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Operation and Evaluation of Hypolimnetic Withdrawal in a Shallow Eutrophic Lake

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Abstract

Chain Lake is a small (46 ha), shallow (z_{mean} = 6 m , z_{max} = 9 m) eutrophic lake in the interior of British Columbia, Canada. It suffers from severe blue-green algae blooms fed by internally loaded phosphorus. A hypolimnetic withdrawal system began operation in 1994, and is operated annually during the ice free period of the year. It is gravity driven (no mechanical pumps) and can operate at rates up to 80 L s^{-1}. A monitoring program implemented as part of the withdrawal installation evaluated total phosphorus export, lake water quality effects, and downstream environmental impacts. The withdrawal does not accelerate hydraulic flushing of the lake (residence time up to 3 years) but preferentially drains the water column below 5 m every 100 days and drains the deepest region of the lake (6-9 m) approximately every two weeks. Total phosphorus export in the first year of operation was 30 kg, and optimization of the operation strategy should increase export to 60 kg per year, resulting in a net export of total phosphorus from the lake. Long term monitoring of water quality has been performed by resident volunteers for nine years (1994 - 2002) using Secchi measurements. Only a few data are available prior to the withdrawal operation. A non-parametric trend test found statistically significant increases of the monthly median Secchi depth for June ($p<0.05$) and August ($p<0.10$). Optimization of the withdrawal operation to maximize phosphorus export can be done by earlier start-up after ice off and increased flow rates during the most anoxic periods. Downstream concerns with respect to the withdrawal operation include: dissolved oxygen depletion observed at the withdrawal site and up to 500 m downstream; nutrient enrichment with elevated concentrations of phosphorus observed in

the withdrawn water; and elevated levels of ammonia, iron, and manganese observed in the withdrawn water in the first year of monitoring. The effects of anoxic water discharge were partially mitigated by a fountain aerator at the discharge point which increased the dissolved oxygen in the withdrawal stream by up to 2.0 mg L^{-1}.

Keywords: lake restoration, hypolimnetic withdrawal, internal loading, phosphorus, shallow lake

Fonctionnement et évaluation d'un système de soutirage d'eau de l'hypolimnion dans un lac eutrophe de faible profondeur

Macdonald, R.H., G.A. Lawrence et T.P. Murphy

Résumé

Le lac Chain est un petit lac (46 ha) eutrophe de faible profondeur (cote moyenne Z = 6 m, cote maximale Z = 9 m) qui se trouve en Colombie-Britannique, au Canada. Il présente de fortes proliférations d'algues bleues alimentées par la charge interne de phosphore. Un système de soutirage d'eau de l'hypolimnion est entré en activité en 1994 et est mis en marche chaque année, pendant la période où le lac est libre de glace. Mû par gravité (sans pompage mécanique), le système peut atteindre un débit de 80 L s^{-1}. Un programme de surveillance mis en œuvre dans le cadre de l'installation du système a permis d'évaluer l'exportation totale de phosphore, les effets sur la qualité de l'eau du lac et les impacts environnementaux en aval. Le soutirage n'accélère pas la chasse hydraulique du lac (jusqu'à 3 ans de temps de séjour), mais il draine plutôt la colonne d'eau sous le niveau de 5 m tous les 100 jours et la partie la plus profonde du lac (6-9 m) toutes les deux semaines environ. L'exportation totale de phosphore au cours de la première année de fonctionnement a été de 30 kg; un fonctionnement optimal devrait permettre d'atteindre 60 kg par année, ce qui représentera une exportation nette de tout le phosphore dans le lac. La surveillance à long terme de la qualité de l'eau a été effectuée bénévolement par des résidents pendant neuf ans (1994 - 2002) au moyen de mesures de la profondeur de non-visibilité du disque de Secchi. Les données antérieures au soutirage sont peu nombreuses. Un test non paramétrique des tendances a permis de constater des augmentations statistiquement significatives de la profondeur mensuelle moyenne d'après le disque de Secchi en juin ($p < 0,05$) et en août ($p < 0,10$). Pour optimiser le soutirage, et maximiser l'exportation de phosphore, on peut mettre en marche le système plus tôt après la disparition de la glace; les débits peuvent également être accrus pendant les périodes où l'anoxie est la plus forte. En aval, les préoccupations liées au soutirage englobent l'épuisement de l'oxygène dissous qui a été observé au site de soutirage et jusqu'à 500 m en aval, l'enrichissement en nutriments et les fortes concentrations de phosphore dans l'eau soutirée, de même que la teneur élevée en ammoniac, en fer et en manganèse de l'eau soutirée qui a été observée pendant la première année de surveillance. Les effets du rejet d'eau anoxique ont été en partie atténués par un aérateur giclant au point de rejet, ce qui a élevé la quantité d'oxygène dissous dans le flux de soutirage dans une proportion pouvant atteindre jusqu'à 2,0 mg L^{-1}.

NWRI RESEARCH SUMMARY

Plain language title
Operation and evaluation of hypolimnetic withdrawal in a shall eutrophic lake

What is the problem and what do sicentists already know about it?
Eutrophication of lakes can be caused by natural or difficult to control sources. At times sediment release of phosphorus can maintain eutrophication independently of external nutrient control. Shallow lakes are particularly susceptible to this type of eutrophication. Hypolimnetic withdrawal had not been done in Canada and implementation in a shallow lake is particularly difficult.

Why did NWRI do this study?
We were asked by the Fish and Wildlife Department of British Columbia to improve water quality of an important recreational lake. The site was naturally eutrophic and presented an excellent site to demonstrate innovative lake management.

What were the results?
The lake treatment required a two step process. The dredging of a hole to facilitate the installation of a bottom withdrawal pipe was difficult but effectively implemented. The disposal of the dredged sediments was awkward. The lake immediately improved and there has been a gradual reduction in the concentration of phosphorus in the lakewater. The process is highly effective and requires minimal supervision.

How will these results be used?
Pine Lake in Alberta used a similar approach and other lakes in Canada can also use this information to improve water quality.

Who were our main partners in the study?
Fish and Wildlife Department of British Columbia, University of British Columbia, Habitat Conservation Fund of B.C., and NSERC.

Sommaire des recherches de l'INRE

Titre en langage clair

Fonctionnement et évaluation d'un système de soutirage d'eau de l'hypolimnion dans un lac eutrophe de faible profondeur

Quel est le problème et que savent les chercheurs à ce sujet?

L'eutrophisation des lacs peut être d'origine naturelle ou avoir des causes difficiles à contrôler. Il arrive que le phosphore rejeté par les sédiments maintienne l'eutrophisation de façon indépendante de l'apport extérieur de nutriments. Les lacs de faible profondeur sont particulièrement vulnérables à cette forme d'eutrophisation. Le soutirage d'eau de l'hypolimnion n'avait jamais été fait au Canada, et sa mise en œuvre dans un lac de faible profondeur est particulièrement difficile.

Pourquoi l'INRE a-t-il effectué cette étude?

Le service des pêches et de le faune nous a demandé d'améliorer la qualité de l'eau d'un important lac utilisé à des fins récréatives. Il s'agit d'un lac naturellement eutrophe qui offre une excellente occasion de mettre à l'épreuve un procédé novateur de gestion des lacs.

Quels sont les résultats?

Le traitement du lac a dû se faire en deux étapes. L'excavation d'un trou visant à faciliter l'installation d'une conduite de soutirage au fond a été difficile, mais s'est bien déroulée. L'élimination des sédiments dragués n'a pas été commode. L'état du lac s'est immédiatement amélioré et la teneur en phosphore de l'eau a graduellement diminué. Le procédé est extrêmement efficace et exige une supervision minime.

Comment ces résultats seront-ils utilisés?

Une approche semblable a été adoptée au lac Pine en Alberta, et l'information recueillie pourrait également être utile pour améliorer la qualité de l'eau d'autres lacs au Canada.

Quels étaient nos principaux partenaires dans cette étude?

Service des pêches et de la faune de la Colombie-Britannique, Université de la Colombie-Britannique, Habitat Conservation Trust Fund de la Colombie-Britannique et CRSNG.

Introduction

Chain Lake is a shallow hyper-eutrophic lake situated 45 km NE of Princeton, in the British Columbia interior of western Canada. Inflows to the lake are a small creek (Hayes Creek) entering from the north and a water diversion from the neighboring Shinish Creek which operates during the summer months (Fig 1). Outflow is via Hayes Creek from south end. The lake is rectangular in shape and flat bottomed with a surface area of 46 ha and an average depth of 6 m (Fig. 2). The watershed around the lake is rural and composed primarily of pine forest; there is a ring of vacation cottages around the shore employing septic or outhouse systems for wastewater disposal. The lake has a valued recreational fishery and is stocked annually with 7 - 15 thousand trout fingerlings. The lake experiences strong algae blooms with historical levels of total phosphorus (TP) and chlorophyll-a (chl<u>a</u>) in the summer of 300 $\mu g\ L^{-1}$ and 100 $\mu g\ L^{-1}$, respectively. The algal community is dominated by blue-green species. Secchi transparency is typically less than 1 m during algae blooms. Physical and chemical characteristics of the lake are summarized in Table 1.

The lake is polymictic. That is, it is intermittently stratified and de-stratified during the summer. The stratification periods are long enough to allow severe oxygen depletion in the bottom of the water column. The classic theory of phosphorus release from anoxic sediments by the reduction and solubilization of iron and co-precipitated phosphorus compounds (Mortimer 1941, 1942) is well supported in Chain Lake. Murphy (1987) estimated the internal phosphorus load during the summer at up to 87% of the total summer phosphorus load.

The lake has not always been eutrophic. Murphy et al. (1990a) examined the sediment core record to evaluate the historical diatom community. They found that organisms representative of both eutrophic and oligotrophic systems have dominated the diatom communities at different times. The establishment of the current trophic status coincides with the construction of a dam at the outlet in 1951 which raised the lake level by approximately 1.3 m, presumably resulting in increased periods of thermal stratification (Stefan and Hanson 1980) which facilitates hypolimnetic oxygen depletion.

Through extensive community involvement and the support of the Fisheries Branch - now of the British Columbia Ministry of Water, Land, and Air Protection (BC MoWLAP), lake restoration activities have been undertaken for over thirty years. Trial treatments with copper sulfate were made and a small windmill-powered air pump was installed to aerate the bottom water and functioned for a few years. A water diversion was built in the 1960s to bring low nutrient water from the neighboring Shinish Creek into Chain Lake to increase hydraulic flushing of the lake which continues to operate today. In 1987/88 an experimental dredging program was implemented to deepen the lake and stabilize the stratifications (e.g. Stefan and Hanson 1980). The result is a small region (70 m by 80 m) at the south end of the lake that is 3 m deeper than the rest of the lake (Fig 2). From 1989 to 1992, the lake residents conducted a maintenance dredging program to remove accumulated sediment from the dredged area (Murphy et. al. 1990b).

Accurate records of these activities are not available. As well, the effect on water quality of all these efforts has been poorly quantified - mostly due to limited resources for monitoring (Murphy et al. 1999). For example, fish kills attributed to summertime oxygen depletion have occurred in the past though official records are rare (e.g. one documented case is noted in the provincial Fisheries Department files dating from 1975).

However, anecdotal evidence from long time residents indicates that fish kills had occurred more than once and have become less frequent since the installation of the Shinish Creek diversion (Murphy, 1987).

Hypolimnetic Withdrawal

Hypolimnetic withdrawal is the removal of water from the hypolimnion of a lake, instead of surface water that would normally leave the lake via the surface outlet. The technique has two objectives. First is to remove the limiting nutrient (usually phosphorus) from the water column before it becomes available to algae or plants. Many eutrophic lakes have limited hydraulic flushing (i.e. long residence times for water) and only a small fraction of the lake volume leaves the lake through a summer. The poor flushing means that internally released nutrients are not removed from the water column. Hypolimnetic withdrawal increases the *phosphorus* export for the limited available *water* export by preferentially removing water with elevated phosphorus levels.

Secondly, hypolimnetic withdrawal can reduce the extent of anoxic conditions in the hypolimnion and at the sediment interface, thus reducing the magnitude of internal loading. This is accomplished by either reducing the size of the hypolimnion to maintain more sediment surface in contact with aerated epilimnetic water, e.g. Lake Kortowo, Poland (Olszewski, 1961, 1973), or by flushing the hypolimnion with directed replacement water during withdrawal, e.g. Lake Ballinger Seattle (Cooke et al 1993).

Study Objectives

A monitoring and evaluation program was established to coincide with the withdrawal installation to evaluate: (i) the effectiveness of the system in exporting phosphorus, (ii) short or long term effects of the withdrawal operation on lake water quality, and (iii) environmental impacts of the withdrawal system on the lake and the downstream receiving waters.

Methodology

Chain Lake Withdrawal System

The system was installed in August 1993 at the south end of Chain Lake (Fig. 2). The withdrawal pipe extends along the lake bottom from the outlet dam to a point 170 m from shore (Fig. 3). The inlet to the withdrawal is located at 6.2 m depth just inside the edge of the dredged hole. This design makes use of existing facilities at the site. Specifically, a culvert pipe through the dam with a sliding plate control valve was part of the dam installation in the 1950s. For the withdrawal installation, a coffer dam 'box' was built around the lakeside (upstream) end of this culvert pipe, and the hypolimnetic withdrawal pipe connects to the box. A fountain/aerator is attached to the downstream end of the culvert pipe to provide aeration to the withdrawn water and act as a barrier to prevent coarse fish from entering the lake. Parallel to the withdrawal, there is a spillway over the existing dam which controls the lake level. The flow from these two lake outlets, the surface overflow and the hypolimnetic withdrawal, combine 50 m downstream of the lake to form Hayes Creek (Fig. 2).

The driving force that moves water through the withdrawal pipe is the difference in elevation between the lake and the downstream discharge. Opening the culvert valve draws water out of the box. This lowers the level of water inside the box. The difference between the lake level and the water level inside the box drives water through the withdrawal pipe (i.e. into the box). The energy (head) losses within the withdrawal pipe are small - primarily due to the large pipe used (18 inch nominal diameter). Minor head losses also occur at the entry and exit from the pipe. The fountain aerator provides the greatest loss of energy as the flow must be diverted vertically upward before release rather than being discharged horizontally. For this installation, there is sufficient elevation difference between the lake level and the downstream Hayes Creek to accommodate the aerator fountain. Flow testing during the installation showed that discharge rates of 80 L s^{-1} are possible with a head difference between the lake and the inside of the box of 7 to 10 cm, while the total head loss (from the lake level to the aerator water level) is typically 1 m.

Monitoring Methods

Water sampling, chemical and physical analysis, and ambient data collection were conducted in Chain Lake and the downstream creeks during 1993 (baseline data) and 1994 (the first year of operation), with increased effort during 1994. A meteorological station and thermistor chain were deployed on a raft in the lake to monitor the weather (wind speed, air temperature, humidity, solar radiation) and thermal conditions of the lake (using a string of six thermistors located between 0.5 m depth and the lake bottom at 6.5 m). Secchi depth measurements were recorded occasionally in 1993 and more frequently in 1994 (by local residents). Withdrawal flow rates were monitored using a propeller style flow meter.

Water samples were collected approximately bi-weekly in the study area. Lake samples were collected at each of three stations along the length of the lake, at 3-4 depths for each station. Additional samples were collected at the outlet weir, at the withdrawal discharge, and at four 4 stations in the downstream Hayes Creek and inflowing Shinish Creek. Synoptic temperature and dissolved oxygen (DO) measurements were made in the field at the time of sample collection using a calibrated YSI DO probe. Analysis was performed on all collected samples for nitrogen (ammonia and nitrite+nitrate), phosphorus - total (TP), total soluble (TSP), and soluble reactive (SRP), iron and manganese (total and soluble), and chlorophyll-a (chl<u>a</u>). Analyses were performed in the field, or samples were filtered and/or preserved in the field for transport to the laboratory. Laboratory analysis was conducted at the Environmental Engineering and Oceanography laboratories at the University of British Columbia.

In subsequent years monitoring has been reduced. In 1995, four sets of chemistry samples were collected at monthly intervals from the lake and the downstream creek stations, and no meteorological data were collected. From 1996 onward monitoring has consisted solely of Secchi depth data collected by volunteer lake residents through the summer months. The Secchi data set consists of 5 to 20 readings per month from May to October for 9 years from 1994 to 2002. Only a few Secchi data are available prior to the withdrawal operation.

Environmental Conditions

Meteorology and Limnology

Detailed weather and lake temperature records were maintained during 1993 and 1994. From the thermistor record average daily water temperatures are calculated (Figure 4). These time series show the polymictic nature of the lake. During both 1993 and 1994 the lake stratified for periods of 7 to 30 days as shown by the difference in temperature between the upper and lower depth thermistors. The lake was frequently de-stratified as shown by the periods of uniform temperature in the water column. This polymictic behavior mixed the top 5 m of the water column regularly. There was also substantial natural variability of the lake stratifications. For example, in 1993, there was a warm spring resulting in a strong stratification in May, and a cold rainy July resulting in weak stratification. In contrast, 1994 featured weakly stratified conditions in the spring, and a strong stratification in July which lasted well over a month.

The deepest thermistor, located at 6.5 m was very near, or at, the sediment-water interface. In Chain Lake the bottom sediments are not a firm layer but rather a region of loose unconsolidated sediments with a fluid like consistency (typically > 98% water content) approximately 0.5 m thick (Macdonald 1995). This region was cooler than at 5 m depth for all but a few days during the summers of 1993 and 1994 and as a result was slightly stratified from the remainder of the water column. Some of the water column mixing events did reach to the full depth of the lake (e.g. isothermal conditions in late August 1994). Additionally, short term temperature variations caused by diurnal heating and cooling and internal seiche movements were not observed to reach the 6.5 m depth (Macdonald and Lawrence 2000).

The small temperature difference between 5 m and 6.5 m is important because it shows that the near bottom water, the sediment-water interface, and the dredged hole region are isolated from the thermal regime of the main body of the lake. Thus, while the main body of the lake was observed as highly polymictic, stratifying and mixing a half dozen or more times in a summer, the bottom 1 m of the main body, and the dredged hole might only mix a couple of times per summer.

Hydraulics of the Withdrawal

In 1994, withdrawal operation was from June to October (Table 2). The flow rate ranged from 15 L s^{-1} to 40 L s^{-1}, averaging 31 L s^{-1}. As a result 288 x 10^3 m^3 of water was removed which is about 10% of the lake volume. The strategy during the first year was to operate at a constant rate all summer, though the flow was decreased for about ten days. However, the withdrawal as built can operate at rates up to 80 L s^{-1} and in subsequent years (1995 onward) the withdrawal has operated at higher rates (approximately 50 L s^{-1}), and for longer periods of the summer. Since 1995 the withdrawal system has been maintained and operated by the Chain Lake Residents Association.

The hydrologic residence time of the lake ranges from 0.5 to 3.0 years, or 180 to 1000 days. Withdrawal flow rates of 50 L s^{-1} represent hydraulic residence times of about 650 days for the entire lake. Thus the withdrawal does not accelerate water export from the lake. In fact, as operated, it is intended only to remove water that would otherwise leave via the surface outlet. Experience at other installations has recommended against altering lake levels during withdrawal (Nürnberg 1987).

The thermal conditions in the lake indicate that the withdrawal preferentially drains a small portion of the water column. The inlet to the withdrawal is at 6.2 m depth while most of the lake is only 6.0 m deep. Water temperature observations show that the withdrawal typically removes water from, or below, the 5 m depth range (Macdonald 1995). Similarly, selective withdrawal calculations based on Fischer et al. (1979) indicate that at flow rates up to 100 L s^{-1}, and with the density stratifications observed in 1994, the system would withdraw water from a vertical range less than 1 m above the withdrawal inlet (i.e. from about 5.2 m and deeper). The residence time through the withdrawal of the portion of the lake below 5 m is about 100 days.

Furthermore, the dredged hole itself contains only about 0.6% of the lake volume. That is, the withdrawal is placed below 99% of the water column. For the portion of the lake within the dredged hole the residence time is 5-10 days. There is evidence that the Shinish Creek diversion water sinks to the bottom of the dredged hole and will replace some of the withdrawn water. First, the diversion water in 1994 was consistently cooler than the withdrawal water (Macdonald 1995) and so some of it was expected to sink below the withdrawal inlet. As well, a dye study by Matthews (1982) observed that the diversion water sinks to at least 5 m depth and was observed to cover 2/3 of the lake area. Thus, some of the Shinish Creek water is expected to replenish the dredged area from below the withdrawal depth.

In summary, the hydraulics of the withdrawal indicate that while the system flushes the whole lake very slowly, it drains the portion near the sediment surface every 100 days (2 times per season), and drains the deepest area every two weeks.

Phosphorus Export

In 1994, withdrawal operation exported 30 kg of TP. Increasing the number of days of operation to include the entire ice free season, and increasing the flow rate to an average of 50 L s^{-1} could increase the TP export rate to approximately 60 kg yr^{-1} (Macdonald 1995). A typical summer phosphorus mass balance including phosphorus export is shown in Table 3. Estimated total phosphorus loading from external sources is approximately 36 kg yr^{-1}. With optimized withdrawal operation, there could be a net export of 24 kg yr^{-1} TP. A long term effect of a net export of TP would be a slow decrease of the sediment phosphorus content available for internal loading. This was observed in Lake Maun (Cooke et. al. 1993) where the phosphorus export exceeds the external loading substantially and is reducing the supply of available phosphorus cycled annually from the sediments. In Chain Lake such an effect would occur very slowly as the net export is small compared to the total sediment available phosphorus which is estimated at 7500 kg (Macdonald 1995).

The total phosphorus export can be expressed as a phosphorus residence time. This is the mass of phosphorus in the total water column divided by the export rate and is analogous to the hydrologic residence time used for water flows. Macdonald (1995) found that at peak withdrawal periods during 1994 the whole lake TP residence time via the withdrawal was about 150 days. At the same time the whole lake water residence time during that month was over 900 days. Thus, by concentrating on removing the deep, high phosphorus concentration water, the withdrawal accelerated phosphorus removal by 6 times above the water removal rate.

Water Quality Effects

First Year Effects

Lake Secchi transparency, chla, and TP concentrations monitored in the initial year of observation (1994) are shown in Figure 5. In May, the visibility was high (Secchi > 5 m), and chla and TP concentrations in the water column were relatively low (chla < 5 $\mu g\ L^{-1}$; TP < 30 $\mu g\ L^{-1}$). At this time there was also a remaining accumulation of TP in the deepest portion of the dredged hole - high phosphorus content water from the winter under-ice stratification, that had not mixed with the entire water column. In June and early July, the Secchi declined to 3 m, and both chla and TP had increased (10 $\mu g\ L^{-1}$ and 30 $\mu g\ L^{-1}$ respectively). By this time the deeper water had mixed with the entire water column and much less elevated TP levels were observed in the dredged area.

In mid-July, the lake became strongly stratified and the hypolimnion, particularly the dredged area became oxygen depleted. Internal phosphorus build-up was observed with TP > 150 μg L^{-1} and total iron from 0.5 to 1.0 mg L^{-1} below 6 m depth (Macdonald 1995). This build-up was restricted to the bottom of the lake by the strong thermal stratification. The accumulated build-up did not appear to contribute to algal productivity as the surface waters were relatively low in chl<u>a</u> (5 μg L^{-1}) and TP (30 μg L^{-1}), and Secchi reached 4.5 m. By early August, the strength of lake stratification decreased. The result was mixing and movement of phosphorus-containing water upwards to the surface, presumably triggering an algal bloom. Chl<u>a</u> reached 50 μg L^{-1}, TP reached 120 μg L^{-1}, and Secchi depth declined to 1 m by the third week of August.

The Secchi, Chl<u>a</u>, TP, and thermal observations are consistent with our understanding of the lake system. Moreover, they are consistent with anecdotal accounts of other years. Historically water quality is good in the spring and declines in June. Algae blooms are observed annually in the summer, and frequently as early as July 1. Once formed, the algae blooms usually remain until the onset of cool weather (about Sept 1). In 1994 the algae bloom did not occur until August. This delay of the summer algae bloom could arguably be due to the withdrawal operation, or simply the result of inter-seasonal variation of weather patterns which in 1994 resulted in a long stratified period in July to prevent vertical nutrient mixing. A conclusive determination cannot be made from the single year of data.

Long Term Effects

Secchi measurements are the only consistent monitoring measurements performed at Chain Lake since 1996. Prior to withdrawal operation the data set is sparse both annually and seasonally – only seven years with any data from 1951 to 1993, with only 1 to 7 data points collected in those years representing both before and after the previous dredging and treatment programs (Table 4). The lack of pre-withdrawal data makes before- and after-withdrawal comparisons difficult.

Since the withdrawal start-up in 1994, the collected data include 5-20 data points per month from May through October. Median monthly Secchi measurements before and after withdrawal operation are shown in Figure 6. Median values provide a reliable measure of central tendency since the data are auto-correlated (Gilbert 1987).

A Mann Kendall test for trend was used with the monthly median Secchi measurements for the period from 1994 to 2002. The test examines the probability of obtaining the observations if there is no real trend in the data (i.e. the null hypothesis is "H0: There is no trend"). The test does not require an assumption of the magnitude, or the shape, or the direction of the trend. As well, it can be applied to the period since withdrawal initiation (1994 onward) and so is not affected by the limited amount of pre-withdrawal data.

The results of the Mann-Kendall test are mixed (Table 4). For the June median Secchi data, there is a rejection of the no-trend hypothesis at the 97.8 % confidence level (i.e. $p = 0.022$ or $p < 0.05$). For August the rejection level is 91.0 % ($p = 0.091$ or $p < 0.10$). Thus, there is significant evidence that the Secchi transparency in the lake is increasing in June and probably in August as well. The changes for other months are less certain with confidence levels below 90% (Table 4).

These results are consistent with the observations made in 1994 and our understanding of the lake behavior. That is, we expect that withdrawal removes TP preferentially from the deep areas of the lake. Exporting phosphorus during short periods of stratification may delay or decrease the severity of an algae bloom. The increased

June Secchi may be the result of removing high TP water from the dredged area that has not circulated to the top of the lake after ice-off. Similarly, the increase of August Secchi may be the result of delaying, or reducing a summer bloom that follows a period of summer stratification.

Secchi Depth and Withdrawal Limitations

The limited statistical certainty of the changes in Secchi disk transparency may be the result of several factors. First, more time may be needed to see statistically significant trends in the Secchi transparency. Lake restoration effects from hypolimnetic withdrawal can require long time scales to become evident (Nürnberg, 1987).

Secondly, the variable Secchi transparency is a surrogate, or composite, measure of other parameters like chla or TP and is limited by the nature of chla to visibility relationships. Numerous studies have correlated Secchi depth data to chla concentrations. (e.g. Dillon and Rigler, 1974, Nürnberg, 1996). Typically these relationships are log-linear, i.e. they are straight line correlations when the data are log-transformed. At the productivity levels in Chain Lake, a dramatic decrease in chla would be required to result in a moderate improvement in visibility. For example, to achieve an improvement of Secchi visibility from 1 m to 2 m would require a reduction of chla from 15 to 5 $\mu g\ L^{-1}$ by the graphical relation of Dillon and Rigler (1975) or from 35 to 12 $\mu g\ L^{-1}$, by the regression of Nürnburg (1996) for North American lakes.

Finally, the limited effectiveness observed may not be a measurement artifact, but a limit of the withdrawal's effectiveness due to nutrient limitation conditions in the lake. Phosphorus may not always be the limiting growth factor in Chain Lake. When phosphorus is not limiting, then export may not result in an improvement of water quality. To examine the nutrient limitation, the chla and TP data collected synoptically in the upper 3 m (well mixed zone) of the lake in 1994 are cross-plotted (Figure 7). Ahlgren et al. (1988) show the ratio of chla to TP in algal body mass is typically around 1:2. A plot line showing this ratio is overlain on Figure 7. Data points which fall on the line indicate that the growth of algae (chla) is to the limit of the available phosphorus, indicating phosphorus limitation. When phosphorus is in excess, the points fall to the right of the line - there is more phosphorus than needed for a specific algal biomass and another factor is limiting. While TP is often the limiting nutrient in Chain Lake, at some points of the year it appears not to be limiting. These observations are consistent with a eutrophic lake, fed by internal phosphorus load, that is dominated by blue-green algae (which can fix nitrogen) - all conditions observed in Chain Lake.

While not intended as a rigorous analysis of nutrient limitation in Chain Lake, this result highlights the potential impact of nutrient limitation on the effect of hypolimnetic withdrawal. In the long term, the effectiveness of the Chain Lake withdrawal may be its capability to export sufficient phosphorus to induce phosphorus limitation or to increase the time period during which phosphorus is the limiting nutrient.

Withdrawal Optimization

The monitoring effort highlights several options for optimizing the withdrawal operation. First, it would be beneficial to start operation as early in the year as possible following ice-off. The thermal structure (Fig 4) and phosphorus concentration data for 1994 (Fig 5c) show that the dredged area is sheltered from the general hydraulic circulation currents and mixing of the main area of the lake. Large TP concentrations observed in February during the winter stratification (under ice) were still present several weeks after ice-off in 1994 (e.g. TP value of 290 μg L^{-1} on May 9 at 7.5 m). Operating at maximum withdrawal rate early in the year would increase the removal of highly bio-available soluble reactive phosphorus (SRP) available to feed a spring algae bloom. In recent years operation has begun in late April or early May and this may explain the observed improvement in median June Secchi. Secondly, the withdrawal export could be optimized by increasing the flow rate during the most anoxic periods during the summer. It is during these periods that the lake is typically stratified and a build-up of nutrients occurs.

Environmental Impacts

Several potential environmental impacts have been observed in other hypolimnetic withdrawal applications (Nürnberg 1987, Livingstone and Schanz 1994). Within the lake, the withdrawal has the potential to lower the water level and to alter heat balances by exporting cold bottom water instead of warm surface water. Downstream of the lake negative effects are associated with releases of anoxic water which may contain high levels of phosphorus, iron, manganese, ammonia and even sulfide. Several tactics have been employed at other withdrawal sites to reduce downstream impacts including fountains to aerate the withdrawn water, mixing of epilimnetic water with the withdrawal water, and even discharge of the withdrawn water into sanitary sewage treatment systems.

Lake Impacts

The withdrawal flow rate in Chain Lake (for the entire summer) is most limited by the hydrology of the catchment and the Shinish Creek water diversion, rather than the hydraulics of the withdrawal system. Nürnberg (1987) recommends against altering lake levels during withdrawal. Significant lake level changes are not likely in Chain Lake. While Hayes Creek entering at the north end often provides no noticeable inflow during mid-summer, the Shinish diversion can provide as much or more water than the withdrawal flow. Even with temporary shut downs of the diversion for maintenance and repairs the withdrawal would not lower lake level by more than 15 cm over a 2 week period (Macdonald 1995). This is within the range of historical fluctuations and is far less than the 1.3 m draw down currently allowed by existing water storage licenses on the lake.

Generally, the issue of lake level draw down is an asthetic and comfort issue for residents. However a concern does exist with the Fisheries Branch of BC MoWLAP that the lake must not be drawn down at the time of ice-over in order to decrease the likelihood of a winter fish kill. Water balances (Macdonald 1995) have shown that as long as the Shinish Creek diversion is reliably supplying water, there would be no difficulties ensuring a full lake by ice over in November - even for a drawdown of 0.5 m or more at Sept 1.

Withdrawal may affect the thermal conditions in the lake. The first reported withdrawal installation was intended to remove a lake hypolimnion and it promoted early destratification (Olszewski, 1961). In another case, Livingstone and Schanz (1994) observed that withdrawal operation encouraged stratification in the spring by keeping newly-warmed surface water in the lake, and it accelerated de-stratification in the fall by removing cool bottom water thus encouraging turnover.

In Chain Lake heat flows through the withdrawal are small compared to natural meteorological heat fluxes. For example, summertime daily heat fluxes at the water surface (i.e. radiation, latent, and sensible heats) are several hundred W m^{-2} at mid-day and up to 100 W m^{-2} on a 24 hour average, resulting in observed temperature fluctuations of several degrees per day in the surface waters. In contrast, a withdrawal flow of 50 L s^{-1} removing 16 °C bottom water (instead of a surface spillway removing 22 °C surface water) is the equivalent of a net heat retention in the lake of about 5 W m^{-2}. This heat retention would be in the surface of the lake. Averaged over the top 2 m of the lake surface it is equivalent to a temperature increase of only 0.05 °C day^{-1}. After a destratification event, this heat would be mixed into the entire lake. As well, heat fluxes are partially self regulating. That is, there is always night time cooling, and if the lake is warmed substantially during the day, then more heat is lost in the nighttime due to convection - thus partially reducing the impact of the gained heat.

Potentially, the withdrawal could accelerate mixing of the bottom 1 m of the lake by removing the cold bottom layer. Then a greater area of the sediments would be exposed to warm surface waters which could accelerate bio-chemical processes and increase the sediment oxygen demand in the lake - potentially reducing the dissolved oxygen content of the water column. It is felt that this effect would be small, if at all, due to the replacement water provided by the Shinish Creek diversion.

Aerator Performance

An aerator fountain on the outlet end of the culvert pipe provides aeration to the withdrawn water. The aerator/fountain design includes the use of many split weirs (i.e. 6" x 1/2" slots cut in the vertical section of pipe) and a plunge pool around the pipe. These features enhance oxygen transfer (e.g. Nakasone 1987). The plunge pool, in which air bubbles are entrained in the water, is especially significant and accounts for the majority of the oxygen transfer.

The effectiveness of this aeration is measured by comparing the DO concentration 'inside' the fountain (as it flows through the dam before release) to the DO level 3 m downstream - just outside the plunge pool surrounding the fountain. The fountain aerator system typically increases the DO level by 1.5 to 2.0 mg L^{-1} (Figure 8). This reduces the severity of any immediate chemical oxygen demand created by the reducing conditions in the withdrawn water. Note that the DO levels shown inside the aerator pipe never reached zero due to leakage of surface water into the coffer dam box. Flow measurements indicate that the discharge at the fountain contains as much as 15% surface water (fully DO saturated) mixed into withdrawn water (DO depleted).

Downstream Impacts

The temperature of the surface water released from the dam spillway varied by several degrees diurnally in the range of 18 - 22 deg C during July. In contrast, the withdrawal releases water of a very constant temperature, varying less than one degree (usually 16 deg C). The discharge of cooler water, with a more stable temperature, is expected to be beneficial to fish species (mostly trout) residing downstream (Ashley, 1994, pers comm).

Low levels of dissolved oxygen in the downstream creek could be of concern to the health of fish species. Transects collected downstream of the withdrawal in 1994 reveal that DO depletion did occur occasionally. Nine transects were recorded (Figure 9). Prior to withdrawal operation in the spring, DO levels were high through Hayes Creek. During the summer stratification a DO deficit was observed at the fountain discharge with DO concentrations below 5 mg L^{-1}. Some immediate increase in DO was observed at the discharge site due to the fountain aerator. Within 500 m downstream the DO was 5 mg L^{-1} and at 2000 m downstream was near 8 mg L^{-1}.

Following lake turnover in August, the withdrawal DO levels were elevated at the fountain (from 5 to 9 mg L^{-1}). At these times the DO level sags noticeably and then recovers. This resulted in DO as low as 2 mg L^{-1} 500 m downstream on October 4 in spite of a well aerated discharge. This sag could be due to biochemical oxygen demand (BOD) loading from the withdrawal or sediment oxygen demand in the downstream swamp, created by beaver dams.

Released phosphorus could result in nutrient enrichment of the downstream Hayes Creek. Transects of TP in Hayes Creek were collected downstream of the withdrawal for pre-discharge and post-discharge conditions during the first year of operation (Figure 10). The data are variable and most are in the range of <100 µg L^{-1}. The transects show some elevated concentrations of phosphorus within 1000 m of the withdrawal during operation. For example the transect of August 15, 1994 show TP greater than 100 µg L^{-1} up to 1750 m downstream.

While much of the phosphorus measured in the downstream creeks is particulate phosphorus in the form of suspended material and likely not readily bio-available, some of it is in the form of soluble reactive phosphorus (SRP). The work of Bothwell (1985) based on the Thompson River, shows that for flowing streams, once phosphorus reaches measurable SRP levels (typically 3-4 µg L^{-1}) it is unlikely to be a limiting nutrient for periphyton. SRP levels in Hayes Creek were observed in the range of 10 - 25 µg L^{-1} during 1994. Additionally, during the early 1990s, the watershed downstream of the lake was undergoing substantial changes including active draining and trenching for pasture, grazing of cattle, logging of some hill slopes on the west side of the valley. Any of these activities could add to the total TP levels in the creek. While some increase of downstream TP and SRP due to the withdrawal is expected, its overall effect on the downstream creek is not expected to be substantial.

The withdrawal can also release ammonia, iron, and manganese to the downstream creeks. Measurements taken at the withdrawal fountain, and at a sample station 1750 m downstream indicate elevated ammonia in the withdrawal observed twice during 1994, once during the July stratification, and again in the fall (Figure 12). Observed concentrations were up to 1 mg L^{-1} NH_3-N. Ammonia concentrations never exceeded the BC MoWLAP defined criteria for peak ammonia concentrations (Nagpal 1995) and are within Canadian Environmental Quality Guidelines (CCME 1999).

The withdrawal fountain flow contained increased concentrations of iron and manganese during the period of lake stratification. These were attenuated through Hayes Creek. That is, the peak value is reduced downstream and the duration of the peak is extended over a longer time period. This is due to the large water volume stored behind beaver dams between the fountain and the Jellicoe Station (at 1750 m). Many complex precipitation and solubilization reactions may occur throughout the season in the downstream regions due to changing hydraulic flows, benthic oxygen demand, and re-aeration. These would all affect the observed downstream iron and manganese levels. No anecdotal, or factual, reports of any dramatic effects - such as a fish kill - in Hayes Creek have been reported in the nine years of withdrawal operation.

Summary

Chain Lake is eutrophic and internally loaded with phosphorus. It is polymictic and overturns several times during a summer. A hypolimnetic withdrawal has operated since 1994 and has increased phosphorus export from the lake. The thermal conditions of the lake stratifications indicate that the withdrawal can flush the lowest, most anoxic, portion of the water column more than once during a season. Since installation water quality, as measured by Secchi transparency, has gradually improved. Median monthly Secchi has shown a statistically significant increase for June ($p < 0.05$) and potentially for August ($p < 0.10$). The withdrawal operation can be optimized to increase nutrient export without affecting lake level. Potential downstream water quality impacts have been partially mitigated by a fountain aerator at the point of release. This case study has applicability to similar lakes with high internal loading of phosphorus.

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Table 1 Physical and Chemical Characteristics of Chain Lake

Physical Parameters		Chemical Parameters	
Mean Depth (m)	6	Alkalinity (mg L^{-1} $CaCO_3$)	80
Maximum Depth (m)	9	Hardness (mg L^{-1} $CaCO_3$)	65
Length (km)	1.6	Conductivity (µS cm^{-1})	135
Width (km)	0.3		
Area (ha)	46	Typical summer TP (µg L^{-1})	> 300
Volume (10^6 m^3)	2.76	Typical summer chla (µg L^{-1})	> 100
Residence Time (yr)	0.5 - 3.0	Typical summer Secchi (m)	< 1.0

Table 2: Withdrawal Operation from 1994 - 2000

Year	Dates of Operation (a)	Days of Operation (b)	Average Flow Rate (L/s) (c)	Total Water Exported (10^3 m^3)
1994	June 20 - Oct 5	106	31	288
1995	June - Sept	76	50	331
1996	June 14 - Sep 13	91	≈ 50	390
1997	May 16 - Sept 19	up to 126	≈ 50	up to 540
1998	May 2 - ≈ Sept 15	up to 126	≈ 50	up to 540
1999	May 2 - Oct 5	up to 156	≈ 50	up to 675
2000	≈ May - ≈ Sept	≈ 100	≈ 50	≈ 400
2001	≈ May - ≈ Sept	≈ 100	≈ 50	≈ 400
2002	Jun 9- ≈ Sept 30	103	≈ 50	≈ 445

Notes: (a) Dates of operation based on best available records.
(b) Withdrawal is intermittently turned off during season. Days of operation is an estimate.
(c) Flow rate estimated for 1995 onward. Volume from flow estimate and days of operation.

Table 3: Summer Phosphorus Mass Balance for Chain Lake

	Concentration (µg/L)	Volume L/s	Load Rate kg/d	Summer Load (April - Oct) kg
Septic Loads (a)				25.6
Groundwater and Hayes Creek inflow (b,c)	30	20	0.05	≅ 10
Total External Load				≅ 36
Optimized Withdrawal Export				60
Net Export				≅ 24

Notes: (a) Septic loads average of 2 inventory estimates Lacelle (1986) and Murphy and Urciuoli (1984)
(b) Inflowing concentrations from Murphy (1987)
(c) Groundwater flow rates from Macdonald (1995)

Table 4: Summary of Secchi Observations

Period	Distribution of observations: June – Sept period	Monthly Value June	July	Aug	Sept
Prior to Withdrawal	year (# of obs)				
Number of Observations	'51(1) '70(4) '93(7) '62(2) '71(4) '67(4) '88(6)	4	7	12	5
Median Secchi measurement		**2.8**	**2.5**	**1.7**	**1.5**
Post Startup median values	n (per month)				
1994	18 - 24	3.4	3.6	1.8	1.8
1995	11 - 22	5.1	2.4	2.3	2.9
1996	9 - 20	3.3	3.5	1.5	2.6
1997	14 - 22	3.5	2.6	2.6	2.5
1998	4 - 19	3.7	3.6	3.1	4.2
1999	8 - 13	4.5	3.6	2.0	1.7
2000	8 - 12	4.7	3.0	2.1	1.6
2001	5 - 9	4.8	3.4	3.4	2.7
2002	3 - 8	4.9	4.3	2.4	2.1
Median of 1994 – 2002 monthly medians	-	**4.5**	**3.5**	**2.3**	**2.5**
Mann-Kendall significance level (α)		**0.02**	**0.21**	**0.09**	**0.31**

Note: Significance level is the probability of obtaining the observed data values if the null hypothesis (H0: There is no trend) is true. Low probability (i.e. rejection of H0) indicates a trend.

Figure Captions

Figure 1: Location map of Chain Lake

Figure 2: Bathymetric map of Chain Lake.

Figure 3: Schematic of Chain Lake withdrawal.

Figure 4: Daily average water temperatures in Chain Lake: (a) 1993, and (b) 1994

Figure 5: Chain Lake response to first year of operation.
(a) Secchi depth measurements, (b) chl<u>a</u> contours, and (c) total phosphorus contours.

Figure 6: Monthly Median Secchi readings, pre 1993 to 2002

Figure 7: Chl<u>a</u> vs. Total Phosphorus in surface water 1994.
The solid line represents a chl<u>a</u>:TP ratio of 1:2 (based on Ahlgren, 1988)

Figure 8: Performance of Fountain Aerator.
The aerator increases the DO concentration in the withdrawal water from the level inside - before release to the level outside outside after the plunge pool.

Figure 9: Dissolved Oxygen Levels in Hayes Creek during 1994.
(a) before withdrawal operation, (b) during operation w/ summer stratification, and (c) during operation after lake turnover.

Figure 10: Hayes Creek Total Phosphorus levels prior to (filled symbols) and during (open symbols) withdrawal operation

Figure 11: Times series of ammonia, iron, and manganese at the withdrawal fountain and at the Jellicoe Road station (1750 m downstream).
(a) ammonia, (b) total iron, and (c) total manganese.

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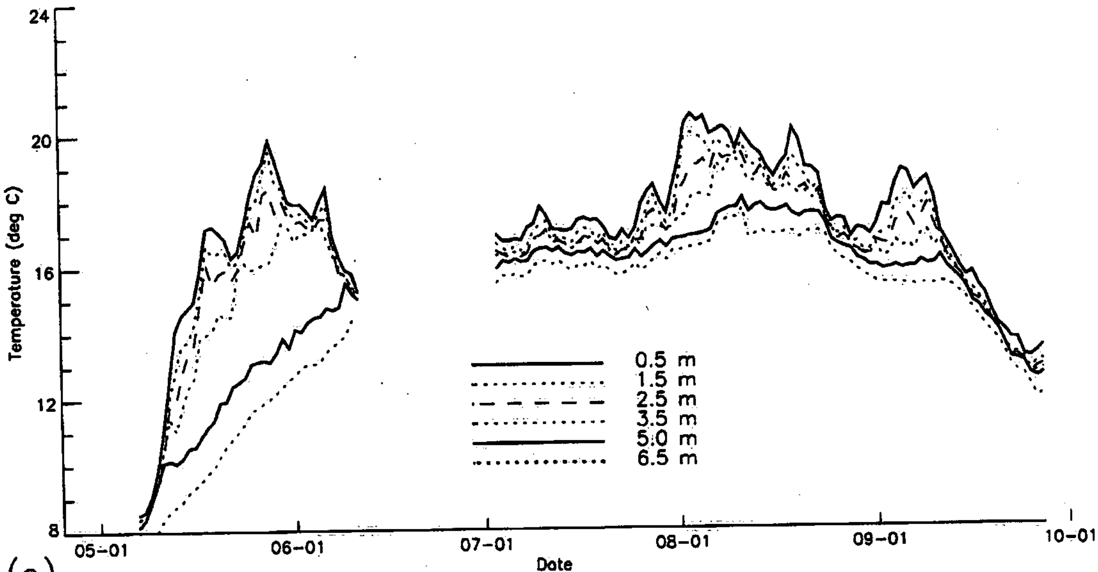
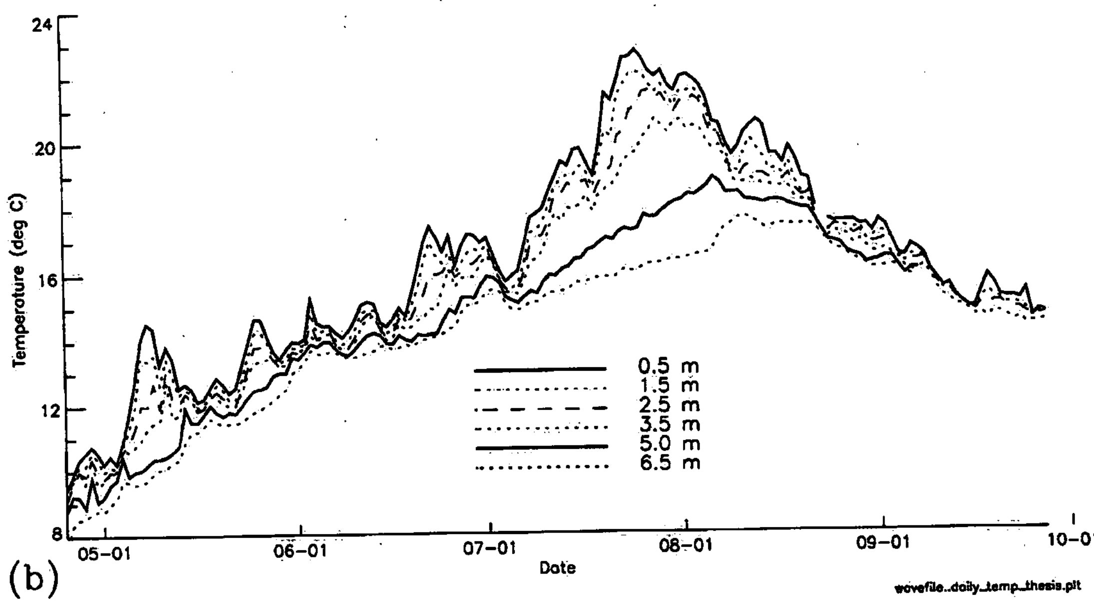


(a)



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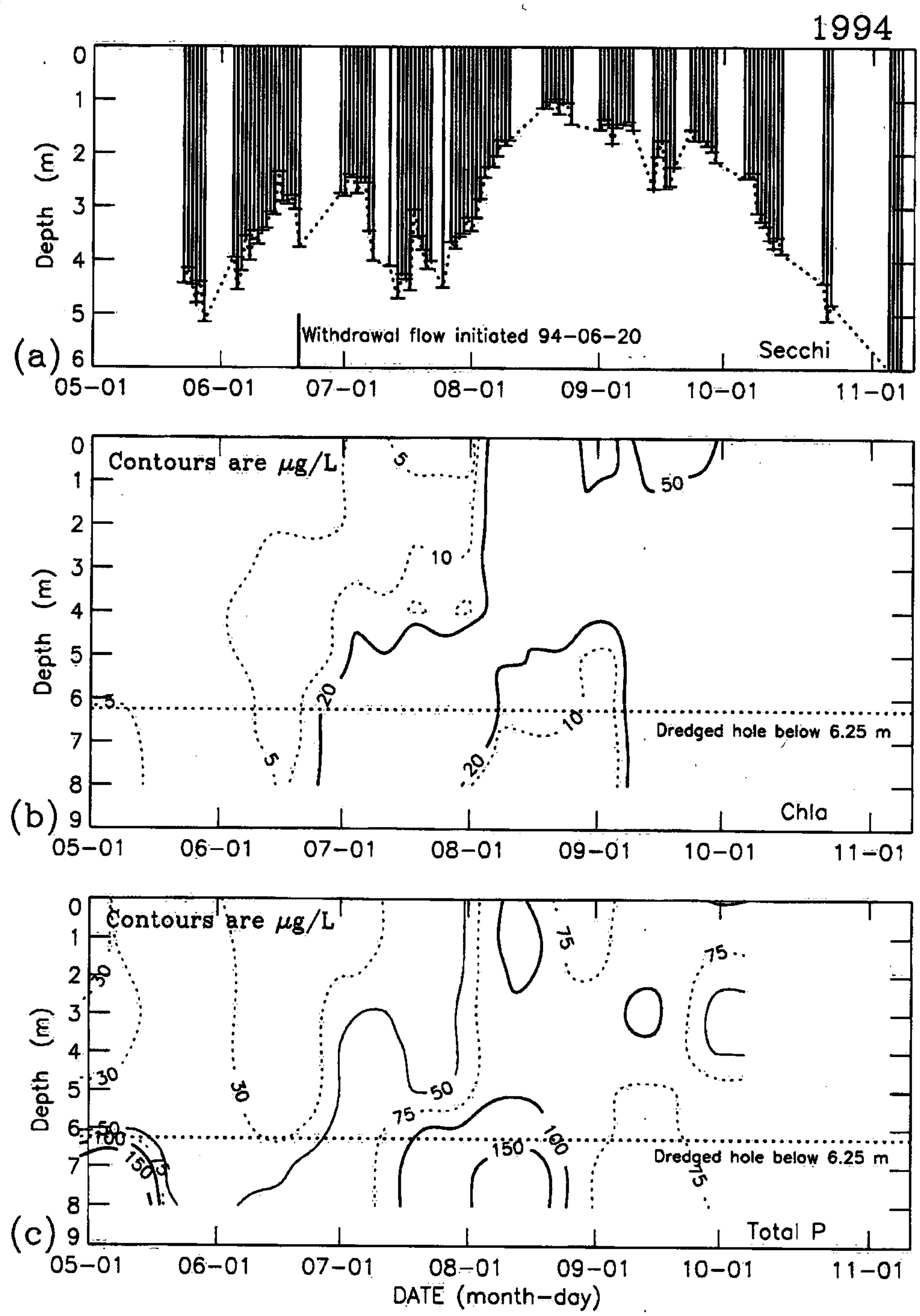

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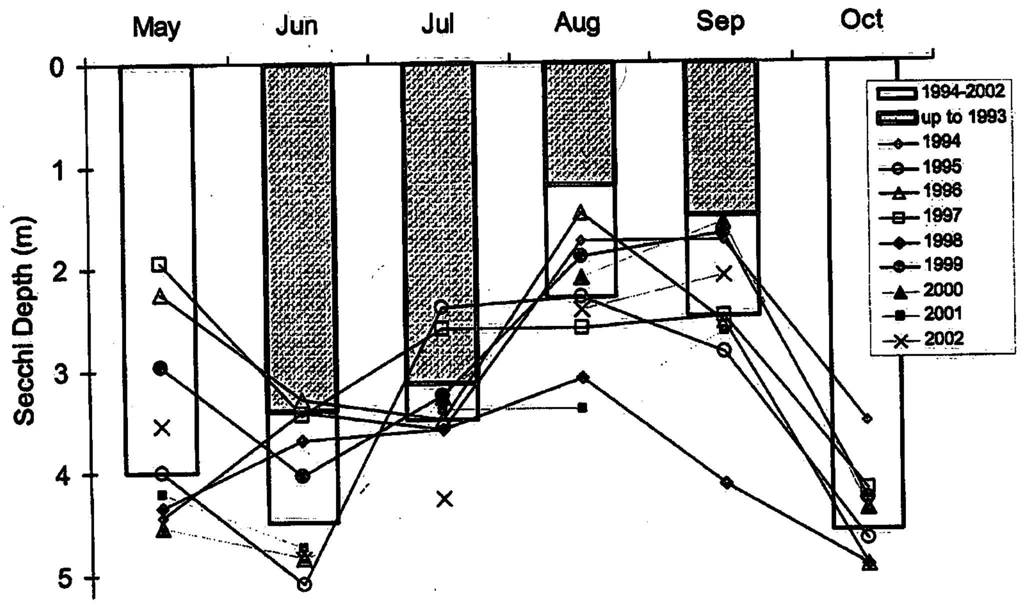

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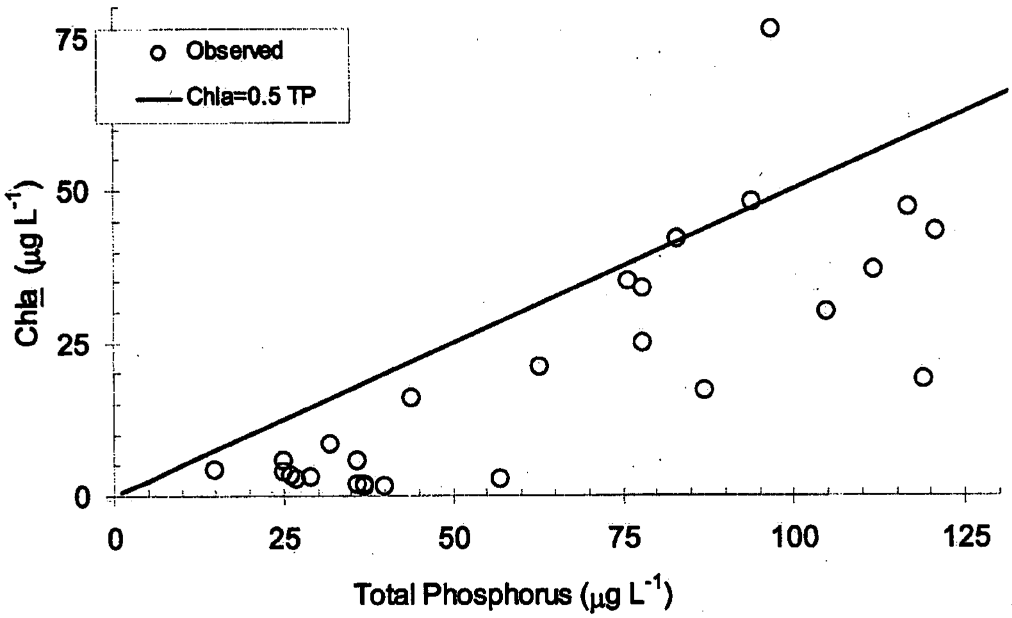

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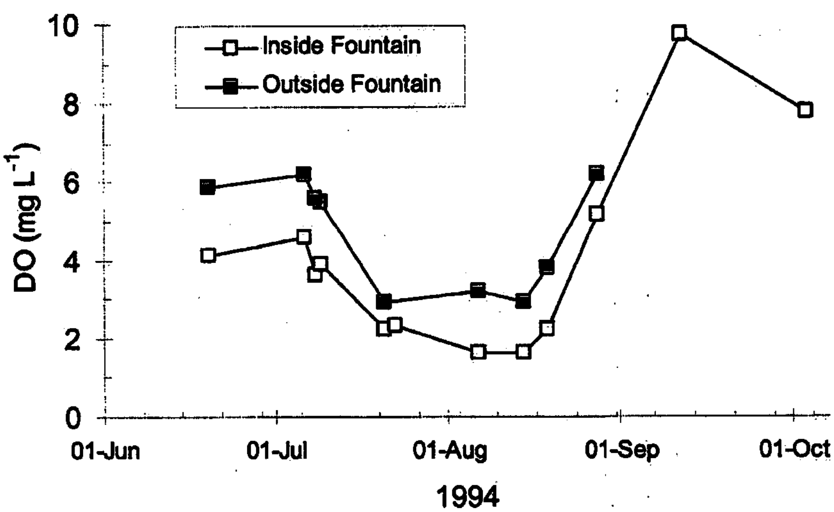

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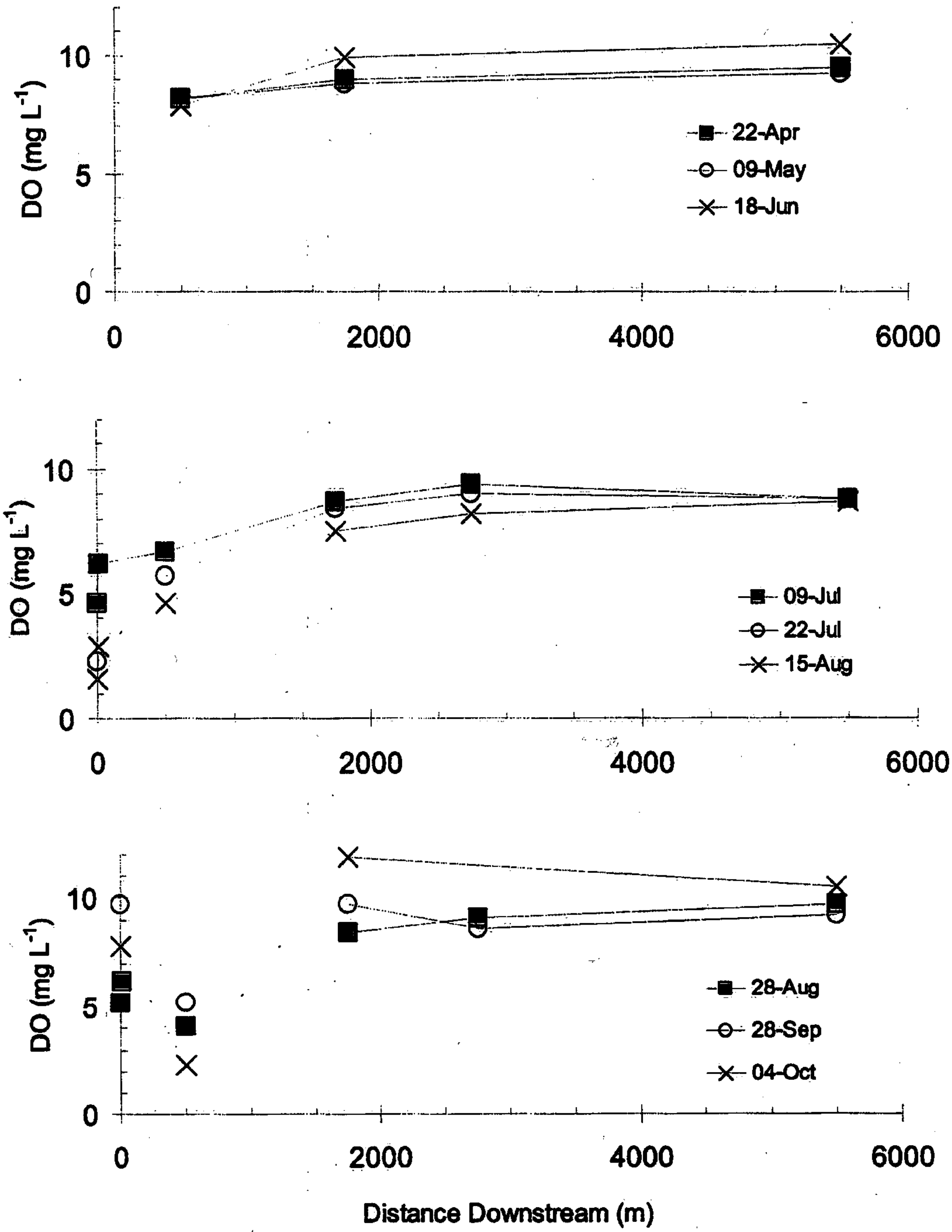

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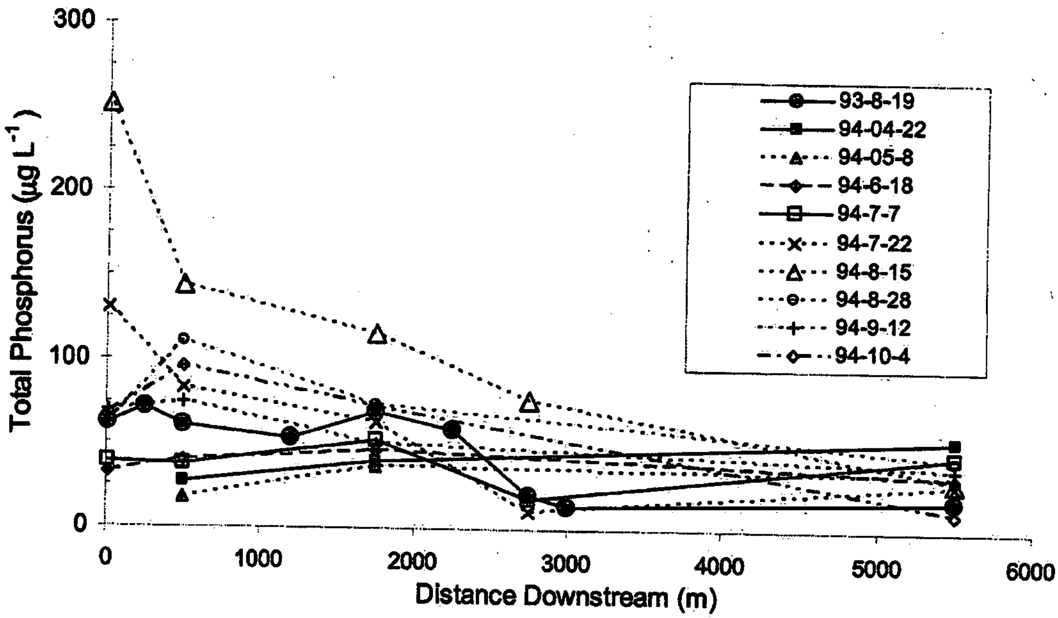

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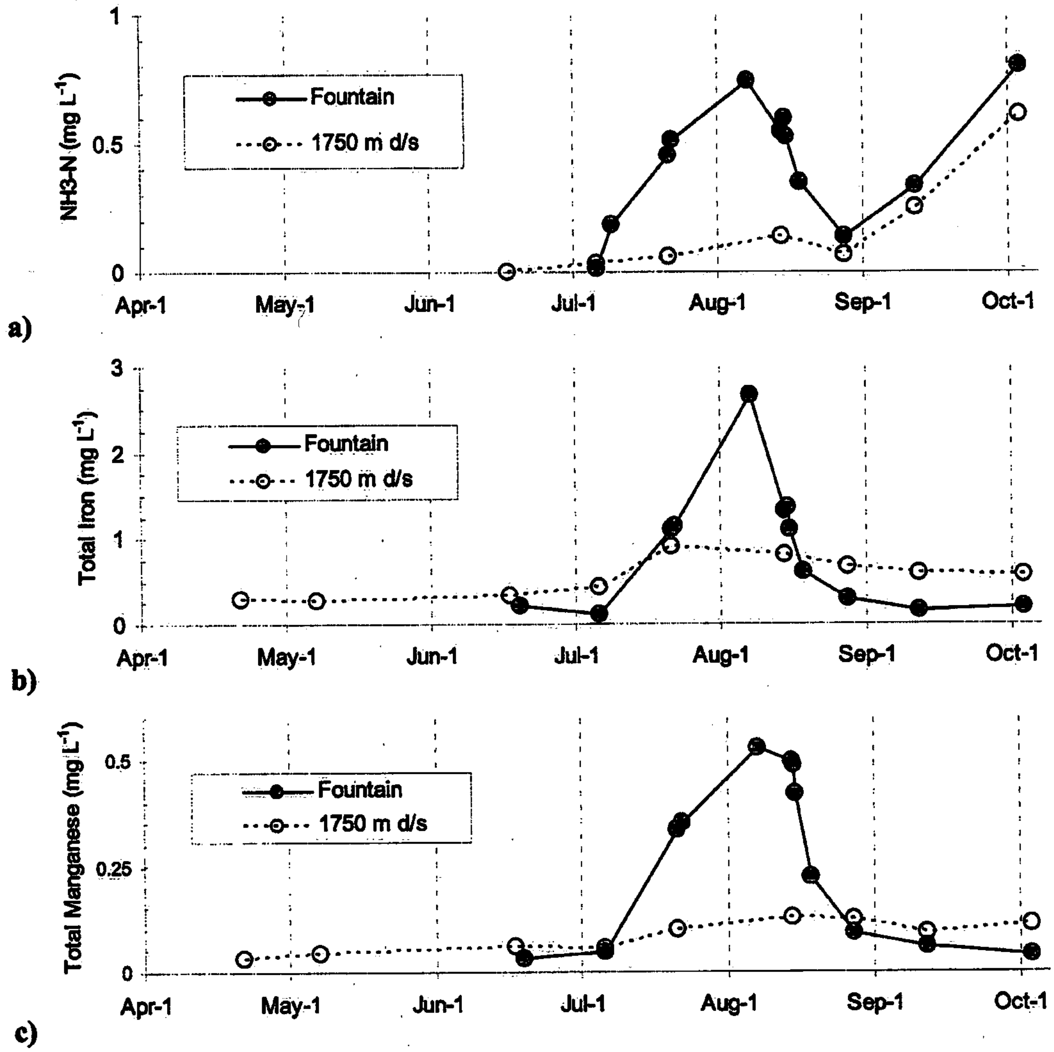

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