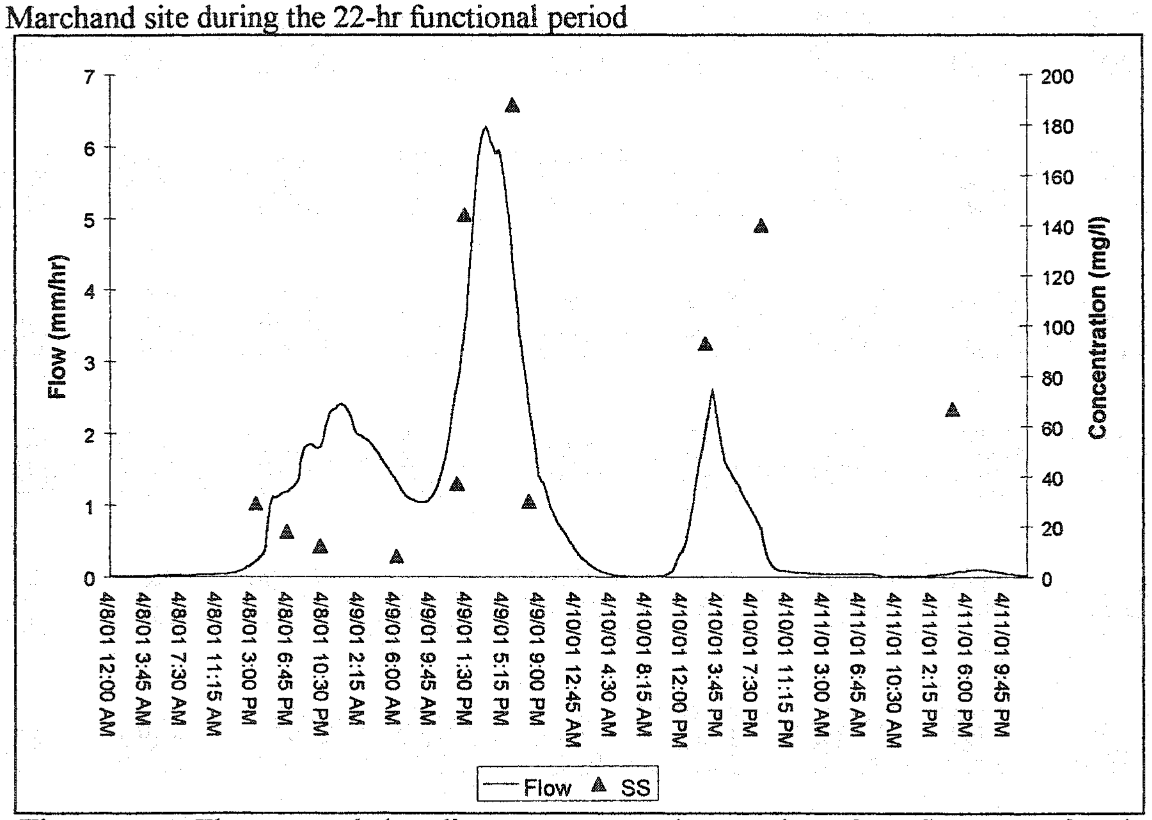

Figure 4.12 The suspended sediment concentrations and surface flow rate for the Gagnon site

4.4.1.5 Flow rate and SS concentration correlation (snowmelt event)

Despite the failure at the Marchand site the sediment at both sites did follow a similar trend, whereby the SS concentrations rose and fell with the flow rate. This is to be expected, as the higher the discharge rate, the greater the carrying capacity and the less time for sediment to settle. Furthermore, concentrated water flow leads to detachment and transport of sediment by means of rill erosion (Schwab et al., 1993). Previous studies have attempted to correlate suspended sediment concentrations with flow rate. When correlating river flow with suspended sediment, Correll et al. (1999) found that linear regressions fit better at moderate to high flows, and exponential regression fit better at low flows. Both the linear and exponential regressions were fit to the data. Data from the Gagnon site coincided with the findings of Correll et al, (1999), in the snowmelt data better fitted a linear regression. However, on the Marchand site the snowmelt data better fit an exponential regression. Because there is no consistency between sites it is difficult to scale up the findings to the watershed scale level. The R^2 values for the spring snowmelt data at the Marchand site were 0.3903 and 0.5838 for the linear and exponential regressions, respectively (Table 4.12).

Table 4.12 Regressions of SS concentrations for both sites with flow rate

Site	*Event*	*Regression*	*Equation*	R^2
Marchand	Snowmelt (22-hr period)	Linear	SS = 103.56(flow) - 46.23	0.3903
		Exponential	$SS = 1.929e^{2.7263(flow)}$	0.5838
Gagnon	Snowmelt	Linear	SS = 23.947(flow) + 25.843	0.2662
		Exponential	$SS = 0.0256e^{0.3011(flow)}$	0.1453

4.4.1.6 TP and SS concentration correlation (snowmelt event)

Many studies (Jordan et al, 1997, Correll et al., 1999, Wall et al, 1996, Hanway and Laflen, 1974) have concluded that sediment losses heavily influence the amount of P in surface runoff. Hanway and Laflen (1974) found a linear correlation between TP concentrations and SS concentrations in surface runoff from four agricultural fields in

Iowa. The coefficients of determination (R^2) ranged from 0.47 to 0.69. Jordan et al. (1997) performed a linear regression on the annual flow-weighed mean concentration of total phosphorus and the annual flow-weighted mean concentration of total suspended solids for watersheds in the Piedmont and Coastal plains of the Cheseapeake Bay region. The Coastal Plain data had a R^2 value of 0.90. The same linear regression was performed at both sites, and the R^2 values were 0.9722 and 0.7018 for the Marchand and Gagnon fields, respectively. The equations and their corresponding R^2 values for the two sites are illustrated in Figures 4.13 and 4.14.

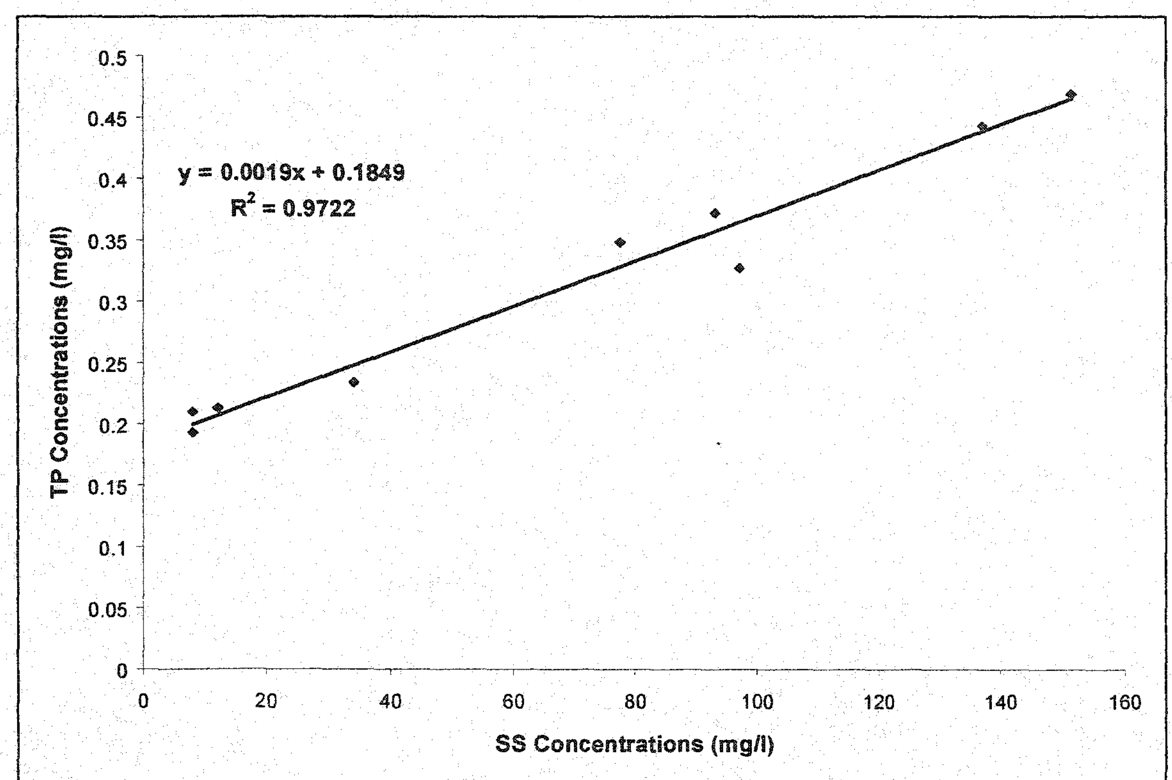

Figure 4.13 Linear regression of the total phosphorus and suspended sediment concentrations for the Marchand site

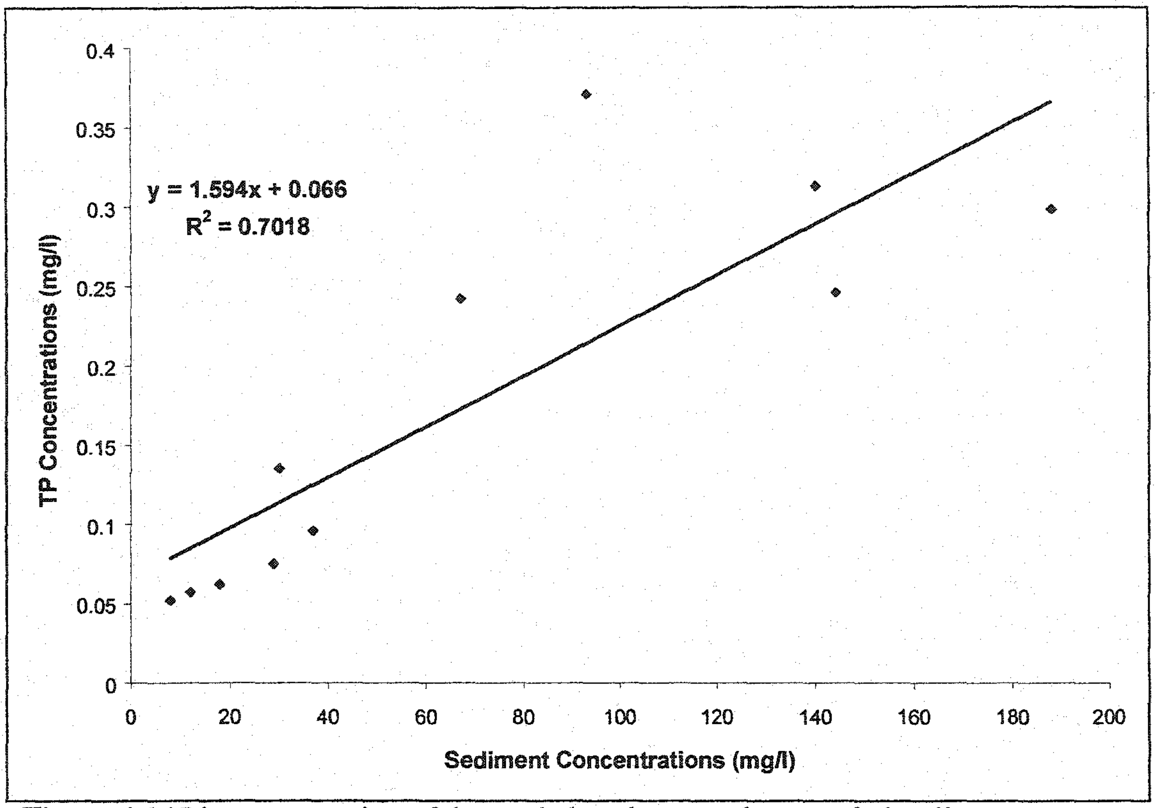

Figure 4.14 Linear regression of the total phosphorus and suspended sediment concentrations for the Gagnon site

The high correlation between TP and SS contributes to previous beliefs that in order to reduce TP losses you must reduce SS losses. Therefore, by implementing erosion control farming practices a reduction in soil and nutrient loss is possible. Studies such as those of Zhao et al. (2001), Gaynor and Findlay (1995), and Culley et al. (1983), have reported significant reductions in TP and SS losses as result of implementing conservation tillage practices. The problem with some conservation tillage practices is that they generally require greater quantities of fertilizer and therefore run the risk of increasing dissolved P losses and perhaps TP losses.

4.4.1.7 Ortho P and bioavailable P concentrations (snowmelt event)

Orthophosphates generally are less of a concern in surface runoff than particulate P, due to the greater quantities of particulate P in surface runoff. Dissolved phosphorus often accounts for 10-20% of the total phosphorus found in surface runoff (Sharpley, 1993). However, the biological impacts of the dissolved forms of phosphorus are much more prominent because they are 100 % bioavailable upon entering surface waters

(Sharpley et al., 1992). Attempts to reduce TP inputs have had little to no effect on the biological productivity in lakes, due to the increasing amount of bioavailable P (BAP) entering surface waters (Sharpley et al., 1992). In our field data the orthophosphate concentrations did not fluctuate as much as the TP, SS and PP concentrations. The bioavailable P appears to vary with flow rate. However the results of the regression analyses were inconclusive. The fluctuation was very much dependent on the variation of the total dissolved phosphorus (TDP) concentrations within the snowmelt event. This was expected due to the bioavailability (100%) of TDP concentrations in surface water. The flow weighted average TDP concentrations (Table 4.13) represented 76% and 80% of the flow weighted average bioavailable P concentrations for the Marchand and Gagnon sites, respectively.

Table 4.13 Flow weighted TDP, Ortho-P and BAP average concentrations for the snowmelt at the both sites

Site	*Average TDP (mg/l)*	*Average Ortho-P (mg/l)*	*Average BAP (mg/l)*	*Average TP (mg/l)*
Marchand	0.161	0.140	0.210	0.295
Gagnon	0.086	0.066	0.118	0.191

The Marchand site TDP, Ortho-P and BAP concentrations approximately doubled those of the Gagnon site. The averages calculated for the Marchand site only account for the 22-hr functional period, and therefore do not account for any possible dilution effect from the melt water created by the snow. However, the peak concentrations of TDP, Ortho- P and BAP were all higher at the Marchand site, which again is a reflection of the higher soil levels. High soil P levels have definite a effect on the amount of DP entering surface waters. Sharpley (1997) found strong exponential relationship (R^2 = 0.87) between increasing Melich III soil P levels and DP concentrations in surface runoff. A threshold of 150 mg/kg of Melich III P was cited as the level at which the potential for DP enrichment of runoff is much greater. The Marchand site had a Melich III P concentration of 147.6 mg/kg, which is very close to this proposed threshold.

4.4.1.8 Rainfall and snowmelt event concentration comparison

As mentioned above, the period between October 1st, 2000 and September 30th, 2001 was dry and very few surface runoff events occurred. The spring snowmelt was the only surface runoff event recorded at the Marchand site, whereas the Gagnon site recorded three small rainfall events on November 26th, 2000, May 19th, 2001 and August 31st, 2001. Only one sample was taken during all three rainfall events. The SS concentrations were 36, 28 and 157 fold higher for the May, November and August events, respectively (Table 4.14). Two of the rainfall-runoff events occurred when the soil was bare, therefore making it easier to detach and transport sediment. Interestingly, the event with the greatest crop cover produced the largest sediment concentration (Table 4.14). One reason may be the crop cover itself; half the drainage area at the Gagnon site was planted in soyabean while the other half was in corn. The most probable reason for the SS concentration differences within the rainfall events were their respective intensities. The August event was created by a rain storm that only lasted 45 minutes, whereas the November and May events lasted 7.5 and 10 hours, respectively. The subsequent rainfall intensities for the November, May and August events were 2.61, 2.77 and 23.2 mm/hr. 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 concentration differences between surface runoff generated by snowmelt and rainfall at the field scale level. Culley et al. (1983) also observed that the higher sediment concentrations from the rainfall events led to larger PP concentrations and therefore larger TP concentrations. The average TP concentrations of the rainfall events nearly doubled the average TP concentration of the snowmelt event. A similar trend was observed at the Gagnon site. The higher sediment concentrations resulted in higher TP concentrations for the rainfall events (Table 4.14). This was to be expected due the significant relationship between SS and TP concentrations observed during the snowmelt event (section 4.4.1.6). The TP concentrations of the November, May and August events increased by 14, 15 and 12 fold over the spring snowmelt concentrations, respectively (Table 4.14). The May and August events had significantly higher ortho-P concentrations than those of the November and spring snowmelt event (Table 4.10). The lower ortho-P concentrations for spring snowmelt and November event may be due to less reducing conditions under colder temperatures (Sallade and Sims, 1997). Gaynor and Findlay (1995) observed at a field scale, similar variations in ortho-P concentrations between the summer (hotter) months and winter (colder) months.

Table 4.14 SS, TP and Ortho-P concentrations from three small rainfall events compared with the same concentrations during snowmelt at the Gagnon site

Event	*Average SS (mg/l)*	*Average TP (mg/l)*	*Average Ortho-P (mg/l)*
November 2000	1946	2.623	0.086
May 2001	2500	2.500	0.310
August 2001	11000	2.200	0.420
Spring 2001 Snowmelt	86	0.191	0.066

4.4.1.9 Rainfall and snowmelt event load comparison

The natural tendency when looking at concentration data is to single out the events with the higher TP concentration levels. In this study the concentration data for all three small rainfall events were higher than the snowmelt event. All events averaged TP concentrations well above the Quebec guideline for TP in surface waters (0.03 mg of TP/l). Often the loads can give a better overall scope of the amount of nutrients lost to surface runoff. The total TP losses for the water year (Table 4.15) were 172.0 g/ha, which is much lower than previous field studies. Culley et al., (1983) reported a two year mean P load of 590 g/ha/yr from continuous cropped cornfields in southern Ontario. Furthermore, Culley et al. (1983) reported increases in SS and TP losses of 6 and 4 times, respectively between a dry and wet year. The TP and SS losses at the Gagnon site were 3.5 and 4.84 times lower than those reported by Culley et al. (1983), respectively. The decreases in TP and SS losses are indicative of the dry year observed at the Gagnon site. In England, Catt et al. (1998) reported over six years annual TP losses ranging from 2.42 to 32.76 kg/ha/yr 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 Gagnon site were 57.9 g/ha (Table 4.15) again lower than previous studies, such as Gaynor and Findlay (1995) who reported annual ortho P losses of 155, 222 and 152 g/ha/y for 1988, 1989 and 1990, respectively. For the Gaynor and Findlay study, the ortho P losses in 1988 were similar to the ortho P losses in 1990. However, the cumulative precipitation in 1988 was 35% lower than the yearly average for the area, whereas the cumulative precipitation in 1990 was 26 % higher than the yearly average for the area. Therefore, ortho-P losses appear to be less affected by dry or wet conditions. The lower ortho-P losses at the Gagnon site may be a result of low soil P levels in the A horizon.

Table 4.15 The total loads of TP, SS and Ortho-P for the water year at Gagnon site

Event	*TP (g/ha)*	*Ortho-P (g/ha)*	*SS (kg/ha)*
Snowmelt	166.36	57.344	75.3
November 2000	2.650	0.087	1.9655
May 2001	2.050	0.254	2.0491
August 2001	0.934	0.178	4.6626
Total	172.0	57.863	83.95

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, the spring snowmelt represented 65% of the total run off for the year. As 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 of a dramatic effect on the SS concentration than the SS loads.

4.4.2 Subsurface samples

4.4.2.1 Fall 2000

During the late fall of 2000 there was visible subsurface drain flow at the Gagnon site. Unfortunately, they were not recorded by the flow meter. However, on November 29th and December 8th, 2000, spot drain flow measurements were made at the outlet. The estimated drain flow was 1.85 l/s and 1l/s for November 29th and December 8th, 2000, respectively. These flow rates assuming they remained constant for the day, translates to a depth of runoff of 1.6 mm/day and 0.864 mm/day for November 29th, and December 8th, 2000, respectively. The TP, SS and Ortho-P concentrations for the two days are illustrated in Table 4.16.

Table 4.16 The TP, SS and Ortho-P concentrations of the subsurface drainage for two days at the Gagnon site

Day	*TP (mg/l)*	*SS (mg/l)*	*Ortho-P (mg/l)*
November 29th, 2000	0.096	0.051	0.037
December 8th, 2000	0.022	0.06	0.04

Due to the insufficient flow data, it is difficult to determine or even estimate the losses that occurred as a result of these two events. However, it could be concluded that these events do not represent a significant portion of the volume lost for the water year. The snowmelt event had an estimated depth 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 (section 4.4.2.2). 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.

4.4.2.2 Subsurface concentrations (snowmelt)

Water from the drains was sampled during the snowmelt event when the drain outlets were completely submerged, either by pulsing the sampler manually, or by remotely pulsing the sampler via the phone line. Unfortunately the IF 200 propeller meter did not function properly and therefore no flow weighed composite samples were taken. Furthermore, no grab samples were taken during the snowmelt event because the drain outlets were completely submerged by the ditch water. A total of 10 samples were taken throughout the months of March and April at each site. The samples were manually pulsed at the site on each day. Beauchemin et al. (1999) were not able to sample any of the drain outlets in their study during the snowmelt because the water level in the ditches had submerged the drain outlets completely. Very little data in Quebec has been published on the phosphorus concentrations in the drains during snowmelt. The drains began to flow April 8th 2001, and functioned at full capacity until April 12th, 2001. By April 17th, 2001 both drains had significantly slowed down and were flowing at extremely low rates. As mentioned earlier, the monthly average for the Philipsburg weather station is 87.4 mm, and in 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 subsurface drainage. However, during April 2001 there was no rainfall after snowmelt, and as such, there was no subsequent drain flow. The dry conditions carried over through the summer and resulted in a lack of sampled drainage events during the summer months.

In Quebec, the water quality standard for TP in surface waters is 0.03 mg /l. The samples taken during the snowmelt event exceeded the Quebec water quality standard at both sites (Figure 4.15). There was a difference in the average SS concentration before the snowmelt and the average SS concentration during the snowmelt (Table 4.15). This difference resulted in an increase of SS concentration of 1.91 and 16.7 times for the Marchand and Gagnon sites, respectively. The higher SS concentration during snowmelt resulted in a 4.06 and 9.64 fold increase in PP concentrations. The soil at the Gagnon site is a hard cracking clay, therefore aiding preferential flow of nutrient rich surface water to the tile drains faster and more frequently (Gaynor and Findlay, 1995). Furthermore, preferential flow may cause interior erosion and colloidal transport of P from the surface layer to the subsurface (Magid et al., 1999). On the Marchand site, the SS and PP concentrations are lower than at the Gagnon site (Table 4.17). Furthermore, an increase in SS concentration of 1.91 fold between pre snowmelt and snowmelt was observed. This is not as dramatic as the increase observed on the Gagnon site (16.7 fold). However, the PP increases on the Marchand site, between pre snowmelt and snowmelt, were as dramatic as the increases observed at the Gagnon site. This would imply that the sediment that makes it to the drains on the Marchand site has higher P levels.

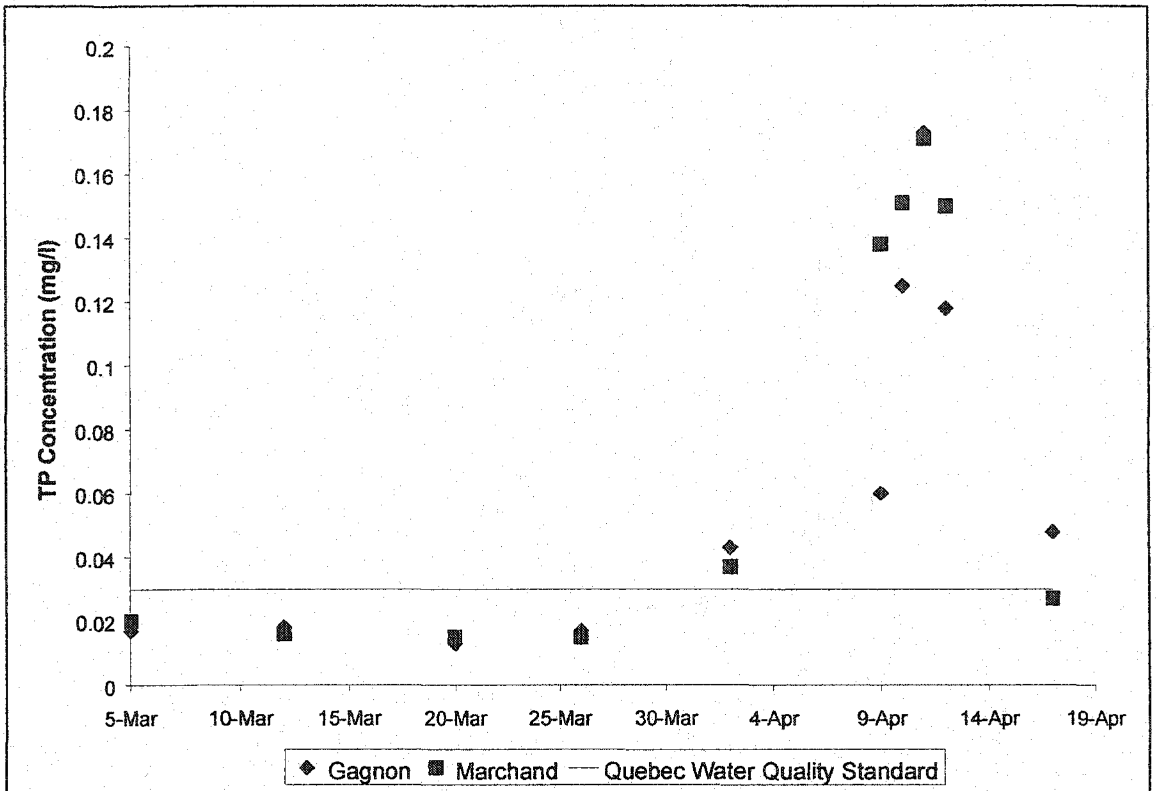

Figure 4.15 Total phosphorus concentrations in subsurface water of both sites prior and during the snowmelt event. (The Quebec water quality standard for surface water is shown by the solid line)

Table 4.17 The average TP, SS, Ortho-P and PP concentrations in the tile drains of both sites prior and during the snowmelt event

Site		*SS (mg/l)*	*TP (mg/l)*	*Ortho-P (mg/l)*	*PP (mg/l)*
Marchand	Winter*	7.2	0.0206	0.0066	0.0070
	Snowmelt**	13.8	0.1274	0.0818	0.0282
Gagnon	Winter*	2.0	0.0216	0.0078	0.0050
	Snowmelt**	33.4	0.1048	0.0368	0.0482

* The average concentrations of subsurface samples between March 5th, 2001 to April 2nd,2001

** The average concentrations of subsurface samples between April 9th, 2001 to April 17th, 2001

Ortho-P concentrations also increased dramatically during the snowmelt period. This data is consistent with the literature, whereby TP concentrations in subsurface runoff are governed by the dissolved P forms (Coale, 2000; Heathwaite et al. 2000; Hooda et al. 1999; Beachemin et al. 1998; Gaynor and Findlay 1995; Heckrath et al. 1995; Culley et al., 1983). The overall snowmelt TP and ortho P concentrations for both sites are 0.1161 and 0.0593, respectively. Hanway and Laflen (1973) studied two continuous corn plots with two different soil types in Iowa and reported an average TP concentration over three years of 0.028 mg/l. Studies such as this concluded that the drains were not a factor. However, in a recent Quebec study, Beauchemin et al. (1998) reported TP concentrations from 27 tiled drained soils. The TP concentrations ranged from 0.01 to 1.17 mg/l. Out of the 27 sites, sampled 14 and 6 exceeded the Quebec water quality standard of 0.03 mg of TP/l for the years 1994 and 1995, respectively. Beauchemin et al., (1998) and other studies (Culley et al. 1983; Gaynor and Findlay, 1995; Heckrath et al., 1995; Dils et al., 1998; Stamm et al., 1998; Catt et al., 1998; Hooda et al., 1999; Heathwaite et al., 2000) have concluded that the drains can no longer be ignored as source of P pollution.

Despite the lack of complete flow data from the tile drains a trend similar to that of other studies did emerge. The drains were observed flowing at full capacity for 4 days during the snowmelt. Presumably the drains began to flow at full capacity late April 8th or early April 9th. This coincided with the first manually pulsed samples. The samples taken on April 9th 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. Laubel et al. (1999) observed initial peaks followed by a dramatic recession in SS, PP and dissolved P (DP) concentrations, despite continuous subsurface discharge rates. This "flushing" effect resulted in the initial SS concentrations to be 70 to 200 times larger than those SS concentrations 7 to 8 hours into the runoff event. It was concluded by Laubel et al. (1999) that "the first, rapid flow flushes the loose particles out such that no loose particles remain, and availability of fine particulate matter consequently decreases in the marcropores and possibly also in the tile drains themselves during a flow period." Dils et al. (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 data was followed by a recession, despite the continuous discharge rate. In both studies the "flushing" effect was attributed to preferential flow of rich surface water to the tile drains.

4.4.2.3 Marchand subsurface concentrations versus Gagnon subsurface concentrations

There were 10 manually pumped samples taken at each site between March 5th and April 17th, 2001. The sampling time between each site ranged from one half hour to 5 hours. It was assumed that the changes in concentrations would not vary in the drains because the flow did not change dramatically over 5 hours between sites. Therefore, a paired T test was performed on manually pumped subsurface samples at both sites. TP, BAP, TDP and PP showed no significant effect between sites (Table 4.18). There was however a significant effect between the Marchand and Gagnon sites for SS and Ortho-P (Table 4.18).

Table 4.18 Paired T test results of subsurface concentrations between the Marchand and Gagnon sites

Source of Variation	*TP*	*TDP*	*Ortho-P*	*PP*	*BAP*	*SS*
Marchand X Gagnon	--	--	*	--	--	**

*,**, *** Denote a significant effect at $\alpha > 0.10$, 0.05, and 0.01, respectively

The strong sediment effect between sites may be due to preferential flow. As mentioned earlier, the Gagnon site is a hard cracking clay, which can create large macropores in the soil and are then able to transport excess surface runoff to the drains much quicker than the natural infiltration rate of the soil (Gaynor and Findlay, 1995). Despite the strong sediment effect between sites, there was no PP effect. Therefore the sediment that entered the Marchand drains carried enough PP to match PP found in the Gagnon drains. The nutrient richer sediment found at the Marchand site might be due to the higher soil level. The significant effect observed in the ortho-P concentrations between both sites is a result of the partitioning of the concentration data in the drains. On the Marchand site the ortho-P concentrations made up 66% of the TP concentrations, whereas the ortho-P concentrations only made up 35% of the TP concentrations at the Gagnon site. The higher soil P levels on the Marchand site generated high ortho-P levels in the soil solution, which moves down to the drains under high flow conditions.

4.4.2.4 Surface concentrations versus subsurface concentrations

It is difficult to assess any differences between the annual concentrations in the drains and the annual surface runoff concentrations, due to the malfunction of both flow meters and the unusually dry conditions. It is possible to compare the differences between average concentrations in the drains for the snowmelt event to the average surface runoff concentrations for the same event. However, as previously stated the surface data collected at the Marchand site did not capture the entire snowmelt event because of the wash out of the berms. Therefore, only the surface and subsurface runoff data collected at the Gagnon site was used. The average subsurface concentrations comprise of all samples taken from the Gagnon site between April 9th to April 17th, 2001. This period includes the four days where the drains were flowing at full capacity, plus the day when the drains had reduced considerably. Although there was no concrete flow data to pin point the beginning and end of the snowmelt event in the drains, it is safe to assume, due to the lack of rainfall, that all subsurface samples taken during April 9th to April 17th, 2001 are representative of the snowmelt event. The average SS concentration in surface runoff was 2.57 times higher than the average SS concentration in the drains. Culley et al. (1983) reported a similar difference between surface and subsurface SS concentrations from conventional tillage plots. Gaynor and Findlay (1995) later confirmed this in a similar study that was conducted on the same field site. The phosphorus concentrations were all higher in surface runoff than subsurface runoff. The TP concentrations were 1.82 times larger for surface runoff than subsurface runoff. The Ortho-P and PP were 1.79 and 2.2 times higher in surface runoff than subsurface runoff, respectively. Similar studies (Hanway and Laflen, 1974; Baker et al., 1975; Culley et al. 1983; Gaynor and Findlay 1995), recorded higher Ortho P concentrations in surface runoff than drain discharge. However, Culley et al. (1983) and Gaynor and Findlay (1996) reported larger cumulative ortho-P losses in the drains.

Table 4.19 Sediment and P concentrations in surface and subsurface runoff at the Gagnon site for the 2001 snowmelt event

	SS (mg/l)	*TP (mg/l)*	*Ortho P (mg/l)*	*PP (mg/l)*
Surface	86	0.191	0.066	0.106
Subsurface	33.4	0.1048	0.0368	0.0482

The surface concentrations were higher than the subsurface concentrations for every parameter. However, the subsurface concentrations were nearly half in magnitude of the surface concentrations. This is significantly higher than previous studies such as Hanway and Laflen (1974) and Baker et al. (1975). Therefore, it can be concluded that the drains are becoming more and more significant as a source of P pollution.

4.4.2.5 Estimated subsurface loads

The estimated loads are based on the estimated subsurface runoff calculated in section 4.3.2.2. Unfortunately, due to the malfunction of the IF-200 propeller meter, a flow-weighted concentration average could not be determined. However, as seen earlier, very little differences were observed between flow weighted average concentrations and overall average concentrations for surface runoff. Therefore, it is reasonable to assume that subsurface loads based on average concentrations multiplied by the total drainage volume would give reasonable estimates. A total of 5 samples were taken from the onset of the drain flow on April 9th 2001 to April 17th 2001 the time at which the drain flow had reduced considerably. The snowmelt event was the only subsurface drainage event for which samples were taken. The IF-200 flow meters were replaced with new ones in mid June. There were indications that the new IF-200 meters were working properly. However the dry conditions did not generate any additional hydrologic substantial events. Therefore, it is difficult to summarize the total losses for the water year at the Gagnon due to the lack of data. However, the partitioning of P losses between surface and subsurface runoff may be evaluated for the snowmelt event. The TP, TDP, Ortho-P, PP and SS losses were all larger in surface runoff then in subsurface runoff (Table 4.20). The 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 the missing data result in to the lower TP losses observed at the Gagnon site. Dry years have an impact on the amount of nutrient losses from a field; Catt et al. (1998) reported a 3 fold increase in TP losses between a dry and wet year.

Table 4.20 Surface, subsurface and combined losses of TP, TDP, Ortho-P, PP, and SS for the snowmelt event at the Gagnon site

	TP		*TDP*		*Ortho-P*		*PP*		*SS*	
	Loss (g/ha)	% Tot	Loss (g/ha)	% Tot	Loss (g/ha)	% Tot	Loss (g/ha)	% Tot	Loss (kg/ha)	% Tot
Surface	166.4	62.88	73.90	58.22	57.34	62.45	92.24	67.13	75.27	70.63
Subsurface	98.20	37.12	53.03	41.78	34.48	37.55	45.16	32.87	31.30	29.37
Total	264.6		126.9		91.82		137.4		106.6	

The total TP losses for the snowmelt event were 264.6 g/ha. Despite the lower losses in tile drainage 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) examined the effects of tillage and nutrient practices on surface and subsurface nutrient losses. The soil type was a Webster clay loam, and the rainfall was induced. They reported that during the rainfall induced event, the TP losses from the drains only accounted for 2.6% of the total losses for the event. The TP losses in the drains at the Gagnon site account for 37.12 % of the total TP losses during the snowmelt event, which is significantly higher than reported by Zhao et al. (2001). The difference may be a result of the partitioning of runoff volume, Zhao et al. (2001) noted that the subsurface runoff volume represented 36.6% percent of the total runoff volume, whereas the subsurface volume at the Gagnon site for the snowmelt event represented 51.8% of the total runoff volume.

5 SUMMARY AND CONCLUSIONS

5.1 Summary

The objective of this study was to design and install two data acquisition systems to measure and evaluate the partitioning of P losses in surface and tile drain flow on agricultural fields. Two field sites were selected and equipped with modern instruments to measure and sample surface and tile drainage flow year round in the Pike River watershed, Southern Quebec. The instrumentation was installed in the summer of 2000 and became operational for the water year 2000/2001 i.e. between October 1st 2000 and September 30th 2001. The water year was unusually dry. As a result of the drier than usual conditions, only one surface runoff event was sampled at the Marchand site and four surface runoff events were sampled at the Gagnon site. For each site, the dominant surface runoff event was the 2001 spring snowmelt. On the Marchand site, the magnitude of the snowmelt event resulted in the failure of the surface runoff flume and consequently surface runoff data was unobtainable. Unfortunately, the IF200 subsurface flow meters failed, which resulted in missing tile drainage flows in late November 2000 and early December 2000. A detailed snow sampling of each field site was undertaken in late March 2001. The equivalent depth of water of the snow prior to the snowmelt was determined and based on a water balance, the tile drainage flow for the 2001 snowmelt was estimated.

5.2 General Conclusions

Based on the limited data collected so far, the following conclusions can be drawn:

- The snowmelt was the only surface event recorded at the Marchand site. In addition to the snowmelt event, three other surface runoff events were recorded at the Gagnon site. However, these three events were insignificant compared to the volume of the snowmelt event, which accounted for 99.8% of the total surface runoff for the water year. The annual depth of surface runoff at the Gagnon site was 87.54 mm/ha. Due the malfunctions of the subsurface flow meters at both sites, it was impossible to obtain good subsurface runoff data. However, in can be concluded that the snowmelt event was visibly the largest event of the water year. The depth of runoff that exited the drains at the Gagnon site during the spring snowmelt based on a water balance calculation was estimated to be 93.7 mm/ha. The total runoff depth that exited the Gagnon site via surface and tile drainage flow was 181.2 mm/ha. During the 2001 snowmelt, the drains at the Gagnon site were a significant portion of the volume that exited the field site, making up 51.7 % of the total volume.

- At the Gagnon site, the suspended sediment concentrations in surface runoff for the November 26th, 2000, May 19th, 2001 and August 31st, 2001 events were 36, 28 and 154 times higher than the average suspended sediment concentration of the 2001 snowmelt, respectively. However, the snowmelt proved to generate greater sediment loads. The suspended sediment loads for the 2001 snowmelt were 75.3 kg/ha, which were 38, 37 and 16 times higher than the suspended sediment loads for the November 26th, 2000, May 19th, 2001 and August 31st, 2001 events, respectively.

- At the Gagnon site, the total phosphorus concentrations in surface runoff for the November 26th, 2000, May 19th, 2001 and August 31st, 2001 events were 14, 15 and 12 times higher than the average total phosphorus concentrations of the 2001 snowmelt, respectively. Despite the higher total phosphorus concentrations in the small surface runoff events, the snowmelt produced greater total phosphorus loads. The total phosphorus loads for the 2001 snowmelt event was 0.166 kg/ha. The three other surface events combined only represented 3.3% of the total phosphorus loads for the entire water year. Therefore, the snowmelt event proved to be the more significant event in terms of P pollution.

- There was no significant correlation between total phosphorus concentration and surface flow rate (Marchand R^2 = 0.3962, Gagnon R^2 = 0.0619). No significant correlation was found between suspended concentrations and surface flow rate

(Marchand R^2 = 0.3903, Gagnon R^2 = 0.2662). A strong correlation was found between TP and SS concentrations in surface runoff for both sites (Marchand R^2 = .9722, Gagnon R^2 = 0.7018). The correlation illustrates that the best way to reduce TP losses from fields is to implement erosion control practices that reduce the amount sediment losses.

- The results of a paired T test showed a significant effect ($\alpha = 0.10$) between field sites for ortho-P concentrations. The average ortho-P concentration in the Marchand drains was nearly double the average ortho-P concentration in the Gagnon drains. The higher soil P levels on the Marchand site generated higher ortho-P levels in the soil solution, which moves to the tile drains under high flow conditions. There was a stronger effect ($\alpha = 0.05$) between sites for SS concentrations. The average SS concentration in the Gagnon drains was 2.43 times higher than the SS concentration found in Marchand drains.

- At the Gagnon site, the average TP and ortho-P concentrations from the tile drains were 45% and 44% lower than the average TP concentrations for surface runoff, respectively. The subsurface drains on the Gagnon site averaged 0.1048 mg/l of TP for the snowmelt event, which is well over the water quality standard (0.03 mg/l of TP) 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 37.12 and 37.55 % of the total TP and ortho P losses for the event, respectively. There were some small subsurface flow events that took place late in Autumn 2000 on the Gagnon site. However the drain flow data was not recorded. It was concluded due to the lower TP concentrations and visibly smaller drain flow, that these events pale in comparison to the snowmelt event. Therefore, the tile drains represented approximately a third of the TP losses for the water year. This indicates that tile drains are significant pathways for phosphorus.

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