A comparative analysis of 4 shallow urban impoundments

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Shallow urban impoundments are known for low water transparency, and generally low water quality. This thesis investigates the effects of land use, management regime, and carp density on the water quality in 4 shallow urban impoundments on the Laurel Creek system in Waterloo, Canada. The focus of this study is to look at how these factors affect suspended solids, total phosphorus, and phytoplankton assemblages within the impoundments. The land upstream of the impoundments is lightly to heavily urbanized. The impoundments differ in how they are managed as well, with the most upstream impoundment being completely drawn-down every year with drastic effects downstream.

Clair and Silver Lakes received significantly higher total inorganic solids (TIS) concentrations compared to Laurel Creek Reservoir and Columbia Lake during the study period; however there were no significant differences between the impoundment inlets for total organic solids (TOS) or total phosphorus (TP) concentrations during the same period.

Three of the four impoundments were found to export significantly higher concentrations of TIS; these were Columbia, Clair and Silver Lakes. Additionally, Clair and Silver Lakes exported significantly higher TIS concentrations than both Columbia Lake and Laurel Creek Reservoir. Laurel Creek Reservoir discharged very low TIS concentrations throughout the study period. The same pattern as TIS concentrations was seen for the TOS concentrations leaving the impoundments, with Columbia, Clair, and Silver Lakes having significantly higher outlet TOS concentrations when compared to Laurel Creek Reservoir; additionally Clair and Silver Lakes discharged significantly higher TOS concentrations when compared to Columbia Lake. There were no significant differences among TP concentrations leaving the impoundments during the study period. In general, Laurel Creek Reservoir and Silver Lake discharged the highest phytoplankton densities; while Columbia and Clair Lakes discharged lower densities; however, there was no significant difference in these discharge densities between the different impoundments.

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A special thanks to all the lab techs that helped me with my field work, including the long days on Columbia Lake, thank you so much Lee, Eric, and Dylan.

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1.0 Introduction

Shallow lakes and impoundments tend to take on one of two stable states (Blindow *et al.* 1993), clear water dominated by aquatic macrophytes or turbid dominated by phytoplankton (Scheffer *et al.* 1993). Aquatic macrophytes improve the sediment stability and provide productive habitat and food for many aquatic invertebrates, fish and birds (Scheffer 2004). Macrophytes also provide large zooplankton with daytime refuge to avoid predation, with both factors suppressing the phytoplankton population. The clear water state can 'switch' to the more turbid state for a variety of reasons, including excess nutrient inputs that promote proliferation of phytoplankton or the destruction of aquatic macrophytes leading to sediment destabilization (Scheffer 2004). The turbid state supports a less diverse biological community dominated by phytoplankton and a few species of benthivorous fish whose feeding activities can significantly increase turbidity, thereby creating a feedback mechanism that facilitates the switch to a turbid state. The most well-known of these fish is the Common Carp (*Cyprinus carpio*) (Breukelaar *et al.* 1994), which can both uproot and destroy macrophytes (Roberts *et al.* 1995). By re-suspending sediment and nutrients, carp can cause a rapid shift to the turbid state, and make macrophyte resettlement nearly impossible. Restoring a lake that has switched to the turbid state can be difficult, as elimination of nutrient inputs may have little effect (Scheffer 2004) because much of the nutrient input has been absorbed into the sediment, which can lead to significant long-term internal loadings. These loadings are exacerbated since the depletion of macrophytes has caused a change in the stability of the sediment, which is now easily disturbed by waves and benthivorous fish (Sheffer 2004).

Impoundments can exhibit the same behaviors as lakes, but differ in that they tend to be managed by people to some extent (Baxter 1977). Impoundments are created for flood control, flow regulation, energy generation or, sometimes, just for recreational purposes. Management for these purposes result in hydrological regimes that are much more varied than those of unregulated lakes (Baxter 1977) and this has significant biological consequences. One common management practice is to draw-down the water level, and this can cause much of the sediment and nutrient base to be expelled, leading to massive amounts of deposition downstream (Shantz *et al.* 2004, Ozersky 2004). Draw-down, especially through the winter, also kills most aquatic macrophytes which will further destabilize the sediment surface and can often lead to the turbid state (Cook, 1980). With the loss of macrophytes, the whole community that was based around the aquatic vegetation will largely be destroyed, such as the invertebrates that live among or seek refuge in the plants, to the fish and birds who feed upon these invertebrates and macrophytes (Scheffer 2004). Draw-down can be very destructive, and is compounded by the effects of urbanization on the quality of water entering the impoundment; in consequence, urban impoundments tend to be highly turbid (Baxter 1977, Walsh *et al.* 2005).

Urban surface waters are typically very degraded by the rapid runoff of contaminated precipitation from impervious surfaces (Walsh *et al.* 2005). This problem is most obvious during development when construction exposes sediment that is easily mobilized into nearby streams and impoundments (Fox 1974). For example, the amount of fine sediment entering the stream draining an area undergoing residential development was 9 times that of rural or natural drainage areas, and that the total volume of sand was 15 times that of nearby rural streams (Fox 1974). In addition to increased sediment input due to urbanization, there is also an abundance of nutrients in these systems. Phosphorus inputs to urban streams were second only to cleared unproductive land (Omernik 1977); these excess nutrients can lead to eutrophication and a switch to the turbid stable state (Scheffer 2004). Reported effects of urbanization on algal assemblages are varied. Munn *et al.* (2002) found a shift from cyanobacteria dominated streams in forests to diatom dominated streams in urban centers. Conversely, Taylor *et al.* (2004) documented a shift from diatom dominance in forested streams to filamentous algae-dominated urban streams. However, the shift from oligotrophic taxa to eutrophic tolerant taxa has been widely documented (Chessman *et al.* 1999, Winter and Duthie 1998, Sonneman *et al.* 2001, Newal and Walsh 2005).

The impoundments along the Laurel Creek system offer several combinations of upstream land use and management regimes, and will be the focus of this manuscript. The system is managed by the Grand River Conservation Authority (GRCA) and the most upstream impoundment (Laurel Creek Reservoir) is completely drawn-down every year, expelling large amounts of sediment and nutrients every autumn. The impoundment has not switched to the turbid state despite the destruction of its aquatic vegetation. The next impoundment downstream (Columbia Lake) was also drawn-down to a low level until 2005/2006, when it was restructured to its current specifications (Yu 2008). The other two impoundments are not drawn-down but are very shallow and highly sedimented. They are very turbid and export large amounts of sediment and nutrients, as well as appearing to support large populations of carp from shoreline observations. They differ in that one (Clair Lake) has no impoundments upstream, and the other (Silver Lake) is downstream of all of the other three impoundments.

The focus of this study is the differences in water quality between the urban impoundments, in terms of suspended solid concentrations, total phosphorus concentrations, and phytoplankton assemblages. I expect that these shallow impoundments would export inorganic and organic suspended solids due to various internal drivers (Scheffer 2004), export elevated concentrations of total phosphorus (especially in more urbanized settings), and phytoplankton assemblages consistent with degraded aquatic systems (Meijer *et al.* 1990, Breukelaar *et al.* 1994, King *et al.* 1997, Lougheed *et al.* 1998, Bergman *et al.* 1999, Walsh *et al.* 2005).

2.0 Methods

2.1 Study Sites

Water quality in 4 urban impoundments within the City of Waterloo was investigated for this study. The four impoundments studied are, Laurel Creek Reservoir, Columbia Lake, Clair Lake and Silver Lake (Fig. 1). All were similar in that they are top-drawn, but differ in management regimes, adjacent land use, upstream sources. All are located in the Laurel Creek system, which runs from the west through the center of Waterloo, continuing east to the Grand River.

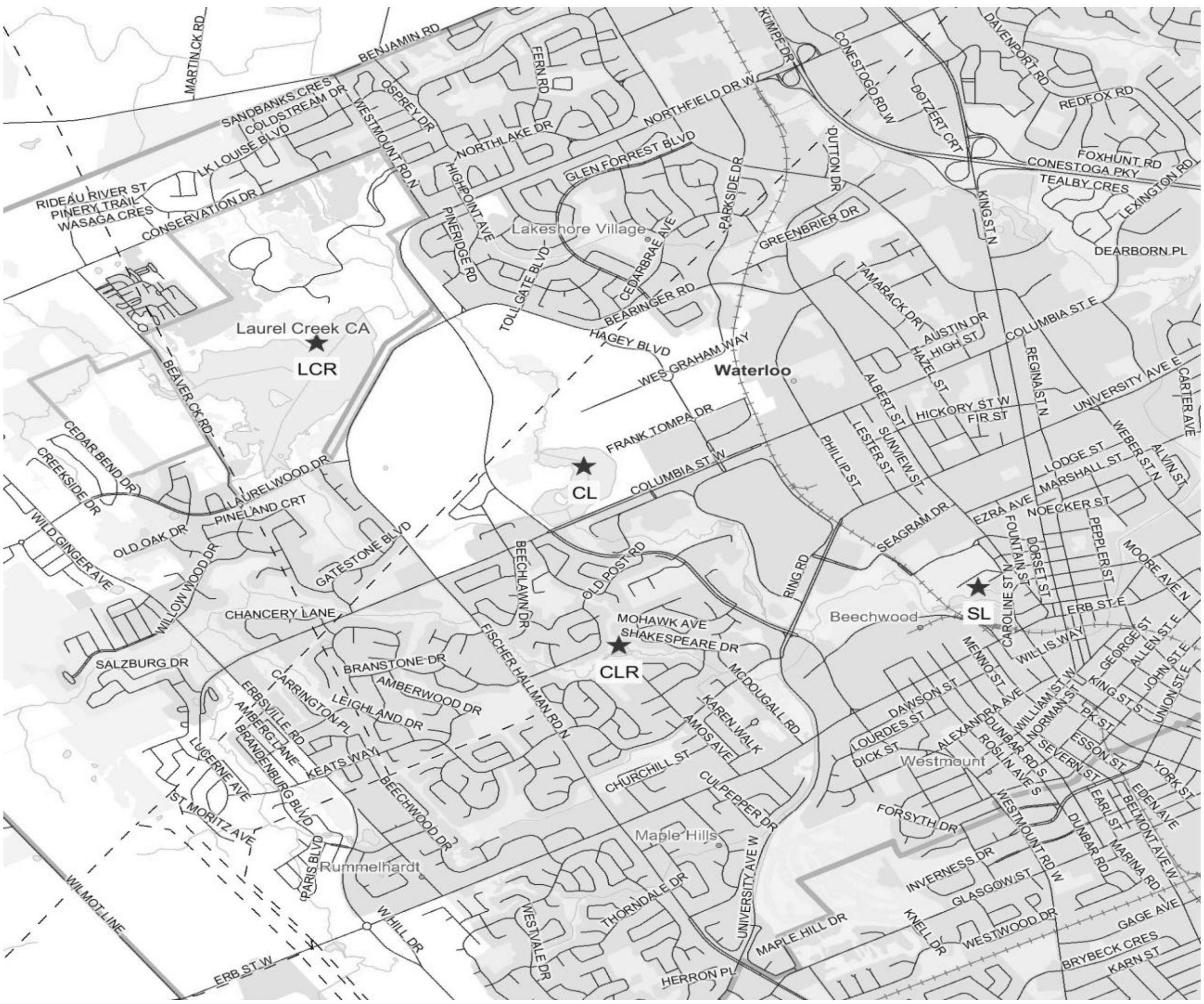


Figure 1. Map of Laurel Creek study sites, LCR=Laurel Creek Reservoir, CL=Columbia Lake, CLR= Clair Lake, and SL=Silver Lake, circle=study lake (GRCA).

Laurel Creek Reservoir is the most upstream impoundment and was constructed for flood control in 1967. It is fed by Laurel Creek and two tributaries draining agricultural land, Monastery Creek and Beaver Creek. The lake is drained yearly in the autumn to channel depth and maintained at this level till mid-spring, or when the threat of spring peak flow diminishes (GRCA). Laurel Creek Reservoir has a surface area of approximately 101 hectares, a mean depth of approximately 1 meter, and a maximum depth of approximately 3 meters. Since this impoundment is drawn-down, there is a small sediment base, and a low density of fish comprising Pumpkinseed (*Lepomis gibbosus*), Bluegill (*Lepomis machrochirus*), Rock Bass (*Ambloplitus rupestris*), Brown Bullhead (*Ameiurus nebulosus*), and small numbers of Common Carp (*Cyprinus carpio*) among others (GRCA).

Columbia Lake is the next impoundment along the system and is directly fed from Laurel Creek Reservoir via a forested channel. Columbia Lake has a surface area of approximately 9.5 hectares, a mean depth of approximately 1.3 meters and an approximate maximum depth of 4 meters. The impoundment was built in 1967, as an ornamental feature of the University of Waterloo campus. In 2005/2006, it was restructured to decrease the export of inorganic solids and total phosphorus (Yu 2008). The impoundment is drawn-down yearly by 0.5m and has numerous small fish, including but not limited to, Largemouth Bass (*Micropterus salmoides*), Pumpkin Seeds, Brown Bullheads, and many cyprinids, including Common Carp.

Clair Lake is a small highly sedimented pond with no upstream impoundments. It is situated in a populated residential area located in Clair Lake Park in the Western part of the city. It is fed by Clair Creek which drains largely residential areas to the West. Clair Lake has an approximate surface area of 0.71 hectares, and an approximate mean depth of 0.6 m, and a maximum depth of less than 1.2m (Conestoga Rovers & Associates 2009). Originally created in 1949 as a small farm pond, the area around the impoundment has recently been an area of extensive residential development. This impoundment has numerous small fish, with a similar composition to the Columbia Lake fish community.

Silver Lake is the most downstream impoundment, located in the center of Waterloo within Waterloo Park. This impoundment has an approximate surface area of 4.25 hectares. No depth measurements were taken, so mean and maximum depths are unknown. Originally a pond used for a grist mill located along Beaver Creek (now Laurel Creek), it was once the focal point of the community and served as part of its economic base. The lake has since been amalgamated into the city proper. The impoundment is heavily used by waterfowl with a fish assemblage is similar to that in Clair Lake (City of Waterloo).

2.2 Sampling

2.2.1 Water Chemistry

Water samples were collected at the inlets and outlets of all impoundments weekly during the summer months (May, June, July and August) in 2007 and 2008, using 1 L polyethylene bottles. Samples were taken 10 cm below the water surface to minimize collection of surface material. Samples were taken at least 3 days after precipitation events heavy enough to cause a perceptible increase in the discharge of Laurel Creek. This constraint could not always be observed during the very wet summer of 2008. 25 ml subsamples were preserved with Lugol's iodine for later identification and enumeration of phytoplankton. During 2008, separate 100 ml samples were taken at the same time and frozen for later analysis of total phosphorus.

2.3 Analysis

2.3.1 Suspended Solids

The 1 L water samples were brought back to the laboratory where they were run through pre-ashed and pre-weighed GF/C filters with a 0.425μm pore size. The volume of water passed through the filter was recorded. Filters were then dried at 60°C for a minimum of 48 hours, weighed and then combusted at 400°C for 2 hours and reweighed to determine concentrations of suspended solid fractions (inorganic and organic).

2.3.2 Water Flow

The water volume entering and leaving Columbia Lake was measured daily for 2007 utilizing the area-velocity method (Manning 1889), and was utilized to estimate the flow volume relationship with precipitation, these flow values were collected and measured by H. Yu. This relationship was used to estimate the inlet and outlet flow volumes for 2008 by finding the precipitation-flow relationship for this impoundment, and utilizing 2008 precipitation values to determine 2008 flow volumes. This relationship was then used with the total inorganic solid concentrations to determine the loadings entering and leaving the impoundment on a given date and precipitation value. This same method was used to determine the relationship between water flow volume and precipitation for Clair Lake; however this impoundment's water flow was only measured in 2009, so it was estimated on 2009 precipitation values (Dixon 2010, personal communication). This relationship was used to estimate the flow relationships for 2007 and 2008, and TIS concentrations were used to determine loadings at the inlet and outlet. These estimates were used to determine if the impoundments acted as net retainers or exporters of TIS during different precipitation values.

2.3.3 Phosphorus

Total phosphorus samples were collected in the inlets and outlets of the 4 different study lakes; these were analyzed using the ascorbic acid method (Stainton and Armstrong 1977, Murphy and Riley 1962, Wetzel and Likens 2000) utilizing the protocols developed by the University of Waterloo (Wang 2007, personal communication).

2.3.4 Phytoplankton

The 25 ml phytoplankton subsamples were placed in phytoplankton settling chambers on top of phytoplankton microscopy slides (Utermöhl 1958). They were left undisturbed for 24 hours to allow sedimentation of the suspended phytoplankton. The excess water was removed and the microscopy slides were analyzed using a Zeiss axiovert 35™ inverted microscope. The phytoplankton were identified to genus or, to functional group (Table 5). They were identified using Wehr and Sheath (2003).

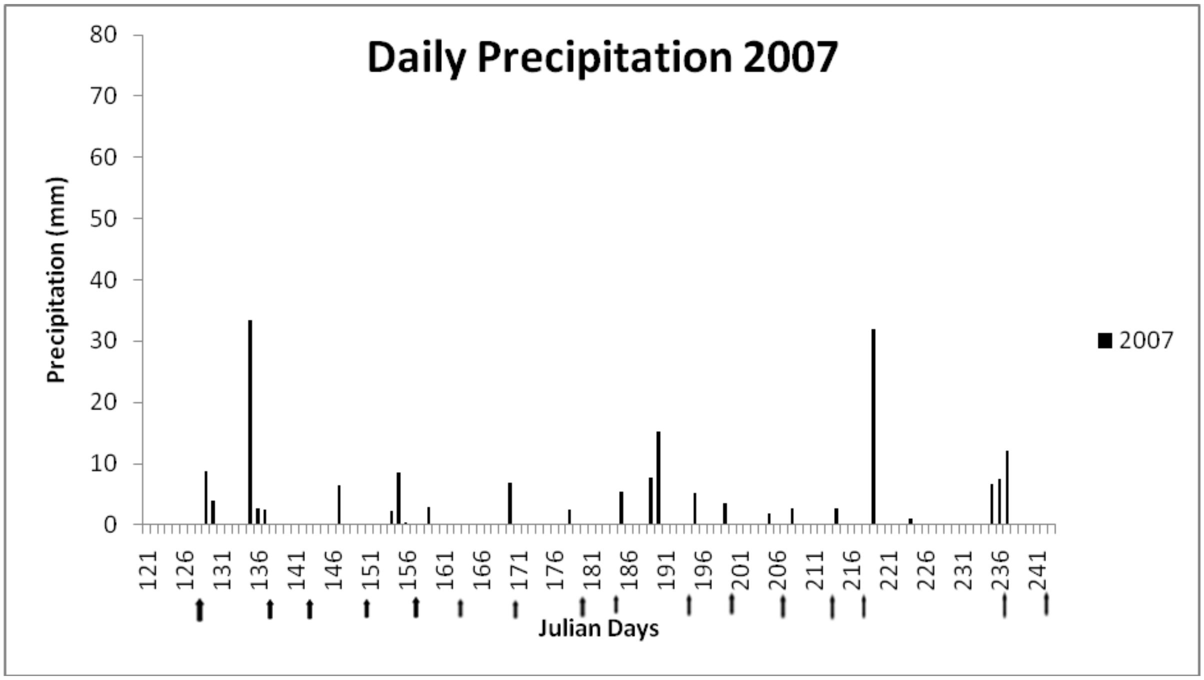
2.4 Data Analysis

Statistical analyses were conducted using PASW Statistics® 17 (SPSS Inc, Chicago, Illinois, licensed from the University of Waterloo) and Microsoft (c) Office Excel 2007. Graphs and figures were created using SPSS inc. Sigmaplot and Microsoft Excel. All data were normalized by $\log_{10}$ transformation. The different variables ([TIS], [TOS], [TP], and total phytoplankton counts) were compared between the 4 impoundments for inlets and outlets, using one-way analysis of variance hereafter referred to as anova. These ANOVA tests were developed further with the Sheffe's post-hoc test to determine the significance if any for internal relationships; these were undertaken with an alpha value of 0.05. Impoundment inlets and outlets were compared for the above variables as well as daily total precipitation values between the two years utilizing paired Student t-tests, with an alpha value of 0.05. Pearson's correlation was undertaken to determine if there were significant liner relationships between precipitation, and the different variables.

3.0 Results

3.1 Precipitation

Daily total precipitation in the Laurel Creek system differed significantly between 2007 and 2008 (paired student t-test, df = 122, t = -3.18, , $p < 0.001$): 2007 was dry with low flow in Laurel Creek throughout the summer, especially from mid-May to mid-August; and 2008 was much wetter with >3.5 times more rainfall (Fig. 2). Not surprisingly, the volume of water entering and leaving Columbia Lake increased with increasing precipitation (Fig. 3). These values were calculated from daily flow measurements taken by H. Yu during 2007, utilizing the area-velocity method (Manning 1889). The volume of water entering and leaving Clair Lake was also measured in a 2009 study (Dixon, 2009), and was shown to have a similar pattern to Columbia Lake where the volume of water entering and leaving the impoundment increased with precipitation and the flow dynamics fitted to the 2007 and 2008 precipitation values (Fig. 4). Linear regression was used to investigate the relationship between TIS in the inflows of the reservoirs and precipitation, sequentially adding rainfall up to 10 days preceding TIS sampling events. Total precipitation during the 7 days prior to sampling was found to be the best predictor (Table.1).



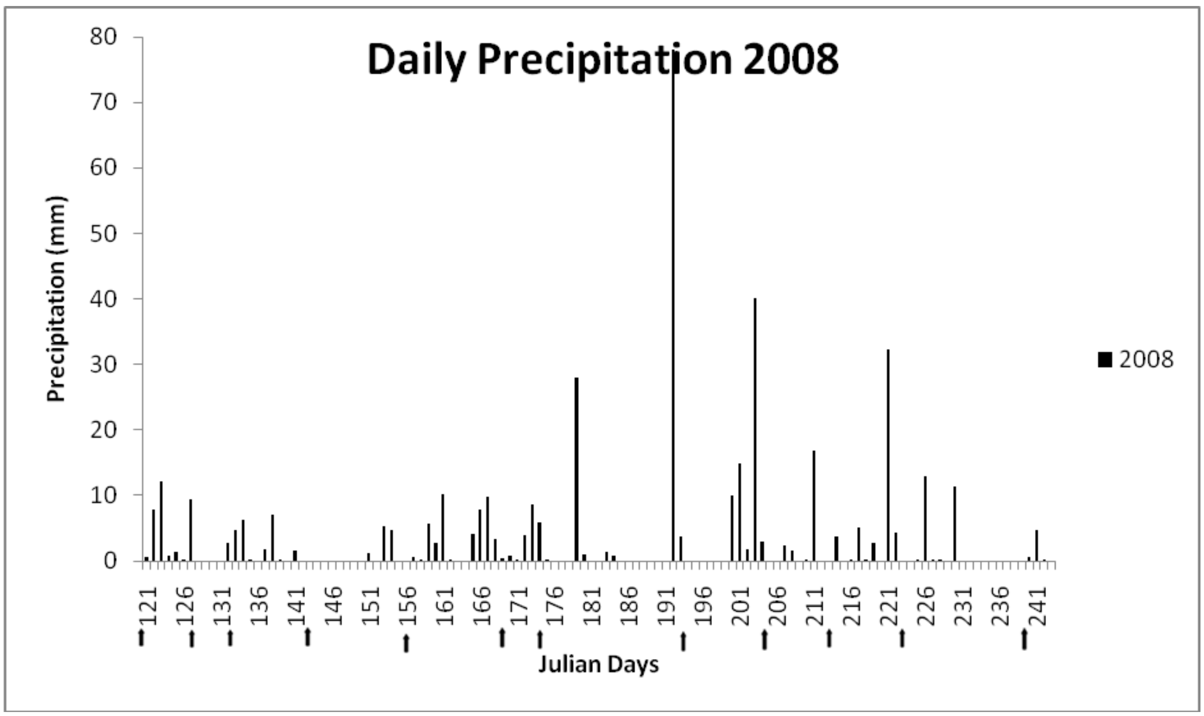


Figure 2: Daily precipitation values for 2007 and 2008 (May to August), black arrows indicate sampling dates.

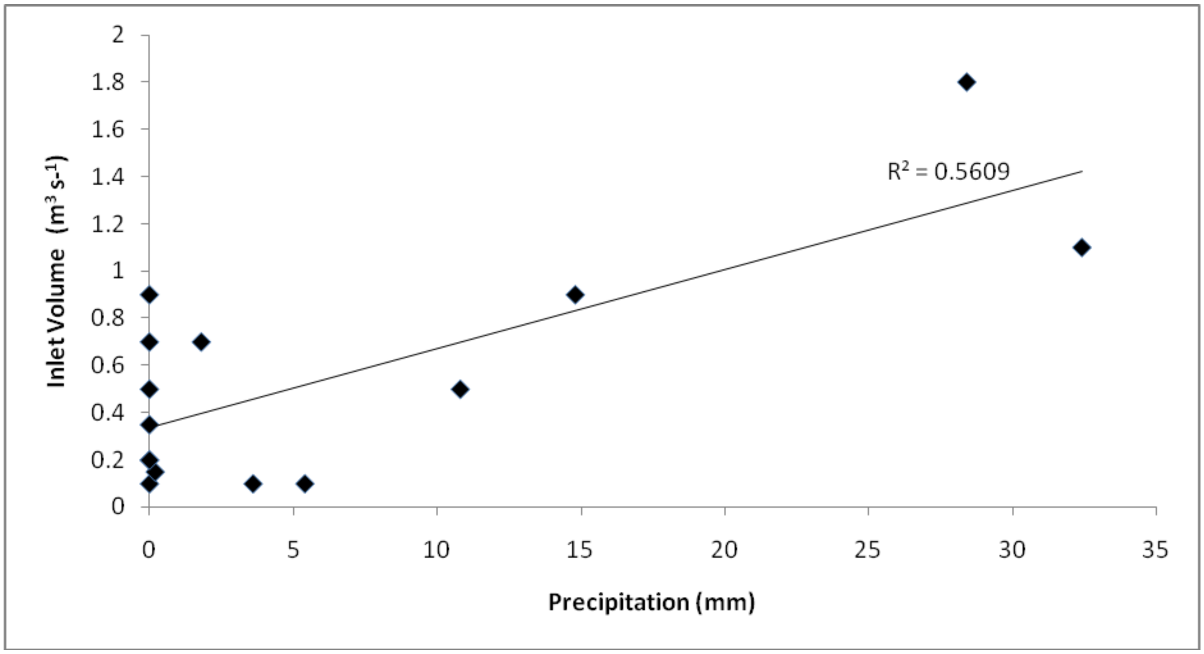


Figure 3a: The relationship between precipitation and inflow water volume for Columbia Lake inflow in 2007, calculated from area velcoity method by H. Yu 2007.

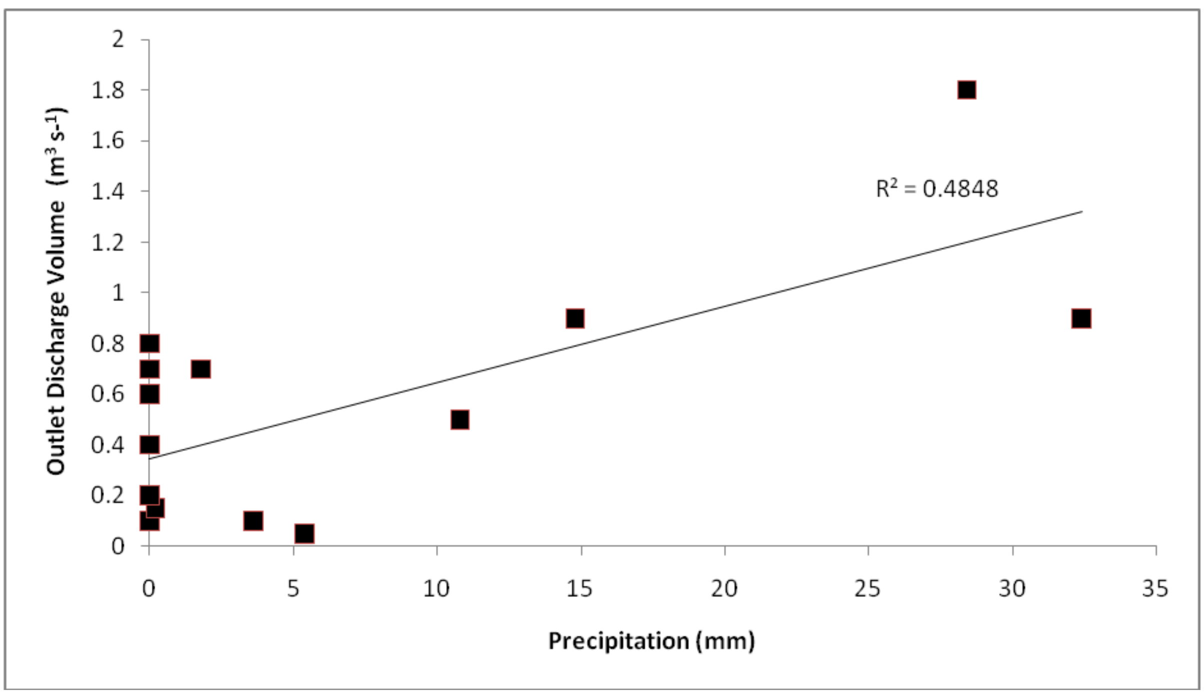


Figure 3b: The relationship between precipitation and outflow water volume (discharge) for Columbia Lake outflow in 2007, calculated from area velocity method by H. Yu 2007.

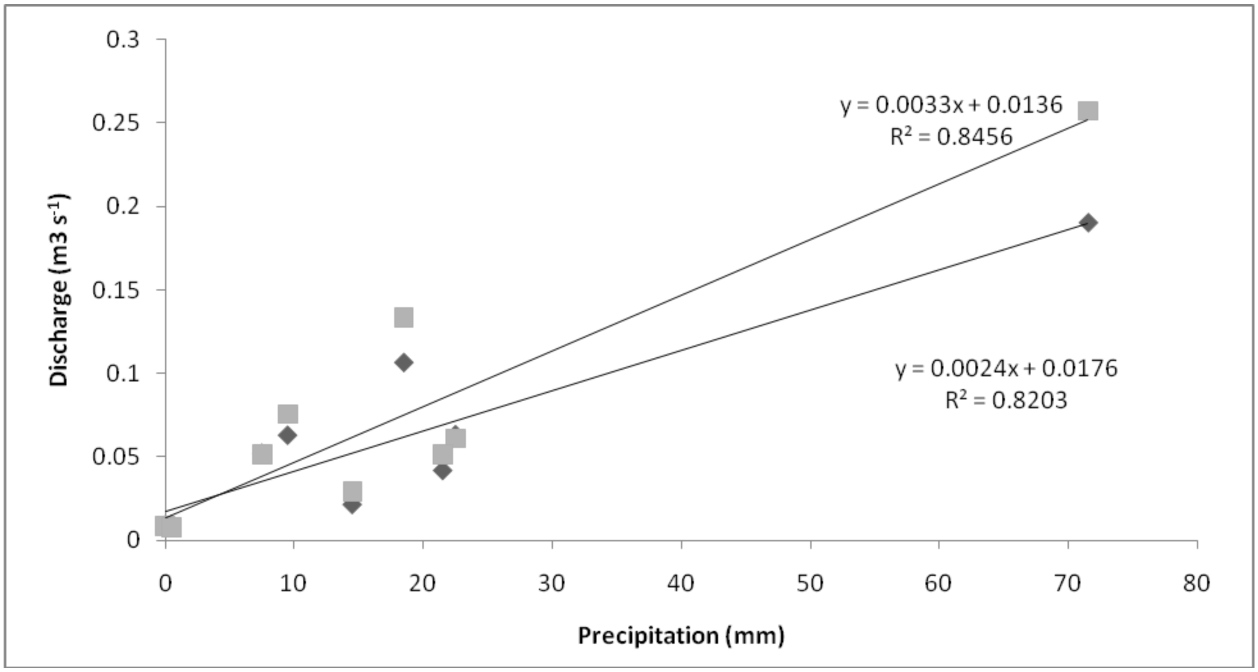


Figure 4: Relationship between Clair Lake inflow and outflow water volume with precipitation for 2009, diamond=inflow and square=outflow, this was used to estimate flow charateristics for 2007 and 2008.

Table1: r^2 values for linear regression between [TIS] and daily precipitation at differing intervals, grey highlight indicates the interval used for this study.

	LRI	CLI	CLRI	SLI
Date	0.064	0.038	-0.036	-0.028
Date+1	0.054	0.105	<0.001	0.001
Date+2	0.008	0.116	0.002	0.022
Date+3	0.064	<0.001	0.239	0.216
Date+4	0.083	0.013	0.217	0.273
Date+5	0.08	0.017	0.203	0.286
Date+6	0.05	0.007	0.187	0.233
Date+7	0.036	0.017	0.259	0.273
Date+8	0.021	0.029	0.301	0.306
Date+9	0.007	0.007	0.493	0.522
Date+10	0.002	0.003	0.493	0.528

3.2 Inlet Characteristics (TIS, TOS, and TP)

Concentrations of TIS at the inlets of Clair and Silver Lakes were significantly correlated with precipitation (Pearson correlation, df=28, r^2=0.259, p=0.005, and df=27, r^2=0.273, p=0.004,) respectively (Table 2). In contrast, concentrations of TIS at the inlets of Laurel Creek Reservoir and Columbia Lake were always very low and did not appear to vary with precipitation (Fig. 5). Total phosphorus (TP) was measured only in 2008; values ranged from 16.80 μg L^{-1} to 138.50 μg L^{-1}. The best predictor of TP was found to be TIS concentration. Pearson correlation confirmed significant positive relationships between TIS and TP in Columbia, Clair and Silver Lakes and a positive non-significant relationship in Laurel Creek Reservoir (Fig.6 and Table.3).

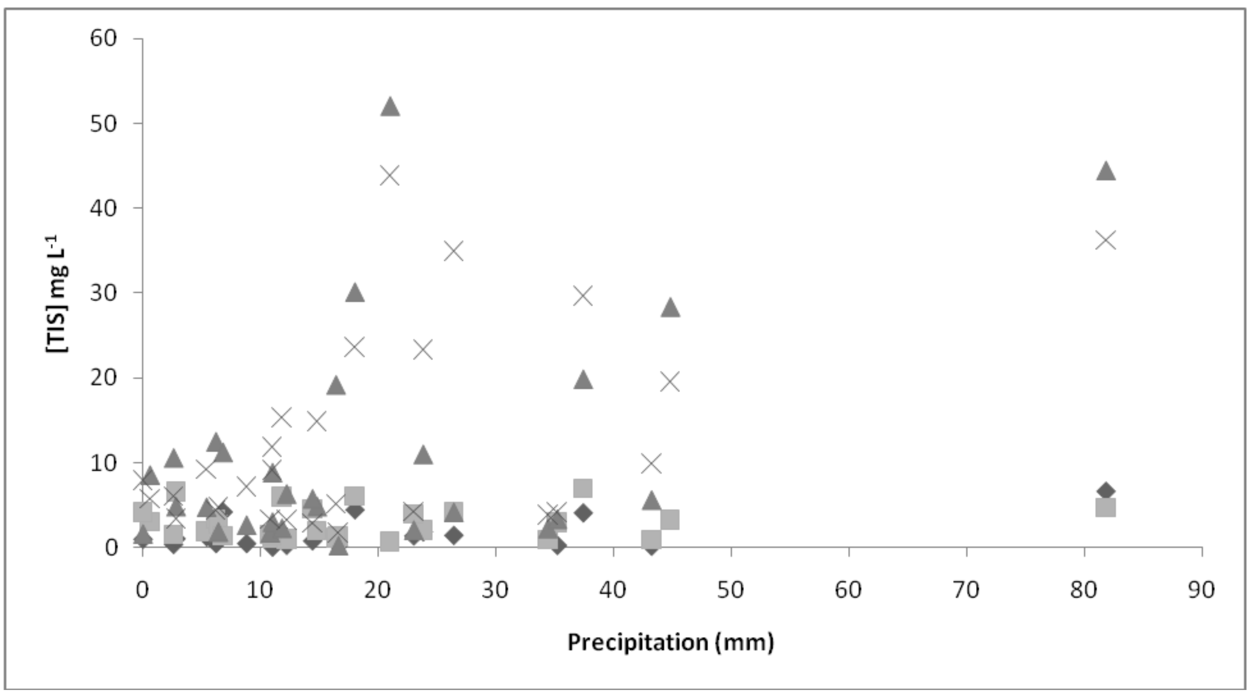


Figure 5: Inlet [TIS] vs. Precipitation from previous 7 days for 2007 and 2008, [TIS]=Total Inorganic solid concentration, diamond = Laurel Creek Reservoir, square = Columbia Lake, triangle = Clair Lake, and X = Silver Lake.

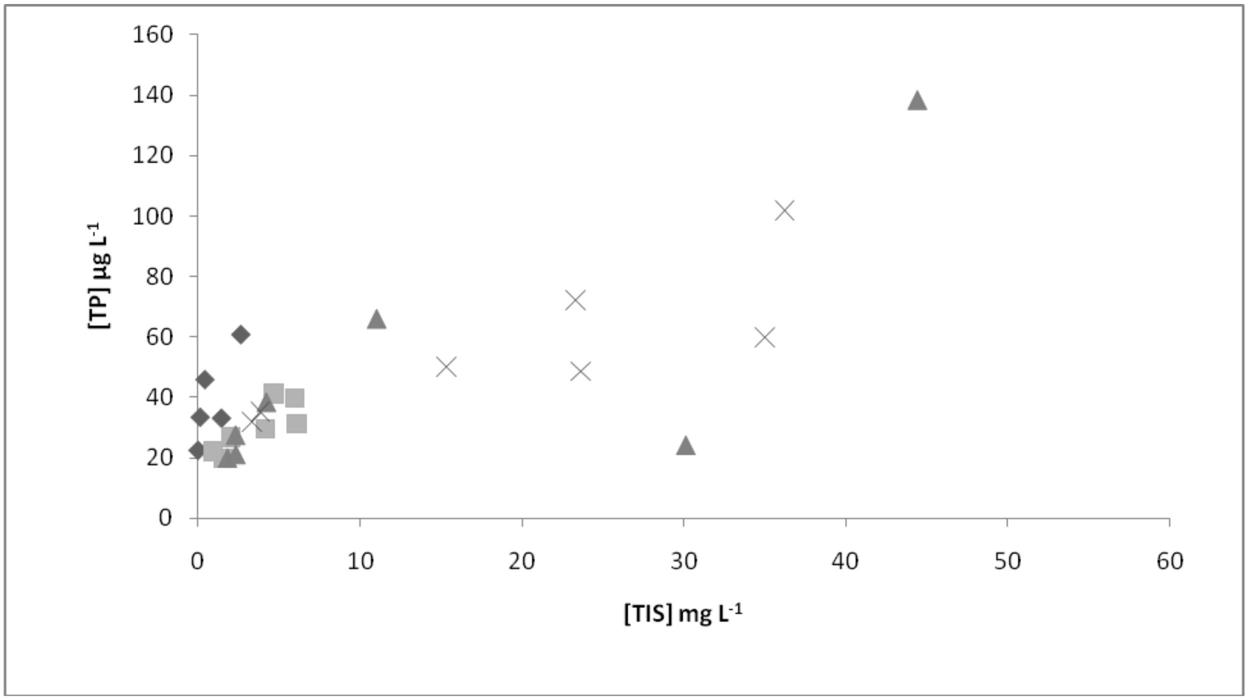


Figure 6a: Inlet relationship between [TP] and [TIS] for 2008, [TP]=Total Phosphorus concentrations, [TIS]=total inorganic solid concentration, diamond = Laurel Creek Reservoir, square = Columbia Lake, triangle = Clair Lake, and X=Silver Lake.

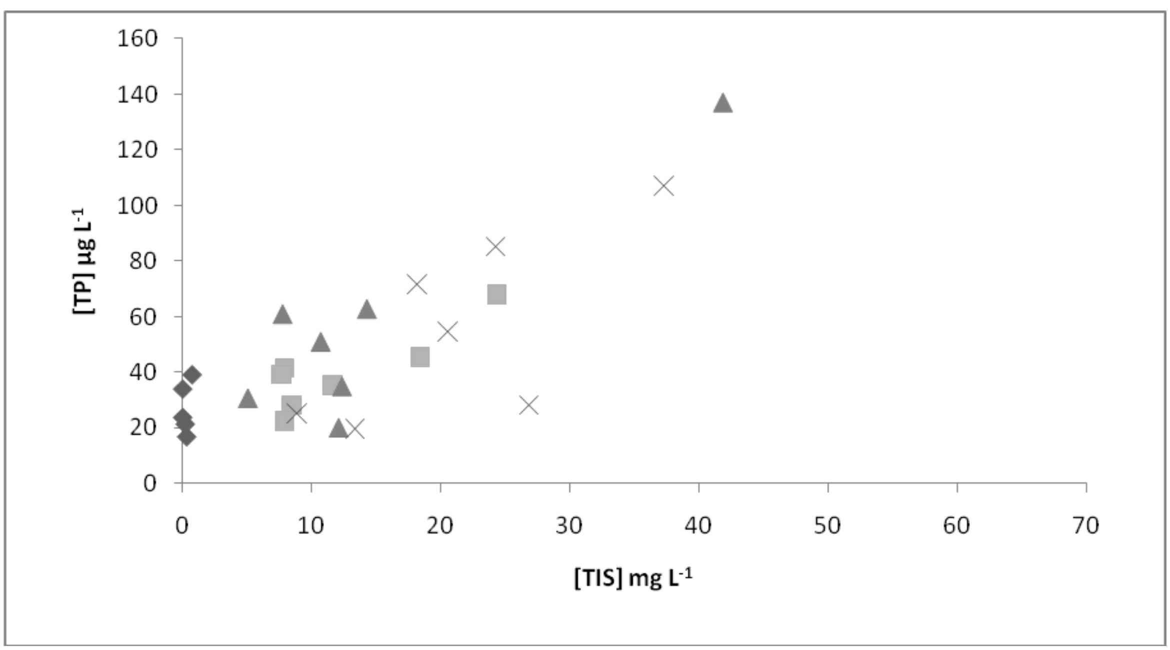


Figure 6b: Outlet relationship between [TP] and [TIS] for 2008, [TP]=Total Phosphorus concentration, [TIS]=total inorganic solid concentration, diamond = Laurel Creek reservoir, square = Columbia Lake, triangle = Clair Lake, and X=Silver Lake.

Total organic solids (TOS) ranged from 0.75mgL^{-1} to 13.39mgL^{-1} in 2007, and 0.17mgL^{-1} to 19.39mgL^{-1} in 2008 (Fig.7). Inlet TOS concentrations were positively, but not significantly, correlated with precipitation for all impoundment (Table 2, Fig.7). Also TOS tended to increase with increasing TP in the inlets for all reservoirs, but these relationships were not significant (Fig. 8) (Table 3). Comparing inlets for both years, there was found to be a significant difference in the TOS concentrations entering Laurel Creek reservoir and Silver Lake (Paired t-test, df=12, p=0.003 and df=14, p=0.013) respectively, but in no other impoundments.

Table 2: Pearson correlations between total inorganic solids [TIS] and Precipitation for 2007 and 2008,*= significant to 0.05, LR=Laurel Creek Reservoir, CL=Columbia Lake, CLR=Clair Lake, SL=Silver Lake, and Precip=total precipitation.

	Precip R^2	Sig.
LR Inlet [TIS]	0.036	0.376
CL Inlet [TIS]	0.017	0.506
CLR Inlet [TIS]	0.259	*0.005
SL Inlet [TIS]	0.273	*0.004
LR Outlet [TIS]	0.130	0.077
CL Outlet [TIS]	0.411	*<0.001
CLR Outlet [TIS]	0.191	*0.018
SL Outlet [TIS]	0.161	*0.031

Table 3: Pearson correlations between [TP] and [TIS] and [TOS], * = Correlation significant at the 0.05 level, LR=Laurel Creek Reservoir, CL=Columbia Lake, CLR=Clair Lake, SL=Silver Lake, [TP]=total phosphorus concentration, [TIS]=total inorganic solid concentration, and [TOS]=total organic solid concentration.

	[TIS]	Sig.	[TOS]	Sig.	df
LR Inlet [TP]	0.602	0.123	0.192	0.460	4
CL Inlet [TP]	0.669	*0.025	0.056	0.609	6
CLR Inlet [TP]	0.574	*0.048	0.242	0.263	6
SL Inlet [TP]	0.680	*0.023	0.035	0.686	6
LR Outlet [TP]	0.175	0.483	0.072	0.663	4
CL Outlet [TP]	0.734	*0.014	0.190	0.328	6
CLR Outlet [TP]	0.806	*0.006	0.225	0.283	6
SL Outlet [TP]	0.534	0.062	0.695	*0.020	6

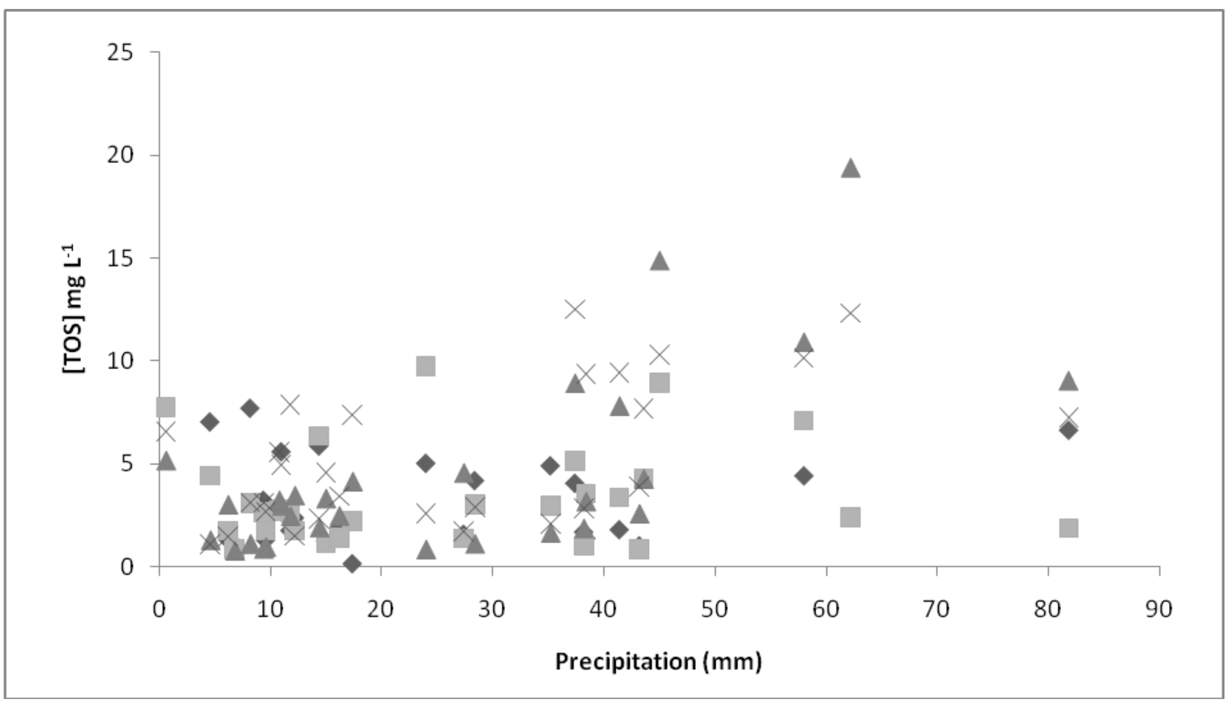


Figure 7: Inlet relationship between [TOS] and Precipitation from previous 7 days for 2007 and 2008, [TOS]=total organic solid concentration, diamond=Laurel Creek Reservoir, square=Columbia Lake, triangle=Clair Lake, and X=Silver Lake.

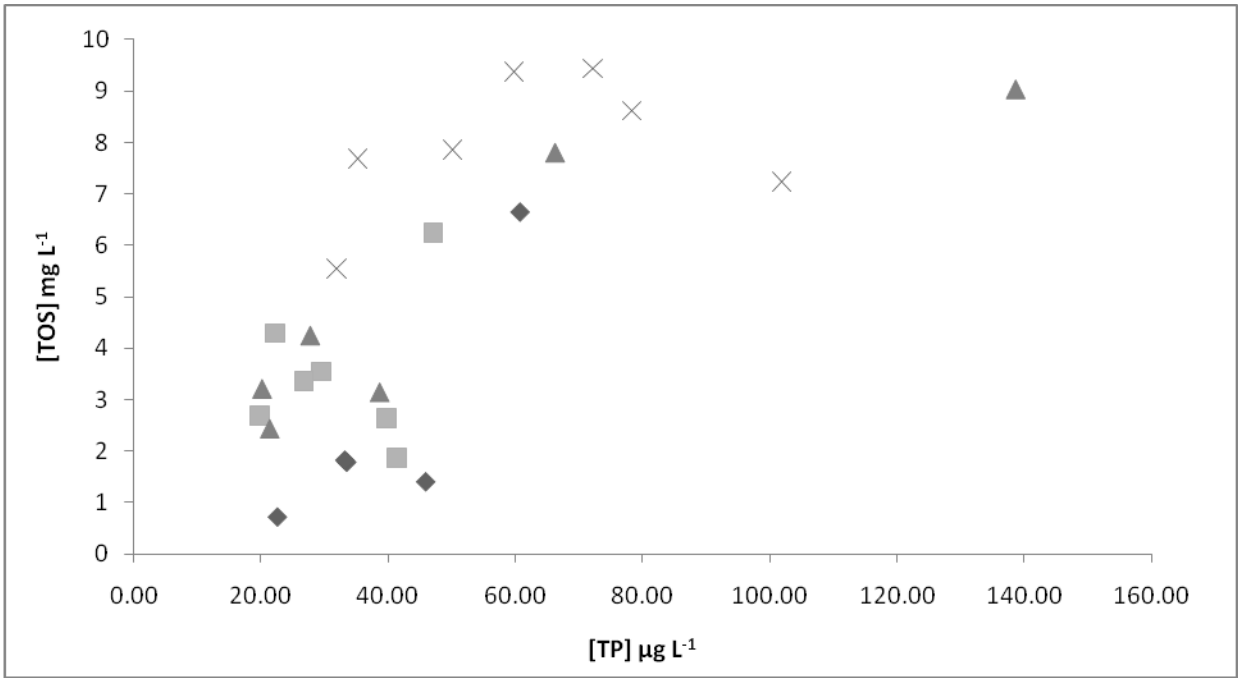


Figure 8: Inlet relationship between [TP] and [TOS] for 2008, [TP]=total phosphorus concentration, [TOS]=total organic solid concentration, diamond=Laurel Creek Reservoir, square=Columbia Lake, triangle=Clair Lake, and X=Silver Lake.

3.3 Inlet comparisons with one-way ANOVA ([TIS], [TOS], and [TP])

Significantly higher TIS concentrations entered Clair and Silver Lakes compared to Laurel Creek Reservoir and Columbia Lake (Table 4) during the study period; however there were no significant differences between the impoundment inlets for the TOS or TP concentrations during the same period (Table 5).

Table 4: Mean and standard deviation values for the inlets and outlets for the different impoundments, [TIS] = total inorganic solids, [TOS] = total organic solids, [TP] = total phosphorus, Phyto = total phytoplankton densities, LCR = Laurel Creek Reservoir, CL = Columbia Lake, CLR = Clair Lake, SL = Silver Lake, I = inlet, and O = outlet.

	LCRI	**CLI**	**CLRI**	**SLI**	**LCRO**	**CLO**	**CLRO**	**SLO**
[TIS] Mean (mgL^{-1})	0.33 ± 0.06	0.57 ± 0.07	0.86 ± 0.15	0.94 ± 0.15	0.28 ± 0.06	0.85 ± 0.08	1.25 ± 0.06	1.23 ± 0.05
[TOS] Mean (mgL^{-1})	0.56 ± 0.06	0.58 ± 0.04	0.61 ± 0.08	0.73 ± 0.06	0.52 ± 0.05	0.73 ± 0.03	0.94 ± 0.03	0.93 ± 0.03
[TP] Mean (μgL^{-1})	1.58 ± 0.03	1.57 ± 0.02	1.59 ± 0.06	1.75 ± 0.02	1.43 ± 0.02	1.65 ± 0.05	1.74 ± 0.05	1.71 ± 0.05
Phyto Mean (cells ml^{-1})	1.85 ± 0.47	1.94 ± 0.24	1.72 ± 0.17	1.86 ± 0.27	1.93 ± 0.49	1.77 ± 0.24	1.72 ± 0.20	1.89 ± 0.28

Table 5: Inlet one-way analysis of variance values conducted at an α value of 0.05, where [TIS] = total inorganic solid concentration (mgL^{-1}), [TOS] = total organic solid concentration (mgL^{-1}), [TP] = total phosphorus concentration (μL^{-1}), and DF = degrees of freedom.

One-way ANOVA	**Inlet DF**	**Inlet F-Value**	**Inlet P-Value**
[TIS]	(3,105)	21.67	<0.01
[TOS]	(3,105)	2.55	0.06
[TP]	(3,40)	2.15	0.11

3.4 Outlet Characteristics (TIS, TOS, TP)

Concentrations of total inorganic solids (TIS) at the outlets of the reservoirs in the Laurel Creek system were generally greater during 2008 than in 2007 (Fig. 9). Very little TIS was collected at the outlet of Laurel Creek reservoir regardless of precipitation, with peaks occurring during moderate rainfall events (Fig. 10), however outlet TIS increased significantly with precipitation during the preceding week in the other 3 reservoirs, with the strongest significant correlation for Columbia Lake (Table 2).

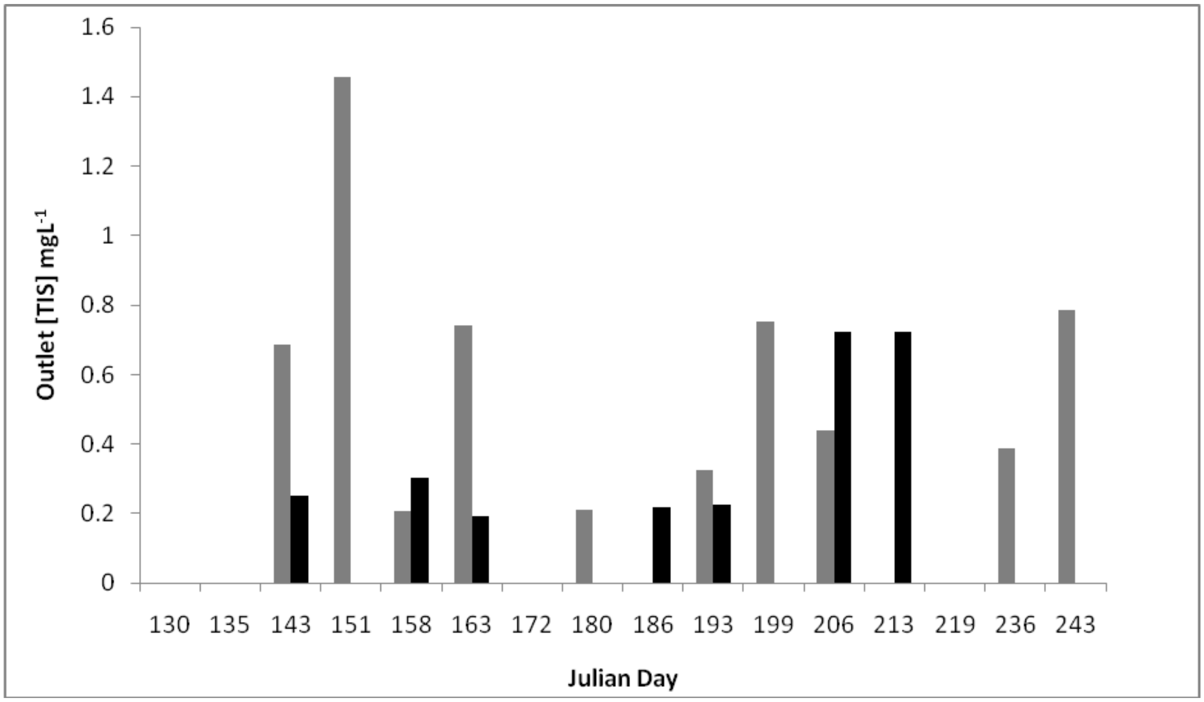


Figure 9a: Laurel Creek Reservoir weekly [TIS] export 2007 vs. 2008, [TIS]= total inorganic solid concentration, grey bars=2007, and black bars=2008.

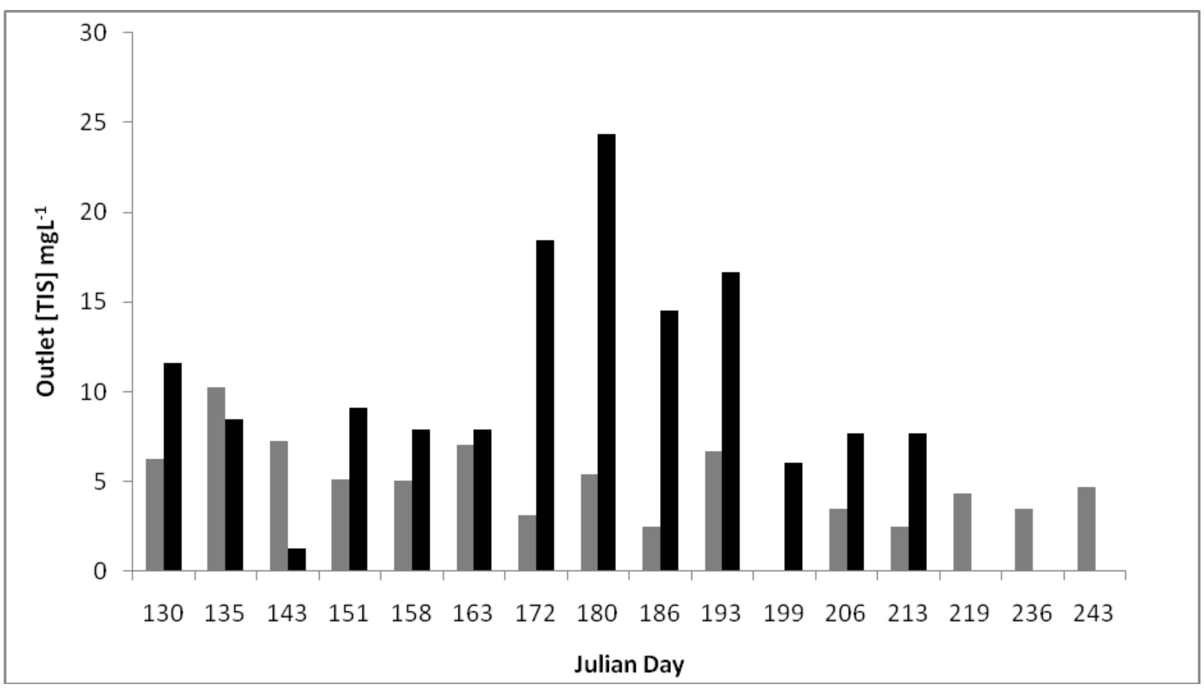


Figure 9b: Columbia Lake [TIS] export 2007 vs. 2008, [TIS]=total inorganic solids concentration, grey bars=2007, and black=2008.

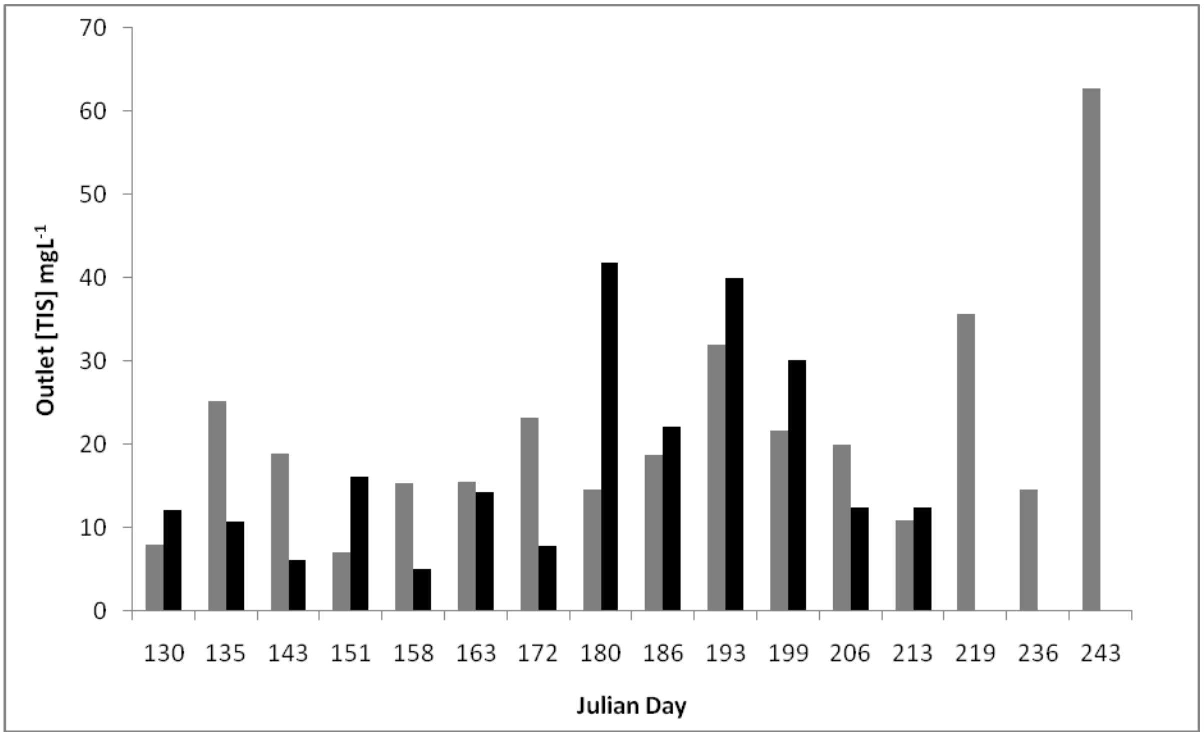


Figure 9c: Clair Lake [TIS] export 2007 vs. 2008, [TIS]= total inorganic solids concentration, grey bars=2007, and black bars=2008.

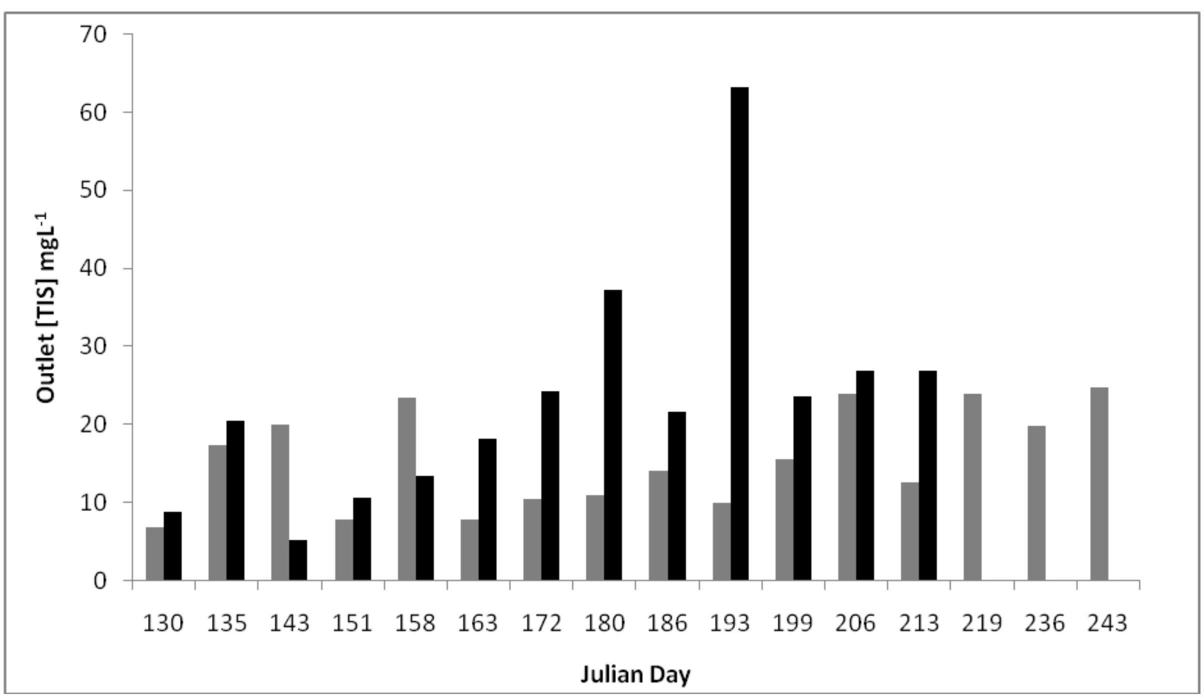


Figure 9d: Silver Lake [TIS] export 2007 vs. 2008, [TIS]= total inorganic solids concentration, grey bars=2007, and black bars=2008.

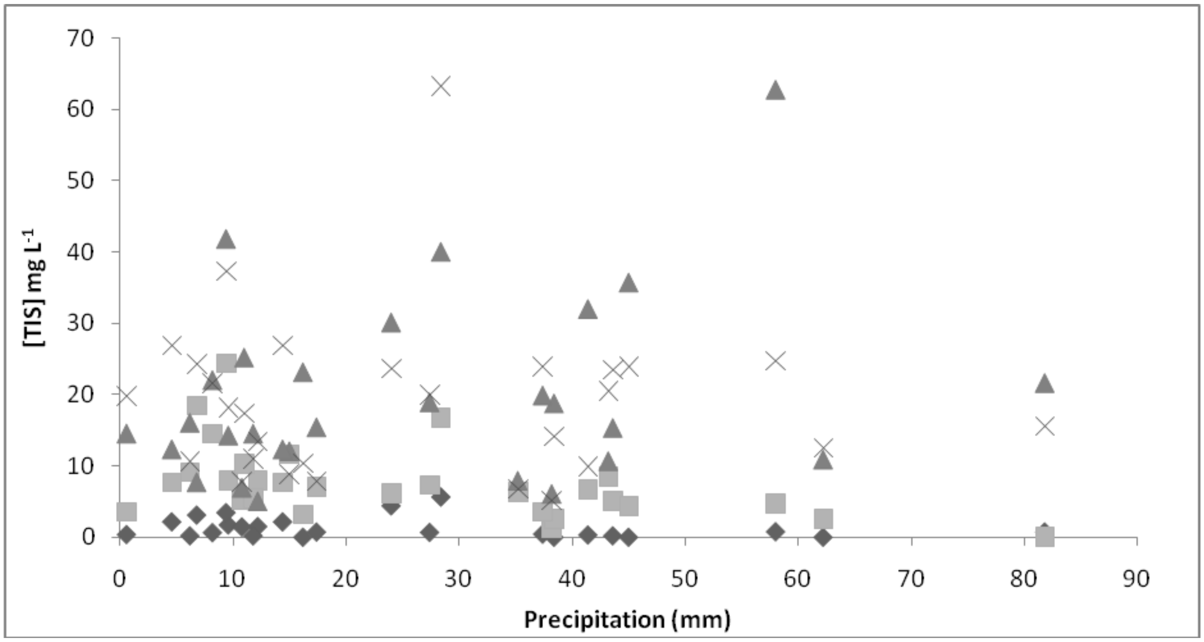


Figure 10: Outlet scatter-plot between [TIS] and Precipitation date+7 for 2007 and 2008, [TIS]=total inorganic solid concentration, diamond=Laurel Creek Reservoir, square=Columbia Lake, triangle=Clair Lake, and X=Silver Lake.

Outlet TOS concentrations were not correlated with precipitation for any of the impoundments (Fig.11 and Table 2). Outflow TOS increased with TP for all of the impoundments along this system (Fig.12), but the only significant relationship was for Silver Lake (Table.3).

TP concentration was also positively correlated with TIS at the outlets of the reservoirs, but this relationship was significant only for Columbia and Clair Lakes (Table 3). The other two impoundments had positive non-significant relationships.

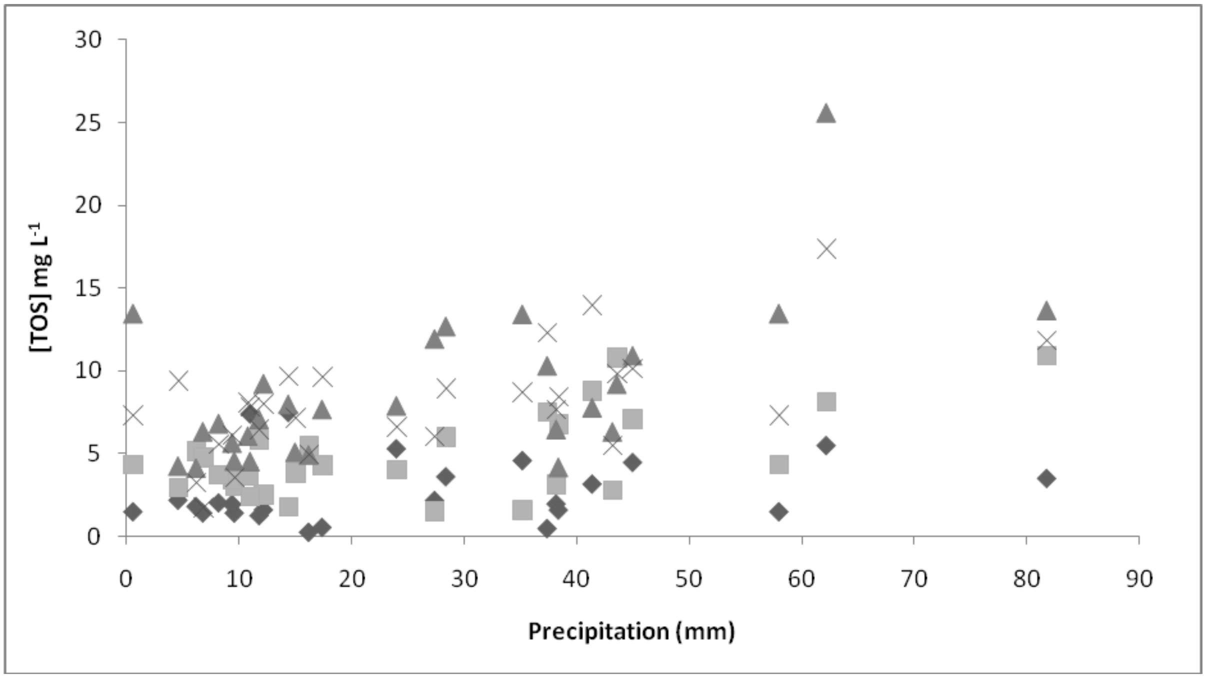


Figure 11: Outlet scatter-plot between [TOS] and Precipitation date+7, 2007 and 2008 [TOS]=total organic solid concentration, diamond=Laurel Creek Reservoir, square=Columbia Lake, triangle=Clair Lake, and X=Silver Lake.

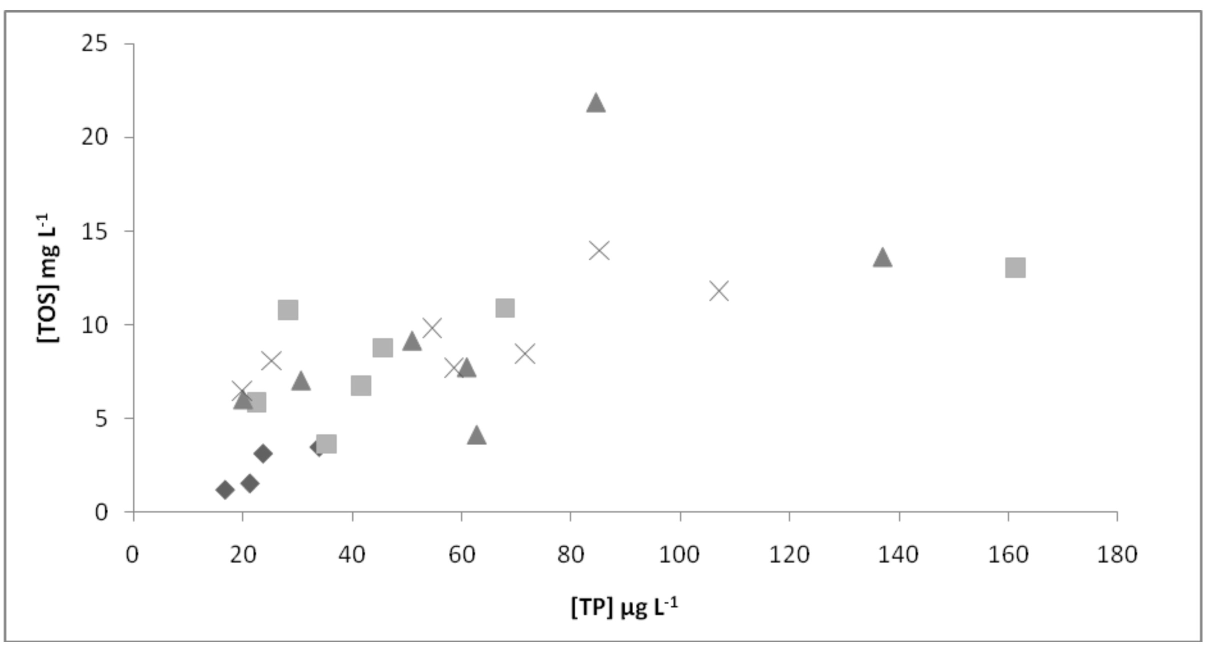


Figure 12: Outlet relationship between [TP] and [TOS] for 2008, [TP]=total phosphorus concentration, [TOS]=total organic solid concentration, diamond=Laurel Creek Reservoir, square=Columbia Lake, triangle=Clair Lake, and X=Silver Lake.

3.5 Outlet comparisons with one-way ANOVA ([TIS], [TOS], [TP], and phytoplankton densities)

Significantly higher TIS concentrations were discharged from Columbia, Clair, and Silver Lakes when compared to Laurel Creek Reservoir (Table 3) (Table 6). In addition, Clair and Silver Lakes discharged significantly higher TIS concentrations compared to Columbia Lake.

The same pattern as TIS concentrations was seen for the TOS concentrations leaving the impoundments (Table 6), with Columbia, Clair, and Silver Lakes having significantly higher outlet TOS concentrations when compared to Laurel Creek Reservoir, additionally Clair and Silver Lakes discharged significantly higher TOS concentrations when compared to Columbia Lake. There were no significant differences between TP concentrations leaving the impoundments during the study period. In general Laurel Creek Reservoir and Silver Lake discharged the highest phytoplankton densities; while Columbia and Clair Lakes discharged lower densities however there was found to be no significant difference in these discharge densities between the different impoundments (Table 4 and 6).

Table 6: Outlet one-way analysis of variance values conducted at an α value of 0.05, where [TIS] = total inorganic solid concentration (mgL^{-1}), [TOS] = total organic solid concentration (mgL^{-1}), [TP] = total phosphorus concentration (μL^{-1}), total phytoplankton = the total number of phytoplankton (cells ml^{-1}), and DF = degrees of freedom.

One-way ANOVA	Outlet DF	Outlet F-Value	Outlet P-Value
[TIS]	(3,107)	82.61	<0.01
[TOS]	(3,106)	31.27	<0.01
[TP]	(3,37)	2.57	0.07
Total Phytoplankton	(3,57)	0.49	0.69

3.6 Inlet and Outlet comparisons with paired t-test ([TIS], [TOS], [TP], and phytoplankton densities)

Significantly higher concentrations of TIS were discharged from Columbia, Clair and Silver Lakes compared to the concentrations entering (Table 4) ($df = 54$, $t = -3.77$, $p < 0.01$, $df = 54$, $t = -4.48$, $p < 0.01$, and $df = 54$, $t = -3.46$, $p < 0.01$ respectively). This was not observed for Laurel Creek Reservoir which generally received higher inlet TIS concentrations than it discharged (Table 4). Similarly Laurel Creek Reservoir received higher TOS concentrations than it discharged, but the difference was not significant (Table 4). Columbia, Clair, and Silver Lakes had significant differences between their inlet and outlet TOS concentrations, with Columbia, Clair and Silver Lakes discharging significantly higher concentrations than they received (Table 4) ($df = 54$, $t = -2.82$, $p < 0.01$, $df = 54$, $t = -5.25$, $p < 0.01$, and $df = 53$, $t = -3.54$, $p < 0.01$ respectively). In general, Laurel Creek Reservoir and Silver Lake received higher concentrations of TP than they discharged, with the opposite occurring for Clair and Columbia Lakes where they generally discharged higher TP concentrations than they received during the course of this study (Table 4), however none of these inlet and outlet differences in TP were significant.

Laurel Creek Reservoir and Silver Lake had higher densities of phytoplankton leaving them than entering. This was opposite of what was observed for Columbia Lake. Clair Lake had very similar inlet and outlet densities during the same period, and none of these differences were significant (Table 4).

3.7 Phytoplankton Characteristics

Phytoplankton samples were collected from mid-spring to mid-fall during 2007 and 2008 (Table. 5), but approximately 75% of the 2008 samples were lost during a lab clean-up, resulting in a weaker data set. A total of 19 different taxa was identified and only the outlet samples were emphasized, as the inlets were considered reflective of inputs from upstream, not the taxa that had grown within the impoundments (Table 5), however inlet concentrations were assessed for those ponds downstream from one or more impoundments, i.e., Columbia and Silver Lakes.

Table 7a: Total cell count per mL of identified phytoplankton taxa for 2007 and 2008, LCR O =Laurel Creek Reservoir outlet.

LCRO (Cells ml^{-1})	31-5-07	07-6-07	12-6-07	21-6-07	29-6-07	05-7-07	18-7-07	25-7-07	01-8-07	07-8-07	24-8-07	13-5-08	06-6-08
Navicula sp.	10.56	3.24	18.48	7.6	14.88	19.76	14.4	97.28	11.76	18.76	15.52	1.4	2
Ankistrodesmus sp.	55.6	5.12	14	7.32	18.84	11.76	54.8	79.28	153.28	64.4	101.92	1.52	1.44
Fragilaria sp.	42.24	1.48	11.32	6.16	37.6	35.2	14	47.2	10.92	1.96	13.92	1.24	0.24
Scenedesmaceae	1.6	0.36	1.8	1.8	1.72	6.28	11.12	4.4	7.04	1.64	12.56	0.24	0.12
Filamentous	1.12	0.16	2.8	2.92	5.72	37.16	41.68	68.8	147.4	117.76	15.04	0.04	0
LRRT	6.4	0.36	0.56	0.52	1.84	16.36	6.48	11.8	2	6.08	0	0	0
Euglenoids	0.4	0	38.64	0.24	188.8	28.48	35.04	57.24	30.72	16.76	140.48	0.04	0
Meridion sp.	0.08	0	0.2	0.08	1.36	0.56	0.16	2.48	0.64	0.36	2.12	0.08	0.12
Cosmarium sp	0.56	0	0.92	0.08	1	2.32	6.32	1.68	0	0.2	3.24	0	0
Pediastrum sp.	0	0.04	0.2	0.08	0	0.16	0.08	0.16	0	0	0	0	0
Ceratium sp.	0	0	0	0	0.16	0	0.16	4.2	0.04	0.36	0.6	0	0
Staurastrum sp	0	0	0.36	0	1.32	2.12	2	1	0.64	0.08	1.36	0	0
Merismopedia sp	0	0	0.64	0	0.56	4.56	4.92	0.4	0.64	0.16	2.6	0	0
Peridinium sp	0.08	0	0.2	0	0.68	0	28.2	0	4.08	0	4.4	0	0
Tabellaria sp	0	0	0.68	0	1.36	5.92	7.72	0	3.44	0.88	4.72	0	0
Volvox sp	0	0	0.2	0	0	0	0	0	0	0	0	0	0
Dinobryon sp	2.4	0	0.68	0	0	0	2.72	0	0	0	11.56	0	0
Codoenllidae	0	0	0	0	0	0	0	0	0	0	0	0	0
Oocyst	0.08	0	0	0	0	0	1.4	0	0	0	2.12	0	0
Total (Cells/ml)	121.12	10.76	91.68	26.8	275.84	170.64	231.2	375.92	372.6	229.4	332.16	4.56	3.92
Benthic Algae (% composition of sample)	0%	0%	0%	0%	80%	10%	67%	0%	0%	25%	25%	0%	0%
Diversity	1.33	1.30	1.46	1.64	1.15	2.09	2.21	1.83	1.38	1.32	1.68	1.39	1.10

Table 7b: Total cell count per mL of identified phytoplankton taxa for 2007 and 2008, CL=Columbia Lake, I=inlet.

CLI (Cells ml^{-1})	07-6-07	12-6-07	21-6-07	29-6-07	05-7-07	18-7-07	25-7-07	01-8-07	07-8-07	24-8-07	07-11-07	23-4-08	07-5-08	13-5-08	06-6-08
Navicula sp.	5.16	43.84	27.76	28.36	66.96	109.92	75.4	58.28	47.96	30.88	12.08	32.56	53.64	16.56	5.08
Ankistrodesmus sp.	1.2	11.48	6.72	9.88	18.44	55.12	29.32	26.72	51.96	57.6	16.36	3.92	45.56	8.76	2.64
Fragilaria sp.	0.96	11.04	10.2	7.96	10.44	28.32	27.52	24.4	16.24	16.44	6.8	6.4	31.96	4.88	1.32
Scenedesmaceae.	0.12	1.48	3.76	2.44	6.76	23.84	4.24	14.76	6	3.12	2.52	0.64	3.6	0.52	0.12
Filamentous	0	2.36	1.2	1.52	0.44	6.16	3.6	4	37.84	3.08	0.48	0.56	0.52	0.36	0.28
LRRT	0	0.64	1.36	6.04	3.08	30.08	11.92	3.16	6.2	46.68	7.96	2.4	0.08	0.04	0
Euglenoids	0	29.08	0.36	71.16	42.04	53.04	13.76	15.6	31.52	70.92	0	2.24	0.52	0	0.08
Meridion sp.	0.04	2.36	1.76	0.8	3.96	3.04	1.56	1.64	1.28	0.44	0.52	3.52	2.04	1.04	0.08
Cosmarium sp	0	1.08	0	0.48	0.2	2.64	0.24	0.12	0.16	0.24	0	0	0	0	0
Pediastrum sp.	0	0.04	0.04	0.04	0.2	0.32	0.08	0.32	0.44	0.16	0	0.16	0	0	0
Ceratium sp.	0	0	0	0	0	0	0	0	0	4.04	0	0	0	0	0
Staurastrum sp	0	0.2	0	0.04	0.6	1.52	0.12	0	0	0.32	0	0	0	0	0
Merismopedia sp	0	0.28	0	1.24	1.48	7.6	0.6	0.36	0.84	0.72	0	0	0	0	0
Peridinium sp	0	0	0	0	0	0	0	0	0	2.68	0	0	0	0	0
Tabellaria sp	0	0.76	0	9.8	68.08	25.44	0.92	2.88	0.96	2.76	0	0.48	0	0	0
Volvox sp	0	0	0	0	7.76	0	0	0.36	0	0	0	0	0	0	0
Dinobryon sp	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0
Codoenllidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oocyst	0	30.84	0	0	0	6	0	0	0	2.8	0	0	0	0	0
Total (Cells/ml)	7.48	135.68	53.16	139.76	230.44	353.04	169.28	152.6	201.4	242.88	46.72	52.88	137.92	32.16	9.6
Benthic Algae (% composition of sample)	0%	10%	0%	0%	10%	20%	0%	25%	17%	17%	0%	0%	0%	0%	0%
Diversity	1.61	1.38	1.44	1.56	1.79	2.05	1.63	1.77	1.98	1.84	1.55	1.36	1.28	1.22	1.20

Table 7c: Total cell count per mL of identified phytoplankton taxa for 2007 and 2008, CL=Columbia Lake, O=outlet.

CLO (Cells ml^{-1})	31-5-07	07-6-07	12-6-07	21-6-07	29-6-07	05-7-07	18-7-07	25-7-07	01-8-07	07-8-07	24-8-07	23-4-08	07-5-08	13-5-08	06-6-08
Navicula sp.	18	6.04	11.4	23.68	9.92	20.76	22.56	14.92	11.12	12.32	15.84	1.76	33.36	2.08	3.44
Ankistrodesmus sp.	14.56	1.04	8.6	18.64	14.04	20.76	17.8	7.6	14.64	35.48	15.72	0.08	104.08	9.16	3.08
Fragilaria sp.	2.8	0.4	7.76	17.24	7.4	10.68	14.76	12.16	3.08	9.56	6.48	0	24.04	0.72	0.2
Scenedesmaceae.	1.16	0.36	0.6	2.56	1.24	1.96	2.52	0.64	1.2	1.2	4.8	0.08	3.76	0.08	0.32
Filamentous	0.08	0	0.56	2.64	6.64	7.6	3.96	0.68	4.32	68.8	1.64	2.88	0.56	0.16	0
LRRT	0.84	6.96	1.56	4	2.56	18.36	29.64	36.44	7.4	4.68	11.56	0	0.04	0.04	0
Euglenoids	2.04	1.92	64.72	0.96	80.36	84.92	45.24	40.12	24.76	25.52	17.04	0.64	0.04	0.12	0
Meridion sp.	0.64	0.04	0.04	0.28	0	0.12	0.4	0.16	0.6	0.08	0.32	0.16	0.48	0.04	0
Cosmarium sp	0	0	0.32	0.04	0.4	0	0.2	0.24	0	0.24	2.96	0	0	0	0
Pediastrum sp.	0.04	0.2	0.24	0.12	0.04	0.08	0	0.08	0	0.04	0.04	0	0.12	0	0
Ceratium sp.	0	0	0	0	0.04	0.2	0.04	0.36	0.4	3.36	0.44	0	0	0	0
Staurastrum sp	0	0.2	0.2	0	0.24	0.04	0.32	0.16	0.12	0.04	0	0	0	0	0
Merismopedia sp	0	0	0.04	0	0.16	0.12	0.2	0.24	0.12	0.2	0.64	0	0	0	0
Peridinium sp	0	0	16.36	0	0.24	0	5.36	0.04	0	0	0	0	0	0	0
Tabellaria sp	0	0	0	0	0.72	0	1.52	0.04	0.16	0.24	0.28	0	0	0	0
Volvox sp	0	0.8	0	0	0.08	0.04	0	0	0.48	0	0	0	0	0	0
Dinobryon sp	0	0.92	1.08	0	0.2	0	1.56	0	0	0	0	0	0	0	0
Codoenllidae	0	0	0.16	0	0	0	0	0	0	0	0	0	0	0	0
Oocyst	0	0.56	0	0	0	0	2.52	0	0	0.44	17.12	0	0	0	0
Total (Cells/ml)	40.16	19.44	113.64	70.16	124.28	165.64	148.6	113.88	68.4	162.2	94.88	5.6	166.48	12.4	7.04
Benthic Algae (% composition of sample)	0%	50%	67%	0%	20%	0%	0%	0%	16%	33%	33%	75%	0%	0%	0%
Diversity	1.33	1.75	1.38	1.57	1.28	1.50	1.95	1.55	1.76	1.62	2.08	1.18	1.03	0.86	0.95

Table 7d: Total cell count per mL of identified phytoplankton taxa for 2007 and 2008, CLR=Clair Lake, O=outlet.

CLRO (Cells ml^{-1})	31-5-07	07-6-07	12-6-07	21-6-07	29-6-07	05-7-07	18-7-07	25-7-07	01-8-07	07-8-07	24-8-07	07-11-07	23-4-08	07-5-08	13-5-08	06-6-08
Navicula sp.	1.88	3.2	5.36	15.48	16.48	38.2	13.6	7.04	40.4	17.76	11.08	6.96	24.72	24.68	1.24	6.52
Ankistrodesmus sp.	0.68	1.44	4.24	3.96	24.72	72.28	14.2	0.6	56	27.2	11.92	1.76	9.76	60.36	1.88	13.6
Fragilaria sp.	0.48	1.64	2.4	6.4	6.6	22.84	5.76	5.4	3.28	5.48	5.16	3.84	5.04	9.28	0.96	0.44
Scenedesmaceae	0.44	0.16	0.28	0.32	0.92	3.8	0.52	0.8	1.48	0.36	0.2	0.28	0	1.64	0	0.84
Filamentous	0	0.08	3.36	0.4	0.4	0.2	0.2	63.52	2.84	1.2	3.4	0.44	7.84	4.8	0.6	12.12
LRRT	28.08	0.76	0.6	0.4	2.4	13.2	3.2	20.32	12.84	15.76	6.96	0.12	1.12	0.32	0.12	0.96
Euglenoids	2.08	1.12	35.44	8.64	47.8	25.48	36.92	56.88	20.08	64.52	10.32	0.12	6.32	4.44	0	0.4
Meridion sp.	0	0.04	0.08	0.16	0.08	0.08	0.16	0.2	0.04	0.24	0.04	0.28	0.32	0.12	0.12	0.32
Cosmarium sp	0	0	0	0	0.04	0	0.08	0.04	0	0	0.52	0	0	0	0	0
Pediastrum sp.	0	0	0	0.04	0	0.08	0	0.32	0	0	0	0	0	0	0	0
Ceratium sp.	0	0	0	0	0	0	0	0.08	0	0.04	0	0	0	0	0	0
Staurastrum sp	0	0	0	0	0.08	0.32	0.12	0.4	0.32	0.24	0	0	0	0	0	0
Merismopedia sp	0	0	0.08	0	0.04	0.08	0	0.04	0	0.08	0.08	0	0	0	0	0
Peridinium sp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tabellaria sp	0	0	0	0	8.08	0	5.36	0.68	0	0	1	0	0	0	0	0
Volvox sp	0	0	0	0	0	0	0	0	1.2	0	0	0	0	0	0	0
Dinobryon sp	0	0	0.16	0	0	0	0.36	0	0	0	0.16	0	0	0	0	0
Codoenllidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oocyst	0	0	0	0	0	0	4.52	0	0	0	0.6	0	0	0	0	0
Total (Cells/ml)	33.64	8.44	52	35.8	107.64	176.56	85	156.32	138.48	132.88	51.44	13.8	55.12	105.64	4.92	35.2
Benthic Algae (% composition of sample)	67%	0%	33%	0%	33%	33%	67%	20%	20%	80%	67%	0%	25%	0%	0%	80%
Diversity	0.68	1.62	0.84	1.43	1.51	1.55	1.69	1.37	1.50	1.42	1.90	1.31	1.52	1.24	1.47	1.38

Table 7e: Total cell count per mL of identified phytoplankton taxa for 2007 and 2008, SL=Silver Lake, I=inlet.

SLI (Cells ml^{-1})	31-5-07	07-6-07	12-6-07	21-6-07	29-6-07	05-7-07	18-7-07	25-7-07	01-8-07	07-8-07	24-8-07	07-11-07	23-4-08	07-5-08	06-6-08	
Navicula sp.	13.04	5.2	35.68	24.84	67.16	24.8	98.04	74.76	171.16	120.68	104.8	7.32	57.68	7.96		5.76
Ankistrodesmus sp.	0.88	0.72	6.76	8	10.52	3.64	18.68	17.6	14.2	6.44	9.28	4.68	5.6	9.96		1.44
Fragilaria sp.	2.32	2.56	10.88	10.12	16.68	7.32	22.6	25	27.92	22.8	23.72	4.92	2.24	1.96		0.4
Scenedesmaceae.	0.84	0.12	0.52	3.24	1.64	0.12	8.92	2.96	3.84	1.52	0.48	0.76	1.04	0.36		0.04
Filamentous	0	0.04	3.68	0.88	0.84	4.12	2.36	4.4	3	1.24	4	0.6	1.44	0.48		0.28
LRRT	0.76	0.36	37.32	2.08	3.64	7.88	16.92	25.92	18.48	6.04	7.36	2.4	0	0.04		0.04
Euglenoids	0.12	0.2	62.44	2.08	36.52	91.28	28.88	36.6	36.64	6.32	31.08	0.12	8.8	0.08		0.12
Meridion sp.	0.56	0.28	2	0.28	2.2	0.16	0.76	0.88	0.36	0.28	0.24	0.04	8.32	0.52		0.08
Cosmarium sp	0	0	0.24	0	0.4	0	0.12	1.16	0.12	0.04	0.32	0	0	0		0
Pediastrum sp.	0.08	0	0.08	0	0.04	0.04	0.16	0.04	0.08	0.08	0	0.04	0.08	0		0
Ceratium sp.	0	0	0	0	0	0	0	0.04	0	0	0	0	0	0		0
Staurastrum sp	0	0	0.04	0	0	0.04	0	0.64	0	0.24	0.08	0	0.08	0		0.04
Merismopedia sp	0	0	0.12	0	0.32	0	0.88	0	0.32	0.32	0.08	0	0	0		0
Peridinium sp	0	0	1.96	0	0	0	0	0	0	0	0	0	0	0		0
Tabellaria sp	0	0	0	0	45.64	0	7.76	2.4	0	0	2.32	0	0	0		0
Volvox sp	0	0	0	0	8.2	0	0	0	8.76	0	0	0	0	0		0
Dinobryon sp	0	0	0	0	0	0	0	0	0	0	0.08	0	0	0		0
Codoenllidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
Oocyst	0	0	0	0	0	0	4.32	0	0	0	1.88	0	1.84	0		0
Total (Cells/ml)	18.6	9.48	161.72	51.52	193.8	139.4	210.4	192.4	284.88	166	185.72	20.88	87.12	21.36		8.2
Benthic Algae (% composition of sample)	0%	0%	<10%	0%	0%	25%	33%	0%	33%	17%	67%	0%	20%	0%		0%
Diversity	1.09	1.27	1.59	1.49	1.61	1.12	1.73	1.72	1.50	1.42	1.90	1.31	1.52	1.24	1.47	1.38

Table 7f: Total cell count per mL of identified phytoplankton taxa for 2007 and 2008, SL=Silver Lake, O=outlet.

SLO (Cells ml^{-1})	**31-5-07**	**07-6-07**	**12-6-07**	**21-6-07**	**29-6-07**	**05-7-07**	**18-7-07**	**25-7-07**	**01-8-07**	**07-8-07**	**24-8-07**	**07-11-07**	**07-5-08**	**13-5-08**
Navicula sp.	21.84	6.96	2.16	22.48	29.64	38.92	18.64	18.16	27.76	38.64	101.36	10.92	6.28	6.2
Ankistrodesmus sp.	9.28	1.48	2.08	15.4	50.32	99.84	11.92	8.56	14.16	11.56	27.72	6.2	4.32	10.32
Fragilaria sp.	1.6	2.8	1	10.52	10.24	4.32	9.96	2.36	45.28	24.24	25.28	4.72	3.08	1.08
Scenedesmaceae.	1.76	0.12	0.04	11.76	4.04	4.84	3.92	10.32	7.12	7.2	4.12	0.64	0.24	0.12
Filamentous	0.16	0.2	2.8	0.52	0.44	0.68	0.8	28.92	8.04	2.88	2.16	1.16	0.68	0.04
LRRT	3.2	1	1.04	1.84	0.76	5.2	20.56	6.8	42.04	53.24	10.8	1.8	0	0
Euglenoids	0	0.2	11.76	14.04	89.76	46.92	54.36	112.64	205.84	104.28	100.68	0.2	0.32	0
Meridion sp.	0.8	0.12	0.08	0.4	0.12	0.36	0.16	0.4	0.12	0.44	0.48	0.12	0.36	0.04
Cosmarium sp	0	0	0.12	0	0.28	0	0.16	0.2	0	0.12	0.32	0	0	0
Pediastrum sp.	0.4	0	0.04	0.28	0.24	0.76	0.2	0.04	0.24	0.2	0.24	0.04	0	0
Ceratium sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Staurastrum sp	0	0	0	0	0.04	0.6	0.16	0.32	0.72	0.32	0.2	0	0	0
Merismopedia sp	0	0	0	0	0.92	0.36	0.2	0.36	0.36	0.4	0.68	0	0	0
Peridinium sp	0	0	0	0	0	0	2.2	0	0	0	6	0	0	0
Tabellaria sp	0.48	0	0	0	28.16	33.36	3.56	0.76	0	0	5.72	0	0	0
Volvox sp	0	0	0	0	4.88	12.08	0	0	0	1.64	0	0	0	0
Dinobryon sp	0	0	0	0.16	0	0.72	1.92	0	0	0	0.12	0	0	0
Codoenllidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oocyst	0	0	0	0	0	0	1.88	0	0	0.24	2.76	0	0	0
Total (Cells/ml)	39.52	12.88	21.12	77.4	219.84	248.96	130.6	189.84	351.68	245.4	288.64	25.8	15.28	17.8
Benthic Algae (% composition of sample)	0%	0%	75%	0%	50%	80%	67%	20%	80%	25%	0%	0%	0%	0%
Diversity	1.34	1.33	0.71	1.73	1.53	1.70	1.82	1.36	1.35	1.59	1.64	1.51	1.42	0.91

Total abundances ranged from <4 cells ml^{-1} to >560 cells ml^{-1}, and were generally higher during the summer months than in the spring or fall (Fig. 13 & Table 7).

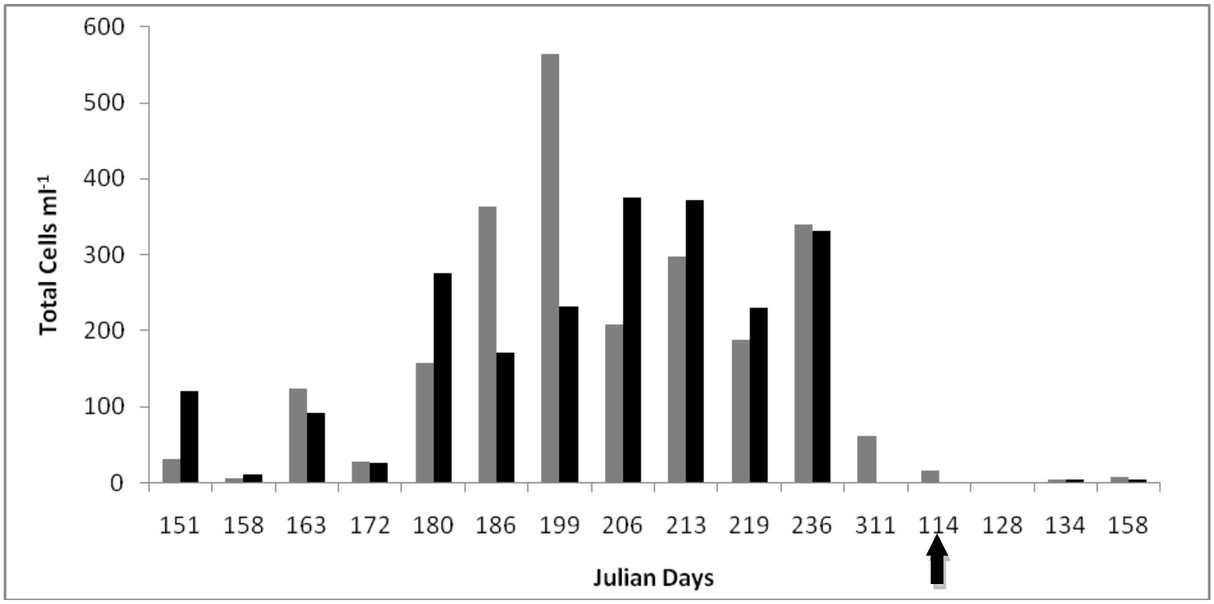


Figure 13a: Laurel Creek Reservoir phytoplankton abundances for 2007 and 2008, grey bars=inlet, and black bars=outlet. Note: black arrow indicates beginning of 2008.

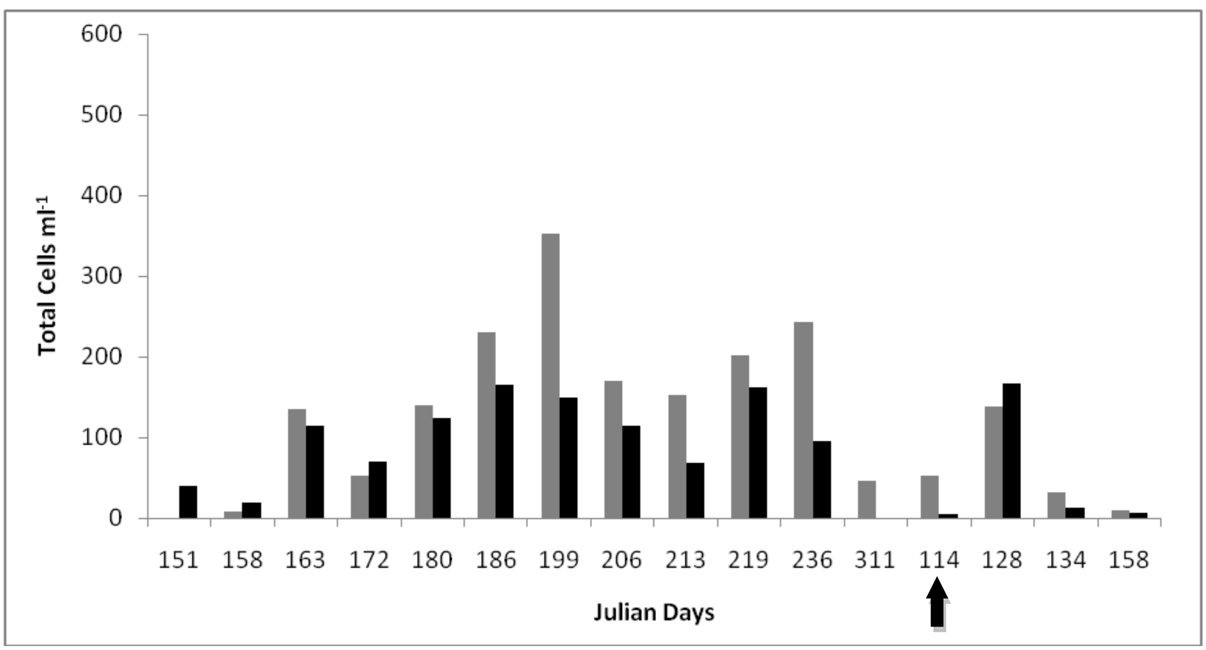


Figure 13b: Columbia Lake phytoplankton abundances for 2007 and 2008, grey bars=inlet, and black bars=outlet. Note: black arrow indicates beginning of 2008.

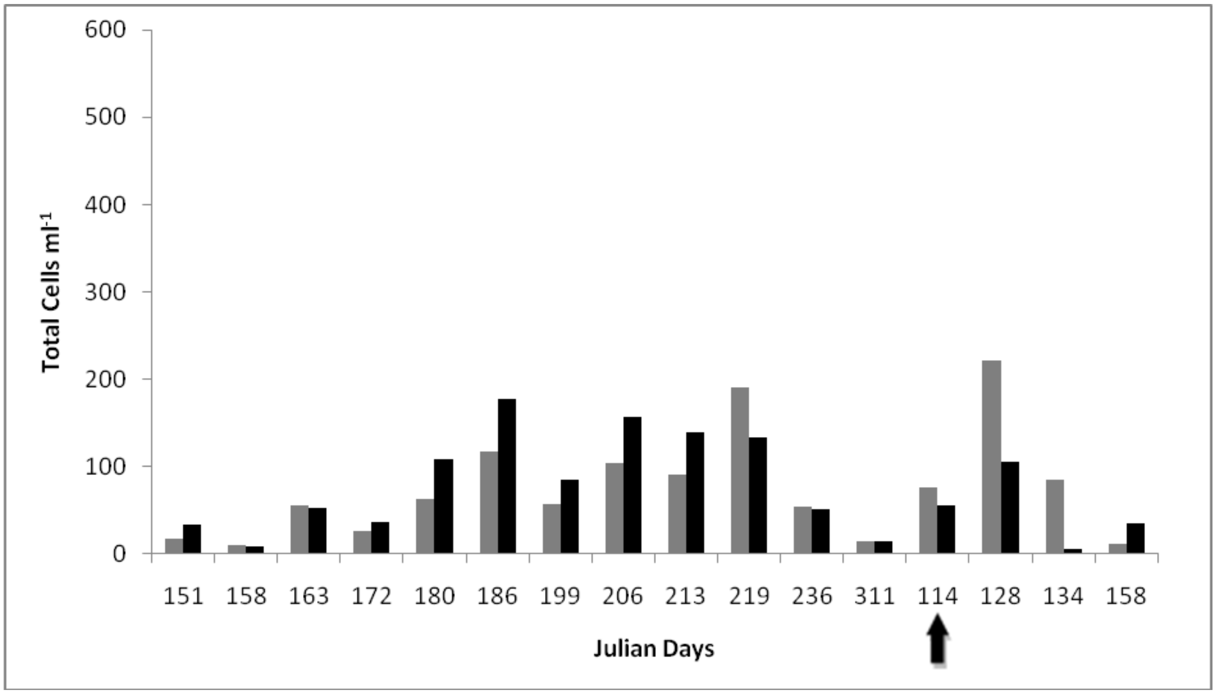


Figure 13c: Clair Lake phytoplankton abundances for 2007 and 2008, grey bars=inlet, and black bars=outlet. Note: black arrow indicates beginning of 2008.

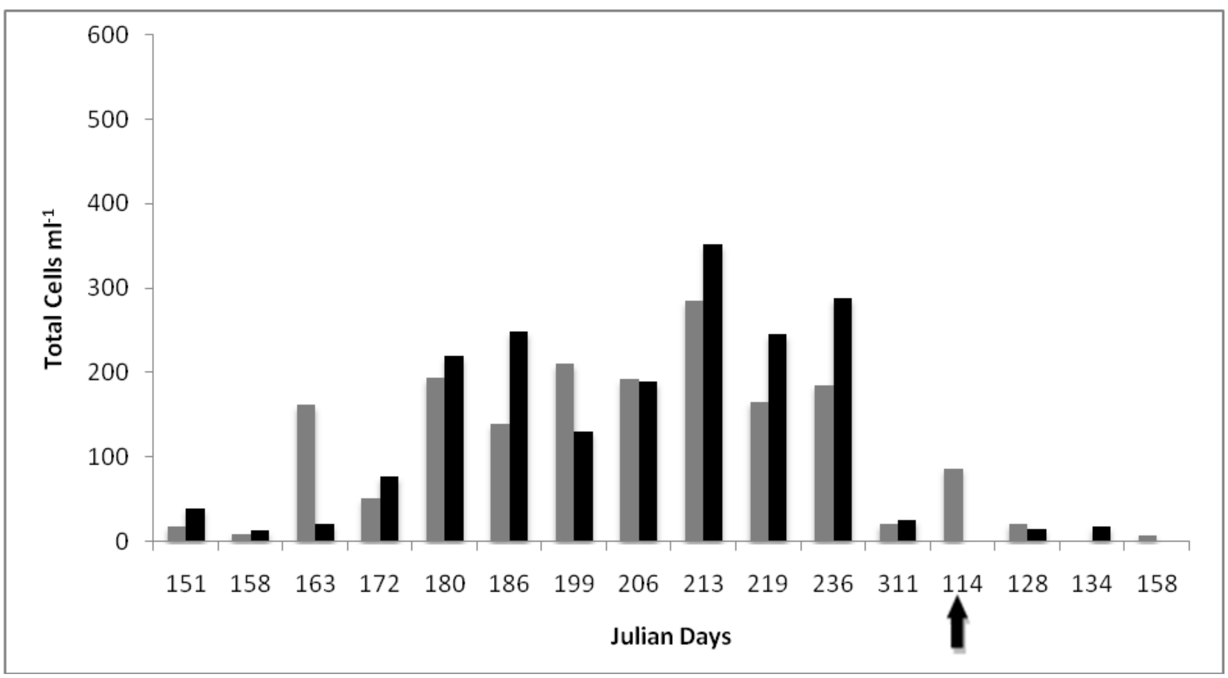


Figure 13d: Silver Lake phytoplankton abundances for 2007 and 2008, grey bars=inlet, and black bars=outlet. Note: black arrow indicates beginning of 2008.

At least a few samples from each of the impoundments had filamentous clumps of green/golden algae that could not be identified. Such aggregations were most likely of benthic origin and were most abundant in samples from Clair Lake. Thus, while fewer total cells ml^{-1} were identified from this impoundment, there was still a large biomass within the 25ml subsample. These algae were also found in all of the impoundments; however were generally less frequent and abundant (Table7). Phytoplankton varied in proportion throughout the season, with no discernable seasonality pattern between the impoundments (Fig. 14).

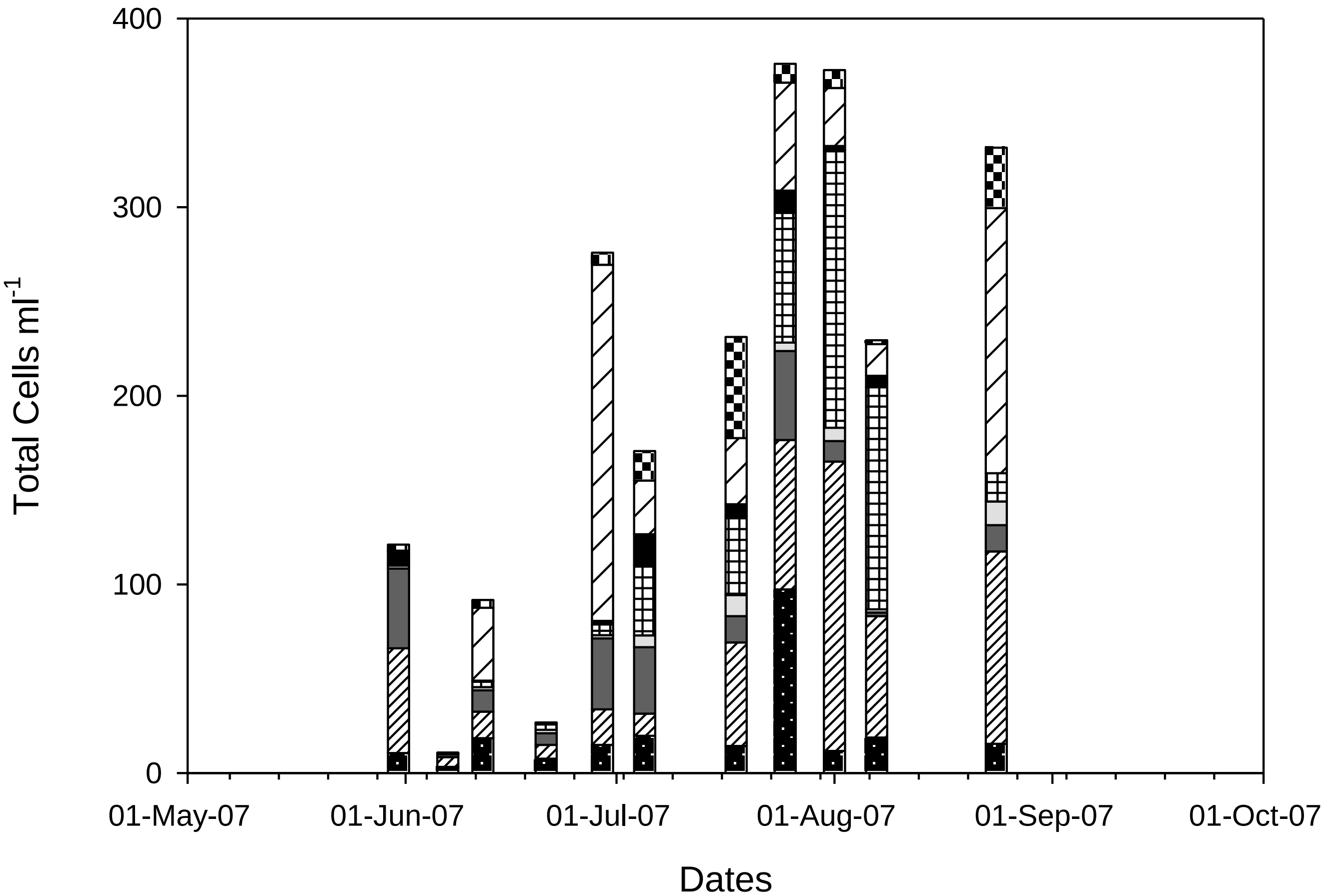


Figure 14a: Laurel Creek Reservoir phytoplankton seasonality by date, showing proportion of the different groups located at the outlet of the impoundment to indicate what is produced within the impoundment. Legend: from bottom to top: black with white dots=*Navicula sp*. Fine diagonal strips= *Ankistrodesmus sp.*, dark grey=*Fragilaria sp.*, light grey=Scenedesmaceae, fine cross hatch=Filamentous algae, black=LRRT, course diagonal strips=Euglenoids, and checkerboard=other, Other comprised ofremaining taxa from table 7.

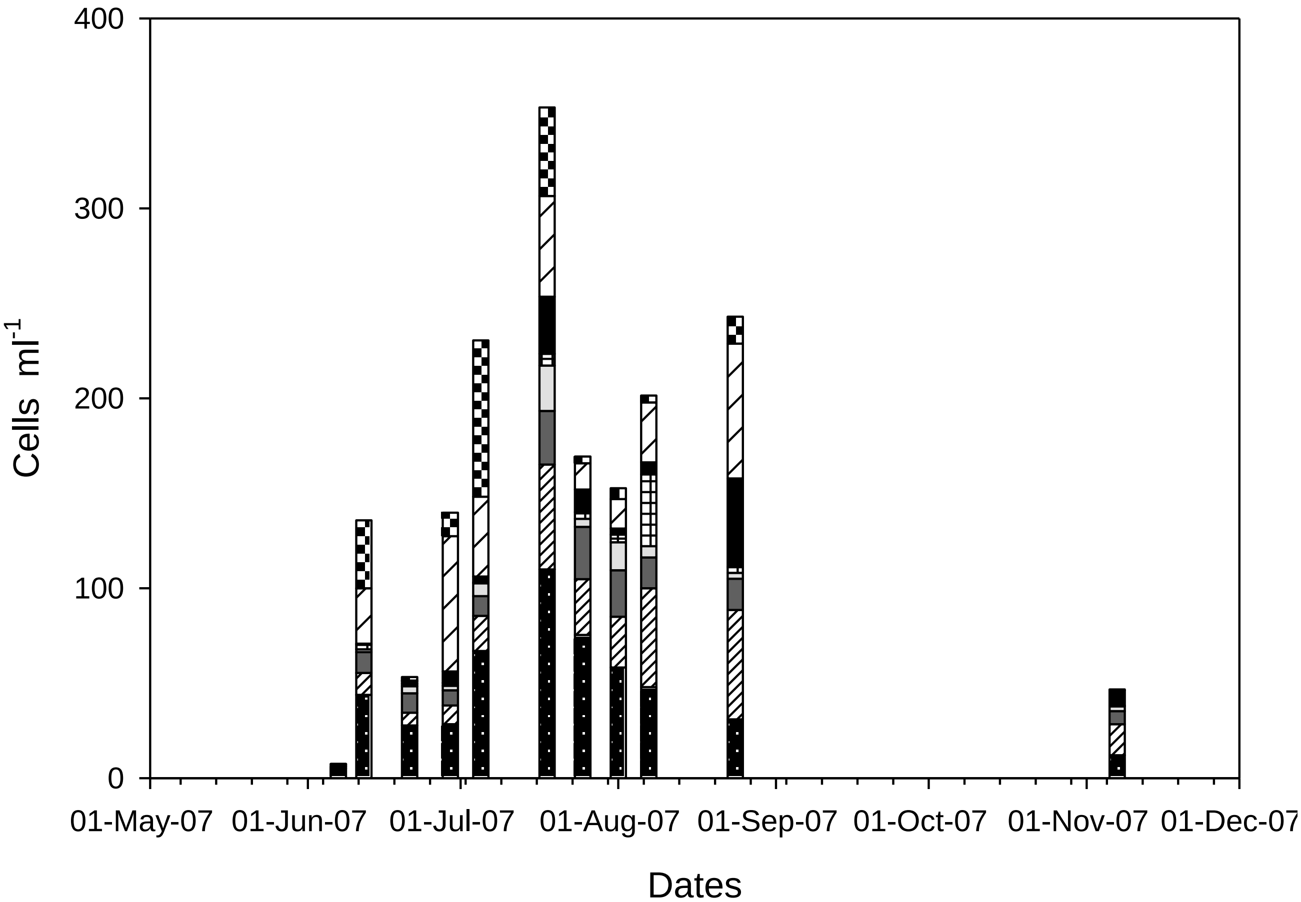


Figure 14b: Columbia Lake phytoplankton seasonality by date, showing proportion of the different groups located at the inlet of the impoundment to indicate what is entering the impoundment, legend as in 14a .

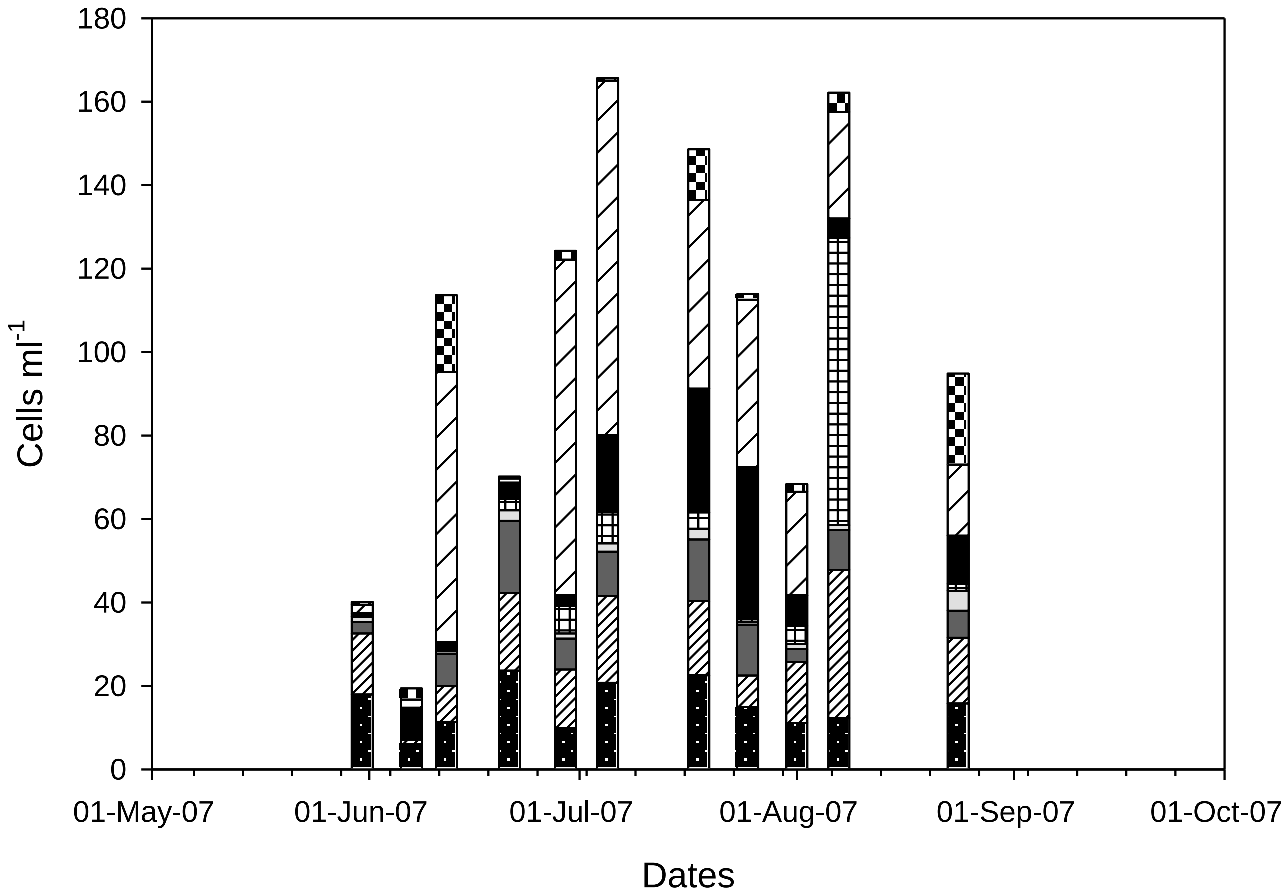


Figure 14c: Columbia Lake phytoplankton seasonality by date, showing proportion of the different groups located at the outlet of the impoundment to indicate what is produced within the impoundment, legend as in 14a.

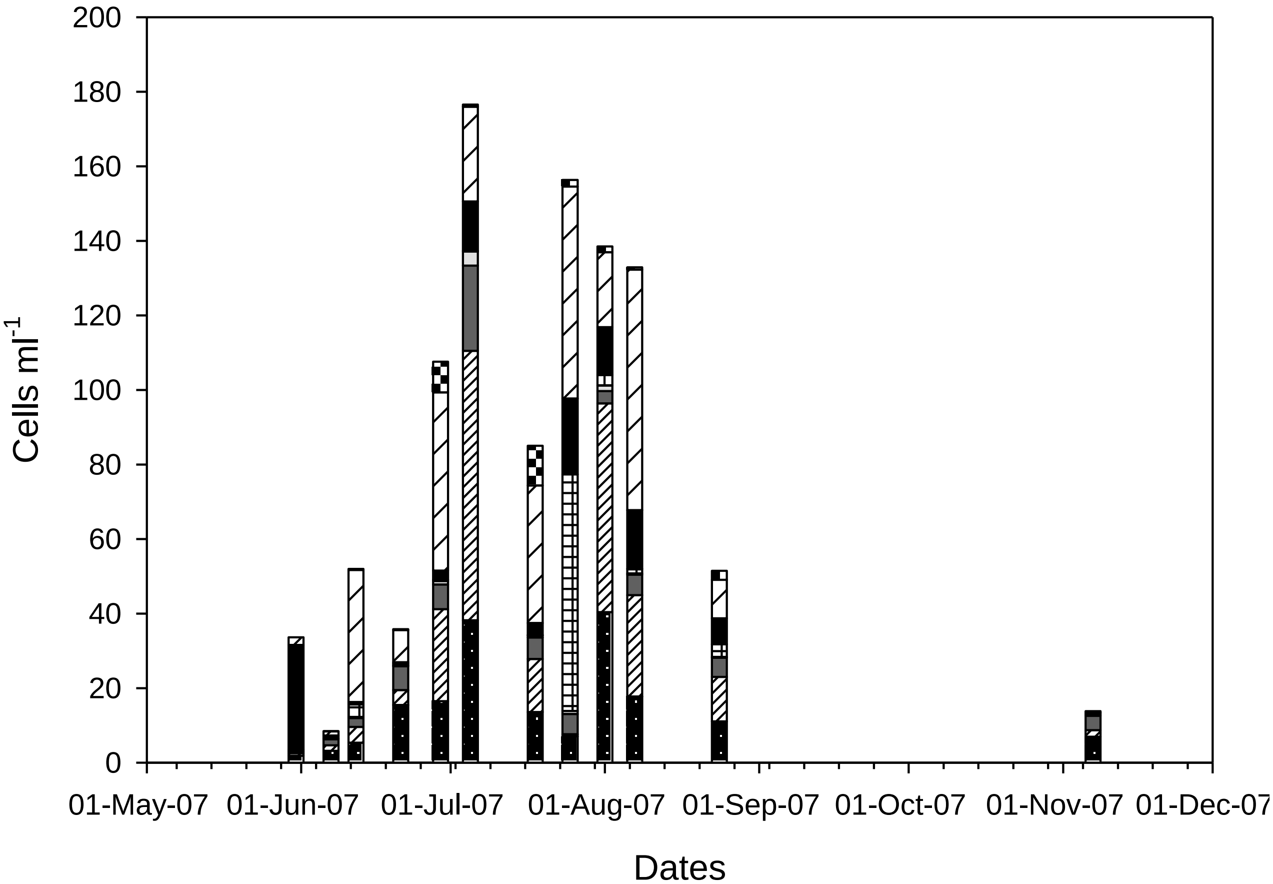


Figure 14d: Clair Lake Phytoplankton seasonality by date, showing proportion of the different groups located at the outlet of the impoundment to indicate what is produced within the impoundment, legend as in 14a.

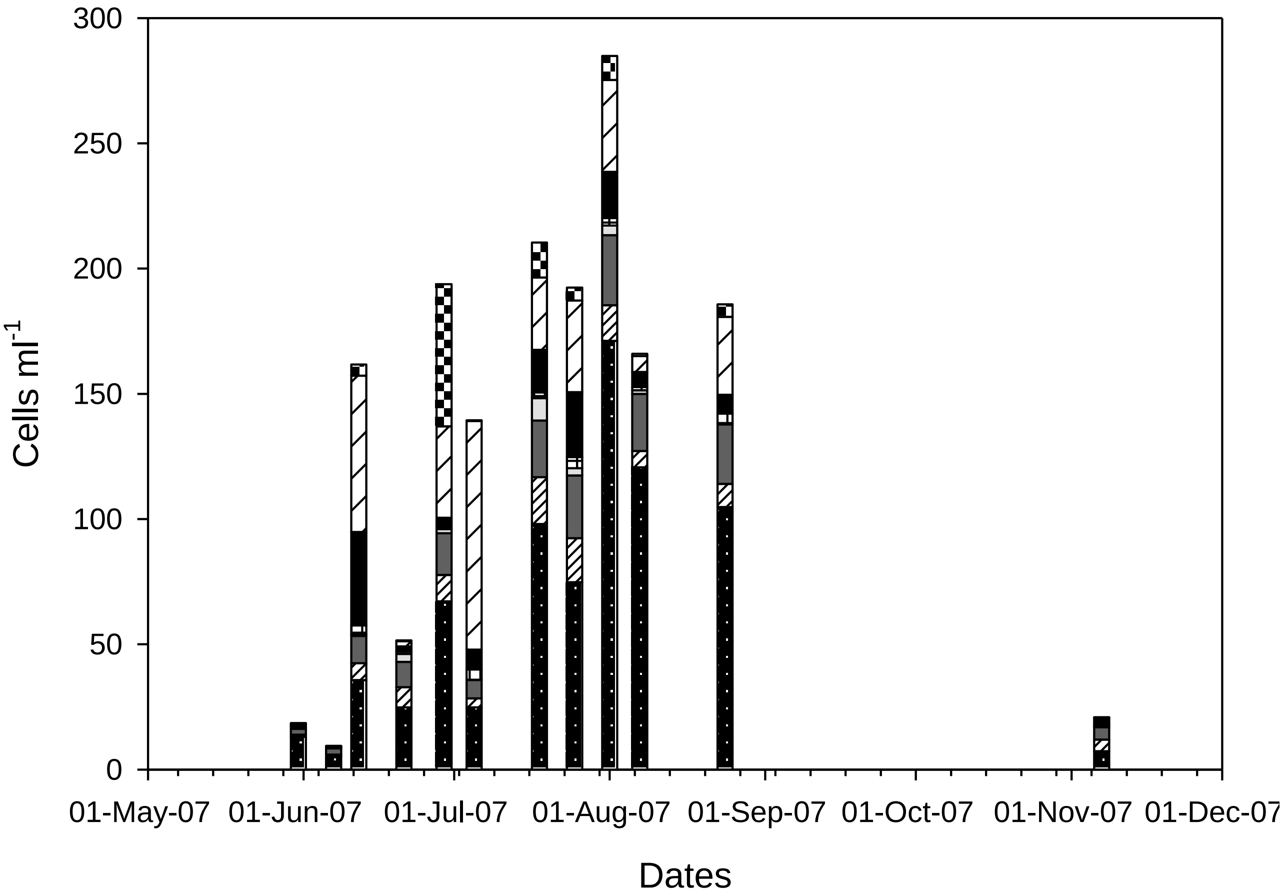


Figure 14e: Silver Lake Phytoplankton seasonality by date, showing proportion of the different groups located at the inlet of the impoundment to indicate what is entering the impoundment, legend as in 14a.

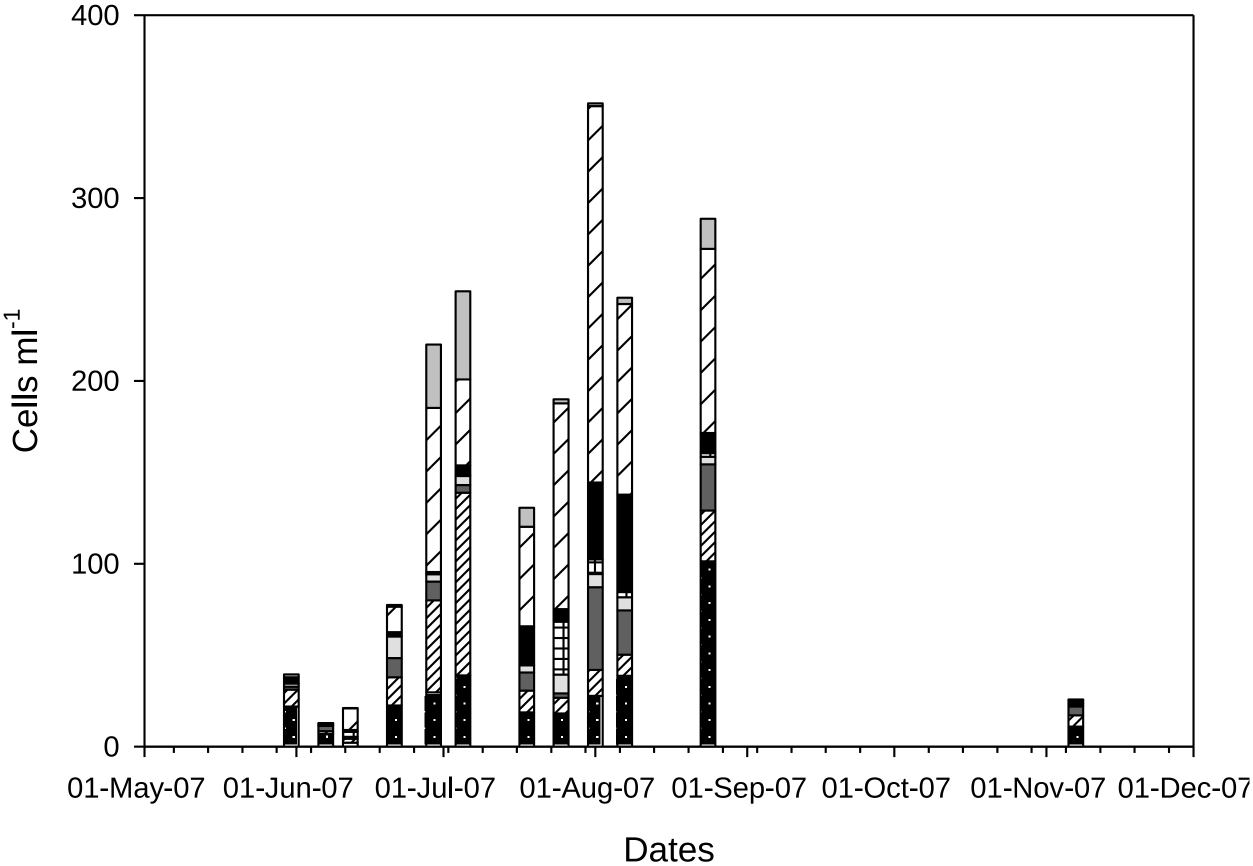


Figure 14f: Silver Lake Phytoplankton seasonality by date, showing proportion of the different groups located at the outlet of the impoundment to indicate what is produced within the impoundment, legend as in 14a.

Water temperature appeared to have little effect on phytoplankton density except that the largest cell counts generally occurred when temperatures exceeded 19°C (Fig. 15). The relationship between total phosphorus and total abundance could not be assessed due to the lack of overlapping data.

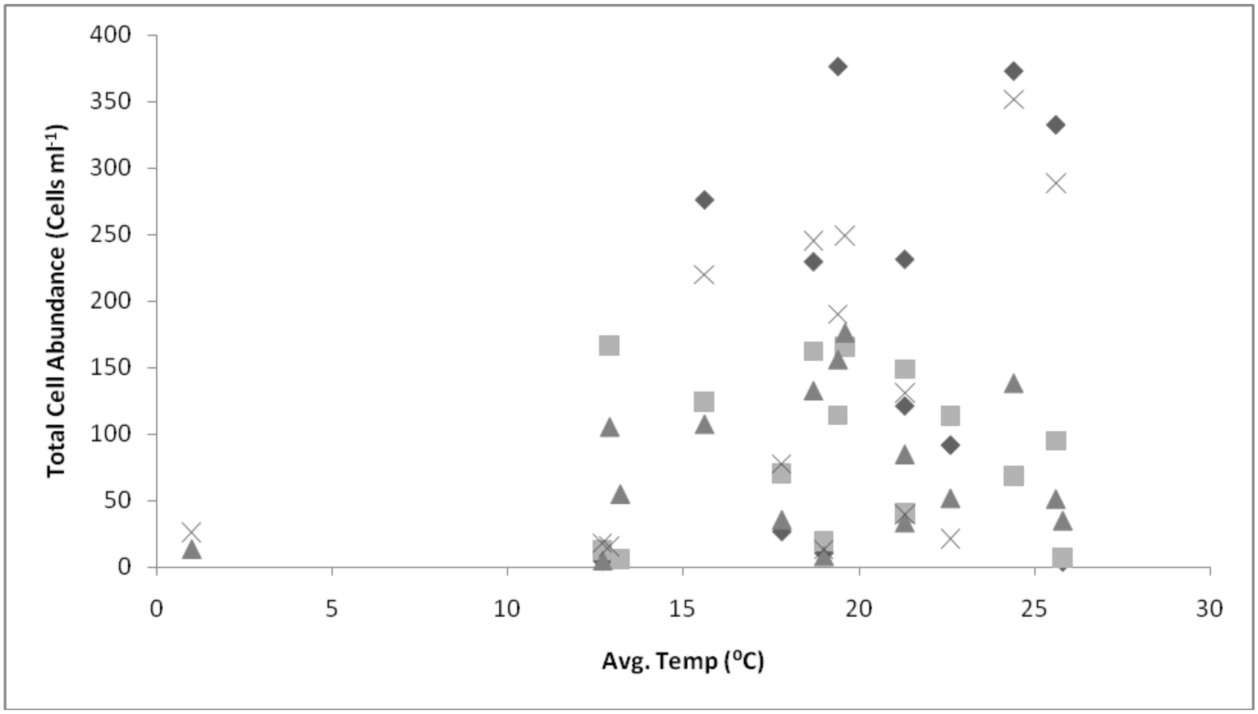


Figure 15: Scatter-plot between average temperature and total cell abundance for Laurel Creek reservoir, diamond=Laurel Creek Reservoir, square=Columbia Lake, triangle=Clair Lake, and X=Silver Lake.

3.8 Phytoplankton Richness (number of taxa), Frequency, and Diversity

Phytoplankton richness (number of taxa sample^{-1}) ranged from 4 to 17, with higher values during the warmer summer months and lower ones during the spring and fall months (Fig.16). Similar numbers of taxa were found in samples from Laurel Creek Reservoir, Columbia Lake and Silver Lake, but richness in Clair Lake was significantly lower than in Laurel Creek Reservoir (Fig. 16) (paired t-test, df=15, p=0.011).

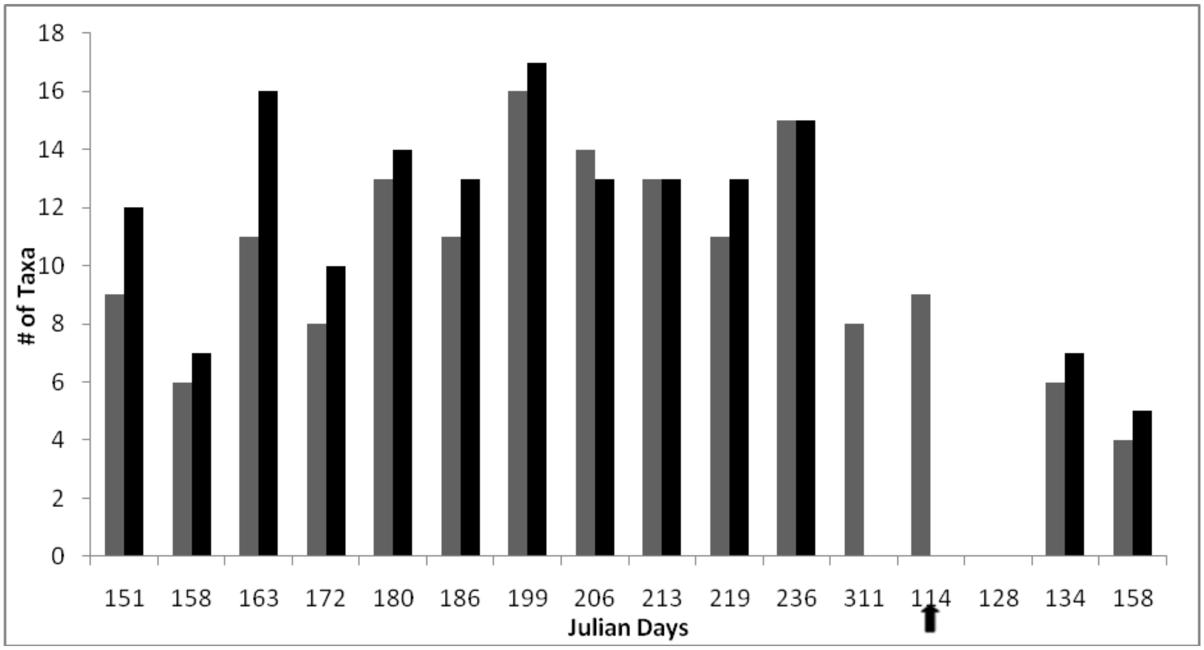


Figure 16a: Laurel Creek Reservoir phytoplankton richness as measured in number of identified taxa for 2007 and 2008, grey bars=inlet, and black bars=outlet. Note: black arrow indicates beginning of 2008.

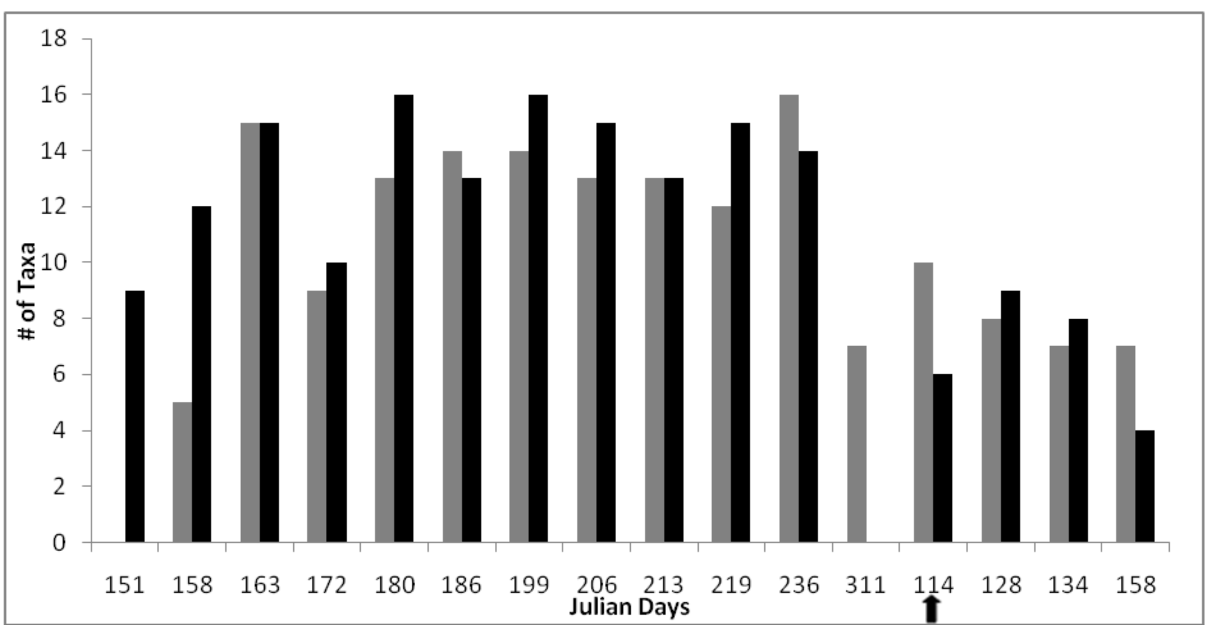


Figure 16b: Columbia Lake phytoplankton richness as measured in number of identified taxa for 2007 and 2008, grey bars=inlet, and black bars=outlet. Note: black arrow indicates beginning of 2008.

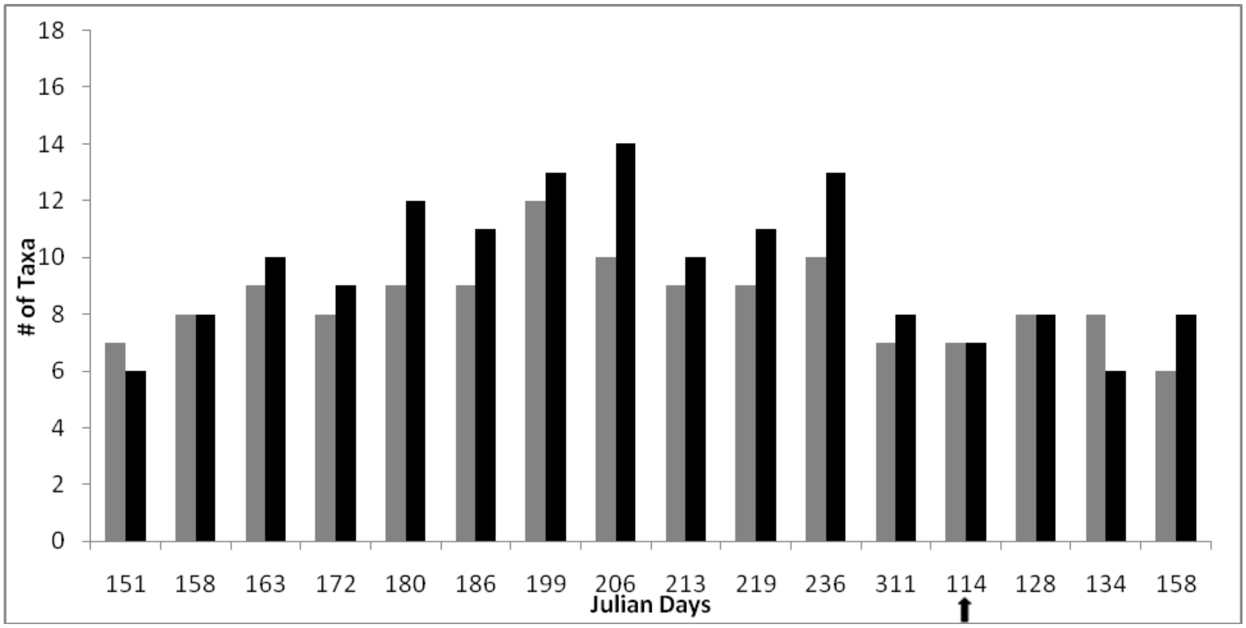


Figure 16c: Clair Lake phytoplankton richness as measured in number of identified taxa for 2007 and 2008, grey bars=inlet, and black bars=outlet. Note: black arrow indicates beginning of 2008.

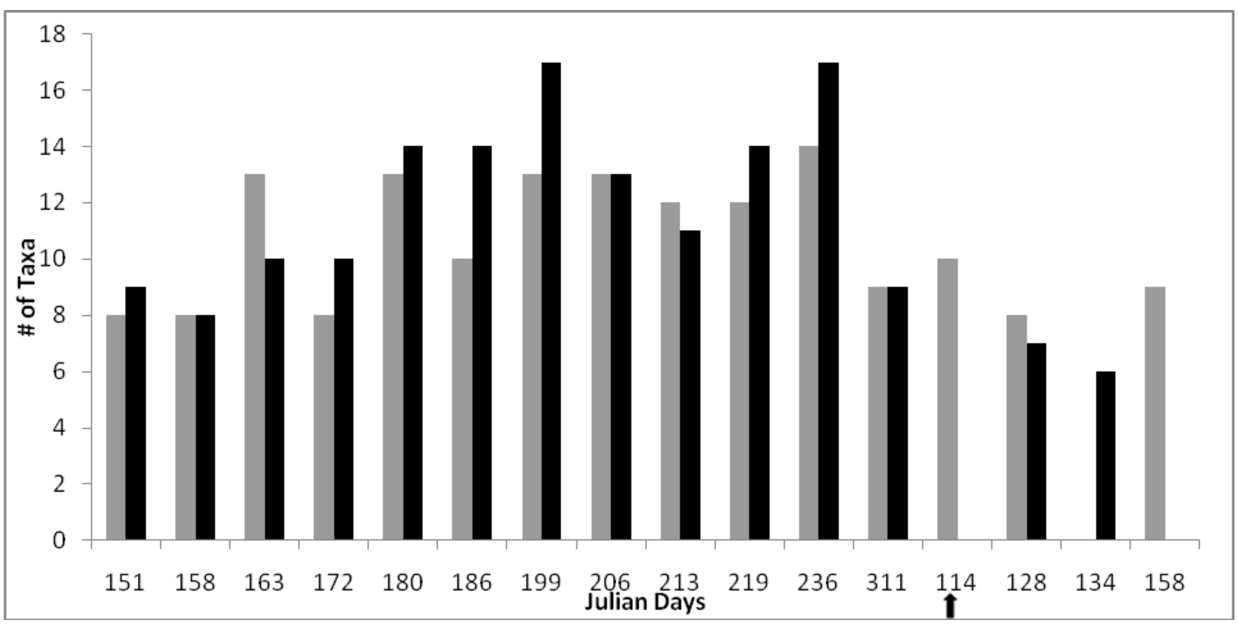


Figure 16d: Silver Lake phytoplankton richness as measured in number of identified taxa for 2007 and 2008, grey bars=inlet, and black bars=outlet. Note: black arrow indicates beginning of 2008.

Seven taxa were frequent within the Laurel Creek system, and occurred in all impoundments at least 60% of the time and contributed most of the biomass (Table 7). Other taxa occurred infrequently (Fig. 14). The most frequently occurring taxa were *Navicula sp.*, *Ankistrodesmus sp.*, *Fragilaria sp.*, and euglenoids (Table. 7). These were found at almost every site on all collection dates (Fig. 14). *Navicula sp.* was never found in very large abundances, with peaks of just over 100 cell ml^{-1} during the summer months, and was most abundant in Laurel Creek Reservoir and Silver Lake. *Fragilaria sp.* occurred in low abundances, with peaks of approximately 40 cell ml^{-1}, and was most abundant in Laurel Creek Reservoir. *Ankistrodesmus sp*. occurred at greater abundances, with peaks in late summer of >150 cells ml^{-1}, and was also most abundant in Laurel Creek Reservoir. Euglenoids were the largest fraction of phytoplankton during the summer months. With peaks of >200 cells ml^{-1}, this group was found frequently in all impoundments, but was most abundant in Silver Lake, especially during the summer months (Fig. 14).

Filamentous algae (identified group) were found throughout the year but peaked during late summer in Laurel Creek Reservoir and Columbia Lake. This taxon was never abundant in Clair or Silver Lakes. The large benthic algal clumps mentioned earlier, were most common in Clair Lake where they occurred throughout the year, comprising a large (but un-quantified) fraction of the total algal biomass. The origin of this group is most likely the sediment surface from which it is re-suspended by mechanical disturbance.

Several of the phytoplankton groups were very rare, as they only appeared in one impoundment on a given collection date, usually in Laurel Creek Reservoir or Columbia Lake (Table 8 & 9).

Table 8: Frequency of taxa occurrence within the different impoundment outlets for 2007 and 2008, as well as average abundance(located in last 4 columns) this graph is not date sensitive, for seasonality information please see Figure 18 for a more exhaustive data summary. For values <0.09 cells ml^{-1} it was counted as zero. LCR=Laurel Creek Reservoir, CL=Columbia Lake, CLR=Clair Lake, SL=Silver Lake and *=filamentous algae, however these were not the same as the benthic algal clumps, as these were seen mostly as single filaments.

	LCR	**CL**	**CLR**	**SL**	**LCR (Cells ml^{-1})**	**CL (Cells ml^{-1})**	**CLR (Cells ml^{-1})**	**SL (Cells ml^{-1})**
Dinobryon sp	31%	19%	0%	<1%	1.3	0.3	0.0	0.2
Merismopedia sp	25%	6%	0%	<1%	1.1	0.1	0.0	0.2
Staurastrum sp	13%	6%	<1%	<1%	0.7	0.1	0.1	0.2
Ceratium sp.	6%	13%	0%	0%	0.4	0.3	0.0	0.0
Navicula sp.	100%	100%	100%	100%	18.1	13.8	14.7	25.0
Fragilaria sp.	100%	100%	100%	100%	17.2	7.8	5.3	10.5
Ankistrodesmus sp.	100%	100%	94%	100%	43.8	19.0	19.0	19.5
Scenedesmaceae	100%	100%	75%	94%	3.9	1.5	0.8	4.0
Euglenoids	81%	88%	94%	88%	41.3	25.9	20.0	52.9
LRRT	81%	75%	94%	88%	4.0	8.3	6.7	10.6
Filamentous algae*	94%	69%	63%	75%	33.9	6.7	6.3	3.5
Meridion sp.	44%	25%	25%	38%	0.6	0.2	0.1	0.3
Tabellaria sp	25%	13%	19%	31%	1.9	0.2	0.9	5.1
Oocyst	6%	19%	6%	13%	0.3	1.4	0.3	0.3
Cosmarium sp	25%	6%	6%	<1%	1.3	0.3	0.0	0.1
Peridinium sp	19%	6%	0%	6%	2.9	1.5	0.0	0.6
Pediastrum sp.	0%	6%	0%	6%	0.1	0.1	0.0	0.2
Volvox sp	0%	13%	6%	19%	0.0	0.1	0.1	1.3
Benthic Filaments	31%	44%	69%	44%	N/A	N/A	N/A	N/A

Table 9: Rare phytoplankton, as defined by occurring only at one of the inlets or outlets for any give collection date, LCR=Laurel Creek Reservoir, CL=Columbia Lake, CLR=Clair Lake, SL=Silver Lake, I=inlet, O=outlet, and **x**=not present.

Rare Taxa	**31/05/2007**	**07/06/2007**	**12/06/2007**	**21/06/2007**	**29/06/2007**	**05/07/2007**	**18/07/2007**	**25/07/2007**
Staurastrum sp.	LCRI	CLO	**x**	**x**	**x**	LCRO	LCRO	**x**
Pediastrum sp.	SLO	CLO	**x**	**x**	**x**	**x**	**x**	**x**
Tabellaria sp.	SLO	**x**	**x**	**x**	**x**	**x**	**x**	**x**
Volvox sp.	**x**	CLO	**x**	**x**	**x**	**x**	**x**	**x**
Dinobryon sp.	**x**	CLO	**x**	**x**	**x**	LCRO	**x**	**x**
Cosmarium sp.	**x**	**x**	**x**	**x**	LCRI	LCRO	**x**	SLI
Perdinium sp.	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
Ceratium sp.	**x**	**x**	**x**	**x**	**x**	**x**	**x**	LCRO
Oocyst	**x**	CLO	CLI	**x**	**x**	**x**	**x**	**x**
Meridion sp.	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
Merispomedia sp.	**x**	**x**	LCRO	**x**	**x**	**x**	**x**	**x**
Codoenllidae	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**

	01/08/2007	**07/08/2007**	**24/08/2007**	**07/11/2007**	**23/04/2008**	**07/05/2008**	**12/05/2008**	**06/06/2008**
Staurastrum sp.	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
Pediastrum sp.	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
Tabellaria sp.	**x**	**x**	**x**	**x**	CLI	**x**	**x**	**x**
Volvox sp.	**x**	SLO	**x**	**x**	LCRI	**x**	**x**	**x**
Dinobryon sp.	**x**	**x**	LCRO	**x**	**x**	**x**	**x**	**x**
Cosmarium sp.	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
Perdinium sp.	LCRO	**x**	**x**	**x**	**x**	**x**	**x**	**x**
Ceratium sp.	CLO	CLO	**x**	**x**	**x**	**x**	**x**	**x**
Oocyst	**x**	**x**	**x**	**x**	SLI	**x**	**x**	**x**
Meridion sp.	**x**	CLI	**x**	**x**	**x**	**x**	**x**	**x**
Merispomedia sp.	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
Codoenllidae	LCRI	**x**	**x**	**x**	**x**	**x**	**x**	**x**

Phytoplankton diversity was expressed using the Shannon-Wiener diversity index, with higher values equating to higher biological diversity. Diversity values for the four impoundments ranged from 0.680 to 2.12 (Table 7), and generally exhibited the same trend as richness and abundance with higher values during the summer months than during spring and fall (Fig. 16). Diversity was significantly greater in the inlet samples from Columbia Lake than from Silver Lake (paired t-test df=12, p=0.022). Outlet diversity was generally higher than inlet diversity; this was true for Columbia and Silver Lakes but these differences were not significant.

4.0 Discussion

The objective of this study was to characterize the water quality of 4 shallow urban impoundments with respect to each other. The focus is on the effect of these impoundments on downstream water quality, with possible management implications. Generally speaking impoundments act as retention basins for inorganic solids (TIS) and total phosphorus (TP), and export organic matter in the form of algae, organic detritus, and zooplankton (Scheffer 2004). However some impoundments export TIS and TP, particularly if they are shallow and highly urbanized; this can lead to low water quality downstream of the impoundments.

I expected that these shallow impoundments would export inorganic and organic suspended solids due to various internal drivers (Scheffer 2004), export elevated concentrations of total phosphorus (especially in more urbanized settings), and phytoplankton assemblages consistent with degraded aquatic systems (Meijer *et al.* 1990, Breukelaar *et al.* 1994, King *et a*l. 1997, Lougheed *et al.* 1998, Bergman *et al.* 1999, Walsh *et al.* 2005). Some of these expectations were met.

Precipitation was found to be an important factor affecting this system, with the summer of 2008 being much wetter than 2007. This is important because precipitation is strongly connected with the input of suspended solids, especially on highly urbanized land (Klein 1979, and Walsh *et al.* 2005), so the fortuitous juxtaposition of a relatively dry and a very wet summer provided some important insights.

Laurel Creek Reservoir imported negligible amounts of TIS and retained most of it during the study period. The other impoundments were net-exporters of TIS, but Clair and Silver Lakes exported roughly twice the concentrations measured in Columbia Lake, in part because of much higher loadings from urban areas upstream. Net-export of TIS might also be partially attributed to the large carp populations found within each of these impoundments, as this species is well known for its ability to degrade shallow water systems, usually through the re-suspension of sediment during foraging, however since no population measurements were taken there is no direct evidence to support this hypothesis (Meijer *et al.* 1990, Breukelaar *et al.* 1994, Roberts *et al.* 1995, King *et al.* 1997, Klein 1979, Lougheed *et al.* 1998, Zambrano & Hinojosa, 1999, Scheffer 2004). This is exacerbated in impoundments that are very shallow because they have accumulated large amounts of fine sediment (Wolman 1964, Fox 1974) so there to is less water volume to dilute material suspended during foraging activities. Unfortunately, I have only observational estimates of the relative abundance of carp, but many were seen in Clair and Silver Lakes, while Columbia Lake has fewer after its restructuring in 2005/2006. Laurel Creek Reservoir supports very few if any carp due to the yearly draw-down (GRCA). Another factor that causes re-suspension of sediment is wind-generated wave action (Scheffer 2004), but this is unlikely to be significant as the two impoundments with the greatest TIS concentrations are sheltered from the wind and have very small fetches. Laurel Creek Reservoir has the largest fetch and the least turbid water. Following heavy precipitation high concentrations of TIS are exported from Columbia Lake this is likely due to the close proximity of the outlet to un-vegetated shoreline that is subject to erosion during precipitation events.

The low concentrations of suspended sediment in Laurel Creek Reservoir are partly due to the low density of urban development upstream, and partly the result of the way in which it is managed by the GRCA. Draining the lake every autumn prevents the long-term accumulation of sediment and effectively eliminates carp. Much of the sediment and associated nutrients that accumulate each year is expelled during the yearly draw-down (Ozersky 2004, Shantz *et al.* 2004). During these draw-down periods, suspended sediment concentrations can be as high as 714 mg L^{-1} (Ozersky 2004), more than an order of magnitude greater than elsewhere in the system. This draw-down has implications for the other impoundments downstream, especially Columbia Lake which is the direct recipient of this sediment load. Draw-down of Laurel Creek Reservoir negatively affects macro-invertebrates downstream, with a majority of the groups found to be significantly less abundant after the draw-down (Ozersky 2004). This sediment flushing was also characteristic of Columbia Lake prior to its reconstruction in 2005/2006. During the 2004 draw-down of Columbia Lake 18.5 tons of sediment and large concentrations of TP were exported over the course of 14 days (Shantz *et al.* 2004). Besides the deleterious effects this sediment has on downstream organisms, it may also increase the eutrophication of downstream impoundments and lakes including Lake Erie (Shantz *et al.* 2004, Zhang 2006).

Suspended sediment was found to have a negative impact on Lake Erie as it receives 75% of its tributary phosphorus load via suspended solids (Stone and English 1993). This sediment was also implicated as an exacerbating factor in Lake Erie's near-shore eutrophication, (DePinto *et al.* 1981, Shantz *et al.* 2004, Zhang 2006). Since this impoundment ultimately drains into Lake Erie it further highlights the importance of this draw-down since it exports significant amounts of sediment and nutrients (Mayer and Manning 1989, Stone and English 1993, Shantz *et al.* 2004, Zhang 2006).

The high concentration of TOS entering Laurel Creek Reservoir is an artifact of the location of the "inlet" sampling point. Samples were collected at a bridge where the creek is pooled and slow moving, creating a very productive habitat that supports relatively large amounts of phytoplankton. The inlet sampling points for Columbia, Clair, and Silver Lakes were in flowing water. Like TIS; Clair and Silver Lakes exported twice the TOS concentrations of Columbia and more than three times that of Laurel Creek Reservoir, owing to their eutrophic waters.

Laurel Creek Reservoir retained TP despite loading from streams draining agricultural grounds. Columbia, Clair, and Silver Lakes were net exporters of total phosphorus, following the same trend as TIS, indicating that these two parameters are linked (Søndergaard *et al.* 2003, Scheffer 2004). The positive relationship between total phosphorus and TOS concentrations seen in all impoundments reflects biological activity associated with higher nutrient concentrations (O'Brien and deNoyelles 1974). As expected, it appeared that total phosphorus and TIS concentrations increased with urbanization, however the exact relationship is un-quantified (Klein 1979).

The striking feature of these impoundments was the homogeneity of the phytoplankton communities, with only subtle differences among them, likely a result of large homogenous nutrient loads. All of the phytoplankton taxa are found throughout North America and are tolerant of moderate to high amounts of eutrophication, especially Scenedesmecae and euglenoids (Wehr & Sheath 2003). When compared to another local reservoir (Harris and Trimbee 1986), total densities appear to be fairly low, even in Laurel Creek Reservoir. This is likely a result of the relatively young age of the impoundment (Guelph Lake) when samples were taken by Harris and Trimbee, causing it to have higher than average nutrient levels promoting increased productivity (Harris and Trimbee 1986), as well as the diverse fish community (GRCA) which likely suppress grazer densities, as well as the inexperience of this author at the identification and enumeration of phytoplankton. It should be emphasized that I did not enumerate smaller taxa (majority of cyanobacteria, picoplankton and nanoplankton), and these likely make up a substantial fraction of the phytoplankton in this system as they are widely found throughout freshwater systems (Wehr and Sheath 2003, Scheffer 2004).

The phytoplankton densities in these impoundments appear to be connected with the densities of zooplankton (Yang 2007). The low relative densities of zooplankton in Laurel Creek Reservoir are likely a result of the yearly draw-down which could be expected to cause heavy mortality on overwintering stages, leading to very small inocula for the following year. This, in turn would lead to relatively high phytoplankton densities because of low grazing pressure. Columbia Lake is only drawn down approximately 0.5 m since its reconstruction and had the highest zooplankton densities (Yang 2007) as well as low outlet phytoplankton densities. These high zooplankton densities are somewhat surprising given the diverse fish community, but are likely a result of the turbidity which lowers predation, coupled with the depth of this impoundment (4m) which provides diel refuge for grazers (Wetzel 1975, Gliwicz 1986)). The low densities of zooplankton reported by Yang (2007) in the shallowest impoundments, Clair and Silver Lakes, may reflect food limitation or fish predation in the absence of deep-water refugia. Very low phytoplankton densities in Clair and Silver Lakes are consistent with light limitation in the very turbid water. The somewhat greater phytoplankton densities in Silver Lake relative to Clair Lake probably reflect inputs from all of the upstream impoundments (as seen in the high inlet densities). Without this recruitment Silver Lake would likely be as dominated by benthic algal clumps as was Clair Lake.

4.1 Conclusions

Although there was very little export of sediment and phosphorus from Laurel Creek Reservoir during my study seasons, it is the stated policy of the GRCA to flush this impoundment yearly, which expels vast quantities of sediment and nutrients downstream. This likely has negative effects on downstream reaches and especially to Columbia Lake, but possibly all the way to Lake Erie. This management practice has negative effects on the downstream fauna and flora. The health of the system as a whole would improve if this management practice ceased. Although un-quantified, the impoundments with larger amounts of upstream urbanization receive high concentrations of TIS, which can lead to high levels of sedimentation. The effect of carp on the different impoundments is unclear but in theory they should act to resuspend and thereby cause export of inorganic sediment and phosphorus, which can lead to increased eutrophication, as well as the re-suspension of phytoplankton cells which had previously sedimented out. The high inputs of sediment from the more urbanized impoundments, along with the carp, likely have a synergistic effect which leads to the high outlet TIS concentrations. The carp also appeared to suspend the benthic algal mats; this was especially true for Clair Lake, where the mats often comprised more than 50% of the sample biomass. As mentioned earlier this algae likely originates from the sediment surface, as it was observed to cover most of the shallow sediment, and the fact that it rapidly sedimented out of the water column. These mats occurred in the highest densities within Clair Lake, but were also found in all of the impoundments to some degree. However due to the lack of data, this study is inconclusive to the exact extent of internal drivers such as carp on suspended solids (inorganic and organic), TP or phytoplankton communities, as these urban systems appear to be more strongly influenced by other factors, such as land use, precipitation and the yearly draw-down, however there does appears to be some evidence to suggest that an internal source(s) is suspending the sediment causing TIS and TP export in 3 of the 4 impoundments regardless of precipitation, this internal source can be attributed at least partially to the foraging of an active carp population (Breukelaar et al. 1994, King et al. 1997, Scheffer 2004), this coupled with the extensive urbanization, causes much of the water in the downstream impoundments to be of low quality.

Large reductions of carp will likely lead to increased water transparency as there is a strong link between high levels of turbidity and infestations, as well as large reductions of the sediment within Clair and Silver Lakes, this can be accomplished through manual dredging of the sediment which will lower the export. However if there is to be a discernable reduction in turbidity within Columbia Lake the shoreline needs to be armoured or the precipitation driven erosion will continue. For overall improvement of this system though, a few changes are needed, one is to disconnect of the impervious surface area from the impoundments, likely through localized water attenuation and treatment. Another major change in management practices is to stop the yearly draw down of Laurel Creek Reservoir for the reasons mentioned earlier; which will lead to less degraded downstream stretches, and has possible implications as far down as Lake Erie. Follow up studies would be interesting, and if reduction of the carp is to be effective, extensive netting during the breeding season paired with local efforts such as carp ‘derbies’ could be an effective approach in managing the carp populations within the Laurel Creek system, especially since it was found that manual seine netting is very difficult in the more urbanized impoundments.

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