Reservoir Water Quality Treatment Study, II

Water Quality Assessment and Modeling for the North Thames River watershed, including its major reservoirs and Pittock Lake on the Thames River

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Prepared for

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1. Executive Summary

Most of the Upper Thames River watershed is agricultural and programs to reduce the impact of agricultural runoff have been implemented for many years (Appendix H and see *Clean Water Project* www.cleanwaterprogram.ca). Increased monitoring in 2005 and long-term data analysis was conducted to help identify the more severe pollution sources, so that the watershed restoration efforts can be improved by focussing on distinct river sections and reservoirs. Our previous study (Freshwater Research 2005) was broadened to encompass not only the major reservoirs, especially Fanshawe Lake, but the whole watershed with its reservoirs of the North Thames River (NTR).

Limnological characteristics and phosphorus mass balances for sections of the NTR watershed, including reservoirs at Mitchell, Stratford and St. Mary's, Wildwood Reservoir and Fanshawe Lake and tributaries were determined from historical and 2005 monitoring efforts including total phosphorus, chlorophyll, Secchi disk transparency and temperature and oxygen profiles. Pittock Reservoir at the South Thames River was investigated as well. Although Pittock's water quality does not affect Fanshawe Lake, treatment options were evaluated because it is probably the reservoir with the most deteriorated water quality in the Upper Thames watershed. Most of the data were made available by the Upper Thames Watershed Conservation Authority (UTRCA), but additional sources were queried, such as the Ontario Ministry of the Environment (MOE).

Long-term flows are variable on an annual and seasonal basis according to climatic variability, but show the expected increase along the river. TP concentration and mass averages in the NTR watershed are more complicated and diverse. To facilitate understanding of this pattern a synopsis of long-term characteristics is presented in Table 4-1 and Figure 3-1. This table shows all locations and sources that provided data on flow and phosphorus, including the impoundments along the river, the main monitored stations and the smaller tributaries with limited amount of data, and waste water treatment plants. It appears that TP concentrations are high in the upper river section below the Town of Mitchell, decrease downstream of St. Mary's and then increase again below Fanshawe Lake. Of the tributaries, the Avon River contributes to the water quality problems of the main stem as its phosphorus concentration is about 50% higher than at the next NTR monitoring location. Of the smaller tributaries only one, Gregory Creek, shows elevated TP concentration and should be investigated further. The upper impoundments, at Mitchell, Stratford, and St. Mary's and the small pond in the Fullarton Conservation Area revealed eutrophic to hyper-eutrophic conditions.

Because of lack of data on algal blooms, an index was developed by Freshwater Research (2005) that relates an easily measurable variable, the period of Low-Nitrate-Days (LND), to the period of nuisance bluegreen blooms. The bloom indicator LND (days/year) was defined as the period of time during summer and early fall, when nitrate concentration of the outflow is below about 1-2 mg/L. Its appropriateness was tested and supported by the 2005 monitoring of nitrate concentrations, Secchi disk transparency and chlorophyll concentration in conjunction with visual observations with respect to blooms (Section 4.2).

The effects of physical characteristics, including annual and seasonal flows, and their relationships with algal bloom indicator, LND, were investigated for the additional reservoirs to determine the important causes of the observed water quality variability. The results of the previous study for Fanshawe Lake, Wildwood and Pittock reservoirs also apply to the other smaller NTR impoundments, so that during high-flow years the water quality is relatively good, while during low-flow years it is poor. This means that poor water quality and higher phosphorus concentrations in the reservoirs is correlated with the lower phosphorus loadings of low-flow years and that the TP concentration is a better determinant of water quality than loads.

The collected new information suggests that the summer 2005 was associated with more eutrophic conditions than average throughout the UTR watershed area, probably due to low flow conditions. Although this is a disturbing result for the individual lakes and streams, it benefits this study, as we now have a well documented worse-case scenario, and any causes in general and TP sources in particular, such as the Avon River and Gregory Creek, were more pronounced and easier to detect.

Recommended treatments for the remediation of the NTR Reservoirs are based on the restoration goals and decision criteria assembled by the Project Management Team (Appendix H). Proposed treatments are summarized in Table 1-1 and consider the reservoirs' position within the watershed, their water quality and uses, size and flow characteristics. With respect to Fanshawe Lake operations, more analyses showed that the current timing of bottom water withdrawal has already maximized TP export, which is the principal mechanism of the lake restoration technique of *hypolimnetic withdrawal*. Therefore no additional benefits to water quality and lake phosphorus concentration can be expected.

Acknowledgement

The commitment and efforts by several volunteers are gratefully acknowledged, as they significantly contributed to the evaluation for the summer 2005 water quality. In particular, Brendan Knight recorded Secchi disk transparency at five locations in Lake Victoria at Stratford. Roslyn Macleod of the Canadian Women's Olympic Rowing Team and other team members recorded Secchi and algal proliferations, turbidity, colour and other visual characteristics throughout Fanshawe Lake in a detailed journal.

A project like this can only be accomplished with support from many knowledgeable technical persons. I am very grateful to the support by staff of the UTRCA, above all, the Senior Water Resources Engineer Mark Helsten, the Water Quality Specialist, Karen Maaskant and the Water Quality Technician Karla Young. Chris Harrington, Coordinator, Planning and Research, skilfully lead the project. The enthusiasm expressed by Sierra Club's Elizabeth May and of course the financial support by Glen Davis was immensely encouraging throughout and made this project possible.

Table 1-1. Treatment Recommendations

Treatment	Impoundment	Decision Criteria[1,2]						
		1	2	3	*	4	5	6
Aluminum precipitation	Small ponds e.g. Fullarton	+/-	+	+/-	+	+	-	?
	Pittock	+/-	+	+/-	+	+	--	?
Hypolimnetic withdrawal	Fanshawe Lake	+/-	+	+	--	+/-	+	+
	Wildwood	+/-	+	+	-	+/-	+	+
1. Water fowl management	Lake Victoria	+/-	+	+	+	+/-	-	?
2. Park grounds management		+/-	+	+	+	+/-	-	+
3. Aluminum precipitation, after 1,2		+/-	+	+/-	+	+	--	?
Further investigation needed	Lake Mitchell, missing upstream load estimates Lake Victoria, missing upstream load estimates Gregory Creek, high and variable TP in 2005							

[1] Decision Criteria

1. Flood control operations
2. Water quality
3. Aquatic habitat
4. Recreational opportunity
5. Capital and operating costs
6. Public input / acceptance

* Effect on downstream waters

[2] Key for expected effects:

+ positive
- negative, -- worse, --- worst
+/- none
? not known

2. Introduction

In the previous report (Freshwater Research 2005) limnological characteristics of Fanshawe Lake and the reservoirs, Pittock and Wildwood, were presented and various options for improving their unsatisfactory water quality investigated. Several open questions are to be addressed in the present follow-up study.

2.1. Purpose of this Study

To find ways to improve water quality in the Upper Thames River and the reservoirs, it is important to "limnologically understand" the entire system. For example, any upstream reservoirs will affect the downstream ones (e.g. Wildwood affects Fanshawe) so that the more eutrophic ones (e.g. Lake Mitchell and Lake Victoria at Stratford) will adversely affect the downstream river sections and reservoirs. Consequently, the previous study that concentrated on Fanshawe Lake, Wildwood and Pittock Reservoirs (Freshwater Research 2005) was expanded throughout the watershed of the Thames River, in particular the North Thames River Branch (NTR).

To achieve these goals the study relies heavily on additional monitoring of eutrophication indicators throughout the NTR. Surface and bottom phosphorus concentration, algal biomass as chlorophyll concentration, Secchi transparency and oxygen depletion are the most important determinants of eutrophication in lakes and reservoirs. Since algal blooms are particular problematic in the discussed reservoirs, emphasis was put on the simultaneous determination of Secchi transparency, chlorophyll and nitrate concentration to compute the period of Low-Nitrate-Days (LNDs) of reservoirs and their outflows in summer and fall. The keeping of a "Journal" on algal blooms helped corroborate the LND and algal bloom relationships described in the previous study; in addition, the applicability of these relationships to less-studied reservoirs and river sections of the NTR were determined. Acquiring Secchi transparencies and entries for the bloom journal involved interested and reliable stakeholders of the specific reservoirs. Volunteers determined Secchi disk depths throughout the summer in the Stratford reservoir, Lake Victoria and a detailed algal journal described the proliferation of algae in Fanshawe Lake.

Most importantly, it is necessary to determine the role of the upstream water course and its nutrient loading in Fanshawe Lake's water quality. Therefore, flows and nutrient loading at various locations within the NTR watershed were determined. In particular, the water quality of several tributaries (including the Avon River and Trout Creek) and reservoirs (at Mitchell, Stratford, and St. Mary's and the Wildwood Reservoir) upstream of Fanshawe Lake were investigated.

With respect to Fanshawe Lake operations, more analyses are presented in Section 4.4 to show whether adjusting the timing of bottom water withdrawal would benefit water quality and decrease lake phosphorus concentration, which is the principal mechanism of the lake restoration technique of *hypolimnetic withdrawal*.

In addition, limnological investigation including monitoring of Pittock Reservoir was continued in 2005, so as to find a treatment option, if possible.

The project's ultimate goal is the improvement of Fanshawe Lake's water quality, as described in the previous study (Freshwater Research 2005): Fanshawe Lake is a reservoir on the NTR constructed by the Upper Thames River Conservation Authority (UTRCA) in 1950 (filled to permanent pool height in 1952) to aid with flood control. Since then many other purposes have been achieved, including the operation of a hydroelectric plant for 400 households and recreation. Recreation has become an important asset as the lake was used for sculling as early as 1952 and has been the National High Performance Rowing Centre for the Canadian Women's Olympic Rowing Team since the eighties. In addition, Fanshawe Lake's proximity to major population centres in Southwest Ontario warrants its frequent use for fishing, sailing, as well as day and overnight camping in adjacent park land owned by the UTRCA. "Poor water quality has been a concern for the past two decades with relatively frequent episodes of blue-green algae and elevated bacterial concentrations", according to the UTRCA (RFP for the first study, June 2004), despite 25 years of upstream diffuse source pollution control.

2.2. Sources of Long-term and 2005 Data

Historic flow and water quality data (including nutrients, but not algal biomass or Secchi disk transparency) are available for several long-term stations at the river and its tributaries, typically monitored by the UTRCA in conjunction with the MOE. Temperature and oxygen profiles are available for the main upstream reservoirs, at Mitchell and Stratford, but nutrient and algal biomass were determined only during the present study from July to October 2005 in these reservoirs.

Therefore, nutrient concentrations at the long-term stations, especially those downstream of the reservoirs, were analyzed in an attempt to determine long-term reservoir water quality development and flow relationships. Flow and water quality stations were not always at the same location and the closest pair was matched according to Table 2-1. In particular, daily flow estimates were matched to daily TP concentrations that were interpolated from mostly monthly samples at the water quality stations to arrive at daily loads. Summation of these daily estimates yielded monthly loads, from which annual and summer (May through September) loads were computed and are presented here. These load estimates were divided by the corresponding flows to arrive at annual and summer volumetric TP concentration.

In addition, the variable Low-Nitrate-Days was computed from nitrate data of the WQ stations. All morphometric, hydrological and water quality data were provided by UTRCA and summarized and analysed by Freshwater Research.

Table 2-1. Water quality (WQ) and flow sites with long-term data.

			Water Quality		Flow	
Rkm	River	Location	Site	Period*	Site	Period
81.8	NTR	d/s Mitchell	44	75-05	1	68-05
55.98	Avon River	d/s Stratford	25	68-05	2	68-05
	Trout Creek	u/s Wildwood	66	79-05	5	68-05
48.85	Trout Creek	d/s Wildwood	64	79-05	4	68-05
	NTR	St. Marys, Park Bridge	15	68-95		68-05
48.32	NTR	2.5 km d/s St. Mary's	45	75-95, 02	3	68-05
37.51	NTR	u/s Fanshawe Lake	50	75-95, 03-05	6	68-05
21.64	NTR	d/s Fanshawe Lake	27	68-05	7	68-05

**There are no WQ data for 1996 and 1997*

The location with respect to the NTR is indicated as river km (Rkm) counting from the downstream Byron Gauge (Rkm=0). In case of the tributaries (Avon River and Trout Creek) Rkm indicates the location of confluence with the NTR. Water quality data for St. Mary's Site 45 were similar to those from Site 15, so that they could be supplemented, where necessary.

Figure 2-1. Map of the Upper Thames River district, indicating flow and water quality sites

From UTRCA, see separate attachment

To complement the information from the long-term river stations, three upstream reservoirs (at Mitchell, St. Mary's and Stratford) and one small eutrophic pond (in the Fullarton Recreation Area) were monitored biweekly from July to October, 2005. Reservoir water quality data sampled in 2005 included total phosphorus (TP), nitrate, algal biomass (chlorophyll concentration) and Secchi disc transparency (for turbidity and algal biomass). Where possible temperature and dissolved oxygen profiles were taken as well. Samples were taken from the surface 1 – 2 meter layer to represent the euphotic zone at up to three sites per reservoir. TP samples were also taken at three different depths at the Fanshawe Lake dam, to test for internal P loading. Field sampling was conducted by UTRCA staff; TP, nitrate and chlorophyll were analyzed in a commercial lab. In addition to the monitoring by UTRCA, a volunteer, Brendan Knight, recorded Secchi disk transparency at five locations in the Stratford Reservoir (Figure 2-2). Roslyn Macleod and other members of the Canadian Women's Olympic Rowing Team recorded Secchi and algal proliferations, turbidity, colour and other visual characteristics in a detailed journal for Fanshawe Lake. All data of the sampling effort in 2005 are listed in Appendix A.

To assess the probability of sediment P release in the upstream reservoirs, sediment samples were taken and analysed for TP, metals and organic content by the laboratory of Prof. Cyr of the University of Toronto (Appendix G).

The data for the three waste water treatment plants are based on monthly and annual summaries for 2002 and 2003 provided by the Ontario Ministry of the Environment (e-mail from May 3, 2006 by Koshy Mathew, Environmental Monitoring & Reporting Branch, Business Monitoring & Reporting Section).

Statistical analysis was used to decide whether a pattern was likely "real" or due to chance alone. Usually linear regression analysis was performed and three statistics are reported: (1) the sample size, n, (2) R^2 that represents the proportion of the variability explained and (3) the significance level p. In testing correlations and regressions, generally a level of 95% or $p=0.05$ or better was applied. As a measure of central tendency the average was computed unless the sample was small and possibly biased; in that case a median was used.

Data are made available separately from this report on file. Reservoir data were typically summarized to represent euphotic zone (i.e. surface layer) average summer concentration.

Figure 2-2. Victoria Lake in Stratford; two sites were sampled by UTRCA and five by the volunteer, Brendan Knight.

2.3. Water Quality Definition – Trophic State and Phosphorus

It is important to evaluate past and present water quality, so that a status quo is determined against which potential future treatment effects can be evaluated. Also, if present and historical water quality can be explained, future conditions involving various restoration techniques can be predicted.

Algal growth in lakes and reservoirs is usually limited by the supply of phosphorus so that blooms increase with increasing phosphorus concentrations (expressed as mass over volume) in the water (e.g. Nürnberg 1996). Changes in the mass of phosphorus (expressed as mass per year or mass per lake surface area and year) entering a lake or reservoir from the watershed (external loading) or lake sediments (internal loading), will change the average concentration of phosphorus within the lake and consequently the abundance of algae.

Nitrogen is the second most important nutrient in lakes and reservoirs, after phosphorus. In fact, it often co-limits algal growth, so that any addition of available nitrogen compounds enhances algal growth and eutrophication. Total nitrogen (TN) and total phosphorus (TP) concentrations are often closely correlated, but generally algae biomass (chlorophyll *a* concentration) is better correlated with TP rather than TN. For this reason and because phosphorus can more easily be controlled than nitrogen, management and restoration efforts typically concentrate on the reduction of phosphorus.

Furthermore, the actual summer algal biomass may be limited by light because of increased turbidity or increased mixing depth in certain reservoir sections. Another limiting factor is that algal cells may be flushed out faster than they can reproduce.

Summer averages of water quality variables are often used to characterize annual trends in lakes, reservoirs, and river sections. Usually, summer is also the season that is most important to users. To facilitate comparison of water quality between lakes and reservoirs, a classification with respect to "trophic state" has been applied by many limnologists. Threshold values of the most important trophic state indicators are listed in Table 2-2 (Nürnberg 1996).

Table 2-2. Trophic state categories based on summer water quality

	Oligotrophic	Mesotrophic	Eutrophic	Hyper-eutrophic
Total Phosphorus (mg/L)	< 0.010	0.010 - 0.030	0.031 - 0.100	> 0.100
Total Nitrogen (mg/L)	< 0.350	0.350 – 0.650	0.650 – 1.200	>1.200
Chlorophyll (μg/L)	< 3.5	3.5 - 9	9.1 - 25	> 25
Secchi Disk transparency (m)	> 4	2 - 4	1 - 2.1	< 1

To evaluate the importance of different phosphorus sources it is necessary to distinguish at least two phosphorus measures that are often determined: TP and SRP (soluble reactive or dissolved reactive phosphorus, sometimes also called ortho-phosphate). The TP analysis measures all the phosphorus compounds in a specific water sample (after digestion and a phosphate-specific analysis); the SRP analysis measures the soluble fraction of TP that consists mostly of the biologically available phosphate (using a phosphate-specific analysis after "filtering away" of particles). Therefore, SRP is only a fraction of TP. Most models and relationships between phosphorus and algae are based on TP, but the determination of SRP can be important in indicating the phosphorus source (e.g. internal versus external source) and the potential short-term effect on algae, since SRP can be more easily taken up and used by micro-organisms (algae and bacteria).

In particular it is important to realize that phosphorus in internal load from anoxic sediments (Section 4.4) and effluent phosphorus from waste water treatment plants (Section 6.3) is much more biologically available (orthophosphate) than phosphorus compounds in regular inflows, which usually have a high proportion of particulate phosphorus. Internally derived phosphorus is in a form that is close to 90% biologically available (Nürnberg and Peters 1984), while the biologically available fraction of the external load (from in-flows and non-point sources) was estimated as about 50%, based on SRP concentration in the inflow. Similarly, phosphorus in effluents is usually assumed to be completely biologically available.

3. North Thames River watershed synopsis

The North Thames River watershed upstream of Fanshawe Lake spreads over an area of 1,447.4 km^2 in south-western Ontario (approximate location of Fanshawe Lake is 43°2' 20" North 81°11'5" West), north of the City of London. The watershed is mainly agricultural with several towns and parks and recreational facilities around reservoirs that are located on the main stem and tributaries (Figure 2-1).

Long-term flows are variable on an annual and seasonal basis according to climatic variability, but show the expected increase along the river. TP concentration and mass averages in the NTR watershed are more complicated and diverse. To facilitate understanding of this pattern a synopsis of long-term characteristics is presented in Table 3-1 and Figure 3-1. This table shows all locations and sources that provided data on flow and phosphorus, including the impoundments along the river, the main monitored stations and the smaller tributaries with limited amount of data, and waste water treatment plants. It appears that TP concentrations are high in the upper river section below the Town of Mitchell, decrease downstream of St. Mary's and then increase again below Fanshawe Lake. Of the tributaries, the Avon River contributes to the water quality problems of the main stem as its phosphorus concentration is about 50% higher than at the next NTR monitoring location. Of the smaller tributary only one, Gregory Creek, shows elevated TP concentration and should be investigated further. The upper impoundments, at Mitchell, Stratford, and St. Mary's and the small pond in the Fullarton Conservation Area revealed eutrophic to hyper-eutrophic conditions.

In Sections 0 to 6 water quality of the various sites in the NTR watershed are analysed in detail and Pittock Lake at the South Thames River branch is presented in Section 7.

Table 3-1. Flows and water quality of tributaries and WWTPs compared to main NTR station 20-year averages

Rkm	River	Location	Site	Flow (10^6 m^3)		TP (mg/L)		TP Load (tonnes)		LND	WQ****
			WQ	Annual	May-Sep	Annual	May-Sep	Annual	May-Sep	(days)	Year
82.0	WWTP	Mitchell		1.5	0.6 **	0.493	0.493	0.74	0.31 **	n.a.	2002-03
81.8	NTR	d/s Mitchell	44	146.7	27.3	0.120	0.108	17.30	3.56	48	1986-05
73.5	Neil Drain	Fullarton		1.4	0.2	0.219	0.208	0.31	0.04 ***	121	2005
73.0	Black Creek		92	57.7	19.6 *	0.064	0.044	3.69	0.86 ***	81	2003-05
56.0	WWTP	Stratford		7.6	3.2 **	0.200	0.200	1.56	0.66 **	n.a.	2002-03
56.0	Avon River	d/s Stratford	25	63.6	14.6	0.151	0.120	9.02	1.62	17	1986-05
54.0	WWTP	St. Marys		1.5	0.6 **	0.465	0.465	0.66	0.28 **	n.a.	2002-03
48.9	Trout Creek	u/s Wildwood	66	18.1	3.2	0.101	0.082	1.77	0.28	9	1986-05
48.9	Trout Creek	d/s Wildwood	64	64.3	22.4	0.080	0.077	4.96	1.54	76	1986-05
48.3	NTR	d/s St. Mary's	15, 45	460.1	97.6	0.083	0.077	37.77	6.81	61	1986-05
60.5	Otter Creek		94	22.1	7.5 *	0.046	0.026	1.02	0.20 ***	39	2003-05
61.0	Flat Creek		89	34.1	11.6 *	0.055	0.051	1.87	0.59 ***	27	2003-05
39.0	Fish Creek		90	59.9	20.4 *	0.065	0.056	3.89	1.14 ***	10	2003-05
40.0	Gregory Creek		95	22.1	7.5 *	0.084	0.085	1.85	0.64 ***	81	2003-05
37.5	NTR	u/s Fanshawe	50	577.4	119.3	0.069	0.057	41.29	6.86	70	1986-05
21.6	NTR	d/s Fanshawe	27	569.0	120.6	0.094	0.093	53.63	11.27	45	1986-05

* Summer flow estimated as 0.34 of annual flow (Mark Helsten, UTRCA)

** Summer flows and loads in WWTP (waste water treament plants) were prorated from annual loads

*** Computed as product of average TP concentration and May-Sep flow

**** There are no WQ data for 1996 and 1997

Figure 3-1. Map of the Upper Thames River district, indicating average flow, TP concentration and load as based on Table 3-1

From UTRCA, see separate attachment

4. Fanshawe Lake

Fanshawe Lake's characteristics (Table 4-1) and relationships with other variables especially flow and water quality were described in detail in Freshwater Research (2005). Here an update including the 2005 monitoring effort and hydrology is presented. Important results from the former study are included in tables and figures to facilitate comparison with previous years. In addition, the algal bloom variable, LND, and increased hypolimnetic withdrawal for remediation purposes are evaluated in more detail.

Table 4-1. Morphometry and hydrology of Fanshawe Lake

Altitude at average pool[1] (m above sea level)	262.4
Watershed area, A_d (km^2)	1,447.4
Surface area[1], A_o (ha)	272.6
Area-Ratio, A_d/A_o	532
Maximum depth (m)	12.1
Mean depth[1], z (m)	4.82
Morphometric index, $z/A_o^{0.5}$	2.93
Volume[1] (10^6 m^3)	13.146
Outflow volume[1] (10^6 m^3 per yr)	560
Water residence time[1], τ (volume/outflow)	0.026 years or 9.5 days
Annual flushing rate[1], $\rho = 1/\tau$ (per yr)	38.4
Annual water load[1], $q_s = z/\tau$ (m/yr)	205

[1] *Longterm average 1954-2004*

(Table from Freshwater Research, 2005)

4.1. General Water Quality in 2005

Inflow summer (May through September) concentration of total phosphorus was 0.047 mg/L, which is similar to the average of 0.046 mg/L for the period of 1990 - 2005, while the flow was low (summer flow rate of 5.1 m^3/s versus 1990 – 2005 average of 9.6 m^3/s). Low flow rates have been related to algal blooms and high eutrophic conditions in previous years and 2005 was no exception, with worse water quality than observed in the last few years. Summer average Secchi transparency at the dam was lower than it was during the two previous summers and surface TP concentration was twice as high as in the previous summer (Table 4-2) indicating highly eutrophic conditions (Table 2-2). The colonization of Fanshawe Lake by the zebra mussel (*Dreissena polymorpha*) could not prevent the low transparency in 2005, because a drawdown operation in the fall and winter 2005 seemed to have eradicated the mussel almost completely.

Contrarily, the chlorophyll concentration was unusually low (Table 4-2) indicating the low reliability of algal pigment in the determination of trophic state. Most likely, chlorophyll spot sampling of the 1 m layer is not an adequate measure of average algal concentration in Fanshawe Lake because of its high variability in space and time.

As in previous years there is a gradient apparent in 2005 that indicates lower water quality and almost hyper-eutrophic conditions at the inflow (station F3), as compared to similar or slightly better conditions at the mid lake station (F2) and even better eutrophic conditions at the dam (F1, Table 4-2, Table 4-3). Such drastic differences in water quality are typical for a run-of-the-river reservoir and have to be considered when setting water quality and treatment goals.

Table 4-2. Summer water quality characteristics in the euphotic zone at the dam (F1)

Year	TP mg/L	Chl µg/L	Secchi m	LND
1973	0.082	7.7	1.10	133
1980	0.052		0.90	
1988	0.060	21.0	1.22	73
1989	0.104	73.1	1.06	103
1990	0.037	10.0	1.64	0
1991	0.060	19.4	0.92	34
1999			1.01	53
2001			1.60	31
2003			2.10	28
2004	0.036	11.8	2.24	28
2005	0.072	6.8	1.83	92

Table 4-3. Water quality in the euphotic zone at three sites in summer 2004 and 2005

	F1	F2	F3	Average
Distance from Dam,	125	2,125	3,975	
TP, mg/L 2004	0.036	0.069	0.116	0.074
TP, mg/L 2005	0.072	0.100	0.099	0.090
Chl, µg/L 2004	11.8	37.5	45.0	31.4
Chl, µg/L 2005	6.8	13.8	25.9	15.5
Secchi, m 2004	2.24	1.21	0.91	1.45
Secchi, m 2005	1.83	1.59	1.03	1.48

4.2. Algal Blooms and Low-Nitrate-Days (LND)

Freshwater Research (2005) created the variable LND, the period of Low-Nitrate-Days, to represent the potential period of bluegreen algal blooms. The decrease of nitrate in lake water can indicate an increase in algae, as they use nitrate for their growth. When nitrate approaches low levels, phytoplankton species composition shifts to nitrogen-fixing bluegreen algae, as has been observed in other systems before. Therefore, Freshwater Research (2005) proposed that low nitrate not only indicates an increase in algal abundance in general, but coincides with the occurrence of bloom-forming bluegreen algae. Such blooms are not only unsightly, but potentially release cyanotoxins, when they die off and cell lysis of the cyanobacteria sets in. To use this information in further analyses, values of LND were calculated as the period of days, where the nitrate concentration is at or below a threshold of about 1 mg/L NO_3-nitrogen. Since nitrate data are often lacking for Fanshawe Lake itself, the nitrate concentration in the outflow was used to determine LND in previous years.

In 2005, LND was determined from a combination of lake samples and outflow data (nitrate concentration was usually similar for coinciding dates). LND was relatively high in 2005 (the highest since 1999), indicating a long period of bluegreen algal blooms. The occurrence of such blooms in Fanshawe Lake 2005 was supported by the Journal of the Canadian Women's Olympic Rowing Team ("Rower's Journal", Appendix B) and observations by Karla Young, UTRCA (Figure 4-1). The observations of poor visibility and "scum" coincided indeed with periods of low nitrate concentration, while the occurrence of "good" flagellate blooms, which are useful as fish food, occurred earlier in the summer, when nitrate concentration was above 5 mg/L. Close inspection of the nitrate concentration reveals that perhaps the threshold for algae blooms to happen may be slightly higher than 1 mg/L, more like 1.5 – 2.0 mg/L nitrate in Fanshawe Lake.

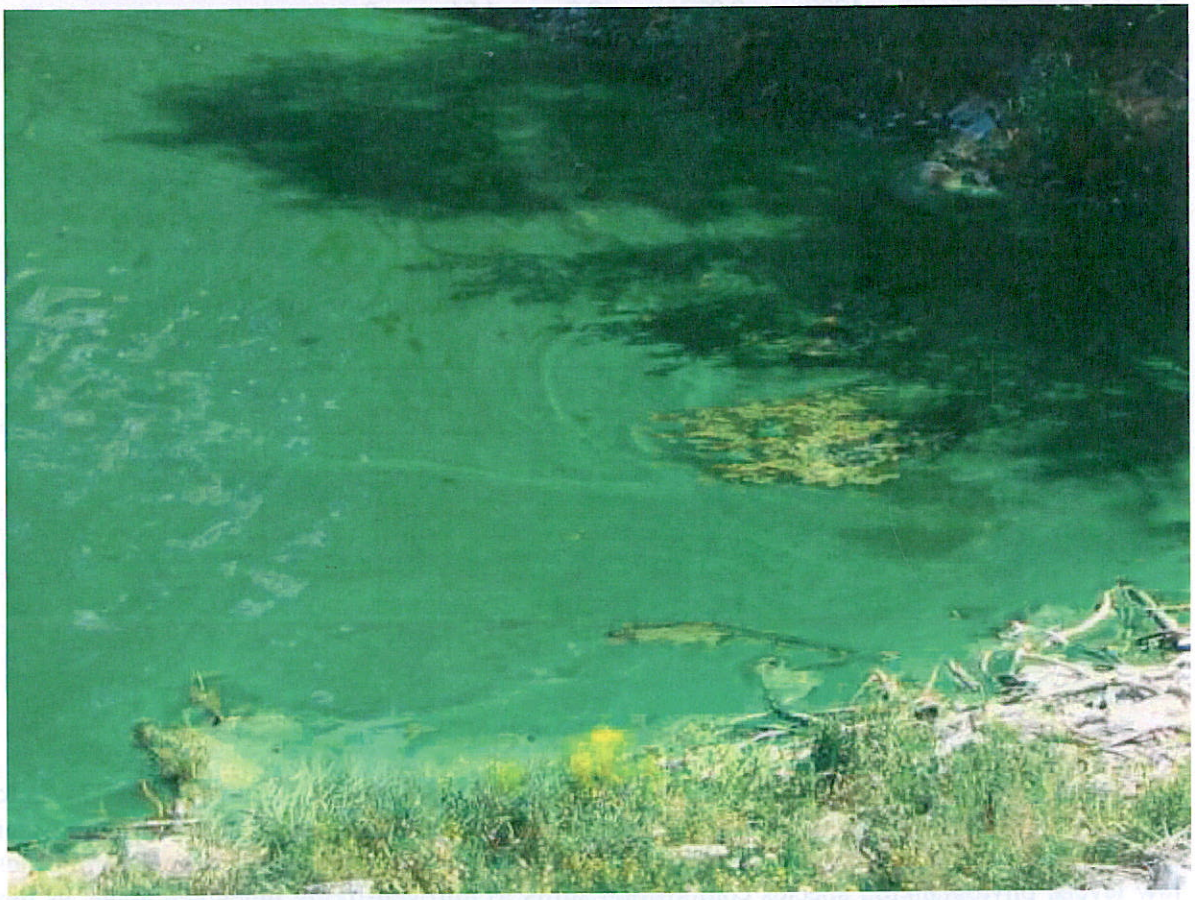

Figure 4-1. Bluegreen algal bloom in Fanshawe Lake on August 26, 2005 (*Karla Young*)

Occasionally, lake users have come forward to indicate that indeed certain years with a high LND were particularly full of algal scum and low transparency. One such year is 1975 when John Nicholson trained on Fanshawe Lake all summer long. He shared this memory following a public presentation. (*Focus on Fanshawe: A Forum for Local London Environmental Concerns*, The Sierra Club of Canada, June 2, 2006, London, ON). Similarly, the former coach of the Canadian Women's Olympic Rowing Team pointed out several matching years in the late eighties.

A more direct test of the LND as indicator for bluegreen blooms is possible with phytoplankton biomass analyses by the MOE near the Fanshawe Lake dam in 1988. This study indicates that the proportion of the algal that are cyanobacteria (bluegreen, %) increased at the same time that nitrate concentration was low (<1 mg/L), in late summer and fall (Figure 4-2). Conversely in the spring and beginning of the summer, high chlorophyll concentration (µg/L), total algal biovolume (mm^3/L), and low Secchi transparency (m) was also observed at higher nitrate concentration, but then bluegreen biomass was low.

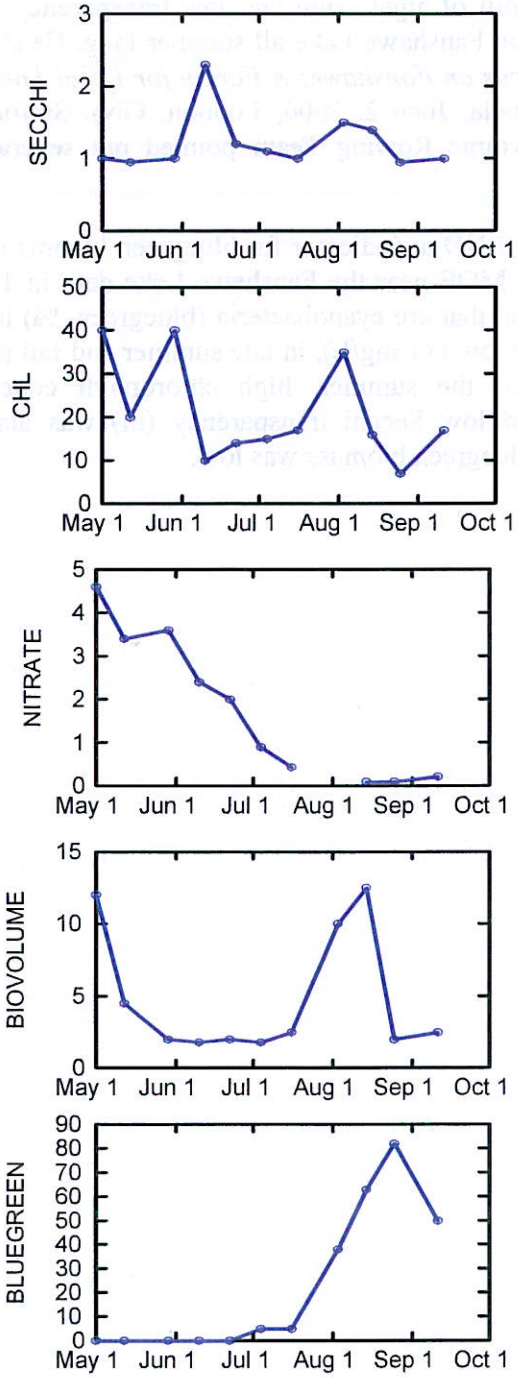

Figure 4-2. Bluegreen algae blooms in 1988 compared to nitrate and other algal indicators.

Variables: Secchi transparency (m), Chl, chlorophyll (µg/L), Nitrate (mg/L), Algae biovolume (mm^3/L), proportion of Bluegreen (%)

These relationships indicate that as expected, LND is more specific for bluegreens than just chlorophyll concentration or Secchi disk transparency alone. Although Secchi was generally low and chlorophyll high when nitrate concentration was low, the reverse is not true and chlorophyll was also high at blooms of other (more beneficial) algae, like diatoms in the spring and flagellates or green algae in the summer. It is therefore understandable that there is no significant relationship of LND with average summer chlorophyll concentration in Fanshawe Lake or all of the NTR reservoirs (Figure 4-3), and the relationship with Secchi only explains 12% of the variation (Figure 4-4). LND in the other NTR reservoirs will be described in more detail in Section 5.4.

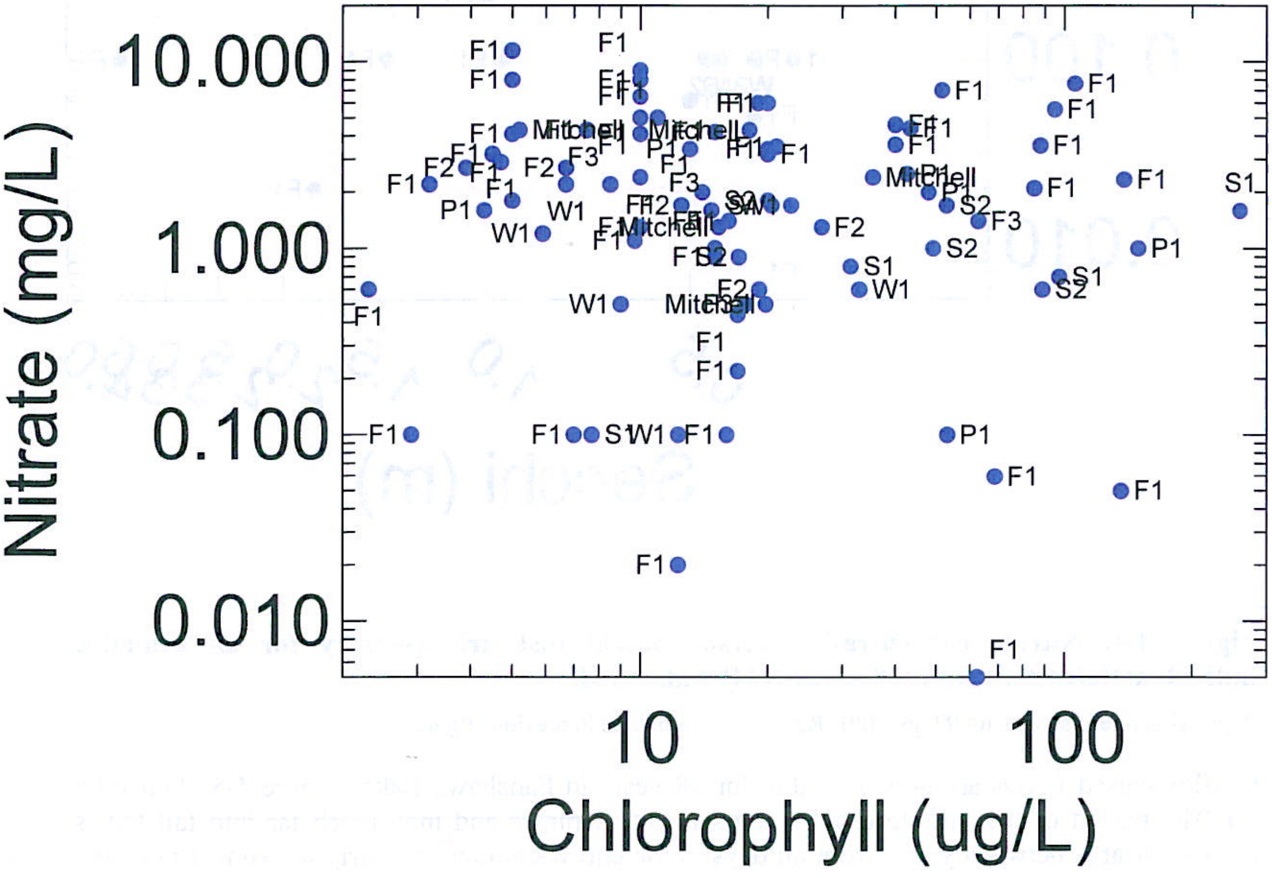

Figure 4-3. Nitrate concentration versus Chlorophyll for all available individual dates starting 1988 of the NTR watershed.

There is no significant correlation, n=82, p=0.39. Symbols indicate F, Fanshawe; P, Pittock; W, Wildwood; S, Stratford, 1, near the dam, 2, in the middle of the reservoir, 3, at the upper end (inflow) of the reservoir.

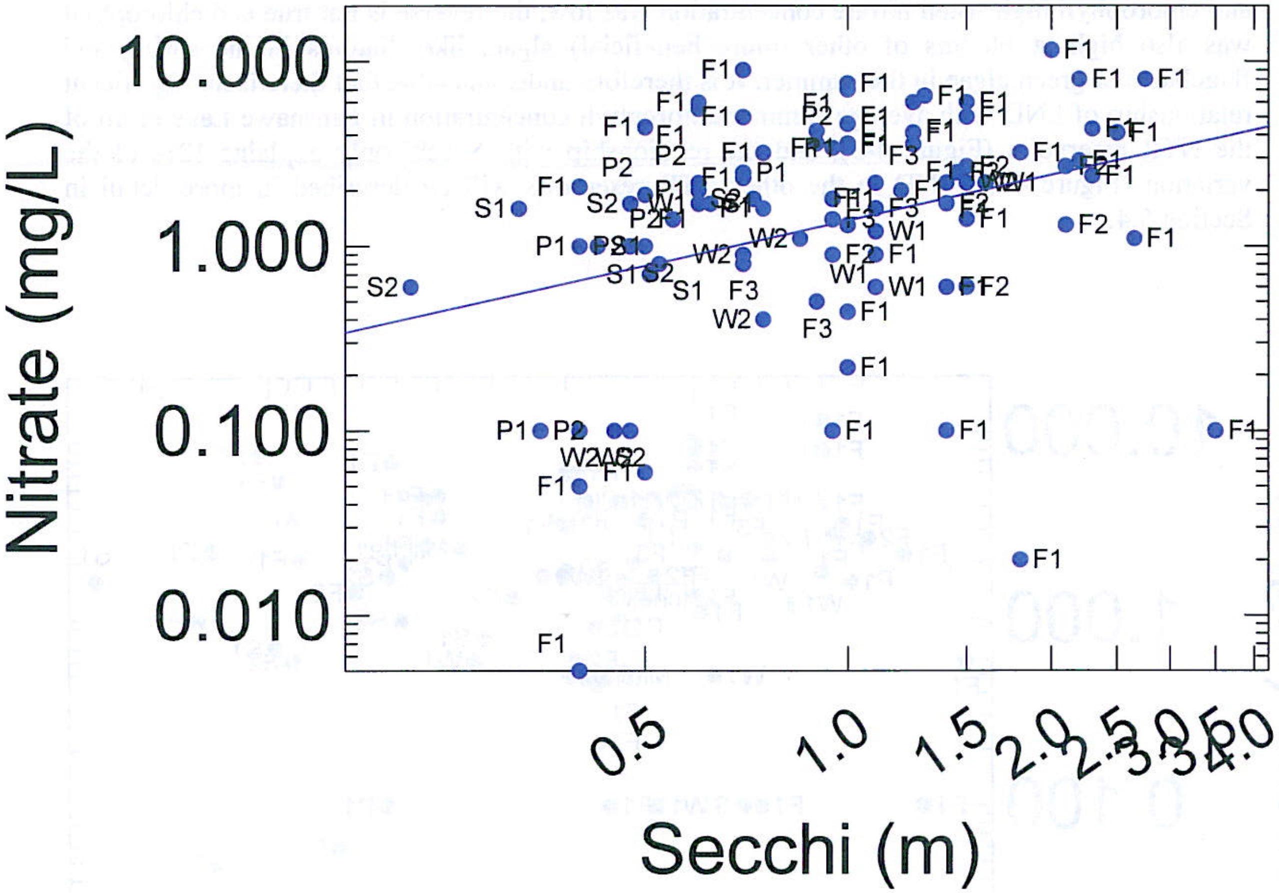

Figure 4-4. Nitrate concentration versus Secchi disk transparency for all available individual dates starting 1988 of the NTR watershed.

Regression line is shown, n= 92, p<0.001, R2= 0.12. Symbols as in previous figure.

Outflow-based LNDs are now available for 38 years in Fanshawe Lake (Figure 4-5, Appendix C). The period of low nitrate usually starts in late summer and may reach far into fall but is highly variable between years, from no days to the entire summer and early fall (0 to 175 days). LND is high in the sixties but decreases in the eighties, with occasional high-bloom years thereafter. Because 2005 had an unusually high LND, the regression of LND on years is less significant than previously and explains only 15% of the variance (n=38, R^2= 0.15, p<0.05). The largest part of the variance in LND is still due to hydrology as discussed next.

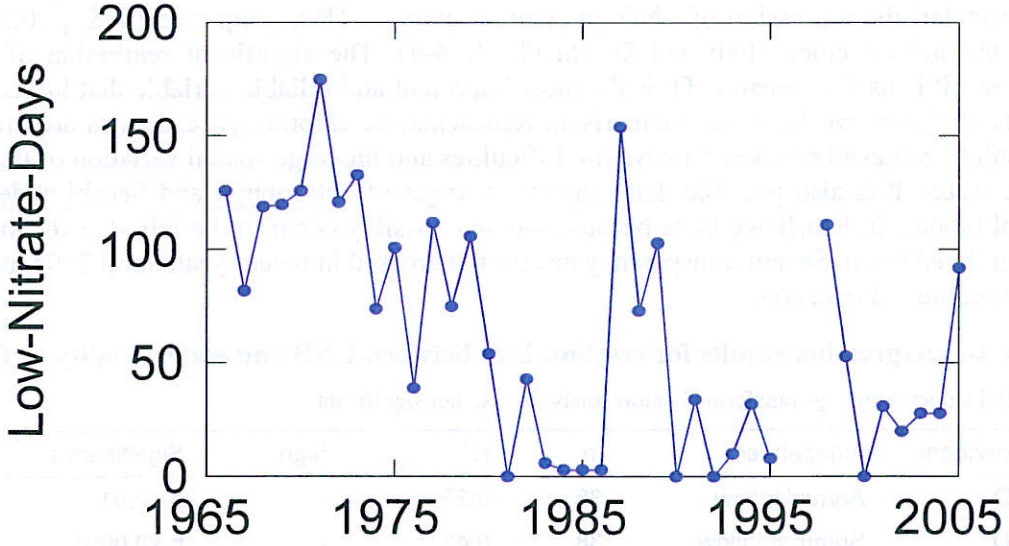

Figure 4-5. Algal bloom indicator. Low-Nitrate-Days (days) in Fanshawe Lake outflow.

No data for 1996 and 1997

Freshwater Research (2005) determined that LND was significantly negatively correlated to in- and outflows for most of the time periods of the summer, including individual summer months. The low flow in 2005 and the high LND value support these results. The LND - summer inflow relationship is presented in Figure 4-6 and Table 4-4. In general, flow rates and their year-to-year variation can have large impacts on water quality, independent of their impact on nutrient loads. Therefore, flow fluctuations have to be taken into account when choosing treatment options.

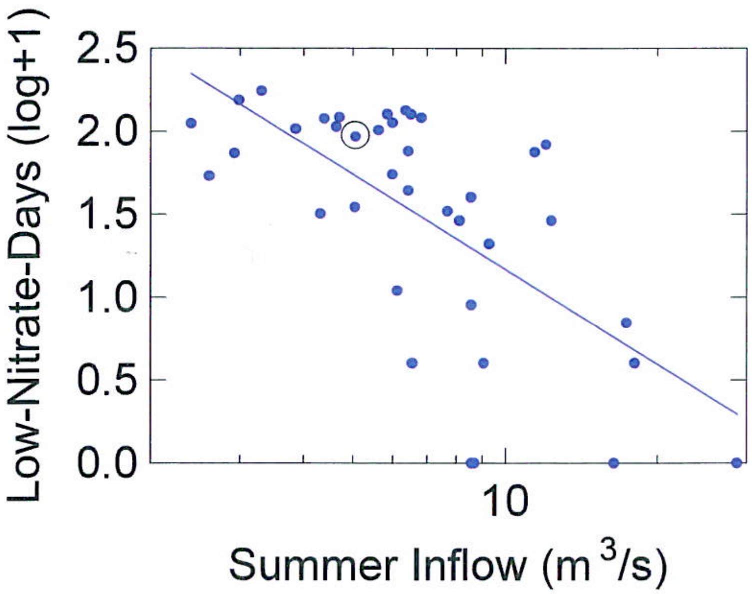

Figure 4-6. Low-Nitrate-Days versus main summer inflow (2005 is circled)

After adding the 2005 data, the LND relationships with water quality variables have not changed. In particular, the regression of LND on summer average TP is supported ($n=8$, $p<0.05$, Figure 4-7), but not on chlorophyll and Secchi (Table 4-4). The significant regression of LND on average TP is useful, because TP is the most important and reliable variable that indicates water quality in Fanshawe Lake. In comparison, representative chlorophyll estimates are much more difficult to achieve because of analytical difficulties and the large spatial variation of the pigment in the water. It is also possible that summer averages of chlorophyll and Secchi underestimate annual blooms in Fanshawe Lake because blooms possibly occur in the fall after the monitoring season. In addition, Secchi transparency has been increased in recent years until 2004, because of the zebra mussel invasion.

Table 4-4. Regression results for relationships between LND and water quality or flow

Note: All values were log-transformed before analysis; n.s., not significant

Dependent	Independent	n	R^2	Sign	Significance
LND	Annual inflow	38	0.23	-	p <0.01
LND	Summer inflow	38	0.43	-	p <0.0001
LND	Year	38	0.15	-	p <0.02
LND	Summer inflow, Year	38	0.55	-, -	p <0.0001
LND	TP	8	0.53	+	p <0.05
LND	Secchi	11	0.13		n.s.
LND	Chlorophyll	6	0.15		n.s.

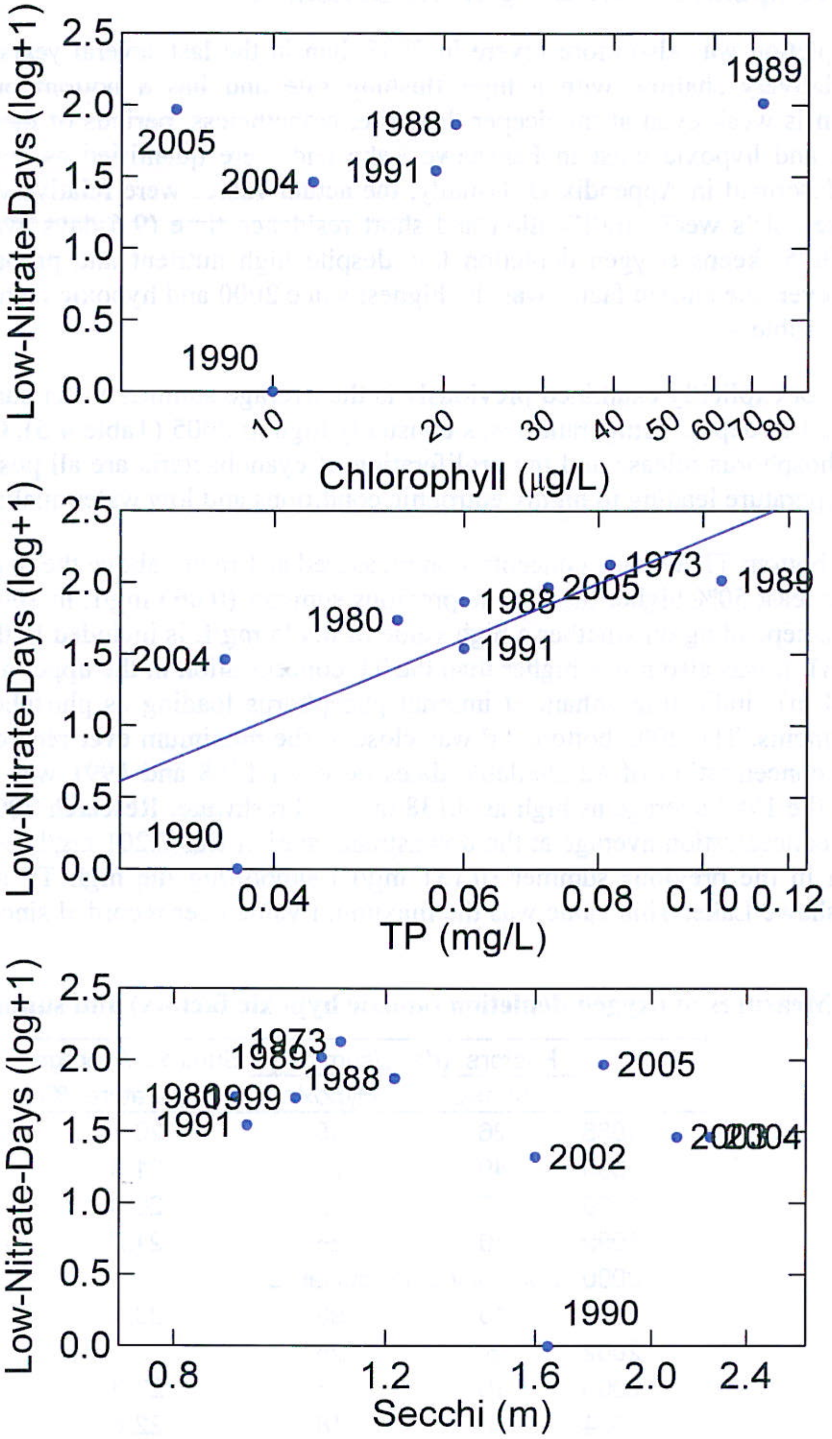

Figure 4-7. Comparison of Low-Nitrate-Days with summer average chlorophyll (top), TP (centre) and Secchi disk transparency (bottom)

4.3. Temperature and Oxygen and Bottom TP

Oxygen depletion was also more severe in 2005 than in the last several years. Since Fanshawe Lake is relatively shallow with a high flushing rate and has a bottom outlet, temperature stratification is weak even at the deeper dam site. Nonetheless, periods of thermal stratification and anoxia and hypoxia exist in Fanshawe Lake and were quantified as anoxic and hypoxic factors as described in Appendix D. Usually, the actual values were relatively low and indicate that the reservoir's weak stratification and short residence time (9.6 days average, Freshwater Research 2005) keeps oxygen depletion low despite high nutrient and probably high organic loads. However, the anoxic factor was the highest since 2000 and hypoxic factor was the highest since 2001 (Table 4-5).

A variable not explicitly examined previously is the average summer water surface temperature, measured at 1 m depth. Temperature was unusually high in 2005 (Table 4-5). Oxygen depletion, sediment phosphorus release and the proliferation of cyanobacteria are all positively influenced by high temperature leading to highly eutrophic conditions and low water quality.

Indeed, the bottom TP average concentration measured at 1 meter above the bottom at the dam in 2005 was at least 50% higher than in the previous summer (0.063 mg/L in 2004 versus 0.092 or 0.159 mg/L, depending on whether a high value of 0.425 mg/L is included in the average or not, Appendix A). It was also much higher than the TP concentration in the upper mixed water layers (1 m and 8 m) indicating enhanced internal phosphorus loading as phosphorus release from anoxic sediments. The 2005 bottom TP was close to the maximum ever recorded. (The average bottom TP concentration of 42 available dates between 1988 and 1991 was elevated at 0.082 mg/L, with the 1989 average as high as 0.138 mg/L, Freshwater Research 2005.) Similarly, the volumetric concentration average at the downstream station was 0.201 mg/L which is also much higher than in the previous summer (0.131 mg/L) supporting the high TP average measured within Fanshawe Lake. This value was the maximum value ever recorded since 1965 except for 1969.

Table 4-5. Measures of oxygen depletion (anoxic hypoxic factors) and summer temperature

	Factors (days/summer)		Summer Average
	Anoxic	Hypoxic	Temperature, ºC
1988	26	45	20.7
1989	49	73	21.3
1990	17	42	20.0
1999	10	28	21.2
2000	not many data, but large		
2001	10	93	23.1
2002	5	25	
2003	10	16	23.3
2004	2	18	22.8
2005	18	43	24.3

4.4. Internal Load and Bottom Withdrawal

External P load was described in detail in Freshwater Research (2005). It was determined as the sum of the main inflow (the North Thames River at Plover Mills), the Wye Creek which flows into Fanshawe Lake about 500 m above the dam, inflow from the immediate watershed and precipitation directly unto the lake. The specific flows were multiplied by corresponding TP concentrations to arrive at loads (Appendix F). External loads were highly variable from year to year because of variable flows. They ranged from 24 to 92 tonnes, with a median of 53 tonnes, or an areal load of 8.9 to 33 $g/m^2/yr$, with a median of 16 $g/m^2/yr$ for a period of 23 years. Approximately 95% of external load arrives via the main inflow.

In Fanshawe Lake TP export is higher than the inflow load, since it happens mostly via the bottom outlet at 8-10 m depth. This hypolimnetic water has higher TP concentration than the euphotic zone (Section 4.3) and the inflow concentration (Figure 4-8), especially in the last two years, when export was about twice that of the input (Figure 4-9, and Figure 4-10). Because other sources (Wye Creek and precipitation) cannot account for the difference and also, because usually some of the incoming TP settles out during its travel through a reservoir, such enhanced export is indicative of internal phosphorus loading.

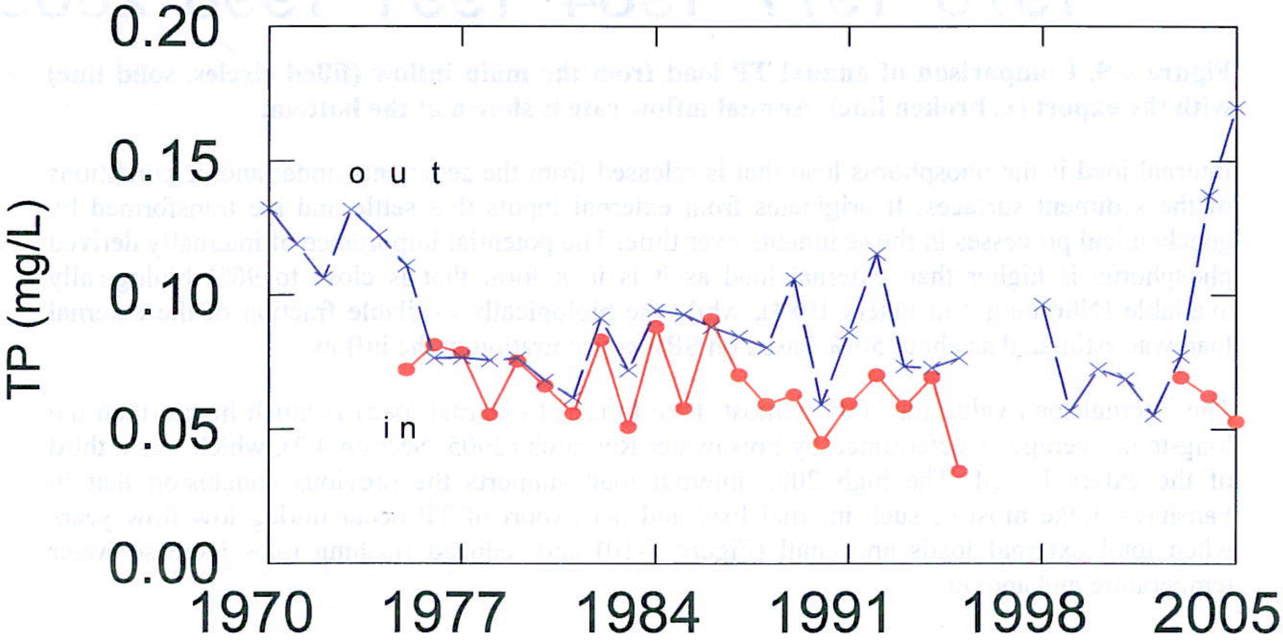

Figure 4-8. Comparison of annual TP concentration average of the main inflow (solid line) with that of the outflow (broken line).

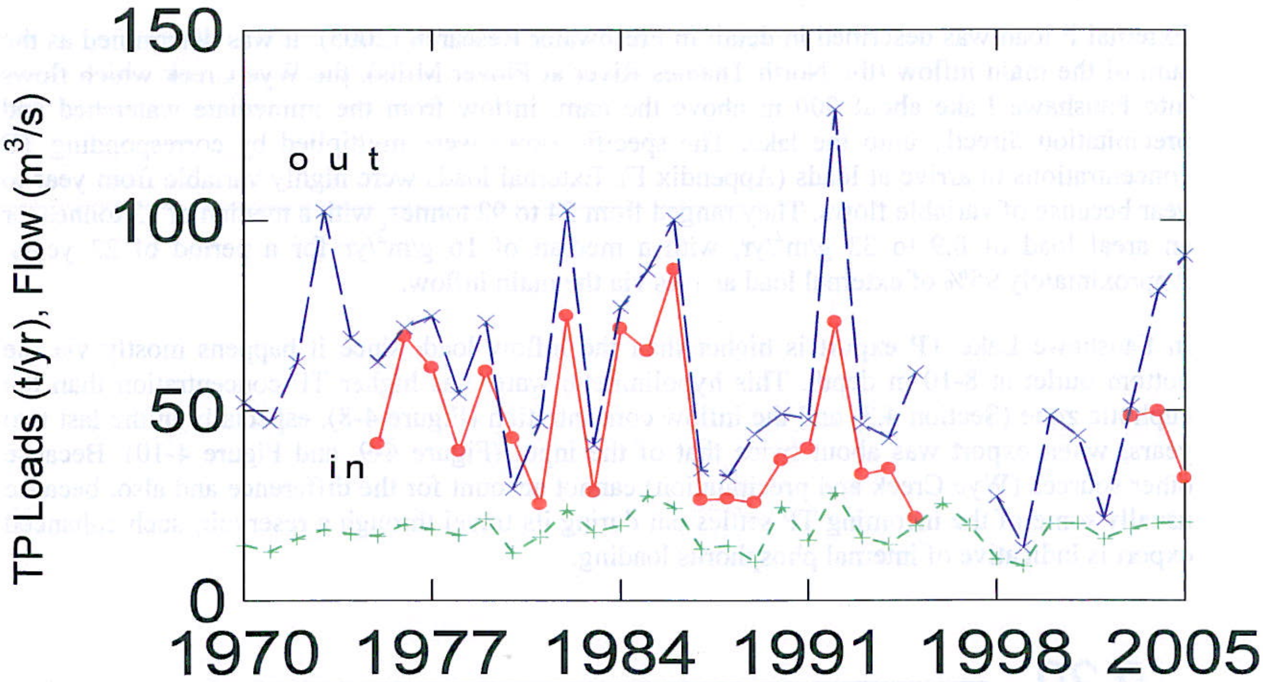

Figure 4-9. Comparison of annual TP load from the main inflow (filled circles, solid line) with the export (x, broken line). Annual inflow rate is shown at the bottom.

Internal load is the phosphorus load that is released from the sediments under anoxic conditions of the sediment surfaces. It originates from external inputs that settle and are transformed by geochemical processes in the sediments over time. The potential importance of internally derived phosphorus is higher than external load as it is in a form that is close to 90% biologically available (Nürnberg and Peters 1984), while the biologically available fraction of the external load was estimated as about 50%, based on SRP concentration in the inflow.

The internal load value for 2005 (almost three times of external load) is much higher than the long-term average as determined by Freshwater Research (2005, Section 4.2), which was a third of the external load. The high 2005 internal load supports the previous conclusion that in Fanshawe Lake most of such internal load and net export of TP occur during low flow years when total external loads are small (Figure 4-10) and reduced flushing rates increase water temperature and anoxia.

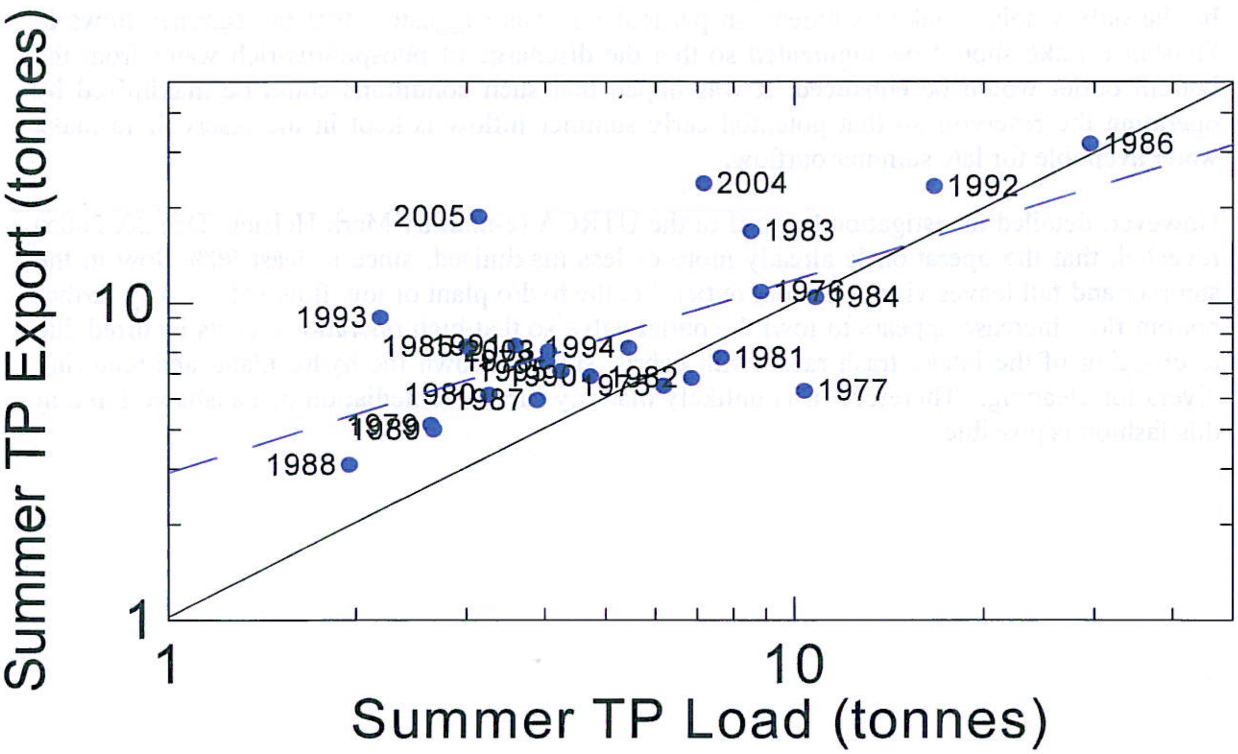

Figure 4-10. Summer TP export versus summer TP load of main inflow.

Note that in most summers export was much higher than load, indicating an internal phosphorus load. Regression line (broken) and 1:1 line are shown.

Net TP export is good for Fanshawe Lake as it indicates that the total mass of TP stored in the lake, including its sediments, has decreased. Also, much of the TP export comes from the hypolimnion; this internal load which otherwise would contribute to the lake surface TP concentration, enhancing algal blooms, is effectively withdrawn and sent downstream. The lake restoration technique of "hypolimnetic withdrawal" is based on this principal and enhances this effect (Nürnberg 1987).

The year 1989 could be seen as a "test year", when only surface withdrawal happened because of work on the low flow gate. 1989 had the highest oxygen depletion with an anoxic factor of almost 50 d/yr and high algal biomass (Table 4-2, Table 4-5). Describing the poor water quality in 1989, D.R. Pearson, UTRCA, concludes (in a letter of Jan 16, 1990 to Dennis Veal, MOE, London) that the hypolimnetic withdrawal benefits the water quality of Fanshawe Lake. However it should be noted, that an unusual low flow rate (Appendix D) may also have contributed to the poor water quality in 1989.

For restoration purposes, any improvement or extension of this process would be beneficial to Fanshawe Lake. Treatment options for Fanshawe Lake were discussed in detail in the previous report (Freshwater Research 2005). Hypolimnetic or bottom water withdrawal was considered to be the only viable in-lake treatment. In particular it was suggested, that the summer flows in Fanshawe Lake should be augmented so that the discharge of phosphorus-rich water from the bottom outlet would be enhanced. It was hoped that such conditions could be maximized by operating the reservoir so that potential early summer inflow is kept in the reservoir to make water available for late summer outflow.

However, detailed investigation by staff of the UTRCA (e-mail by Mark Helsten, Dec 20, 2005) revealed, that the operation is already more or less maximised, since at least 90% flow in the summer and fall leaves via the bottom outlet (i.e. the hydro plant or low flow valve). Any further bottom flow increase appears to fowl the outlet valve so that high operational costs incurred due to clogging of the intake trash racks with debris, shutting down the hydro plant, and requiring divers for cleaning. Therefore, it is unlikely that any further remediation of Fanshawe Lake in this fashion is possible.