SWAT-predicted influence of different landscape and cropping system alterations on phosphorus mobility within the Pike River watershed of south-western Québec

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Michaud, A. R., Beaudin, I., Deslandes, J., Bonn, F. and Madramootoo, C. A. 2007. **SWAT-predicted influence of different landscape and cropping system alterations on phosphorus mobility within the Pike River watershed of south-western Québec**. Can. J. Soil Sci. **87**: 329–344. An agreement between the governments of the province of Québec and the State of Vermont calls for a 41% decrease in phosphorus (P) loads reaching Missisquoi Bay, the northern portion of Lake Champlain. The agreement particularly targets the agricultural sector, since 80% of non-point source P inputs to the bay are associated with cultivated lands. In order to identify sustainable cropping practices likely to help meet the target P loads, the SWAT (soil and water assessment tool) model was employed to assess hydrological performance, erosion processes and P mobility on the bay's principal Québec P contributing tributary, the 630 km^2 Pike River watershed. Strong in-watershed spatial clustering of vulnerability to non-point source exports highlights the need for targeted implementation of sustainable agricultural practices and soil conservation works to derive the reduction in P loads. Planting cover crops over the 10% most vulnerable lands would result in roughly a 21% drop in overall P exports at the watershed outlet, whereas the same 10% randomly distributed over the watershed would only contribute to a 6% drop in P exports. The study of different field-scale management scenarios indicated that achieving the targeted 41% reduction in P exports would require the widespread (half the land devoted to annual crops) implementation of sustainable cropping practices, and the conversion of a specific 10% of the territory to either cover crops or permanent prairie land. Meeting the P target-loads would require additional investments in the protection of floodplains and riparian strips, the targeted construction of runoff-control structures, and the rapid soil incorporation of manures on lands dedicated to annual crops.

Key words: Soil and water assessment tool, modelling, sediment, phosphorus, cropping system, scenario, best agricultural management practices

Michaud, A. R., Beaudin, I., Deslandes, J., Bonn, F. et Madramootoo, C. A. 2007. **Modélisation de l'influence du paysage et des systèmes culturaux alternatifs sur la mobilité du phosphore dans le basin versant de la rivière aux Brochets, Québec.** Can. J. Soil Sci. **87**: 329–344. La réduction de 41 % des flux de phosphore à la baie Missisquoi, portion septentrionale du lac Champlain, a fait l'objet d'une entente entre les gouvernements de la province de Québec et de l'état du Vermont. L'entente interpelle particulièrement le secteur agricole, puisque 80 % des apports diffus de phosphore (P) atteignant la baie y originent. À l'aide de SWAT (Soil and Water Assessment Tool), une modélisation du fonctionnement hydrologique, des processus d'érosion et de la mobilité du P a été réalisée à l'échelle du bassin versant de la rivière aux Brochets (630 km^2), principal contributeur de P à la baie en territoire québécois, afin d'identifier les scénarios d'intervention agroenvironnementaux susceptibles de rencontrer les charges-cibles de P. La forte discrimination spatiale dans la vulnérabilité du territoire aux exportations diffuses de P met en relief la pertinence de cibler l'implantation de pratiques agricoles ou ouvrages de conservation des sols afin d'en optimiser les retombées environnementales. L'implantation ciblée de cultures de couverture sur 10 % du parcellaire le plus vulnérable se traduit, par exemple, en une réduction de l'ordre de 21 % des exportations globales de P à l'exutoire du bassin versant, comparativement à une réduction de 6 % pour une implantation aléatoire des mêmes pratiques sur une superficie équivalente. L'étude de différents scénarios de gestion du parcellaire indique que la rencontre de l'objectif de 41 % de réduction des exportations de P serait tributaire d'une implantation généralisée (50 % du parcellaire en cultures annuelles) de pratiques culturales de conservation, de même que d'une conversion ciblée de 10 % du parcellaire le plus vulnérable en culture de couverture ou prairie permanente. La rencontre des charges-cibles ferait par ailleurs appel à des investissements, de façon complémentaire, dans la protection systématique des plaines inondables et des bandes riveraines, l'implantation ciblée de structures de contrôle du ruissellement et à l'incorporation hâtive des engrais de ferme sur le parcellaire en cultures annuelles.

Mots clés: SWAT, modélisation, sédiment, phosphore, système cultural, scénario, PGB

Abbreviations: **BMP**, best agricultural management practice; **HRU**, hydrological response unit; **NSC**, Nash Sutcliffe coefficient; **PTEC**, pollutant trapping-efficiency coefficients

Stakeholders in the State of Vermont and the province of Québec are making a concerted effort to free northern Lake Champlain's Missisquoi Bay from recurring cyanobacterial blooms. A targeted 41% reduction in phosphorus (P) loads reaching the bay, an intervention priority, was the crux of an agreement between the two governments. The issue of P loss to the lake is one that impacts upon the agricultural sector, inasmuch as 80% of non-point source P has been shown to arise from cultivated lands within the watershed (Hegman et al. 1999). Watershed-scale modelling of hydrological performance, erosion processes and P mobility on the bay's principal Québec P contributing tributary, the 630 km^2 Pike River watershed (Deslandes et al. 2007), was implemented to support the planning of action by the region's stakeholders working towards the watershed and bay's sustainable development. The hydrological model of Deslandes et al. (2007) highlighted the significant spatial clustering of P exports across the watershed. Under current soil and crop management practices, over 50% of P loads reaching the watershed's outlet arose from only 10% of the watershed's area. Spatial variability in hydrological activity and P mobility within the region under study was also brought to the fore in the context of field- (Michaud and Laverdière 2004), watershed- (Michaud et al. 2004) and regional-scale (Deslandes et al. 2004) studies. Such spatial gradients in surface hydrological activity have been reported elsewhere in North America (Zollweg 1996; Gburek 2000) and in Scandinavia (Kronvang et al. 1997; Ulen et al. 2003).

Strong spatial clustering in the mobility of P and other water contaminants indicates, within an operational focus, the need for a spatially specific targeting of agri-environmental interventions. The hydrological modelling of best agricultural management practices (BMPs) effects on water quality thus emerges as a tool of choice in aiding to develop and implement a basin scale work plan dedicated to non-point source phosphorus control. Given its high spatial resolution and ability to model the influence of alternative cultural practices, as modulated by field-scale-specific physical and chemical properties, the SWAT hydrological model (Arnold et al. 1998) was chosen as a decision-support system for stakeholders involved in the sustainable development of the Pike River watershed. The results of hydrological modelling associated with the simulation of different watershed-scale agri-environmental management scenarios for the Pike River basin are presented here. The relative effectiveness of selected best management practices was evaluated in comparison with a reference scenario, representing current agricultural production systems employed in the watershed (Deslandes et al. 2007). This comparison of scenarios based on different interventional spatial-targeting strategies seeks the attainment of P target-loads established in the Québec-Vermont agreement (Governments of the Province of Québec and State of Vermont 2002).

MATERIALS AND METHODS

Study Site

With its source in the forest-dominated Appalachian piedmont, and its lower reaches in the relatively flat farmlands of the St. Lawrence lowlands, the Pike River watershed drains an area of 630 km^2. The watershed's climate, topography, and agricultural productions systems are described in Deslandes et al. (2007). The watershed's water balance for 2000–2003 showed exports of 476 mm yr^{-1}, of which 218 mm yr^{-1} were associated with surface runoff, arising from 1154 mm yr^{-1} in precipitation, of which 326 mm yr^{-1} fell as snow. Overall, roughly half the watershed's area is dedicated to agricultural pursuits. The downstream portions of the watershed are more intensively farmed than are the upstream portions, reflecting a spatial gradient in landscapes across the watershed. Downstream cropping systems, dominated by corn, receive a P input to topsoil of roughly 47 kg P ha^{-1}, compared with 21 kg P ha^{-1} upstream where the land use is dominated by hay crops.

Manures account for roughly two thirds of P inputs to agricultural lands, the remaining third coming from inorganic fertilizers. Under the current field-scale management practices, represented in the reference scenario, total P exports from cultivated areas were 1.3 kg P ha^{-1} yr^{-1}. In combination with the watershed's urban and forested areas, total P exports at the Pike River's outlet were estimated to be 44 t P yr^{-1}. This P load concurs with those postulated by the Lake Champlain Basin Program (Hegman et al. 1999), placing the Pike River's P loads amongst the highest in the entire Lake Champlain basin.

Model Calibration and Validation

The methodology and performance of the SWAT hydrological model applied to the Pike River watershed were presented in Deslandes et al. (2007). These simulation results, referred to as the reference scenario, served as the computational basis for prediction of BMP's effects on hydrology, erosion and P transport processes. The model's parameterisation was supported by a characterisation and spatial representation of agricultural landscapes and production systems according to a field-scale partitioning of cultivated lands into over 2400 hydrological response units (HRU), each distinctive in its combination of soil properties, topography, fertilizer inputs, and inclusion within one of 99 subwatersheds in the region under study. The model's accuracy with respect to measured data was evaluated with three statistical indices: (i) the Pearson correlation coefficient (*r*), (ii) the Nash Sutcliffe coefficient (NSC), and (iii) percent deviation of predicted water, sediment or nutrient yield from measured data. Stream flows predicted by the model were compared with measurements taken at four hydrometric stations (Table 1; Centre d'Expertise Hydrique du Québec 2005). Only streamflow was recorded at the two stations located on the main channel of the Pike River. The first is located at the outlet of the gently rolling, mainly forested portion of the waterhed, upstream from the town of Bedford ($PR_{up,}$ 385 km^2). The other, downstream from Bedford, encompasses some additional flat agricultural lands (PR_{down}, 561 km^2). Within the Pike River watershed, two smaller (< 8 km^2) experimental subwatersheds of the Walbridge Creek (WC_{up} and WC_{down}) were monitored for suspended solids and P loads in addition to streamflow. All stations were equipped with bubble-type depth gauges. A minimum of six stream

Table 1. Hydrometric Stations in the Pike River Watershed

Station ID	Associated watershed	Area (km^2)	Description	Measurements
PR_{up}	Pike River upstream from Bedford	385	Rolling landscape, mainly wooded	Stream flow
PR_{down}	Pike River downstream from Bedford	561	Drains the rolling and forested lands of the watershed's headwaters and a portion of the flat, agricultural lands	Stream flow
WC_{up}	Walbridge Creek BMPs applied	6.3	Rolling and agricultural (61%), typical landscape of the Appalachian piedmont	Stream flow, sediments, and P
WC_{down}	Walbridge Creek standard	7.9	Flat and agricultural (63%), long slopes, typical of St. Lawrence lowlands	Stream flow, sediments, and P
Beaver	Beaver Brook	11	Flat and agricultural (97%), long slopes, typical of St. Lawrence lowlands	Stream flow, sediments, and P

gaugings was used in annual updates of discharge rating curves. Hydrometric data were corrected to account for backflow caused by the presence of ice or macrophytes in the stream or riverbed. Sediment and phosphorus exports were characterized between 2000 and 2003, with 166 water samples drawn at the outlet of each of the Walbridge experimental watersheds. Point measurements of water quality and continuous monitoring of stream flow, along with concentration-discharge rating curves established for three streamflow ranges, allowed for the Flux 5.0 (Walker 1998) software-assisted modelling of P and sediments.

Lack of sufficiently long time series of water quality monitoring data on the Walbridge experimental watersheds did not permit a traditional calibration-validation of the model. Consequently, a spatial and temporal validation of the calibrated-SWAT model was also done on a third small subwatershed, the Beaver Brook basin, which drains roughly 11 km^2 of flat agricultural lands. Between March 1997 and September 2002, sediment and phosphorus loads were measured using the same method as on the Walbridge subwatersheds (Michaud et al. 2005) and monthly data were compiled for validation of the model.

The calibrated model's predicted flows, sediment and total P exports closely matched those measured over the study period at the four hydrometric stations located on the Pike River watershed. Overall, SWAT satisfactorily predicted streamflow at the two stations on the Pike River's main channel (PR_{up}, PR_{down}), as well as those on the two branches of the Walbridge Creek watersheds (WC_{up}, WC_{down}) (Table 2). The statistics, compiled across the calibration and validation phases of the study, indicate a good fit of the model predictions for monthly sediments and P exports as well (Table 3). However, predicted flows from station PR_{down} showed a 20% underestimate of streamflows over the calibration period, despite an *r* value of 0.76, and a NSC of 0.55. This underestimate is essentially attributable to the winter periods of January–February 2002, when exceptionally unseasonable near-zero and above-zero temperatures were recorded, some as high as 10°C. Similar conditions have also been observed during the validation period (March and December 2003). Under such conditions, SWAT had, given its weather generating subroutine being based on daily mean temperature, difficulty distinguishing rainfall and snowfall. Given the magnitude of peak flows associated with winter thaws, which represent more than 20% of the annual water yield, predictions of water depths were strongly affected. Overall, the model tended to underestimate sediment and P exports during winter and fall, while overestimating in early spring and summer. This reflects in large part the modelled watershed's hydrology. Further comments on the calibration and validation results are presented in Deslandes et al. (2007).

Modelling of Agri-Environmental Scenarios

The effect of different BMPs on water balance, sediment and P exports were modelled for the study period (2000–2003) over the entire Pike River watershed. Timely manure incorporation, cover cropping, conservation tillage, riparian buffers and structural runoff control were selected for the simulation since their feasibility has been generally documented in field studies and on-farm trials in the North-East (Angers et al. 1997; Gangbazo et al. 1997; Duchemin and Majdoub 2004; Kleinman et al. 2005). Modelling of these BMPs in agri-environmental scenarios using SWAT was done by modifying the values of parameters influencing the water balance and the sediment and P exports from the calibrated reference scenario (Deslandes et al. 2007), while maintaining the climatic variables, biophysical descriptors and hydrological calibration parameters. Previous sensitivity analyses of the SWAT model (Lenhart et al. 2002; Holvoet et al. 2005) have highlighted a number of parameters that strongly influence runoff levels, sediment yields and phosphorus exports. Based on these sensitivity analyses and on information provided by Neitsch et al. (2002), SCS curve numbers and manning's surface roughness were the two parameters, notwithstanding the changes made in the management operations, that saw their values changed in the different scenarios described below.

Moreover, a common modelling period for the reference and intervention scenarios allowed for a comparison across different spatial scales (individual HRU to full watershed) and different temporal scales (daily to multi-year) of the relative effect of selected BMPs on non-point source sediment and nutrient exports. Modelling of BMPs followed a two-step approach. Individual BMPs effects on water, sediment and phosphorus yield were first investigated. Then, the influence of mixed scenarios, combining various levels of implementation and spatial targeting of BMPs at the HRU

Table 2. Calibration and validation of SWAT model closeness of fit parameters for monthly stream flow at four hydrometric stations over study period

		Monthly streamflow		
Watershed	Period	D_v	*r*	NSC
PR_{up}	Calibration: 04/1998 to 12/2000 and 05/2001 to 12/2002	–3%	0.93	0.85
	Validation: 01/2003 to 12/2003	–8%	0.97	0.91
PR_{down}	Calibration: 11/2001 to 12/2002	–20%	0.82	0.52
	Validation: 01/2003 to 12/2003	–33%	0.88	0.60
WC_{up}	Calibration: 11/2001 to 12/2002	–9%	0.74	0.49
	Validation: 01/2003 to 12/2003	+19%	0.93	0.64
WC_{down}	Calibration: 11/2001 to 12/2002	+3%	0.78	0.60
	Validation: 01/2003 to 12/2003	–15%	0.94	0.85

Table 3. Calibration and validation of SWAT model closeness of fit parameters for monthly sediment and total P export predicted at the outlet of the Walbridge Creek subwatersheds and validated on the Beaver Creek subwatershed

		Sediment			Total P exports		
Watershed	Period	r	NS	D_v	r	NS	D_v
WC_{up}	Calibration: 11/2001 to 12/2002	0.86	0.70	10%	0,88	0.76	–13%
WC_{down}	Calibration: 11/2001 to 12/2002	0.82	0.55	–4%	0.87	0.73	7%
Beaver	Validation: 03/1997 to 09/2002	0.92	0.84	–8%	0.94	0.87	–20%

scale were modelled. Two considerations guided the construction of mixed scenarios: meeting a 41% reduction in total P loads at the outlet of the Pike River watershed, and minimizing the technical and economic constraints associated with BMP's implementation. BMPs presenting the fewest constraints were applied over the whole watershed, whereas those presenting more constraints were applied to HRUs having a high vulnerability to P loss. As such, BMP's implementation followed this decreasing order: Timing of manure inputs and incorporation » Buffer strips » Conservation tillage » Cover cropping » Structural runoff control. Whether modelling the effect on water balance, sediment or P mobility, the implementation of BMPs, singly or in combination, was done at three levels of spatial targeting: 10, 50 and 100% of watershed lands dedicated to annual crops. In order to evaluate the effect of targeting the most vulnerable HRUs, the results of a random allocation of BMPs to any HRUs was compared with one targeted to those HRUs exhibiting the greatest P export rates under the reference scenario (Fig. 1). The characteristics and areas of BMP implementation targeted to high P-exporting HRUs are presented in Table 4.

Timing and Incorporation of Manure Inputs

Regulations in Québec calls for a balance P budget, a maximum soil-test P and limits on manure inputs following Oct. 01 (Ordre des Agronomes du Québec 2007). Both reference and agri-environmental scenarios respect these regulations. Moreover, we took advantage of SWAT's capacity to operate on a daily time-step to quantify the effect of different seasons and lag times in soil incorporation of farm manures on P exports. An initial sensitivity analysis on the model's hydrological subroutines showed lags in incorporation to be a P mobility risk factor of greater consequence than the seasonality of spreading. By altering spreading dates so as to precede tillage by a single day, the simulated incorporation-lag in the BMP's scenario was set at ≤ 24 h for all manure-borne P inputs to annual crops. A comparison of the BMP's (≤ 24 h lag) and reference (variable lags) scenarios allowed one to deduce the net effect of optimizing the incorporation on land receiving manure, which accounts for roughly half of the watershed's area. Reference scenario lags during spring and fall for the study period (2000–2003), fixed according to a criterion of a minimum of 48 rain-free hours between spreading and incorporation, ranged from 6 to 16 d, corresponding to cumulative rainfall heights of 4 to 87 mm (Deslandes et al. 2007).

Farm manure spreading dates integrated within the management schedules specific to cover cropping and no-till practices were also systematically subjected to a lag optimisation (<24 h) respecting the constraints inherent to each BMP, as outlined below.

Cover Cropping

Underseeding of red clover into small grain crops has been credited for improvements in soil quality (Abdallahi and N'Dayegamiye 2000) and nitrogen fertilizer economy and having beneficial residual effects on crop yield (N'Dayegamiye and Sen Tran 2001) within dairy, horticultural and cereal cropping systems (Côté et al. 1994; Kleinman et al. 2005). Similarly, soil science research and on-farm trials demonstrated that late-season cruciferous cover crops established by mid-august following hay or small grain crops benefit soil quality, provide a time frame

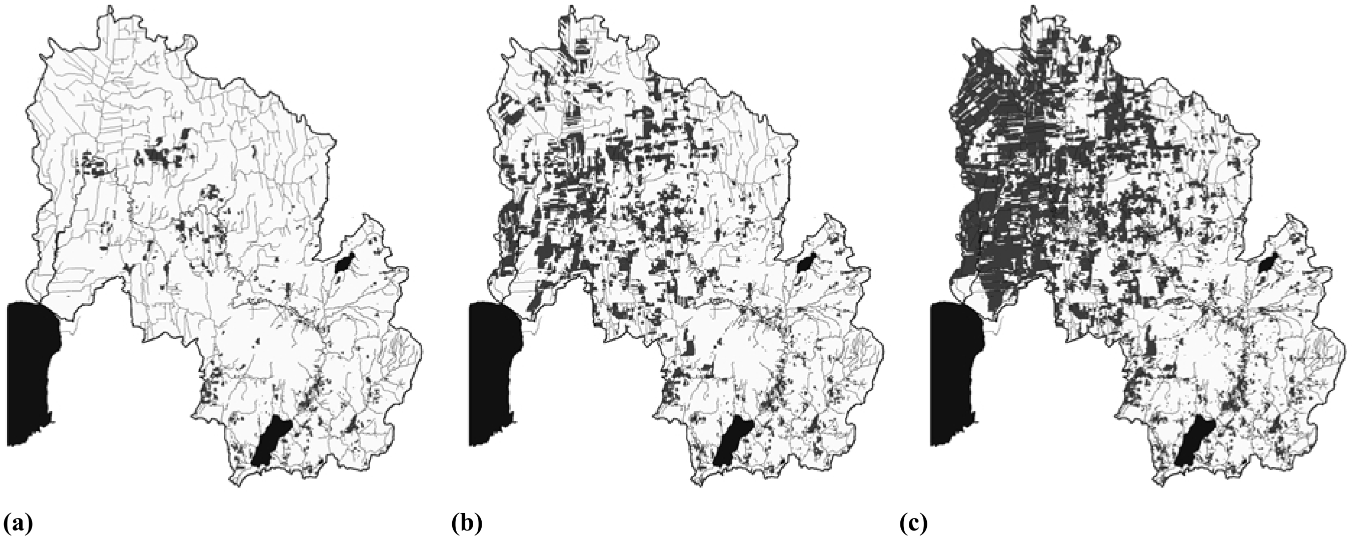

Fig. 1. Spatial distribution of annual cropped HRUs targeted by the implementation of BMPs at rates of 10% (a); 50% (b) and 100% (c).

Table 4. Characteristics of lands targeted in the simulation of scenario implementation at rates of 10, 50 and 100%

		% of fields targeted by decreasing vulnerability to P export					
		10%		50%		100%	
Tot. area (ha)		1 726		9 115		18 379	
Land use	Corn	91%		92%		67%	
	Soybean	4%		4%		8%	
	Cereals	4%		5%		24%	
	Hay or pasture	0%		0%		0%	
		Mean	SD	Mean	SD	Mean	SD
HRU Characteristics	Runoff (mm)	256	72	255	79	238	98
	Sediment yield (Mg ha^{-1})	5.7	5.1	2.3	4.0	1.4	2.7
	Soluble P yield (kg ha^{-1})	0.38	0.28	0.38	0.23	0.31	0.19
	Total P yield (kg ha^{-1})	7.1	5.8	3.2	4.4	1.9	3.0
	Tot. P input (kg ha^{-1})	53	60	67	51	58	44
	Mean slope (m/m)	0.04	0.023	0.021	0.029	0.017	0.028
	Erodibility factor (0.013 Mg m^2 h m^{-3} Mg cm)	0.24	0.11	0.22	0.10	0.21	0.09

Means are weighted according to HRU areas, SD = standard deviation.

to value manure nitrogen and protect soils from erosion through the dormant season (Abdallahi and N'Dayegamiye 2000).

In the present study, cover crop agri-environmental scenarios assume the establishment of (i) a perennial legume or grass cover crop (CC_{per}), (ii) a small grain intercropped with red clover (IC_{sg+rc}), or (iii) a small grain followed by a late season cruciferous cover crop ($CC_{sg\rightarrow cr}$), on lands formerly devoted to annual crops. The model's field management schedules were altered in such a manner as to integrate new manure spreading protocols. Whereas, on a mass basis, the reference scenario's manure applications were split 45, 36 and 19%, between spring, post-emergence and fall, respectively, under the $CC_{sg\rightarrow cr}$ and IC_{sg+rc} scenarios, applications were split 55% and 45% between pre-plant and mid-August post-harvest, respectively. The CC_{per} scenario followed the reference scenario's three dates of manure application, set in accordance with the timing of hay cuttings. Cover crop growth parameters were adjusted so as to reflect biomasses documented for Québec (Institut de la statistique du Québec 2002). The cover/inter-crop scenarios required adjustments to the value of the Manning coefficient, the curve number (CN), as well as to the crop type and fertilizing schedule (Table 5). In order to better represent the reduced runoff production associated with cover crops, curve numbers typical of small grain crops with residues (SCS Engineering Division 1986) were used at the beginning of the growing season and updated daily by SWAT, based on daily rainfall and soil water content. Manning's roughness coefficients were raised by 0.2, bringing them to the higher range for grasses (Engman 1983), to account for the increased presence of biomass and residues on the soil surface.

Conservation Tillage

No tillage and reduced tillage acreages have increased considerably over the past decades in the US and Canada.

However, fall mouldboard ploughing remains the dominant soil tillage strategy under Québec's cropping systems (Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec 2001), where grain corn crops dominate the rotations, and where clay-textured soils and short growing season have historically limited the feasibility of no-till and reduced tillage practices. However, on-farm research networks demonstrated the economic feasibility of growing soya and corn under no-tillage systems over light- to medium-textured soils in southern Québec (Harvey 2005), while the recommended practice following grain corn calls for a conventional tillage on clays or poorly drained soils. Taking into account the limitations of no-till or reduced tillage cultivation on soils with poor internal drainage, modelled conservation tillage scenarios were assigned according to the crop type and soil hydrological group and include: (i) reduced tillage with fall stubble ploughing (RT_f); (ii) reduced tillage with spring stubble ploughing (RT_s); (iii) no-till seeding with post-emergence drilling of farm manure (NT_{pe}) (Table 5). For small grains and corn, NT_{pe} was assigned to soils of hydrological groups A and B, whereas RT_s and RT_f practices were assigned to groups C and D, respectively. For soybean, no-till seeding was initially applied to the entire area devoted to the crop. However, preliminary modelling indicated that switching to no-till seeding was only marginally effective in reducing total P exports from soils of hydrological groups C and D. Consequently, RT_f and RT_s practices, similar to those for corn, were retained for soybean on these soils.

Given the greater mobility of P sources remaining on the soil surface with conservation tillage, farm manure spreading was adapted so that the lag in manure incorporation was set to less than 24 h. For no-till seeding of corn, all manure applications were shifted to post-emergence, using disk sets mounted on low pressure spray bars for in-row incorporation. The reference (fall) manure spreading methods were maintained for RT_f, whereas for RT_s the volume of manure destined under reference conditions for fall application was shifted to the spring, preceding the spring stubble ploughing, and post-emergence in summer. For small grains under NT_{pe}, manure spreading was limited to the spring, simulating superficial burial with trail hoses.

Simulating different cultural practices required the adjustment of some hydrological modelling parameters. The use of different tillage implements (Table 5) led to alterations in the depth and degree of mixing of the tilled topsoil, which, in turn altered P distribution in this soil layer. Manning roughness coefficients were adjusted to reflect the state of non-tilled and/or residue-covered soil surfaces and SCS curve numbers were reduced by three points, to account for the presence of biomass and residue (SCS Engineering Division 1986). As with the previous scenarios, the curve number and the cover management factor (MUSLE C factor) were updated daily through the model routines based on rainfall, predicted soil water and crop growth on individual HRUs.

Riparian Buffers and Structural Runoff Control

The effects of agricultural water conservation practice implementation over the entire Pike River watershed was simulated in an entirely empirical manner, using pollutant trapping-efficiency coefficients (PTECs). Attributing given PTECs to a given HRU resulted in attenuating the proportion of daily HRU-scale modelled sediment or P loads allowed to reach the hydrographical network within the model's hydrological portion.

This approach's main difficulty arises within the context of the watershed's specific climate and land development for correctly representing the trapping efficiency associated with projected changes. Water quality monitoring at the outlet of the experimental Beaver Creek watershed in the downstream portion of the Pike River watershed (Michaud et al. 2005) showed a mean decrease in peak runoff P concentrations of 25% after the installation of shrub buffer strips and in-ditch catch-basin inlets at low-lying sites on the watershed's most hydrologically active lands. This reduction in P load was attributed to the break in the hydrologic connectivity between the fields and the stream, as well as the trapping of sediments and P by these structures prior to reaching larger waterways (Fig. 2). The relative contributions of buffer strips and catch-basin inlets in the trapping of sediments were set according to coefficients drawn from the literature (Edwards et al. 1999; Jarrett 2001; Lawrance et al. 2002; Duchemin and Majdoub 2004), as well as in proportion to lands draining to buffer strips (33%) or to catch-basin inlets (67%). This partitioning of runoff routing was based on a high-resolution digital terrain model prepared for the region under study (Duguet et al. 2002). The resulting PTEC used in the model were, respectively, 9 and 16% for buffer strips and catch-basin inlets. These were applied to the export of the particulate fraction of P from individual HRU.

Mixed Scenarios

Hydrological modelling of mixed agri-environmental scenarios implies that a combination of different BMPs is implemented on different targeted cropped parcels of land. This process makes the most of SWAT's spatial modelling capacities, allowing different plot management regimes to be allocated to the desired HRUs. The strategy underlying the selection and spatial distribution of BMPs was subject to three main criteria:

(a) A 41% decrease in annual mean total P loads across the Pike River watershed, as stated in the Québec-Vermont agreement.

(b) Prioritising of BMP simulation to those parcels of land with the greatest vulnerability to P exports, as drawn from the reference scenario HRU-scale mean annual P loading distributions. Heightened priority is also accorded to flood plains bordering the Pike River's main reaches. Given the SWAT model's limitations in handling the spatial representation of such lands, a map of flood plains developed by the Centre d'expertise hydrique du Québec (2005) served to identify HRUs prone to flooding by in a one-in-twenty year flood.

(c) In order to generate realistic scenarios, while minimizing constraints and enhancing environmental benefits, a three-step cumulative approach to the selection and targeting of BMPs was implemented:

Table 5. Cultural practices associated with different cropping practices and soil hydrological groups used in the modeling of the reference and no-till scenarios

Scenarios	Crop	Hydrologic group	Scenario	Spring tillage	Fall tillage	Manning coeff.	Manure application
Reference	Soybean, corn and small grains	All	Reference	Field cultivator	Moldboard plow	0.120	45% Spring, 36% Summer, 19% Autumn
Cover crops	Soybean, corn and small grains	All	Intercrop	Field cultivator	None	0.325	55% Spring, 45% post harvest
			Late cover crop	Field cultivator	Field cultivator	0.325	55% Spring, 45% post harvest
Conservation tillage	Corn	A, B	NT_{pe}	None (No-till)	None	0.325	100% summer
		C	RT_s	Disk chisel (Mulch tiller)	None	0.320	55% spring, 45 % summer
		D	RT_f	Field cultivator	Disk chisel (Mulch tiller)	0.300	55% spring, 45 % summer
	Small grains	A, B	NT_{pe}	None (No-till)	None	0.220	100% Spring
		C	RT_s	Disk chisel (Mulch tiller)	None	0.210	55% spring, 45 % summer
		D	RT_f	Field cultivator	Disk chisel (Mulch tiller)	0.200	55% spring, 45 % summer
	Soybean	A, B	NT_{pe}	None (No-till)	None	0.250	None
		C	RT_s	Disk chisel (Mulch tiller)	None	0.250	None
		D	RT_f	Field cultivator	Disk chisel (Mulch tiller)	0.200	None

Fig. 2. Installation of catch inlets (a) and riparian buffer strips (b) within the Pike River watershed.

(i) *The basic agri-environmental scenario* insures the protection of the watershed flood plains (290 ha), the generalised implementation of a 3-m-wide buffer strips along the municipal waterways (1-m-wide buffers are mandatory in Québec), and reduce delays to 24 h for in soil incorporation of farm manures.

(ii) *The conservation cropping practices scenario* supports the implementation of conservation tillage and cover crops, without altering the crop rotation. From a technico-economic perspective, these practices require adjustments to machinery, timing of operations and inputs.

(iii) *The crop substitution scenario* supports the shift of most P-loss vulnerable annual crops to small grains with a cover or catch crop. Considering the current price of commodities and revenue compensation policy in Québec, a shift from corn or soya to small grains is not cost effective for the farmer. Such marginal costs would thus have to be compensated through policy adjustment, and BMPs should be implemented on critical P-source areas in order to optimize the ecologic compensation cost:benefit ratio.

For all three mixed scenarios, the implementation of surface runoff control structures was incorporated in the simulations of the river's downstream subwatersheds (approximately 124 km^2 of agricultural lands) exhibiting significant surface runoff given their soil types and the prevalence of annual crops.

RESULTS AND DISCUSSION

Model Sensitivity to Selected Input Parameters

Based on the inputs and outputs extracted from the reference scenario, an analysis of the relative weights of some chosen SWAT parameters having an influence on P exports variability was undertaken. Table 6 illustrates input parameters' relative influence over P exports by presenting linear correlation coefficients for the relationships between SWAT input parameters and runoff, sediment and P (soluble and/or particulate) loads for corn and grassland plots.

Overall, under both corn cultivation and grassland, predicted soluble and particulate P loads were poorly correlated (Table 6), which shows the hydrological model's capacity to discriminate the processes involved in soluble P runoff enrichment and transport of particulate P. Under corn, total predicted P loads remain strongly correlated with the predicted erosion rate, HRU slope and soil erodibility factor. Under grasslands, the soluble fraction accounts for 76% of total P loads and correlates with agricultural P inputs, initial soil labile-P richness, annual mineralised P in the topsoil (Table 6), and is dependant on the hydrologic group (Fig. 3c), which has a strong influence on surface runoff.

Mean soluble and particulate P loads for all cultivated HRUs on the watershed over the period extending from 2000 to 2003 are shown in Fig. 3a. While each agricultural land use shows a great variability in total predicted P loads, a gradient in P speciation stands out from the bulk of HRU-scale observations made. The model thus allocates essentially all exports arising under soybean cultivation to the particulate form. Given that this crop received no P inputs under the crop's management protocol, the model's soil phase subroutines then drew from soil stocks of moderately to weakly labile P to supply plant requirements during growth, thus leaving little available labile P in the topsoil to enrich surface runoff. The opposite conditions occur in grasslands where the soluble form of P dominates at the surface as the result of P stratification within the soil profile due to surface-applied P inputs (fertilizer, manure), and the vegetative cover's minimization of sediment detachment and mobilisation. Small cereal crops and corn present a variable speciation of P exports, reflecting the model's capacity to simulate the interaction of source and transport factors on P mobility.

Across all cropping systems, particulate P loads are linearly correlated to erosion rate ($0.90 < r < 0.95$) (Fig. 3b), whereas soluble P loads during runoff events are strongly correlated ($0.64 < r < 0.76$) with P inputs, reflecting the interaction of the model's soil and routing portions. These trends in soluble and particulate speciation of predicted P loads match those reported by Michaud and Laverdière (2004), which showed a 2–80% variation in soluble P loads from simulated-rainfall runoff plots, differing in fertiliser applications and vegetative cover, installed on benchmark soils common to the Pike River watershed.

Results of Agri-environmental Scenarios

A comparison of water balance elements, mean annual P and sediment exports for the period of 2000–2003 over the entire extent of the Pike River watershed, following the targeted or random implementation, to different degrees and spatial coverages, of individual BMPs are presented in Tables 7 and 8. It should be noted that these simulations, indicative of the effects of BMP implementation on overall sediment and P exports at the watershed's outlet, also include the contribution of non-BMP-targeted HRUs (forested lands, wetlands, urban lands, etc.).

Timing and Incorporation of Manure Inputs

The elimination of delays in soil incorporation of farm manures, compared with the reference scenario, resulted in a 3% overall watershed-wide decline in P exports. However, several factors in the current modelling setup tend to minimise the potential influence of event-based P transport. The period between manure spreading and soil incorporation under the reference scenario remains relatively short (4–16 d), thus only accounting for a limited portion (4–87 mm) of annual runoff. Also, the reduction of soil incorporation delays only occurs on a quarter of lands planted to annual crops. It should be noted that in the reference scenario, the rate of manure incorporation upon spreading is set at 80%, the rate recommended by SWAT's designers (Neitsch et al. 2002). However, at the HRU scale, the magnitude of the reduction in delay is rather variable reflecting variations in rainfall received between manure spreading and soil incorporation, tillage practice, HRU-specific soil permeability, and the quantity of manure applied. Significant reductions in simulated P exports thus only apply to a limited portion of lands, but can be up to 1.3 kg P ha^{-1}, a 60% reduction compared with the exports simulated under the reference scenario for HRUs with low soil permeability and high P inputs through manuring.

Cover Cropping

While on a watershed scale cover crops only had a marginal effect on hydrology, at the HRU-scale, a 100 mm yr^{-1} drop in runoff occurred when lands devoted to annual crops were converted to perennial grass prairie or legume forage crop (CC_{per}). The influence of cover crops on surface runoff depths strongly influenced watershed scale P and sediment exports; 81% lesser sediment loads at the watershed's outlet were simulated when annual crops were shifted to prairie or cereal-clover (IC_{sg+rc}) intercropping (Table 7). A slightly lesser decrease (68%) occurred with a small grain crop followed by a cruciferous cover crop ($CC_{sg\rightarrow cr}$). It should be recalled that for IC_{sg+rc} and $CC_{sg\rightarrow cr,}$ stubble is buried in the spring, leaving a window in the spring when the soil is uncovered, and to which the model assigns higher annual runoff rates than for permanent prairie (CC_{per}). Notwithstanding its greater export of sediments, the IC_{sg+rc} scenario gave a lower P load than CC_{per}. Such trends in predicted sediment and P loads can be attributed to the differences in soil and manure management practices, and associated effects on the mobilisation of soluble P. Indeed, the model's algorithms simulate a stratification of topsoil P

Table 6. Linear correlation matrix of model export predictions (2000–2003) with model input parameters at HRU Scale for Corn and Grassland Prairie

	Model predictions (exports)					Model parameters				
	Phosphorus fractions									
Parameters^y	Soluble	Particulate	Total	Sediment	Runoff	P input	Soil labile P	Mineralised P	HRU slope	Soil erodibility
Soluble		0.22**	0.27**	0.12*	0.56**	0.76**	0.26**	0.60**	N.S.	0.19**
Particulate	**0.08***		0.99***	0.94**	0.33*	0.12**	N.S.	0.17**	0.55**	0.35**
Total	**0.98***	**0.27****		0.94**	0.35**	0.15**	N.S.	0.19**	0.54**	0.36**
Sediment	**N.S.**	**0.95****	**0.20****		0.30**	N.S.	N.S.	0.12*	0.57**	0.42**
Runoff	**0.64****	**0.38****	**0.69****	**0.37****		0.15*	N.S.	N.S.	N.S.	0.36**
P Input	**0.64****	**–0.25*****	**0.57****	**–0.31*****	**N.S.**		0.10*	0.74**	0.10*	N.S.
Soil Labile P	**0.31****	**–0.20*****	**0.26****	**–0.25*****	**N.S.**	**0.39****		N.S.	–0.15***	N.S.
Mineralised P	**0.61****	**–0.22*****	**0.54****	**–0.30*****	**N.S.**	**0.97****	**0.37****		0.16**	N.S.
HRU Slope	**–0.38*****	**0.51****	**–0.26*****	**0.57****	**–0.12****	**–0.46*****	**–0.46*****	**–0.42*****		0.09*
Soil Erodibility	**0.21****	**0.42****	**0.28****	**0.48****	**0.41****	**–0.13*****	**N.S.**	**N.S.**	**N.S.**	

Regular letters = HRU in corn (N = 567)
Bold letters = HRU in grassland prairie (N = 690)
*, **, ***Significant at the 0.05, 0.01 and 0.001 probability levels, respectively; NS, not significant.

in prairie soils, which translates to an enrichment of surface runoff waters with soluble P. Manure spreading after the third hay-cut on the CC_{per} prairie, during a relatively hydrologically active portion of study period, resulted in a greater predicted soluble P load. On the other hand, the IC_{sg+rc} and $CC_{sg\rightarrow cr}$ scenarios include the soil incorporation of farm manure and as there is no manure spreading in the fall, the model attributes a relatively lesser proportion of soluble P than under prairie CC_{per}. Thus, while the full (100%) theoretical conversion of lands devoted to annual crops to CC_{per} would result in the predicted soluble P fraction at the watershed outlet rising from 25% (reference) to 73%, such a conversion to IC_{sg+rc} and $CC_{sg\rightarrow cr,}$ scenarios would only shift the soluble P fraction to 59 and 50%, respectively (Table 7). Such a proportion in the fractionation of P forms concurs with observations cited in the literature for simulated precipitation on experimental plots as well as with natural precipitation within the study region (Michaud and Laverdière 2004) or elsewhere in North America (Young and Mutchler 1976; Sharpley and Halvorson 1994).

Comparing reductions in P and sediment loads amongst rising rates of targeted or random cover crop or inter-crop implementation (Table 7) highlights the effect of spatial targeting of BMPs on the overall export balance. While the targeted conversion of the most vulnerable 10% of annual crop lands would result in 21–24% and 27–31% decreases in predicted P and sediment loads at the watershed outlet, respectively, a similar but randomly assigned land conversion would only result in a third of the decrease in predicted P and sediment loads. The merits of spatial targeting of BMP implementation reflect the strong field-scale spatial clustering in vulnerability within the study watershed, which is often reported in watershed studies done elsewhere in North America (Sharpley et al. 1994; Daniel et al. 1994).

Conservation Tillage

Compared with the reference scenario's conventionally tilled HRUs planted to annual crops, reduced tillage (RT_s and RT_f) led to a mean decreases in runoff depth, sediment loads and P loads of 42, 46, and 53%, respectively. Such predicted effectiveness concurs with North American reports of natural or simulated rainfall-impacted plot studies (McDowell et al. 1984; McGregor et al. 1999; Meyer et al. 1999; Franti et al. 1999; Dabney et al. 2000). Reduction in predicted P load largely reflects the reduction in predicted sediment yield. These reductions are not only sensitive to the type of conservation practice that governs the protection of the soil, but also to the crop type and the hydrologic group, as can be seen in Fig. 4, and on P inputs as demonstrated in Fig. 3d. Typically, predicted P reductions' dependency on P applied demonstrates the model ability to account for the nutrient stratification in no-till cropping system.

The impact of different levels of spatially discrete implementation of no-till cropping, NT_{pe}, on overall sediment, and P exports across the Pike River watershed is shown in Table 7. Similar to the projected effects of cover crops, the conversion of 1726 ha (10%) of the watershed's most vulnerable lands under annual crops to no-till results in reductions in sediment and P exports of 5000 t yr^{-1} and 4.6 t yr^{-1}, respectively, corresponding to 10 and 16% of their respective total exports.

Riparian Buffer and Structural Runoff Control

Particulate phosphorus trapping coefficients of 9 and 16%, respectively, for buffer strips and runoff control structures implemented on the watershed's 1726 ha (10%) of most vulnerable lands planted to annual crops resulted in a 4% simulated decline in total P exports at the watershed outlet (Table 8). From a practical perspective, the predicted effect of buffers and structural runoff controls reflects the overall trapping efficiency measured following land improvements implemented within the Beaver Creek experimental watershed (Michaud et al. 2005). In this watershed, catch basin inlets at the outlets of non-subsurface drained fields (50 structures per 10 km^2) were installed on the most hydrologically active parcels of land (42% of the total watershed by area) and permanent buffer strips of roughly 3 m above the bank were established along 4 km of the waterway's main reaches.

Table 7. Effects of conservation cropping practices on water balance, SWAT-predicted Pike River watershed outlet sediment and P exports according to a rising percent of implementation and to random (R) *vs.* spatially targeted (T) implementation

		Scenarios result by type and application rate																				
		Timely manure incorp.	Perennial cover crop CC_{per}					Intercropping IC_{sg+rc}					Late season cover crop $CC_{sg\rightarrow cr}$					Conservation tillage NT, RT_s, RT_f				
	REF.	100%	100%	10%T	50%T	10%R	50%R	100%	10%T	50%T	10%R	50%R	100%	10%T	50%T	10%R	50%R	100%	10%T	50%T	10%R	50%R
Evapotranspiration (mm)	566	575	575	567	570	567	571	567	566	567	566	567	567	566	567	566	567	561	566	565	567	564
Runoff (mm)	218	218	191	215	204	215	204	204	217	211	217	211	202	216	210	216	210	208	217	213	217	213
Water yield (mm)	476	476	469	476	473	476	472	476	476	476	476	476	476	476	476	476	476	481	477	478	477	479
Total P exports (t)	47.0	44.9	17.4	35.6	22.4	43.6	32.7	15.0	35.5	20.7	43.3	31.1	21.1	37.2	25.0	43.9	34.2	31.7	42.4	35.2	45.2	39.3
Soluble P (%)	25%	25%	73%	33%	55%	27%	37%	59%	32%	48%	26%	33%	50%	31%	44%	26%	32%	30%	27%	30%	25%	27%
Sediment yield (t)	31300	31300	4400	21500	10000	28400	18600	5900	21800	10600	28500	19000	10000	23000	13000	28900	21000	17400	26300	20300	29700	24500
Total P reduction (%)		3%	63%	24%	52%	7%	30%	68%	24%	56%	8%	34%	55%	21%	47%	6%	27%	32%	10%	25%	4%	16%
Sed. yield reduction (%)		0%	86%	31%	68%	9%	40%	81%	30%	66%	9%	39%	68%	27%	57%	8%	33%	44%	16%	35%	5%	22%

Table 8. Effects of conservation runoff control structures on SWAT-predicted Pike River watershed outlet sediment and P exports according to a rising percent of implementation and to random (R) vs. spatially targeted (T) implementation

		Scenarios result by type and application rate									
		Buffer strip					Runoff control structure				
	REF	100%	10%T	50%T	10%R	50%R	100%	10%T	50%T	10%R	50%R
Total P export (t)	47.0	43.0	45.1	43.9	45.8	44.8	40.6	44.3	42.1	45.6	43.8
Sediment yield (t)	31300	27800	29600	28600	30300	29400	25600	29000	27100	30100	28500
Total P red. (%)		7%	2%	5%	1%	3%	12%	4%	9%	1%	5%
Sed. yield red. (%)		9%	3%	6%	1%	4%	16%	5%	11%	1%	7%

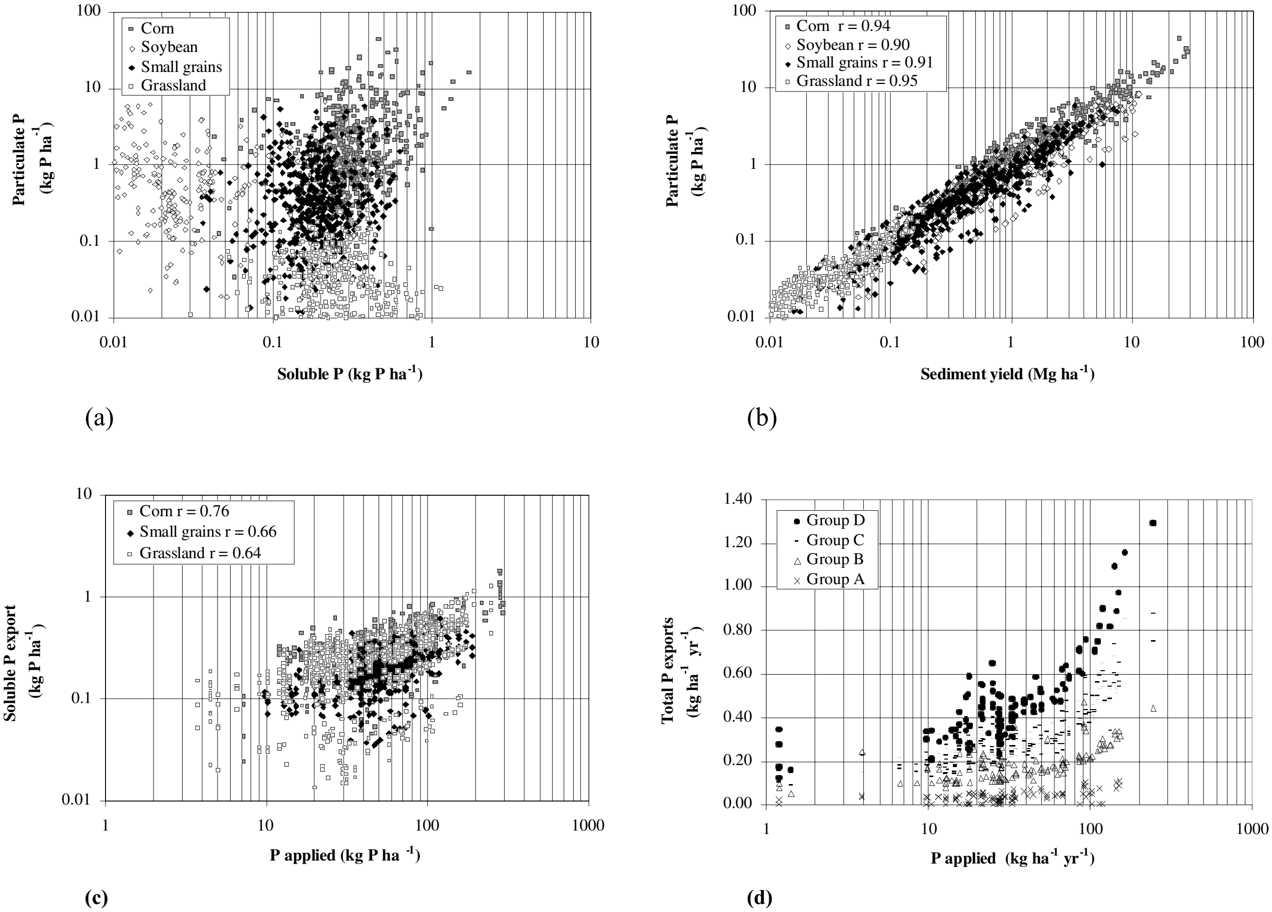

Fig. 3. HRU scale SWAT predictions for the 2000–2003 period: (a) Mean annual soluble vs. particulate P loadings, (b) mean annual particulate P loadings vs. sediment yield, (c) mean annual soluble P loadings vs. annual P applied and (d) mean total P loadings vs. P applied on grassland by hydrologic groups.

Basic Agri-environmental Scenarios

The effects of mixed BMP scenarios on the hydrological balance, erosion and P mobility are shown in Table 9. Converting annual cropped lands prone to periodic flooding with permanent prairie, without farm manure imports, results in a 0.7% simulated drop in total P exports at the watershed's outlet. This very conservative estimate is based solely on the substitution of flood plain management practices on 290 ha or 0.5% of the watershed's area and ignores water depths attributable to hydrological backflow, not modelled in the present study. Overall, the conversion of flood plains to prairie, combined with the optimisation of delays in manure incorporation, and the installation of buffer strips and runoff control structures, would translate into a 21.4% drop in simulated P exports at the Pike River watershed's outlet.

Scenarios Involving Changes in Agricultural Practices

Agri-environmental scenarios 9 to 16 (Table 9) indicate the influence of implementing conservation practices randomly or in a targeted manner over various portions of agricultural lands. For example, the adoption of conservation tillage on all HRUs cropped to corn or soybean, combined with intercropping of leguminous forages and small grains within the watershed, would result in a 35% predicted drop in P loads from the watershed's cropped lands. Combining the contributions of flood plain protection, optimized manuring and buffer stripping, sediment and P exports would be predicted to drop by 53 and 40%, respectively.

The effects of a progressive and targeted implementation of different conservation agricultural practices on overall watershed-wide erosion rates and P mobility are shown in Fig. 5. Spatial clustering in cultivated parcels susceptible to erosion processes and P mobilisation are such that the marginal effectiveness of BMPs declines as they are applied to a greater area of annual cropping lands. While implementing BMPs on the half most vulnerable cropped lands brings a 52% P reduction, implementing BMPs on the remainder of the cropped land presents marginal benefits, bringing the reduction to only 61%. A comparison of the curves on Fig. 5 bears witness to the implementation of cover crops or intercrops' greater potential to diminish non-point source P

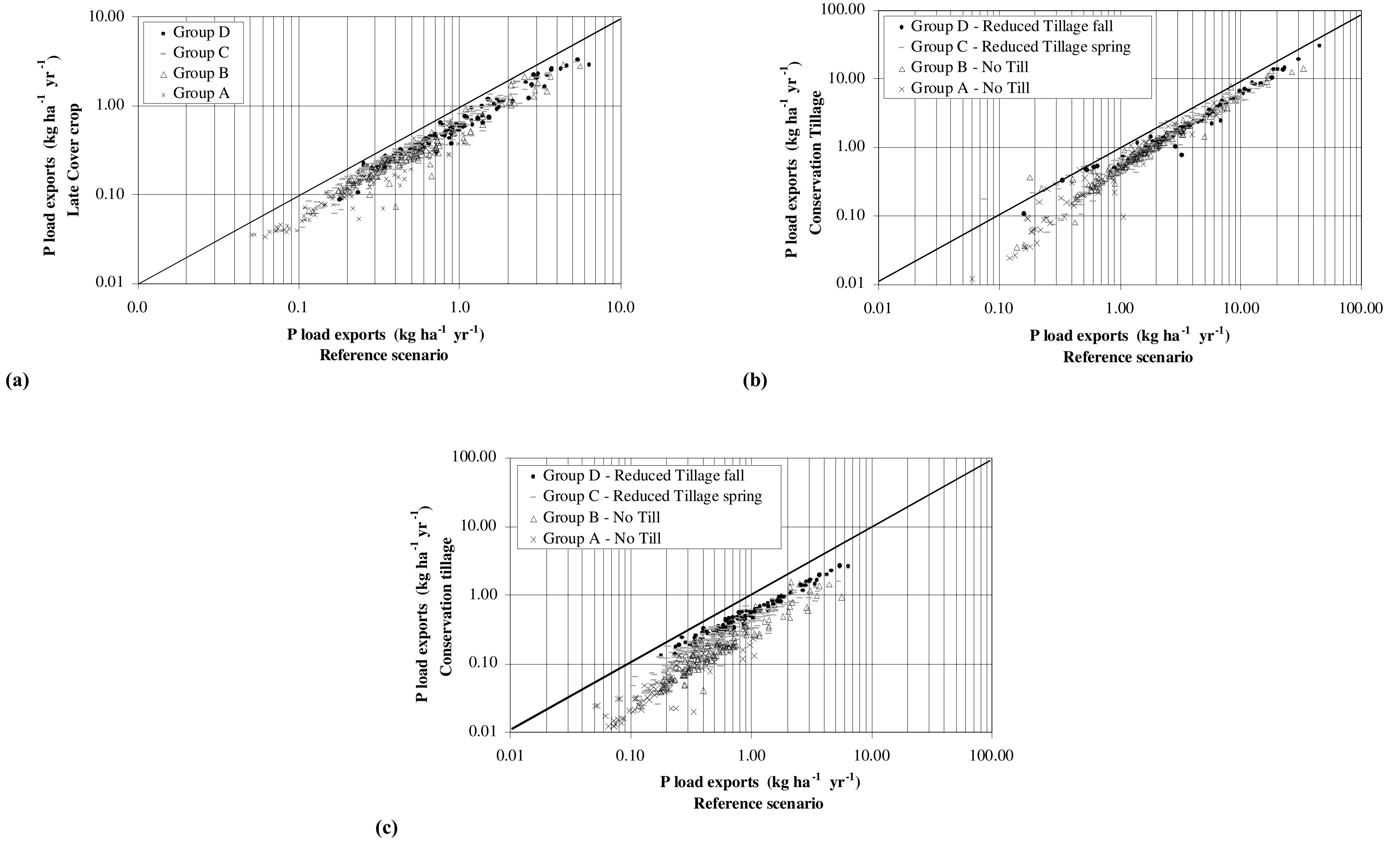

Fig. 4. Effect of different conservation practices on P loads exports: (a) late cover crop on small grains (b) no till and reduced tillage on corn and (c) no till and reduced tillage on small grains.

Table 9. Predicted sediment, soluble and total P exports at the Pike River watershed's outlet associated with the implementation of agri-environmental scenarios, and percent reduction with respect to the reference scenario

No. Scenario	Late season cover crop	Conservation tillage or Intercroping	Timely manure incorp.	Perennial cover crop	Buffer strip	Runoff control structure	Runoff		Sediments		Total P		Soluble P	
							mm	% reduction[z]	t	% reduction	t	% reduction	t	% reduction
Reference scenario							181		30 500		46.1		11.7	
Derivatives of the reference scenario														
1				FP			181	0%	30 200	1%	45.8	1%	11.8	0%
2			ALL				182	0%	30 500	0%	44.9	3%	11.2	4%
3					ALL		181	0%	27 800	9%	43.0	7%	11.7	0%
4						ALL	181	0%	25 600	16%	40.6	12%	11.7	0%
5			ALL	FP			182	0%	30 200	1%	44.6	3%	11.3	4%
6					ALL	ALL	181	0%	22 900	25%	37.5	19%	11.7	0%
7			ALL	FP	ALL		182	0%	27 400	10%	41.6	10%	11.3	4%
8			ALL	FP	ALL	ALL	182	0%	22 500	26%	36.3	21%	11.3	4%
Scenarios involving a shift to conservation agricultural practices														
9		ALL					171	6%	16 100	47%	30.1	35%	9.2	22%
10		ALL	ALL	FP	ALL		171	6%	14 300	53%	27.9	40%	9.2	21%
11		T 10%	ALL	FP	ALL		180	0%	22 900	25%	37.6	19%	11.1	5%
12		T 10%	ALL	FP	ALL	ALL	180	0%	18 900	38%	32.9	29%	11.1	5%
13		R 50%	ALL	FP	ALL		176	3%	21 000	31%	34.8	25%	10.3	12%
14		R 50%	ALL	FP	ALL	ALL	176	3%	17 300	43%	30.5	34%	10.3	12%
15		T 50%	ALL	FP	ALL		176	3%	17 200	44%	31.4	32%	10.4	12%
16		T 50%	ALL	FP	ALL	ALL	180	1%	14 200	53%	27.7	40%	11.3	4%
Scenarios with shifts in crops														
17	T 10%						180	1%	22 200	27%	36.3	21%	11.6	1%
18	T 10%		ALL	FP	ALL		180	1%	19 900	35%	32.9	29%	11.2	5%
19	T 10%	R 45%	ALL	FP	ALL		175	4%	15 600	49%	28.0	39%	10.3	12%
20	T 10%	T 45%	ALL	FP	ALL		176	3%	14 300	53%	26.7	42%	10.4	11%
21	T 10%	R 45%	ALL	FP	ALL	T 10%	175	4%	15 000	51%	27.2	41%	10.3	12%
22	T 10%	R 45%	ALL	FP	ALL	ALL	175	4%	12 900	58%	24.9	46%	10.3	12%
23	T 50%		ALL	FP	ALL		173	4%	11 200	63%	22.4	51%	10.9	7%
24	T 50%	+ 50%	ALL	FP	ALL		168	8%	8 300	73%	18.9	59%	9.7	17%
25	T 50%	+ 50%	ALL	FP	ALL	ALL	168	8%	6 800	78%	17.3	63%	9.7	17%

% reduction with respect to the reference scenario; T = targeted implementation of the BMPs on a certain percentage of annual cropped lands; R = random implementation of the BMPs on a certain percentage of annual cropped lands; FP = flood plains; ALL = BMP applied to all cultivated lands; + 50% indicates that the BMPs are applied to the remaining 50% of cultivated lands in the watershed.

exports than conservation tillage. As previously stated, the effectiveness of cover crops to reduce P losses is not only tied to their capacity to limit soil erosion, but also to the advantages the practice presents in terms of farm manure incorporation.

Crop Shift Scenarios

Model predictions of the effect of the conversion of the watershed's most vulnerable annual cropped lands to cover crops is reported in Table 9, scenarios 17 to 25. Given that within the hydrological model, cover crops are highly efficient in reducing P exports, a targeted shift of 10% of the most vulnerable annual cropping lands to cover crops would result in a 21% predicted drop in non-point P exports (scenario 17). This, combined with the shift to conservation cultural practices of an additional 45% of annual cropped lands (scenarios 19 to 22), meets the objectives of the Québec-Vermont agreement. In this regard, scenario 21 appears most compatible with the objective of a 41% decrease in P inputs to the Missisquoi Bay. A spatially random distribution of conservation cropping practices represents the voluntary response of agribusiness owners, whereas the shift of 10% of vulnerable lands to late-season cover crops as well as the implementation of runoff control structures on critical cropped lowlands (2500 ha) are better suited to targeted interventions, supported by an incentive programme.

To date, very few studies exist where the costs and benefits of implementing complex sets of BMPs at the watershed scale (as presented here) have been comprehensively analysed. Snapp et al. (2005) have recently reviewed the costs, benefits and performance of cover crops used in four cropping system niches. In 2003, Gitau published a quantitative assessment of BMP effectiveness for phosphorus pollution control in a New York state watershed. A wide set of BMPs, from animal waste storage, filter strips to full nutrient management plans, was analysed for optimal environmental benefits and costs of implementation. A full costs and benefit analysis of the various scenarios discussed here goes beyond the scope of the current work. However, with the agreement between the governments of the province of Québec and the State of Vermont to reduce by 41% the P loads reaching the bay by 2009, the scenarios proposed here will likely undergo further evaluation and a full analysis of costs and benefits is planned in the near future.

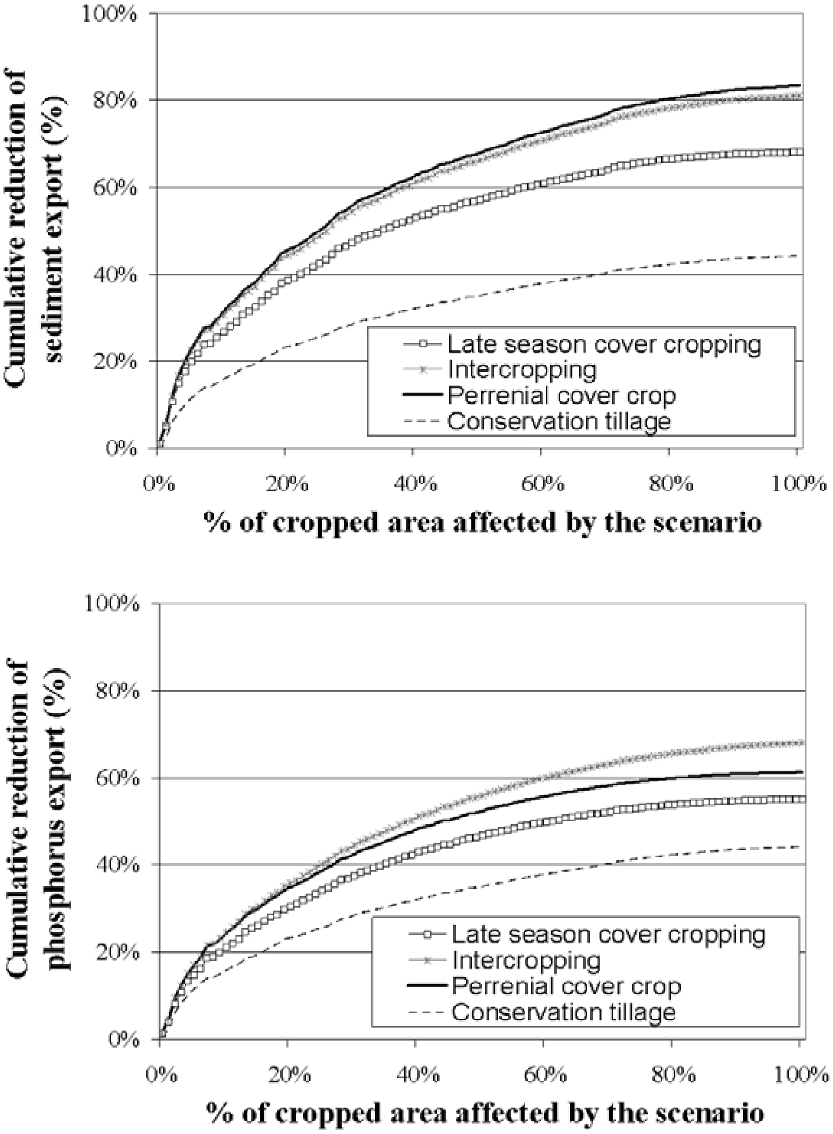

Fig. 5. Reduction in sediments (a) and phosphorus (b) associated with a progressive and targeted implementation of different conservation agricultural practices on overall watershed-wide.

CONCLUSIONS

From an operations perspective, the foremost finding of the current study is the feasibility of attaining the objective of reducing P loads entering the Missisquoi Bay by 41%, as agreed upon in the Québec-Vermont agreement to develop and enhance the bay. Notwithstanding the uncertainties associated with hydrological modelling, the simulation of the different agri-environmental scenarios brings to the fore the fact that reaching these objectives represents an agri-environmental endeavour of great scope, including, in particular, the implementation of conservation cropping practices over half the annual cropped lands, and the shift of the 10% most vulnerable of these lands to cover crops or perennial prairie. Attaining P target loads would call for investments in the systematic protection of flood plains and buffer strips, the targeted implementation of runoff control structures, and the rapid soil incorporation of farm manure on annual cropped lands.

The modelling of different agri-environmental scenarios highlights the importance of spatial targeting when implementing BMPs. Overall, the modelling results call to attention that a targeted implementation of BMPs on the most vulnerable of annual cropping land, can result in environmental gains fourfold greater than a random implementation over an equivalent area. With respect to the different BMPs' efficacy, the model attributes the greatest decreases in P exports to cover crops, followed by conservation tillage practices, and runoff control structures. The large capacity to decrease non-point source P exports attributed to cover crops by SWAT (74% on average on annual cropped HRUs) is tied to a combination of their ability to limit erosion and to a field management protocol, which allows for rapid soil incorporation of farm manures. Different conservation tillage practices also substantially reduce predicted P exports (46% on average on annual cropped HRUs). However, given the influence of soil properties on runoff depths and accumulation of nutrients in the layer of topsoil that interacts with surface runoff, the relative effectiveness of these cultural practices shows a greater variability than that of cover crops. With respect to agricultural water conservation practices, it should be pointed out that the efficacy of trapping of sediments and P employed in modelling (25%) reflect a particular set of interventions, combining in-ditch catch-basin inlets and shrubby buffer strips, whose efficacy was documented on an experimental watershed. One finding derived from the relative efficacy of the different BMPs modelled is the priority that should be given to the implementation of field-level cultural practices as a first line of agri-environmental defence, with runoff control structures providing a complementary role in reducing exported flows.

With respect to strategic planning of targeted water quality interventions, the structure of the GIS database developed in combination with SWAT's predictive capabilities constitutes a tool of choice in agricultural extension support and of the agricultural community's different stakeholders in the planning and concerted implementation of realistic plans of action likely to meet the majority of the population's expectations.

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Abdallahi, M. M. and N'Dayegamiye, A. 2000. Effets de deux incorporations d'engrais verts sur le rendement et la nutrition en azote du blé (*Triticum aestivum* L.), ainsi que sur les propriétés physiques et biologiques du sol. Can. J. Soil Sci. **80**: 81–89.

Angers, D. A., Bolinder, M. A., Carter, M. R., Gregorich, E. G., Voroney, R. P., Drury, C. F., Liang, B. C., Simard, R. R., Donald, R. G., Beayert, R. et Martel, J. 1997. Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada. Soil Tillage Res. **41**: 191–201.

Arnold, J. G., Srinivasan, R., Muttiah, R. S. and Williams, J. R. 1998. Large area hydrologic modeling and assessment part I: model development. J. Am. Water Res. Assoc. **34**: 73–89.

Centre d'expertise hydrique du Québec. 2005. Cartographie des zones inondables en eau libre, Région hydrographique 03 – Saint-Laurent sud-ouest, Cartes 1 :10 000 numéro 31H03-100-5101, Ministère du développement durable, Environnement et Parcs. [Online] Available: http://www.cehq.gouv.qc.ca/zones-inond/cartographie/ [2004 Jan. 01].

Côté, D., Bernard, C. and Angers, D. A. 1994. Effects of perennial forage species intercropped with silage corn on soil quality in eastern Quebec, International Soil Tillage Research Organization, Proc. of 13th Int. Conf. **1**: 147–152.

Deslandes, J., Michaud, A. R. and Bonn, F. 2004. Use of GIS and remote sensing to develop indicators of phosphorus non-point source pollution in the Pike River basin. Pages 271–290 *in* T. O. Manley, P. L. Manley, and T. B, Mihuc, eds. Lake Champlain: Partnerships and research in the new millennium. Kluwer Academic/Plenum Publishers, New York, NY.

Deslandes, J., Beaudin, I., Michaud, A., Bonn, F. and Madramootoo, C. A. 2007. Influence of landscape and cropping system on phosphorus mobility within the Pike River Watershed of southwestern Québec. Can. Water Res. J. **32**: 21–42.

Dabney, S. M., Raper, R. L., Meyer, L. D. and Murphree, C. E. 2000. Management and subsurface effects on runoff and sediment yield from small watersheds. Int. J. Sed. Res. **15**: 217–232.

Daniel, T. C., Sharpley, A. N., Edwards, D. R., Wedepohl, R. and Lemunyon, J. L. 1994. Minimizing surface water eutrophication from agriculture by phosphorus management. J. Soil Water Cons. **49** (Suppl.): 30–38.

Duchemin, M. et Majdoub, R. 2004. Les bandes végétales filtrantes : de la parcelle au bassin versant. Vecteur Environnement **37**: 36–50.

Duguet, F., Michaud, A. R., Deslandes, J., Rivest, R. and Lauzier, R. 2002. Gestion du ruissellement et de l'érosion pour limiter les pertes en phosphore en bassin versant agricole. Agrosol **13**: 140–148.

Edwards, C. L., Shannon, R. D. and Jarrett, A. R. 1999. Sedimentation basin retention efficiencies for sediment, nitrogen and phosphorus from simulated agricultural runoff, Trans. ASAE **42**: 403–409.

Engman, E. T. 1983. Roughness coefficients for routing surface runoff. Proc. Spec. Conf. Frontiers of Hydraulic Eng.

Franti, T. G., Laflen, J. M. and Watson, D. A. 1999. Predicting soil detachment from high-discharge concentrated flow, Trans. ASAE, Am. Soc. Agric. Eng. **42**: 329–335.

Gburek, W. J., Sharpley, A. N. and Folmar, G. J. 2000. Critical areas of phosphorus export from agricultural watersheds. *In* A. N. Sharpley, ed., Agriculture and phosphorus management: the Chesapeake bay. Lewis Publishers, Boca Raton, FL.

Gitau, M. W. 2003. A quantitative assessment of BMP effectiveness for phosphorus pollution control: The Town Brook Watershed, NY. Ph.D. thesis, the Pennsylvania State University, PA. 247 pp.

Governments of the Province of Québec and State of Vermont. 2002. Agreement concerning the phosphorus reduction in Missisquoi Bay, 5 p. [Online] Available: http://www.lcbp.org/PDFs/missbay_agreeEN.pdf [2005 Aug. 01].

Harvey, J.-M. 2005. Le semis direct, l'unique operation de travail du sol. Colloque en agroenvironnement. Des outils d'intervention à notre échelle. 24 février 2005, Drummundville, QC.

Hegman, W., Wang, D. and Borer, C. 1999. Estimation of Lake Champlain basinwide nonpoint source phosphorus export. Technical Report No. 31. Lake Champlain Basin Program. Grand Isle, VT, 69 p.

Holvoet, K., van Griensven, A., Seuntjens, P. and Vanrolleghem, P. A. 2005. Sensitivity analysis for hydrology and pesticide supply towards the river in SWAT. Physics Chem. Earth **30**: 518–526.

Institut de la statistique du Québec. 2002. Superficie des grandes cultures, rendement à l'hectare et production, par région administrative, Statistique Canada, [Online] Available: http://www.stat.gouv.qc.ca/donstat/econm_finnc/filr_bioal/culture/culture/am110002.htm [2005 Jan. 01].

Jarrett, A. R. 2001. Designing sedimentation basins for better sediment capture. Pages 63–66 *in* J. C. Ascough II and D. C. Flanagan, eds. Soil erosion res. for the 21st century. Proc. Int. Symp., Honolulu, HI.

Kleinman, P. J. A., Salon, P., Sharpley, A. N. and Saporito, L. S. 2005. Effect of cover crops established at time of corn planting on phosphorus runoff from soils before and after dairy manure application. J. Soil Water Cons. **60**: 311–22.

Kronvang, B., Laubel, A. and Grant, R. 1997. Suspended sediment and particulate phosphorus transport and delivery pathways in an arable catchment, Gelbaek stream, Denmark, Hydrol. Proces. **11**: 627–642.

Lawrence, R., Dabney, S. and Schultz, R. 2002. Improving water and soil quality with conservation buffers, J. Soil Water Cons. **57**: 37A–43A.

Lenhart, T., Eckhardt, K., Fohrer, N. and Frede, H.-G. 2002. Comparison of two different approaches of sensitivity analysis. Physics Chem. Earth **27**: 645–654.

McDowell, L. L. and McGregor, K. C. 1984. Plant nutrient losses in runoff from conservation tillage corn. Soil Tillage Res. **4**: 79–91.

McGregor, K. C., Cullum, R. F. and Mutchler, C. K. 1999. Long-term management effects on runoff, erosion, and crop production, Trans. ASAE **42**: 99–105.

Meyer, L. D., Dabney, S., Murphree, C. E. and Harmon, W. C. 1999. Crop production systems to control erosion and reduce runoff from upland silty soils. Trans. ASAE **42**: 1645–1652.

Michaud, A. R., Lauzier, R. and Laverdière, M. R. 2004. Temporal and spatial variability in nonpoint source phosphorus in relation to agricultural production and terrestrial indicators : the Beaver brook case study. Pages 97–121 *in* T. O. Manley, P. L. Manley, and T. B. Mihuc, eds. Lake Champlain: Partnerships and research in the new millennium. Kluwer Academic/Plenum Publishers, New York, NY.

Michaud, A. R. and Laverdière, M. R. 2004. Cropping, soil type and manure application effects on phosporus export and bioavailability. Can. J. soil Sci. **84**: 284–295.

Michaud, A. R., Lauzier, R. and Laverdière, M. R. 2005. Mobilité du phosphore et intervention agroenvironnementale en bassin versant agricole : Étude de cas du Ruisseau au Castor, tributaire de la Rivière aux Brochets, Québec. Agrosol **16**: 47–59.

Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec. 2001. Fiche d'enregistrement des exploitations agricoles. Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec, QC.

N'Dayegamiye, A. and Sen Tran, T. 2001. Effects of green manures on soil organic matter and wheat yields and N nutrition. Can. J. Soil Sci. **81**: 371–382.

N'Dayegamiye, A. and Sen Tran, T. 2000. Effets de deux incorporations d'engrais verts sur le rendement et la nutrition en azote du blé (*Triticum aestivum* L.), ainsi que sur les propriétés physiques et biologiques du sol. Can. J. Soil Sci. **80**: 81–89.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R. William, J. R. and King, K. W. 2002. Soil and water assessment tool. Theoretical Documentation, Grassland, Soil and Water Res. Lab., Agric. Res. Serv., TX. 458 pp.

Ordre des agronomes du Québec. 2007. Ligne directrice de l'Ordre des agronomes du Québec (OAQ) sur la gestion des matières organiques. version 2006–2007. OAQ, Québec, QC. 13 pp.

SCS Engineering Division. 1986. Urban hydrology for small watersheds. US Department of Agriculture, Technical Release 55.

Sharpley, A. N., Daniel, T. C. and Edwards, D. R. 1994. Phosphorus movement in the landscape. J. Prod. Agric. **6**: 492–500.

Sharpley, A. N. and Halvorson, A. D. 1994. Management of soil phosphorus. Pages 7–91 *in* R. Lal and B. A. Stewart, eds. Soil processes and water quality. Lewis Publ., CRC Press, Boca Raton, FL.

Snapp, S. S., Swinton, S. M., Labarta, R., Mutch, D., Black, J. R., Leep, R., Nyiraneza, J. and O'Neil, K. 2005. Evaluating cover crops for benefits, costs and performance within cropping system niches. Agron. J. **97**: 322–332.

Ulen, B. and Persson, K. 2003. Field-scale phosphorus losses from a drained clay soil in Sweden. Hydrol. Proc. **13**: 2801–2812.

Walker, W. 1998. Flux, stream loads computations. Version 5.0. Environmental Laboratory, US Army Engineers, Waterways Experiment Station. Vicksburg, MS.

Young R. A. and Mutchler, C. K. 1976. Pollution potential of manure spread on frozen ground. J. Environ. Qual. **5**: 174–1979.

Zollweg, J. A. 1996. Field study to support hydrologic Management. Pages 129–134 *in* Proc. of watershed restoration management – physical, chemical, and biological considerations. Am. Water Res. Assoc., Middleburg, VA.