# Phosphorus Loading to Missisquoi Bay from Sub-Basins in Vermont and Québec, 2002-2005

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# CONTENTS

Background and Purpose of the Report .......... 2
Methods .......... 2
Monitoring Network .......... 2
Sampling Methods .......... 7
Laboratory Analytical Methods .......... 8
Flow Data .......... 9
Sub-Basin Delineation .......... 10
Phosphorus Load Estimation .......... 10
Statistical Analyses .......... 11
Results .......... 12
Phosphorus Concentrations .......... 12
Sub-Basin Phosphorus Loads .......... 13
Comparison with 1991 Base Year Loads .......... 13
Conclusions and Recommendations .......... 19
References .......... 21

# Background and Purpose of the Report

The *Agreement between the Gouvernement du Québec and the Government of the State of Vermont Concerning Phosphorus Reduction in Missisquoi Bay*[1] (signed August 26, 2002) adopted a total target phosphorus load of 97.2 metric tons per year (mt/yr) for the Missisquoi Bay watershed. The agreement assigned 58.3 mt/yr (60%) of this total target load to sources in the Vermont portion of the watershed, and 38.9 mt/yr (40%) to Québec sources. The parties committed in the agreement to achieving their respective target loads for the Missisquoi Bay watershed in a manner consistent with implementation plans developed by the Lake Champlain Basin Program and with the Québec, New York, and Vermont Memorandum of Understanding on Environmental Cooperation on the Management of Lake Champlain.

The June 2000 Report of the Missisquoi Bay Phosphorus Reduction Task Force[2] recommended that progress toward achieving these target phosphorus loads be monitored by enhancing the stream flow gage and water quality sampling network in the Missisquoi Bay watershed in order to permit the direct measurement of phosphorus loads from Vermont and Québec, including the establishment of monitoring sites where the Missisquoi, Pike, and Rock Rivers cross the international border. Accordingly, the 2002 phosphorus reduction agreement stated that "the Parties will enhance phosphorus monitoring of Missisquoi Bay tributaries and wastewater effluent from treatment facilities in the watershed." The Québec Ministère du Développement durable, de l'Environment et des Parcs (MDDEP), the Vermont Department of Environmental Conservation (VT DEC), and cooperating agencies such as the U.S. Geological Survey (USGS) have since established new sampling and flow gage stations for this purpose in the Missisquoi Bay watershed.

The MDDEP and the VT DEC analyzed data from these new sites and from a number of previously existing stations in order to estimate annual mean phosphorus loads to Missisquoi Bay from each sub-basin in Vermont and Québec for period of water years 2002-2005 (October 1, 2001 to September 30, 2005). The results of this analysis are presented in this report.

# Methods

## Monitoring Network

Direct measurement of annual phosphorus loads in rivers requires data on flow rates and total phosphorus concentrations. Previous phosphorus load estimation studies in the Lake Champlain Basin[3] have used continuously recorded flow measurements made at gage stations, combined with analysis of phosphorus samples obtained at discrete times throughout the year, with an emphasis on high flow conditions. This general approach to load estimation was used for the Missisquoi Bay Watershed Phosphorus Load Monitoring Program, using the network of flow gages and sampling stations described below.

### River Flow Gages

There are nine continuous flow gages on rivers in the Missisquoi Bay watershed that are relevant to the purposes of this program. These gages are shown in Figure 1 and listed in Table 1. These gages include long-term stations operated by the USGS on the Missisquoi River at Swanton, East Berkshire, and North Troy, Vermont, and on the Rivière aux Brochets (Pike R.) by the MDDEP at Bedford, Québec. Historical average daily flow values for the Vermont gages are available from the USGS website[4].

Three new flow gage stations have been added recently to support the phosphorus load monitoring programs, including sites on the Rivière aux Brochets at Notre-Dame-de-Stanbridge, Québec, the Pike River at East Franklin, Vermont, and the Rivière de la Roche (Rock R.) in St. Armand, Québec. In addition to these stations, the MDDEP and the ministère de l'Agriculture, des Pêcheries et de l'Alimentation (MAPAQ) also installed four continuous flow gage stations on the main tributaries of the Rivière aux Brochets, namely the Castor, Ewing, Morpions, and Walbridge Brooks. However, of these last four only the Castor and Ewing gages are of direct value for the present program because they flow into the R. aux Brochets downstream of the other gages on the main stem of this river. The flow and phosphorus load contributions of the Morpions and Walbridge Brooks are captured by the other gages and sampling stations on the R. aux Brochets.

**River Sampling Stations**

There are eleven water quality monitoring stations in the Missisquoi Bay watershed that are relevant to the purposes of this program. These sampling stations are shown in Figure 1 and listed in Table 2. These stations include two long-term tributary monitoring sites (Missisquoi R. at Swanton, Vermont and R. aux Brochets at Pike River, Québec) sampled by the VT DEC as part of the Lake Champlain Basin Program Long-Term Water Quality and Biological Monitoring Program[5]. The R. aux Brochets sampling site at Pike River, Québec has also been sampled by the MDDEP since 1979 (station 03040015).

Ten additional monitoring stations were established more recently by the MDDEP. Six of them were located on the R. Missisquoi, R. aux Brochets, R. Sutton, and R. de la Roche near the border crossings to support the phosphorus load monitoring program. Four others have been installed on the main tributaries of R. aux Brochets (the Ewing, Castor, Morpions and Walbridge Brooks). The Ewing and Castor Brook stations are of direct value to this load monitoring program, since they flow into R. aux Brochets downstream of the stations located on the main stem of the Pike River (PIKE01/03040015). Phosphorus measurements taken at the sampling site located at Pike River do not take into account the load of these two brooks.

**Wastewater Treatment Facilities**

There are eight wastewater treatment facilities in the Vermont portion of the Missisquoi River watershed. The permitted flow rate, permitted phosphorus concentration limit, TMDL phosphorus wasteload allocation[6], and the mean phosphorus load discharged during calendar years 2002-2005 is listed for each facility in Table 3.

Similar information is provided for the Québec facilities in Table 3. In 2002, after the merging of the village and canton of Sutton, and the amalgamation of Stukely with Eastman, 29 municipalities were totally or partially found within the boundaries of the Missisquoi Bay watershed in the Province of Québec. Among the 18 municipalities most likely to discharge wastewater in the rivers and streams of the watershed, 11 were served by sewers. However, at the time of this study, only eight of them had their wastewater treated by a total of six treatment plants (Bedford, Eastman, Potton, Sutton, Saint-Armand, and Venise-en-Québec).

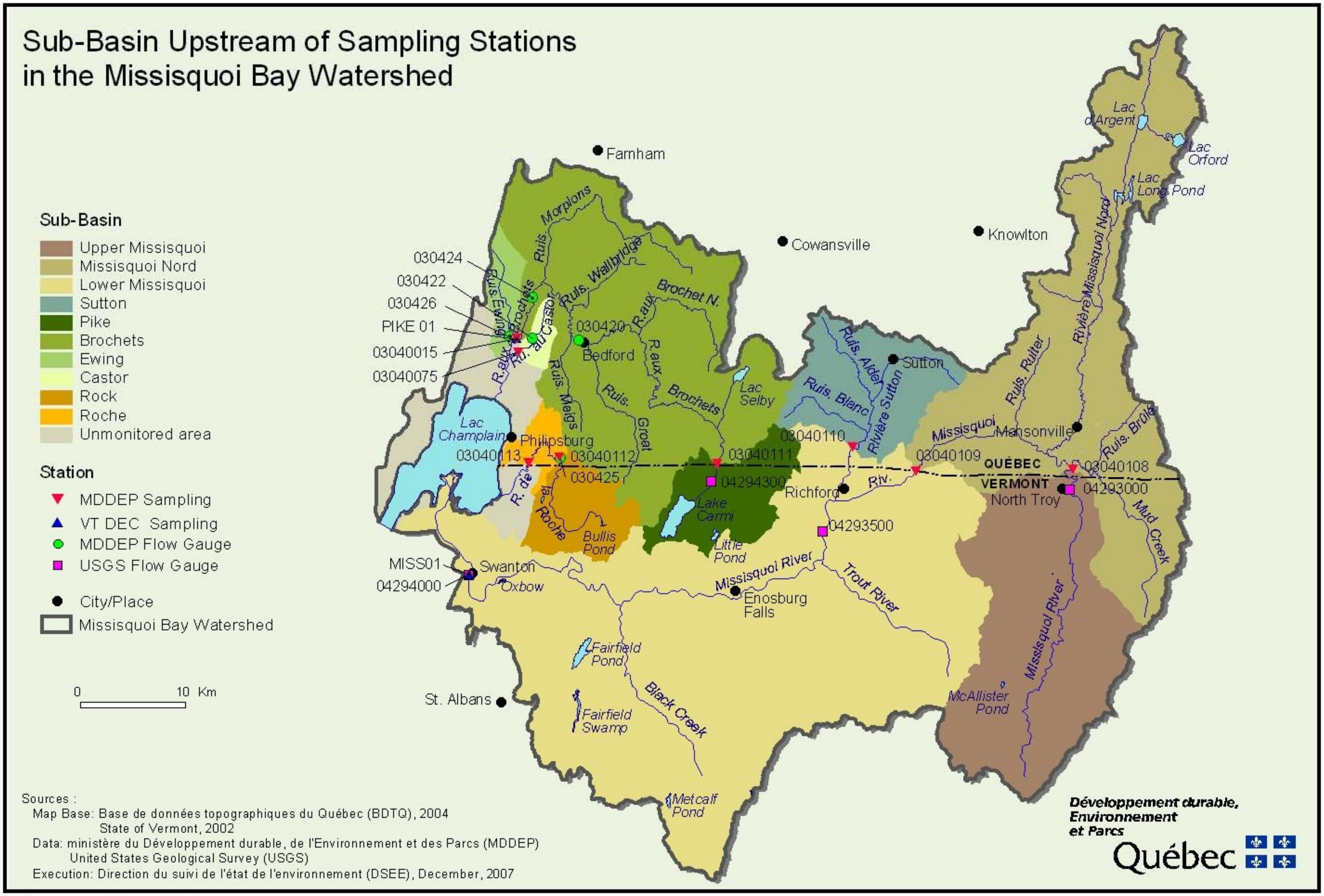




**Figure 1. Stream flow gages and phosphorus sampling stations in the Missisquoi Bay watershed, and sub-basins defined for this analysis.**

**Table 1. List of river flow gages in the Missisquoi Bay watershed.**

| Agency | Reference | Location | Latitude °N | Longitude °W | Start Year | Drainage Area ($km^2$) |
|---|---|---|---|---|---|---|
| USGS | 04294000 | Missisquoi River at Swanton | 44.9167 | 73.1289 | 1990 | 2,201 |
| USGS | 04293500 | Missisquoi River at East Berkshire | 44.9600 | 72.6969 | 1915 | 1,240 |
| USGS | 04293000 | Missisquoi River at North Troy | 44.9728 | 72.3858 | 1931 | 339 |
| USGS | 04294300 | Pike River at East Franklin | 45.0028 | 72.8356 | 2001 | 89.3 |
| MDDEP | 030420 | Rivière aux Brochets à Bedford | 45.1219 | 72.9942 | 1979 | 404 |
| MDDEP | 030424 | Rivière aux Brochets à Notre-Dame-de-Stanbridge | 45.1586 | 73.0506 | 2002 | 586 |
| MDDEP | 030425 | Rivière de la Roche à Saint Armand | 45.0217 | 73.0161 | 2002 | 70.9 |
| MAPAQ | 030422 | Ruisseau Castor | 45.1103 | 73.0736 | 1997 | 11.0 |
| MDDEP | 030426 | Ruisseau Ewing à Saint-Pierre-de-Véronne-à-Pike-River | 45.1253 | 73.0772 | 2002 | 29.1 |

**Table 2. List of river phosphorus sampling stations in the Missisquoi Bay watershed.**

| Agency | Reference | Location | Latitude °N | Longitude °W | Start Year | Drainage Area ($km^2$) |
|---|---|---|---|---|---|---|
| VT DEC | MISS01 | Missisquoi River at Swanton | 44.9205 | 73.1272 | 1990 | 2,201 |
| VT DEC | PIKE 01[a] | Pike River at Pike River, Rt. 133 | 45.1230 | 73.0697 | 1990 | 594 |
| MDDEP | 03040015[a] | Rivière aux Brochets at Pike River, Rt. 133 | 45.1230 | 73.0697 | 1979 | 594 |
| MDDEP | 03040108 | Rivière Missisquoi upstream of Mud Brook | 45.0132 | 72.3974 | 1998 | 369 |
| MDDEP | 03040109 | Rivière Missisquoi near East Richford | 45.0121 | 72.5879 | 1998 | 938 |
| MDDEP | 03040110 | Rivière Sutton, bridge on Road 139 near Abercorn | 45.0325 | 72.6625 | 1998 | 149 |
| MDDEP | 03040111 | Rivière aux Brochets, north of border near 188, Highway 237 | 45.0177 | 72.8255 | 1998 | 98.2 |
| MDDEP | 03040075 | Ruisseau au Castor, bridge near its mouth | 45.1095 | 73.0750 | 2001 | 11.0 |
| MDDEP | 03040073 | Ruisseau Ewing, bridge near its mouth | 45.1195 | 73.0791 | 2001 | 30.8 |
| MDDEP | 03040112 | Rivière de la Roche, north of border | 45.0243 | 73.0168 | 1998 | 70.9 |
| MDDEP | 03040113 | Rivière de la Roche, north of border (111, Bradley Rd.) | 45.0177 | 73.0519 | 1998 | 97.8 |

[a] Same location; results from these two stations were pooled for this analysis.

**Table 3. List of wastewater treatment facilities in the Missisquoi Bay watershed, including their permit requirements and phosphorus loads discharged.**

| Facility | Sub-Basin[a] | Permit Flow Limit (mgd) | Permit Flow Limit ($m^3$/d) | Permit Conc. Limit (mg/L) | Wasteload Allocation[b] (mt/yr) | 2002-2005 Mean Load (mt/yr) |
|---|---|---|---|---|---|---|
| Vermont | | | | | | |
| Enosburg Falls | Lower Missisquoi | 0.450 | 1,703 | 0.8 | 0.373 | 0.093 |
| Newport Center | Missisquoi Nord | 0.042 | 159 | | 0.006 | 0.005 |
| North Troy | Upper Missisquoi | 0.110 | 416 | | 0.760 | 0.182 |
| Richford | Lower Missisquoi | 0.380 | 1,438 | 0.8 | 0.420 | 0.755 |
| Rock Tenn Co. | Lower Missisquoi | 3.500 | 13,248 | 0.8 | 1.260 | 0.156 |
| Sheldon Springs | Lower Missisquoi | 0.054 | 204 | | 0.373 | 0.061 |
| Swanton | Lower Missisquoi[c] | 0.900 | 3,407 | 0.8 | 0.746 | 0.334 |
| Troy/Jay | Upper Missisquoi | 0.200 | 757 | 0.8 | 0.221 | 0.286 |
| Vermont Total | | | | | 4.159 | 1.873 |
| Québec | | | | | | |
| Abercorn[d] | Sutton | 0.048 | 182 | 1.0 | 0.066 | 0.219 |
| Bedford[e] | Brochets | 1.156 | 4,375 | 1.0 | 2.008 | 0.771 |
| Eastman | Missisquoi Nord | 0.064 | 243 | 1.0 | 0.110 | 0.039 |
| Notre-Dame-de-Stanbridge[d] | Brochets | 0.037 | 140 | 1.0 | 0.051 | 0.307 |
| Potton | Missisquoi Nord | 0.064 | 244 | 1.0 | 0.110 | 0.037 |
| Potton (Owl's Head area)[f] | Missisquoi Nord | 0.099 | 375 | 1.0 | 0.241 | 0.016 |
| Stanbridge East[d] | Brochets | 0.016 | 60 | 1.0 | 0.022 | 0.318 |
| Stukely-Sud[g] | Missisquoi Nord | 0.016 | 60 | 1.0 | 0.015 | 0.002 |
| Sutton | Sutton | 0.388 | 1,468 | 1.0 | 0.475 | 0.344 |
| Saint Armand | Roche | 0.030 | 115 | 0.5 | 0.029 | 0.121 |
| Québec Total[h] | | | | | 3.124 | 2.174 |

[a] Sub-basins are shown in Figure 1.

[b] Vermont wasteload allocations (metric tons per year) are as defined in the Lake Champlain Phosphorus TMDL. As of 2007, all Vermont facilities were meeting their TMDL wasteload allocations following treatment upgrades at Richford and Troy/Jay.

[c] Discharges downstream of river sampling station.

[d] No treatment facility. The 2002-2005 actual loads were estimated using 2.0 g/person/d and the total sewered population of the municipality. MAMR announced in January 2008 that Stanbridge East, Notre-Dame-de-Stanbridge and Frelighsburg will each have a treatment facility in the near future. Frelighsburg (not listed in the table) has no sewer system and its dwellings rely on individual septic systems to treat their wastewaters.

[e] The Bedford wastewater treatment facility (WWTF) is also serving Stanbridge Station.

[f] This is a private facility serving a ski resort area.

[g] This is a private facility serving a camp and trailer park. Stukely-Sud has 91% of its territory located in the Yamaska River watershed.

[h] The Venise-en-Québec facility (not listed in table) also treats the wastewater of Saint-Georges-de-Clarenceville and discharges the treated wastewater to the Rivière du Sud, outside of the Missisquoi Bay watershed.

Although the Venise-en-Québec treatment plant, which serves Venise-en-Québec and Saint-Georges-de-Clarenceville, is located within the watershed, it is not listed in Table 3 because it discharges its treated wastewater in the Rivière du Sud, outside the limits of the Missisquoi Bay watershed, since December 1994. Two of Québec's treatment facilities listed in Table 3 are small scale private projects serving a campground and trailer park (Stukely-Sud) and a ski resort area (Owl's Head). The municipalities of Abercorn, Notre-Dame-de-Stanbridge and Stanbridge East, which had no facility at the time of this study, are also listed in Table 3 along with their estimated 2002-2005 mean discharge.

The Abercorn treatment plant has been in operation since August 2007. In addition, wastewater treatment facility construction projects were announced in January 2008 for the municipalities of Notre-Dame-de-Stanbridge, Frelighsburg and Stanbridge East. Finally, also of interest is the announcement that the 320 residences found on Pointe Jamieson, in Venise-en-Québec, which had been relying in the past on individual septic systems, will have their wastewater collected in 2008 by a sewer system and treated by the existing Venise-en-Québec facility.

## Sampling Methods

### Vermont River Samples

The Vermont tributary sampling stations in the Missisquoi Bay Watershed were sampled as part of the Lake Champlain Long-Term Water Quality and Biological Monitoring Program[5], supported by the Lake Champlain Basin Program. This monitoring project includes many other stations on Lake Champlain and its tributaries, and many other sampling parameters in addition to total phosphorus.

Tributary samples were obtained from bridges using depth and velocity-integrating sampling devices (USGS DH-48 or DH-59 suspended sediment samplers). An effort was made to obtain up to 20 total phosphorus samples per year at each tributary site, including as high a proportion of samples as possible during high flow conditions in order to improve the precision of annual mass loading estimates.

### Québec River Samples

The Québec tributary sampling stations in the Missisquoi Bay Watershed were sampled as part of the Québec River Monitoring Network (Réseau-rivières) supported by the MDDEP. As it is the case for Vermont, this monitoring project also includes many other stations located in more than 40 different watersheds, and many other sampling parameters in addition to total phosphorus.

For most of the stations, tributary samples were obtained from bridges using a depth-integrating sampling device (open bottle mounted on a sampling iron)[7]. For a few small tributaries, grab samples were obtained by using an open bottle mounted at the end of an aluminum pole. Since 2001, Québec has been duplicating Vermont's approach and making an effort to obtain up to 20 total phosphorus samples per year at each tributary site, including as high a proportion of samples as possible during high flow conditions in order to improve the precision of annual mass loading estimates.

### Vermont Wastewater Samples

Vermont wastewater treatment facilities were sampled for total phosphorus in the final effluent by the plant operators under the terms of their state discharge permits. The phosphorus samples were generally obtained monthly as 8-hr composites. Wastewater flows were monitored continuously. The monthly average flow and total phosphorus results were reported by the plant operators to the VT DEC.

### Québec Wastewater Samples

As part of an agreement with the MDDEP, the ministère des Affaires municipales et des Régions (MAMR) operates a municipal wastewater treatment facility monitoring program to assess plant performance and determine whether or not environmental requirements are met. Environmental requirements were determined for one or many of the following parameters, depending upon the facility type and equipment: total phosphorus, biochemical oxygen demand (BOD), suspended solids and fecal coliforms. For most of the facilities, monthly average wastewater flows and total phosphorus results were reported by the plant operators to the MAMR.

## Laboratory Analytical Methods

### Vermont River Samples

Samples obtained at Vermont monitoring stations for total phosphorus analysis were immediately placed without filtration or preservation into 75 ml borosilicate glass test tubes. The samples were analyzed at the VT DEC Laboratory using acid-persulfate digestion in their original containers followed by colorimetric analysis using the ascorbic acid method[8].

### Québec River Samples

Samples obtained at Québec monitoring stations for total phosphorus analysis were immediately placed without filtration or preservation into 500-ml high density polyethylene bottles. Samples were kept refrigerated at 4 degrees Celsius before analysis, which took place within 48 hours. Filtration through a 1.2-µm pore diameter GF/C membrane filter separated dissolved from suspended forms of phosphorus in the Québec River Monitoring Network. This analytical technique was adopted many years ago, instead of the standard 0.45-µm pore diameter membrane filtration, to make a gross separation between dissolved and suspended forms of phosphorus. The choice was made to reduce filtration time and hence the cost of the analyses. The dissolved and suspended forms were added to produce the total phosphorus concentration.

The samples were analyzed at the MDDEP Laboratory, known as the Centre d’expertise en analyses environnementales du Québec (CEAEQ), using ultraviolet digestion followed by colorimetric analysis using the ascorbic acid method[8].

### Comparability of Results Between Laboratories

The sample processing and analytical procedures for total phosphorus differed somewhat between Vermont and Québec. In order to determine the comparability of the river sampling results, sampling crews met on two dates (once in 2005 and once in 2006) to exchange split samples for concurrent analysis at both laboratories. A total of 30 split samples were obtained from the various sampling stations for this comparison.

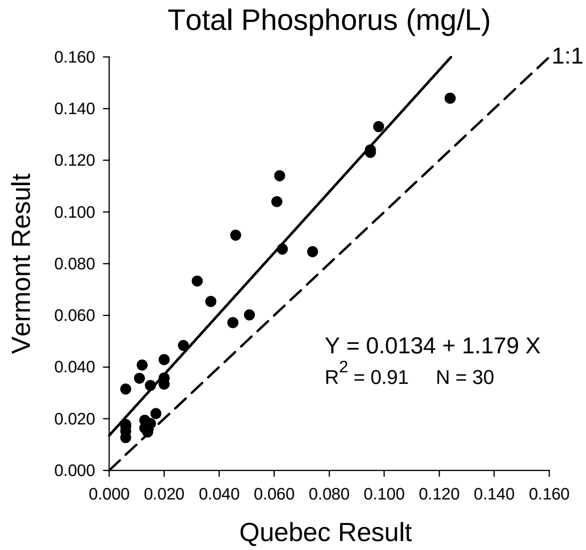


**Figure 2. Comparison of Vermont and Québec laboratory results for split total phosphorus samples.**

The total phosphorus concentrations obtained from the Vermont laboratory tended to be greater than the Québec results (Wilcoxon matched pairs test, $p < 0.001$), probably due to the more complete digestion obtained by the Vermont laboratory using acid-persulfate. A regression equation was developed (Figure 2) so that the Québec results could be converted to values comparable to what would have been obtained using the Vermont method. For the purposes of this report, all Québec laboratory results for total phosphorus were converted to the Vermont method equivalent using the regression equation in Figure 2.

## Flow Data

Average daily flow values for each gage station listed in Table 1 were obtained from their respective agency sources. These flow data are made available on a water year basis (October – September) once they are checked and published as final by the responsible agency. The phosphorus loading analysis in this report used flow data for the four year period of October 2001 to September 2005 (water years 2002-2005). Final flow data for the Québec gages were not available for this analysis beyond water year 2005. All daily flow values were converted for this analysis to units of cubic hectometers per year (1 $hm^3/yr = 10^6 m^3/yr$).

Four of these stream gages had some days for which flow values were missing. In these cases, the missing values were estimated using inter-gage regression equations developed from $\log_{10}$-transformed daily flow values at another reference gage having a complete flow record. The regression equations used to regenerate the missing daily flow values are given in Table 4.

**Table 4. Inter-gage regression equations used to regenerate missing daily flow values. Flow units for X and Y are $hm^3/yr$.**

| Gage Number (Y) | Number of Missing Flow Values[a] | Reference Gage (X) | Regression Equation | $R^2$ |
|---|---|---|---|---|
| 030424 | 32 | 030420 | log Y = 0.390 + 0.887 log X | 0.94 |
| 030426 | 65 | 030424 | log Y = -1.757 + 1.090 log X | 0.81 |
| 030422 | 16 | 030424 | log Y = -2.130 + 1.053 log X | 0.73 |
| 030425 | 36 | 030420 | log Y = -0.954 + 1.004 log X | 0.87 |

[a] from the total 1,461 day record

## Sub-Basin Delineation

The watersheds upstream of each of the ten separate phosphorus sampling stations listed in Table 2 were delineated by the MDDEP Direction du suivi de l'état de l'environnement (DSEE). The drainage areas upstream of each station are listed in Table 2. These sampling stations were used to define the ten sub-basins within the Missisquoi Bay watershed named in Figure 1. Some of these sub-basins are nested within the larger watersheds of downstream sampling stations. The sub-basin boundaries do not correspond exactly with the political border between Québec and Vermont, but each sub-basin is predominantly located within one or the other jurisdiction. A relatively small amount of the total Missisquoi Bay watershed area (about 6% of the total 3,125 $km^2$ area) was not monitored by any sampling station.

## Phosphorus Load Estimation

### River Loads

Phosphorus loads in the Missisquoi Bay tributary rivers were estimated using the U.S. Army Corps of Engineers FLUX program[9,10]. The FLUX program has been used previously to estimate tributary phosphorus loading to Lake Champlain in several applications, including a lakewide phosphorus budget and modeling analysis[3], a phosphorus status and trends analysis[11], and an assessment of the effects of the Québec Municipal Wastewater Abatement Program in the R. aux Brochets watershed[12].

Mean phosphorus loading rates at each sampling station listed in Table 2 were estimated for the period of 2002-2005 (water years) using the phosphorus concentration results for dates within this time period with the daily flow data from the nearest appropriate gage station. In order to adjust for differences in the watershed areas captured by the flow gages vs. the sampling stations, the loading estimates were multiplied by the ratio between the drainage area at the phosphorus sampling station and the drainage area at the flow gage station.

All ten sampling stations had a statistically significant, positive relationship between the phosphorus concentration and the average flow on the day of sampling. Loading estimates were therefore based on log-scale regressions between the phosphorus concentration and the daily flow (FLUX Method 6[10]). When regression residuals were found to be dependent on flow, separate regression relationships were established for different flow strata in order to eliminate the residual dependence. An error-analysis procedure in the FLUX program was used to estimate the coefficient of variation (CV) for the mean loads and their 95% confidence intervals.

### Wastewater Loads

Phosphorus loads discharged from the wastewater treatment facilities in the Missisquoi Bay watershed were captured in the samples obtained at the sampling stations shown in Figure 1. The exception was the Swanton, Vermont facility which discharges downstream of the monitoring sites on the Missisquoi River. Wastewater phosphorus loads were calculated for each facility listed in Table 3 so that the total loads from each sub-basin could be separated into point and nonpoint source components. Nonpoint source loads were calculated simply by subtracting the wastewater loads from the total loads determined from the FLUX loading analysis.

Wastewater flows and phosphorus concentrations were reported monthly by the facility operators to the VT DEC or the Québec MAMR. This information was compiled annually by VT DEC and MAMR, and the annual phosphorus loads from each facility were calculated as the product of the annual average flow and the annual average total phosphorus concentration. The average phosphorus loads discharged by each facility during the study period are given in Table 3.

## Statistical Analyses

In this study, we used a **before/after** design[13] to detect whether a discrete water quality change due to watershed management actions occurred between the reference period 1990-1992 and the post-treatment period 2001-2005. An analysis of covariance procedure (ANCOVA), applied with the General Linear Model (PROC GLM; SAS Institute inc.[14]), was used to test for significant differences in the log-scale regressions between the phosphorus concentration and the daily flow calculated for the 1990-1992 and the 2001-2005 time periods, for both the Missisquoi and the Pike Rivers. Separate analyses were performed for each flow stratum.

A test for homogeneity of slopes was used to determine the probability that the slopes of the concentration-flow regression lines were equal between the two periods. The effect of the classification variable "period" on concentration at a given flow was determined by the probability that the intercepts of the regression lines were equal. Differences were not considered significant when probability values (P) were greater than 0.05. A probability plot of the residuals (PROC UNIVARIATE; SAS Institute inc.[14]) indicated that the normality assumption was reasonable. Constant variance and autocorrelation of the residuals were checked in SAS using the GLM and GPLOT procedures. A plot of the residuals versus predicted values showed no obvious pattern, suggesting that the assumptions of independence and equal variance were also reasonable.

# Results

## Phosphorus Concentrations

The distributions of phosphorus concentrations measured at the ten river monitoring stations in the Missisquoi Bay watershed are shown in Figure 3. The Castor, Rock, and Ewing had the highest median phosphorus concentrations. Sites on the Brochets (lower Pike) and Missisquoi Rivers had intermediate phosphorus median values, but their concentrations spanned a wide range that included some high values. Lowest concentrations were found in the upper reaches of the Pike, Missisquoi, and Sutton Rivers.

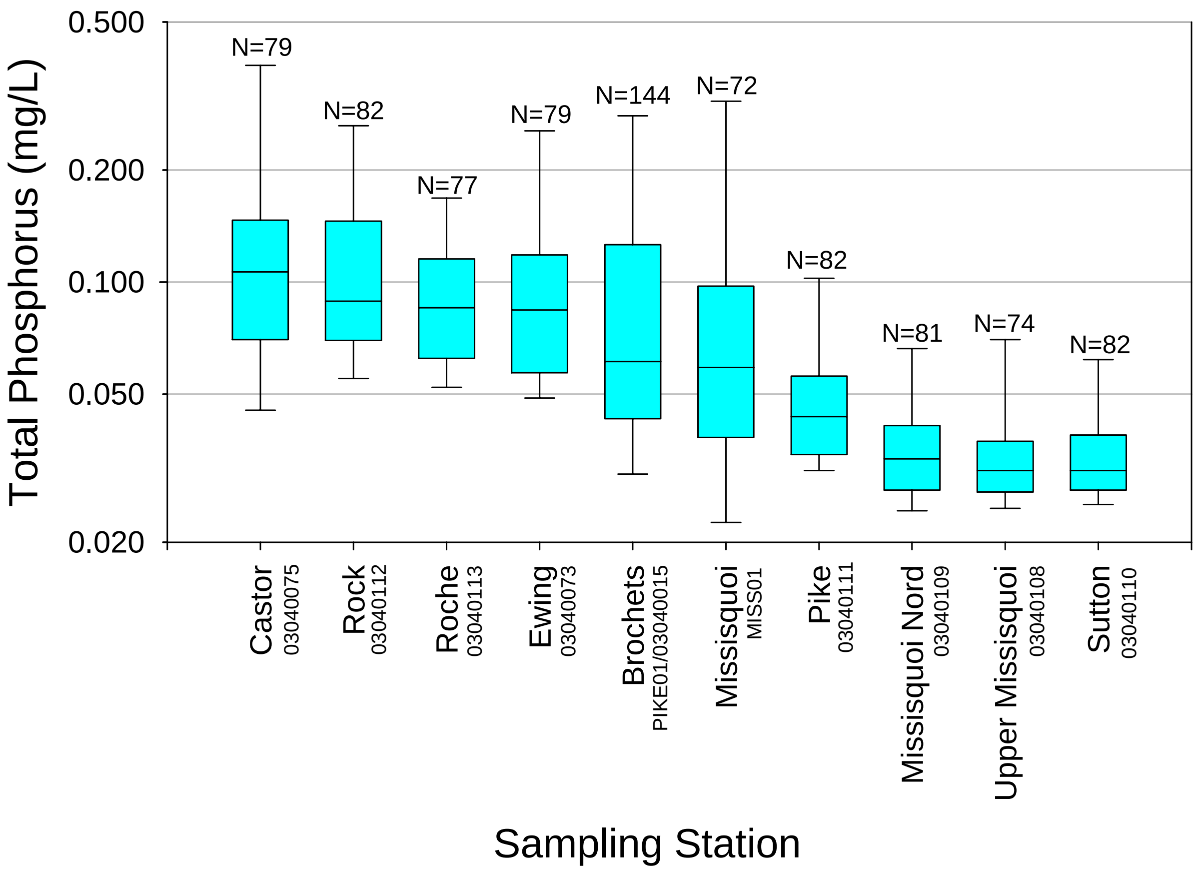


**Figure 3. Distributions of total phosphorus concentrations at river sampling stations. Box plots show 5$^{th}$, 25$^{th}$, median, 75$^{th}$, and 95$^{th}$ percentiles for all sample results obtained during water years 2002-2005. Number of samples (N) for each station are indicated.**

## Sub-Basin Phosphorus Loads

The mean phosphorus loads calculated at each sampling station during water years 2002-2005 are given in Table 5. Where the watersheds upstream of the sampling stations included more than one sub-basin as defined in Figure 1, the loads estimated at upstream stations were subtracted in order to calculate the loads for individual sub-basins. The individual sub-basin loads are listed in Table 6 and shown in Figure 4. The wastewater components of the loads shown in Figure 4 were derived from the data provided in Table 3.

As would be expected, the largest loads came from the largest sub-basins. A tabulation of the loads for the Québec and the Vermont sub-basins indicated that 69.5 mt/yr (37%) of the total load was derived from Québec and 118.4 mt/yr (63%) of the total came from Vermont. Wastewater discharges made up 3.1% of the total load from Québec and 1.6% of the total from Vermont. The assignments of phosphorus loads to Québec and Vermont are only approximate because the sub-basin hydrologic boundaries do not match the political boundaries exactly (Figure 1).

The areal phosphorus export rates (kg/ha/yr) for each sub-basin are listed in Table 6 and compared in Figure 5. Areal export rates provide an indication of the density of phosphorus sources within each sub-basin. The highest export rates were measured in the small, highly agricultural Castor and Ewing Brook watersheds, and in the Rock River sub-basin in Vermont. The Lower Missisquoi sub-basin also had relatively high phosphorus export rates. The Vermont portion of the Missisquoi Bay watershed had, on average, a higher phosphorus export rate (0.716 kg/ha/yr) than the Québec portion (0.542 kg/ha/yr).

## Comparison with 1991 Base Year Loads

The mean phosphorus loading rate to Missisquoi Bay from all sub-basins during water years 2002-2005 was estimated to be 188 mt/yr (Table 6). This load was 13% higher than the rate of 167 mt/yr measured during the 1991 base year that was used as a reference point in the Lake Champlain Phosphorus TMDL[6] and the Québec-Vermont water quality agreement of 2002[1]. The 2002-2005 mean loading rate was substantially above the target load of 97 mt/yr established for the bay in these documents.

The higher river flow rates recorded during 2002-2005 in the Missisquoi River, the largest sub-basin of the watershed, are likely the major reason why phosphorus loads were greater in the Missisquoi Bay watershed during 2002-2005 than during the 1991 base year. The mean flow at the Missisquoi River gage in Swanton, VT during water years 2002-2005 was 1,621 $hm^3$/yr, which was 26% higher than the 1991 base year flow of 1,284 $hm^3$/yr. However, the 2002-2005 mean flow at the Rivière aux Brochets (Pike River) gage at Bedford, QC was only 5% higher than the 1991 mean flow (196 vs. 187 $hm^3$/yr).

In order to compare the phosphorus loads estimated for 2002-2005 with the 1991 base year loads under comparable hydrologic conditions, the FLUX program was used to recalculate the 2002-2005 mean loads to Missisquoi Bay from the Missisquoi and Pike Rivers using the 1991 hydrologic data. The phosphorus concentration vs. flow regression relationships determined for these rivers for the 2002-2005 monitoring period were used with the daily flow records during the 1991 base year to estimate the phosphorus loading rates that would have occurred during

**Table 5. Mean flows and phosphorus loads at gages and sampling stations during water years 2002-2005.**

| Sub-Basin | State/ Province | Sampling Station | Flow Gage | Mean Flow at Gage ($hm^3$/yr) | Drainage Area Ratio[a] | Mean Load at Sampling Station (mt/yr) | CV[b] |
|---|---|---|---|---|---|---|---|
| Upper Missisquoi | VT | 03040108 | 04293000 | 277.0 | 1.09 | 18.3 | 0.170 |
| Missisquoi Nord | QC | 03040109 | 04293500 | 948.3 | 0.76 | 40.2 | 0.072 |
| Sutton | QC | 03040110 | 04293500 | 948.3 | 0.12 | 8.2 | 0.283 |
| Lower Missisquoi | VT | MISS01 | 04294000 | 1620.9 | 1.00 | 137.2 | 0.081 |
| Pike | VT | 03040111 | 04294300 | 51.9 | 1.10 | 4.1 | 0.075 |
| Brochets | QC | PIKE01/03040015 | 030424 | 281.1 | 1.01 | 36.9 | 0.076 |
| Ewing | QC | 03040073 | 030426 | 10.9 | 1.06 | 3.7 | 0.107 |
| Castor | QC | 03040075 | 030422 | 4.7 | 1.00 | 1.7 | 0.129 |
| Rock | VT | 03040112 | 030425 | 26.0 | 1.00 | 7.2 | 0.167 |
| Roche | QC | 03040113 | 030425 | 26.0 | 1.38 | 8.4 | 0.310 |

[a] Drainage area of sampling station / drainage area of flow gage station.
[b] Coefficient of variation of the mean phosphorus load.

**Table 6. Individual sub-basin mean phosphorus loads and areal export rates during water years 2002-2005.**

| Sub-Basin | State/ Province[a] | Upstream Sub-Basins[b] | Individual Sub-Basin Load (mt/yr) | Individual Sub-Basin Area ($km^2$) | Individual Sub-Basin Export Rate (kg/ha/yr) |
|---|---|---|---|---|---|
| Upper Missisquoi | VT | None | 18.3 | 369.3 | 0.495 |
| Missisquoi Nord | QC | Upper Missisquoi | 21.9 | 568.4 | 0.386 |
| Sutton | QC | None | 8.2 | 148.9 | 0.548 |
| Lower Missisquoi | VT | Upper Miss., Miss. Nord, Sutton | 88.8 | 1114.4 | 0.797 |
| Pike | VT | None | 4.1 | 98.2 | 0.415 |
| Brochets | QC | Pike | 32.8 | 496.0 | 0.662 |
| Ewing | QC | None | 3.7 | 30.8 | 1.200 |
| Castor | QC | None | 1.7 | 11.0 | 1.566 |
| Rock | VT | None | 7.2 | 70.9 | 1.015 |
| Roche | QC | Rock | 1.2 | 26.9 | 0.441 |
| | | Québec Total | 69.5 (37%) | 1,282 | 0.542 |
| | | Vermont Total | 118.4 (63%) | 1,653 | 0.716 |
| | | Missisquoi Bay Watershed Total | 187.9 (100%) | 2,935 | 0.640 |

[a] Sub-basin boundaries are based on sampling station watersheds and do not correspond exactly to political boundaries.
[b] Loads at upstream sampling stations (Table 5) were subtracted to calculate individual sub-basin loads.

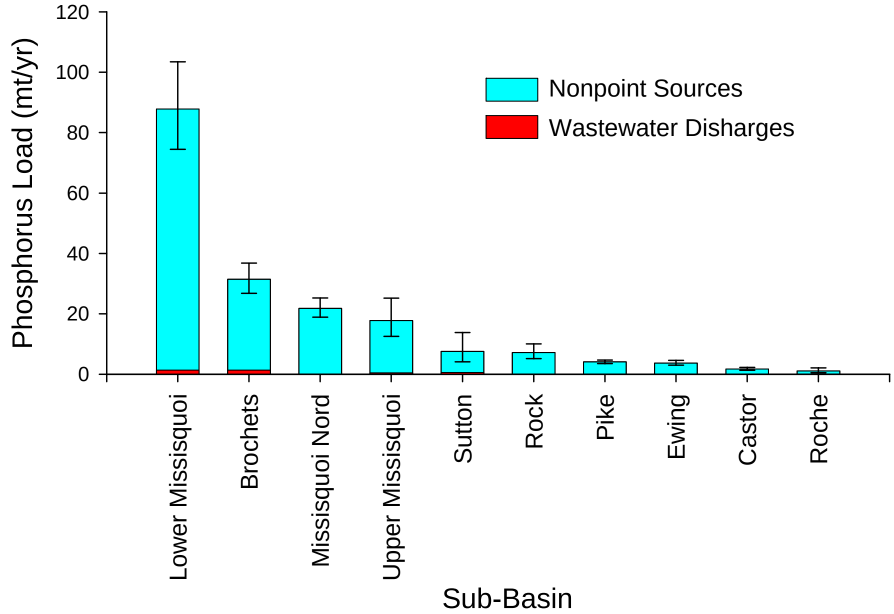


**Figure 4. Mean phosphorus loading rates from Missisquoi Bay watershed sub-basins during water years 2002-2005. Error bars are 95% confidence intervals, calculated according to FLUX program procedures[9]. Wastewater components of the total load are from Table 3.**

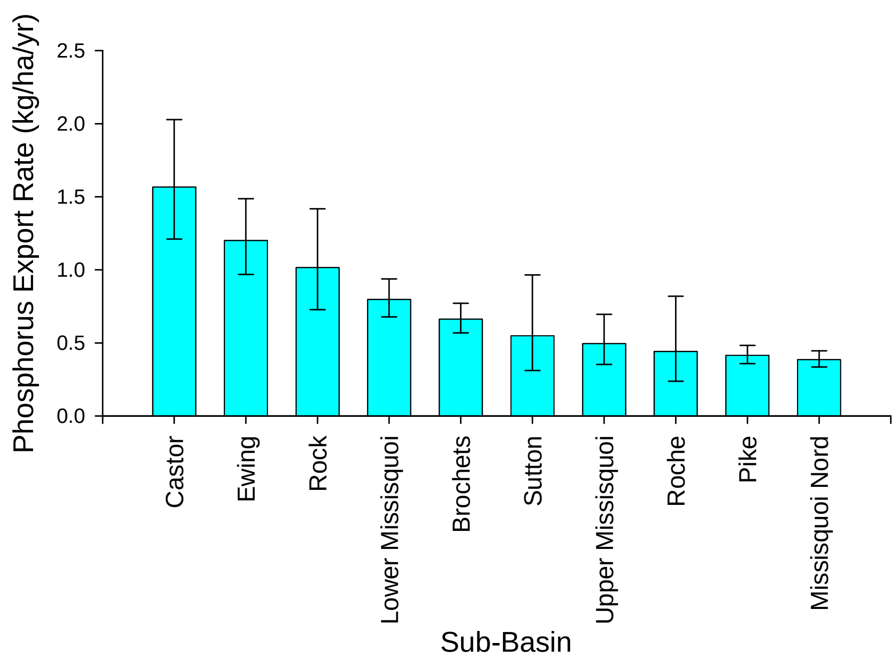


**Figure 5. Areal phosphorus export rates from Missisquoi Bay watershed sub-basins during water years 2002-2005. Error bars are 95% confidence intervals, calculated according to FLUX program procedures[9].**

2002-2005 if the hydrologic conditions had been the same as in 1991. The results (Figure 6) indicated that the phosphorus loading rate from both rivers would have been lower during 2002-2005 than in 1991 under 1991 flow conditions, although the differences were not statistically significant. A statistical analysis of flow-adjusted phosphorus concentrations over the period of 1990-2004 done for the Lake Champlain Basin Program[15] produced similar conclusions that there was no significant trend in the Missisquoi River over this time period, and a decreasing trend in the Pike River.

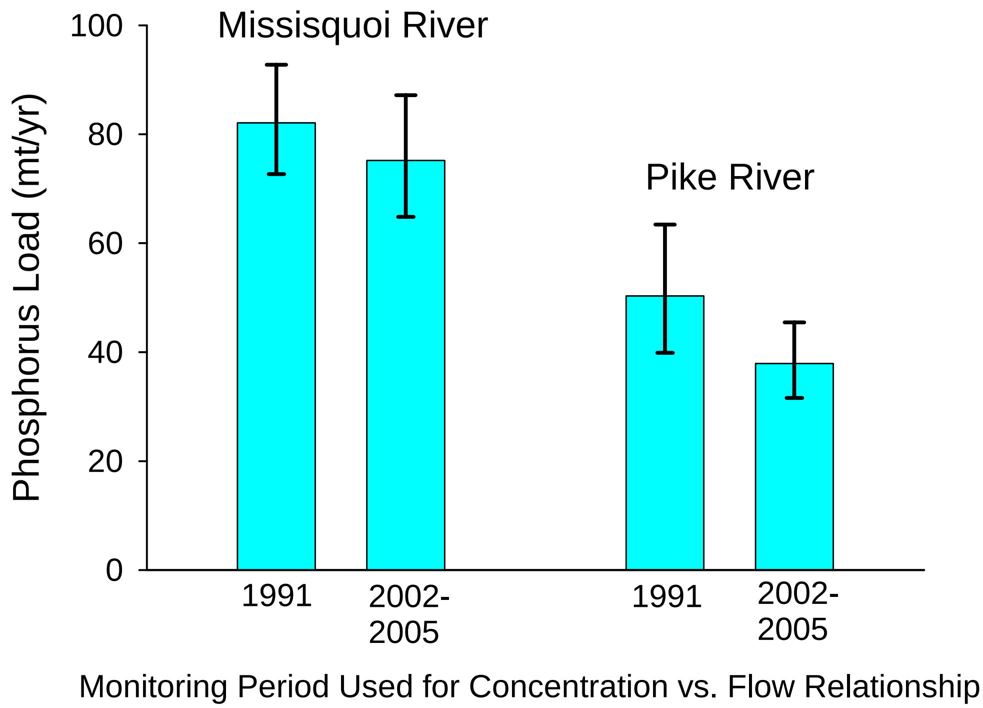


**Figure 6. Comparison of phosphorus loading rates at the mouths of the Missisquoi and Pike Rivers calculated using 1991 base year hydrologic conditions. Loading estimates for the 1991 base year[3] are compared with estimates using the phosphorus concentration vs. flow regression relationships from water years 2002-2005. Error bars are 95% confidence intervals calculated according to FLUX program procedures[9].**

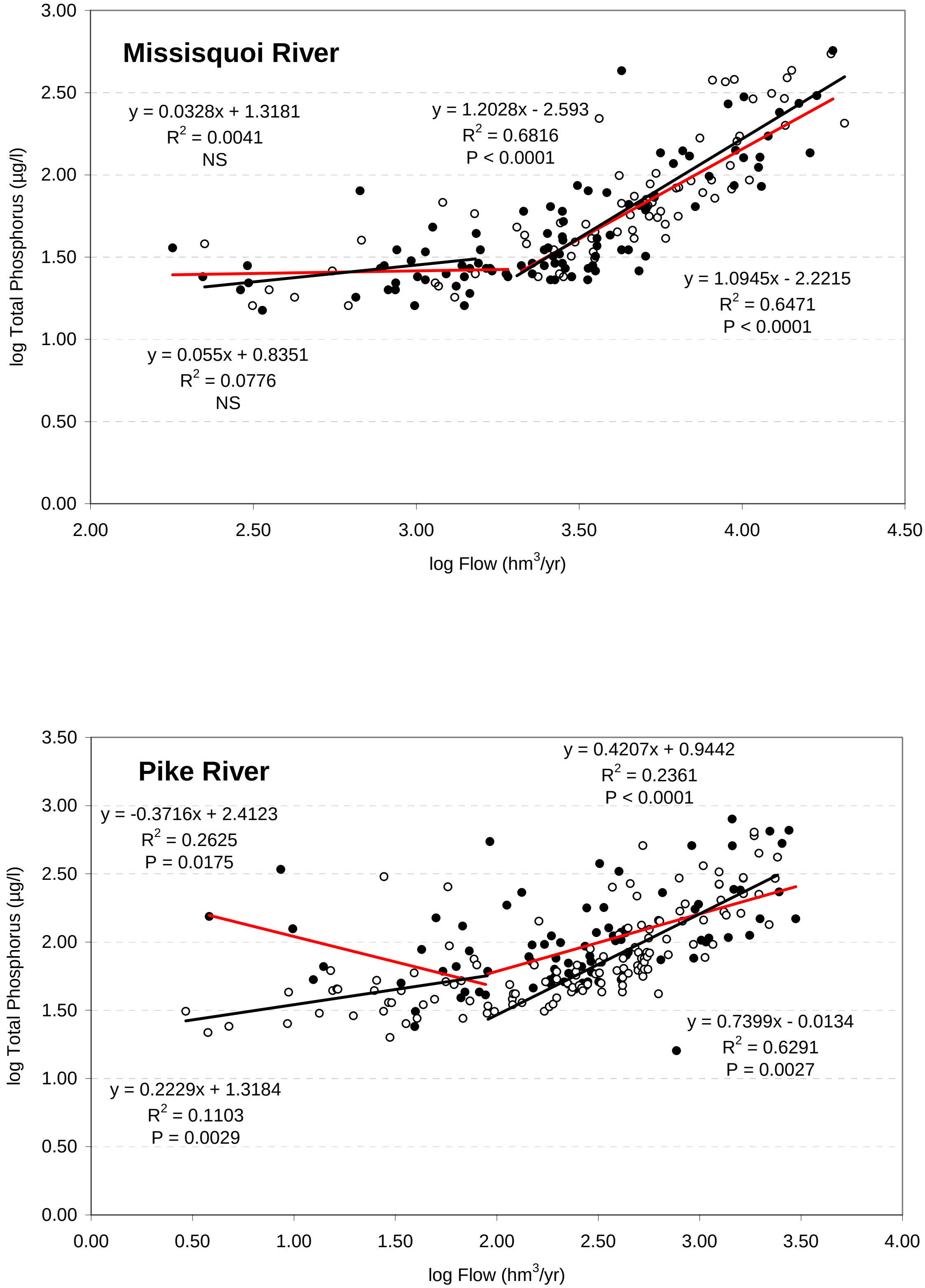


**Figure 7. Comparison of the log-scale regressions between the total phosphorus concentration and the daily flow calculated for the 1990-1992 (red lines and black dots) and the 2001-2005 time periods (black lines and open dots), for both the Missisquoi and Pike Rivers (see text for details). Separate regression relationships were established for different flow strata in order to eliminate the residual dependence.**

A comparison of the log-scale regressions between total phosphorus concentration and the daily flow calculated for the 1990-1992 and the 2001-2005 time periods, for both the Missisquoi and Pike Rivers, provided some interesting observations. As shown by Figure 7 and confirmed by the results of the analysis of covariance performed on the Missisquoi River data, it appears that the concentration-flow relations, calculated for two flow strata, did not change significantly between the two periods. Phosphorus concentrations did not vary (slope = 0.033; t = 0.33; P = 0.746) and remained the lowest (median = 25 µg/l) in the low-flow range of the data (between 100 and 2,000 $hm^3$/yr). The strong positive regression observed in 1990-1992 for the high-flow range data (slope = 1.094; t = 10.90; P < 0.0001) remained unchanged in the 2002-2005 period (t = 0,72; P = 0.4746). These observations explain why the mean phosphorus loading in the Missisquoi River, calculated using the 1991 hydrological data and the 2002-2005 concentration-flow relation, was only 8 % lower than the mean 1991 phosphorus loading.

On the other hand, results obtained for the Pike River (Figure 7) show that the concentration-flow relations changed significantly between the two time periods for both the low-flow and the high-flow range data. The very significant change in the low-flow range from a negative slope in the 1990-1992 period (slope = -0.372; t = -2.46; P = 0.0175) to a positive slope in the 2002-2005 period (slope = 0.594; t = 3.14; P = 0.0029) reflects the effects of the point source treatment that took place between 1992 and 1995 in Bedford, QC. The significant change also observed in the high-flow stratum for the 2002-2005 period (slope = 0.319; t = 3.05; P = 0.0027), with respect to the significant regression noted for the 1990-1992 period (slope = 0.421; t = 5.52; P < 0.0001), suggests that other actions that have taken place in the watershed as part of the Québec Wastewater Abatement Programs may have begun to show positive results. These significant changes observed for the Pike River explain the 25% reduction recorded in the mean phosphorus loading for the 2001-2005 period, even though a 5% increase was observed in the mean flow rate.

The comparison of the 2002-2005 results with those of the reference year 1991 suggests that the wastewater treatment upgrades and watershed management actions taken since 1991 have been beneficial in limiting phosphorus loading to Missisquoi Bay. While higher flows brought more phosphorus to the bay during 2002-2005 than in 1991, it is likely that the phosphorus loading increase that resulted from the higher flows was less than it would have been without these management efforts in place, especially in the Pike River watershed. Since most of the phosphorus load that reaches Missisquoi Bay comes from nonpoint sources, the results of this study emphasize the importance of pursuing efforts to implement best management practices in order to reduce the amount of phosphorus that is transported to water courses through runoff and erosion processes. In spite of the apparent improvement, the concentration–flow relations of both the Missisquoi River and the Pike River still show a very strong and positive slope which stresses the importance of nonpoint sources in these “rain-driven” watersheds.

## Conclusions and Recommendations

1. The mean phosphorus loading rate to Missisquoi Bay estimated for water years 2002-2005 was 188 mt/yr. This was higher than the rate of 167 mt/yr measured during the 1991 base year, and substantially above the target load of 97 mt/yr established for the bay in the Lake Champlain Phosphorus TMDL and in the Québec and Vermont water quality agreement of 2002.

2. Higher river flows during 2002-2005 in the Missisquoi River, the largest sub-basin in the watershed, are likely the major reason for the increased phosphorus loading rate compared with the 1991 base year. An analysis of phosphorus loads to Missisquoi Bay from the Missisquoi and Pike Rivers under comparable hydrologic conditions suggested that phosphorus loading to the bay would have decreased if flow conditions had remained as they were during 1991.

3. A comparison of the concentration-flow relationships obtained for the 1990-1992 reference period and the 2001-2005 post-treatment period showed no significant differences for the Missisquoi River in both the low-flow and the high-flow range data. The same comparison revealed significant differences for the Pike River in both the low-flow and the high-flow range data, with generally lower phosphorus concentrations observed during 2001-2005 than during 1990-1992 at equivalent flow rates. These findings suggest a beneficial effect of the wastewater treatment upgrades and watershed management efforts that have taken place since 1991 in the Pike River watershed.

4. The division of phosphorus loading between Vermont and Québec during 2002-2005 was essentially the same (within limits of statistical uncertainty) as the 60/40% estimate derived from the land use modeling analysis[16] that was used as the basis for the 2002 water quality agreement. The results confirm that the 60/40 ratio was a reasonable basis for the division of responsibility between Québec and Vermont.

5. The mean phosphorus loading rates (mt/yr) estimated by this analysis provided an indication of which sub-basins within the Missisquoi Bay watershed had the highest loads of phosphorus. Sub-basins having the highest mean phosphorus loading rates were the Lower Missisquoi, Brochets, Missisquoi Nord, and Upper Missisquoi.

6. Areal phosphorus export rates (kg/ha/yr) estimated by this analysis provided an indication of which sub-basins within the Missisquoi Bay watershed had the highest density of phosphorus sources. Sub-basins having the highest areal phosphorus export rates included the Castor, Ewing, and Brochets in Québec, and the Rock and Lower Missisquoi in Vermont.

7. Wastewater discharges were a relatively small source of phosphorus loading to Missisquoi Bay during 2002-2005, representing only 1.6% of the total phosphorus load from Vermont and 3.1% of the total load from Québec. Wastewater phosphorus loading rates have declined by 73% in Vermont and by 74% in Québec, relative to the loading rates that existed during 1991[2].

8. The MDDEP, MAPAQ, VT DEC, and USGS should continue monitoring river flows and phosphorus concentrations at the stations established for this purpose so that long-term changes in phosphorus loading can be measured. Future data analyses would be aided if

final flow data from all the gages could be provided within one year after the end of each water year.

9. Future analyses of the data produced by this monitoring program should focus on detection of trends in phosphorus loading rates over time at each sampling station using appropriate statistical methods, including analysis of flow-adjusted concentrations[11] and analysis of covariance[13]. The four years of data currently available are not yet sufficient for trends analysis, but it will be important in the future to use the data from this program to document phosphorus reductions achieved from water quality management actions in the Missisquoi Bay watershed.

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