Influence of Landscape and Cropping System on Phosphorus Mobility within the Pike River Watershed of Southwestern Quebec: Model Parameterization and Validation

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Abstract: Hydrological performance, erosion processes and phosphorus mobility were modelled for the 630 km^2 Pike River watershed, an important Quebec tributary of Lake Champlain. Given the recurring issue of cyanobacterial blooms in Missisquoi Bay, intervening to reduce the influx of phosphorus to the bay became a priority and led to an agreement between the governments of the province of Quebec and the state of Vermont. The model's parameterization was supported by a characterization and spatial representation of agricultural landscapes and production systems according to a field-scale partitioning of cultivated lands into over 2,400 hydrological response units, 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 calibration and validation were based on data from four hydrometric stations as well as the monitoring of water quality at the outlet of two small (six to eight km^2) experimental watersheds of contrasting physical attributes. A differential setting of baseline values for the upstream and downstream portions of the watershed led to a better matching of hydrological model output to measured discharge on different branches of the Pike River, as well as a closer reproduction of sediment and phosphorus loads at the outlet of the two reference basins. On a watershed scale, the model-derived sediment and phosphorus loads showed a clear spatial pattern: under present soil and crop management methods, over 50% of modelled phosphorus loads originated over roughly 10% of the watershed's area. Typically, these areas showed high surface runoff depths, high erosion rates or significant phosphorus enrichment of the topsoil.

Résumé : Une modélisation du fonctionnement hydrologique, des processus d'érosion et de la mobilité du phosphore a été supportée à l'échelle du bassin versant de la Rivière aux Brochets (630 km^2), important tributaire québécois du Lac Champlain. Compte tenu de la problématique récurrente de prolifération de cyanobactéries dans la Baie Missisquoi, la réduction des flux de phosphore à la baie constitue une priorité d'intervention et a fait l'objet d'une entente entre les gouvernements de la province de Québec et de l'état du Vermont. Le paramétrage du modèle s'est appuyé sur la caractérisation et la représentation

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spatiale des paysages et des systèmes de production agricole selon un découpage du parcellaire en culture en plus de 2,400 unités de réponse hydrologique, chacune présentant des propriétés distinctes en termes de type de sol, de relief, de pratiques culturales, d'apports de nutriments et d'appartenance à l'un des 99 sous-bassins versants du territoire à l'étude. Le calibrage et la validation de la modélisation s'est appuyée sur les données de quatre stations hydrométriques, de même que sur le suivi de la qualité d'eau de deux bassins versants expérimentaux (6-8 km^2) présentant des propriétés physiques contrastées. La différenciation des paramètres de calage pour les portions amont et aval du bassin a permis un bon ajustement du modèle hydrologique aux débits observés sur les différents tronçons de la Rivière aux Brochets, de même qu'une bonne reproduction des flux de sédiments et de phosphore mesurés aux embouchures des deux bassins de référence. La modélisation des flux de sédiments et de phosphore à l'échelle du bassin versant met en relief une forte discrimination spatiale dans la distribution des exportations. Sur la base des conditions actuelles de régie des sols et des cultures, plus de 50 % du flux de phosphore modélisé provient d'environ 10 % de la superficie totale du bassin. Typiquement, ces secteurs sont associés à d'importantes lames d'eau ruisselées, des taux d'érosion élevés ou un enrichissement important de la couche arable en phosphore.

Introduction

Reducing agricultural non-point source water-borne particulate and dissolved phosphorus (P) reaching trans-border Lake Champlain from its 21,326 km^2 of feeder watersheds in the province of Quebec, Canada, and states of New York and Vermont in the United States, has been cited as a critical priority by the multi-stakeholder Management Conference on Lake Champlain (Vermont, New York and Quebec, 1993). A severe impairment of water quality by cyanobacterial blooms in the lake's northerly-situated Missisquoi Bay led to the governments of Quebec and Vermont reaching a specific agreement on phosphorus loads in the bay (Gouvernement du Quebec and Government of Vermont, 2002). Phosphorus loads entering the bay were apportioned 60% to Vermont and 40% to Quebec. Given that 80% of the non-point P load has been linked to agricultural sources (Hegman *et al.*, 1999), management plans have focused on agricultural best management practices (BMPs) of soil and water resources. Vermont and Quebec have cooperatively monitored P concentrations in the bay and its two largest tributary watersheds (Missisquoi and Pike Rivers). Annual mean total-P concentrations in the bay have consistently exceeded Vermont and Quebec's water quality criterion of 25 μg P l^{-1}, neither rising nor declining significantly between 1990 and 2000. Phosphorus loads contributed to the bay through its two largest tributary watersheds have consistently exceeded the management targets derived from watershed load allocations (Medalie and Smeltzer, 2004).

A research program was initiated in 1997 within the Pike River basin, an important tributary watershed situated within Canada, seeking to describe non-point source P transfer to aquatic ecosystems. The research was undertaken on a wide range of scales: (i) plot-scale—testing of effects and interactions of benchmark soils properties, manure inputs and crop cover on P loads and speciation (Michaud *et al.,* 2004b); (ii) field-scale (10 ha)—monitoring of P losses in surface runoff and subsurface drainage waters (Enright and Madramootoo, 2004); (iii) meso-scale (six to ten km^2) —characterization of spatio-temporal variability in P fluxes across the watershed (Michaud *et al.*, 2004a; 2005), and assessment of management effects on water quality through a paired-basin design (Michaud *et al.*, 2004a); and (iv) macro-scale (630 km^2)—indexation of P mobility (Deslandes *et al.*, 2004).

Having extensively characterized the Pike River watershed, questions pertaining to the potential efficacy of BMPs in reducing P loads can be answered more quickly, cheaply and over a greater time-scale through modelling. Given its well documented capability to support long-term simulations of the effects of different land use management scenarios on water transfers and transport of sediments and associated nutrients over large, heterogeneous watersheds, the SWAT model (Soil and Water Assessment Tool; Arnold *et al.*, 1998) was chosen to devise cropping systems and land development scenarios that could meet target P-loads set by the Quebec-Vermont agreement. Conceptually, the semi-distributed deterministic model is drawn from a number of previously-developed agri-environmental modelling tools, namely: SWRRB (Williams *et al*., 1985), EPIC (Williams *et al*., 1984), CREAMS (Knisel,1980) and GLEAMS (Leonard *et al*., 1987). In North America and Europe SWAT has been widely used to predict non-point source sediment, nutrient and pesticide loads (Santhi *et al*., 2001; Neitsch *et al*., 2002b; Arnold *et al*., 2005; Van Griensven and Bauwens, 2005).

To extrapolate potential effects of alterations in management practices, the hydrologic model must be calibrated and validated. This paper presents calibration and validation results of the SWAT hydrological model on the Pike River watershed (630 km^2), an important Canadian tributary to Missisquoi Bay. A focus is given to spatial gradients in landscape attributes, soil P stocks, agricultural inputs and cropping systems and how they relate to model sensitivity in predictions of runoff depth, sediment loads and P fluxes.

Methods and Materials

Site Description

The Pike River has been identified as one of the main contributors of P to Missisquoi Bay (Hegman *et al*., 1999). It originates in Lake Carmy, Vermont, roughly eight km south of the Vermont-Quebec border (Figure 1). Its drainage basin covers 630 km^2, of which 99 km^2 (15.7%) are located in Vermont. The watershed presents clear spatial gradients in land-use and geophysical attributes. Spanning the Appalachian piedmont the watershed's upstream region (390 km^2) is dominated by sandy and shaly loams, dominantly humic gleysols and podzols. Elevations range from 50 to 710 m above mean sea level (AMSL), with a 5° mean slope. Given the types of soils and the land's rugged features, this region is ill-suited for intensive agriculture. Overall, only 35% of the region's area is devoted to agriculture, 22% to perennial forage crops and 13% to annual crops, reflecting the predominance of dairy and swine production.

Stretching from the town of Bedford to the river's mouth, the watershed's downstream region (240 km^2) draws upon the plains of the St. Lawrence lowlands and Appalachians. Clays of marine and lacustrine origin (gleysolic) occupy the low-lying areas, whereas calcareous and shaly tills (brunisolic and podzolic) occupy the higher elevations and rolling hills. Elevation ranges from 20 to 130 m AMSL, with flatter slopes (0.6° (1%) on average). Three-quarters of the downstream region is cultivated, and of cultivated lands roughly 20, 30 and 50% respectively, are devoted to hay crops, perennial forages, and field crops (corn—*Zea mays* L. and soybean—*Glycine max* (L.) Merr.) Animal production follows the same pattern as in the upstream region of the watershed, albeit more intensively. The downstream region contains the industrial and population (approximately 9,000) centres of the region.

Model Parameterization

The implementation of the SWAT modelling project, covering the study period of 1997 to 2003, followed the procedures of Di Luzio *et al*. (2002). For the land phase of the hydrological cycle, SWAT subroutines allowed the daily simulation of the soil's evolving nutrient content, of plant growth and nutrient uptake, as well as water, sediment and nutrient exports from the field to the hydrological network. Simulations were undertaken at the level of the individual hydrologic response unit (HRU), each such unit representing a unique combination of physical properties, land use, and localization within one of the 99 sub-watersheds of the region under study. For the routing phase of the hydrological cycle, exports of water, sediments and nutrients, cumulated at the sub-watershed scale, were drawn upon by subroutines to simulate the processes of erosion, deposition, resuspension, biodegradation and transformation within the hydrographical network.

Climatic Data

Daily precipitation and temperature data for the 1997-2003 study period were drawn from the Philipsburg (45°02'N and 73°05'W, elev. 53.30 m), Farnham (45°18'N and 72° 54'W, elev. 68.00 m) and Sutton (45°09'N and 72°38'W, elev. 243.80 m) weather stations, located around the periphery of the watershed (MDDEPQ, 2003). Solar radiation, wind speed and relative humidity were drawn from SWAT's weather generator database for the nearby Plattsburgh weather station (44°42'N and 73°30'W; Arnold and Fohrer, 2005). Thirty-year (1971-2000) annual mean

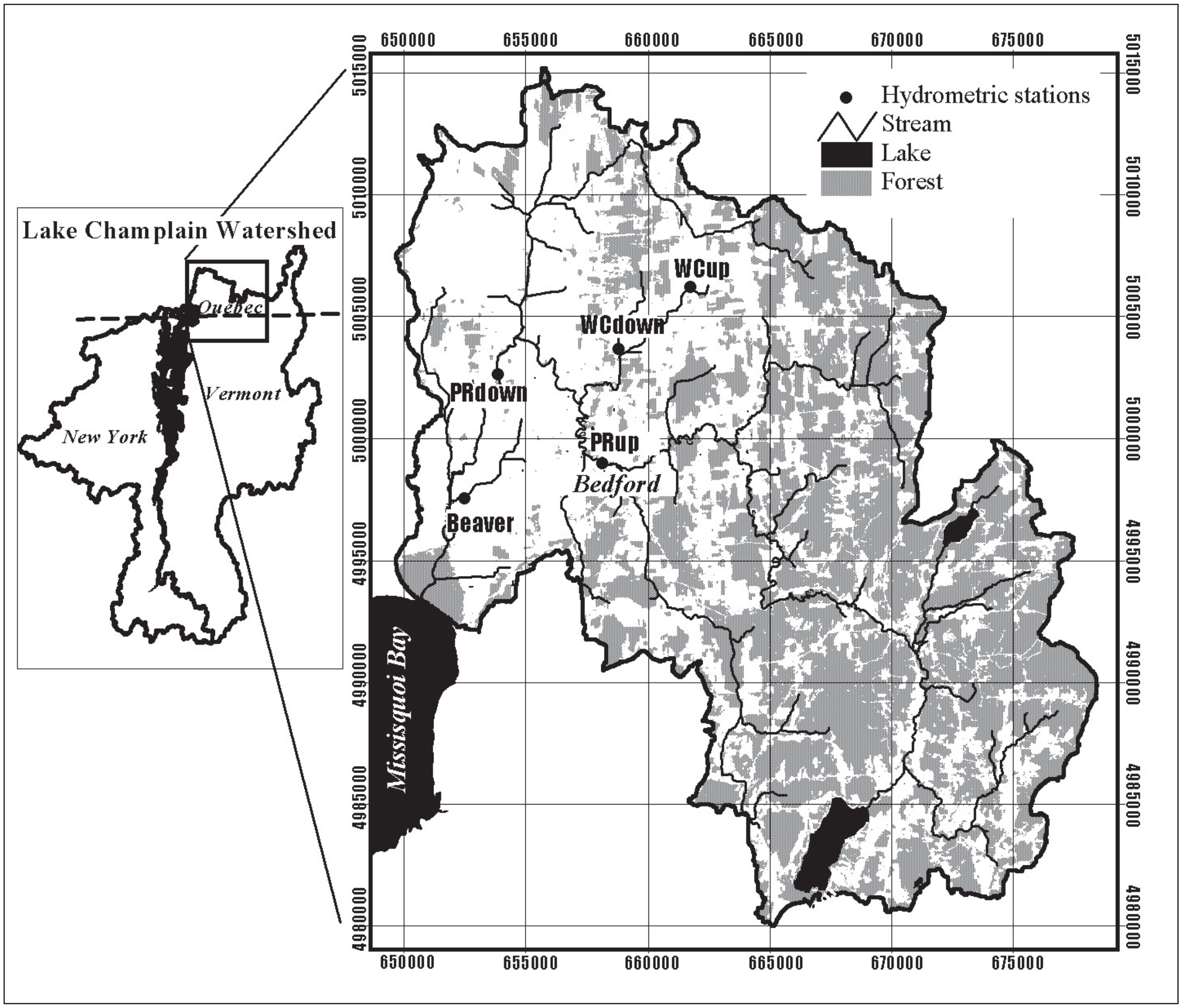

Figure 1. The Pike River Watershed of the Lake Champlain Basin.

precipitation at the Farnham, Philipsburg and Sutton stations were 1156 mm, 1095 mm and 1272 mm, respectively, highlighting the orographic gradient existing across the watershed (30 to 210 m). Annual mean temperature and snowfall ranged from 5.8° and 390 mm in Sutton, near the higher elevations of the basin's headwaters, to 6.8° and 247 mm in Philipsburg on the shores of Missisquoi Bay.

Overall, the annual precipitation received during the study period remained within 11% of the norm, while mean annual temperatures matched long-term means. Crop growth modelling was adjusted on the basis of a corn heat unit (CHU) range of 2500 to 2900, typical of the region (Bootsma *et al*., 1999). Crop growth parameters were adjusted in successive iterations to generate biomass and yields as generally observed in the region.

Landscape Attributes

The task of delimiting the watershed and sub-watersheds initially involved an integrated analysis of hydrographical, topographical, hydrological and land use data from the Quebec and Vermont portions of the Pike River watershed. A digital elevation model (DEM), developed from a multi-source 30 m pixel-scale database (Deslandes *et al*., 2004) showed an accuracy of roughly 1.3 m in elevation, as estimated by comparison to a high resolution elevation map developed for the Walbridge reference sub-watershed (Duguet *et al.*, 2002). A Landsat 7 ETM+ image (5 July 1999) served in land use mapping (Cattaï, 2004), while soil-type mapping drew from a number of sources (Talbot, 1943; Cann *et al.*, 1946; USDA-NCRS, 1999). Soil physical and chemical properties, including particle size analysis, saturated hydraulic conductivity, bulk density and percent organic matter were drawn from Quebec (Tabi *et al.*, 1990) and American (USDA-NCRS, 1999) databases. Soil particle size analyses and organic matter content served to determine available soil water (USDA-NCRS, 2005), while soil erodibility factors were drawn from Bernard (1996) or estimated from Wischmeier *et al.* (1971). The exact extent of subsurface drainage in the basin was unknown, therefore, for modelling purposes the area under annual field crops was taken as being drained. The resulting field-scale drained area of 60% was comparable to those inventoried on experimental subwatersheds within the study region (Michaud *et al.,* 2004a; b). Based on standard drainage design encountered in Quebec (Beaulieu, 2001) and for modelling purposes, mean drain depth was set at 0.9 m, time to reach field capacity at 48 hours, and time for water to reach a stream at 10 hours.

Soil Phosphorus

The SWAT model's daily HRU-scale modelling of phosphorus mineralization and solubilization were initialized on the basis of given labile and organic soil phosphorus contents (mg kg^{-1}). Derived from 1328 soil test P determinations, the initial spatial distribution of soil P richness was input at a subwatershed-scale (Deslandes *et al.,* 2004). Values of soil test P, assayed by the Mehlich-III method (Mehlich, 1984), were converted to Olsen method (Olsen *et al*., 1954) equivalents using a calibration curve developed with Quebec soil series (Sen Tran *et al*., 1990). Labile P was derived from Olsen bioavailable P using the equation developed by Sharpley *et al*. (1984). Initial organic P contents were based on typical soil organic matter content of relevant soil series, and on soil organic matter C:N and N:P ratios of 12.4:1 and 8:1, respectively (Neitsch *et al*., 2002a). To reflect the greater mean P richness of soils dedicated to corn production (Tabi *et al*., 1990), P content of HRUs under grain corn were increased by 50%. For the cultivated lands of the subwatersheds located in the United States, labile P richness was assigned a default value of 25 mg kg^{-1} (Cope *et al*., 1981).

Cropping Systems and Nutrient Management

The cornerstone of the field-scale modelling of water balance, erosion processes and phosphorus mobility was a composite reference management scenario developed from those of each of the study watershed's 2253 agricultural HRUs, by implementing the following simplifications and choices. The spatial distribution of crops, derived from the classification of a 1999 satellite image (Cattaï, 2004) was maintained throughout the modelling process. Sowing, tillage, and fertilizer application dates were adjusted annually according to the type of crop, probable field-scale management schedule, and 2000-2003 precipitation patterns. Given the practices that prevail in the region, the actual date of broadcast manure application in spring was set at the end of the first 72-hour precipitation-free period starting in the last week of April. Similarly, a 48-hour precipitation-free period had to occur prior to secondary tillage, sowing and banded subsurface fertilizer application. Such rules led to a six to 16 day delay in manure incorporation. Manure incorporation delays for summer and fall applications followed the same rules. Based on standard practices in the region, a single soil tillage practice of fall ploughing and spring harrowing was maintained for all annual crops.

Phosphorus and nitrogen inputs were based on annual expenditures in inorganic fertilizers drawn from government farm registration forms, as well as on the types of livestock and crops produced. An initial spatial distribution of organic (farm manure) and inorganic fertilizer inputs was established at the subwatershed scale, then refined to the crop level using as a benchmark soil and crop management data collected at the field-scale, pursuant to an in-depth study of three experimental subwatersheds (Michaud, 2004a; b). On a volumetric basis, farm manure inputs were allocated 45% to preplant, 36% to post-emergence, and 16% to fall applications, reflecting quantities declared on government farm registration forms. Inorganic nitrogen fertilizer inputs were split equally between preplant and post-emergence applications, whereas inorganic phosphorus fertilizer was applied in a single operation at sowing. Lacking relevant data on nutrient inputs on the American portion of the watershed, mean estimated inputs for the downstream portion of the watershed located in Quebec were substituted.

Model Calibration and Validation

Four PERL (Practical Extraction and Report Language) utilities (White *et al.*, 2002), served, along with a critical evaluation of modelling results in light of local and North American literature, in the optimization of model fitting parameters. In both calibration and validation phases, the model's accuracy with respect to measured data was evaluated according to three statistical indices: (i) the Pearson correlation coefficient (r); (ii) the Nash Sutcliffe coefficient (NSC), an indicator of goodness of fit recommended by the American Society of Civil Engineers for use in hydrological studies (ASCE, 1993)—a value of one indicates a perfect fit between observed and predicted data, while a value of zero indicates that the model predicted no better than using the mean of the observed data; and (iii) percent deviation of predicted water, sediment or nutrient yield from measured data. During calibration, differences between observed and predicted fluxes were minimized by adjusting model parameters. During subsequent validation the calibrated model's accuracy was evaluated based on its performance with a new set of weather data.

Hydrology

Streamflows predicted by the model were compared to measurements taken at four hydrometric stations (Table 1; MDDEPQ, 2005). Streamflow only was measured at two stations located on the main channel of the Pike River, one at the outlet of the portion of the rolling, mainly forested watershed upstream from the town of Bedford (PR_{up}, 385 km^2), the other downstream from Bedford encompassing some additional flat agricultural lands (PR_{down}, 561 km^2). Within the larger Pike River watershed two smaller (<8 km^2) experimental watersheds within the agricultural (>60% by area) watershed of the Walbridge Creek, were monitored for suspended solids and P loads in addition to streamflow. One of these stations was located at the outlet of a watershed characterized by rolling upland landscapes typical of the Appalachian piedmont (WC_{up}, 6.3 km^2) while the other was characterized by flatter lands typical of the St. Lawrence lowlands (WC_{down}; 7.9 km^2). All stations were equipped with bubble-type depth gauges. A minimum of six stream gaugings were 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 river-bed. The hydrometric data of station PR_{up} for the months of January to April 2001 were excluded from model closeness of fit evaluation due to inability to accurately correct for effects of ice on streamflows.

An upsteam to downstream approach was employed in calibrating the model's hydrologic components, thus taking into account the significant shift in landscapes that occurs across the Pike River watershed. The SCS method's (USDA-SCS, 2006) overestimation of runoff depth required a 20% across-the-board decrease in curve number, compared to values recommended for the surface conditions under study (Neitsch *et al.*, 2002a). Such inequities of the SCS methods have been reported for the St. Lawrence lowlands (Perrone and Madramootoo, 1998). Being originally developed using regional data, mostly from the Midwestern United States, the application of this empirical method to other geographic or climatic regions should be viewed with caution (Ponce and Hawkins, 1996) and might therefore need some adjustment. Indeed, Tolson and Shoemaker (2004) and Saleh *et al*. (2000) have applied similarly reduced curve number (CN2) adjustments in their SWAT-based simulations in the states of New York and Texas, respectively.

Site specific snow cover parameters were used for watersheds WC_{up}, WC_{down}, and for the entire basin when calibrating hydrological components of the model, to account for the spatial gradient in landscape and land use across the Pike River watershed.

Sediment and Phosphorus Exports

Given the contrasting geomorphologies and hydrological responses, the Walbridge experimental watersheds (Michaud *et al.*, 2004a) served as the basis for assigning values to SWAT calibration parameters related to exported P and sediment loads, for the upstream versus downstream portions of the Pike River watershed. Between 2000 and 2003, some 166 water samples were drawn at the outlet of each of the Walbridge experimental watersheds.

Table 1. Hydrometric stations on 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	Streamflow
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	Streamflow
WC_{up}	Walbridge Creek BMPs applied	6.3	Rolling and agricultural (61%), typical landscape of the Appalachian piedmont	Streamflow, sediments, and P
WC_{down}	Walbridge Creek standard	7.9	Flat and agricultural (63%), long slopes, typical of St. Lawrence lowlands	Streamflow, sediments, and P
Beaver	Beaver Brook	11	Flat and agricultural (97%), long slopes, typical of St. Lawrence lowlands	Streamflow, sediments, and P

These samples were kept at 4°C until analysis in the laboratory. Suspended solids were quantified by filtration (<0.45 μm). Following filtration and persulfate mineralization, respectively, concentrations of soluble reactive and total water-borne P were determined by automated colourimetry (Murphy and Riley, 1962). Point measurements of water quality and continuous monitoring of streamflow, 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. The coefficients of variation of load estimates remained within acceptable limits for the modelling of small tributaries (Walker, 1998). An inspection of regression residuals for concentration-discharge and load-discharge relationships demonstrated the independence of residuals with respect to discharge, date, season, concentration and load. No outliers were detected (5% confidence level).

Following the calibration of the model's hydrological components, Manning roughness coefficients and the maximum half-hour rainfall peak rate adjustment factor (APM) were adjusted to mimic as closely as possible sediment and nutrient export dynamics at the outlets of the Walbridge experimental watersheds. With respect to channel erosion, the Muskingum method was chosen to evaluate the spatial variability of streamflow across the hydrographic network governing the transport of sediments and nutrients. Little is known regarding sedimentation/resuspension dynamics under the climatic conditions in the study region. Wang *et al.* (1999), in quantifying the retention process operating within one of Lake Champlain's tributaries, showed it to be similar in magnitude to the annually exported load. Such balanced sedimentation/resuspension dynamics would argue for a rather marginal net contribution of sediments originating within the hydrological network. It was estimated, on a hypothetical basis, that erosion of the hydrological network contributed less than 20% of the sediment load exported from the watershed. Export dynamics were fine-tuned by way of the model's sediment routing parameters, which govern the stream's capacity to take up material from the stream bed.

With respect to loadings and speciation of predicted P, a number of parameters proved to be important in properly calibrating the model, including the sediment P-enrichment factor, the phosphorus availability index, and the phosphorus soil partitioning coefficient, which affects the fraction of topsoil P that can contribute to soluble phosphorus in surface runoff. The proportion of nutrients retained within the topsoil (ten mm) during fertilizer application, and tillage practice parameters, particularly those of soil mixing efficiency and depth, also warranted close attention.

Lack of proper water quality monitoring data on the Walbridge experimental watersheds did not permit a traditional validation of the model. Consequently, a spatial and temporal validation of the calibrated-SWAT model was done on a third small subwatershed, the Beaver Brook basin, which drains roughly 11 km² of flat agricultural lands. Between March 1997 and September 2002, sediment and phosphorus loads were measured using the same method as for the Walbridge subwatersheds (Michaud *et al.*, 2005) and monthly data were compiled for validation of the model.

Results and Discussion

Closeness of Fit: Hydrological Components

Model sensitivity analysis (not shown) showed land slope characteristics and evapotranspiration compensation coefficients to be the most sensitive parameters in the adjustment of SWAT-predicted runoff depths for the Pike River watershed. Soil profile depth, bulk density and saturated hydraulic conductivity proved to be the most sensitive soil parameters with respect to surface to subsurface partitioning of runoff within individual HRUs. With respect to subsurface flow, adjustment of the model parameters related to water exchanges between soil horizons, shallow groundwater and deep groundwater was also essential in matching observed streamflows to model predictions. The sensitivity of SWAT's hydrological predictions to these calibration parameters has been reported by others (Lenhart *et al.*, 2002; Tolson and Shoemaker, 2004; Spruill *et al.*, 2000).

Overall, the allocation of water to the different elements of the water balance appeared to be consistent with local agroclimatic conditions. The mean predicted annual water balance for 2000 through 2003 (Table 2) shows that of the 1154 mm yr^{-1} of precipitation across the Pike River watershed, roughly half (566 mm) was lost through evapotranspiration. Surface runoff, lateral flow, and tile flow accounted for 218, 39 and 46 mm yr^{-1}, respectively. Some 211 mm yr^{-1} contributed to shallow groundwater on the way to the stream, while 60 mm was lost to deep aquifers. However, while one might believe tile flow to be underestimated, one must keep in mind that this water balance reflects conditions across the entire watershed, whereas only 30% of its area is tile drained. Limiting the water balance assessment to tile drained fields, the depth of tile flow rises to 180 mm yr^{-1}, compared to 170 mm yr^{-1} for surface runoff. Comparing predictions of the model's hydrological component to measurements made, over the same study period, on instrumented field sites in the downstream portion of the Pike River watershed, Enright and Madramootoo (2004) suggested that tile drainage depths might be underestimated in favour of fluxes arising from shallow groundwater and surface runoff. Model predictions during the recession limb of stream and river flows generally showed a good fit, suggesting a satisfactory representation of subsurface flows (tile drainage, lateral flux, and resurgence of shallow groundwater) as a whole, if not without a certain degree of uncertainly as to the different compartments' relative contributions.

The closeness of fit of the calibrated model's predicted flows to those measured over the study period at the four standard hydrometric stations located on the Pike River watershed (Table 3), indicates that, overall, SWAT satisfactorily predicted streamflow at the two stations on the Pike River's main channel (PR_{up}, PR_{down}), as well as on the two branches of the Walbridge Creek experimental watersheds (WC_{up},WC_{down}). The statistics, compiled across the calibration and validation phases of the study, indicate a good fit of model predictions to monthly and daily streamflow (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 NSC of 0.55. This underestimate is essentially attributable to the winter periods of January to February 2002 and of March, 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 (December 2003). Under such conditions, SWAT had difficulty distinguishing between rainfall and snowfall because its weather generating subroutine is based on daily mean temperature. Given the important magnitude of peak flows associated with winter thaws, which represents more than 20% of the annual water yield, predictions of water depths were strongly affected. It is also quite likely that the accumulated ice cover on the river led to an overestimation of standard limnimeter-measured streamflow. These winter-related problems can be perceived in the statistical coefficients, the validation statistics being better than the calibration

Table 2. Mean predicted annual water balance for 2000 through 2003 at the outlet of the Pike River Watershed.

Parameter, Annual Mean	Depth ($mm\ yr^{-1}$)
Total precipitation	1154
Snow precipitation	326
Snowmelt	296
Runoff contribution to streamflow	218
Transmission losses: water lost from tributary channels in the HRU via transmission through the bed. This water becomes recharge for the shallow aquifer.	37
Tile drain contribution to stream (30% of watershed area; 180 mm for tiled area only)	46
Groundwater contribution to streamflow	211
Lateral flow contribution to streamflow: water flowing laterally within the soil profile that enters the main channel	39
Water in the shallow aquifer returning to the root zone in response to a moisture deficit	16
Deep aquifer recharge	60
Recharge entering aquifers	254
Water yield	476
Actual evapotranspiration	566
Potential evapotranspiration	805

ones. This has been attributed to the fact that the calibration period encompasses more winter seasons than the validation period. With the exception of peak flows associated with winter thaws, the predicted daily hydrograph shows the model's capacity to accurately reproduce the watershed's hydrologic behaviour.

With respect to summer events, small aberrant predicted runoff peaks occurred at all stations, but more prominently for station PR_{up} than for the other watersheds monitored (Figure 2). The SCS curve number method of runoff depth prediction does not allow the correction of this flaw without the underestimation of runoff peaks during the late winter/early spring period. This seasonal contrast in the model's closeness of fit likely relates to the fact that infiltration-excess runoff most likely prevails under the summer's high intensity rainfall events, whereas saturation-excess runoff prevails in the late winter and early spring. This would call for additional calibration parameters to account for shallower water tables and landscape spatial controls for subsurface flow among HRUs. Furthermore, the model failed to reproduce the high rainfall intensities of certain summer thunderstorm events, as, for example, the 52 mm rainfall event of June 11, 2002 (Figure 2). The resulting discrepancies highlight the limitations of the model when operating on a daily time-step, leading to an underestimation of the exceptional erosivity of the very short and intense rainstorm.

Spatio-Temporal Variability in Hydrologic Activity

From an operational perspective, the model's capacity to discriminate in the partitioning of runoff from rainfall is critical since the depth of surface runoff serves as an input parameter in the prediction of MUSLE-derived soil loss, which determines the quantity of particulate P exported. Figure 3 illustrates the model's capability to discriminate the hydrologic response among two HRUs cropped to corn in the northern part of the Pike River watershed, but differing significantly in their soil physical properties (poorly drained sandy loam (HRU_{SL-D}) versus well drained sandy-gravelly loam (HRU_{SGL+D})). The greater vulnerability to surface net runoff of HRU_{SL-D}, compared to HRU_{SGL+D}, is illustrated by the total runoff of 143 mm on HRU_{SL-D} being almost four times that on HRU_{SGL+D} (50 mm; Figure 3). Similarly, given its greater depth of runoff, transmission losses within the hydrographic network of HRU_{SL-D} (60 mm) were greater than those of HRU_{SL-D} (35 mm). On both sites the main runoff events occurred in the spring or fall, when the soil was either frozen or

Table 3. Calibration and validation SWAT model closeness of fit parameters for streamflow at four hydrometric stations over study period, (i) monthly streamflow and (ii) daily streamflow. Parameters include Pearson correlation coefficient (*r*), Nash-Sutcliffe coefficient (NSC) and percent predicted to measured deviation (D_v). Watershed abbreviations as in Table 1.

Watershed	Period	D_v	Monthly Streamflow		Daily Streamflow	
			r	NSC	r	NSC
PR_{up}	Calibration: 04/1998 to 12/2000 and 05/2001 to 12/2002	-3%	0.93	0.85	0.75	0.56
	Validation: 01/2003 to 12/2003	-8%	0.97	0.91	0.71	0.50
PR_{down}	Calibration: 11/2001 to 12/2002	-20%	0.82	0.52	0.76	0.55
	Validation: 01/2003 to 12/2003	-33%	0.88	0.60	0.86	0.64
WC_{up}	Calibration: 11/2001 to 12/2002	-9%	0.74	0.49	0.77	0.58
	Validation: 01/2003 to 12/2003	+19%	0.93	0.64	0.78	0.44
WC_{down}	Calibration: 11/2001 to 12/2002	+3%	0.78	0.60	0.77	0.59
	Validation: 01/2003 to 12/2003	-15%	0.94	0.85	0.82	0.66

saturated, as well as during the spring snowmelt. The relative importance of snowmelt was corroborated by measurements made by Jamieson *et al*. (2003) on two experimental fields located within the Pike River watershed. Spring snowmelt runoff represented 60 and 80% of total annual predicted runoff on HRU_{SL-D} and HRU_{SGL+D}, respectively. This contrast in the seasonality of surface runoff from the two sites shows how the lesser soil permeability of HRU_{SL-D} translated into a greater vulnerability to generating surface runoff through the year.

With respect to subsurface flows, the paucity of relevant measurements precludes a validation of the model's relative allocation to lateral flow, shallow groundwater, and tile flow. On watershed HRU_{SL-D} tile drainage and all forms of subsurface runoff reaching streams represented 34% and 65% of total runoff, respectively, whereas on watershed HRU_{SGL+D}, these values were 63% and 89%. On an annual basis, the model predicted an almost two-fold greater volume of subsurface flows for the well-drained HRU. The sum of all surface and subsurface flows suggests that for the same corn crop HRU_{SL-D} contributes 407 mm to the watercourse, whereas HRU_{SGL+D} contributes some 10% less.

On a larger scale, Figure 4 maps the spatial gradient in annual mean SWAT-predicted runoff on the Pike River's subwatersheds between 2001 and 2003. Predicted runoff on the Pike River's 99 subwatersheds correlates significantly with the percent agricultural usage (r = 0.64; P < 0.001). Nonetheless, in the southeast portion of the watershed, where agricultural land use is marginal, runoff depth remains relatively high. This disparate spatial distribution in surface runoff activity can in part be attributed to differences in rainfall over the watershed's 710 m orographic gradient favouring the watershed's uplands.

Closeness of Fit: Predicted Erosion and Phosphorus Mobility

Notwithstanding that SWAT was developed for use with large watersheds, the calibrated model was able to satisfactorily predict ($0.82<r<0.88$; $0.55<NSC<0.76$; maximum relative error, 13%) monthly sediment and P loads at the outlet of the six to eight km^2 Walbridge experimental watersheds (Table 4). Between November 2001 and December 2002, the sediment and P exports measured on the WC_{up} watershed were 117 Mg (0.19 Mg ha^{-1}) and 572 kg (0.95 kg ha^{-1}), respectively, while the model assigned values of 128 Mg (0.21 Mg ha^{-1}) and 498 kg (0.83 kg ha^{-1}). Likewise, the sediment and P exports measured on the WC_{down} watershed were 294 Mg (0.49 Mg ha^{-1}) and 713 kg (1.18 kg ha^{-1}), respectively, while the model assigned values of 282 Mg (0.47 Mg ha^{-1}) and 765 kg (1.27 kg ha^{-1}). Overall, the model tended to underestimate sediment and P exports during winter and autumn, while overestimating in early spring and summer (Figure 5). This reflects, in large part,

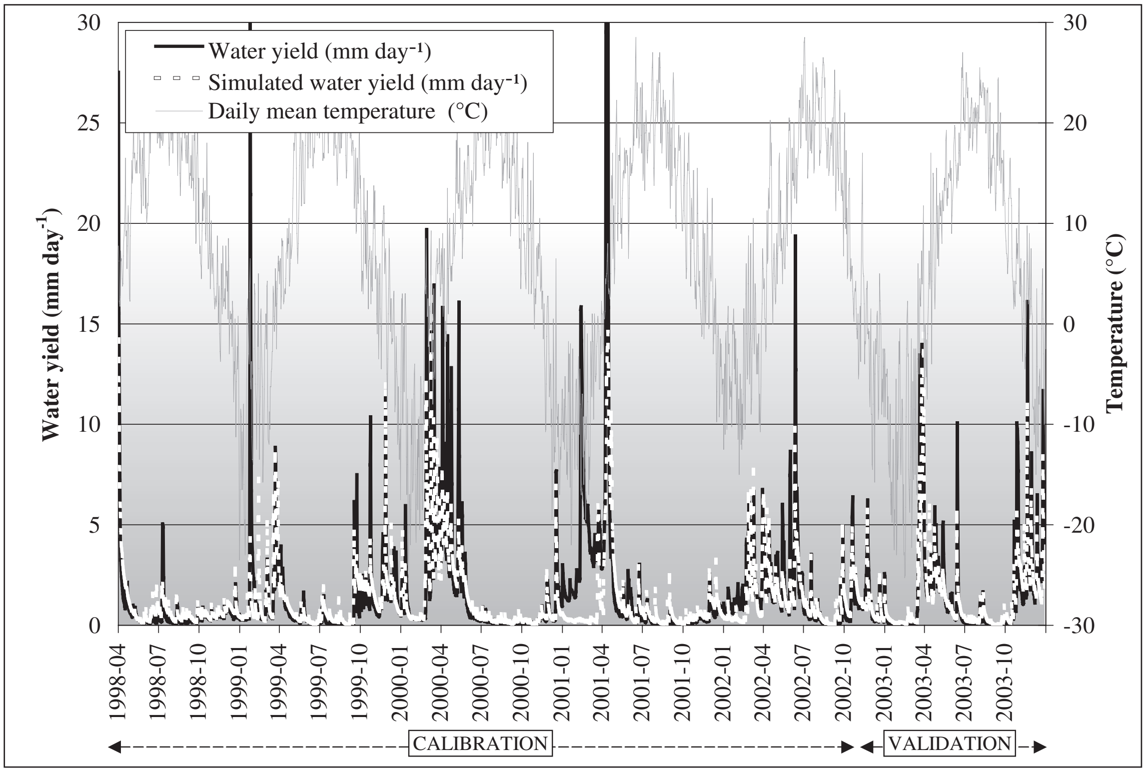

Figure 2. Daily mean temperature, measured and predicted water yield (April 1998 to October 2003) at the Pike River hydrometric station PR_{up}, upstream of Bedford.

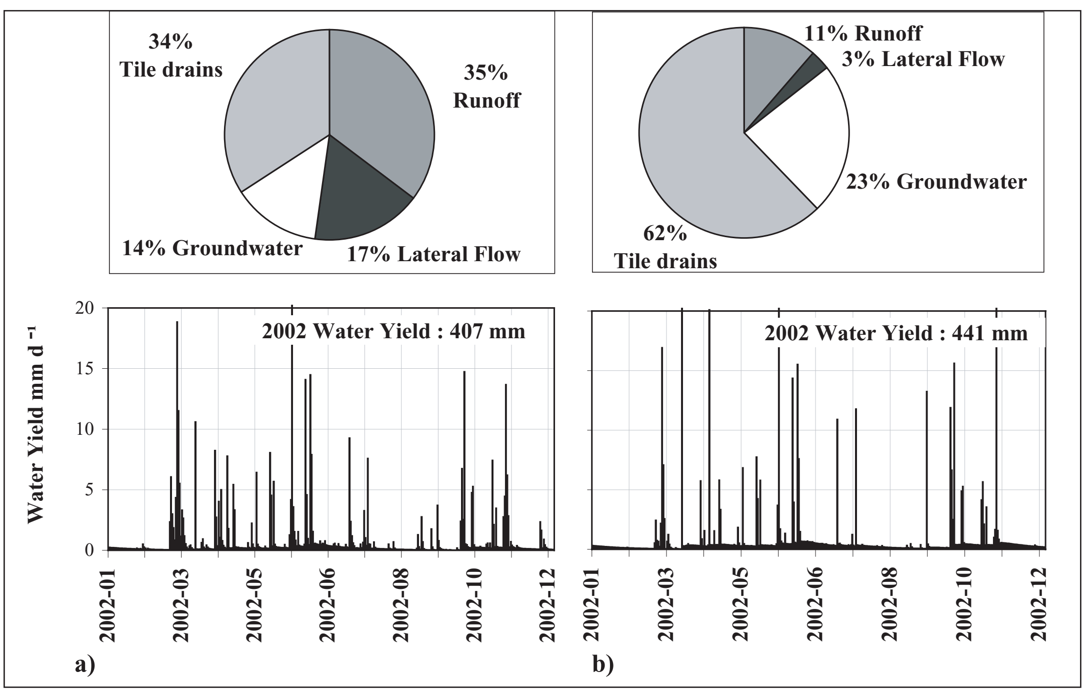

Figure 3. Daily fractioned water yield of two HRUs cropped to corn (a) on Milton soil series, a poorly drained sandy loam (HRU_{SL-D}), and (b) on Rougement soil series, a well drained sandy-gravelly loam (HRU_{SGL+D}).

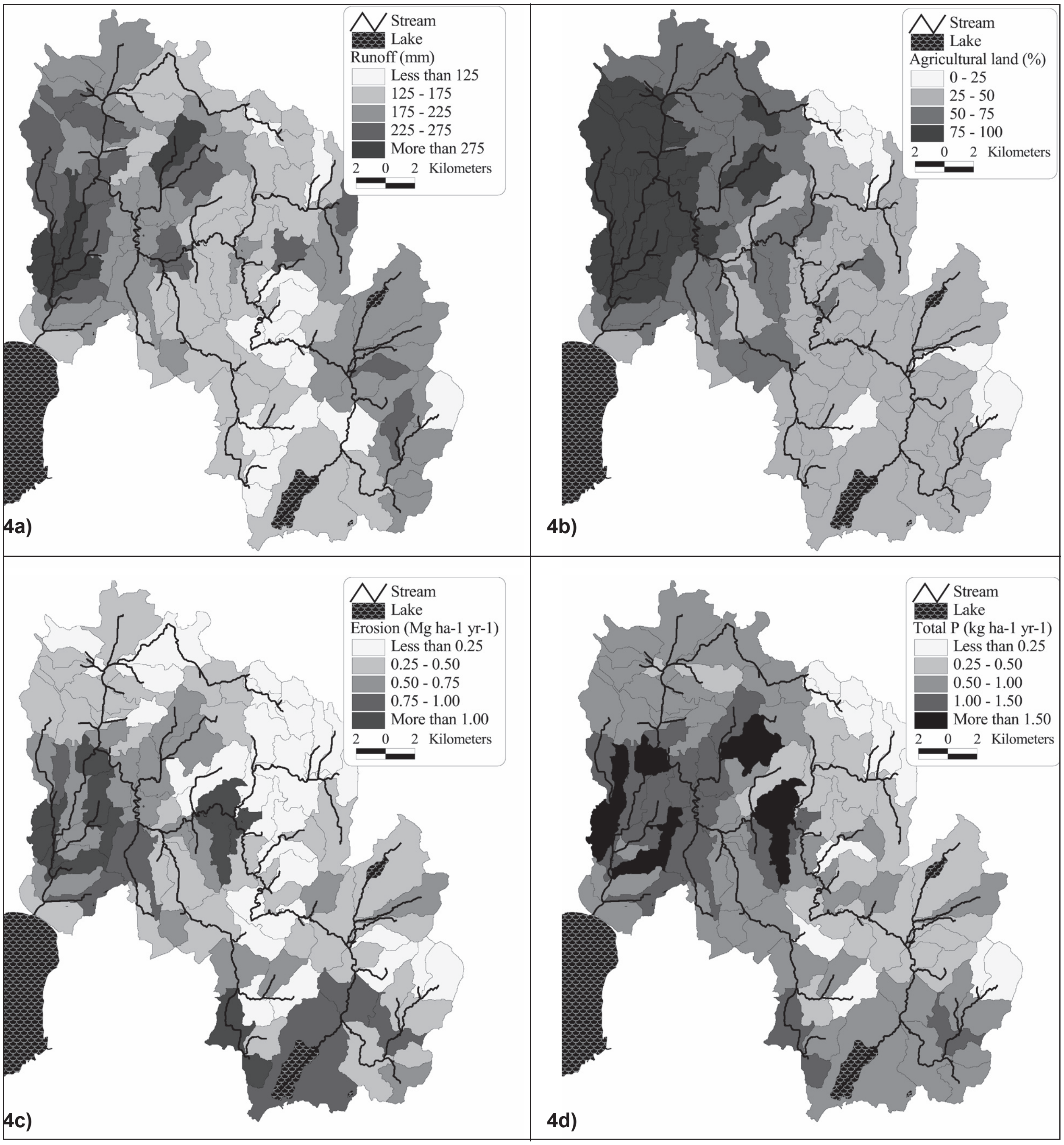

Figure 4. Spatial distribution of mean annual (2000-2003) (a) runoff volumes, (b) agricultural land use, (c) soil loss, and (d) total P exports predicted by SWAT for the Pike River subwatersheds.

the modelled watershed's hydrology. For example, in the calibration period of the two Walbridge subwatersheds, water yields were overestimated by roughly 20% during the winter thaw episodes. This caused a 54% and 37% overestimation of sediment and P exports in the 50 days when snowmelt occurred (between November 2001 and December 2002).

For validation purposes, even though the model was not calibrated on the Beaver Brook subwatershed, the statistical indices showed SWAT's efficiency to reproduce monthly sediment (r = 0.92, NSC = 0.84, Dv = -8%) and P exports (r = 0.94, NSC = 0.87, Dv = -20%) between March 1997 and September 2002. The complete validation of SWAT would have required more spatial and temporal water quality data, especially at the Pike River downstream station (PR_{down}). Unfortunately, only sparse data were available at that station. Nevertheless, the ability of SWAT to successfully reproduce the exports at the Beaver Brook subwatershed shows that the calibration parameters, obtained from the Walbridge subwatersheds, are well adapted to reproduce exports from agricultural lands in the watershed.

Within the hydrodynamic components of the model, the routing of sediments varied substantially between 2000 and 2003. On average, the model's land phase routines routed 31.27 Gg yr^{-1} to the Missisquoi Bay, whereas its aquatic phase routines routed some 15% more (37.04 Gg yr^{-1}).

Spatio-Temporal Variability in Soil Losses

The analysis of daily export totals at the outlet of the Walbridge Creek experimental watersheds over time, highlights the very episodic nature of hydrologic events leading to erosion. For example, 80% of sediment loads predicted in 2002 arose during short periods totaling 28 days or 8% of the year. This distribution essentially reflects that of field-scale surface runoff depths and is concentrated during the hydrologically active periods of spring and fall.

Overall, a significant downstream to upstream increment in sediment export rates can be seen at the HRU level (Table 5). Notwithstanding the relatively lesser agricultural use of lands in the upstream portion of the watershed, 60% of annual sediment exports originated there according to the model. Predicted soil loss rates from corn, soybean and small grains were roughly three-fold greater there than in the downstream portion. This difference in soil loss is largely attributable to the spatial gradient in the landscape's proneness to erosion, the downstream lowlands' relatively flat landscapes contrasting with the rolling and mountainous Appalachian landscape of the upstream regions. The mean (± standard deviation) slope of cultivated agricultural lands on the upstream portion of the watershed was 3.2% (±3.5%), compared to roughly 1% on downstream agricultural lands.

Land use patterns are also involved in creating a significant gradient in field-scale-modelled erosion rates. Indeed, roughly 50% of the erosion modelled was associated with less than 10% of the watershed's total area. Predicted soil losses were greatest under corn cultivation, followed by those under soybean, and those from urban areas. While corn cultivation covers 20% of the watershed's territory it is associated with 69% of the watershed's total predicted sediment exports (Table 5). This significant contribution of corn cultivation to soil loss derives from the relatively large MUSLE's soil cover parameter, C, associated with this

Table 4. Model closeness of fit indicators for SWAT calibration for monthly sediment and total P export predicted for the study period (November 2001 to December 2002) at the outlet of Walbridge Creek subwatersheds (abbreviations as in Table 1).

Watershed	Period	Sediment			Total P Exports		
		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%

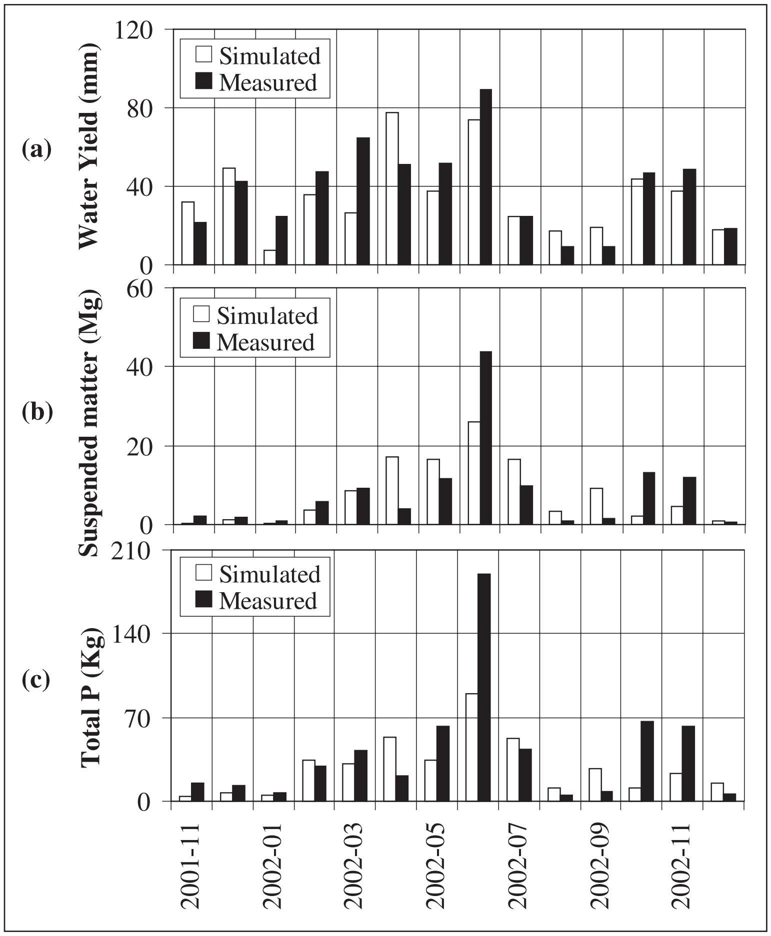

Figure 5. (a) Monthly water yield, (b) sediment and (c) total P export predicted at the outlet of the WC_{up} Walbridge Creek subwatershed from November 2001 to May 2003.

wide-row crop, compared to small grains or soybean which present a better soil cover.

Spatio-Temporal Variability in Phosphorus Losses

The model estimated that over the period of 2000 to 2003, mean exports of P to the watershed's hydrographical network were 47 Mg yr^{-1} (0.74 kg ha^{-1} yr^{-1}). The model's routing phase predicted an annual P loss at the watershed outlet of roughly 44 Mg yr^{-1}. The difference in P losses, roughly 3 Mg yr^{-1}, represents the net balance between P storage and release within the hydrographical network. Total predicted net P exports towards the Missisquoi Bay modelled within this study were of a similar order of magnitude as those reported by Hegman *et al.* (1999), which served as a benchmark in the determination of target-loads agreed to in the 2002 Quebec-Vermont Missisquoi Bay Phosphorus Reduction Agreement. Spatial trend projections of P fluxes drawn from the present hydrological modelling can, within the terms of reference established by Quebec and Vermont, serve as an element in the decision-support process involved in addressing the agreement's target loads.

As with sediment loads, exports of P, as modelled by SWAT, occur on a rather episodic basis (Figure 3). For example, at the outlet of WC_{up} the modelling of daily P exports for 2002 indicated that 80% of the P was exported over a total of 67 days (17% of the year), mainly during significant spring and fall hydrological events. This episodic nature of modelled P fluxes parallels observations made on a number of instrumented agricultural watersheds in the region (Michaud *et al.*, 2004a; b; Meals, 2004).

Overall, SWAT modelling indicated the preeminence of the particulate form of P (67% of total P) in the P mobilized across the entire Pike River watershed. This speciation is consistent with those observed on experimental watersheds in the region (Michaud *et al.*, 2004a; b) and in the American Northeast (Sharpley *et al.*, 1992) where particulate forms account for roughly 60% to 90% of P carried in surface runoff arising from agricultural lands. Model predictions showed a gradient in P speciation with land use (Table 5), with exports from less erosion-prone regions (grassland/pastures, forest, orchards/vineyards) being dominated by soluble forms of P, whereas highly erosion-prone regions (corn, soybean, cereals, urban) tended toward particulate forms of P.

At the HRU level, the model predicted crop-specific mean total P loads were greatest for corn (2.47 kg ha^{-1} yr^{-1}), followed by soybean (1.12 kg ha^{-1} yr^{-1}), small grains (0.74 kg ha^{-1} yr^{-1}) and finally grasslands (0.32 kg ha^{-1} yr^{-1}). As for the simulated dynamics of soil erosion, the effects of differences in landscape physical attributes are at the origin of the large range of P loads observed, in both upstream and downstream portions of the Pike River watershed, for a given crop (Figure 4d). Table 6, in 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, illustrates input parameters' relative influence over P exports. Overall, under both corn cultivation and grassland, predicted soluble and particulate P loads were poorly correlated (Table 6), which illustrates 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, and annual mineralized P in the topsoil (Table 6).

Mean soluble and particulate P loads for all cultivated HRUs on the watershed over the period extending from 2000 to 2003 are shown in Figure 6. While each agricultural land use shows 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 phosphorus inputs (fertilizer, manure) and the vegetative cover's minimization of sediment detachment and mobilization. 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 ($0.90 < r < 0.95$), 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/particulate speciation of predicted P loads match those reported by Michaud *et al.* (2004b), which showed a 2-80% variation in soluble P loads borne in simulated-rain-generated surface runoff from plots, differing in fertilizer applications and vegetative cover, installed on benchmark soils common to the Pike River watershed.

Conclusions

Based on spatial integration of landscape attributes and cropping systems specific to Pike River farmland, water, sediment and phosphorus yields predicted by SWAT provided a good fit to measured data from the experimental Walbridge meso-scale watersheds. The model was able to reflect the contrasting landscapes of the watershed. The model's fairly accurate replication of the recession phase of streamflows during hydrological events demonstrated the model's capacity to effectively replicate subsurface flows. Even following a roughly 20% decrease in the curve numbers relative to those generally employed in the literature, the comparison of model-predicted and field-measured tile flows indicated their underestimation by the model. Given the importance of preferential transfer of P to tile drainage waters reported in Quebec, the improvement of SWAT's capacity to accurately predict drain flow remains a research priority. Due to the study region's

Table 5. Mean 2000-2003 annual sediment and phosphorus exports by land use classes for downstream, upstream portions (abbreviations as in Table 1) and overall Pike River watershed.

	PR_{up}						PR_{down}						Entire watershed				
	Area		Sediment		Total P		Area		Sediment		Total P		Sediment		Total P		
Land use	ha	%	Mg	Mg ha^{-1}	kg	kg ha^{-1}	ha	%	Mg	Mg ha^{-1}	kg	kg ha^{-1}	Mg ha^{-1}	SD*	kg ha^{-1}	SD*	% soluble
Grassland/pasture	5863	24%	123	0.02	2512	0.43	8322	22%	980	0.12	3016	0.36	0.08	0.10	0.39	0.22	76%
Orchard/vineyard	88	0%	1	0.01	4	0.04	1039	3%	106	0.10	97	0.09	0.09	0.08	0.09	0.05	52%
Corn	8907	36%	10096	1.13	16556	1.86	3493	9%	11509	3.29	14144	4.05	1.74	3.87	2.48	4.36	11%
Market gardening	19	0%	10	0.50	20	1.02	0	0%	—	—	—	—	0.50	0.13	1.02	0.20	16%
Urban	854	3%	1163	1.36	1643	1.92	1788	5%	2345	1.31	3521	1.97	1.33	2.92	1.95	1.86	28%
Forest	4570	18%	6	0.00	43	0.01	20960	54%	191	0.01	371	0.02	0.01	0.01	0.02	0.01	65%
Cereals	2712	11%	828	0.31	1492	0.55	1711	4%	1804	1.05	1807	1.06	0.60	0.93	0.75	0.82	28%
Soybean	1113	5%	864	0.78	831	0.75	444	1%	1243	2.80	917	2.07	1.35	2.00	1.12	1.40	2%
Wetland	585	2%	—	—	—	—	891	2%	—	—	—	—	—	—	—	—	—
TOTAL	**24710**	**100%**	**13090**	**0.53**	**23102**	**0.93**	**38648**	**100%**	**18177**	**0.47**	**23872**	**0.62**	**0.49**	**2.39**	**0.74**	**2.30**	**33%**

*SD, Standard deviation

— not estimated or does not apply

Table 6. Linear correlation matrix of model export predictions (2000-2003 averages) with model input parameters at HRU scale for corn and grassland/pasture land uses.

Parameter [(2)]	Model predictions (exports) [(1)] Phosphorus fractions: Soluble	Particulate	Total	Sediment	Runoff	Model parameters: P Input	Soil labile-P	Mineralised P	HRU Slope	Soil erodibility
Soluble P		0.22**	0.27**	0.12*	0.56**	0.76**	0.26**	0.60**	N.S.	0.19**
Particulate P	0.08*		0.99***	0.94**	0.33**	0.12**	N.S.	0.17**	0.55**	0.35**
Total P	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.	

[(1)] HRU in corn (N=567) (values above the diagonal, light shading)
HRU in grassland/pasture (N=690) (values below the diagonal, dark shading)

[(2)] N.S., ***, **, *: Respectively non significant, and significant at the 0.001, 0.01, 0.05 probability levels.

climatic conditions, significant efforts should also be made to improve the model's capacity to simulate snowmelt events, which generate an important proportion of annual sediment- and P-bearing runoff indices to the watershed's hydrographic network. The capability to discriminate snowmelt parameters and snowcover characteristics at the sub-watershed scale would prove an important asset, allowing one to consider the impact of gradients in elevation and in land use across large heterogeneous watersheds. Furthermore, given the SWAT model's limitations in distinguishing between snowfall and rainfall on a daily time-scale, and its important hydrological implications, the capability for the user to input daily rain/snow depths would significantly improve the model's accuracy during the spring and fall periods.

From a management perspective, modelling results from 2353 hydrologic response units provide a good spatial representation of gradients in P mass balance and hydrologic activity. Predicted P fluxes at HRU and sub-watershed scales demonstrate an important spatial discrimination in P mobility across farmland and provide a sound basis for interpretation of critical areas in terms of source- and transport-related factors. As a result of the agronomic intervention scenarios that it supports, the SWAT model is a promising management tool for Quebec and American environmental managers taking charge of the watershed and Missisquoi Bay's development and improvement. The possibility exists to test various alternative management practice combinations that could potentially be applied to the Pike River watershed's farmlands, by simulating their implementation with the calibrated model. This will allow for a realistic evaluation of the different potential intervention strategies.

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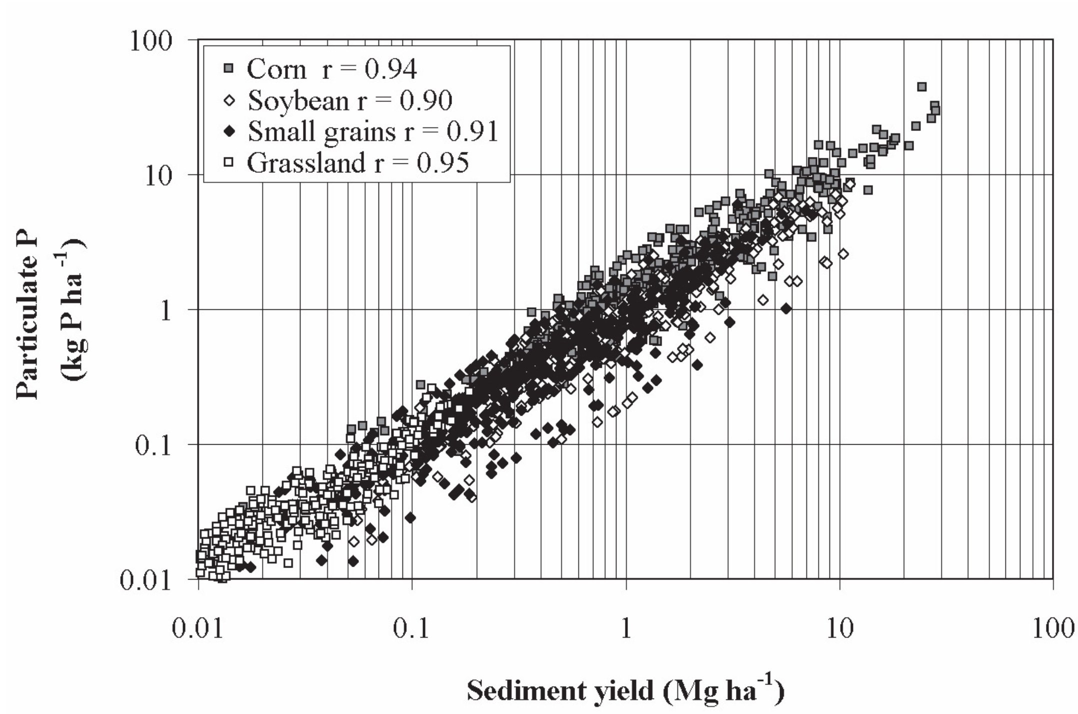
6a)



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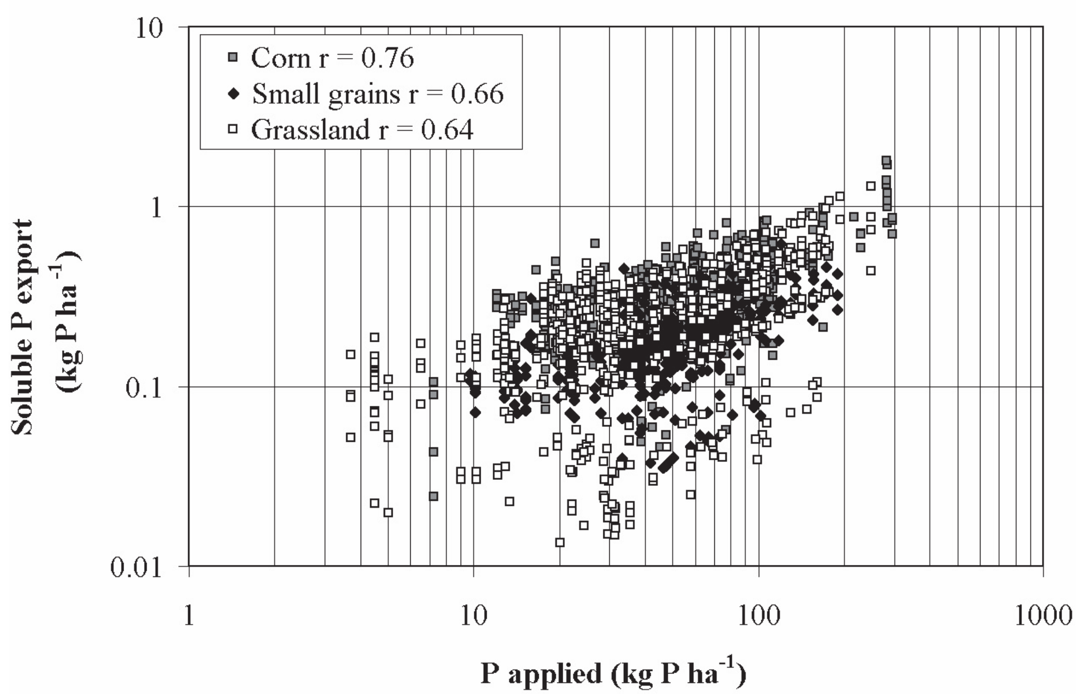

Figure 6. Mean annual soluble versus particulate P loadings predicted by SWAT at HRU scale for the 2000-2003 period: (a) mean annual particulate P loadings in relation to sediment yield, (b) mean annual soluble P loadings in relation to annual P inputs.

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