LANDSCAPE AND MANAGEMENT OF AGRI-ECOSYSTEM: IMPACT ON PHOSPHORUS TRANSFER

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Abstract

Reduction of non-point source phosphorus (P) related to agricultural land use has been identified as a priority for Lake Champlain, a 1124 km^2 surface area water body shared by Canada and United States. Objectives of a co-operative research effort initiated in 1997 within the Beaver experimental watershed (11 km^2) tributary to the lake were: 1) to describe the non-point source P transfer to the aquatic ecosystem through landscape and agricultural production systems descriptors and 2) to evaluate the effectiveness of surface runoff management on P transfer. Over the first three year period of study, mean annual exports of dissolved reactive soluble (DRP), bioavailable (BioP) and total phosphorus (TP) from the watershed were 0.57, 0.93 and 1.54 kg ha^{-1} P respectively which were episodic in nature: 75% of total P exports occurred within 6% of the monitoring period corresponding to peak stream flow events and under late-winter/early-spring conditions. Monitoring data also suggest that subsurface flow inputs of P to the main channel as well as in-stream storage and release of highly bioavailable particulate P were important mechanisms of P transfer. Statistical analysis of water quality data using stream flow as a covariate highlighted a landscape-driven hydrologic control on the spatial pattern of P transfer, despite an opposing gradient in terrestrial soil P enrichment. Management of manure P sources influenced P transfer amongst sub-watersheds with comparable levels of hydrological activity. Yearly trend in P concentrations at the downstream stations also indicated an improvement in water quality in response to the establishment of riparian buffers and catch basins along the stream main stem.

Additional Keywords: eutrophication, phosphorus, watershed, non-point source pollution, management practices, runoff control.

Introduction

Over 79% of the yearly P load (143 Mg yr^{-1} P) received by the Missisquoi Bay (northern portion of the Lake Champlain in Canada) has been attributed to agricultural land use, which accounts for 26% of the total watershed area (Hegman *et al.* 1999). P in surface runoff has often been linked to soil test P, but this approach is limited and should be used in conjunction with an estimate of the site's potential for runoff and soil erosion (Wolf *et al.* 2000).

Surface runoff is generally considered as the primary hydrological pathway for P flux and given the distribution of precipitation intensities saturation-excess runoff is typical. Consequently, the occurrence of overland flow is generally controlled by cumulative rainfall and snowmelt events rather than by rainfall intensity (Lapp 1996). Saturation-excess runoff is function of landscape, rises in water table and stream level, impermeable subsoils, slope breaks and convergent subsurface flows and these processes reveal hydrologically active variable-source areas (VSA) (Beven and Wood 1983). Subsurface through flow by preferential (macropore) and tile drain flow has also been identified as a significant pathway for P fluxes. Subsurface P exports are of particular concern where manures are applied to drained cracking-clay soils (Beauchemin *et al.* 1998).

Though effective control of P flux relies on management of both source and transport factors, limited number of studies have described how these factors interact at a watershed scale. The objectives of this research are thus to: (i) document the mechanisms of P transfer in the watershed, (ii) link P sources and transport mechanisms to the spatial variability of P exports in order to support farm and watershed-scale planning and management of non-point P.

Materials and Methods

Study area description and terrestrial measurements

The Beaver Brook drains into the Pike River, a major tributary of Lake Champlain's Missisquoi Bay (Figure 1c). Its 6.4 km main channel drains an 11 km^2 watershed devoted to agriculture on 88% of its area which is partially tile drained. The watershed is subject to warm spring and summer growing periods and cold winters. Long-term mean annual precipitation is about 1057 mm. The western-most portion of the watershed is flat while its eastern portion consists of rolling hills. Elevation rises from about 30 m at the outlet to about 60 m above MSL in the eastern uplands (Figure 2a). Dominant soils (Typic Humaquepts) were developed on poorly-drained lacustrine and marine clays in the western portion and lined the main stream channel, and on glacial calcareous tills at higher elevations.

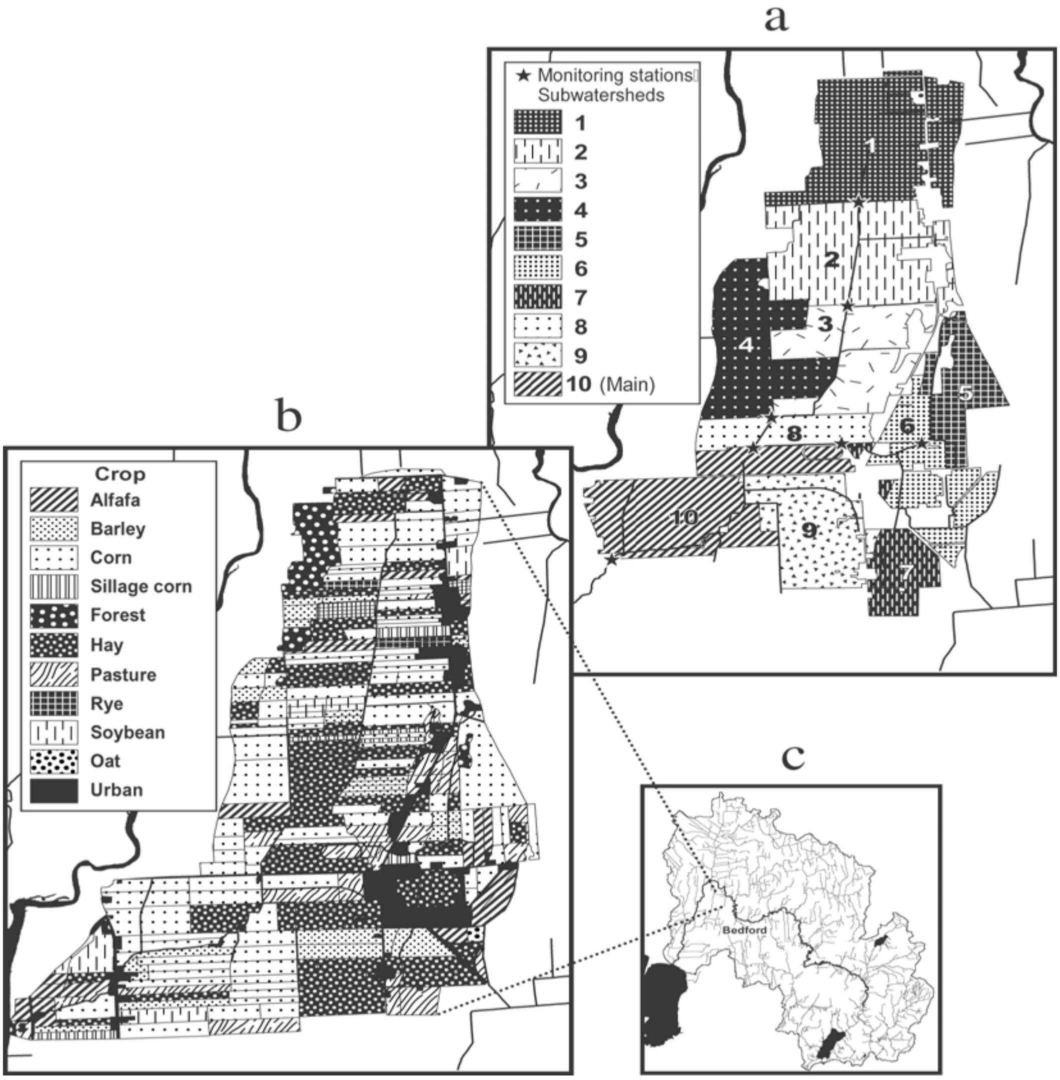

Figure 1. Beaver Brook (a) sub-watersheds and monitoring stations, (b) crop distribution for year 1999 and (c) location within Pike River watershed.

Dairy farming and cash crops are the dominant productions on the 24 farms within the watershed along with some hog and poultry operations. Small grains, corn (*Zea mays* L.), hay and soybeans (*Glycine max* Merr.) are cultivated in rotation. Most fields are long and narrow; land use and cropping patterns for the 1999 growing-season are presented in Figure 1b. Fields in the watershed were aggregated into 267 soil management units (SMU) based on physical boundaries or homogeneity of management. Information relative to mineral fertilizers and manures applications for each SMU for the 1998 and 1999 growing seasons, were obtained from farm owners and coupled with regional crop P uptake (Beaudet 2002) to generate annual P mass balance surpluses or deficits. All available data for each SMU were entered into a GIS database (MAPINFO 1996).

From spring 2000, shrubs an herbaceous riparian buffer strips were implemented along stream main stem. Catch inlets were systematically installed on lateral ditches connecting fields that were not tile drained to stream main stem (Figure 2a). Nutrient management plans were also put in place on all farms of the watershed.

Soils from all SMUs were sampled and tested for Mehlich-3 soil P levels (Mehlich 1984). Phosphorus saturation levels were calculated for each SMU based on the Mehlich-3 P/Al ratio used as a P desorption indicator (Giroux and Tran 1996). Soil loss was estimated according to the Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.* 1993). Runoff coefficients were calculated from the curve number (CN) method adapted for Quebec conditions (Monfet *et al.* 1979). Hydrologic group and soil erodibility index of each SMU were based on cropping, tillage practices, subsurface drainage conditions, recent soil survey data (Grenon *et al.* 1999) and observations from runoff plot studies carried on some benchmark soils from the watershed (Michaud and Laverdiere 2004). These parameters, along with slope length and gradients (LS) and estimates of the RUSLE crop management factor (C) were entered into the GIS database for each SMU/crop-year combination.

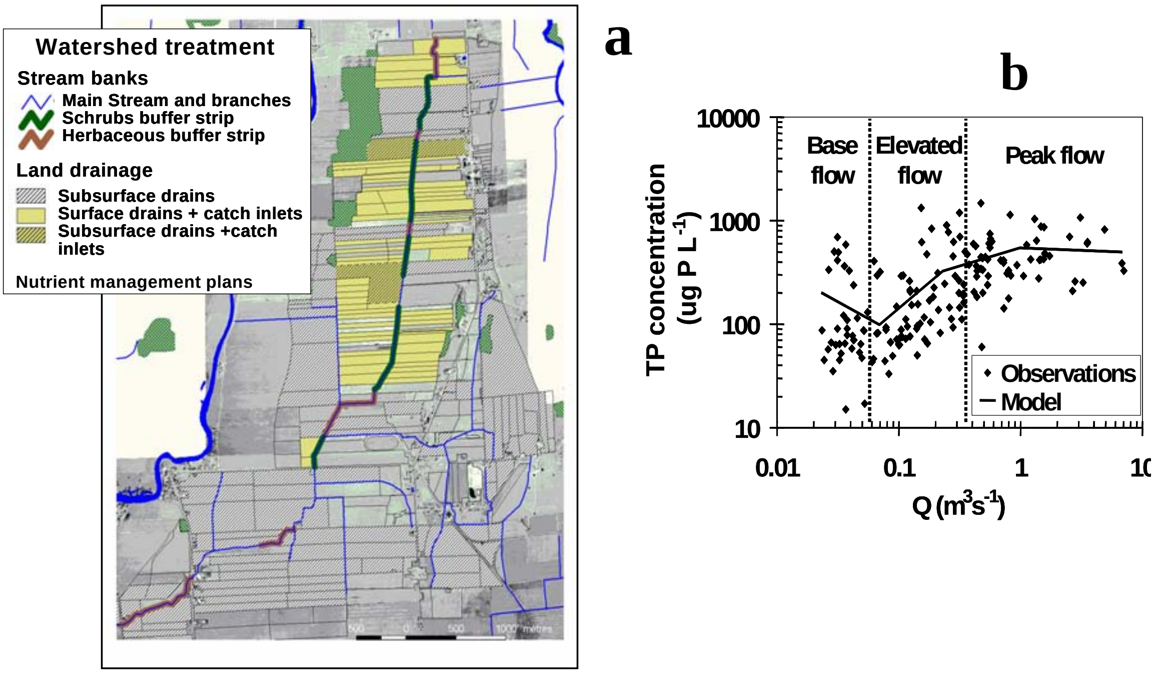

Figure 2. (a) Structural runoff management and riparian buffers on Beaver brook watershed and (b) total P concentration in relation with stream flow rate at downstream monitoring station (no. 10).

Hydrologic and water quality monitoring

The watershed was divided into 10 sub-watersheds, flow and water quality from each one was monitored (Figure 1a). The Main Station (№ 10), located at the outlet, provided a continuous record of flow from a V-notch flume equipped with a bubbler type stage recorder. Stream monitoring also included 9 upstream Sampling Stations comprising sub-watersheds № 1-9, each equipped with a lymnimetric scale and passive peak water level gauge.

169 grab samples were collected at the Main Station over the first three years of study, using a protocol biased for elevated and peak flows. 38 sampling campaigns were carried out at the 9 other stations: 30 during periods of elevated and peak flow in late fall, winter and early spring and 8 during base flow. These samplings were complemented by field observations of overland runoff, subsurface drain activity and channel flow conditions. Water samples were kept at 4˚C until analysis. Total suspended solids (TSS) were determined by filtration through a 0.45 µm filter (Greenberg *et al.* 1992a) and dissolved reactive phosphorus (DRP) on filtered samples (<0.45 µm) using the molybdenum-blue method (Murphy and Riley 1962). Bioavailable phosphorus (BioP) was determined using the 0.1 N NaOH extraction (Sharpley *et al.* 1991). Total phosphorus (TP) concentration was measured using the persulphate digestion technique (Greenberg *et al.* 1992b).

Data analysis

Daily sediment fluxes and P export from the watershed (Main Station) were computed using the FLUX 5.0 software (Walker 1998). The four flow-strata regression was based on a log concentration/flow (log C/Q) relationship of the mean daily flow (Q) and water quality concentrations (C). Spatial and temporal variability and relationships among the sub-watersheds, cropping systems data, water quality and flow data (9 Sampling Stations) were analysed with SAS (SAS 2000), using the analyses of variance (ANOVA) and covariance (ANCOVA) procedures, using stream flow rate as covariate Water quality data were log-transformed prior to analysis.

Results and Discussion

Runoff and soil loss descriptors

Runoff coefficients computed for individual SMUs, ranged from a low of 58 for hay production on permeable soils with subsurface drainage, to a high value of 89 for row crop production on low permeability soils, without subsurface drainage. Longitudinal spatial topographic gradients, soil parent-material permeability and extent of subsurface drainage systems within the Beaver Brook watershed were responsible for contrasting runoff coefficients among sub-watersheds. Curve number estimates for upland sub-watersheds (№ 5, 6, 7) were lower than those from the lowland (№ 1, 4, 9) or of the main channel (№ 2, 3, 8) (Table 1).

Table 1. Selected agronomic and hydrologic descriptors of Castors brook sub-watersheds derived from individual soil management units (SMU) data weighed for surface area and averaged for 1998 and 1999 reference crop years.

Catchments		P budget						Hydrologic descriptors					
No.	Type [1]	Soil P [2] Satur. (%)	Manure Inputs (kg/ha)	Mineral Inputs (kg/ha)	Crop Uptake (kg/ha)	Balance (kg/ha)	Manured Land (%)	Elevation Min (m)	Elevation Range (m)	Sub. Drain (%)	Tilled Area (%)	Runoff CN	Soil Loss RUSLE (T ha-1)
1	M, T	7.9	11.1	14.0	18.4	6.7	20	42.0	6.7	50	77	83	2.9
2	M	8.2	11.8	15.5	18.5	8.8	18	40.6	16.4	58	82	82	2.6
3	M	8.5	10.6	15.5	17.6	8.5	20	38.1	18.9	49	74	82	2.6
4	T	7.7	11.5	17.8	16.5	12.8	19	38.2	5.1	40	69	84	2.6
5	T	19.4	10.5	14.7	17.3	7.8	15	52.1	13.4	84	69	68	3.2
6	T	16.0	9.4	11.6	15.8	5.3	18	46.1	19.3	67	51	71	2.1
7	T	18.3	44.9	4.8	15.0	34.7	41	44.6	8.6	83	83	72	1.2
8	M	10.2	13.6	14.3	16.9	11.1	21	38.0	9.9	53	68	80	2.4
9	T	11.0	25.8	3.5	13.6	15.8	24	37.1	15.9	43	48	81	1.9
10	M	10.2	12.8	14.8	16.8	10.7	18	35.0	30.4	55	68	80	2.3

(1) M: Main stem; T: Tributary
(2) Mehlich-3 extractible P/Al.
(3) Mineral + manure inputs - Crops uptake

Mean estimated annual soil loss (RUSLE) from individual watershed SMUs was 2.25 Mg ha^{-1} (Table 1). Maximum soil loss estimate for any single SMU was 14 Mg ha^{-1} in corn production on rolling terrain within sub-watershed № 5. Sub-watershed-scale estimates of soil loss, weighed for individual SMU surface areas (Table 1), were relatively homogeneous within watersheds, averaging 2.5 Mg ha^{-1}. Higher soil loss estimate for sub-watershed № 5 (3.2 Mg ha^{-1}) was related to steeper gradients among its SMUs.

Phosphorus budget

Soil surface P mass balance for the whole watershed (∑[mineral + manure inputs]- ∑[crop uptake]) indicated that manure and mineral P inputs exceeded crop uptake by 11.30 and 8.61 Mg P, respectively, for the 1998 and 1999 cropping seasons. Mineral fertilizer was the dominant P input with watershed area-weighted averages of 16.0 kg ha^{-1} P in 1998, down to 13.5 kg ha^{-1} P in 1999 whereas manure P inputs remained relatively constant with means of 13.1 and 12.5 kg ha^{-1} P for the same periods. Due to a wet fall in 1999, manured area was nearly half that of 1998. Area-weighted P surpluses from manure inputs, were consistently higher for sub-watershed № 7 in 1998 (37 kg ha^{-1} P) and 1999 (32 kg ha^{-1} P), than in any other one.

Distribution of soil P saturation values for the SMUs in the watershed indicates that 34% of its cropped area had reached the supra-optimal soil P saturation ratio value (Mehlich-3 P/Al) of 10% (Giroux and Tran 1996), while an additional 10% had a P saturation ratio above the critical agroenvironmental threshold of 20%. From a sub-watershed-scale perspective, area-weighted soil P saturation values indicate a spatial gradient in soil P enrichment in upland sub-watersheds № 5, 6 and 7 (Table 1). Higher P saturation ratio values in this portion of the watershed reflect elevated farm-scale P mass balances, limitations in land base available for manure applications and higher rates of manure P inputs.

Phosphorus concentrations and loading

Throughout the monitoring period, TP (Figure 2b) and TSS concentrations in the watershed were strongly dependent upon stream flow. Under FLUX modelling, following flow-stratification of data, all P fractions and TSS concentrations showed significant linear relationships with stream discharge ($P < 0.01$). Examination of the C/Q relationship at the outlet, coupled with field observations led to the identification of three stream flow regimes: base flow ($Q<0.06$ m^3 s^{-1}), elevated flow ($0.06<Q<0.35$ m^3 s^{-1}) and peak flow ($Q>0.35$ m^3 s^{-1}). The inverse C/Q relationship under the base flow regime (Figure 2b) is indicative of accumulation of P stock within the main channel of the watershed. Increases in stream discharge typically result from groundwater flow and promote the dilution of P concentrations in the water column. The resuspension of particulate P stocked within the hydrological network in response to active interflow (subsurface runoff) during the elevated flow regime, would explain the steep C/Q slope. Under peak flow conditions, P concentrations were at their maximum in response to overland runoff activity on significant portions of the landscape. Since most intense surface runoff events occurred in late winter and early spring under frozen soil conditions, a flat to negative C/Q slope suggests that the erosive potential of runoff was likely triggered by consolidation of soil aggregates.

According to FLUX modelling, mean annual DRP, BioP, TP and TSS loads were 0.57, 0.93, 1.54 and 820 kg ha^{-1} respectively. Over 75% of the TP load was concentrated into only 6% of the first three-year monitoring period. This flashy temporal distribution reflects the hydraulic efficiency of the watershed's surface and subsurface drainage system. From a mass balance perspective, annual TP loading accounted for 6% of total annual P inputs, implying that 85% of the mineral and manure P inputs applied in excess of crop uptake is stocked within the watershed. This 15% TP export/balance ratio for the Beaver Brook watershed is consistent with the 16% reported for the entire Pike River watershed, based on TP loading of 1.4 kg ha^{-1} P (Hegman *et al.* 1999).

Sampling stations on lateral branches and upstream reaches of the main channel (Figure 1a) enabled comparisons among sub-watersheds with distinctive management or physiographic properties: lowland (tributary sub-watersheds № 1, 4, 9) and upland conditions (tributary sub-watersheds № 5, 6, 7). Water quality data from the Spatial sampling Network indicated that hydrologic controls exerted a dominant influence over soil P levels in explaining spatial variability within the Beaver Brook data. ANOVA-adjusted means of TP concentrations for individual sub-watersheds and crop-year combinations (N=20) were found to be significantly correlated with sub-watershed area-weighted runoff coefficients (CN) for peak flow (r=0.68; P<0.01) as well as elevated flow conditions (r=0.61; P<0.01). Mobilisation of the relatively manure-rich topsoil in sub-watersheds № 7 and 9 also explained spatial pattern of P transfer amongst sub-watersheds with comparable levels of hydrological activity.

Impacts of management practices implemented (buffer strips, catch basins, and nutrient management plans) on water quality within the Beaver Brook watershed were estimated from statistical analysis of data collected prior and after their implementation. Analysis of covariance (ANCOVA) using outlet stream flow rate as covariate showed a significant trend in TP concentration reduction which was attributed to annual differences in both weather and field management within the watershed (Figures 3a and 3b).

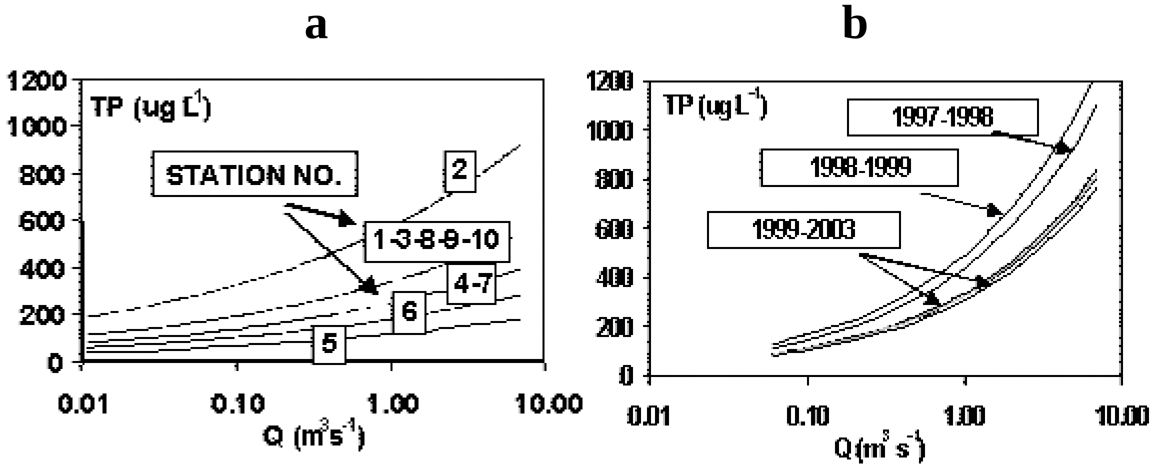

Figure 3. ANCOVA models for total P concentration monitored in Beaver Brook sub-watersheds under spatial sampling protocol in 1998-2000 (a) and 1997-2003 yearly variability at outlet gauging station (b) using stream flow rate as covariate.

Conclusions

Spatial discrete water sampling and continuous flow gauging allowed a description of temporal and spatial patterns in P exports from the Beaver Brook watershed. Most of the annual load in TP was associated with flashy peak flow events in late winter and early spring period, when saturation-excess overland runoff developed over extended field surfaces. C/Q relationships for downstream stations supported the identification of distinct flow regimes and proved to be useful in describing spatial variability of water quality descriptors among upstream sub-watersheds. Analyses of variance and covariance of water quality data provided contrasting spatial patterns among them. Flow-dependent water quality data and landscape descriptors indicated that contrasting terrestrial flow paths prevailed among sub-watersheds during peak stream flow regime.

Agroenvironmental indicators combining cropping systems and physical landscape attributes provided a coherent explanation of observed spatial patterns in P fractions and concentrations. Spatial patterns in sub-watershed P concentrations were best revealed by the surface runoff descriptor (CN) and sub-watershed elevation within landscape. If landscape hydrology was shown to exert a dominant influence on P exports, at the watershed scale, manure P management was also shown to influence P exports. The significant downward trend in stream outlet TP concentration suggests that structural runoff management, riparian buffers and nutrient management plans were effective in reducing P transfer to stream.

Planning and implementation of measures to prevent agricultural non-point P exports must be based on landscape hydrological activity and address to both nutrient and runoff management. Long term control of topsoil P enrichment remains of critical importance, particularly for lowland units subject to subsurface preferential P transfer and overland runoff

Acknowledgements

This work was sponsored by the Quebec Ministry of Agriculture Fisheries and Food. We acknowledge the collaboration of the Centre d'Expertise hydrique du Quebec, the 24 farm owners of the Beaver Brook watershed, the Cooperative de Solidarite de la Riviere-aux-Brochets and Pierre Audesse and his team from IRDA laboratory.

References

Beauchemin, S., Simard, R.R. and Cluis, D. (1998). Forms and concentration of phosphorus in drainage water of twenty-seven tile-drained soils. *Journal of Environmental Quality* 27, 721-728.

Beaudet, P. (2002). La fertilisation et la gestion du risque agroenvironnemental. In Colloque sur le phosphore : une gestion éclairee. Ordre des agronomes du Quebec (ed. Cd-rom) 20 p.

Bevin, K. and Wood, E.F. (1983). Sub-watershed geomorphology and the dynamics of runoff contributing areas. *Journal of Hydrology* 65, 139-158.

Giroux, M., Carrier, D. and Beaudet, P. (1996). Problematique et methode de gestion des charges de phosphore appliquees aux sols agricoles en provenance des engrais de ferme. *Agrosol* 9, 36-45.

Giroux, M. and Tran, T.S. (1996). Criteres agronomiques et environnementaux lies à la disponibilite, la solubilite et la saturation en phosphore des sols agricoles du Quebec. *Agrosol* 9, 51-57.

Greenberg, E.A., Clesceri, L.S. and Eaton, A.D. (1992a). Total Suspended Solids Dried at 103-105ºC. Standard method for examination of waste and wastewater, 18th ed., pp 2-56.

Greenberg, E.A., Clesceri, L.S. and Eaton, A.D. (1992b). Persulfate Digestion Method. Standard method for examination of waste and wastewater, 18th ed, pp. 4-112.

Grenon, L., Cossette, J. M., Deschenes, M. and Lamontagne, L. 1999. Etude pedologique du comte de Rouville, Quebec. Agriculture et Agroalimentaire Canada, Direction generale de la recherche, Centre de recherche et de developpement sur les sols et les grands cultures.

Hegman, W., Wang, D. and Borer, X.C. (1999). Estimation of Lake Champlain basin wide non-point source phosphorus export. Technical report № 31. Lake Champlain Basin Program publication series.

Lapp, P. (1996). The hydrology and water quality of an intensive agricultural watershed in Québec. M.Sc. Thesis. Department of Agricultural Engineering, McGill University, Montreal, Canada.

MAPINFO (1996). Mapinfo Corporation. Troy, NY.

Mehlich, A. (1984). Mehlich-3 soil extractant: A modification to Mehlich-2 extractant. *Communications in Soil Science and Plant Analysis* 15, 1049-1416.

Michaud, A. R. and Laverdiere, M.R. 2004. Effects of cropping, soil type and manure application on phosphorus export and bioavaibility. *Canadian Journal of Soil Science* (under review).

Monfet, J. (1979). Evaluation du coefficient de ruissellement à l'aide de la methode SCS modifiée. Service de l'hydrometrie, Ministere de l'Environnement du Quebec, Publication № HP-51, Quebec.

Murphy, J. and Riley, J.R. (1962). A modified single solution method for the determination of phosphates in surface waters. *Analytica Chimica Acta* 27, 31-36.

Renard, K.G., Foster, G.R., Weesies, G.A., McCooland, D.K. and Yoder, D.C. (1993). Predicting erosion by water: A guide to conservation planning with the revised universal soil loss equation (RUSLE). USDA-ARS agricultural Handbook.

Sharpley, A.N., Troeger, W.W. and Smith, S.J. (1991). The measurement of bioavailable phosphorus un agricultural runoff. *Journal of Environmental Quality* 20, 235-238.

Statistical analysis system. (2000). SAS 8.0 for Windows. SAS Institute Inc. Cary, NC.

Walker, W. (1998). Flux, Stream loads computations, version 5.0. Environmental laboratory USAE Waterways Experiment Station. Vichsburg, Mississippi, USA.

Wolf, A., Sharpley, A.N., Ressler, L., Esser, T. and Lanyon L. E. (2000). Concerns and recommendations of the workgroups. In Agriculture and phosphorus management: the Chesapeake bay, A.N. Sharpley, ed., Lewis Publishers, Boca Raton, Florida.