# DEVELOPMENT OF PREDICTIVE NUTRIENT-BASED WATER QUALITY MODELS FOR LAKE BELLAIRE AND CLAM LAKE

**Submitted to:**

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## EXECUTIVE SUMMARY

Great Lakes Environmental Center (GLEC) and Three Lakes Association (TLA) have cooperated in the development of a predictive nutrient-based water quality model for the Three Lakes System (Lake Bellaire and Clam Lake) located in Michigan's Antrim and County. This project was funded by a water quality monitoring grant from the Michigan Department of Environmental Quality (MDEQ). The primary goals of this project include: (1) the collection of data necessary to develop a mathematical model of water quality in the Three Lakes System; (2) model calibration and confirmation; and, (3) application of the model to address present water quality concerns and forecast future changes in water quality due to increased nutrient loadings associated with changing land uses and development. Lake Bellaire and Clam Lake have been the focus of monitoring and modeling. This project follows a previous effort to model the water quality of Torch Lake (Endicott et al., 2006) which was also conducted cooperatively by GLEC and TLA, and was funded by a grant from MDEQ to TLA.

Results from this project provide the Three Lakes Association and its decision-making partners with an objective tool for evaluating changes in nutrient loadings to expected short- and long-term changes in water quality in Lake Bellaire and Clam Lake. Specifically, this deliverable is intended to address the following questions:

$ What is the current (baseline) water quality in Lake Bellaire and Clam Lake, and how does it vary with season?

$ What are the current loadings of phosphorus (the nutrient limiting algal growth) to Lake Bellaire and Clam Lake from all sources, including tributaries, atmospheric deposition, groundwater, and direct point and non-point sources such as runoff, septic systems, and in-place (sediment) sources?

$ How will water quality in Lake Bellaire and Clam Lake be affected by changes in nutrient loadings?

$ How is water quality in the Three Lakes affected by water quality upstream in the Elk River Chain of Lakes?

$ What factors (other than phytoplankton) affect water transparency in Clam Lake and Lake Bellaire?

The water quality models for Lake Bellaire and Clam Lake are tools which can inform the decision-making process related to maintaining and preserving water quality in these Lakes, and eventually the entire Elk River Chain of Lakes Watershed. The Three Lakes Association expects that this tool will be used by local units of government, lake associations, property owners, developers and the general public interested in more effective management of water quality in Lake Bellaire and Clam Lake.

Field data collection was an important aspect of this project. Water quality sampling was conducted from July of 2004 through October of 2005. During that time, TLA sampled lake water, tributaries, precipitation, groundwater and lake sediment. 478 samples were analyzed by GLEC for phosphorus concentrations, and a significant number of these samples were analyzed for other water quality parameters, including dissolved phosphorus, chlorophyll-a, calcium and alkalinity. The resulting data present a complete description of water quality in Lake Bellaire and Clam Lake. The volume-weighted average (VWA) total phosphorus concentration in Lake Bellaire during 2006 was determined to be 3.7 parts per billion (ppb), while the VWA total phosphorus concentration in Clam Lake was 4.5 ppb. These averages, which are consistent with phosphorus concentrations measured in these lakes during the previous four years, are low in comparison to other lakes in northwestern lower Michigan. Chlorophyll-a concentrations were generally low, ranging from 0.85 to 2.1 ppb in Lake Bellaire and 0.62 to 3.7 ppb in Clam Lake. Dissolved oxygen (DO) concentrations were nearly saturated over winter and spring, but declined during late summer in the deep waters of both lakes. DO concentrations declined to below 5 parts per million (ppm) in the hypolimnion of Lake Bellaire during October in both 2005 and 2006. In Clam Lake, DO concentrations below 5 ppm were measured in July of 2005 and August of 2006. Water transparency was generally high in each lake, with Secchi disk depths in Lake Bellaire ranging from 6.1 meters (m) in May to 3.1 m in July. Secchi disk depths were about 0.6 m greater in Clam Lake. The summer decline in water transparency is observed in Lake Bellaire and Clam Lake each year, and appears to be the result of calcium carbonate precipitation, a naturally-occurring phenomenon in many lakes. We observed the same phenomenon in Torch Lake (Endicott et al. 2006), which was confirmed by subsequent investigations in that lake during 2006 (Homa and Chapra, 2007). Comparison of the project data to other recent monitoring data show little change in water quality over the past 5 years, but some improvements since the 1980s and 1990s.

The field data were used to construct a hydrologic (water) budget for Lake Bellaire and Clam Lake. Components of the hydrologic budget for the project year (November 2005-October 2006) are shown in Tables 1 and 2. To the degree that the water level of each lake remains essentially constant, the sources (tributary inflow; precipitation; and groundwater seepage) and sinks (outflow; evaporation) of water will balance one another. Tributary flows clearly dominate the hydrologic budget for both lakes. Based on the rates of outflow in Tables 1 and 2, the hydraulic residence time is calculated to be 219 days in Lake Bellaire and a very short 7.4 days in Clam Lake.

**Table 1. Hydrologic Budget for Lake Bellaire (November 2005 - October 2006)**

| Flow Component (inflows and outflows) | Flow (cubic foot[1] per second, cfs) | % of water source | % of water loss |
|---|---|---|---|
| Upper Intermediate River | 51 | 28 | |
| Cedar River | 107 | 58 | |
| Butler and Maury Creeks | 1 | 0.5 | |
| Precipitation | 6 | 3 | |
| Groundwater seepage | 20 | 11 | |
| Grass River outflow | 164 | | 95 |
| Evaporation | 9 | | 5 |
| Change in Storage | -2 | | |

Note: (1) 1 cubic foot = 7.5 gallons

**Table 2. Hydrologic Budget for Clam Lake (November 2005 - October 2006)**

| Flow Component (inflows and outflows) | Flow (cfs) | % of water source | % of water loss |
|---|---|---|---|
| Grass River | 164 | 68 | |
| Cold Creek | 29 | 12 | |
| Finch Creek | 36 | 15 | |
| Shanty Creek | 10 | 4 | |
| Precipitation | 1 | 0.5 | |
| Groundwater seepage | 0 | 0 | |
| Clam River outflow | 237 | | 98 |
| Evaporation | 4 | | 2 |

The data were also used to calculate mass balances for phosphorus in Lake Bellaire and Clam Lake, which were subsequently refined by modeling. Phosphorus is a water quality parameter of particular concern, because this nutrient controls the growth of phytoplankton (algae) in lakes. High inputs of phosphorus can lead to increased phytoplankton growth, which is in turn associated with a variety of water quality impairments (e.g., loss of water clarity, nuisance algae blooms, depletion of dissolved oxygen). Calculating the mass balance for phosphorus is the first step towards understanding how to manage this nutrient. In Lake Bellaire and Clam Lake, phosphorus inputs include loading from the major tributaries, inputs from precipitation and groundwater, and release of phosphorus from the lake sediments. Phosphorus losses include sedimentation (i.e., settling with particles and eventual burial in the lake sediments) and outflow. The phosphorus mass balances for the project year are shown in Tables 3 and 4. Tributary loading dominates the input of phosphorus to each lake. We included phosphorus loading from the Bellaire wastewater treatment plant (WWTP) to Lake Bellaire, although the plant effluent is discharged to a drainage field near the Intermediate River, so only a portion of this load is believed to enter the lake. On a lake-area basis, the phosphorus loading to Lake Bellaire is 0.27 $gP/m^2/yr$, and loading to Clam Lake is 0.96 $gP/m^2/yr$. These loadings exceed phosphorus limits recommended by Vollenweider (1968) for control of lake eutrophication.

Settling was by far the most significant phosphorus loss in Lake Bellaire. Of the total annual loading of phosphorus to Lake Bellaire, 79% is removed by settling. Settling was a less significant loss process in Clam Lake, where most of the phosphorus was lost with the lake outflow. Release of phosphorus from the sediments of each lake were roughly comparable (172 and 150 kg). In Clam Lake, the growth of extensive beds of macrophytes (rooted aquatic plants) was estimated to remove 24 kg of phosphorus from the water column.

**Table 3. Phosphorus mass balance for Lake Bellaire (November 2005 - October 2006)**

| Component | Loading or loss, kg/yr | % of P loading | % of P loss |
|---|---|---|---|
| Upper Intermediate River | 372 | 18 | |
| Cedar River | 1295 | 64 | |
| Butler and Maury Creeks | 12 | 1 | |
| Bellaire WWTP | 29 | 1 | |
| Atmospheric deposition | 125 | 6 | |
| Groundwater | 214 | 11 | |
| Sediment release | 172 | 8 | |
| Settling loss | 1609 | | 73 |
| Grass River outflow | 591 | | 27 |

**Table 4. Phosphorus mass balance for Clam Lake (November 2005 - October 2006)**

| Component | Loading or loss, kg/yr | % of P loading | % of P loss |
|---|---|---|---|
| Upper Grass River | 595 | 36 | |
| Cold Creek | 733 | 44 | |
| Finch Creek | 135 | 8 | |
| Shanty Creek | 34 | 2 | |
| Atmospheric deposition | 26 | 2 | |
| Groundwater | 0 | 0 | |
| Sediment release | 150 | 9 | |
| Settling loss | 630 | | 38 |
| Torch River outflow | 1014 | | 61 |
| Macrophyte uptake | 24 | | 1 |

Phosphorus-based predictive water quality models were developed for Lake Bellaire and Clam Lake using the Lake2K-Lite framework. Lake2K-Lite simulates the seasonal and long-term dynamics for a number of significant water quality parameters (including flow, temperature, light, nutrients, dissolved oxygen, the planktonic food chain and calcium carbonate formation) in a seasonally-stratified lake. The model was calibrated and confirmed using data from the project and other data collected in 2003 through 2005. Lake2K-Lite is a development version of LAKE2K (Chapra, 2003), and was graciously provided to TLA and GLEC for use on this project by Dr. Stephen Chapra of Tufts University. Model parameters were adjusted within the ranges recommended by Chapra (1997), Bowie et al. (1985), and Manhattan College (1996). Settling rates for all particulate nutrients were specified according to fluxes measured in sediment traps. The model predictions of temperature, dissolved oxygen, total phosphorus, chlorophyll and Secchi depth were judged to be acceptable in comparison to data for 2003-2006.

A number of simple tests were conducted with the models, to illustrate the expected water quality responses to changes in phosphorus loadings. These tests demonstrated that:

$ Water quality in Lake Bellaire and Clam Lake, including phosphorus and chlorophyll-a concentrations, DO and Secchi depth, is not expected to change if loadings remain at their current levels; efforts to prevent or minimize future increases in phosphorus loadings are expected to maintain the present lake water quality.

$ Total phosphorus concentrations in the surface layers of each lake vary in proportion to changes in the total phosphorus loading to lake. Peak chlorophyll-a concentrations in the surface layers of each lake are more sensitive to phosphorus loading changes, while minimum DO concentrations in the deep lake layers and Secchi depth are much less sensitive;

- $ Water quality is predicted to change rapidly (within a year in Lake Bellaire, and much more rapidly in Clam Lake) in response to changes in loading: less than a year in Lake Bellaire and days to weeks in Clam Lake.
- $ Other factors including sediment fluxes, zooplankton grazing, organic carbon loading and calcite formation, were demonstrated to affect specific water quality parameters.

Although nutrient loadings to the Three Lakes were estimated based upon monitoring, such estimates cannot be related directly to land use in the watershed. A watershed modeling approach was developed and applied to address this critical linkage in the Three Lakes watershed (Moskus et al., 2007). The watershed model was applied to predict current and future watershed phosphorus loads to each of the lakes for a number of scenarios intended to represent realistic population growth and development. Changes in phosphorus loadings to each of the Three Lakes were calculated with the watershed model for developments in Alden and Shanty Creek. The changes in phosphorus loading predicted by the watershed model for each of the scenarios were used in conjunction with the water quality models to simulate the expected water quality response to the loading changes. These results illustrate that the models are capable of forecasting water quality changes to evaluate the impacts of development and land use changes.

There are a number of caveats and limitations that should be kept in mind when considering the accuracy of model results. These include:

- $ These forecast results do not convey the uncertainty in the predictions due to errors in either the model structure or the calibrated parameters;
- $ The forecasts assume that future forcing functions (e.g., meteorology, tributary flows, settling fluxes) can be reasonably extrapolated from prior data.
- $ The models simulate water quality as whole-lake average concentrations. Any horizontal gradients in water quality will not be resolved in Lake2K-Lite. In fact, the data for both lakes suggest that total phosphorus concentrations tend to be higher in shallow, nearshore water than at the deep-water stations.
- $ Because the model simulates lake-wide average water quality, no discernable changes in water quality are predicted for phosphorus loading changes smaller than about 50 kg/y. Therefore, it is not appropriate to use the model to forecast water quality for scenarios involving smaller changes in loading, even though localized water quality impacts are possible.

Despite these shortcomings, we believe that the Lake Bellaire and Clam Lake models, in conjunction with the watershed model, are useful tools to address water quality management questions. To remain useful, the water quality model needs to be updated periodically; TLA should conduct additional model confirmation as data become available from surveillance monitoring. This should include monitoring of DO concentrations in Lake Bellaire, which reach low levels near the lake bottom at the end of each summer. Other recommendations are offered in the Conclusions and Recommendations section.

# INTRODUCTION

The Three Lakes (Bellaire, Clam and Torch) are part of the Elk River Chain of Lakes, an outstanding natural resource in northern lower Michigan. This 500 square mile watershed contributes 60% of the water entering Grand Traverse Bay. Lake Bellaire is fairly shallow, has moderate nutrient levels, and receives drainage from Intermediate Lake, Cedar River, and a relatively large watershed. Clam Lake is extremely shallow and because its length exceeds its width by many times, it resembles a wide river in character. Clam Lake acts as a connector between Lake Bellaire and Torch Lake. Torch Lake is by far the largest of the Three Lakes; it is long and deep, with excellent water quality. Despite the differences in size among the Three Lakes, the drainage basins for each lake (Figure 1) are approximately equal. Lake dimensions are summarized in Table 5.

**Table 5. Dimensions of the Three Lakes**

| Lake | Length | Surface Area | Average Depth | Volume | Watershed Area |
|---|---|---|---|---|---|
| Bellaire | 7.2 km | 757 hectares[1] (ha) | 12.3 m | $9.3x10^{+7}$ $m^3$ | 11,100 ha |
| Clam | 5.6 km | 158 ha | 2.5 m | $4.3x10^{+6}$ $m^3$ | 9,350 ha |
| Torch | 29 km | 7,400 ha | 43.3 m | $3.2x10^{+9}$ $m^3$ | 11,600 ha |

Notes: (1) 1 hectare = 2.47 acres

Land use in the Chain of Lakes watershed is shown the Figure 2. The project study area is predominantly undeveloped with the majority of land being forested or used for agricultural uses (cropland and pasture). Approximately 7% of the study area is developed. Current land use is tabulated in Table 6.

**Table 6. Current land use distribution in the Three Lake watershed**

| Land Use | Lake Bellaire Watershed | Clam Lake Watershed | Torch Lake Watershed |
|---|---|---|---|
| Forest | 69% | 71% | 65% |
| Pasture | 10% | 9% | 7% |
| Cropland | 8% | 11% | 16% |
| Low density development | 6% | 4% | 9% |
| Golf course | 4% | 2% | 1% |
| Wetland | 2% | 2% | 2% |
| High density development | 1% | 0% | 0% |

Within the Three Lakes watershed, 15% of the developed land is currently serviced by sewer. This percentage varies considerably between watersheds. Thirty-seven percent of developed land in the Lake Bellaire watershed is serviced by sewer and 19% of development is served by sewer in the Clam Lake watershed. Developments in the Torch Lake watershed are all on septic systems. There are three wastewater treatment plants (WWTPs) in the study area (Schuss Mountain Resort, Summit Village and the Bellaire wastewater treatment plant). Each WWTP treats the wastewater (including phosphorus removal) and then discharges the treated effluent to drain fields

Maintaining and preserving water quality in the Three Lakes is a long-standing goal of TLA, residents and other interest groups. Given trends in regional land use, it appears that the greatest immediate threat to the water quality of Lake Bellaire and Clam Lake is nutrient enrichment due to increased population and associated development, which tends to be concentrated near the lakes. Between 1964 and 2004, the population of Antrim County grew by 75%, and is projected to grow by another 33% by 2020. According to the Michigan Society of Planning Officials (MSPO, 1995), the northern lower peninsula of Michigan will continue to experience gains in population with a large portion coming from in-migration.

Information regarding the current status of water quality in Lake Bellaire and Clam Lake was limited prior to this project. A study of water quality in Lake Bellaire was conducted in 1982 by TLA and the Institute for Water Quality Research (Canale et al. 1982). Water transparency, temperature, dissolved oxygen (DO), total phosphorus and chlorides were measured at 4 lake stations from July through October. Secchi depths decreased through the summer to levels of less than 3 m in mid-August, then increased significantly at all lake stations by late fall. Temperature profiles indicated strong vertical stratification at the three deep water monitoring stations. Phosphorus concentrations ranged from 5.5 to 17.5 parts per billion (ppb); concentrations at the lake surface were generally 1 to 3 ppb lower than phosphorus concentrations at the lake bottom. Overall, Lake Bellaire was categorized as mesotrophic (moderately nutrient enriched) based on phosphorus concentrations. Phosphorus concentrations measured in tributaries were generally lower than lake concentrations, which is the opposite of what is usually observed. Dissolved oxygen concentrations near the bottom of the deepest station dropped to below 3 mg/L from August 11 through the end of the study (October 27), and were below 1 mg/L for a period of over 40 days. The low DO concentrations at the deepest station (and to a lesser extent at the other 2 deep water stations) were considered to be significant because they are lower than water quality standards set be the State of Michigan for preserving aquatic life. The DO concentrations observed in the 1982 Lake Bellaire study were low enough to hamper the development and stability of a balanced aquatic ecosystem. It was also noted that low DO concentrations promote the release of phosphorus from the lake bottom sediments, and that a strong correlation was observed in the lake-bottom data between the decrease in DO and an increase in phosphorus concentrations.

Water quality data for Lake Bellaire and Clam Lake are also available from monitoring conducted by the Tip of the Mitt (TOM) Watershed Center. TOM has collected data for pH and concentrations of total phosphorus and dissolved oxygen in these lakes periodically since 1992. Total phosphorus data, plotted in Figure 3, suggest that concentrations of this nutrient have declined through the 1990s in both lakes. The dissolved oxygen data (Figure 4) show that summertime depletion of dissolved oxygen near the bottom Lake Bellaire is a persistent problem. TOM also collected chlorophyll-a concentrations and Secchi depths in 2003 (these data are presented with the model calibrations).

Looking toward the future, it is not clear how current and anticipated development pressures will impact water quality in each of the lakes. This project was conducted to address this lack of information and understanding, as a basis for more effective management of water quality in Lake Bellaire and Clam Lake. In addition, this project also provides a framework to integrate information gained from other efforts (e.g., surveys of septic system performance; proposals to centralize wastewater treatment; and land use planning). The ultimate goal of water quality modeling for the Elk River Chain of Lakes is to protect the entire watershed while encouraging managed economic growth in Antrim County.

This project developed water quality models for Lake Bellaire and Clam Lake to simulate current conditions and forecast future trends. We intended to address a number of water quality concerns expressed by TLA members:

- $ Increasing phosphorus loadings and concentrations due to population growth and development, and associated nonpoint sources (from septic systems, lawn fertilization, runoff, etc.)
- $ Increased concentrations of phytoplankton as a result of nutrient enrichment
- $ Decline and fluctuation in water clarity
- • Maintaining dissolved oxygen and the cold water fishery

The project combined a comprehensive water quality monitoring program with a modeling approach designed to address the water quality issues of concern. The monitoring/modeling approach is well-accepted as “state of the art” in terms of assessing and evaluating water quality, and develops a scientifically-defensible tool to predict how changes in nutrient mass loadings will affect water quality.

A water quality model is a mathematical description of a body of water, which simulates how water quality responds to factors such as flows and mass loadings. *A model is a simplified version of reality that can be tested* (Chapra, 1997). A water quality model is based on applying principles such as mass, momentum and energy conservation. Simple examples include the water balance and phosphorus mass balances for the lake:

**<u>Water Balance</u>:**
**Change in water storage = tributary inflow - outflow**
**+ groundwater seepage + precipitation – evaporation**

**<u>Phosphorus mass balance:</u>**
**Change in Total Phosphorus (TP) mass**
**= Mass loading (tributaries + groundwater + precipitation)**
**- Settling - Outflow ± Sediment flux**

Water quality models can be useful, in a number of ways, to those interested in protecting and managing water quality. They can help assess the current water quality status of a water body, because they provide a framework to integrate different information, including hydrology, pollutant sources and inventories, transport, transformations and losses, and relationships between different water quality parameters. They also provide paradigms for understanding how and why water quality responds to external and internal factors. If properly calibrated and confirmed to site-specific data, they can also be applied to forecast expected changes in water quality; for example, testing alternative population growth, land use, or waste management scenarios. Each of these applications can offer an improved understanding of water quality resources, and help prevent surprises.

Many of the water quality issues facing the Three Lakes are related to land use in the watershed. Changes in land use, in the form of development pressure from a growing population, increase pollutant (including nutrient) loading to surface waters. Although nutrient loadings to the Three Lakes were estimated based upon monitoring in this project, such estimates cannot be related directly to land use in the watershed. For this reason, a watershed modeling approach was developed and applied to address the critical linkage between land use and pollutant loading in the Three Lakes watershed. The watershed model was developed by Limno-Tech (LTI; Moskus et al., 2007) to predict watershed phosphorus loads to each of the lakes as a function of land use in each lake's watershed.

# FIELD DATA COLLECTION AND ANALYSES

Modeling water quality is a data-intensive endeavor. Therefore, field data collection was an important aspect of this project. This section identifies the information that was needed to build water quality models for Lake Bellaire and Clam Lake, and describes the data collection that was carried out by TLA and GLEC to meet these needs.

An understanding of water resources begins with hydrology. This includes the annual cycles of tributary inflows and outflows, flow rates between the lakes, precipitation and evaporation, and seepage from groundwater. This information was collected during 2005 and 2006, and was used to calculate water balances for Lake Bellaire and Clam Lake. The flow data were also combined with nutrient concentration measurements to estimate the mass fluxes entering and leaving the lake. These were used to calculate a mass balance for phosphorus, the critical nutrient in freshwater lakes. Calculating the phosphorus mass balance is the first step towards understanding how to manage this nutrient. Therefore, two principal objectives of the field sampling and analyses were to construct hydrologic and nutrient mass budgets for Lake Bellaire and Clam Lake.

Our goal was to develop water quality models for each lake that would predict the response of water quality to changes in external loadings. Again, data play essential roles in the model development process. Water quality parameters were measured in order to both calibrate (tune) and confirm (test) the water quality model. These measurements included the significant variations in water quality with season, depth, and location in Lake Bellaire and Clam Lake. Because our objectives included modeling long-term changes in water quality, we included other monitoring data collected over the past half-decade by organizations such as the USGS, Tip of the Mitt Watershed Center, as well as TLA's own long-term monitoring, in the confirmation process.

## Site Map, Sampling Locations and Bathymetry

A map of the various monitoring and sampling points described in this Section is provided in Figure 5. The major tributary flows entering Lake Bellaire include the Intermediate Lake outflow to the upper Intermediate River and the Cedar River, which joins the Intermediate River above the dam in Bellaire. The outflow from Lake Bellaire enters the upper Grass River, which also receives flow from Shanty, Cold and Finch Creeks before entering Clam Lake. Clam Lake is connected to Torch Lake by the very short Clam River.

Bathymetric data was digitized from depth soundings and contours plotted on charts of Lake Bellaire and Clam Lake (Mapping Unlimited, 2000). These data were interpolated to create volumetric models, which were then used to determine the depth, area and volume properties presented in Table 3. The volumetric model was also used to develop the elevation-surface area and elevation-volume curves required to describe the lake bathymetry to the water quality model.

## Meteorology

Observations for a number of meteorological parameters are required for water balance and heat flux calculations: air temperature and dew point, wind speed, solar radiation, and precipitation. Hourly data were obtained from three Michigan Automated Weather Network (MAWN) stations located in Elk Rapids, Kewadin, and Eastport. Nearly continuously observations were available from one or more of these stations, beginning in May of 2003. Data were processed by daily averaging and, when available from more than one station, Thiessen weighting was applied to calculate lake-wide values.

## Flow Monitoring

### Tributary and Inlet/Outlet Flows

Tributaries were expected to be major components of flow in the hydrologic budget for Lake Bellaire and Clam Lake. Unfortunately, no routine monitoring of flows is conducted in the Chain of Lakes. Flow rates were measured on 8 tributaries flowing into Lake Bellaire and Clam Lake, as well as the connecting channels (Intermediate, Grass and Clam Rivers) between the lakes. Flow measurement locations are identified in Table 7 and located on Figure 5. Flows were measured by a TLA team employing a current meter, according to USGS methods. On several smaller tributaries (Butler and Little Butler Creeks, Maury Creek) the flow was too shallow and/or slow for use of a current meter, so time-of-travel of a floating object was used to measure flow rates.

Water level elevations were also monitored on the major tributaries, for use in conjunction with stage-discharge relationships to estimate flows. On four of the largest tributaries (Intermediate River at the Bellaire bridge, Cedar River, Grass River and Cold Creek) automated water level recorders were deployed. These instruments provided hourly water level data, which was especially important during large rainfall events, during which rapid changes in water levels and flows took place. In addition, water level elevations were monitored on each of the Three Lakes.

**Table 7. Tributary Flow Measurement Locations**

| Tributary | Label (Figure 5) | Description |
|---|---|---|
| Intermediate River | upper Intermediate River | downstream from Intermediate Lake |
| | Intermediate River (Bellaire) | below dam at the Bellaire bridge |
| Cedar River | | at Burrel Road crossing |
| Butler Creek | | |
| Little Butler Creek | (not shown in Figure 5) | East of Butler Creek |
| Maury Creek | | |
| Grass River | upper Grass River | downstream from Lake Bellaire |
| | lower Grass River | at Grass River Nature Area (GRNA) dock |
| Shanty Creek | | |
| Clod Creek | | at Alden Highway crossing |
| Finch Creek | | at Alden Highway crossing |
| Finch Creek (west branch) | (not shown in Figure 5) | Enters Clam Lake downstream from GRNA dock |
| Clam River | | at Dockside |

<u>Shallow Groundwater Flow</u>

Groundwater seepage was believed to be an important contributor of flow and possibly nutrients to Lake Bellaire and Clam Lake, based on our experience monitoring groundwater in Torch Lake (Bretz et al., 2005). Throughout northern lower Michigan, including the TLA region, the surficial aquifer system is hydraulically connected to streams and rivers because of its shallow depth, ease of recharge by precipitation, and short groundwater flow systems. The region's lakes are also generally an extension of the water table in the surrounding surficial aquifer system.

To monitor shallow groundwater flows and nutrient fluxes, a network of 8 shallow (3-10' deep) wells or piezometers were installed around Lake Bellaire and Clam Lake. Each piezometer was hammered into place several feet offshore in shallow (2-3' deep) water, and a ¼" plastic tube was installed to allow sampling and measure piezometric head. The wells were placed more or less uniformly around the lake, as shown by the locations on Figure 5. The piezometers were monitored in May, July and September of 2006. Hydraulic conductivity, the hydrostatic pressure gradient, and groundwater flow rates were measured using methods described by Hvorslev (1949), Welsh and Lee (1989), and summarized in Lamb and Whitman (1969). Groundwater samples were collected from each piezometer using a peristaltic pump. Samples of lake water were collected at the same time and location as each piezometer sample.

## Water Quality Sampling and Analysis

TLA volunteers collected samples and other water quality information from Lake Bellaire and Clam Lake and their tributaries, precipitation, groundwater, and settling solids and sediment. Sampling was conducted from July of 2005 through October of 2006, with the major sampling effort taking place during the 2006 April-October field season. This section describes the various components of the sampling effort.

### Tributary Sampling

Tributaries are a potentially significant source of nutrients to each of the lakes. Water samples were collected from the major tributaries, generally at the same time that flow measurements were taken. Samples were collected at mid-channel and mid-depth from tributaries by hand, using a pre-cleaned and rinsed Erlenmeyer flask. Tributary samples were then iced and transported to GLEC's Traverse City laboratory for total phosphorus analysis.

Automated samplers were deployed on two of the major tributaries (Cedar River and Cold Creek) to collect a series of water samples during high flow events. These samples were needed to calculate tributary loadings during periods of high flows, which are often associated with elevated phosphorus concentrations. As a consequence, tributary phosphorus loadings during high flow may be disproportionately large in comparison to loadings during base flow.

### Precipitation Sampling

Atmospheric deposition was also expected to be a contributor of phosphorus to Lake Bellaire and Clam Lake. Wet deposition of phosphorus was measured by collecting rain samples from two locations near Bellaire. Rain samples were collected from individual events using a sampler consisting of a 12" polypropylene funnel atop a pre-cleaned Erlenmeyer flask. Samplers were manually deployed at the start of a precipitation event. Rain samples were removed from the flask within 8 hours, acidified and held at 4 °C until analysis. Rain samples were collected between May and September of 2006.

Dry deposition is also known to be an important atmospheric flux pathway for phosphorus. Unfortunately, the dry deposition flux is very difficult to measure. All of the available, scientifically-defensible methods of monitoring dry deposition were prohibitively expensive for this project and were therefore not pursued.

### Lake Sampling

Water samples were collected from Lake Bellaire and Clam Lake at deep-water stations in each lake (Figure 5). The Lake Bellaire station is located near the center of the lake, in approximately 30 meters of water. The Clam Lake station is located near the western end of that lake, in 8 meters of water. The lakes were sampled in 2006 from

April through October, with sampling every other week from June thru August. The sampling schedule was intended to capture the expected seasonal variation in water quality parameters related to thermal stratification, nutrient loading, plankton productivity, and oxygen-demanding processes. Water quality parameters related to these processes vary significantly through the spring, summer and fall.

TLA volunteers followed a consistent lake sampling protocol throughout the project. A HydroLab sensor was initially lowered into the lake to obtain vertical profiles of pH, temperature, dissolved oxygen and conductivity. The Secchi disk depth was also measured. Discrete water samples were collected from multiple depths at each station (Table 8). Samples from each lake layer were composited in the laboratory prior to TP analysis. Surface layer (epilimnion) samples were composited for chlorophyll-a, dissolved (field filtered) phosphorus, calcium and alkalinity. Middle layer (metalimnion) samples were composited for chlorophyll-a and dissolved phosphorus. Duplicate samples were collected at a 10% rate.

**Table 8. Lake Bellaire and Clam Lake water sampling depths**

| lake | layer | depth (m) |
|---|---|---|
| L. Bellaire | surface | 0.6 |
| | | 1.2 |
| | | 1.8 |
| | | 2.4 |
| | | 3.0 |
| | middle | 4.6 |
| | | 7.6 |
| | | 11 |
| | deep | 15 |
| | | 21 |
| | | 27 |
| Clam L. | surface | 0.6 |
| | | 1.2 |
| | | 1.8 |
| | | 2.7 |
| | middle | 3.7 |
| | | 4.9 |
| | | 6.1 |
| | deep | 6.7 |

**Sediment Sampling**

Sediment cores were collected in Lake Bellaire and Clam Lake by the Central Michigan University Water Research Center, in order to characterize the physical-chemical properties of the sediments and to determine the magnitude of internal phosphorus-release and sediment oxygen demand (SOD). These data were used to estimating the flux of phosphorus released from the lake sediments if dissolved oxygen concentrations were depleted near the lake bottom (Holmes and McNaught, 2005).

**Sediment Traps**

Four-inch diameter cylindrical sediment traps were deployed in Lake Bellaire near the water sampling station from June thru October of 2006. The traps, which were loaned to GLEC by the National Atmospheric and Oceanographic Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL), capture particulate matter as it settles through the water column and collect this material in a sample bottle. The sediment traps were deployed in duplicate at a depth of 24 meters. This depth corresponds to the base of the thermocline, where the flux of particulate matter settling out of the photic zone can be determined most unambiguously (B. Eadie, personal communication).The traps were retrieved at the end of the field season, and the particulate matter they collected was removed and analyzed for dry mass and total phosphorus concentrations. The sediment trap data was used to calculate the settling flux of phosphorus, a major loss mechanism for phosphorus in lakes. It was not possible to deploy a sediment trap in Clam Lake, due to it's shallow depth.

**Phytoplankton and Zooplankton Sampling**

Phytoplankton and zooplankton samples were collected monthly from June through September in Lake Bellaire, for microscopic analysis to determine cell counts for each of the functional groups. The phytoplankton samples were composited from the surface layer of the lake. Zooplankton samples were collected by raising a plankton net from near the bottom of the lake to the surface.

**Macrophyte Sampling**

Macrophytes (rooted aquatic plants) grow abundantly in shallow regions of eastern Clam Lake, potentially removing a significant amount of phosphorus from the lake water. To address this loss, TLA conducted macrophyte surveys in Clam Lake during June and September of 2006. For each survey, three transects were established from the north shore of the lake. Along each transect, sampling locations were defined at 8, 15, 23 and 30 meter distances from shore. At each sampling location, a SCUBA diver harvested all plant material from a $0.1m^2$ area. The plant material from each location was placed in a mesh bag, and iced for transport to the lab. The plant samples were cleaned and dried prior to weighting and nutrient analyses. "Cleaning" primarily consisted of removing many small (2-5mm) zebra mussels from the majority of the plant samples.

## Sample Analyses

All analyses were performed by GLEC personnel at the Traverse City, Michigan laboratory, unless otherwise noted below. The GLEC laboratory has an outstanding record for analytical data quality, particularly for low-level concentrations of phosphorus. Table 9 identifies the analytes which were measured in lake water, tributary, precipitation, groundwater and sediment trap samples.

Due to the special requirements of this project, GLEC successfully lowered its detection and reporting limits for total phosphorus analysis (Endicott et al., 2006). The resulting method detection limit (MDL) was calculated to be 0.153 ppb. GLEC's low-level phosphorus analysis also passed a proficiency test conducted by the Canadian Center for Inland Waters (CCIW).

Sediment samples were analyzed by the Central Michigan University Water Research Center (Mt. Pleasant, MI). Phytoplankton and zooplankton samples were counted for functional groups by Phycotech, Inc. (St. Joseph, Michigan). Dried and homogenized macrophyte samples were analyzed for nutrient composition by A & L Great Lakes Laboratories (Fort Wayne, Indiana).

**Table 9. Identification of water quality parameters analyzed in Lake Bellaire and Clam Lake samples**

| Parameter | Water column profiles | Lake samples | Tributaries, groundwater and precipitation | Sediment |
|---|---|---|---|---|
| Temperature | x | | | |
| pH | x | | | |
| Dissolved Oxygen | x | | | |
| Conductivity | x | | | |
| Secchi disk depth | x | | | |
| Total Phosphorus | | x | x | x |
| Dissolved Phosphorus | | x | x | |
| Chlorophyll a | | x | | |
| Calcium | | x | | |
| Alkalinity | | x | | |

# ANALYSIS OF FIELD DATA

## Introduction

This section presents the results of the Lake Bellaire and Clam Lake sampling efforts described in the previous section and explains what was done to analyze and interpret this information. The data were used to perform a number of important tasks, including:

$ Estimating flows and phosphorus loadings (the product of flow and concentration) from tributaries, groundwater and precipitation,
$ Calculating the water balance and the phosphorus mass balance,
$ Reducing data for comparability with model input and predictions,
$ Determining spatial and temporal trends in the water quality data, and
$ Comparing project data to longer-term monitoring data.

## Hydrology

### Climatic Data

Lake-wide, daily average meteorological data were derived from the MAWN observations from 2003 though 2006. These data included forcing functions for the heat flux, vertical mixing, and gas exchange calculations within the water quality model. They were also used to compute the rates of precipitation and evaporation for each lake, which were component of the water balance.

Ice cover data was obtained from several sources, including residents of each lake who observe and record dates of ice formation and break-up. Ice generally forms on Lake Bellaire around January 1; ice usually forms on Clam Lake a week earlier. The ice on Clam Lake breaks up around April 1. The date of ice break-up on Lake Bellaire is more variable, and has ranged from March 30 to April 15 over the last four winters. The observers also noted that in some years, the ice did not cover the center of Lake Bellaire.

### Evaporation and Precipitation

Lake Bellaire and Clam Lake evaporation rates were calculated from the lake-wide meteorological data, using a standard engineering estimate of the conduction/convection flux and Dalton's law (Chapra, 2003). The resulting evaporation rates, averaged on a monthly basis, show strong seasonal variability as shown in Figure 6. The calculated evaporation rates are low in spring, increase rapidly through the summer months, decline slowly in fall and then drop rapidly as winter begins.

The evaporation rates are also compared to precipitation in Figure 6. Over the 12 month project period (November 2005-October 2006), evaporation (29.0 inches) significantly exceeded precipitation (22.8 inches). Such an imbalance is unusual, as an annual balance between precipitation and evaporation is expected for lakes in the Great Lakes region.

Tributary and Inlet/Outlet Flows

The tributary flow rates measured by TLA are presented in Table 10. This table does not include flows measured on Butler, Little Butler and Maury Creek, each of which was less than 1 cfs.

**Table 10. Flow Data for Lake Bellaire and Clam Lake Tributaries**

| date | Upper Inter-mediate River | Cedar River | Inter-mediate River (Bellaire) | upper Grass River | Shanty Creek | Cold Creek | Finch Creek | West branch Finch Creek | {ower Grass River | Clam River outflow |
|---|---|---|---|---|---|---|---|---|---|---|
| **6/23/05** | | | | | | | | | | > 143 |
| **6/25/05** | | | | | 10.2 | 33.9 | 28.8 | | | |
| **7/14/05** | | | 90 | 59 | | | | | 211 | 211 |
| **8/11/05** | | | | | | | | | | 219 |
| **8/18/05** | | | | 130 | | | | | 131 | |
| **10/21/05** | | 78 | | | | | | | | |
| **4/27/06** | | 107 | 120 | 160 | | 28 | 27.2 | | | |
| **5/11/06** | | 188 | | | | | | | | |
| **6/8/06** | | | | | | | | | 225 | 224 |
| **6/29/06** | 62 | | 104 | 124 | | | | | | |
| **7/13/06** | | | | | | | | 23 | 157 | 195 |
| **8/24/06** | | 170 | 107 | | | | | | | |
| **10/3/06** | | | | 181 | | | | | | |
| **10/4/06** | | 219 | 265 | | | | | | | |

Based upon these flow measurements, average flow rates were calculated (Table 11). The average flow data show that the lower Intermediate River (comprising flow from the upper Intermediate River and the Cedar River) are the major tributaries to Lake Bellaire, while the Grass River and Cold and Finch Creeks are the major tributaries to Clam Lake. Some redundancy was built into the flow monitoring, which allowed us to check the accuracy and consistency of these measurements. For example, the sum of the average flows in the upper Grass River, Shanty Creek, Cold Creek and Finch Creek is 200 cfs, which is about 10% higher that the flow in the lower Grass River. Theoretically, these flows should be the same. However, since the flow measurements were not all made at the same times, we considered these measurements to be highly consistent.

**Table 11. Average Measured Tributary Flow Rates**

| Tributary | Average flow (cfs) |
|---|---|
| upper Intermediate River | 62 |
| Cedar River | 152 |
| Intermediate River (Bellaire) | 137 |
| Butler and Little Butler Creeks | 2 |
| Maury Creek | 0.2 |
| upper Grass River | 131 |
| Shanty Creek | 10 |
| Cold Creek | 31 |
| Finch Creek | 28 |
| lower Grass River | 181 |
| West branch of Finch Creek | 23 |
| Clam River | 212 |

Water level elevation data, in conjunction with stage-discharge relationships, allowed tributary flow rates to be estimated on a nearly continuous basis for much of the 2006 field season on the Cedar River, Intermediate River (at the Bellaire bridge), upper Grass River and Cold Creek. An example of the water level data for the Cedar River is shown in Figure 7. An example of the water flow data for the Cedar River, Cold Creek, Upper Grass River, and Intermediate River is shown in Figure 7.

To estimate tributary flow rates from water level elevation data, a stage-discharge relationship must be derived for each location, by regressing flow rate measurements against water level elevation data. The observations must include measurements for the full range of elevations and flows (including base flow and high-flow events) in order to produce an accurate stage-discharge relationship. Because TLA measured flows on a predetermined schedule, they were unable to collect sufficient observations of flow and elevation under high-flow conditions to develop accurate regressions. As a consequence, the accuracy of the tributary flow rates estimated from water level elevations may be suspect.

To overcome some of the gaps and other limitations of the tributary flow data, we correlated flows on each of the major tributaries to Lake Bellaire and Clam Lake to daily flows measured by the U.S. Geologic Survey (USGS) on the Sturgeon River. Sturgeon River flows have been monitored daily since 1942, and are often correlated to flow rates in other northern lower Michigan tributaries (R. Minnerick, personal communication). We found that daily and monthly flows in the Sturgeon River correlated well with flows calculated from our measurements and stage-discharge estimates on the Cedar River (monthly flow correlation $r^2$=0.62), upper Grass River ($r^2$=0.73), Intermediate River (Bellaire) ($r^2$=0.70) and Cold Creek ($r^2$=0.93). Using these correlations, we were able to estimate monthly tributary flow rates for unmonitored periods.

Lake Water Levels

Water levels on each of the Three Lakes were monitored weekly during the 2006 field season to determine changes in lake storage (volume). The lake level data are graphed in Figure 8. Intermediate Lake levels, measured and reported by the USGS, are also included in this figure. Between April and the end of September, the water level of Lake Bellaire dropped by 20 cm. Most of the drop occurred in April. Water levels also declined by about 5 cm in Clam and Torch Lakes. The drop in lake levels is consistent with evaporation exceeding precipitation over the project period.

As previously noted, the Intermediate, Grass and Clam Rivers act as connecting channels between the Three Lakes. The flow rates in connecting channels can often be correlated to the difference between the levels of the upstream and downstream lakes. This approach can be an attractive alternative to tributary flow monitoring, since much less effort is involved. We tested this approach by comparing the difference between the levels of Lake Bellaire and Clam Lake with the flows monitored in the upper Clam River. The results are plotted in Figure 9. In general, there appears to be good agreement between flows in the Grass River and the difference in lake levels. Some of the difference between the two may be due to differences in the monitoring frequency: the flows were based on water levels measured on an hourly basis, while the lake levels were recorded weekly.

We also compared the difference between the levels of Intermediate Lake and Lake Bellaire with the flows monitored in the Intermediate River at the Bellaire bridge (not shown). This comparison was not favorable. Water levels on the Intermediate River and Lake Bellaire were significantly impacted by the operation of the Intermediate River dam in Bellaire. The dam operator made frequent (as often as several times a week) adjustments to the flow gates (M. Stone, personal communication), which were observed as transients in the water levels recorded by the gauge located at the Bellaire bridge on the Intermediate River. Since the water levels and flow rates were being manipulated by the dam operation, it is not surprising that Intermediate River flows do not correlate with the lake level difference.

Shallow Groundwater Flow

The flow of shallow groundwater was measured at 6 piezometer/shallow well locations around the perimeter of Lake Bellaire, and one location on Clam Lake. The well data are summarized in Table 12 and in Appendix I. The hydrostatic pressure gradient (i.e., the difference in pressure between the shallow groundwater and the lake) and the hydraulic conductivity (the resistance to groundwater flow) were determined, based upon 2-4 monthly measurements at each well. The hydraulic conductivity measurements are consistent with values expected for clean to silty sands, the soil types most representative of the subsurface sediments where these measurements were made.

### Table 12. Groundwater Flow Data

| Well ID / Lake | Distance around Lake perimeter (mi) | Shoreline length (ft) | average hydraulic conductivity, Kh (ft/s) | hydrostatic pressure gradient (ft/ft) | average groundwater flow (cfs) | Standard deviation |
|---|---|---|---|---|---|---|
| Well #1 / L. Bellaire | 0.0 | 8,000 | $9.1x10^{-5}$ | 0.100 | 8.4 | 6.83 |
| Well #2 / L. Bellaire | 2.1 | 1,000 | $1.6\ x10^{-4}$ | 0.028 | 0.47 | 0.36 |
| Well #3 / L. Bellaire | 5.1 | 23,000 | $4.4\ x10^{-5}$ | 0.115 | 6.5 | 3.66 |
| Well #4 / L. Bellaire | 8.6 | 1,000 | $7.2\ x10^{-5}$ | 0.161 | 1.2 | 0.54 |
| Well #5 /L. Bellaire | | 8,000 | $3.2\ x10^{-5}$ | 0.129 | 3.1 | 0.039 |
| Well #6 / L. Bellaire | 9.6 | 8,000 | $1.5\ x10^{-4}$ | 0.024 | 2.9 | 1.64 |
| Well #7 / Clam L. | | 47,000 | $1.1\ x10^{-4}$ | 0.082 | 31.4 | 15.5 |

Notes: Shoreline length represented by corresponding well # in flow calculation

The well data were also used to estimate the total groundwater flow to Lake Bellaire and Clam Lake, by applying Darcy's law and assuming the shallow lake area associated with the groundwater flow rate measured at each well. These estimates are also presented (as "average flow") in Table 12. The sum of flows from the individual well areas produces a total groundwater flow rate of 20 cfs for Lake Bellaire. For Clam Lake, a total groundwater flow rate of 31 cfs was estimated from the data. However, this estimate is questionable because it was based on data from a single well. TLA had difficulty siting wells on Clam Lake because there were no simple gravel shorelines, and/or wells would not pump groundwater because of clogging by sit, clay and organic matter in the sediment.

Bretz et al. (2006) discuss the errors and uncertainties associated with the groundwater flow estimates. They concluded that the major unknown was how far offshore the shallow groundwater flow persists. The flows in Table 12 are calculated assuming that, at each well location, shallow groundwater enters the lake from a 100-foot wide area along the shoreline. In fact, this width is unknown and is also likely to vary between locations.

Water Balance

The water balances for Lake Bellaire and Clam Lake were based upon the following equation, which is simply a volumetric (i.e., mass) balance for all water entering and leaving the lake:

**Change in water storage = tributary inflow - outflow + groundwater seepage + precipitation – evaporation**

The water balances were calculated for the 12 month period, November 2005 through October of 2006. Over this period, the changes in lake storage were calculated from the observed fluctuations in lake levels. When the flow balance was initially calculated for Lake Bellaire, we found that the difference between sources and losses of water was significantly greater than the change in lake storage. This was not surprising, since large numbers based on flow estimates containing errors were being added and subtracted to yield a comparatively small residual. A number of possible adjustments to individual flows were considered to correct the water balance. We concluded that the most reasonable adjustment was to reduce the estimated flows of the Intermediate River by 20%, which also reduced upper Intermediate River flows. Figure 10 shows how this flow adjustment reduces the flow residual (imbalance) in Lake Bellaire to nearly zero for the months of May through October. With this adjustment, we obtained the hydrologic budget for Lake Bellaire shown in Table 13.

**Table 13. Hydrologic Budget for Lake Bellaire (November 2005 - October 2006)**

| Flow Component (inflows and outflows) | Flow (cubic foot[1] per second, cfs) | % of water source | % of water loss |
|---|---|---|---|
| Upper Intermediate River | 51 | 28 | |
| Cedar River | 107 | 58 | |
| Intermediate River (Bellaire) | 155[2] | | |
| Butler and Maury Creeks | 1 | 0.5 | |
| Precipitation | 6 | 3 | |
| Groundwater seepage | 20 | 11 | |
| Upper Grass River (Lake Bellaire outflow) | 164 | | 95 |
| Evaporation | 9 | | 5 |
| Change in Storage | -2 | | |

Notes: (1) 1 cubic foot = 7.5 gallons; (2) The sum of the upper Intermediate River and Cedar River flows should equal the flow of the Intermediate River at Bellaire.

In Clam Lake, there was a similar problem with the initial flow balance. In this case, however, the flow residuals were nearly constant from month to month. This led us to suspect the groundwater flow estimate, which we already considered to be unreliable. By zeroing out the groundwater flow, a balanced hydrologic budget was obtained for

Clam Lake, as shown in Table 14.

**Table 14. Hydrologic Budget for Clam Lake (November 2005 - October 2006)**

| Flow Component (inflows and outflows) | Flow (cfs) | % of water source | % of water loss |
|---|---|---|---|
| Upper Grass River | 164 | 68 | |
| Cold Creek | 29 | 12 | |
| Finch Creek | 36 | 15 | |
| Shanty Creek | 10 | 4 | |
| Precipitation | 1 | 0.5 | |
| Groundwater seepage | 0 | 0 | |
| Clam River outflow | 237 | | 98 |
| Evaporation | 4 | | 2 |

The hydraulic residence time (HRT), the average time that water remains in the lake, is obtained by dividing the volume of the lake by the rate of outflow. Based on an outflow rate of 164 cfs, the HRT for Lake Bellaire is 219 days. The HRT for Clam Lake, based on an outflow rate of 237 cfs, is a very short 7.4 days.

## Water Quality Data

### Introduction

This section describes the water quality data that where collected during this project. Phosphorus was a parameter of particular importance, because it is the controlling nutrient for phytoplankton productivity and is related to the other water quality parameters of concern, and its loading reflects anthropogenic influences. Phosphorus data were used to calculate mass loadings and initial conditions for the lake; data for phosphorus and other parameters (T, DO, chlorophyll, Secchi depth) were also to confirm model predictions of water quality.

### Total Phosphorus Concentrations in Lake Water

A total of 137 lake water samples were analyzed for total phosphorus during the Lake Bellaire and Clam Lake project. Summary statistics for total phosphorus concentrations are provided in Table 15. In this table, the lake water samples are categorized according to depth layers at the deep water stations, and shallow water samples which were collected at the time and place of the well sampling. Phosphorus concentrations in lake water exceeding 10 ppb were censored from these statistics and all subsequent analyses, assuming that such elevated concentrations indicate sample contamination (a total of 9 lake water samples were censored). Phosphorus concentrations in Lake Bellaire are lower by 0.5 to 1.3 ppb than those in Clam Lake, except in the deep lake layers, where phosphorus concentrations are slightly higher in Lake Bellaire. In other respects, the results for the two lakes are quite similar. The statistics indicate that phosphorus concentrations tend to be somewhat higher in shallow, nearshore water, while phosphorus concentrations are most variable in the deep layers of both lakes.

**Table 15. Summary Statistics for Total Phosphorus in Lake Bellaire and Clam Lake Water (concentrations in ppb)**

| | Lake Bellaire | | | Clam Lake | | |
|---|---|---|---|---|---|---|
| sample type | average | median | SD | average | median | SD |
| all lake water | 3.8 | 3.8 | 1.12 | 4.3 | 4.3 | 0.83 |
| shallow | 5.1 | 5.1 | 0.35 | 6.3 | 6.3 | |
| surface | 3.6 | 3.6 | 0.87 | 4.5 | 4.5 | 0.76 |
| middle | 3.4 | 3.5 | 0.62 | 4.1 | 3.9 | 0.65 |
| deep | 4.3 | 4.5 | 1.61 | 4.1 | 4.1 | 1.20 |

Volume-weighted averaging (VWA) was used to calculate lake-wide average concentrations of total phosphorus from the deep water station data. The VWA total phosphorus concentration in Lake Bellaire was 3.7 ppb, while the VWA total phosphorus concentration in Clam Lake was 4.5 ppb. These are fairly low phosphorus concentrations, as indicated by comparison to other regional water bodies (Table 16):

**Table 16. Total Phosphorus Concentrations in Northern Lower Michigan Water Bodies**

| Water Body | Data Source | Total Phosphorus Concentration (ppb) |
|---|---|---|
| Northern Lake Michigan | EPA/GLNPO, 1994-95 | 2.2 |
| Torch Lake | GLEC/TLA, 2005 | 2.6 |
| Lake Bellaire | This report | 3.7 |
| Clam Lake | This report | 4.5 |
| Grand Traverse Bay | MDEQ, 2001 | 4.5 |
| Platte Lake | PLIA, 2003 | 8.1 |

We also compared the total phosphorus data for Lake Bellaire and Clam Lake to concentration data from previous years, collected by the TOM Watershed Center. TOM's monitoring consisted of collecting surface and bottom water samples in one or both lakes, 3 or 4 times a year. These data were plotted in Figure 3. The range of phosphorus concentrations measured each year between 2001 and 2004 suggests that the data sets appear to be generally comparable, and that no significant changes in total phosphorus concentrations have occurred over the past 5 years. TOM data also suggest that total phosphorus concentrations in both lakes were higher in the 1990s.

Tributary Total Phosphorus Concentrations and Loading Estimates

Total phosphorus concentrations were measured in 8 Lake Bellaire and Clam Lake tributaries. Summary statistics for these data are presented in Table 17. Phosphorus concentrations were higher and more variable in the Cedar River and Cold Creek, the two tributaries where automated sampling was conducted during high flow events. Figure 11 plots the streamflow and total phosphorus concentrations measured on the Cedar River and Cold Creek during five events. Elevated total phosphorus concentrations appear to accompany the initial flow increase for most (but not all) of the high flow events monitored in this project.

**Table 17. Summary Statistics for Total Phosphorus in Tributaries (concentrations in ppb)**

| Tributary | n | average | median | SD | max |
|---|---|---|---|---|---|
| Upper Intermediate River | 4 | 6.0 | 5.7 | 2.5 | 9 |
| Intermediate River (Bellaire) | 2 | 6.0 | 6.0 | 0.57 | 6.4 |
| Cedar River | 20 | 26 | 17 | 22 | 70 |
| Butler Creek | 1 | 16 | | | |
| Maury Creek | 1 | 14 | | | |
| Upper Grass River | 2 | 4.2 | 4.2 | 1.2 | 5 |
| Lower Grass River | 2 | 4.9 | 4.9 | 0.82 | 5 |
| Cold Creek | 22 | 51 | 35 | 44 | 209 |
| Finch Creek | 2 | 4.2 | 4.2 | 0.07 | 4.2 |
| Shanty Creek | 2 | 3.7 | 3.7 | 0.35 | 3 |
| Clam River | 2 | 4.25 | 3.1 | 1.1 | 5 |

Annual tributary loads for the major tributaries (Upper Intermediate River, Cedar River, Intermediate River (Bellaire Bridge), upper Grass River, Finch Creek, and Cold Creek were calculated using AutoBeale, a computer implementation of the stratified Beale Ratio Estimator (Richards, 1998). AutoBeale was unable to calculate reliable total phosphorus loadings for the Cedar River and Cold Creek, due to the high-flow sampling bias associated with automated event sampling on those tributaries. This was corrected by separating the data for low-flow and high-flow periods, recalculating the loadings, and adding together the results. The estimated loads are presented in Table 18. The phosphorus loading estimates generated by AutoBeale are fairly uncertain for several tributaries, especially the Cedar River, as indicated by the width of the 95% confidence intervals. Total phosphorus loads for the other (minor) tributaries were estimated as the product of measured flows and concentrations, and then summed and averaged to calculate annual values.

**Table 18. Tributary Loading Estimates for Total Phosphorus (units of kg/yr)**

| Tributary | TP load | 95% confidence interval |
|---|---|---|
| Upper Intermediate River | 372 | 168 - 575 |
| Intermediate River (Bellaire bridge) | 820 | 713 - 927 |
| Cedar River | 1,295 | 378 - 2214 |
| Upper Grass River | 614 | 372 - 856 |
| Cold Creek | 733 | 416 - 1,050 |
| Finch Creek | 135 | 132 - 138 |
| Butler and Maury Creeks | 12 | |
| Shanty Creek | 34 | |

The total tributary phosphorus loading to Lake Bellaire is 1,680 kg/y; the largest component of this load (77% of the total) comes from the Cedar River. The total tributary phosphorus loading to Clam Lake is 1,520 kg/y, with the largest load components coming from Cold Creek (48%) and Grass River (41%). It is interesting to note that the total tributary phosphorus loadings to each lake are quite similar. This should not be surprising, considering that the watershed areas for each lake are also similar (Table 5).

Precipitation Total Phosphorus Concentrations and Atmospheric Deposition Loading

Total phosphorus concentrations were measured in precipitation samples collected between June and September of 2006 at two locations along the western shore of Lake Bellaire. These data are summarized in Table 19. The distributions of phosphorus concentrations in rain were positively skewed and approximately lognormal. Phosphorus concentrations were not correlated with either season or amount of rainfall. The data from both stations were pooled, and the unbiased logmean phosphorus concentration (18.8 ppb) was multiplied by the total precipitation for the November-October project period (22.8 inches) to obtain wet atmospheric loadings of 82 kg/yr to Lake Bellaire and 17 kg/y to Clam Lake.

**Table 19. Summary Statistics for Total Phosphorus in Precipitation (concentrations in ppb)**

| Location | n | average | median | SD | Min | Max |
|---|---|---|---|---|---|---|
| Bellaire (north) | 6 | 41 | 21 | 44 | 7.0 | 122 |
| Bellaire (south) | 7 | 19 | 18 | 15 | 4.9 | 48 |

The phosphorus loading from atmospheric dry deposition was estimated as a proportion of the wet deposition loading, an approach recommended by the Environmental Protection Agency (EPA, 2001). Twaroski and Reding (2003) determined that dry deposition accounted for 19-53% of the total atmospheric deposition of phosphorus across the 10 major watersheds in Minnesota. Based on the land use characteristics of these watersheds, we determined that the Lake Bellaire and Clam Lake watershed was most similar to Minnesota's Lake Superior watershed. For this watershed, Twaroski and Reding (2003) determined that dry deposition loading was 52% of the phosphorus loading from wet deposition. Extrapolating this ratio to Lake Bellaire and Clam Lake, the dry deposition loadings are 43 kg/y and 9 kg/yr, respectively. The total atmospheric loadings of phosphorus to Lake Bellaire is then 125 kg/y, and 26 kg/y to Clam Lake.

Groundwater Total Phosphorus Concentrations and Loading

Groundwater samples were collected from the shallow wells at the same time the flow rates were measured. These samples were analyzed for total and/or dissolved phosphorus; since no differences were found between total and dissolved measurements, the data were combined. Summary statistics for these data are presented in Table 20. For the wells sampled around Lake Bellaire, the phosphorus concentrations in shallow groundwater were, on average, 3 times higher than the surface water concentrations measured at the same locations. At the one well sampled in Clam Lake, the groundwater-to-surface water concentration ratio was only 1.1, suggesting that either phosphorus concentrations in shallow groundwater were fairly low, or that surface water was being drawn down through the sediment and being sampled by the piezometer at this location.

**Table 20. Summary Statistics for Total Phosphorus in Groundwater (concentrations in ppb)**

| Well ID / Lake | Average groundwater P concentration (ppb) | n | SD | Shallow water P concentration (ppb) | Sample blank P concentration (ppb) |
|---|---|---|---|---|---|
| Well #1 / L. Bellaire | 6.1 | 3 | 2.1 | 2.5 | 1.4 |
| Well #2 / L. Bellaire | 6.8 | 3 | 0.5 | 2.0 | |
| Well #3 / L. Bellaire | 13.2 | 3 | 5.1 | 9.3 | |
| Well #4 / L. Bellaire | 10.9 | 3 | 8.0 | 6.8 | 2.0 |
| Well #5 / L. Bellaire | 16.8 | 2 | 6.2 | 5.3 | 0.6 |
| Well #6 / L. Bellaire | 22.6 | 2 | 9.9 | 5.2 | |
| Well #7 / Clam L. | 7.0 | 4 | 2.7 | 6.3 | 0.9 |

Phosphorus loadings from shallow groundwater to each lake were calculated using unbiased logmean concentrations (12 ppb for Lake Bellaire and 6.1 ppb for Clam Lake) and the shallow groundwater flow rates. The total phosphorus groundwater loading for Lake Bellaire was 214 kg/yr. Based on the hydraulic balance, we had assumed there to be no groundwater entering Clam Lake, therefore the phosphorus loading from groundwater was also assumed to be zero.

### Wastewater Treatment Plants

All three wastewater treatment plants in the study area (Bellaire, Schuss Mountain Resort and Summit Village) treat wastewater to remove phosphorus and then discharge the treated effluent to drain fields. Phosphorus loadings for each of the point sources are presented in Table 21 (Moskus et al., 2007). Additional phosphorus removal that likely occurs in the ground is not considered in these loading calculations. The phosphorus load that migrates from the Schuss Mountain WWTP drain field to the Cedar River is presumably accounted for in tributary monitoring and loading estimates. Likewise, the phosphorus load that migrates from the Summit Village drain field to Lake Bellaire is accounted for in the shallow groundwater monitoring loading estimate. Phosphorus loading from the Bellaire WWTP) was added to the tributary loading estimates for the Intermediate River, because of the proximity of the drain field to the river and adjacent wetlands. It should be recognized, however, that only a portion of this load is believed to reach the river and lake.

**Table 21. Summary of point source phosphorus loads**

| Facility | Location (subwatershed) | Estimated population served | Average annual flow (MGD) | Average phosphorus concentration (ppm) | Annual phosphorus load (kg /yr) |
|---|---|---|---|---|---|
| Schuss Mountain Resort | Cedar River | 933 | 0.023 | 0.28 | 8.9 |
| Summit Village | Lake Bellaire Direct Drainage | | 0.054 | 0.65 | 48.5 |
| Bellaire WWTP | Lower Intermediate River | 1,525 | 0.218 | 0.096 | 28.9 |

### Sediment Trap Fluxes

Sediment traps were deployed in Lake Bellaire from June 22 through October 1, to collect the particulate mass settling down though the thermocline of the lake. The data from the two duplicate traps are presented in Table 22. Reproducibility of the data collected in the duplicate traps was excellent. The phosphorus concentrations measured on the trap solids (472 ppm) are 2.5 times higher than the concentration measured in sediment samples from Lake Bellaire (189 ppm). The dry mass flux measured in Lake

Bellaire (1.26 g/m$^2$/d) are slightly higher than the flux measured in Torch Lake during the summer of 2005 (1.15 g/m$^2$/d), while the phosphorus flux are considerably larger (0.59 mg/m$^2$/d in Lake Bellaire vs. 0.21 mg/m$^2$/d in Torch Lake). Normalizing the phosphorus settling flux by the VWA concentration (3.7 ppb), a theoretical[1] settling rate of 0.16 m/d is obtained for total phosphorus in Lake Bellaire.

**Table 22. Lake Bellaire Sediment Trap Data**

| ID | Trap depth (m) | total dry mass (grams) | mass flux (gm/m$^2$/d) | Total phosphorus concentration (mg/kg) | Total phosphorus flux (mg/m$^2$/d) | TP settling velocity (m/d) assuming 3.7 ppb concentration |
|---|---|---|---|---|---|---|
| A | 24 | 1.05 | 1.29 | 471 | 0.605 | 0.16 |
| B | 24 | 1.01 | 1.23 | 472 | 0.582 | 0.16 |

Visually, the appearance of the trap solids was very similar to the solids trapped in the summer of 2005 from Torch Lake: very flocculent, with particle sizes ranging from colloidal to the size of large snowflakes. When dried, a few macrozooplankton were found in the samples; however, the great majority of the dried solids had the appearance of a fine white powder, like ground chalk.

The sediment trap fluxes were used to measure the rate of phosphorus settling in the lake. This information was used in both the phosphorus mass balance (as a lakewide phosphorus loss) and the water quality model (to confirm the settling fluxes for particulate phosphorus). Converting the measured phosphorus flux to an annualized value and multiplying by the surface area of the lake, a phosphorus settling loss of 1,640 kg/yr is calculated for Lake Bellaire. If the same flux is applied to Clam Lake, a phosphorus settling loss of 342 kg/yr is calculated

<u>Sediment-Water Fluxes</u>

Results of the flux experiments conducted on Lake Bellaire and Clam Lake sediments are summarized in Table 23. The rates of dissolved phosphorus release from Lake Bellaire and Clam Lake sediment were found to be small (>500 ppm/m$^2$/d), for both oxygenated and anoxic (oxygen-deficient) overlying water conditions (Holmes and McNaught, 2005). Based on the experimental results, these authors concluded that there was likely to be little or no exchange of dissolved phosphorus compounds between the sediment and the overlying water in Lake Bellaire and Clam Lake, when compared to more eutrophic lakes. Rates of sediment oxygen demand were also quite low, 0.5 to 1.1 g $O_2$/ m$^2$/day. Both the phosphorus release and SOD fluxes were higher in Clam Lake than in Lake Bellaire.

1 This value is a *theoretical* settling rate because not all of the total phosphorus is in a particulate form that can settle.

**Table 23. Results of Sediment Flux Experiments for Sediments Collected from Lake Bellaire and Clam Lake**

| Lake | Sample Depth (m) | Sediment Oxygen Demand ($g-O_2/m^2/d$) | Oxic Phosphorus Release ($ug-P/m^2/d$) | Anoxic Phosphorus Release ($ug-P/m^2/d$) |
|---|---|---|---|---|
| **Bellaire** | 30 | 0.54 | -9 | 282 |
| **Clam** | 8 | 1.08 | 137 | 497 |

Lakewide estimates of sediment phosphorus release were made using the average of the oxic fluxes (64 $ug-P/m^2/d$) and the lake surface areas. For Lake Bellaire, sediment is estimated to release 177 kg/y of phosphorus while for Clam Lake the estimate is 37 kg/y. We used the oxic phosphorus release fluxes because the water overlying sediments in both lakes are predominantly oxygenated.

Phosphorus Associated with Macrophytes

Results of the macrophyte surveys conducted in eastern Clam Lake are presented in Table 24. Both the plant biomass and the phosphorus associated with the biomass increased from June to September, and for both surveys these quantities were greater for macrophytes growing in shallower (1-2 m) lake depths. Macrophytes were generally not found at greater depths. The lake areas associated with macrophyte beds were estimated from a mosaic of aerial photographs taken from a low-flying plane. The extent of macrophyte beds were clearly visible in these photos, as shown by the examples in Figure 12.

**Table 24. Results of Macrophyte Surveys Conducted in Eastern Clam Lake on June 8 and September 7, 2006**

| Depth range | Biomass ($g-dry/m^2$) (June) | Biomass ($g-dry/m^2$) (Sept.) | Phosphorus ($mg/m^2$) (June) | Phosphorus ($mg/m^2$) (Sept.) | Area (HA) | Phosphorus (kg) (June) | Phosphorus (kg) (Sept.) |
|---|---|---|---|---|---|---|---|
| **1 to 2 m** | 19.2 | 24.8 | 30.6 | 44.4 | 52 | 16.5 | 23.9 |
| **2 to 3 m** | 0 | 7.4 | 0 | 9.6 | 5.6 | 0 | 0.6 |
| **Total** | | | | | 57.6 | 16.5 | 24.4 |

The total mass of phosphorus associated with macrophytes in Clam Lake was obtained by multiplying the phosphorus content of each depth interval by the corresponding area, and then summing the results. As shown in Table 24, the total mass of phosphorus associated with macrophytes in Clam Lake was estimated to increase from 16 kg in June to 24 kg in September. Assuming (1) no macrophyte biomass in the lake in early spring, (2) macrophytes primarily take up phosphorus from the water column and (3) primarily release phosphorus to the sediment in the fall, these estimates were used to calculate loss rates for this mechanism in the phosphorus mass balance for Clam Lake.

Total Phosphorus Mass Balance

Phosphorus is the rate-limiting nutrient for phytoplankton growth in Lake Bellaire and Clam Lake, as is the case in most freshwater lakes. This means that the eutrophication process is driven by the concentration of this nutrient, and it follows that managing and protecting water quality in Lake Bellaire and Clam Lake depends upon understanding the sources and sinks of phosphorus. Calculating a mass balance is a first step towards such understanding. At this point, we have all the information necessary to calculate the mass balances for phosphorus in Lake Bellaire and Clam Lake, which are worked out below for the project period.

The mass balance for phosphorus in Lake Bellaire can be written as:

**Accumulation = Loadings + Sediment Release – Outflow – Settling**

Phosphorus loadings include contributions from tributaries, atmospheric deposition, and shallow groundwater. The total tributary loading from Intermediate River to Lake Bellaire was calculated by summing up the loading estimates (Table 18) from the upper Intermediate River, Cedar River and the Bellaire WWTP; to this was added the loading estimates from the minor tributaries, Butler and Maury Creeks. Phosphorus is lost from the lake by outflow and settling with particles, which are ultimately incorporated into the sediment bed. The phosphorus loading, sediment release and settling loss terms have already been calculated:

Total Phosphorus Loading = Tributary Loading + Atmospheric Deposition + Groundwater Loading
= 1,680 kg/y + 125 kg/y + 214 kg/ = 2,020 kg/y
Sediment Release = 177 kg
Phosphorus Settling = 4,110 kg

The loss due to outflow is simply the product of the rate of outflow and the average lake concentration:

Outflow = (31.54) · 4.97 $m^3/s$ · 3.7 ppb = 580 kg/yr

For the annual project period, the phosphorus mass balance for Lake Bellaire is:

**Accumulation = Loadings + Sediment Release – Outflow – Settling**
**= 2,020 kg/y + 177 kg/y– 580 kg/y - 4,110 kg/y**
**= -25 kg/y**

For Clam Lake we must add a term to the mass balance to account for phosphorus removal by macrophytes:

**Accumulation = Loadings + Sediment Release – Outflow – Settling - Macrophyte Uptake**

The phosphorus loading, sediment release and settling loss terms for Clam Lake have also been calculated:

Total Phosphorus Loading = Tributary Loading + Atmospheric Deposition
= 1,520 kg/y + 26 kg/y = 1,540 kg/y
Sediment Release = 37 kg
Phosphorus Settling = 342 kg
Macrophyte Uptake = 24 kg

Outflow = (31.54) · 6.76 $m^3/s$ · 4.5 ppb = 959 kg/yr

For the annual project period, the phosphorus mass balance for Clam Lake is:

**Accumulation = Loadings + Sediment Release – Outflow – Settling – Macrophytes**
**= 1,540 kg/y + 37 kg/y – 959 kg/y - 342 kg/y – 24 kg/y**
**= 254 kg/y**

Tributary loading dominates the input of phosphorus to each lake. On a lake-area basis, the phosphorus loading to Lake Bellaire is 0.28 $gP/m^2/yr$, and loading to Clam Lake is 0.86 $gP/m^2/yr$. These loadings exceed the "dangerous" total phosphorus loading values presented by Vollenweider (1968) for eutrophication control in lakes: 0.2 $gP/m^2/yr$ for Lake Bellaire and 0.13 $gP/m^2/yr$ for Clam Lake (these limits depend on mean lake depth). These loadings also significantly exceed the "permissible" phosphorus loads suggested by Vollenweider: 0.1 $gP/m^2/yr$ for Lake Bellaire and 0.07 $gP/m^2/yr$ for Clam Lake.

Settling was by far the most significant phosphorus loss in Lake Bellaire, removing 79% of the phosphorus entering the lake from the water column. Settling was a less significant loss process in Clam Lake, with only 41% of the phosphorus entering that lake removed by settling. Instead, most of the phosphorus was lost from Clam Lake via outflow. The overall mass balance for phosphorus in Lake Bellaire indicates a net annual loss of 25 kg (less than 1% of the total mass of phosphorus in the lake). Thus, the sources and sinks of phosphorus were found to nearly balance in Lake Bellaire and, at an annual time scale, the phosphorus concentrations in Lake Bellaire should be nearly constant. In fact, this is consistent with monitoring data from the last 4 years.

On the other hand, the mass balance for phosphorus in Clam Lake indicates a net annual accumulation of 254 kg/y, which is clearly in error since the total mass of phosphorus in Clam Lake is only 19 kg. However, the cause for this error is not obvious. It may reflect overestimation of one or more of the loading terms and/or underestimation of the losses. The lake-wide phosphorus mass balances will be revised based on the results of water quality modeling.

Phytoplankton

Phytoplankton were measured as chlorophyll-a concentrations in the surface and middle layers of Lake Bellaire and Clam Lake. Summary statistics for chlorophyll concentrations are provided in Table 25. Chlorophyll concentrations were fairly consistent between the surface and middle depth layers in Lake Bellaire, but in Clam Lake they were higher in the surface layer. The chlorophyll data are also plotted as time series in Figure 13. In Clam Lake, there is a pronounced peak in chlorophyll-a concentrations around the beginning of July. The chlorophyll-a concentrations were more stable in Lake Bellaire, with maximum values measured in early to mid August.

**Table 25. Summary Statistics for Chlorophyll-a Concentrations (concentrations in ppb)**

| Lake | Depth layer | n | average | median | SD |
|---|---|---|---|---|---|
| Lake Bellaire | Surface | 11 | 1.5 | 1.6 | 0.397 |
| | Middle | 9 | 1.6 | 1.6 | 0.323 |
| Clam Lake | Surface | 11 | 2.2 | 2.1 | 0.895 |
| | Middle | 10 | 1.7 | 1.5 | 0.972 |

Plankton Functional Groups

Phytoplankton samples were collected from the surface layer of Lake Bellaire each month during the summer. These samples were microscopically examined to determine the composition of the phytoplankton. The results are shown in Table 26, which includes the number of cells counted (cells /mL) in 6 phytoplankton divisions , or functional groups. Over the course of the summer, the results show a consistent decline in the abundance if diatoms, a significant increase followed by a decline in green algae, and a significant increase in the abundance of blue-green algae especially between July and August. Although budget constraints prevented us from obtaining species identification and biovolumes, we still calculated crude biovolume and biomass estimates using median cell volumes calculated from Wetzel (1975, Table 14-6). The results, which are graphed in Figure 14, show that blue-green algae clearly dominate the late summer phytoplankton carbon "pool" in Lake Bellaire.

**Table 26. Cell Counts for Phytoplankton Functional Groups in Lake Bellaire**

| sampling date: | 6/15/2006 | 7/13/2006 | 8/15/2006 | 9/14/2006 |
|---|---|---|---|---|
| Phytoplankton division | Counts (cells/mL) | | | |
| *Bacillariophyta* (diatoms) | 2473 | 1465 | 597 | 620 |
| *Chlorophyta* (greens) | 143 | 1224 | 486 | 323 |
| *Chrysophyta* (golden) | 110 | 241 | 253 | 109 |
| *Cryptophyta* (flagellates) | 19 | 148 | 52 | 77 |
| *Cyanophyta* (blue-green) | 805 | 4765 | 12,965 | 8586 |
| *Pyrrhophyta* (dinoflagellates) | 2 | 0 | 26 | 14 |

Research from Lake Erie, Saginaw Bay, as well as inland lakes has shown that blue-green algae blooms (especially *Microcystis*) have occurred a few years after the invasion of zebra mussels. Blooms of *Microcystis* are of concern because *Microcystis* is poor food for the aquatic food chain and because it contains a potent toxin called microcystin that is harmful to the aquatic food chain, including fish, and to other animals that might drink the water. Experiments have shown that zebra mussels selectively filter and reject phytoplankton so as to promote and maintain *Microcystis* blooms (Vanderploeg et al., 2001). Even in years when blooms occur, zebra mussel filtering causes the water to be very clear during spring and early summer before the blooms "take off". This process may be occurring in Lake Bellaire, and would explain the dominance of blue-green algae in summer.

Concentrations of microcystines in Lake Bellaire were measured in early September of 2006, as part of a new Michigan Lakes & Streams program to compare microcystines concentrations in Michigan lakes with and without zebra mussels (Sarnelle and Wandell, 2007). Microcystines are natural substances produces by blue-green algae. Samples of surface water were collected in North arm, South arm, and deep basin in Lake Bellaire and transported by M-DEQ to Michigan State University for analysis. Microcystine concentrations in Lake Bellaire were found to range from 90 to 150 ppt (parts per trillion, or ng/L), well below the World Health Organization's water quality criteria of 1,000 ppt for microcystines. The concentrations of microcystines in Lake Bellaire were consistent with other lakes infested with zebra mussels. According to Sarnelle and Wandell (2007), microcystine concentration are not expected to increase in the future, unless the growth of the blue-green algae is stimulated, perhaps by increases in the amount of phosphorus entering the lake.

Secchi Disk Depth and Water Clarity

TLA volunteers measured the water clarity in Lake Bellaire and Clam Lake using a Secchi disk in 2005 and 2006. Secchi disk depths for these two lakes were also measured independently by Michigan Lakes and Streams Association (MLSA) volunteers. In addition, Secchi depths were reported for 2003 by the TOM Watershed Center. These data are plotted together as annual time series for each lake in Figure 15. The seasonal pattern of Secchi disk depths appear to follow regularly-repeating cycles in each lake, although there is also variation by as much as a meter from one week's measurement to the next. In Lake Bellaire, high Secchi depths (>7 m) are measured in spring, and then steadily decline until early August, when Secchi depths reach their minimum (<4 m), although a value this low was not observed in 2005. High Secchi depths return by mid-September. In Clam Lake, Secchi depths generally follow a similar seasonal pattern, although it questionable whether this trend occurred in 2003.

Light extinction, a more precise measure of water clarity, was also measured on several cruises. A Licor light intensity meter was lowered down through the water column to measure the decline in light intensity as a function of depth. Light extinction coefficients ($K_d$) were calculated from these data. We found that the light extinction coefficients correlated well with the Secchi depths in Lake Bellaire (Figure 16):

$$K_d \text{ (1/m)} = 0.738 - 0.095 \times \text{SD (m)} \qquad (r^2 = 0.813, n=6)$$

Light extinction coefficients were also measured in Clam Lake although, as shown in Figure 16, a similarly strong correlation to Secchi depth was not observed.

### Dissolved Oxygen

Trends in dissolved oxygen concentrations in Lake Bellaire and Clam Lake were generally similar. The average DO concentrations in each layer of both lakes, calculated from the HydroLab profile data, are plotted in Figure 17 and in Appendix II. Surface and middle layer DO concentrations were generally near saturation values. In the deep layer of both lakes, there was a tendency for DO concentrations to drop in the late summer. This was especially apparent in Lake Bellaire, as average deep layer DO concentrations dropped from 8.7 ppm in early August to 4.5 ppm in early October. In addition, DO concentrations were low in the deep layer of Clam Lake in winter.

Intensive HydroLab profiling was conducted at14 stations in Lake Bellaire on September 14, 2006, to better delineate the extent of low DO concentrations in the deep layer. Depths at these stations ranged from 12 to 28 m. The average near-bottom DO concentration was 5.1 ppm, with a minimum value of 2.7 ppm. In general, lower near-bottom DO concentrations were measured at deeper stations around the lake.

We also compared our HydroLab data to the DO measurements reported in Lake Bellaire by Canale et al. (1982). One of the locations sampled in 1982 was close to our deep water sampling station, so we compared our data to DO values reported at that location. Near-bottom DO concentration timeseries measured in 1982 and 2006 are plotted together in Figure 18 (2 data points from TLAs surveillance sampling in 2005 are plotted as well). It appears that deep-water DO concentrations were nearly comparable up until the end of July in 1982 and 2006. However, in 1982 the DO concentrations continued to drop in August and September, and remained below 1 ppm (as low as 0.3 ppm) for the duration of their field season. In comparison, in 2006 the DO concentrations only decline to 2.6 ppm, although in 2005 a near-bottom DO of 1.5 ppm was measured. Late summer near-bottom temperatures were comparable (not shown), so the differences in DO levels appear to reflect a decline in sediment oxygen demand. Over a 24 year time span SOD has declined, but there is still enough to significantly deplete DO in the deep layer of Lake Bellaire. This layer (the hypolimnion) is 17 meters thick in Lake Bellaire, but it accounts for less than 30% of the total lake volume.

The DO concentrations measured in Lake Bellaire indicate a significant impairment of water quality in the deep layer. Michigan's water quality standards for dissolved oxygen state that for intolerant warmwater fish, the average daily DO value should not be less than 5 ppm, nor should any single value be below 4 ppm. For intolerant coldwater fish, the DO should not be less than 6 ppm at any time. As was the case in 1982, dissolved oxygen concentrations in Lake Bellaire in 2005 and 2006 were low enough to hamper the development and stability of a balanced aquatic ecosystem. In addition, low DO concentrations promote the release of phosphorus from the lake bottom sediments, thereby increasing the "internal loading" of phosphorus from the lake sediments, possibly leading to further degradation of water quality.

Calcium Carbonate

An important factor related to water transparency in the Three Lakes is the formation of calcite (solid $CaCO_3$), which scatters light and reduces transparency in the water column. Lake Bellaire and Clam Lake are hardwater lakes (average hardness = 150 ppm calcium carbonate), due to the predominantly calcerous soils in the drainage basin. According to Wetzel (1975):

> "Hard-water lakes with high suspensions of $CaCO_3$ characteristically backscatter light that is predominantly blue-green"

and:

> "Colloidal $CaCO_3$, common to very hardwater lakes, scatters light in the greens and blues and gives these waters a very characteristic color appearance".

From the chemical equilibrium calculations, we can safely assume that Lake Bellaire and Clam Lake are saturated or supersaturated with $CaCO_3$ at least seasonally. Furthermore, colloidal $CaCO_3$ is probably suspended in the water column throughout the year.

The equilibrium chemistry of $CaCO_3$ is well understood. If the solubility limit of calcium carbonate is exceeded, solid $CaCO_3$ (calcite) will precipitate. We used the Visual MINTEQ model[2] to calculate $CaCO_3$ equilibria, based on measurements of the relevant water quality parameters: temperature, pH and calcium and alkalinity concentrations. These are plotted for Lake Bellaire in Figure 19 (similar parameter values were observed in Clam Lake), along with the Visual MINTEQ predictions of the corresponding equilibrium calcite concentrations. Equilibrium calcite concentrations increase from near zero in April to maximum values in May, and then decline slowly and continuously through the summer. It is evident from Figure 19 that changes in equilibrium calcite are mostly a function of the change in water temperature. Calcium concentrations also generally decline through summer, presumably due to loss with the settling calcite.

We expect to see transparency decline while calcite is precipitating, and then increase as the particulate calcite settles.

## LAKE2K-LITE CALIBRATION AND CONFIRMATION

The major goal of the Lake Bellaire and Clam Lake project was the development and application of predictive water quality models for each lake, to simulate and forecast water quality in response to changes in phosphorus loadings. The field data presented in the previous sections were used to develop a water quality model for the lake, using a prototype of Lake2K-Lite, a development version of the LAKE2k modeling framework (Chapra, 2003). Lake2K-Lite is a model designed to compute seasonal trends in water

2 Visual MINTEQ: An equilibrium speciation model, which calculates chemical equilibria in aqueous systems at low ionic strength. (http://www.lwr.kth.se/English/OurSoftware/vminteq/)

quality in stratified lakes, based on numerical integration of mass balance equations similar to the water and phosphorus mass balances presented in the previous section. The model simulates lake-wide water quality in three vertical layers (surface, middle and deep layers, defined consistently with the water quality data for each lake) to represent the seasonal stratification of the water column. The Lake2K-Lite framework includes a water balance, vertical mixing, thermal balance, and ice, light and sediment flux (diagenesis) submodels. The model predicts the most important water quality parameters in freshwater lakes: water temperature, DO, organic and inorganic nutrients, phytoplankton and zooplankton concentrations, and water clarity. What differentiates Lake2K-Lite from LAKE2k is the inclusion of a state variable for solid calcium carbonate (calcite), a kinetic submodel for calcite formation and dissolution, ion balance and equilibria equations to calculate carbonate and other ionic species as well as pH, and enhancements to the sediment diagenesis submodel (Homa and Chapra, 2007). These changes significantly improve Lake2K-Lite as a water quality modeling framework for the Three Lakes. LAKE2k and Lake2K-Lite are programs implemented using spreadsheet software commonly found on personal computer (Microsoft Excel). A beta test version (0105a) of the Lake2K-Lite model was graciously provided to TLA and GLEC for this project by Dr. Steven Chapra of Tufts University.

Several pre- and post-processor spreadsheets were developed for use with Lake2K-Lite. For example, total phosphorus loadings were preprocess and converted into equivalent tributary concentrations, because only tributary loadings can be input to the model. Another spreadsheet was used to link the output of Lake Bellaire model water quality predictions to the input for the Clam Lake model. A third spreadsheet was used to generate the graphs that were used in this report to display the model predictions and compare them to project data.

Initial conditions and loadings used for model calibration were calculated from the field data. It was necessary to divide total phosphorus loadings into organic and inorganic fractions, because Lake2K-Lite uses these two forms of phosphorus as state variables. We assumed that the inorganic fraction of total phosphorus was 10% in tributary loads (Wetzel, 1975), 50% in atmospheric deposition (naïve assumption), and 80% in groundwater loading (MPCA, 1999).

Models for each lake were calibrated using project data as well as other data collected in 2003 through 2005. A 4-year calibration period was chosen because multi-year model runs prevent initial conditions from excessively influencing the simulations. MAWN data were used to describe meteorological forcing functions for this period and tributary flows were extrapolated from USGS daily flows for the Jordan River. Phosphorus loadings were calculated as described in the previous section, using precipitation and tributary flowrates from the MAWN and USGS sources. We also assumed that total phosphorus concentrations measured in tributaries, groundwater and precipitation during the 2006 project year would be representative of concentrations in the 3 prior years, and were used to estimate loadings for the 2003-2006 period.

Calibration involved adjusting model parameters within the ranges recommended by Chapra (1997), Bowie et al. (1985), and Manhattan College (1996), in order to obtain the best fit of the data. Settling rates for all particulate nutrients were specified according to the fluxes measured in the Lake Bellaire sediment traps, as discussed previously. We used the O'Connor reaeration formula, the Arrhenius temperature model for phytoplankton growth, and the Steele light model. We modeled a single phytoplankton class and, although it had no impact on phytoplankton concentrations during the calibration, herbivorous zooplankton as well. The optimal values of the model parameters for each lake, based upon calibration, are presented in Table 27. Although there are many parameters, the models for Lake Bellaire and Clam Lake are fairly insensitive to the values of the majority of parameters. Calibration results for each lake model are presented and discussed below.

## Lake Bellaire Model Calibration and Calibration

Calibration/confirmation graphs are provided for the Lake Bellaire model in Figures 20 though 22.

### Temperature

The simulation of temperature by the Lake Bellaire model and the comparison to temperature data in the three vertical layers of the lake is shown in Figure 20. The model does a good job of simulating water temperatures in each layer, as well as differences in temperature which develop between layers during summer. The seasonal progression of temperatures in the epilimnion and metalimnion can be seen to differ between the 4 years, indicating the extent to which climatic variability influences the lake. Vertical mixing between the lake layers was calculated in the model according to the Munk-Anderson (MA) formulation, and two parameters (coefficients in the MA formula) were adjusted to calibrate temperature.

### Dissolved Oxygen

The calibration of the Lake Bellaire model to dissolved oxygen data in the three vertical layers of the lake is also shown in Figure 20. In the surface (epilimnion) and middle (metalimnion) layers, the model simulations agree well with the DO data. In the deep (hypolimnion) layer, the simulated DO is too low in winter, but fits the decline in DO over the course of the summer stratified period quite well. No parameters were adjusted to calibrate dissolved oxygen. The model predicted low rates of sediment oxygen demand (summer maximum values of 0.9, 0.4 and 0.3 g-$O_2$/$m^2$/d in the surface, middle and deep layers), in agreement with the results of the sediment flux experiments.

### Total Phosphorus

The calibration of the model to total phosphorus concentration data in the three vertical layers of the lake is shown in Figure 21. The simulated total phosphorus concentrations are predicted to be fairly constant in the surface and middle lake layers, close to 4 ppb, while the data indicate somewhat more variability in total phosphorus concentrations. In the deep lake layer, both the model predictions and the data indicate considerably more variability in total phosphorus concentrations, with model predictions cycling between 4 and 6 ppb. Overall, the total phosphorus simulations appear to be unbiased in comparison to the data in the surface and deep layers, with a small tendency to overpredict total phosphorus concentrations in the middle layer. The settling flux of total phosphorus predicted by the model, 0.7 mg-P/m$^2$/d, was 17% higher than the flux measured in the sediment traps for the same period, which we considered to be good agreement. The model predicted low rates of sediment phosphorus release (summer maximum values of 0.3, 0.2 and 0.04 mg-P/m$^2$/d in the surface, middle and deep layers), which also agree favorably with the results of the sediment flux experiments.

Inorganic and Dissolved Phosphorus

The simulation of inorganic phosphorus concentrations in the Lake Bellaire model is also shown in Figure 21, for the surface and middle lake layers. Inorganic phosphorus concentrations are predicted to decline to about 1 ppb in summer. This is because inorganic phosphorus is the bioavailable form of the nutrient in the model, and is rapidly taken up by phytoplankton during their "growing season". We have plotted dissolved phosphorus data for comparison to the inorganic phosphorus predictions, although these forms of phosphorus are not exactly comparable (i.e., dissolved phosphorus includes some organic phosphorus which is not bioavailable). The dissolved phosphorus data generally suggest that inorganic phosphorus is depleted from the epilimnion in summer, which agrees with the model.

Chlorophyll-a

The simulation of chlorophyll-a by the Lake Bellaire model and the comparison to chlorophyll data in the surface and middle layers of the lake is shown in Figure 22. The predictions show that phytoplankton growth begins as soon as the ice cover breaks up around April 1, in response to increasing temperature and light intensity, and reaches a peak each year in July to August. Chlorophyll-a concentrations then gradually decline through the remainder of the year, due to the depletion of available phosphorus from the photic zone and increasing phytoplankton losses, primarily via respiration, settling and death. At such low chlorophyll concentrations, the herbivorous zooplankton simulated in the model were unable to grow and reach abundances where their grazing would affect phytoplankton. The model predicts the magnitude and duration of the phytoplankton bloom fairly well, as indicated by comparison to the chlorophyll data, in both the surface and middle lake layers.

Secchi Depth and Light Extinction

The calibration of the Lake Bellaire model to Secchi depth data is also shown in Figure 22. The model does a good job of reproducing the recurring annual decline observed in Secchi depths each year. For the most part, the decline in Secchi depth predictions reflects the formation of calcite in Lake2K-Lite, which has significant light-scattering ability. Calcite concentrations (not shown) are predicted to reach concentrations of 5 ppm in June of each year, and remain at that level until October. We have also plotted the comparison between simulated and measured light extinction coefficients (although we calibrated the light model to Secchi depth, not the extinction coefficient). The model tends to overpredict the measurements of the light extinction coefficient by about 0.1m.

## Clam Lake Model Calibration and Confirmation

Calibration/confirmation graphs are provided for the Clam Lake model in Figures 23 though 25.

### Temperature

We were unable to calibrate temperatures in a vertically-stratified representation of Clam Lake, using either the MA mixing formulation or manual tuning of mixing rates. Clam Lake may be too shallow to maintain a stratified water column and/or the residence time may be too short for vertical mixing to be calibrated in this framework. Regardless of the cause, we were forced to model Clam Lake as a vertically-integrated (i.e., completely mixed) water column. This was accomplished by specifying arbitrarily high rates of vertical mixing (5 to 10 $cm^2/s$) in the model. Consequently, there are essentially no differences in the water quality predictions for the 3 lake layers. However, since water quality data were collected in each layer, we will show the comparisons of model simulations to data in all appropriate layers.

The simulation of temperature by the Clam Lake model and the comparison to temperature data in the three vertical layers of the lake is shown in Figure 23. In general, the model does an adequate job of simulating water temperatures in each layer, except for overpredicting the temperatures by a few degrees in the middle and bottom layers in the early summer (May through July) stratified period.

### Dissolved Oxygen

The calibration of the Lake Bellaire model to dissolved oxygen data in the three vertical layers of the lake is also shown in Figure 23. In the surface layer, the model simulations tends to underpredict the DO data, while in the deep layer the simulation overpredicts the DO in winter. The simulated decline in DO over the course of the summer stratified period agrees quite well with the data, especially in the deep layer. The Clam Lake model predicted somewhat higher rates of sediment oxygen demand (summer maximum values of 1.0 $g\text{-}O_2/m^2/d$) than the Lake Bellaire model, which again agrees favorably with the results of the sediment flux experiments.

### Total Phosphorus

The calibration of the model to total phosphorus concentration data in the three vertical layers of the lake is shown in Figure 24. The simulated total phosphorus concentrations are predicted to be fairly constant in the range of 4 to 6 ppb, which is consistent with the data for the surface and middle layers of the lake. In the deep layer, the data are somewhat more variable, but the model prediction is still unbiased. The Clam Lake model predicts a higher sediment phosphorus release rate (summer maximum values of 0.8 mg-P/m$^2$/d) than the Lake Bellaire model, in agreement with the results of the sediment flux experiments.

Inorganic and Dissolved Phosphorus

The simulation of inorganic phosphorus concentrations in the Clam Lake model is also shown in Figure 24, for the surface and middle lake layers. Inorganic phosphorus concentrations are again predicted to decline to about 1 ppb in summer. Dissolved phosphorus data are plotted for comparison to the inorganic phosphorus predictions. The dissolved phosphorus concentrations are about twice as high as the inorganic phosphorus predictions, and there appears to be little trend in the data.

Chlorophyll-a

The simulation of chlorophyll-a by the Clam Lake model and the comparison to chlorophyll data in the surface and middle layers of the lake is shown in Figure 25. The model predictions fit the 2006 chlorophyll-a data fairly well in both surface and middle layers of the lake, although the data appear fairly “noisy”. It is also somewhat difficult to judge the fit of the phytoplankton bloom in 2003, because one point is so much higher than all of the other data.

Secchi Depth and Light Extinction

The calibration of the Clam Lake model to Secchi depth data is also shown in Figure 25. As was the case in Lake Bellaire, the Clam Lake model does a good job of reproducing the recurring annual decline observed in Secchi depths each year. The decline in Secchi depth predictions again reflect the formation of calcite simulated in Lake2K-Lite; calcite concentrations in Clam Lake are predicted to reach maximum concentrations of 2 ppm. Again, the comparison between simulated and measured light extinction coefficients is also plotted in Figure 25.

Overall, the Lake Bellaire and Clam Lake model simulations shown above demonstrate that both models are reasonably well calibrated, and for most state variables this is confirmed by the agreement between predictions and observations for more than one year. The calibrations were also fairly robust since, with a few exceptions, the same parameter values were used in both models (Table 27).

## Table 27. Calibrated Parameter Values for Lake2K-Lite Models of Lake Bellaire and Clam Lake

| Parameter | Units | Lake Bellaire calibration value | Clam Lake calibration value | suggested[1] | | |
|---|---|---|---|---|---|---|
| | | | | low | moderate | high |
| Stoichiometry: | | | | | | |
| Dry weight | gD | 100 | 100 | | 100 | |
| Carbon | gC | 40 | 40 | | 40 | |
| Nitrogen | gN | 7.2 | 7.2 | | 7.2 | |
| Phosphorus | gP | 1 | 1 | | 1 | |
| Chlorophyll | gA | 1 | 0.5 | 0.5 | | 1 |
| Chlorophyll:Carbon | ugA/mg C | 25 | 25 | 10 | 25 | 50 |
| Particulate organic carbon: | | | | | | |
| Hydrolysis rate | /d | 0.03 | 0.03 | 0.02 | | 0.05 |
| Temperature parameter | | 1.047 | 1.047 | 1.02 | | 1.047 |
| Dissolved organic carbon: | | | | | | |
| Oxidation rate | /d | 0.01 | 0.1 | | | |
| Temperature parameter | | | 1.047 | | | |
| Organic phosphorus: | | | | | | |
| Hydrolysis rate | /d | 0.06 | 0.06 | 0.03 | | 0.14 |
| Temperature parameter | | | 1.045 | 1.02 | | 1.08 |
| Settling rate | m/d | 0.6 | 0.6 | | | |
| Dissolved oxygen: | | | | | | |
| Temperature parameter for reaeration | | 1.024 | 1.024 | | | |
| Oxygen per C oxidized | gO2/gC | 2.69 | 2.69 | | | |
| Total Phytoplankton: | | | | | | |
| Maximum growth rate | /d | 0.75 | 0.8 | 1.3 | 1.8 | 2.5 |
| Theta | | 1.066 | 1.066 | | 1.066 | |
| Respiration rate | /d | 0.05 | 0.05 | 0.05 | | 0.2 |
| T parameter for resp. and death | | 1.08 | 1.08 | | 1.08 | |
| Death rate | /d | 0.01 | 0.01 | 0.01 | 0.02 | 0.1 |
| Phosphorus half saturation | mgP/L | 1.2 | 1.2 | 0.5 | 2.5 | 30 |
| Steele (optimal) light parameter | langleys/d | 50 | 75 | 100 | 350 | 400 |
| settling rate | m/d | 0.1 | 0.1 | 0.05 | | 0.2 |
| Herbivorous Zooplankton: | | | | | | |
| Maximum grazing rate | $m^3$/gC/d | 3 | 3 | | | |
| T parameter for grazing | | 1.08 | 1.08 | | | |
| Respiration rate | /d | 0.03 | 0.03 | | | |

| Parameter | Units | Lake Bellaire calibration value | Clam Lake calibration value | suggested[1] | | |
|---|---|---|---|---|---|---|
| | | | | low | moderate | high |
| Death rate | /d | 0 | 0 | | | |
| Grazing efficiency | | 0.6 | 0.6 | | | |
| Algae half-saturation conc. | ugA/L | 1 | 1 | | | |
| Calcite | | | | | | |
| Non-calcium alkalinity | ppm | 29.9 | 29.9 | | | |
| Calcite kinetic coefficient | | 500 | 100 | | | |
| Calcite settling velocity | M/d | 0.3 | 0.3 | | | |
| Calcite light scattering coefficient | $m^2/g$ $CaCO_3$ | 0.22 | 0.3 | | | |
| Light | | | | | | |
| Color absorption coefficient | /m | 0.4 | 0.2 | | | |

note: (1) Various sources, including Chapra (1997), Manhattan College (1996) and Bowie et al., 1985)

## Revision of the Phosphorus Mass Balances Based on Model Results

The simulations made by the Lake Bellaire and Clam Lake water quality models are computed by numerically integrating ordinary differential equations based on the principle of conservation of mass. The model simulations can be interrogated to obtain each of the components of the phosphorus mass balance for the lakes. Since the water quality models impose consistency on the mass balances at higher temporal and spatial resolutions, and include computations for a number of internal processes that are otherwise difficult to estimate, the phosphorus mass balances based on the models are a significant refinement on the mass balances presented previously.

The revised phosphorus mass balances for Lake Bellaire and Clam Lake are presented in Tables 28 and 29. The mass balances are also shown graphically in Figure 26. Tributary loading dominates the input of phosphorus to each lake. On a lake-area basis, the phosphorus loading to Lake Bellaire is 0.27 $gP/m^2/yr$, and loading to Clam Lake is 0.96 $gP/m^2/yr$. We included phosphorus loading from the Bellaire wastewater treatment plant (WWTP) to Lake Bellaire, although the plant effluent is discharged to a drainage field near the Intermediate River so only a portion of this load enters the lake. Even if all of the WWTP loading entered Lake Bellaire, it would only represent 1% of the total phosphorus load to the lake. Note that the upper Grass River phosphorus loading is now calculated from the simulated outflow of the Lake Bellaire model.

Settling was by far the most significant phosphorus loss in Lake Bellaire. Of the total annual loading of phosphorus to Lake Bellaire, 79% is removed by settling. Settling was a less significant loss process in Clam Lake, where most of the phosphorus was lost with the lake outflow. Release of phosphorus from the sediments of each lake were roughly comparable (172 and 150 kg). In Clam Lake, the growth of extensive beds of macrophytes (rooted aquatic plants) removed 24 kg of phosphorus from the water column.

**Table 28. Phosphorus mass balance for Lake Bellaire (November 2005 - October 2006)**

| Component | Loading or loss, kilograms | % of P loading | % of P loss |
|---|---|---|---|
| Upper Intermediate River | 372 | 18 | |
| Cedar River | 1295 | 64 | |
| Butler and Maury Creeks | 12 | 1 | |
| Bellaire WWTP | 29 | 1 | |
| Atmospheric deposition | 125 | 6 | |
| Groundwater | 214 | 11 | |
| Sediment release | 172 | 8 | |
| Settling loss | 1609 | | 73 |
| Grass River outflow | 591 | | 27 |
| Mass in water column | 405 | | |

**Table 29. Phosphorus mass balance for Clam Lake (November 2005 - October 2006)**

| Component | Loading or loss, kilograms | % of P loading | % of P loss |
|---|---|---|---|
| Upper Grass River | 559 | 36 | |
| Cold Creek | 733 | 44 | |
| Finch Creek | 135 | 8 | |
| Shanty Creek | 34 | 2 | |
| Atmospheric deposition | 26 | 2 | |
| Groundwater | 0 | 0 | |
| Sediment release | 150 | 9 | |
| Settling loss | 630 | | 38 |
| Torch River outflow | 1014 | | 61 |
| Macrophyte uptake | 24 | | 1 |
| Mass in water column | 19 | | |

## Model Sensitivity Analysis

As mentioned in the introduction of this report, a model is a simplified version of reality that can be tested. A number of fairly simple tests were initially carried out with the Lake Bellaire and Clam Lake water quality models to explore how the models predict water quality changes in response to changes in loading address the following concerns:

- Under present conditions (i.e., loadings), will water quality in Lake Bellaire and Clam Lake remain the same, improve, or degrade?
- If loadings were to change, how would this change affect water quality? (i.e., which water quality parameters?; change in proportion to the change in loading, or some other relationship?)

- If loadings were to change, how rapidly would this change be reflected by water quality in Lake Bellaire and Clam Lake?
- How does water quality in Lake Bellaire impact Clam Lake?
- What other factors have a substantial impact on the water quality simulations?

Tests of the water quality models which address each of these questions are discussed in the sections below.

No Change

The model simulations used for calibration and confirmation were based on forcing functions derived from meteorological and streamflow data for the period 2003 though 2006. Because these data includes natural variability, the forcing functions tend to vary from one season and year to another. The annual phosphorus loadings to Lake Bellaire, for example, vary by about 140 kg/y between years over the simulated calibration period. This annual variation in the forcing functions may result in some trends in the simulation results, which we wish to separate from trends due to other factors (changes in loading due to scenarios, etc.).

To remove the influence of annual variation in the forcing functions, we ran a "no change" simulation with both models, in which all forcing functions were specified from 2006 data. The same forcing functions were applied to each year of the no change simulations, so any differences in the model predictions from one year of the simulation to another are due to factors other than flow rates, boundary conditions, meteorological forcing functions, or loadings.

Results of the no change simulation run with the Lake Bellaire model are shown in Figures 27 and 28. Repeating the 2006 forcing functions results in a simulation in which the water quality varies very little from one year to the next, in comparison to the calibration simulation. The year-to-year variability in DO, total phosphorus and Secchi depth were each reduced by a factor of 10 as measured by the standard deviation between annual averages. For chlorophyll-a, the variability in the annual averages was reduced by greater than a factor of 25 in comparison to the calibration simulation.

The no change simulation results for Clam Lake are shown in Figures 29 and 30. As was the case in Lake Bellaire, repeating the 2006 forcing functions results in a simulation for Clam Lake in which the water quality varies very little from one year to the next, in comparison to the calibration simulation. The year-to-year variability in DO, total phosphorus and especially chlorophyll-a and Secchi depth were significantly reduced.

The results for the no change simulations in both lakes confirm that water quality is expected to remain the same as long as the phosphorus loadings and other forcing functions remain at their present values and conditions. However, this also implies that the appropriate role of land use and water quality managers is to preventing or minimizing future increases in phosphorus loadings in order to maintain the current water quality of Lake Bellaire and Clam Lake. This will be further demonstrated by simulating changes in lake water quality for the watershed development scenarios, as presented below.

Proportional Loading Change

Of course, there are different kinds of models. Our intuition is in fact a kind of model: one person may believe that increasing nutrient loads to a lake will have no effect on water quality, another may believe that water quality will change in proportion to the loading increase, while another may believe that a much more substantial change in water quality will result. This is one of the values of a water quality model based on mass balance principles: it provides an objective tool to help us understand how different water quality parameters change in response to external factors, with phosphorus loading being the most important in terms of anthropogenic activities. The water quality models are not perfect, but they are far more rational and defensible than intuition.

Our first test of phosphorus loading change with the models, was to simply double the total phosphorus loading to each lake and then compare the simulation results to the calibration simulation. Simulations of the two models were linked together for this test; in other words, the simulated water quality of the Lake Bellaire model outflow was used calculate phosphorus loadings in the upper Grass River, which were then input to the Clam Lake model. The results for the Lake Bellaire model are shown in Figures 31 and 32; “Double P load” simulations can be compared to calibration simulation results for DO, total phosphorus, inorganic/dissolved phosphorus, chlorophyll-a and Secchi depth. Total and inorganic phosphorus concentrations are substantially higher in the double P load simulations, as are the chlorophyll-a concentrations. DO and Secchi depths, on the other hand, are relatively unchanged from the calibration simulations.

Quantitatively, the double P load and calibration simulations for Lake Bellaire were compared by focusing on the 2006 predictions. Minimum DO concentrations in the deep lake layer decreased by 2%. Average total phosphorus concentrations increased by 100% in the surface layer, and by nearly as much in the middle and deep layers. Average inorganic phosphorus concentrations increased by about 100% in the deep lake layer (not shown), and by 130% in the surface and middle layers. In the surface layer, the minimum inorganic phosphorus concentration increased by only 30%. Peak chlorophyll-a concentrations increased by 120% and 70% in the top and middle lake layers, respectively. Average and minimum Secchi depths both declined by about 1%.

Results for the Clam Lake model are shown in Figures 33 and 34. Generally, a similar response in water quality variables to the doubled P load is seen, although some differences between the lake simulations can be seen as well. The average 2006 total phosphorus concentrations increased by 103%, while average inorganic phosphorus concentrations increased by about 140%. Peak chlorophyll-a concentrations increased by 46 % in the top and middle lake layers, compared to the calibration simulation. Minimum DO and Secchi depths both declined by less than 1%. In Clam Lake, the water quality simulations reflect not only the doubling of phosphorus loads directly to that lake, but also a portion of the increased loading to Lake Bellaire, which is propagated to Clam Lake via the Grass River connecting channel.

The chlorophyll-a concentrations peaks very abruptly in the double P load simulations, for both lake models. This becomes more apparent in the later years of each simulation. This is due to the grazing of phytoplankton by herbivorous zooplankton. Zooplankton only become a factor in the model simulations if there are sufficient phytoplankton to support their growth. As the models are calibrated, the threshold for significant zooplankton growth is around a chlorophyll-a concentration of 3 ppb. However, since chlorophyll-a concentrations never reach this threshold in the calibration simulations, there is no way to confirm either the simulation of zooplankton growth or their grazing of phytoplankton. To explore this further, we repeated the double P load simulations with zooplankton removed from the model. These are the results labeled "Double P load (no zooplankton)" in Figures 31 through 34. The changes in simulated chlorophyll-a concentrations when zooplankton are removed are quite dramatic. Without the pressure of zooplankton grazing, the annual blooms of phytoplankton indicated by the elevated chlorophyll-a concentrations are both substantially elevated as well as prolonged. This is especially evident in the Clam Lake "no zooplankton" simulation.

Overall, the results of the "double P load" tests illustrate that the water quality responses to a change in phosphorus loading vary, depending upon the parameter. Total phosphorus concentrations in the lake surface layers vary in proportion to the magnitude of the loading change. The change in surface chlorophyll-a concentrations was more than proportional, while DO and Secchi depths were much less sensitive to phosphorus loading.

Phosphorus Loading Cutoff

The second simple test of phosphorus loading change, was to eliminate ("Cutoff") the total phosphorus loading to each lake at a specific time in the model simulation. In the cutoff scenario, phosphorus loads were eliminated at the start of the third year, 2005. Although unrealistic, this scenario illustrates how rapidly water quality in Lake Bellaire and Clam Lake changes in response to a change in loadings. The cutoff simulations were performed both with and without linking the lake models. Results of this test were again compared to the calibration simulation results.

In the Lake Bellaire model simulations, total phosphorus (Figure 31) and inorganic phosphorus (Figure 32) concentrations are simulated to decline quite rapidly following the cut-off of phosphorus loadings. Average total phosphorus concentrations are simulated to drop by 42% (deep layer) to 59% (surface layer) in the first year after loading cutoff; in the second year after cutoff, total phosphorus concentrations drop by about 80% in all layers. Average phytoplankton concentrations are simulated to decline somewhat faster, while the declines in inorganic phosphorus concentrations are a little slower. Minimum DO concentrations in the deep lake layer increase by 3% and 5% in the first and second years after loading cutoff, while minimum Secchi depths increase by 5% and 6%.

In the Clam Lake model simulations that were not linked to the Lake Bellaire model, total phosphorus ("2005 P load cutoff (Clam Lake only)", Figure 33) and inorganic phosphorus (Figure 34) concentrations are simulated to decline extremely rapidly following the cut-off of phosphorus loadings. Average total phosphorus concentrations are simulated to drop by 89% in the first year after loading cutoff, and by 98% in the second year. Average phytoplankton concentrations are simulated to drop by more than 99% in the first year following loading cutoff, and are zero in the second year. Minimum Secchi depths increase by about 8% in both years.

When the loading cutoff simulations of the 2 models were linked, a more gradual water quality response was predicted in Clam Lake (Figures 33 and 34, “2005 P load cutoff (linked models)”). In fact, the rates of change following loading cutoff fall in-between the rates simulated in Lake Bellaire and those simulated in (unlinked) Clam Lake. For example, the average total phosphorus concentrations are simulated to drop by 73% in the first year after loading cutoff, and by 90% in the second year. Peak phytoplankton concentrations are simulated to drop by 76% in the first year following loading cutoff, and 95% in the second year. Minimum Secchi depths increase by 7% and 9% in the first and second years after loading cutoff.

Results of the loading cutoff scenarios can be used to calculate the half-life of total phosphorus in each lake, the time required for half of the phosphorus mass to be lost from the water column. In Lake Bellaire, the half lives for total phosphorus in the different lake layers range from 0.7 years (250 days) to 0.9 years (320 days). In Clam Lake itself, the half life for total phosphorus is 0.4 years (145 days). Although these response times were based on a loading reduction scenario, the water quality responses are similar in the case of a loading increase. Interestingly, the half life for chlorophyll-a in Clam Lake is only 4 days: once the loadings (which include a specified chlorophyll-a boundary condition) are cut off, the chlorophyll-a is washed out of Clam Lake according to the hydraulic residence time (7.4 days). With such a short residence time, there is no opportunity for phytoplankton to grow.

## Sensitivity of Model Predictions to Organic Carbon Loadings

The sediment diaganesis model in Lake2K-Lite calculates SOD and nutrient fluxes in response to the degradation of organic carbon deposited in the sediments by settling. This organic carbon includes phytoplankton, particulate organic carbon (POC) derived from dead plankton, and POC from other sources including the watershed. This latter component of POC was input to the models as constant concentrations specified for the boundary conditions (i.e., the inflow). POC concentrations were not measured in this project, so the concentrations were input to the models using representative values from other freshwater ecosystems. POC boundary concentrations to each lake were further adjusted to calibrate the SOD and the simulated rate of DO decline in the deep layers of each lake. Through this process, we arrived at POC boundary concentrations of 0.1 ppm for Lake Bellaire and 0.5 ppm in Clam Lake. Although these are reasonable values for oligotrophic-mesotrophic water bodies, we were interested to see how the selection of the POC boundary concentrations influenced the water quality predictions of the two models.

To test the models’ sensitivity to this input, we repeated the calibration simulations, only in this case the POC boundary concentrations were doubled (0.2 ppm for Lake Bellaire and 1 ppm in Clam Lake). The results of these simulations (“Double organic carbon BC”) are plotted in Figures 35 and 36 for Lake Bellaire, and Figures 37 and 38 for Clam Lake. By comparison to the calibration simulations, we can see that the models’ sensitivity to the organic carbon boundary condition is limited to the predictions of dissolved oxygen. In Lake Bellaire, doubling the POC boundary concentration reduces the minimum DO concentration in the deep layer by 0.6 ppm, or 12%. In Clam Lake, the doubling of POC boundary concentration reduces the minimum DO concentration by 1.25 ppm, or 20%.

Given the significance of DO depletion as a water quality concern in Lake Bellaire, it would be prudent to collect measurements of POC to confirm the boundary concentrations used in the Lake Bellaire model. If POC concentrations were found to be substantially different than the calibrated values, additional model refinement would be warranted.

Sensitivity of Model Predictions to Calcite Formation

We also used the water quality models to test the significance of the calcite formation process on lake water quality, by running simulations in which this process was "turned off". This test illustrates, for example, what the water quality of Lake Bellaire and Clam Lake might be if the soils in the Three Lakes watershed were not calcerous. The results are again shown in Figures 35 through 38. With calcite formation "turned off", there is little change in the simulated phosphorus concentrations. Chlorophyll-a concentrations decline slightly in the surface layer of Lake Bellaire (peak concentration drops 9%), but increase in the middle layer (7%). No change in chlorophyll-a is simulated in Clam Lake. As expected, Secchi depths are dramatically higher in both lakes without calcite formation, increasing by an average of 3.6m (65%) in Lake Bellaire and by 2.3 m (37%) in Clam Lake. The annual summer decline in Secchi depth is almost eliminated, with Secchi depths simulated to remain greater than 8 m in both lakes. It is obvious from these results that the formation, settling and dissolution of calcite is responsible for essentially all of the variability in water clarity in these lakes.

Sensitivity of Model Predictions to Sediment Fluxes

Finally, we used the water quality models to test the significance of the sediment flux processes on lake water quality, by running simulations in which the sediment flux submodel was "turned off". The results, shown in Figures 35 through 38, indicate that sediment fluxes play a significant role for each of the water quality parameters. For DO, turning off sediment fluxes noticeably increases DO in the middle and especially the deep layers (120%) of Lake Bellaire, because SOD has been eliminated. In Clam Lake, the increase in DO is not so dramatic (minimum DO increased by 9%). Total phosphorus concentrations, on the other hand, decline significantly (about 20% in Lake Bellaire and 14% in Clam Lake) because sediment phosphorus fluxes have been zeroed. Inorganic phosphorus concentrations also decline, although not as much as total phosphorus. Chlorophyll-a concentrations decline considerably (38% in both the surface and middle layers of Lake Bellaire and 27% in Clam Lake), in response to the drop in phosphorus. Surprisingly, Secchi depths also decline, by an average 0.5m in Lake Bellaire, with the elimination of sediment fluxes. Overall, the sediment fluxes are shown to play an important role for each of these water quality parameters.

## WATERSHED MODELING

Watershed phosphorus loads originate from a variety of sources. These sources include surface runoff from different land uses, as well as septic systems, point sources and other natural and anthropogenic sources, which can enter surface water from ground water. A watershed model was developed for current (2006) conditions and calculates annual phosphorus loads from each lake's watershed, from a variety of sources. The watershed model was developed by Penelope Moskus, Tad Slawecki and coworkers at Limno-Tech, Inc. (Ann Arbor, Michigan). Development and application of the watershed model for the Three Lakes is described in a separate report (Moskus et al., 2007).

Consistency between the watershed and the lake models was a concern, because the watershed model calculates baseline (i.e., current) phosphorus loadings using an approach which is substantially different from the data-based loading estimates used to develop the lake water quality models. Fortunately, we found there to be reasonable agreement between the two. In Lake Bellaire, the total phosphorus loading based on the sum of tributary loading estimates (Table 18) was 1680 kg/yr, while the baseline load calculated by the watershed model was 1950 kg/yr. The difference, 270 kg, is quite reasonable given the uncertainty in the tributary loading estimates. For Clam Lake, the total phosphorus loading based on the sum of tributary loading estimates was 1520 kg/yr, while the baseline load calculated by the watershed model was 1013 kg/yr. In this case, the difference in phosphorus loadings is more substantial, 510 kg. Much of the difference can be attributed to the phosphorus loadings estimates for Cold Creek, which reflect elevated phosphorus concentrations (44 to 209 ppb) measured in that tributary. However, this difference was again considered acceptable given the uncertainty in the tributary loading estimates, as well as the undefined uncertainty in the watershed model results.

Two development scenarios were provided by the Three Lakes Association as seeds for discussion, and the watershed model was applied to predict how the development in each scenario would change the total phosphorus loadings to each of the Three Lakes. These scenarios both included changes in land use. For the Alden scenario, 652 acres in four subwatersheds would be developed, while 1362 acres in seven subwatersheds would be developed in the Shanty Creek scenario (plus an additional 110 acres that drain to Lake of the Woods). For both scenarios, development was assumed to be evenly distributed across presently forested land. Each scenario was evaluated both with and without the installation of sewers to collect wastewater. The changes in phosphorus loadings predicted by the watershed model for each development scenario, both with and without sewers, are summarized in Table 30. Without sewers, the watershed model assumed that the wastewater generated by the residents of the new developments would be treated using conventional on-site septic systems and discharged to the ground via drain fields. For the results with sewers, no additional point source loading was included to account for the additional wastewater discharge, which ultimately must be treated and discharged. The estimated phosphorus loadings from sewered development of 642.5 acres near Alden is 75 kg/year, and from 1,359 acres of sewered development near Shanty Creek is 150 kg/yr.

**Table 30. Changes from "Baseline" Phosphorus Loads Predicted by Watershed Model for Three Lakes Watershed Development Scenarios**

| Development scenario | Change in phosphorus loading from baseline watershed loading (kg/y) | | |
|---|---|---|---|
| | Lake Bellaire | Clam Lake | Torch Lake |
| Alden: 642.5 ac development, ~5,000 added residents | | | |
| Unsewered | 0 | +79 | +492 |
| Sewered | 0 | +28 | +174 |
| Shanty Creek: 1,359 ac development, ~10,000 added residents | | | |
| Unsewered | +606 | +236 | 0 |
| Sewered | +215 | +59 | 0 |

The changes in phosphorus loadings predicted by the watershed model (Table 30) were run through the Lake Bellaire and Clam Lake water quality models, as described in the next section, to forecast how each of these development scenarios would impact water quality in the Three Lakes. Although the water quality model developed for Torch Lake (Endicott et al., 2006) was not run as part of this project, we could still forecast water quality changes in Torch Lake based on results presented in that report.

## WATER QUALITY MODEL FORECASTS FOR LAKE BELLAIRE AND CLAM LAKE

The Lake Bellaire and Clam Lake models were applied to forecast water quality for each of the development scenarios of interest to TLA, based on changes to phosphorus loadings predicted by the watershed model. More generally, these forecasts illustrate how can the models can be used in the planning process to manage and protect water quality in Lake Bellaire and Clam Lake. Details regarding each of these scenarios are provided below. Of course, there are a number of caveats and limitations that impact the accuracy and reliability of these forecasts. These include:

$ These forecast results do not convey the uncertainty in the predictions due to errors in either the model structure or the calibrated parameters;

$ The forecasts assume that future forcing functions (e.g., meteorology, tributary flows, settling fluxes) can be reasonably extrapolated from prior data. Such extrapolation cannot anticipate factors such as global warming impacts, exotic species introduction, etc.

$ The models simulate water quality as whole-lake average concentrations. Any horizontal gradients in water quality will not be resolved in these models. The data for both lakes (Table 15) suggest that total phosphorus concentrations tend to be higher in shallow, nearshore water than at the deep-water stations, although the sampling design was not intended to detect horizontal spatial gradients.

Despite these shortcomings, we believe that the watershed model together with the Lake Bellaire and Clam Lake models provides a useful tool to test what impacts future development in the Three Lakes watershed will likely have on water quality.

The water quality forecasts were conducted by repeating the 2003-2006 linked simulations with the Lake Bellaire and Clam Lake models, modifying only the tributary phosphorus loadings according to the watershed loading changes predicted by the watershed model. The water quality impacts of each scenario can then be evaluated by comparing the scenario forecast results to the calibration/confirmation results (hereafter referred to as the "no development" scenario), which were discussed in some detail in a previous section of this report.

## Alden Development Scenario

### Unsewered Development

The unsewered Alden development scenario would result in an additional 79 kg/y watershed phosphorus loading to Clam Lake and an additional 492 kg/y watershed loading to Torch Lake, according to the watershed model predictions (Table 30). Because this scenario results in no additional watershed phosphorus loadings to Lake Bellaire, the Clam Lake model was linked to the no development scenario results of the Lake Bellaire model. Results of the Clam Lake model simulation of the unsewered Alden development scenario are presented and compared with the no development scenario results for corresponding state variables in Figures 39 and 40. There were only minimal differences (less than 1%) between the simulations of DO in Clam Lake for the unsewered Alden development scenario versus the no development scenario. For other water quality parameters simulated in Clam Lake, the differences are also fairly small. Average total phosphorus concentrations increase by 0.22 ppb (5%) for the unsewered Alden development scenario versus the no development scenario. Peak chlorophyll-a concentrations are simulated to increase by about 0.15 ppb (6%), while minimum Secchi depths are simulated to decrease by about 0.07 m (1.4%).

### Sewered Development

The sewered Alden development scenario would result in an additional 28 kg/y watershed phosphorus loading to Clam Lake and an additional 174 kg/y watershed loading to Torch Lake, according to the watershed model predictions. Results of the Clam Lake model simulation of the sewered Alden development scenario are also presented and compared with the no development scenario results for corresponding state variables in Figures 39 and 40. Again, there were essentially no differences between the simulations of DO in Clam Lake for the sewered Alden development scenario versus the no development scenario. For the other water quality parameters, the differences between the development and no development simulations are smaller than for the unsewered Alden scenario. Average total phosphorus concentrations increase by 0.1 ppb (2%) for the sewered Alden development scenario versus the no development scenario. Peak chlorophyll-a concentrations are simulated to increase by about 0.05 ppb (2%), while minimum Secchi depths are simulated to decrease by about 0.09 m (1.8%).

We can also forecast the impact of the Alden development scenario on water quality in Torch Lake. Phosphorus loading to Torch Lake would increase from watershed loads directly to Torch Lake (from Spencer Creek, direct runoff and groundwater flow), as well as the increased loading to Clam Lake, a portion of which will be conveyed to Torch Lake via the Clam River. The direct watershed loads are provided in Table 30. The increased phosphorus loadings from the Clam River are provided by the Clam Lake model simulations: 47 kg/y (unsewered) and 17 kg/y (sewered). Considering both these loading components, the cumulative increase in phosphorus loading to Torch Lake for the unsewered Alden development is calculated to be 539 kg/y, while the cumulative increase in phosphorus loading for the unsewered Alden development is 191 kg/y. Using the load-response relationship developed from the Torch Lake water quality model (Endicott et al., 2006), these loadings are forecast to increase total phosphorus concentrations in Torch Lake by 6% (from 2.36 to 2.49 ppb) for the unsewered Alden development, and by 2% (to 2.41 ppb) for the sewered Alden development.

As this scenario demonstrates, the phosphorus loading impact of an individual development needs to be fairly large to impact water quality at the scale of the Three Lakes. This was demonstrated by the sewered Alden development scenario: a 28 kg phosphorus loading increase was simulated to result in a 0.1 ppb increase in total phosphorus concentrations in Clam Lake. Such a change would be too small to detect. On the other hand, water quality is affected *cumulatively* by the sum of loadings to the lake, based on decisions made at many potential development sites, so the model may be more valuable in terms of forecasting changes occurring at the scale of the watershed or the drainage basin.

## Shanty Creek Development Scenario

### Unsewered Development

The unsewered Shanty Creek development scenario would result in an additional 606 kg/y watershed phosphorus loading to Lake Bellaire and an additional 236 kg/y watershed loading to Clam Lake, according to the watershed model predictions (Table 30). Because this scenario indicates that watershed phosphorus loadings would increase to both Lake Bellaire and Clam Lake, the models were linked for this simulation.

Results of the Lake Bellaire model simulation of the unsewered Shanty Creek development scenario are presented and compared with the no development scenario results for corresponding state variables in Figures 41 and 42. Total phosphorus concentrations in the different lake layers increase 1 to 1.4 ppb (26 to 30%) in this simulation, compared to no development. Peak chlorophyll-a concentrations increase by 0.7 to 0.75 ppb (37 to 41%), while minimum Secchi depths are reduced by 1.3 % (0.08 m).The minimum dissolved oxygen concentrations in the deep layer of Lake Bellaire is predicted to be about 0.11 ppm (2.3%) lower for the unsewered Shanty Creek development scenario versus the no development scenario (not shown).

The Clam Lake model simulation of the unsewered Shanty Creek development scenario are presented and compared with the no development scenario results for corresponding state variables in Figures 43 and 44. The minimum dissolved oxygen concentrations in Clam Lake are predicted to be about 0.03 ppm (0.4%) lower for the unsewered Shanty Creek development scenario versus the no development scenario (Figure 43). Total phosphorus concentrations are predicted to increase by about 1.2 ppb (26%). Although the average concentrations of inorganic phosphorus are also predicted to increase, the minimum (summer) values are barely affected (less than 0.02 ppb or 1.6% difference; Figure 44). For the unsewered Shanty Creek development scenario versus the no development scenario, peak chlorophyll-a concentrations are predicted to increase by about 1.0 ppb (37%), while minimum Secchi depths decrease by about 0.08 m (1.7%).
It is interesting to note that for this scenario, water quality was more affected in Clam Lake, even though the total phosphorus loading change was substantially larger in Lake Bellaire. This reinforces the concept that water quality is affected *cumulatively* by the sum of loadings to the lake, based on decisions made at many potential development sites. As this scenario demonstrated, this includes loadings to upstream lakes which may be passed downstream.

Sewered Development

The sewered Shanty Creek development scenario would result in an additional 215 kg/y watershed phosphorus loading to Lake Bellaire and 59 kg/y watershed loading to Clam Lake, according to the watershed model predictions (Table 30). Again, because this scenario indicates that watershed phosphorus loadings would increase to both Lake Bellaire and Clam Lake, the models were linked for this simulation.

Results of the Lake Bellaire model simulation of the sewered Shanty Creek development scenario are presented and compared with the no development scenario results for corresponding state variables in Figures 41 and 42. Total phosphorus concentrations in the different lake layers increase 0.35 to 0.5 ppb (9 to 10%) in this simulation, compared to no development. Peak chlorophyll-a concentrations increase by about 0.25 ppb (13 to 14%), while minimum Secchi depths are reduced by 0.7 % (about 0.03 m).The minimum dissolved oxygen concentrations in the deep layer of Lake Bellaire is predicted to be about 0.04 ppm (0.8%) lower for the sewered Shanty Creek development scenario versus the no development scenario (not shown).

The Clam Lake model simulation of the sewered Shanty Creek development scenario are presented and compared with the no development scenario results for corresponding state variables in Figures 43 and 44. The minimum dissolved oxygen concentrations in Clam Lake are predicted to be only marginally (<0.1%) lower for the sewered Shanty Creek development scenario versus the no development scenario (Figure

43). Average total phosphorus concentrations are predicted to increase by about 0.4 ppb (8%). Average inorganic phosphorus concentrations are predicted to increase by 4.8%, although the minimum (summer) values are again barely affected (less than 0.01 ppb or 1.2% difference; Figure 44). For the sewered Shanty Creek development scenario versus the no development scenario, peak chlorophyll-a concentrations are predicted to increase by about 0.3 ppb (11%), while minimum Secchi depths decrease by about 0.04 m (0.7%).

The model results can also be used to evaluate the water quality benefits of installing sewers with new development. According to the watershed model, sewered development reduces phosphorus loading to Lake Bellaire by 391 kg/y compared to unsewered development, and a reduction of 177 kg/y to Clam Lake. In Lake Bellaire, the model simulations show that the average total phosphorus concentrations are reduced by 0.64 ppb (top layer) to 0.91 ppb (bottom layer), an average reduction of 14%, for sewered vs. unsewered development. Peak chlorophyll-a concentrations are reduced by 0.46 to 0.49 ppb, or 19%. In Clam Lake, the average total phosphorus concentrations are reduced by 0.87 ppb or 14%; peak chlorophyll-a concentrations are reduced by 0.70 ppb, or 19%.

As we did for the Alden development, we can also forecast the impact of the Shanty Creek development scenario on water quality in Torch Lake. In this case, phosphorus loading to Torch Lake would only increase from the loading to Lake Bellaire and Clam Lake, a portion of which will be conveyed to Torch Lake via the Clam River, because for this scenario there would be no watershed loads directly to Torch Lake. The increased phosphorus loadings from the Clam River are provided by the Clam Lake model simulations: 263 kg/y (unsewered) and 78 kg/y (sewered). Again using the load-response relationship developed from the Torch Lake water quality model, these loadings are forecast to increase total phosphorus concentrations in Torch Lake by 3% (from 2.36 to 2.43 ppb) for the unsewered Shanty Creek development, and by 1% (to 2.38 ppb) for the sewered Shanty Creek development. Although the water quality changes forecast for Torch Lake in this scenario are small, they still demonstrate that development in the upstream watershed have an impact on the downstream lakes.

# CONCLUSIONS AND RECOMMENDATIONS

1. The water quality of Lake Bellaire and Clam Lake is generally good in comparison to the normal measures of lake trophic status, as demonstrated by the data collected in this project:

| Variable | Torch Lake | Lake Bellaire | Clam Lake | Oligotrophic | Mesotrophic | Eutrophic |
|---|---|---|---|---|---|---|
| **Total Phosphorus (ppb)** | ***2.6*** | ***3.7*** | ***4.5*** | <10 | 10-20 | >20 |
| **Chlorophyll (ppb)** | ***0.55*** | ***1.5*** | ***2.2*** | <4 | 4-10 | >10 |
| **Secchi Disk Depth (m)** | ***5-10*** | ***3.6-7.6*** | ***3-6*** | >4 | 2-4 | <2 |
| **Hypolimnetic Dissolved Oxygen (% saturation)** | ***100*** | ***<40*** | ***<80*** | >80 | 10-80 | <10 |

   Average total phosphorus and chlorophyll-a concentrations place both lakes in the oligotrophic (nutrient-poor) category, although both are mesotrophic according to minimum (summer) Secchi depths and DO concentrations.
2. Comparisons to recent monitoring data indicate little change in water quality over the past 5 years. Comparison to 1982 data shows some improvement in dissolved oxygen depletion in Lake Bellaire.
3. Because water clarity primarily responds to the precipitation of calcium carbonate, Secchi depth measurements cannot be used to monitor changes in the concentrations of either chlorophyll-a or phosphorus.
4. Management should emphasize protection of existing Lake Bellaire and Clam Lake water quality.
5. Total phosphorus loadings to both lakes, expressed on an area-normalized basis, exceed "permissible" levels established for controlling eutrophication in lakes.
6. Water and phosphorus mass balances demonstrate that flow, loading and loss estimates appear reasonable in comparison to independent estimates and data for other water bodies; however, accuracy of some of these components were less than desired due to lack of data.
7. Tributaries contribute most of the phosphorus loadings to Lake Bellaire and Clam Lake.
8. Settling removed 79% of the phosphorus entering Lake Bellaire, but only 41% from Clam Lake.
9. Release of phosphorus from the sediments of each lake were roughly comparable (172 kg/y in Lake Bellaire and 150 kg/y in Clam Lake). In Clam Lake, the growth of extensive beds of macrophytes (rooted aquatic plants) in the summer removed 24 kg of phosphorus from the water column.

10. A watershed modeling approach was developed and applied to address the linkage between land use change and phosphorus loadings in the Three Lakes watershed (Moskus et al., 2007). The watershed model was applied to predict current and future watershed phosphorus loads to each of the lakes for a number of scenarios intended to represent realistic population growth and development. The scenarios included (1) an increase of 5,000 residents in 652 acres of development in Alden and (2) an increase 0f 10,000 residents in 1362 acres in Shanty Creek.
11. The changes in phosphorus loading predicted by the watershed model for each of the scenarios were used in conjunction with the water quality models to simulate the expected water quality response to the loading changes. These results illustrate that the models are capable of forecasting water quality changes to evaluate the impacts of development and land use changes.
12. Phosphorus and chlorophyll-a concentrations were forecast to respond substantially to increased phosphorus loadings from the development scenarios. Dissolved oxygen concentrations and Secchi depths (water clarity) were less responsive to the phosphorus loading increases. The forecasts indicated that water quality responses should also be expected to occur in the lakes "downstream" from the watersheds where development occurs.
13. The lake models predict that water quality parameters will respond rapidly to changes in loading. In Lake Bellaire, the "half lives" for total phosphorus range from 0.7 years (250 days) to 0.9 years (320 days), depending on the depth layer. In Clam Lake, the half life for total phosphorus is 0.4 years (145 days).
14. We believe that the watershed model together with the Lake Bellaire and Clam Lake models provides a useful tool to test what impacts future development in the Three Lakes watershed will likely have on water quality.
15. To remain useful, the water quality model needs to be updated periodically. TLA should conduct additional model confirmation as data become available from surveillance monitoring. This should include monitoring of DO concentrations in Lake Bellaire, which reach low levels near the lake bottom at the end of each summer. Other recommendations include:

$ TLA should consider an ongoing program to monitor the mainstem flow rate of the Elk River in at least one location on a connecting channel (lower Intermediate River, upper Grass River or Clam River). Such flow information is fundamental for understanding and managing water resources, which may be impacted by various factors such as climate change. For example, regional evaporation rates in the past 2 years (2205 and 2006) have been the highest ever recorded. The easiest way to monitor mainstem flow appears to be the approach of correlating Grass River flows to the difference in water levels between Lake Bellaire and Clam Lake.

$ TLA should recognize the value of the meteorological data provided by the three MAWN stations located in the Three Lakes drainage basin, and support the maintenance of this resource.

$ Further monitoring is required to confirm source of high phosphorus concentrations in Cold Creek, which on average were considerably higher than in any other tributary monitored in this project.

$ The density of zebra mussel infestation and the summer development of nuisance blue-green algae (especially *Microcystis* ) should be monitored annually, recognizing the possible linkages between the two.

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Appendix I

# Characterization of Groundwater Phosphorus in Lake Bellaire

by
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Apr.. 2007

# Lake Bellaire Groundwater

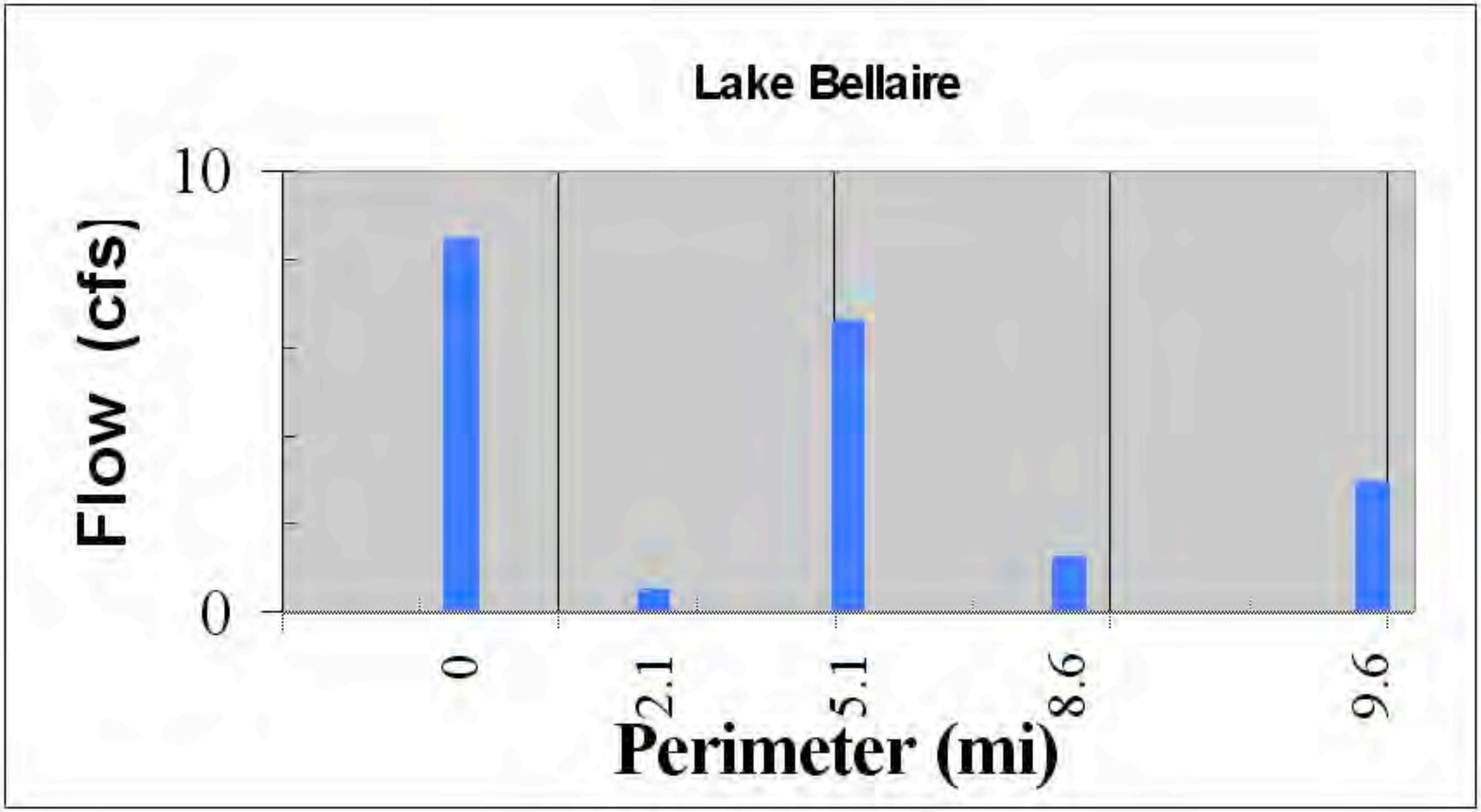
The groundwater sampling and analysis protocol for Lake Bellaire is the same as that for Torch Lake. Refer to Appendix I of The Development of a Predictive Nutrient-Based Water Quality Model for Torch Lake by the Great Lakes Environmental Center and Three Lakes Association by D. Endicott and M. DeGrave, Mar. 17., 2006.

| Well | Peri Dist | Date | | Blank TP | Well TP | Lake TP | dl | dh | T2-T1 | H2 | H1 | D | L | K(10**4) | dh/dl | S | A(10**-4) | Q | TPQ AVG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | (mi) | 2006 | | (ppb) | (ppb) | (ppb) | (in) | (in) | (s) | (in) | (in) | (in) | (in) | (ft/s) | | (ft) | (ft) | (cfs) | (kg/yr) |
| #1 | | 5/19 | Unfilt. TP | 1.2 | | | 42.0 | | | 24.0 | 12.0 | 0.170 | 3.0 | | | | | | |
| | | 6/8 | Unfilt. TP | | 5.6 | 2.6 | 42.0 | 4.0 | | 24.0 | 12.0 | 0.170 | 3.0 | | | | | | |
| | | 7/13 | | | | | 42.0 | 1.8 | | 24.0 | 12.0 | 0.170 | 3.0 | | | | | | |
| | | 7/20 | Unfilt. TP | 1.7 | | | 42.0 | 6.5 | 5.0 | 24.0 | 12.0 | 0.170 | 3.0 | 0.50 | 0.0429 | 8,000 | 80 | 1.70 | |
| | | 7/27 | Filt. TP | | 8.4 | 2.4 | 42.0 | 5.0 | 2.0 | 24.0 | 12.0 | 0.170 | 3.0 | 1.24 | 0.1548 | 8,000 | 80 | 15.34 | |
| | | 9/7 | Filt. DP | | 4.2 | | 42.0 | 4.3 | 2.5 | 24.0 | 12.0 | 0.170 | 3.0 | 0.99 | 0.1024 | 8,000 | 80 | 8.12 | |
| | 0.0 | | AVG | 1.4 | 6.1 | 2.5 | | | | | | | | | | | AVG | 8.4 | 45.2 |
| | | | | | | | | | | | | | | | | | | | |
| #2 | | 5/19 | | | | | 42.0 | | | 24.0 | 12.0 | 0.170 | 3.0 | | | | | | |
| | | 6/8 | Unfilt. TP | | 37.9 | 12.1 | 42.0 | 1.0 | 2.0 | 24.0 | 12.0 | 0.170 | 3.0 | 1.24 | 0.0238 | 1,000 | 10 | 0.30 | |
| | | 7/13 | | | | | 42.0 | | | 24.0 | 12.0 | 0.170 | 3.0 | | | | | | |
| | | 7/27 | Filt. TP | | 7.1 | 2.0 | 42.0 | 1.5 | 1.0 | 24.0 | 12.0 | 0.170 | 3.0 | 2.48 | 0.0357 | 1,000 | 10 | 0.89 | |
| | | 9/7 | Filt. DP | | 6.4 | | 42.0 | 1.0 | 2.5 | 24.0 | 12.0 | 0.170 | 3.0 | 0.99 | 0.0238 | 1,000 | 10 | 0.24 | |
| | 2.1 | | AVG | | 6.8 | 2.0 | | | | | | | | | | | AVG | 0.5 | 2.8 |
| | | | | | | | | | | | | | | | | | | | |
| #3 | | 5/25 | | | | | 42.0 | | | 24.0 | 12.0 | 0.170 | 3.0 | | | | | | |
| | | 6/8 | Unfilt. TP | | 19.0 | 9.3 | 42.0 | 5.0 | 7.0 | 24.0 | 12.0 | 0.170 | 3.0 | 0.35 | 0.1190 | 23,000 | 230 | 9.70 | |
| | | 7/13 | Unfilt. TP | | | | 42.0 | 1.3 | 7.0 | 24.0 | 12.0 | 0.170 | 3.0 | 0.35 | 0.0310 | 23,000 | 230 | 2.52 | |
| | | 7/27 | Filt. TP | | 11.1 | | 42.0 | 6.0 | 11.0 | 24.0 | 12.0 | 0.170 | 3.0 | 0.23 | 0.1429 | 23,000 | 230 | 7.40 | |
| | | 9/3 | Filt. DP | | 9.6 | | 42.0 | 7.0 | 3.0 | 24.0 | 12.0 | 0.170 | 3.0 | 0.83 | 0.1667 | 23,000 | 230 | 31.67 | |
| | 5.1 | | AVG | | 13.2 | 9.3 | | | | | | | | | | | AVG | 6.5 | 76.9 |
| | | | | | | | | | | | | | | | | | | | |
| | | 4/27 | Unfilt. TP | | | 7.1 | | | | | | | | | | | | | |
| | | 7/6 | Unfilt. TP | | | 6.4 | | | | | | | | | | | | | |
| #4 | | 7/13 | Unfilt. TP | 2.0 | | | | | | 24.0 | 12.0 | 0.170 | | | | | | | |
| | | 7/20 | Filt. TP | | 20.0 | | 42.0 | 8.0 | 3.0 | 24.0 | 12.0 | 0.170 | 3.0 | 0.83 | 0.1905 | 1,000 | 10 | 1.57 | |
| | | | Unfilt. TP | | 5.3 | | 42.0 | | | 24.0 | 12.0 | 0.170 | 3.0 | | | | | | |
| | | 9/7 | Filt. DP | | 7.4 | | 42.0 | 5.5 | 4.0 | 24.0 | 12.0 | 0.170 | 3.0 | 0.62 | 0.1310 | 1,000 | 10 | 0.81 | |
| | 8.6 | | AVG | | 10.9 | 6.8 | | | | | | | | | | | AVG | 1.2 | 11.6 |

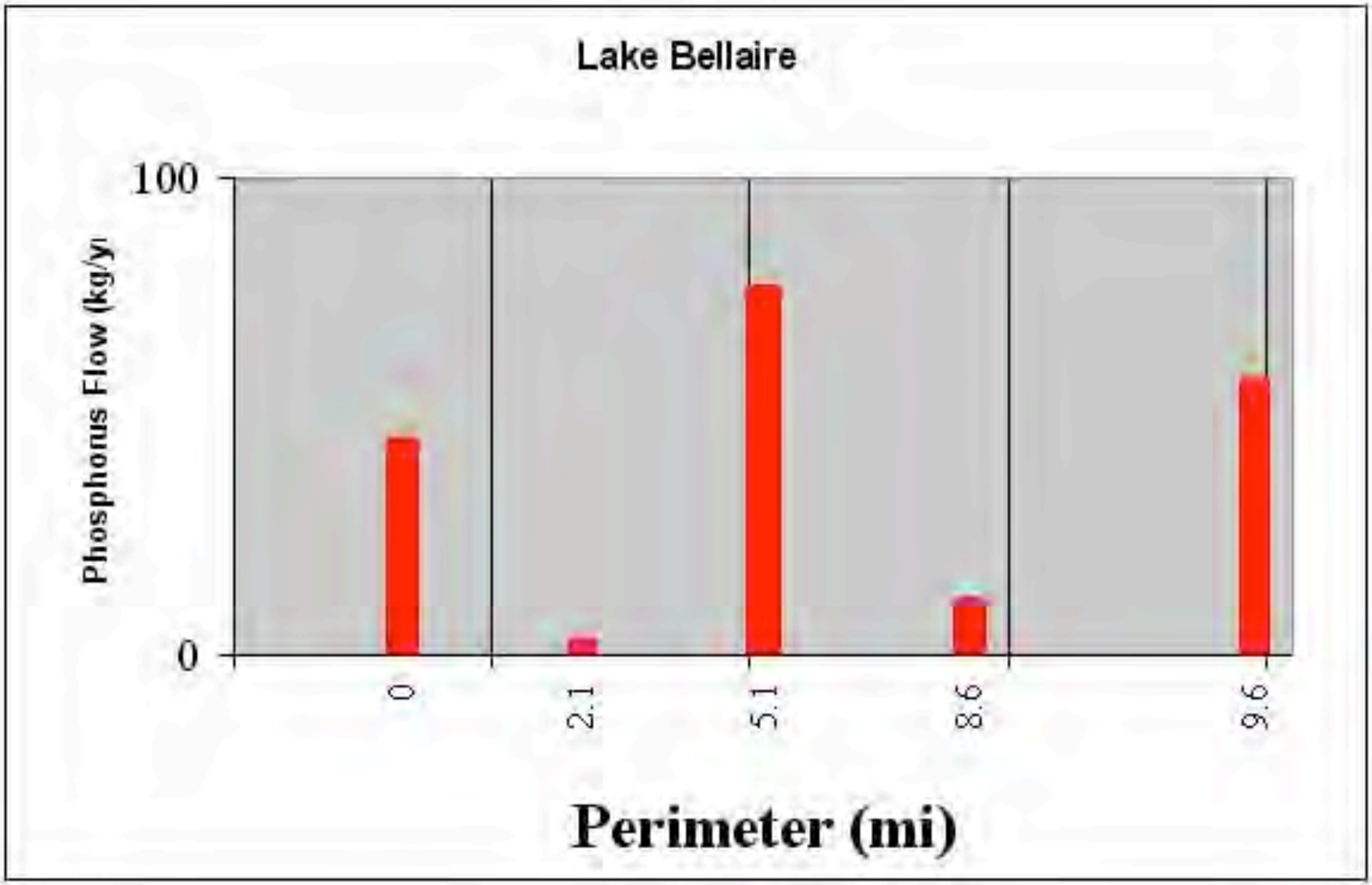
| Well # | Peri Dist (mi) | Date 2006 | | Blank TP (ppb) | Well TP (ppb) | Lake TP (ppb) | dl (in) | dh (in) | T2-T1 (s) | H2 (in) | H1 (in) | D (in) | L (in) | K(10**4) (ft/s) | dh/dl | S (ft) | A(10**-4) (ft) | Q (cfs) | TPQ AVG (kg/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| #5 | | 7/20 | Filt. TP | 0.6 | | | 42.0 | 4.5 | 5.0 | 24.0 | 12.0 | 0.170 | 3.0 | 0.50 | 0.1071 | 8,000 | 80 | 4.25 | |
| | | 7/27 | Filt. TP | | 21.2 | 5.3 | 42.0 | 6.5 | 12.0 | 24.0 | 12.0 | 0.170 | 3.0 | 0.21 | 0.1548 | 8,000 | 80 | 2.56 | |
| | | 9/7 | Filt. DP | | 12.4 | | 42.0 | 5.3 | 10.0 | 24.0 | 12.0 | 0.170 | 3.0 | 0.25 | 0.1262 | 8,000 | 80 | 2.50 | |
| | 8.6 | | AVG | 0.6 | 16.8 | 5.3 | | | | | | | | | | | AVG | 3.10 | |
| | | | | | | | | | | | | | | | | | | | |
| #7 | | 5/25 | Unfilt. TP | | | | | | | | | | | | | | | | |
| | | 6/22 | Unfilt. TP | | 29.6 | | 42.0 | 1.0 | 1.0 | 24.0 | 12.0 | 0.170 | 3.0 | 2.48 | 0.0238 | 8,000 | 80 | 4.72 | |
| | | 7/13 | | | | | 42.0 | 1.0 | 3.0 | 24.0 | 12.0 | 0.170 | 3.0 | 0.83 | 0.0238 | 8,000 | 80 | 1.57 | |
| | | 9/7 | Filt. DP | | 15.6 | | 42.0 | 1.0 | 2.0 | 24.0 | 12.0 | 0.170 | 3.0 | 1.24 | 0.0238 | 8,000 | 80 | 2.36 | |
| | 9.6 | | AVG | | 22.6 | 5.2 | | | | | | | | | | | AVG | 2.9 | 57.9 |
| | | | | | | | | | | | | | | | | | | | |
| #1 | 12.5 | | AVG | | 12.7 | 5.2 | | | | | | | | | | | Total | 22.6 | 194.5 |

| Table Summary | | Average | Range | Units |
|---|---|---|---|---|
| Bellaire | Lake TP Samples | 6.2 | 2.0-12.1 | ppb |
| | Well TP Samples | 14.5 | 4.2-29.6 | ppb |
| | Water Flow | 20 | | cfs |
| | Phosphorus Flow | 194 | | kg/yr |

Summary of previous spreadsheet showing the average and range of the lake, piezometer, water and TP flows




Groundwater flow (cfs) versus Lake Bellaire perimeter clockwise starting with north central piezometer station #1.




Groundwater phosphorus flow (kg/yr) versus Lake Bellaire perimeter clockwise starting with north central piezometer station #1.

Appendix II

# Seasonal Variations of

# Temperature, Dissolved Oxygen,

# pH, and Specific Conductivity

# in Lake Bellaire and Clam Lake

# 2005-2006

Three Lakes Association
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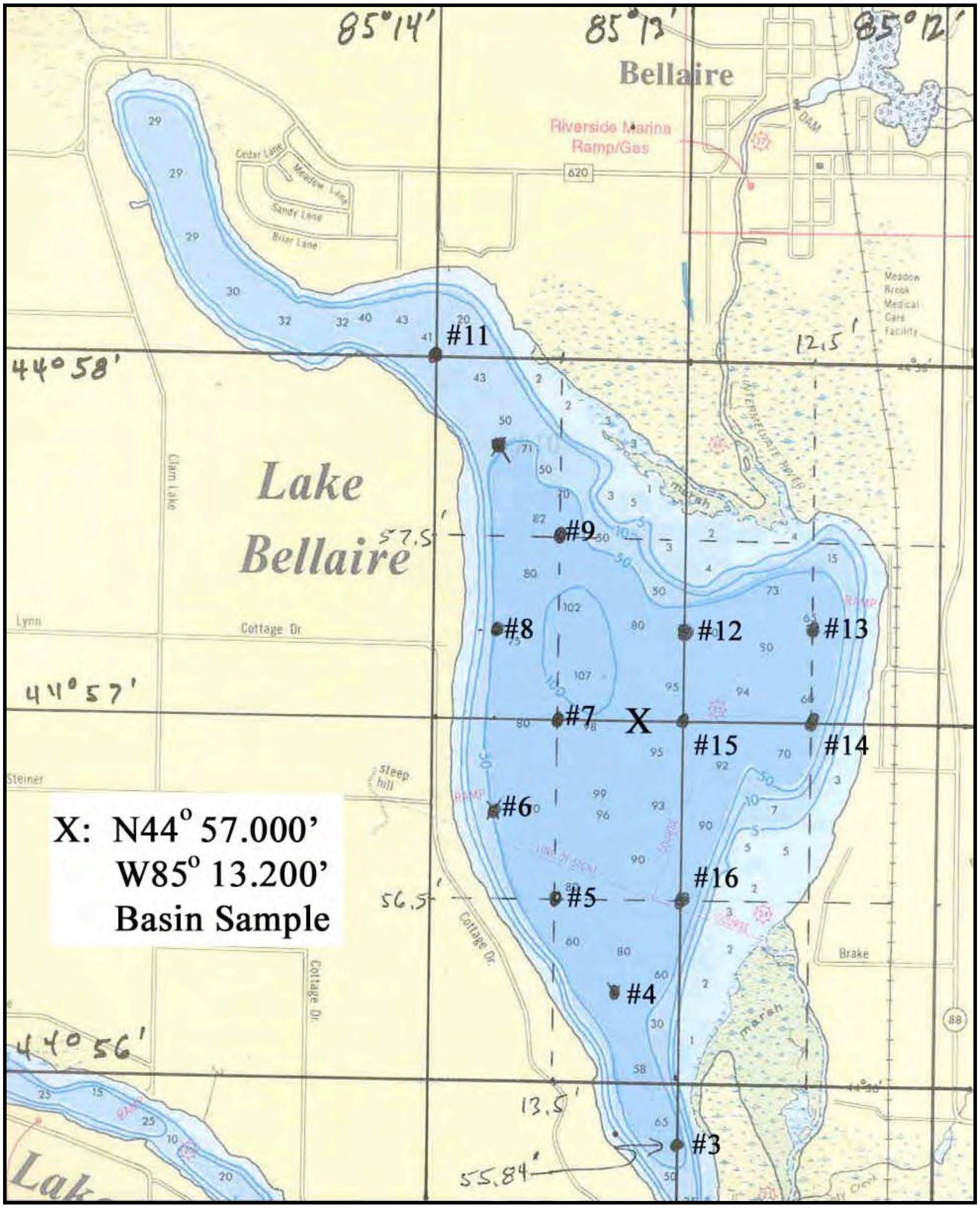
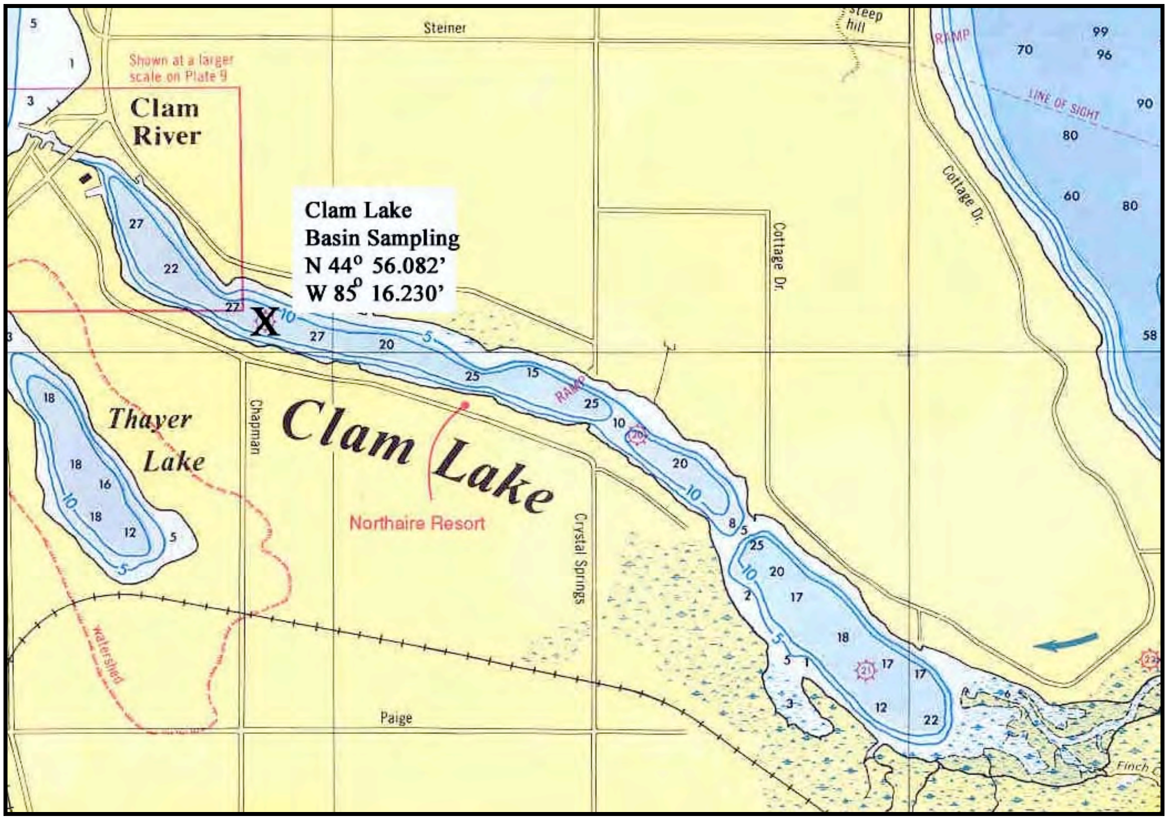
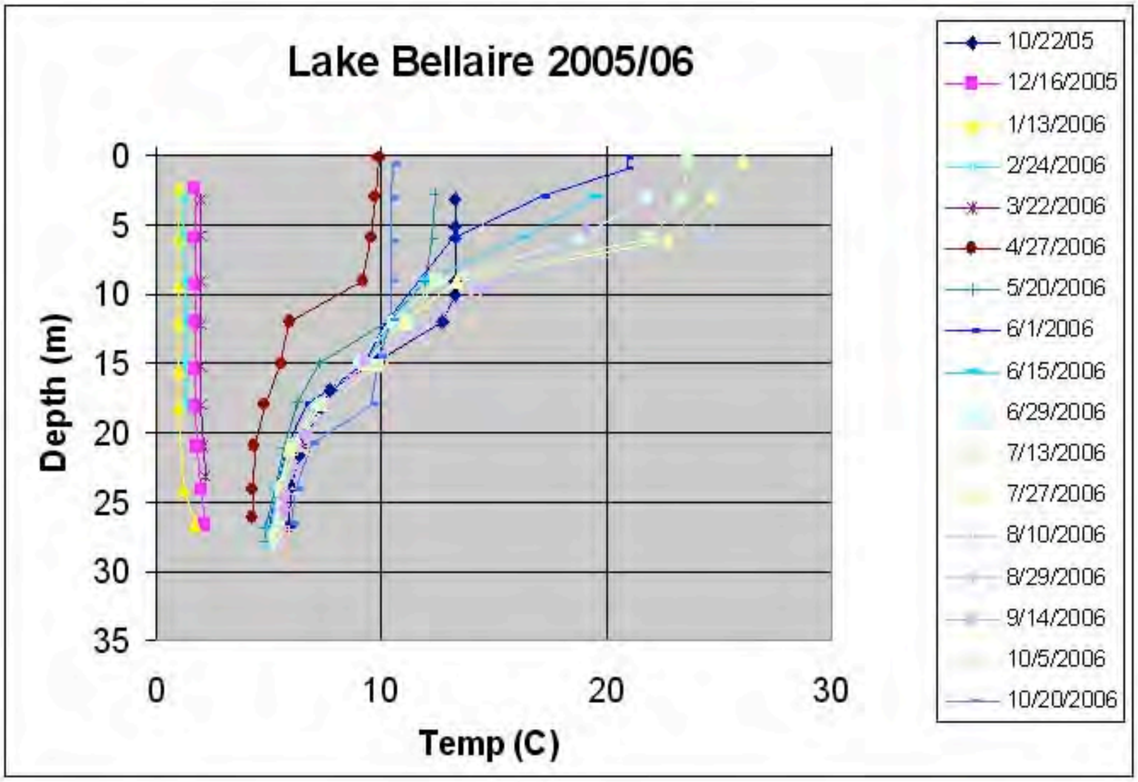
Apr. 2007



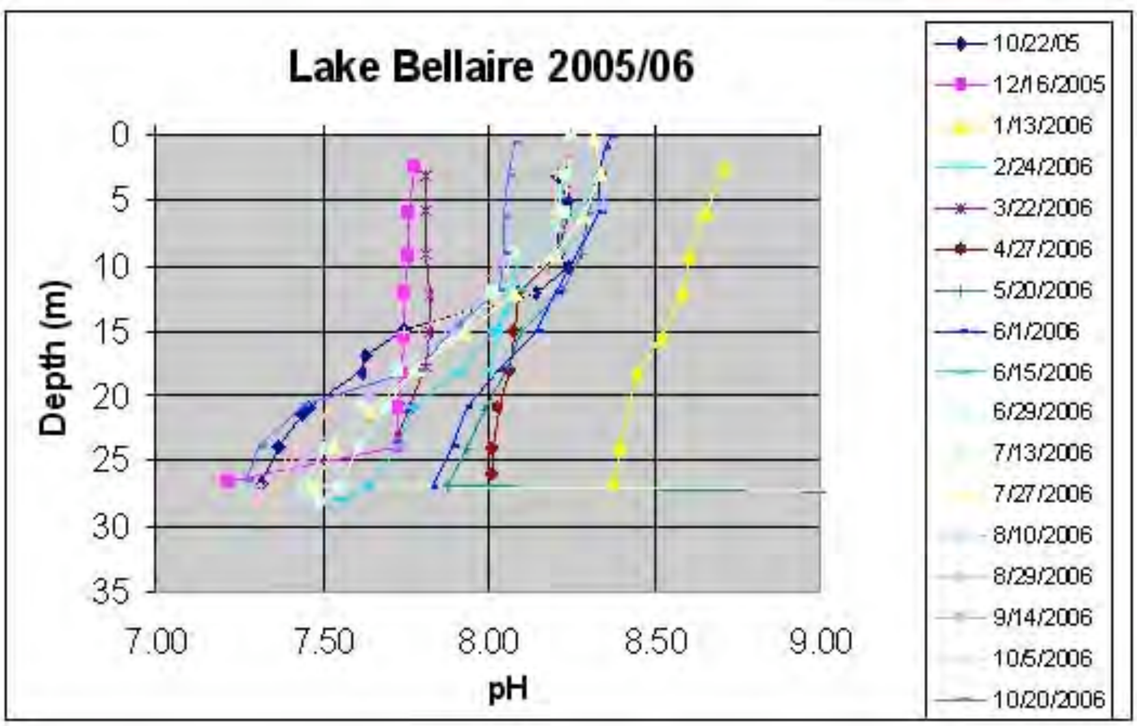

Map of Lake Bellaire showing sampling locations.



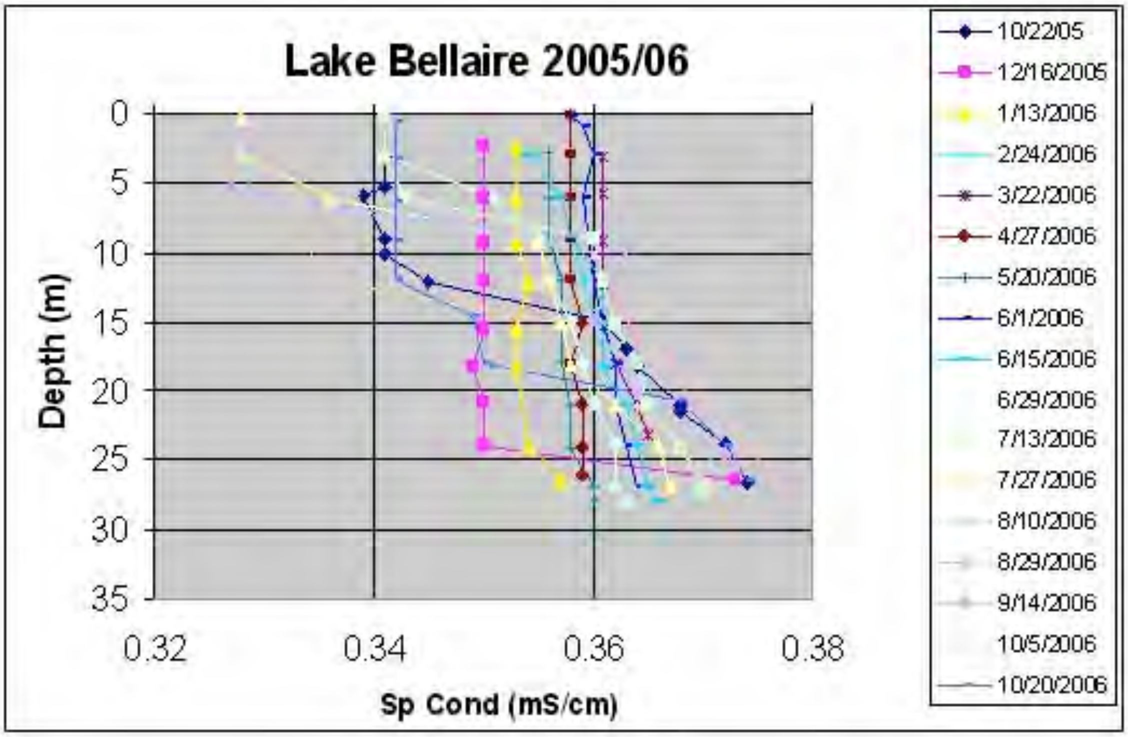

Map of Clam Lake showing sampling location



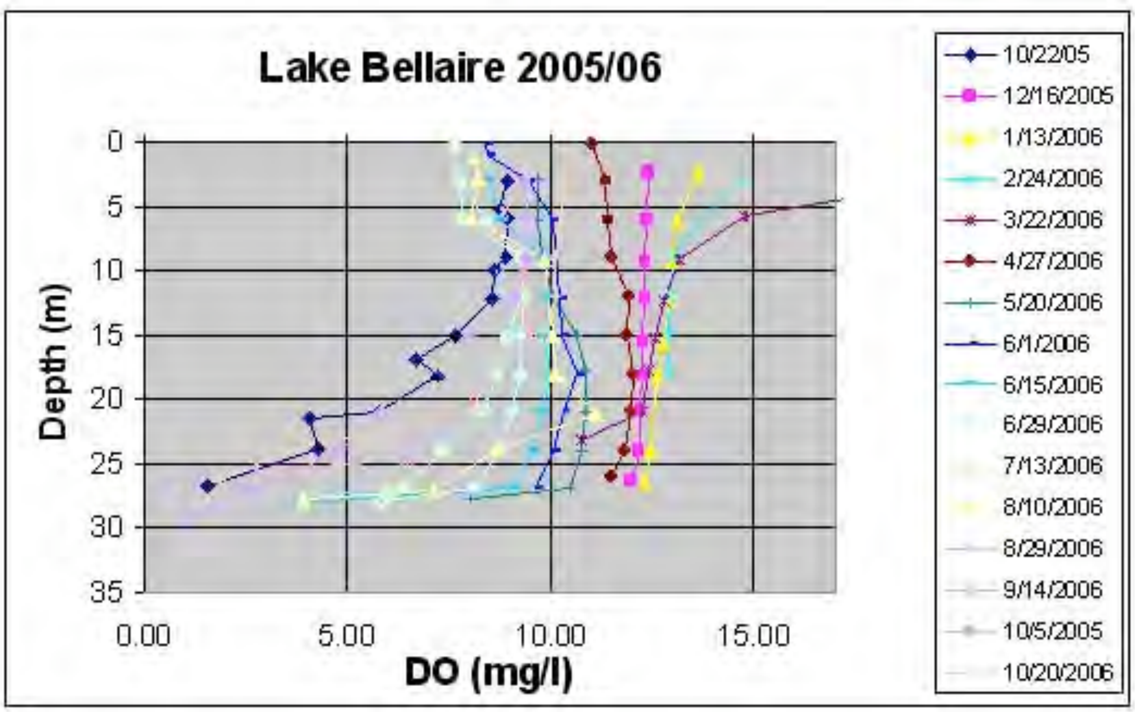

Seasonal temperature profiles from 2005/6 for the Lake Bellaire deep basin



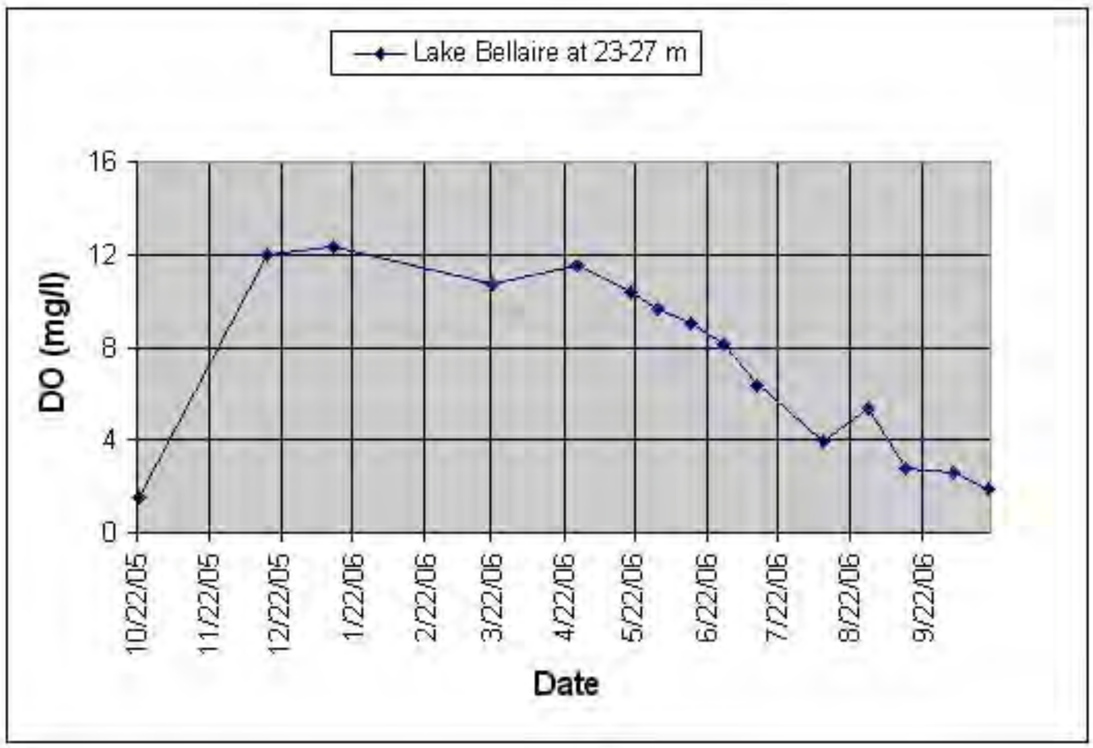

Seasonal pH profiles from 2005/6 for the Lake Bellaire deep basin



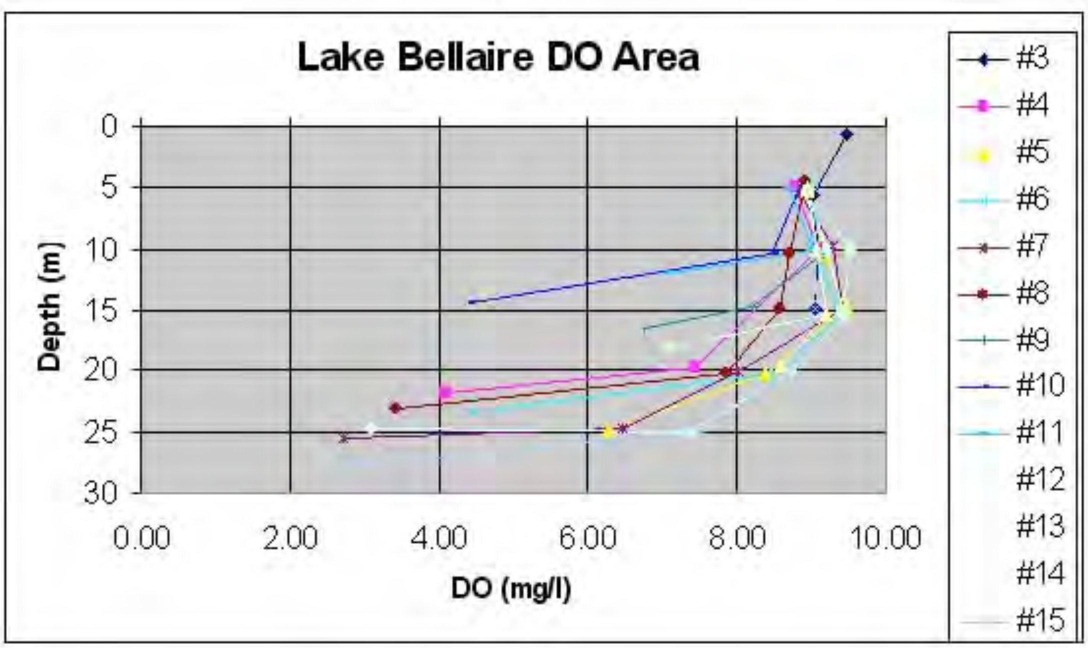

Seasonal specific conductivity profiles from 2005/6 for the Lake Bellaire deep basin



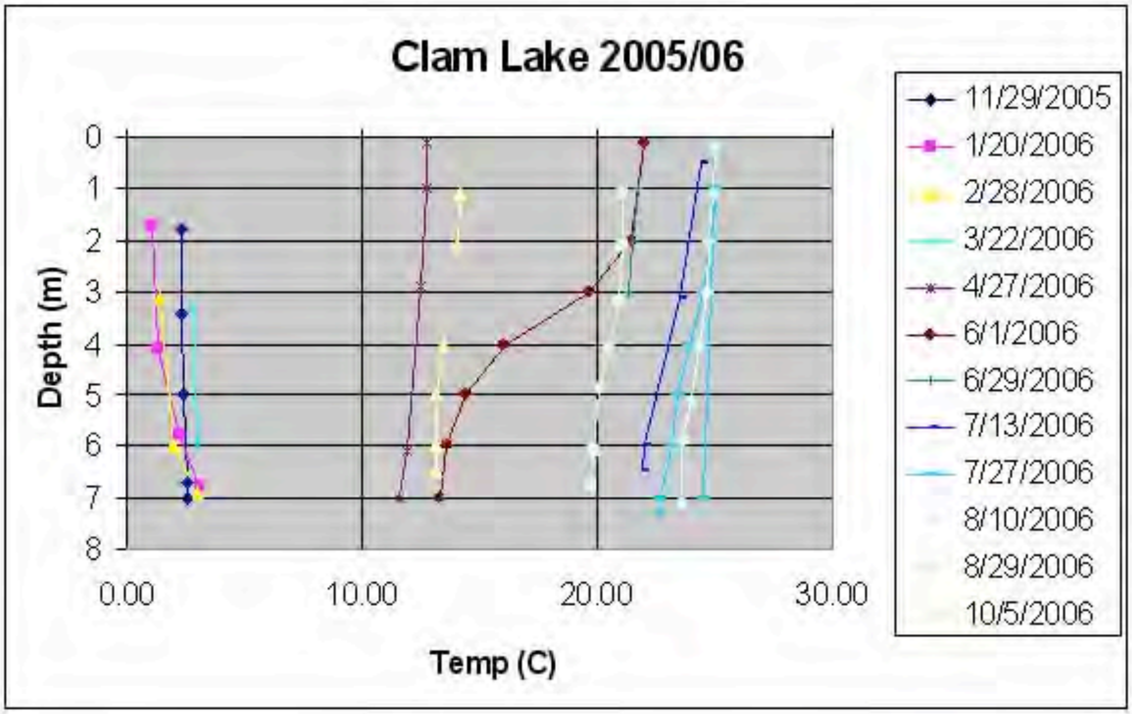

Dissolved oxygen profiles from 2005/6 for the Lake Bellaire deep basin



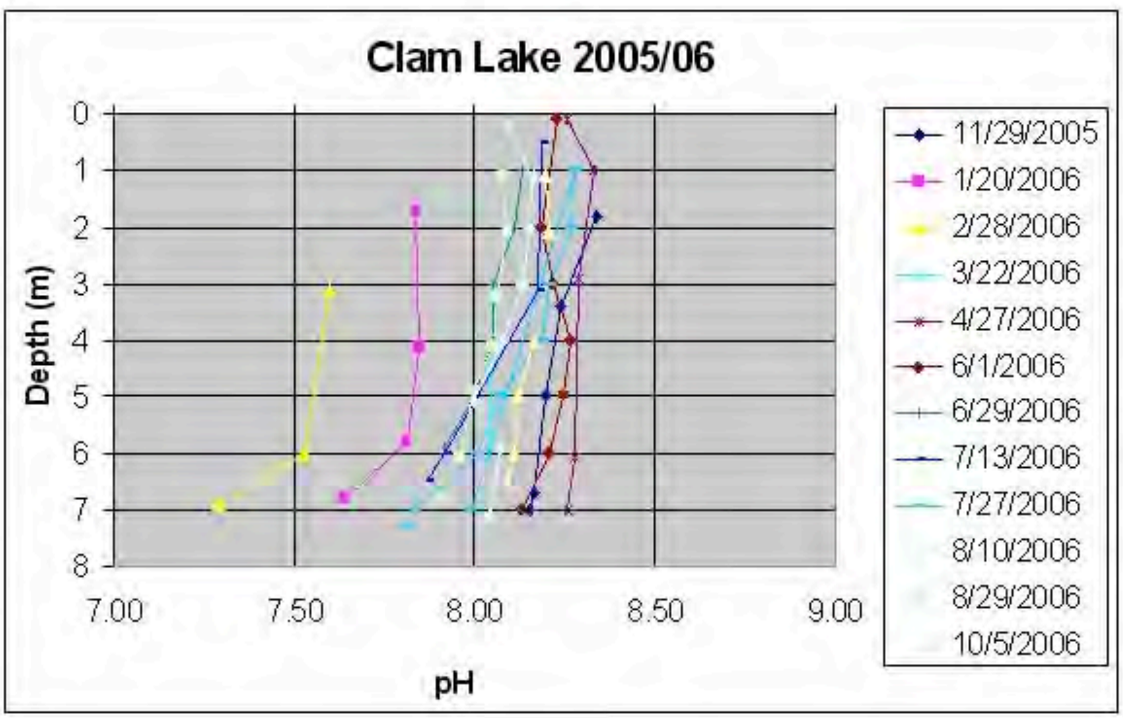

Dissolved oxygen seasonal changes at 23-27m in the Lake Bellaire deep basin



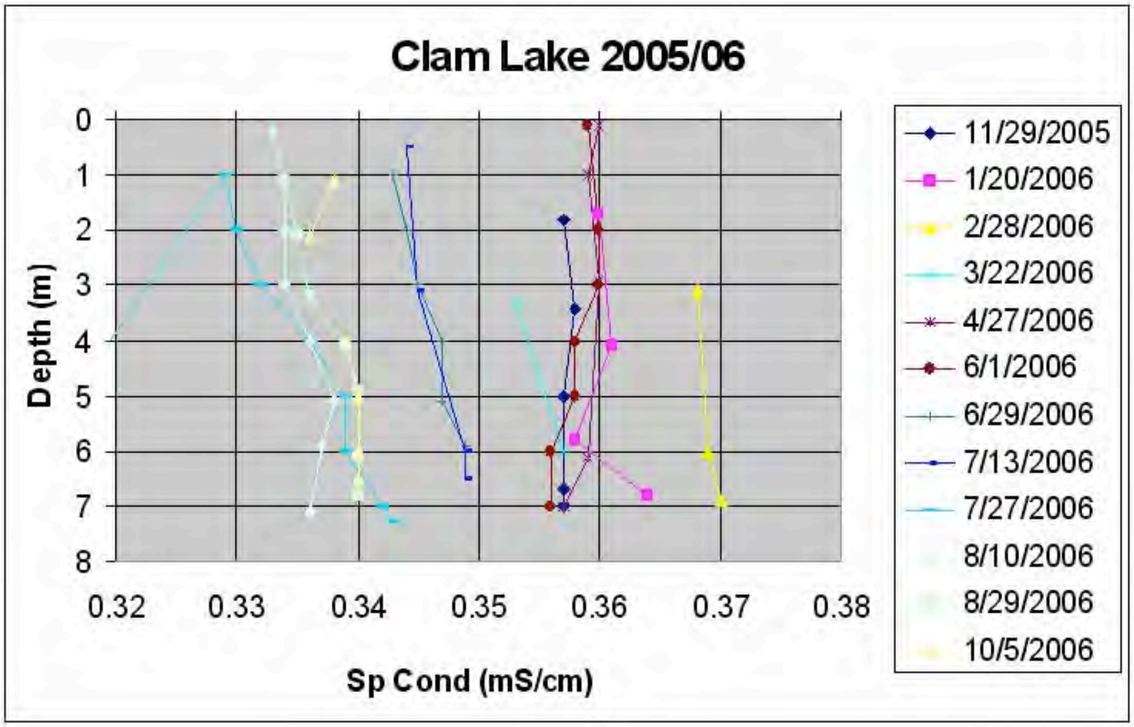

Areal survey of DO profiles in Lake Bellaire



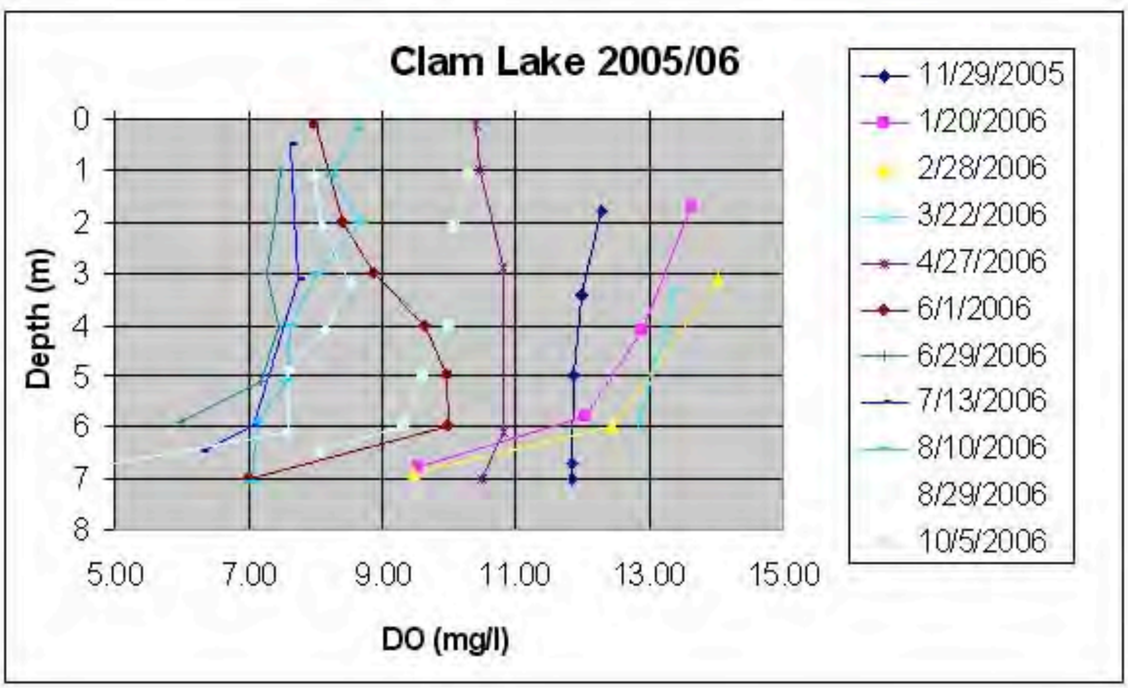

Seasonal temperature profiles from 2005/6 for the Clam Lake deep basin




Seasonal pH profiles from 2005/6 for the Clam Lake deep basin




Seasonal Specific Conductivity profiles from 2005/6 for the Clam Lake deep basin




Seasonal Dissolved Oxygen profiles from 2005/6 for the Clam Lake deep basin

| Date (dd//mm/yyyy) | Location | GPS | Depth (m) | Temp (C) | DO (mg/L) | pH | SpC (mS/cm) |
|---|---|---|---|---|---|---|---|
| 10/22/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 3.1 | 13.2 | 8.9 | 8.21 | 0.341 |
| 10/22/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 5.2 | 13.2 | 8.8 | 8.24 | 0.341 |
| 10/22/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 5.9 | 13.2 | 9.0 | 8.21 | 0.339 |
| 10/22/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 9.0 | 13.2 | 8.9 | 8.21 | 0.341 |
| 10/22/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 10.0 | 13.2 | 8.6 | 8.24 | 0.341 |
| 10/22/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 12.1 | 12.7 | 8.6 | 8.14 | 0.345 |
| 10/22/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 14.9 | 9.8 | 7.7 | 7.75 | 0.361 |
| 10/22/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 16.9 | 7.7 | 6.7 | 7.63 | 0.363 |
| 10/22/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 18.1 | 7.3 | 7.2 | 7.62 | 0.364 |
| 10/22/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 21.0 | 6.4 | 5.8 | 7.46 | 0.368 |
| 10/22/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 21.5 | 6.4 | 4.1 | 7.44 | 0.368 |
| 10/22/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 23.9 | 6.0 | 4.3 | 7.37 | 0.372 |
| 10/22/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 26.7 | 5.9 | 1.6 | 7.32 | 0.374 |
| 12/16/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 2.4 | 1.7 | 12.4 | 7.78 | 0.350 |
| 12/16/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 6.0 | 1.7 | 12.4 | 7.76 | 0.350 |
| 12/16/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 9.3 | 1.7 | 12.3 | 7.76 | 0.350 |
| 12/16/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 12.1 | 1.7 | 12.3 | 7.75 | 0.350 |
| 12/16/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 15.5 | 1.7 | 12.3 | 7.75 | 0.350 |
| 12/16/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 18.1 | 1.8 | 12.3 | 7.74 | 0.349 |
| 12/16/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 20.9 | 1.8 | 12.2 | 7.73 | 0.350 |
| 12/16/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 24.0 | 2.0 | 12.2 | 7.73 | 0.350 |
| 12/16/2005 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 26.5 | 2.2 | 12.0 | 7.22 | 0.373 |
| 1/13/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 2.4 | 1.0 | 13.6 | 8.71 | 0.353 |
| 1/13/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 6.0 | 1.0 | 13.1 | 8.65 | 0.353 |
| 1/13/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 9.3 | 1.0 | 13.0 | 8.61 | 0.353 |
| 1/13/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 12.1 | 1.0 | 12.9 | 8.59 | 0.354 |
| 1/13/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 15.5 | 1.0 | 12.8 | 8.52 | 0.353 |
| 1/13/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 18.1 | 1.0 | 12.6 | 8.45 | 0.353 |
| 1/13/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 24.0 | 1.2 | 12.5 | 8.40 | 0.354 |
| 1/13/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 26.5 | 1.7 | 12.3 | 8.38 | 0.357 |
| 2/24/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 3.0 | 1.1 | 14.6 | 8.35 | 0.358 |
| 2/24/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 6.0 | 1.2 | 13.7 | 8.26 | 0.358 |
| 2/24/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 9.0 | 1.3 | 13.0 | 8.09 | 0.358 |
| 2/24/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 12.0 | 1.3 | 12.9 | 8.07 | 0.359 |
| 2/24/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 14.8 | 1.3 | 12.9 | 8.03 | 0.360 |
| 2/24/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 18.1 | 1.4 | 12.9 | 8.00 | 0.362 |
| 3/22/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 3.1 | 2.0 | 19.8 | 7.81 | 0.361 |
| 3/22/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 5.8 | 2.0 | 14.8 | 7.81 | 0.361 |
| 3/22/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 9.1 | 2.0 | 13.2 | 7.81 | 0.361 |
| 3/22/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 12.2 | 2.0 | 12.8 | 7.82 | 0.361 |
| 3/22/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 15.1 | 2.0 | 12.6 | 7.82 | 0.361 |
| 3/22/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 17.9 | 2.0 | 12.4 | 7.81 | 0.362 |
| 3/22/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 21.0 | 2.1 | 12.3 | 7.76 | 0.364 |
| 3/22/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 23.2 | 2.2 | 10.8 | 7.73 | 0.365 |

| Date (dd//mm/yyyy) | Location | GPS | Depth (m) | Temp (C) | DO (mg/L) | pH | SpC (mS/cm) |
|---|---|---|---|---|---|---|---|
| 4/27/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 0.1 | 9.9 | 11.0 | 8.25 | 0.358 |
| 4/27/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 3.0 | 9.8 | 11.4 | 8.24 | 0.358 |
| 4/27/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 6.0 | 9.6 | 11.4 | 8.24 | 0.358 |
| 4/27/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 9.0 | 9.2 | 11.5 | 8.21 | 0.358 |
| 4/27/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 12.0 | 5.9 | 11.9 | 8.09 | 0.358 |
| 4/27/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 15.0 | 5.5 | 11.9 | 8.08 | 0.359 |
| 4/27/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 18.0 | 4.9 | 12.0 | 8.07 | 0.358 |
| 4/27/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 21.0 | 4.4 | 12.0 | 8.03 | 0.359 |
| 4/27/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 24.1 | 4.3 | 11.8 | 8.01 | 0.359 |
| 4/27/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 26.1 | 4.3 | 11.5 | 8.01 | 0.359 |
| 5/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 2.8 | 12.4 | 9.7 | 8.33 | 0.356 |
| 5/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 6.0 | 12.3 | 9.7 | 8.30 | 0.356 |
| 5/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 9.0 | 11.9 | 9.8 | 8.28 | 0.356 |
| 5/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 11.9 | 10.3 | 10.1 | 8.22 | 0.357 |
| 5/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 15.0 | 7.3 | 10.7 | 8.10 | 0.357 |
| 5/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 17.8 | 6.3 | 10.9 | 8.06 | 0.357 |
| 5/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 21.1 | 5.6 | 10.9 | 7.99 | 0.358 |
| 5/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 24.1 | 5.3 | 10.8 | 7.94 | 0.358 |
| 5/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 26.9 | 4.8 | 10.4 | 7.88 | 0.360 |
| 5/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 27.8 | 4.8 | 8.0 | 7.86 | 0.360 |
| 6/1/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 0.1 | 20.9 | 8.4 | 8.37 | 0.358 |
| 6/1/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 1.0 | 20.9 | 8.5 | 8.35 | 0.359 |
| 6/1/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 3.0 | 17.2 | 9.4 | 8.33 | 0.360 |
| 6/1/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 6.0 | 13.2 | 10.1 | 8.33 | 0.359 |
| 6/1/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 12.1 | 10.2 | 10.2 | 8.20 | 0.360 |
| 6/1/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 15.0 | 9.3 | 10.3 | 8.15 | 0.361 |
| 6/1/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 18.0 | 6.6 | 10.7 | 8.03 | 0.362 |
| 6/1/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 21.0 | 5.8 | 10.3 | 7.93 | 0.362 |
| 6/1/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 24.0 | 5.4 | 10.1 | 7.89 | 0.363 |
| 6/1/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 27.0 | 5.0 | 9.7 | 7.83 | 0.364 |
| 6/15/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 2.9 | 19.5 | 8.5 | 8.22 | 0.354 |
| 6/15/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 6.0 | 16.3 | 8.8 | 8.23 | 0.357 |
| 6/15/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 8.9 | 12.0 | 9.8 | 8.21 | 0.358 |
| 6/15/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 11.9 | 10.4 | 10.0 | 8.09 | 0.361 |
| 6/15/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 15.0 | 9.3 | 9.9 | 8.02 | 0.361 |
| 6/15/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 18.2 | 7.1 | 10.0 | 7.91 | 0.361 |
| 6/15/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 21.0 | 6.0 | 9.8 | 7.77 | 0.363 |
| 6/15/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 24.0 | 5.3 | 9.6 | 7.73 | 0.364 |
| 6/15/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 27.0 | 5.1 | 9.0 | 7.64 | 0.365 |
| 6/15/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 28.1 | 5.1 | 3.7 | 7.56 | 0.366 |

| Date (dd//mm/yyyy) | Location | GPS | Depth (m) | Temp (C) | DO (mg/L) | pH | SpC (mS/cm) |
|---|---|---|---|---|---|---|---|
| 6/29/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 3.0 | 21.8 | 7.8 | 8.22 | 0.341 |
| 6/29/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 6.0 | 18.8 | 8.4 | 8.21 | 0.351 |
| 6/29/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 9.0 | 12.5 | 9.3 | 8.20 | 0.355 |
| 6/29/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 12.0 | 10.4 | 9.4 | 8.02 | 0.356 |
| 6/29/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 14.9 | 9.0 | 9.3 | 7.92 | 0.358 |
| 6/29/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 18.0 | 7.1 | 9.2 | 7.78 | 0.359 |
| 6/29/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 20.9 | 6.0 | 9.1 | 7.69 | 0.360 |
| 6/29/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 23.9 | 5.4 | 8.8 | 7.61 | 0.362 |
| 6/29/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 27.0 | 5.3 | 8.2 | 7.55 | 0.362 |
| 6/29/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 28.0 | 5.2 | 5.8 | 7.49 | 0.363 |
| 7/13/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 0.3 | 23.6 | 7.7 | 8.25 | 0.341 |
| 7/13/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 3.2 | 23.3 | 7.7 | 8.24 | 0.341 |
| 7/13/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 6.0 | 22.0 | 7.9 | 8.23 | 0.343 |
| 7/13/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 9.0 | 12.4 | 9.3 | 8.08 | 0.360 |
| 7/13/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 12.1 | 11.2 | 9.2 | 8.01 | 0.361 |
| 7/13/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 15.2 | 9.8 | 8.9 | 7.91 | 0.362 |
| 7/13/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 18.0 | 7.4 | 8.7 | 7.73 | 0.364 |
| 7/13/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 21.0 | 6.2 | 8.4 | 7.62 | 0.365 |
| 7/13/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 24.1 | 5.5 | 7.3 | 7.51 | 0.368 |
| 7/13/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 26.9 | 5.4 | 6.4 | 7.45 | 0.370 |
| 7/13/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 27.5 | 5.4 | 6.0 | 7.45 | 0.370 |
| 7/27/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 0.3 | 26.1 - | | 8.32 | 0.328 |
| 7/27/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 3.0 | 24.7 | | 8.34 | 0.328 |
| 7/27/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 6.1 | 22.8 | | 8.29 | 0.336 |
| 7/27/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 9.1 | 13.4 | | 8.20 | 0.355 |
| 7/27/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 12.0 | 11.0 | | 8.08 | 0.356 |
| 7/27/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 15.0 | 9.3 | | 7.93 | 0.357 |
| 7/27/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 17.9 | 7.4 | | 7.79 | 0.358 |
| 7/27/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 21.1 | 6.0 | | 7.65 | 0.362 |
| 7/27/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 24.0 | 5.6 | | 7.54 | 0.366 |
| 7/27/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 27.0 | 5.4 - | | 7.47 | 0.367 |
| 8/10/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 1.1 | 25.1 | 8.2 | 8.29 | 0.328 |
| 8/10/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 2.9 | 25.1 | 8.2 | 8.31 | 0.328 |
| 8/10/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 5.9 | 24.5 | 8.1 | 8.29 | 0.329 |
| 8/10/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 9.1 | 14.3 | 9.8 | 8.19 | 0.356 |
| 8/10/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 9.1 | 14.3 | 9.8 | 8.19 | 0.356 |
| 8/10/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 15.0 | 9.3 | 10.1 | 7.87 | 0.361 |
| 8/10/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 18.0 | 7.5 | 10.1 | 7.72 | 0.364 |
| 8/10/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 21.2 | 6.5 | 11.1 | 7.62 | 0.366 |
| 8/10/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 23.9 | 5.8 | 8.7 | 7.50 | 0.370 |
| 8/10/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 27.1 | 5.6 | 7.1 | 7.44 | 0.372 |
| 8/10/2006 | Bellaire Dp Bsn | N 44$^{o}$ 57.000' W 85$^{o}$13.200' | 27.7 | 5.5 | 3.9 | 7.41 | 0.369 |

| Date (dd//mm/yyyy) | Location | GPS | Depth (m) | Temp (C) | DO (mg/L) | pH | SpC (mS/cm) |
|---|---|---|---|---|---|---|---|
| 8/29/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 0.9 | 22.0 | 8.1 | 8.25 | 0.329 |
| 8/29/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 4.0 | 21.8 | 8.0 | 8.25 | 0.331 |
| 8/29/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | | 20.9 | | 8.16 | 0.336 |
| 8/29/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 10.2 | 14.0 | 8.8 | 8.02 | 0.360 |
| 8/29/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 16.1 | 8.7 | 9.2 | 7.74 | 0.364 |
| 8/29/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 18.0 | 7.7 | 8.4 | 7.65 | 0.367 |
| 8/29/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 21.0 | 6.4 | 8.5 | 7.53 | 0.369 |
| 8/29/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 24.2 | 5.9 | 6.8 | 7.41 | 0.374 |
| 8/29/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 27.1 | 5.6 | 5.3 | 7.32 | 0.378 |
| 8/29/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 28.1 | 5.6 | 2.0 | 7.30 | 0.378 |
| 9/14/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.500' | 5.4 | 19.1 | 8.9 | 8.35 | 0.327 |
| 9/14/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.500' | 9.7 | 14.5 | 9.3 | 8.05 | 0.363 |
| 9/14/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.500' | 14.8 | 9.3 | 9.4 | 7.90 | 0.360 |
| 9/14/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.500' | 20.1 | 6.6 | 8.0 | 7.64 | 0.364 |
| 9/14/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.500' | 24.7 | 5.7 | 6.5 | 7.45 | 0.372 |
| 9/14/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.500' | 25.6 | 5.7 | 2.7 | 7.43 | 0.373 |
| 10/5/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 3 | 14.54 | 9.4 | 8.2 | 0.333 |
| 10/5/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 6.1 | 14.53 | 9.5 | 8.2 | 0.333 |
| 10/5/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 9.1 | 14.51 | 9.4 | 8.2 | 0.333 |
| 10/5/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 12.1 | 14 | 9.2 | 8.13 | 0.337 |
| 10/5/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 15.1 | 9.94 | 8.0 | 7.75 | 0.358 |
| 10/5/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | | 7.57 | | 7.6 | 0.361 |
| 10/5/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 21.2 | 6.7 | 5.8 | 7.52 | 0.364 |
| 10/5/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 24.1 | 6.14 | 4.8 | 7.43 | 0.368 |
| 10/5/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 27.1 | 5.88 | 2.6 | 7.36 | 0.371 |
| 10/5/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 29.5 | 5.84 | 1.1 | 7.34 | 0.372 |
| 10/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 0.6 | 10.5 | 10.3 | 8.08 | 0.342 |
| 10/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 3.2 | 10.49 | 10.3 | 8.06 | 0.342 |
| 10/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 6.3 | 10.49 | 10.2 | 8.05 | 0.342 |
| 10/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 9.1 | 10.49 | 10.1 | 8.05 | 0.342 |
| 10/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 11.9 | 10.48 | 10.1 | 8.03 | 0.342 |
| 10/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 14.5 | 9.93 | 9.9 | 7.9 | 0.349 |
| 10/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 18 | 9.59 | 8.5 | 7.79 | 0.35 |
| 10/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 20.8 | 6.89 | 8.1 | 7.44 | 0.368 |
| 10/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 24 | 6.19 | 3.5 | 7.31 | 0.372 |
| 10/20/2006 | Bellaire Dp Bsn | N 44° 57.000' W 85°13.200' | 26.5 | 5.99 | 1.8 | 7.27 | 0.374 |

| Date (dd//mm/yyyy) | Location | GPS | Depth (m) | Temp (C) | DO (mg/L) | pH | SpC (mS/cm) |
|---|---|---|---|---|---|---|---|
| 9/14/2006 | #3 | N 44° 55.840' W 85°13.000' | 0.6 | 19.7 | 9.5 | 8.40 | 0.329 |
| 9/14/2006 | #3 | N 44° 55.840' W 85°13.000' | 5.6 | 19.1 | 9.0 | 8.35 | 0.327 |
| 9/14/2006 | #3 | N 44° 55.840' W 85°13.000' | 5.4 | 19.1 | 9.0 | 8.36 | 0.327 |
| 9/14/2006 | #3 | N 44° 55.840' W 85°13.000' | 10.1 | 14.7 | 9.1 | 8.06 | 0.357 |
| 9/14/2006 | #3 | N 44° 55.840' W 85°13.000' | 14.9 | 8.8 | 9.1 | 7.67 | 0.360 |
| 9/14/2006 | #4 | N 44° 56.250' W 85°13.250' | 5.0 | 19.1 | 8.8 | 8.34 | 0.326 |
| 9/14/2006 | #4 | N 44° 56.250' W 85°13.250' | 10.1 | 14.4 | 9.1 | 8.03 | 0.355 |
| 9/14/2006 | #4 | N 44° 56.250' W 85°13.250' | 19.8 | 6.6 | 7.4 | 7.60 | 0.364 |
| 9/14/2006 | #4 | N 44° 56.250' W 85°13.250' | 21.8 | 6.2 | 4.1 | 7.49 | 0.369 |
| 9/14/2006 | #5 | N 44° 56.500' W 85°13.500' | 5.2 | 19.1 | 9.0 | 7.83 | 0.327 |
| 9/14/2006 | #5 | N 44° 56.500' W 85°13.500' | 10.4 | 13.8 | 9.2 | 7.86 | 0.353 |
| 9/14/2006 | #5 | N 44° 56.500' W 85°13.500' | 14.7 | 9.1 | 9.5 | 7.72 | 0.360 |
| 9/14/2006 | #5 | N 44° 56.500' W 85°13.500' | 20.2 | 6.4 | 8.4 | 7.48 | 0.364 |
| 9/14/2006 | #5 | N 44° 56.500' W 85°13.500' | 24.9 | 5.9 | 6.3 | 7.37 | 0.369 |
| 9/14/2006 | #6 | N 44° 56.750' W 85°13.750' | 4.7 | 19.1 | 9.0 | 8.40 | 0.326 |
| 9/14/2006 | #6 | N 44° 56.750' W 85°13.750' | 9.8 | 14.9 | 9.0 | 8.07 | 0.357 |
| 9/14/2006 | #6 | N 44° 56.750' W 85°13.750' | 15.5 | 9.0 | 9.4 | 7.86 | 0.357 |
| 9/14/2006 | #6 | N 44° 56.750' W 85°13.750' | 20.3 | 6.2 | 8.5 | 7.63 | 0.363 |
| 9/14/2006 | #6 | N 44° 56.750' W 85°13.750' | 23.5 | 6.0 | 4.4 | 7.53 | 0.372 |
| 9/14/2006 | #7 | N 44° 57.000' W 85°13.500' | 5.4 | 19.1 | 8.9 | 8.35 | 0.327 |
| 9/14/2006 | #7 | N 44° 57.000' W 85°13.500' | 9.7 | 14.5 | 9.3 | 8.05 | 0.363 |
| 9/14/2006 | #7 | N 44° 57.000' W 85°13.500' | 14.8 | 9.3 | 9.4 | 7.90 | 0.360 |
| 9/14/2006 | #7 | N 44° 57.000' W 85°13.500' | 20.1 | 6.6 | 8.0 | 7.64 | 0.364 |
| 9/14/2006 | #7 | N 44° 57.000' W 85°13.500' | 24.7 | 5.7 | 6.5 | 7.45 | 0.372 |
| 9/14/2006 | #7 | N 44° 57.000' W 85°13.500' | 25.6 | 5.7 | 2.7 | 7.43 | 0.373 |
| 9/14/2006 | #8 | N 44° 57.250' W 85°13.750' | 4.5 | 19.0 | 8.9 | 8.35 | 0.327 |
| 9/14/2006 | #8 | N 44° 57.250' W 85°13.750' | 10.3 | 14.5 | 8.7 | 7.92 | 0.357 |
| 9/14/2006 | #8 | N 44° 57.250' W 85°13.750' | 14.9 | 9.0 | 8.6 | 7.85 | 0.361 |
| 9/14/2006 | #8 | N 44° 57.250' W 85°13.750' | 20.2 | 6.4 | 7.9 | 7.61 | 0.365 |
| 9/14/2006 | #8 | N 44° 57.250' W 85°13.750' | 23.1 | 6.0 | 3.4 | 7.45 | 0.366 |
| 9/14/2006 | #9 | N 44° 57.500' W 85°13.500' | 4.9 | 19.0 | 9.0 | 8.34 | 0.328 |
| 9/14/2006 | #9 | N 44° 57.500' W 85°13.500' | 10.3 | 14.1 | 9.2 | 7.93 | 0.361 |
| 9/14/2006 | #9 | N 44° 57.500' W 85°13.500' | 14.7 | 9.4 | 8.2 | 7.84 | 0.360 |
| 9/14/2006 | #9 | N 44° 57.500' W 85°13.500' | 16.6 | 8.1 | 6.8 | 7.70 | 0.362 |
| 9/14/2006 | #10 | N 44° 57.750' W 85°13.750' | 4.9 | 19.0 | 8.9 | 8.34 | 0.328 |
| 9/14/2006 | #10 | N 44° 57.750' W 85°13.750' | 10.3 | 14.9 | 8.5 | 7.89 | 0.357 |
| 9/14/2006 | #10 | N 44° 57.750' W 85°13.750' | 14.3 | 9.4 | 4.4 | 7.75 | 0.361 |
| 9/14/2006 | #11 | N 44° 58.000' W 85°14.000' | 5.1 | 19.0 | 8.7 | 8.32 | 0.328 |
| 9/14/2006 | #11 | N 44° 58.000' W 85°14.000' | 10.1 | 14.2 | 9.0 | 7.88 | 0.360 |
| 9/14/2006 | #11 | N 44° 58.000' W 85°14.000' | 12.0 | 9.8 | 7.1 | 7.79 | 0.361 |

| Date (dd//mm/yyyy) | Location | GPS | Depth (m) | Temp (C) | DO (mg/L) | pH | SpC (mS/cm) |
|---|---|---|---|---|---|---|---|
| 9/14/2006 | #12 | N 44° 57.250' W 85°13.000' | 5.2 | 19.0 | 9.0 | 8.36 | 0.326 |
| 9/14/2006 | #12 | N 44° 57.250' W 85°13.000' | 10.1 | 14.7 | 9.2 | 8.05 | 0.353 |
| 9/14/2006 | #12 | N 44° 57.250' W 85°13.000' | 15.4 | 9.0 | 9.5 | 7.85 | 0.359 |
| 9/14/2006 | #12 | N 44° 57.250' W 85°13.000' | 20.1 | 7.0 | 8.7 | 7.69 | 0.362 |
| 9/14/2006 | #12 | N 44° 57.250' W 85°13.000' | 25.0 | 6.0 | 7.4 | 7.47 | 0.370 |
| 9/14/2006 | #12 | N 44° 57.250' W 85°13.000' | 24.7 | 6.0 | 3.1 | 7.45 | 0.369 |
| 9/14/2006 | *#13* | N 44° 57.250' W 85°12.500' | 5.2 | 19.1 | 9.0 | 8.34 | 0.329 |
| 9/14/2006 | *#13* | N 44° 57.250' W 85°12.500' | 10.1 | 13.6 | 9.5 | 8.06 | 0.359 |
| 9/14/2006 | *#13* | N 44° 57.250' W 85°12.500' | 15.0 | 9.2 | 9.4 | 7.84 | 0.362 |
| 9/14/2006 | *#13* | N 44° 57.250' W 85°12.500' | 18.2 | 7.7 | 7.1 | 7.66 | 0.364 |
| 9/14/2006 | #14 | N 44° 57.000' W 85°12.500' | 5.1 | 19.1 | 9.0 | 8.34 | 0.327 |
| 9/14/2006 | #14 | N 44° 57.000' W 85°12.500' | 10.0 | 14.0 | 9.1 | 8.07 | 0.361 |
| 9/14/2006 | #14 | N 44° 57.000' W 85°12.500' | 15.3 | 9.1 | 9.2 | 7.86 | 0.360 |
| 9/14/2006 | #14 | N 44° 57.000' W 85°12.500' | 19.7 | 7.1 | 8.6 | 7.65 | 0.364 |
| 9/14/2006 | #15 | N 44° 57.000' W 85°13.000' | 4.8 | 19.1 | 9.0 | 8.34 | 0.327 |
| 9/14/2006 | #15 | N 44° 57.000' W 85°13.000' | 10.3 | 13.7 | 9.1 | 8.01 | 0.358 |
| 9/14/2006 | #15 | N 44° 57.000' W 85°13.000' | 14.8 | 9.4 | 9.1 | 7.86 | 0.361 |
| 9/14/2006 | #15 | N 44° 57.000' W 85°13.000' | 19.9 | 6.9 | 8.7 | 7.71 | 0.362 |
| 9/14/2006 | #15 | N 44° 57.000' W 85°13.000' | 25.1 | 5.9 | 7.5 | 7.49 | 0.370 |
| 9/14/2006 | #15 | N 44° 57.000' W 85°13.000' | 27.8 | 5.8 | 2.8 | 7.41 | 0.373 |
| 9/14/2006 | #16 | N 44° 57.500' W 85°13.000' | 4.9 | 19.1 | 9.0 | 8.36 | 0.327 |
| 9/14/2006 | #16 | N 44° 57.500' W 85°13.000' | 10.0 | 14.5 | 9.3 | 8.05 | 0.356 |
| 9/14/2006 | #16 | N 44° 57.500' W 85°13.000' | 14.8 | 8.9 | 9.6 | 7.82 | 0.361 |
| 9/14/2006 | #16 | N 44° 57.500' W 85°13.000' | 20.1 | 6.4 | 8.4 | 7.60 | 0.367 |


Fig. 1 Map of the Three Lakes and their Respective Watersheds

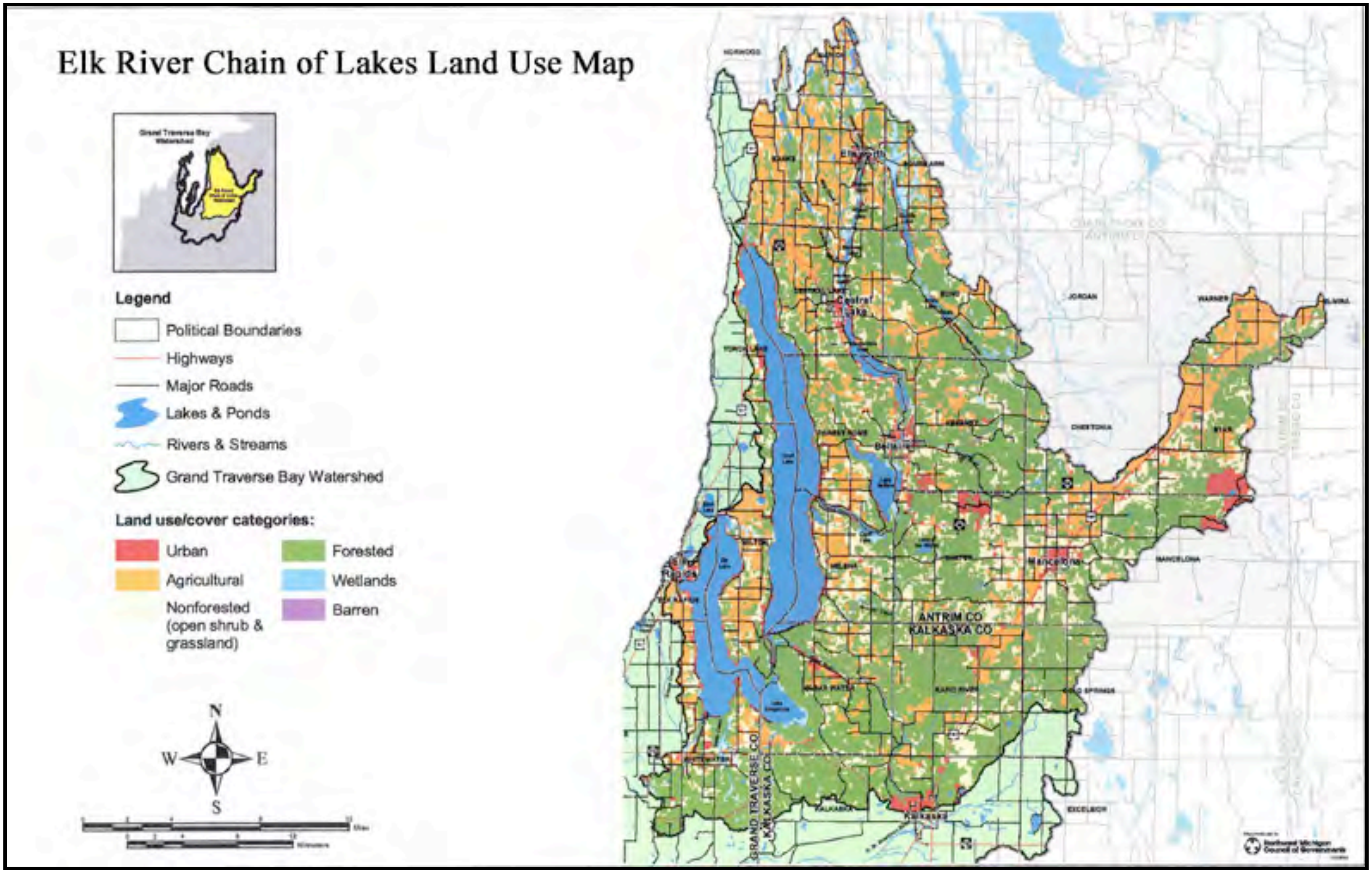



Fig. 2. Map of Land Use in the Elk River Chain of Lakes Watershed

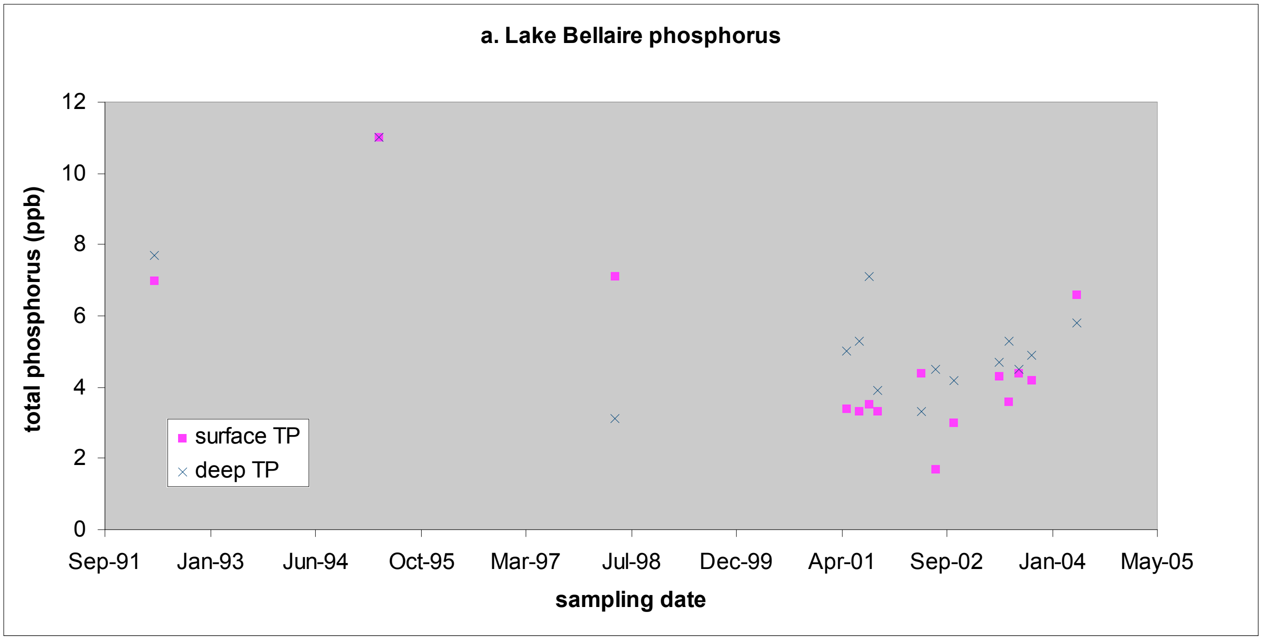



Fig. 3a Total phosphorus concentrations measured in Lake Bellaire by the Tip of the Mitt (TOM) Watershed Center

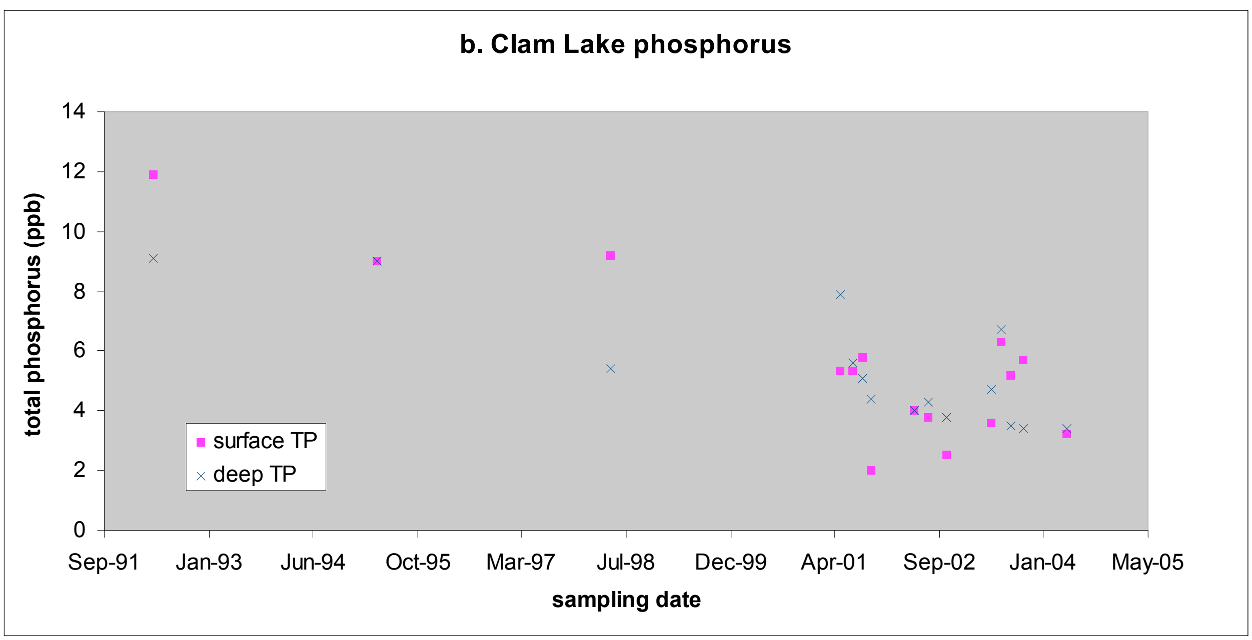



Fig. 3b Total phosphorus concentrations measured in Clam Lake by the Tip of the Mitt (TOM) Watershed Center

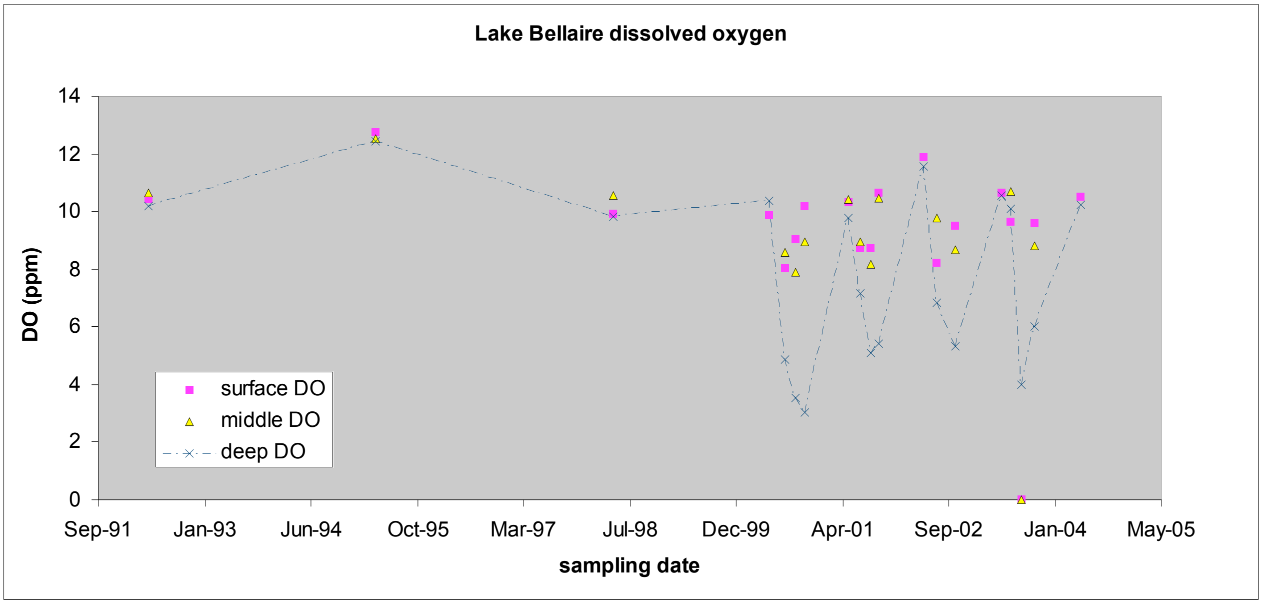



Fig. 4a Dissolved oxygen concentrations measured in Lake Bellaire by the Tip of the Mitt (TOM) Watershed Center

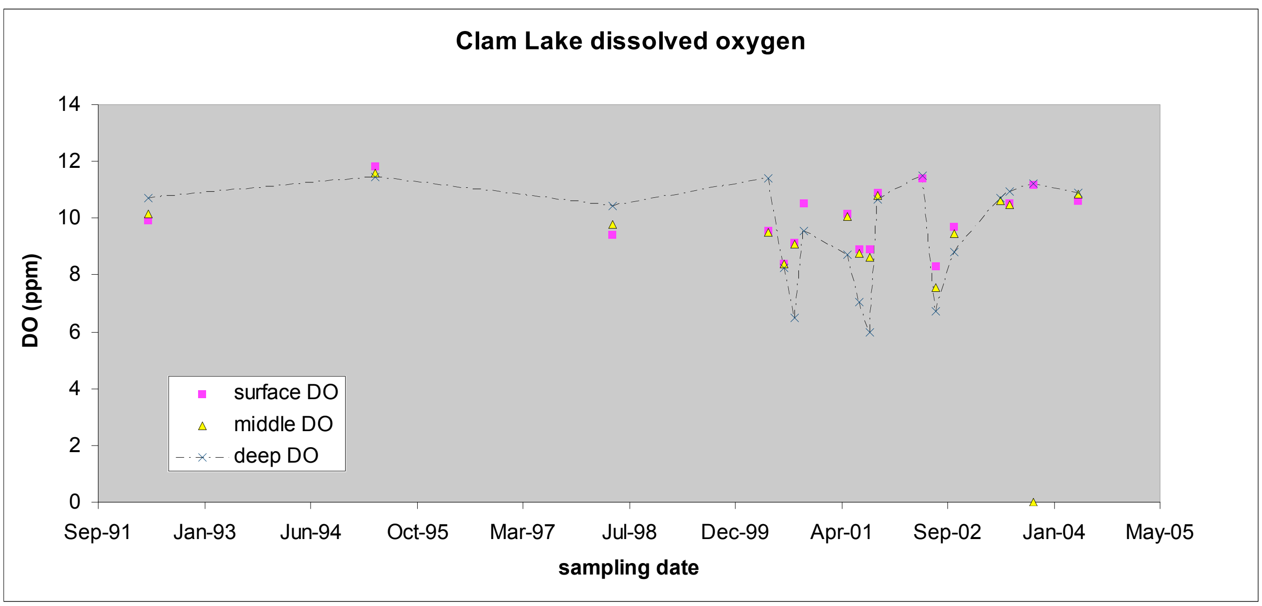



Fig. 4b Dissolved oxygen concentrations measured in Clam Lake by the Tip of the Mitt (TOM) Watershed Center


Fig. 5. Sampling Locations for Lake Bellaire and Clam Lake (shallow well locations are italicized)

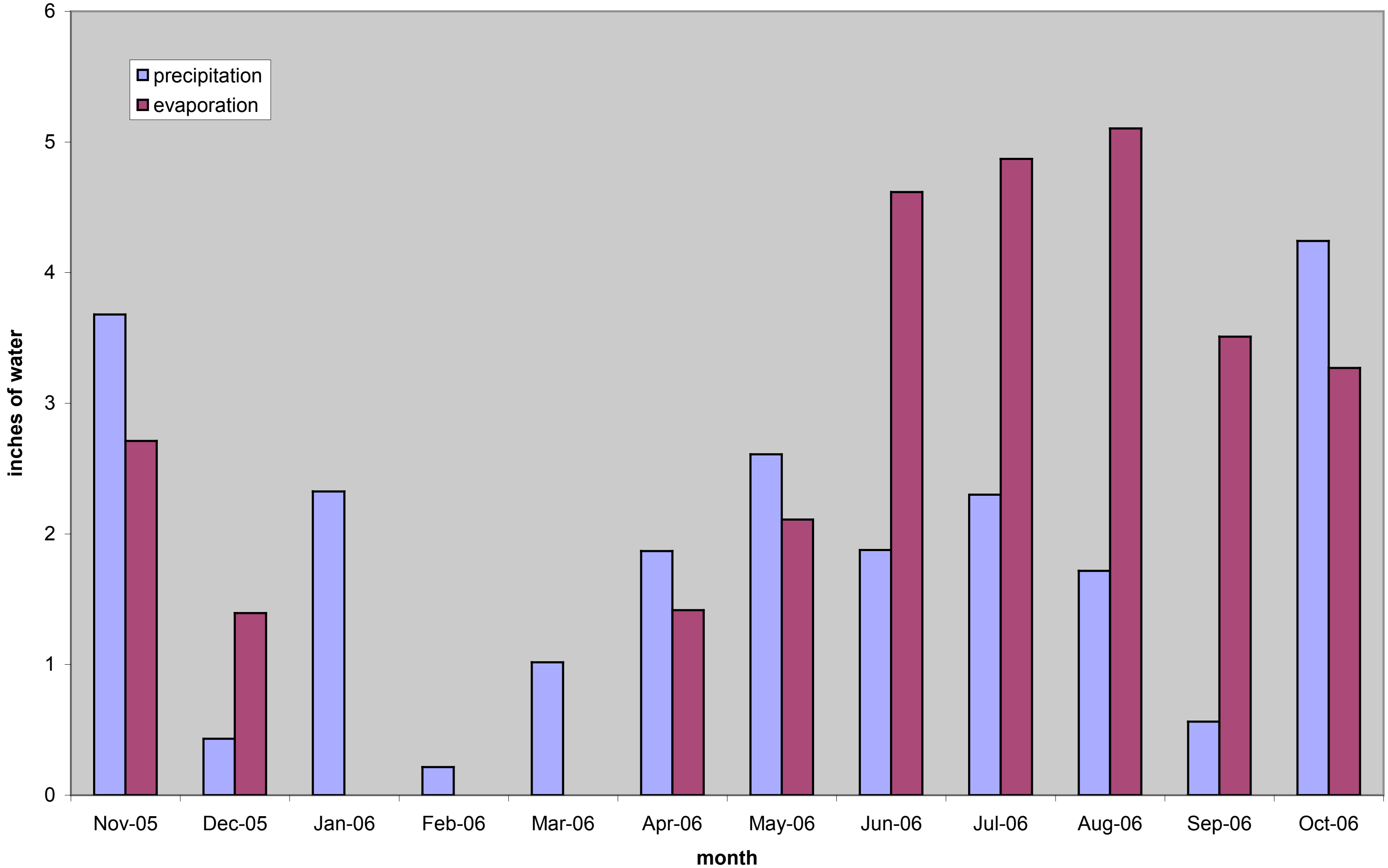



Fig. 6 Monthly rates of evaporation and precipitation for Lake Bellaire and Clam Lake for 2005-2006.

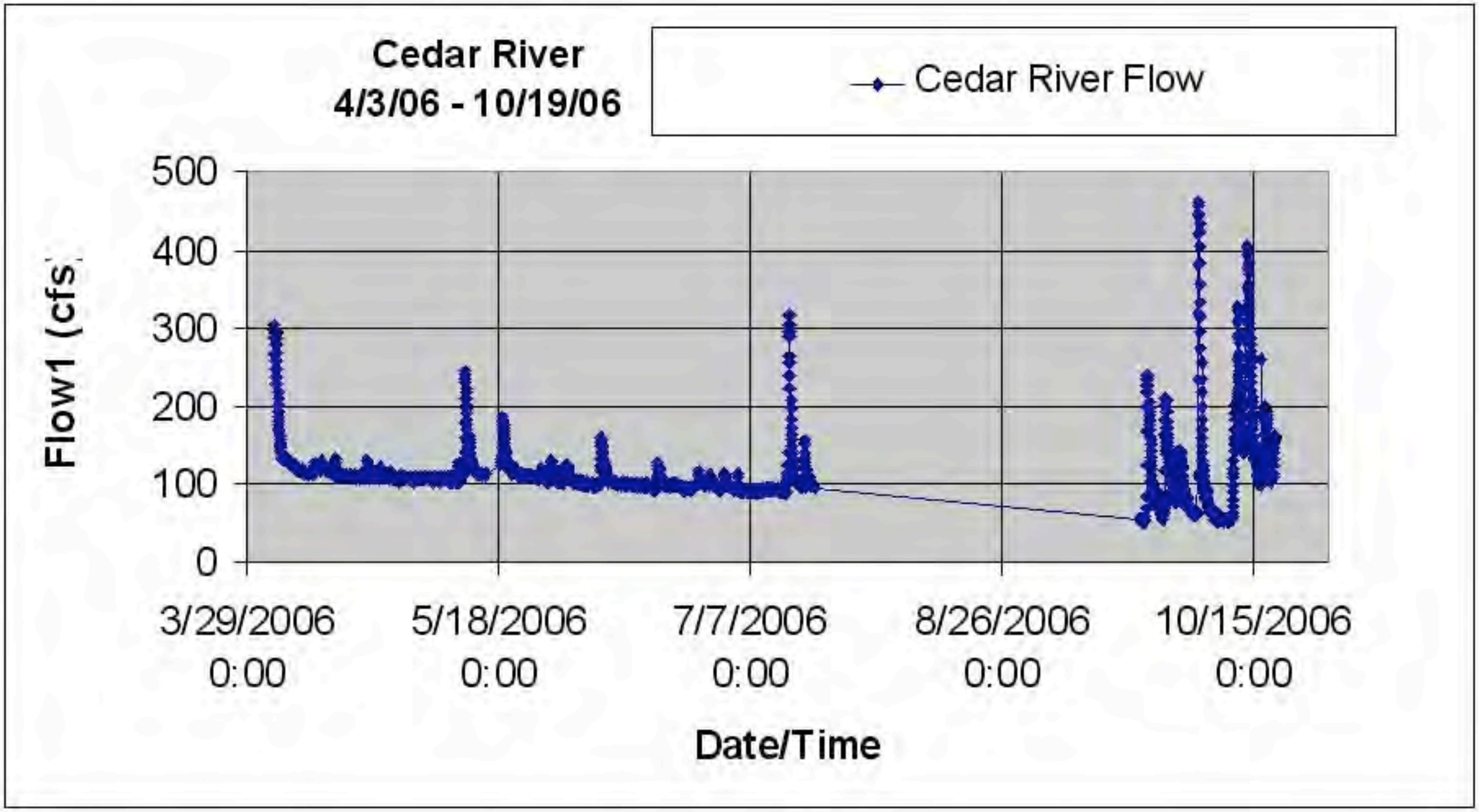



Fig. 7a Flow data from an automated gauge on the Cedar River taken at hourly intervals. The gap in the flow was caused by a gauge failure.

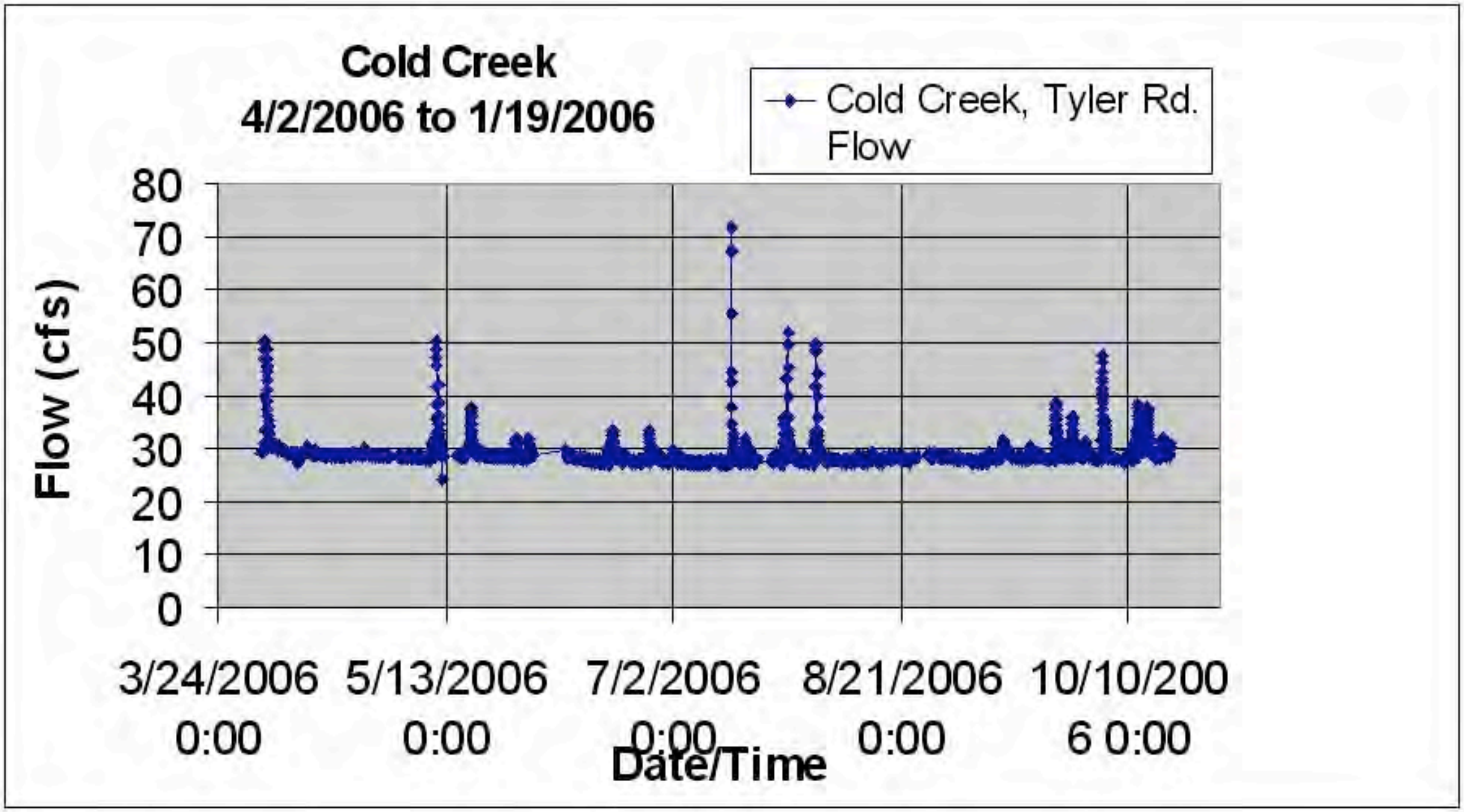



Fig. 7b Flow data on Cold Creek from an automated gauge at hourly intervals.

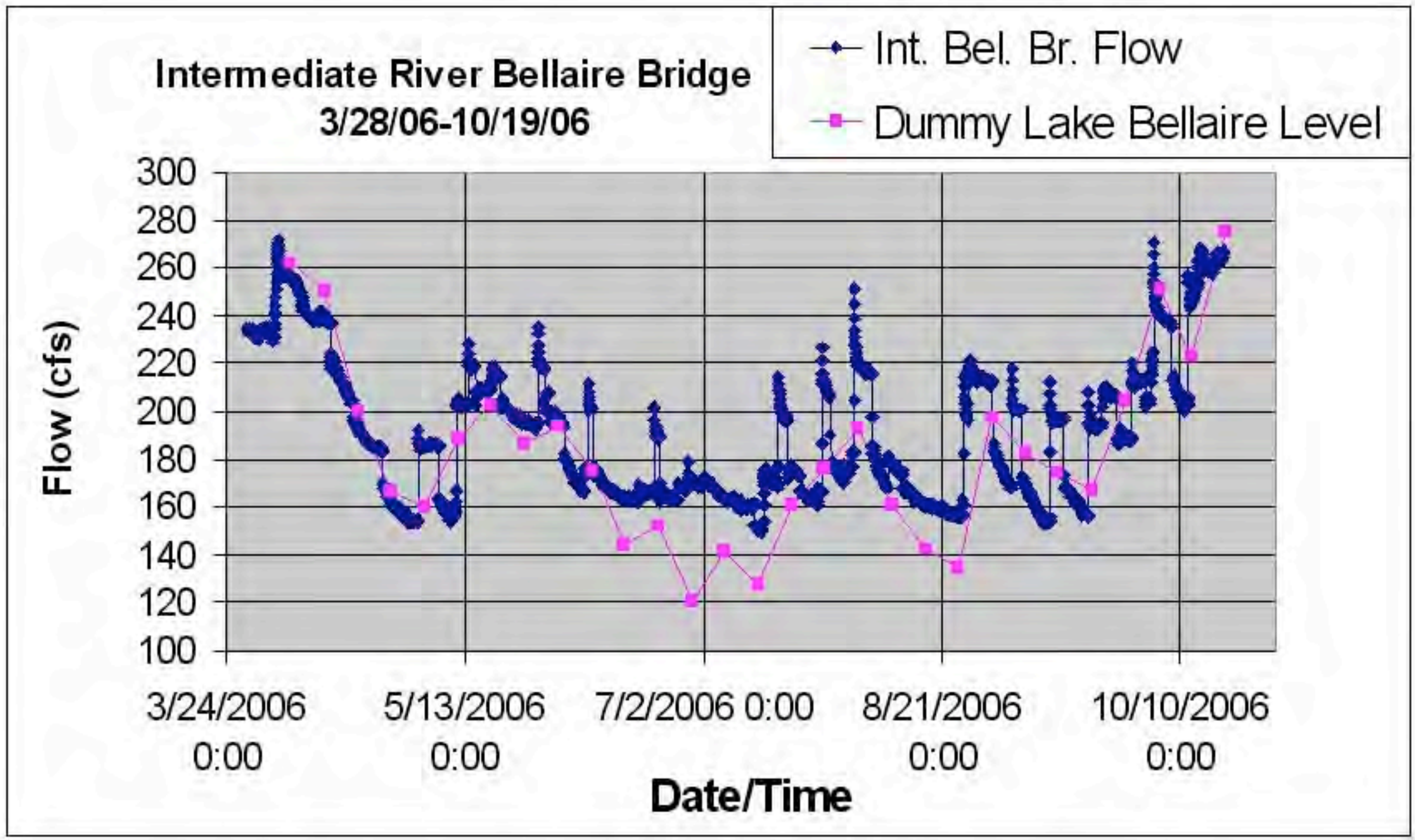



Fig. 7c Flow data on Intermediate River below the Bellaire Dam taken at hourly intervals. Abrupt jumps in flow correspond to openings and closings of the dam to keep the level of Intermediate Lake approximately constant. Also shown is value proportional to the Lake Bellaire Level.

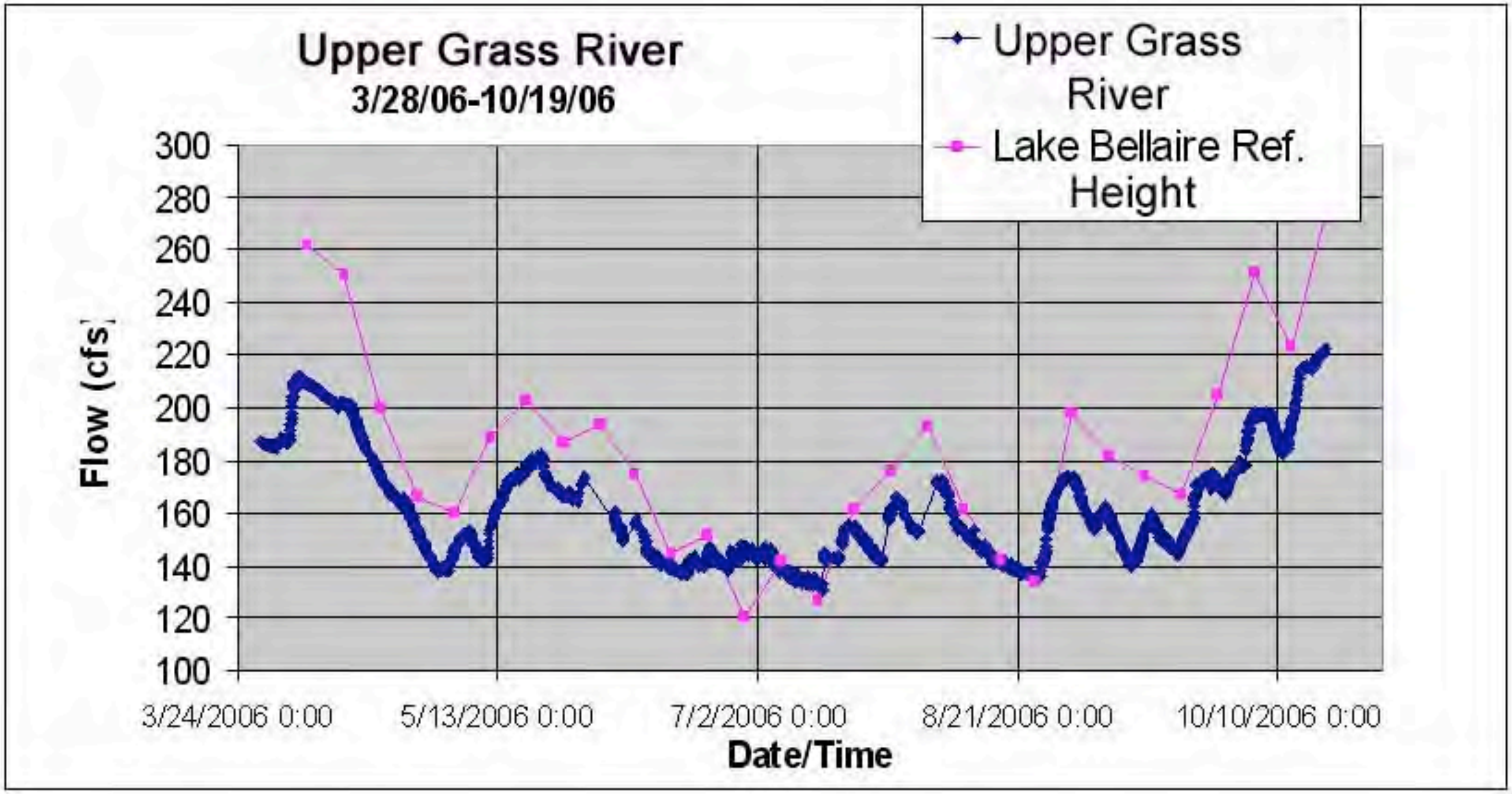



Fig. 7d Flow data on Upper Grass River taken at hourly intervals. Also shown is value proportional to the Lake Bellaire Level.

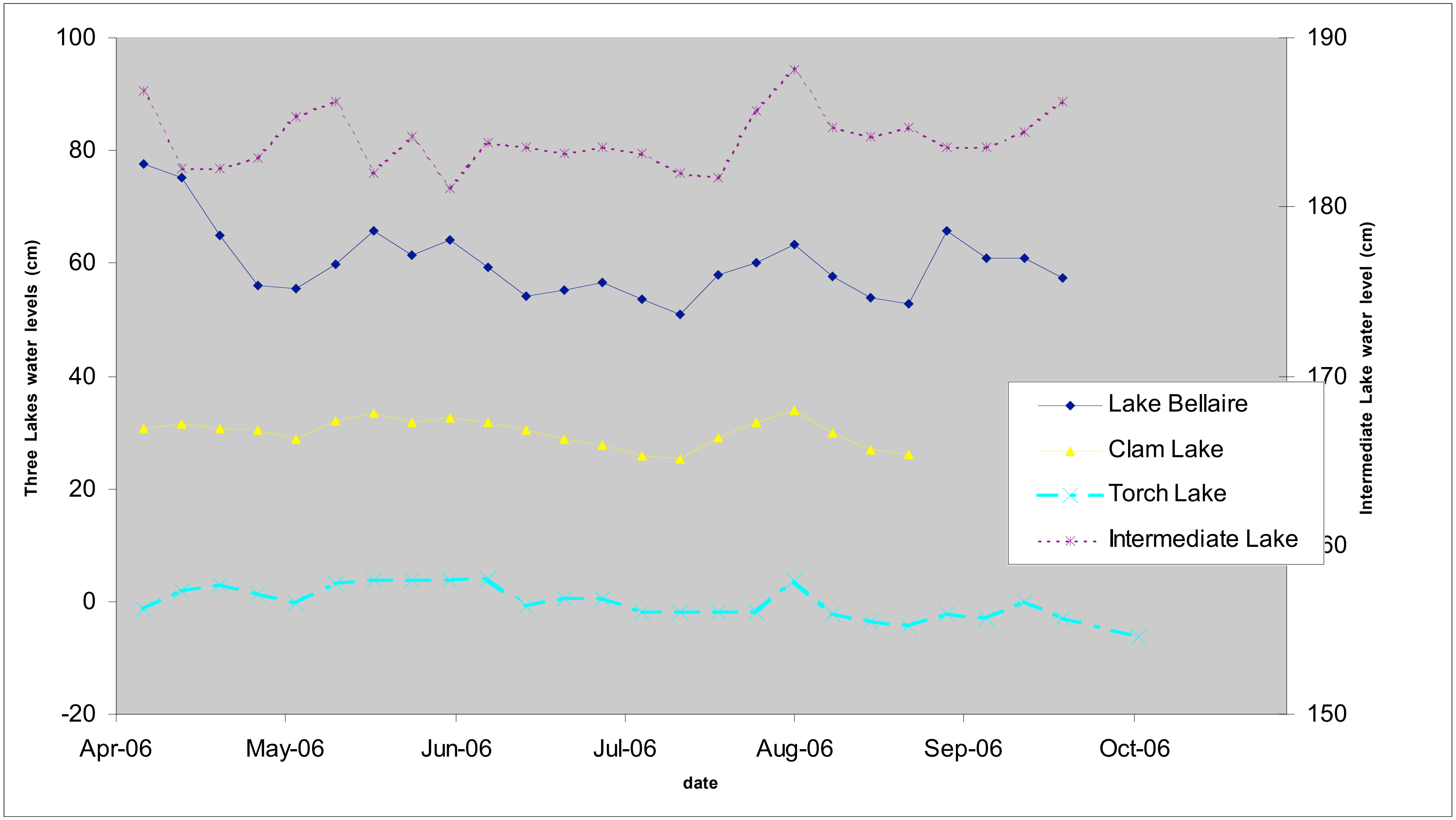



Fig. 8 Water level measurements for each of the Three Lakes and Intermediate Lake during the 2006 field season (weekly observations; levels are not referenced to a common datum).

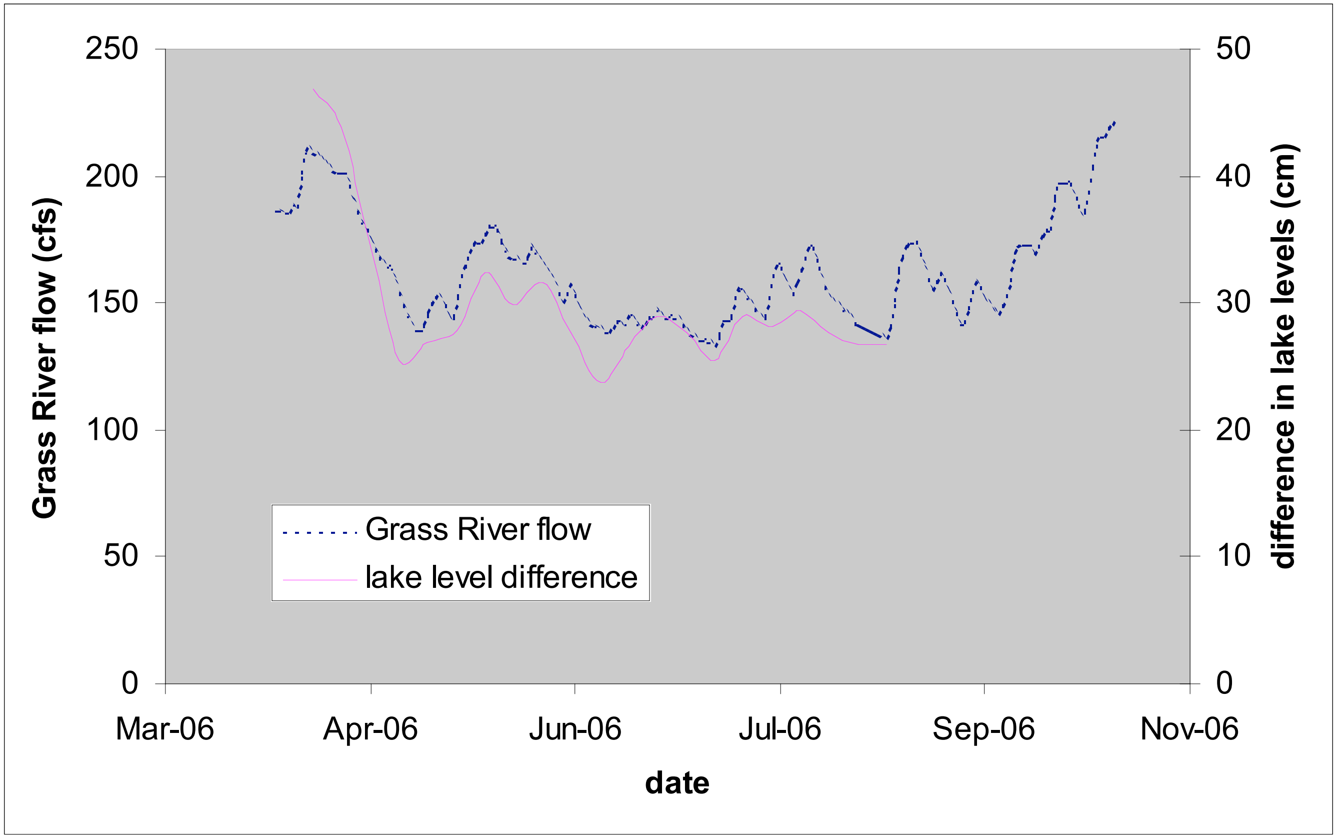



Fig. 9 Plots of (1) the difference between the levels of Lake Bellaire and Clam Lake and (2) upper Grass River flow rate.

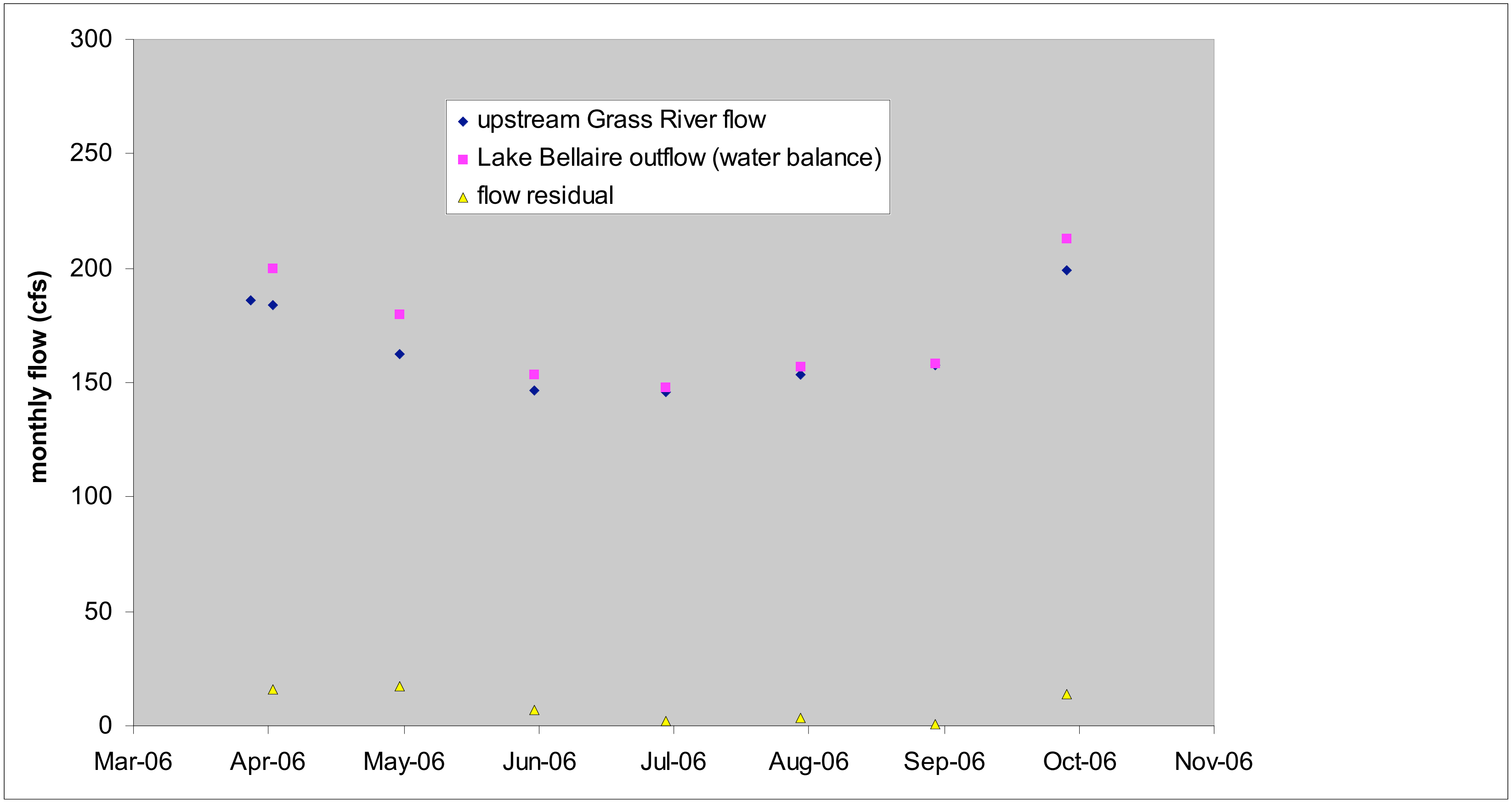



Fig. 10 Monthly flow residual (imbalance) in Lake Bellaire, calculated as the difference between upstream Grass River flows and the Lake Bellaire outflow (calculated from the lake water balance). Intermediate River flows were reduced by 20%, which resulted in near-zero residuals for the months of May through October.

## Cedar River May 11-19, 2006

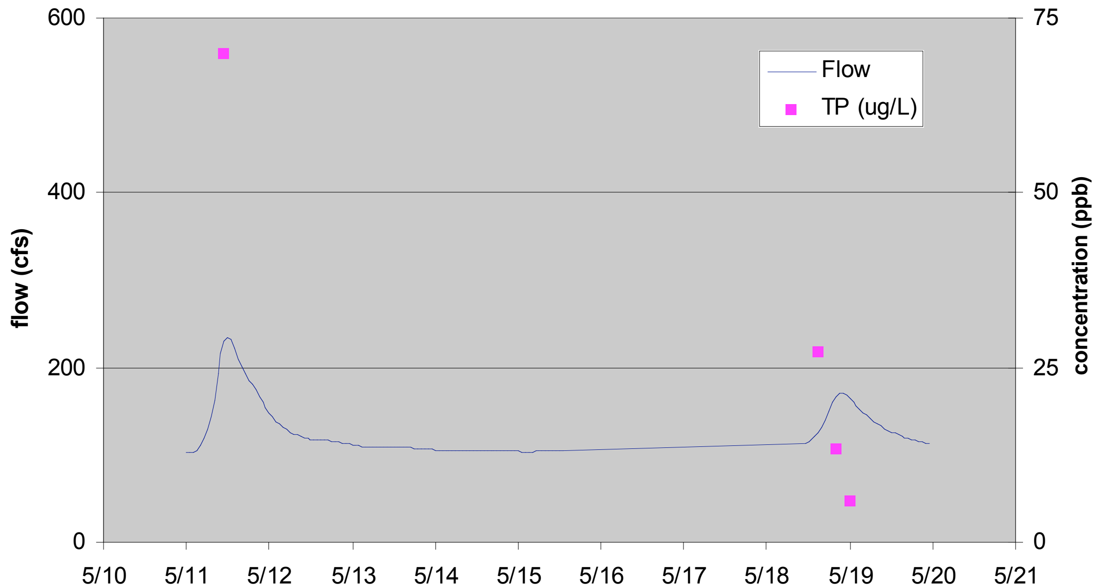



Fig. 11a Stream flow and total phosphorus concentrations measured on the Cedar River during one of four high-flow events.

## Cedar River July 14-15, 2006

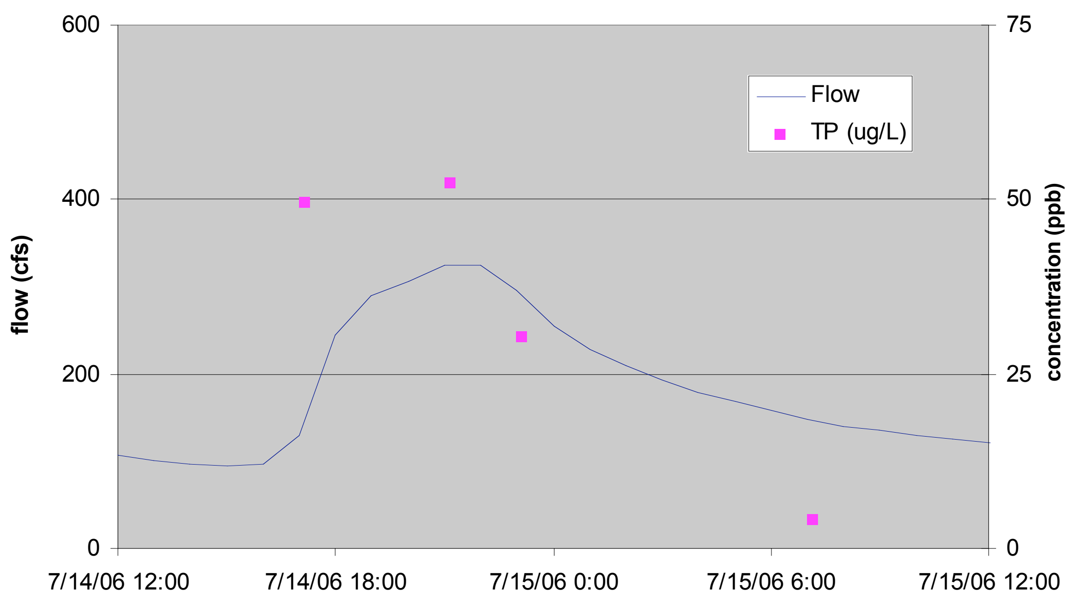



Fig. 11b Stream flow and total phosphorus concentrations measured on the Cedar River during one of four high-flow events.

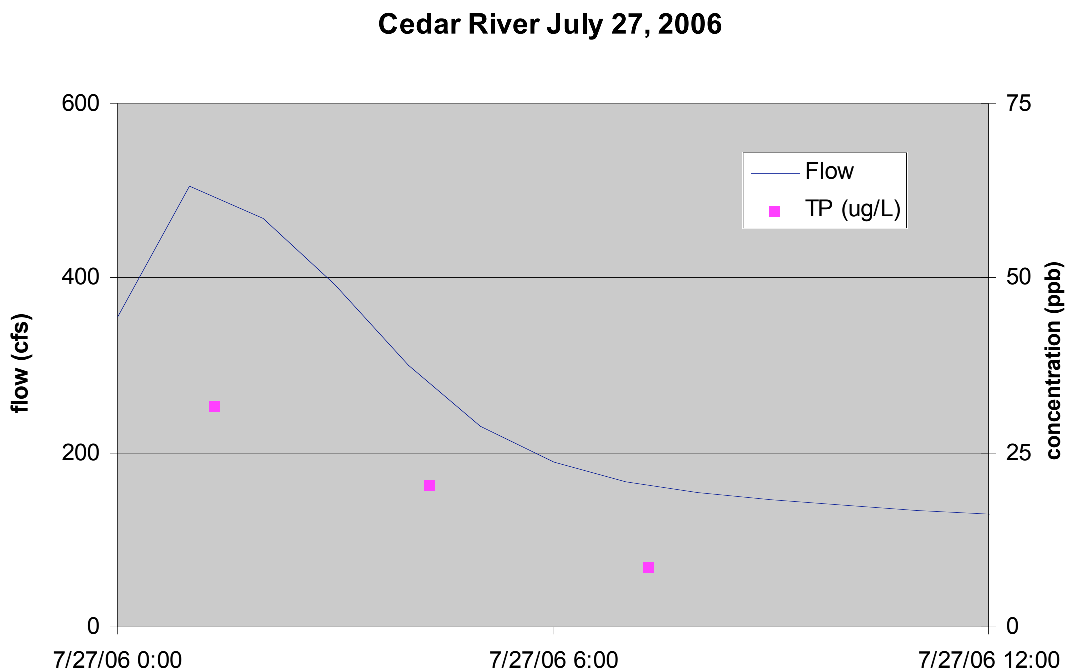



Fig. 11c Stream flow and total phosphorus concentrations measured on the Cedar River during one of four high-flow events.

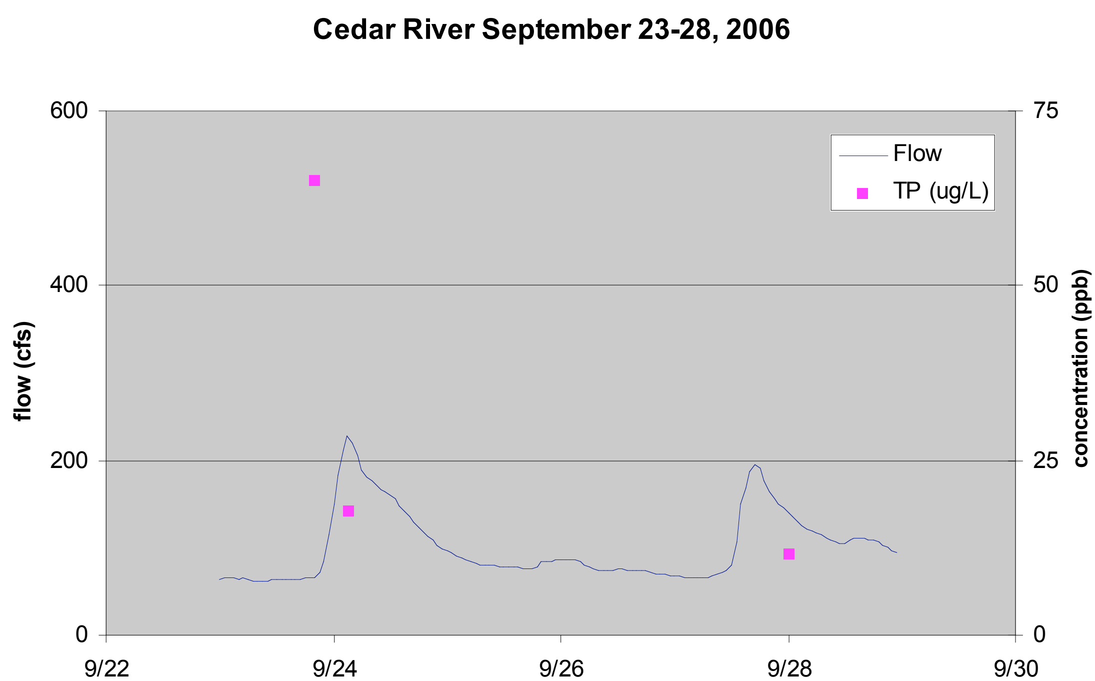



Fig. 11d Stream flow and total phosphorus concentrations measured on the Cedar River during one of four high-flow events.

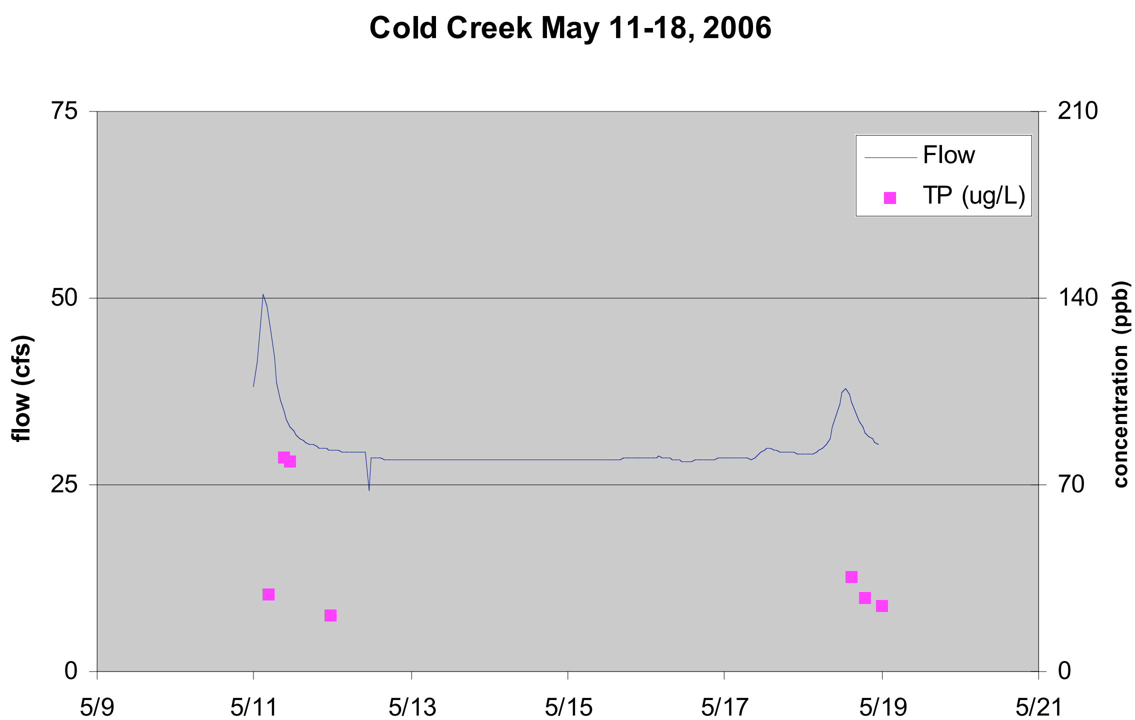



Fig. 11e  Stream flow and total phosphorus concentrations measured on the Cold Creek during one of four high-flow events.

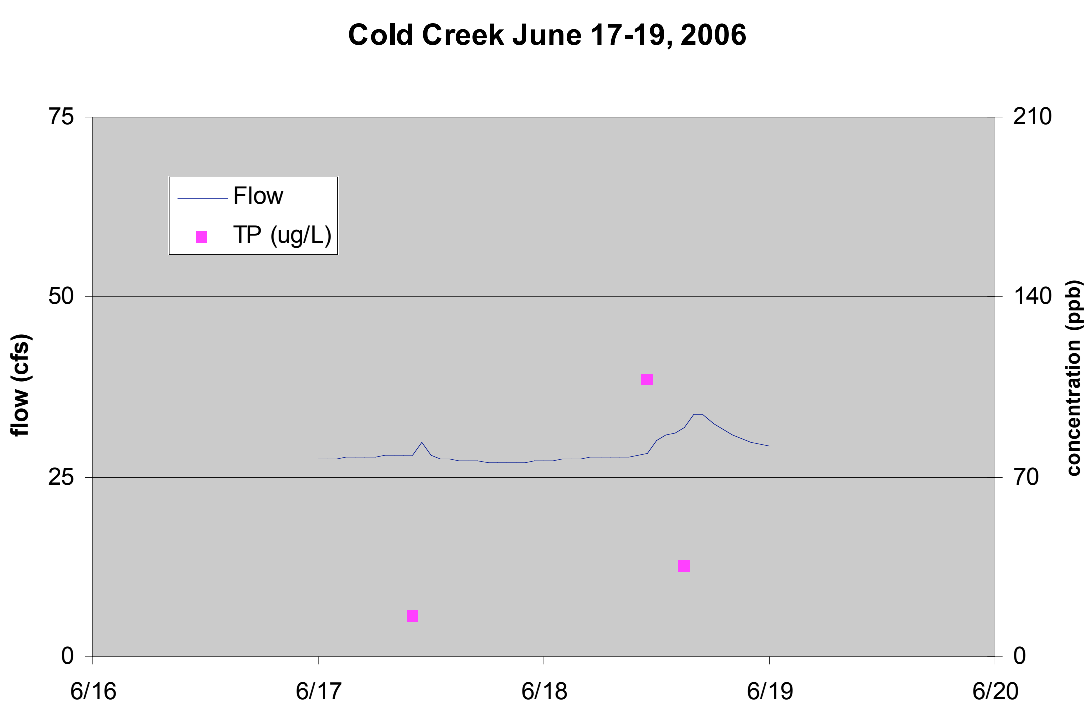



Fig. 11f  Stream flow and total phosphorus concentrations measured on the Cold Creek during one of four high-flow events.

**Cold Creek July 14 and 15, 2006**

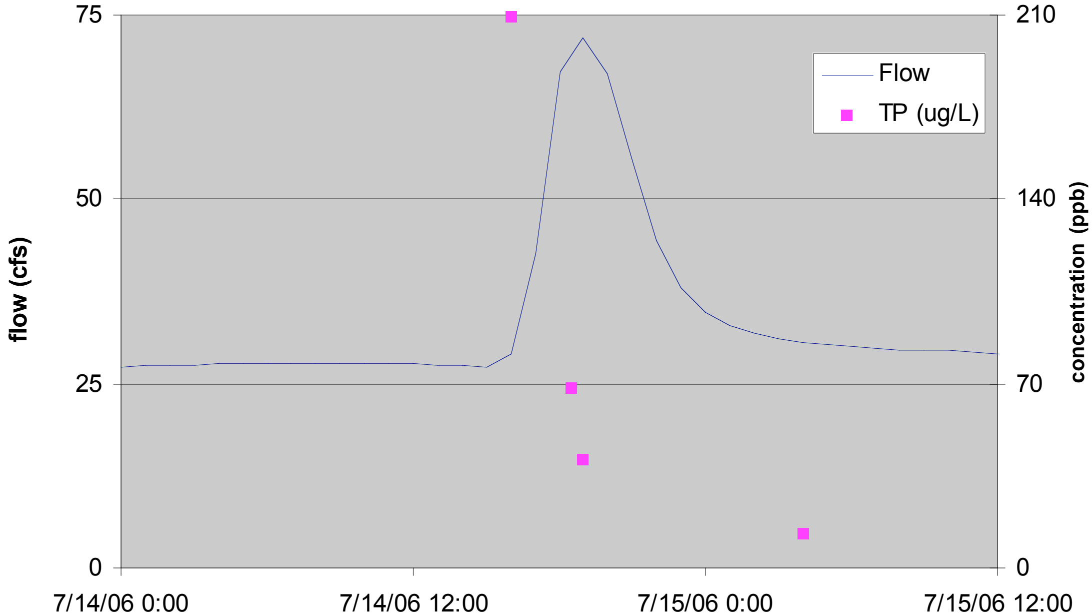



Fig. 11g Stream flow and total phosphorus concentrations measured on the Cold Creek during one of four high-flow events.

**Cold Creek September 23-28, 2006**

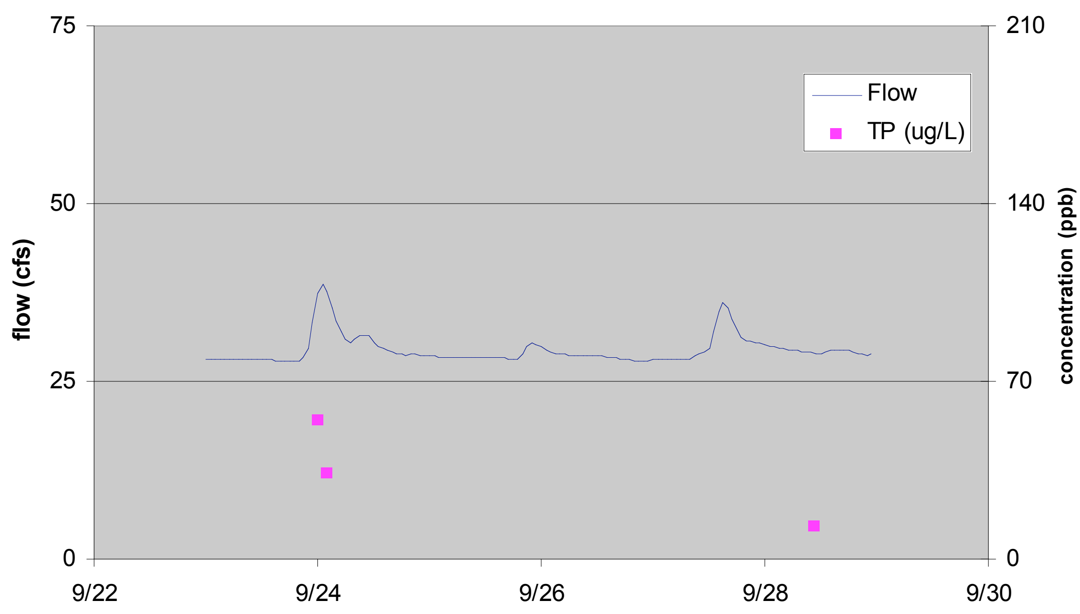



Fig. 11h Stream flow and total phosphorus concentrations measured on the Cold Creek during one of four high-flow events.

Fig. 12. Aerial photos of Clam Lake nearshore areas with visible macrophytes (August 31, 2006)

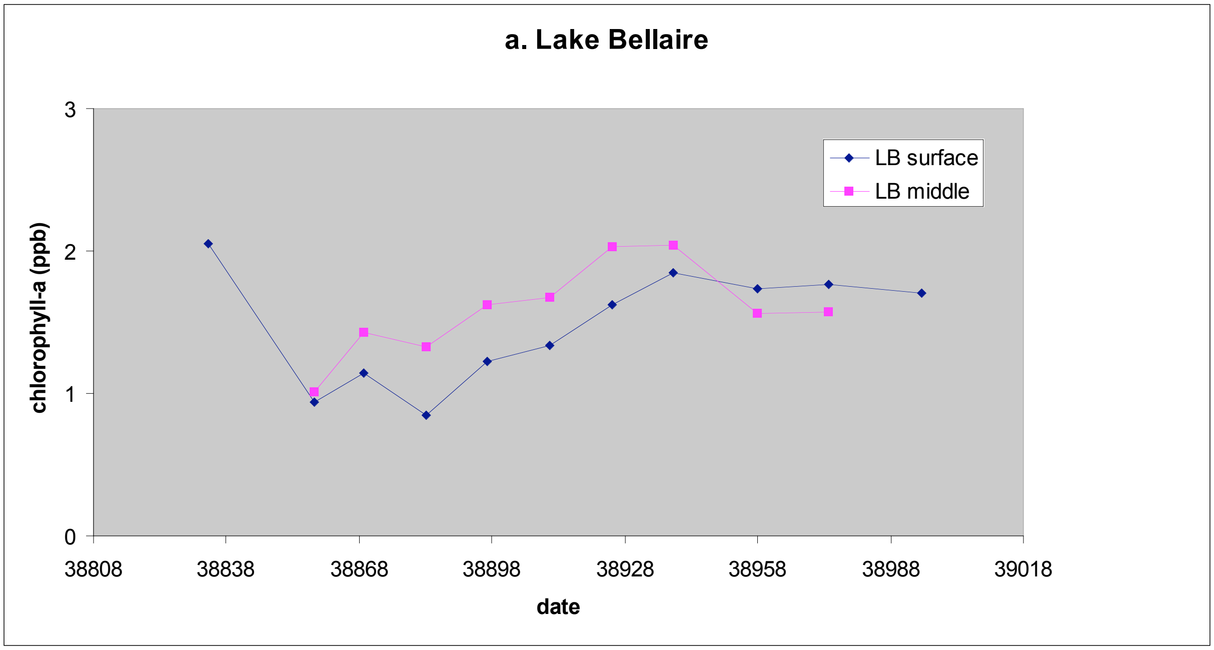



Fig. 13a  Measurements of chlorophyll-a concentrations in Lake Bellaire.

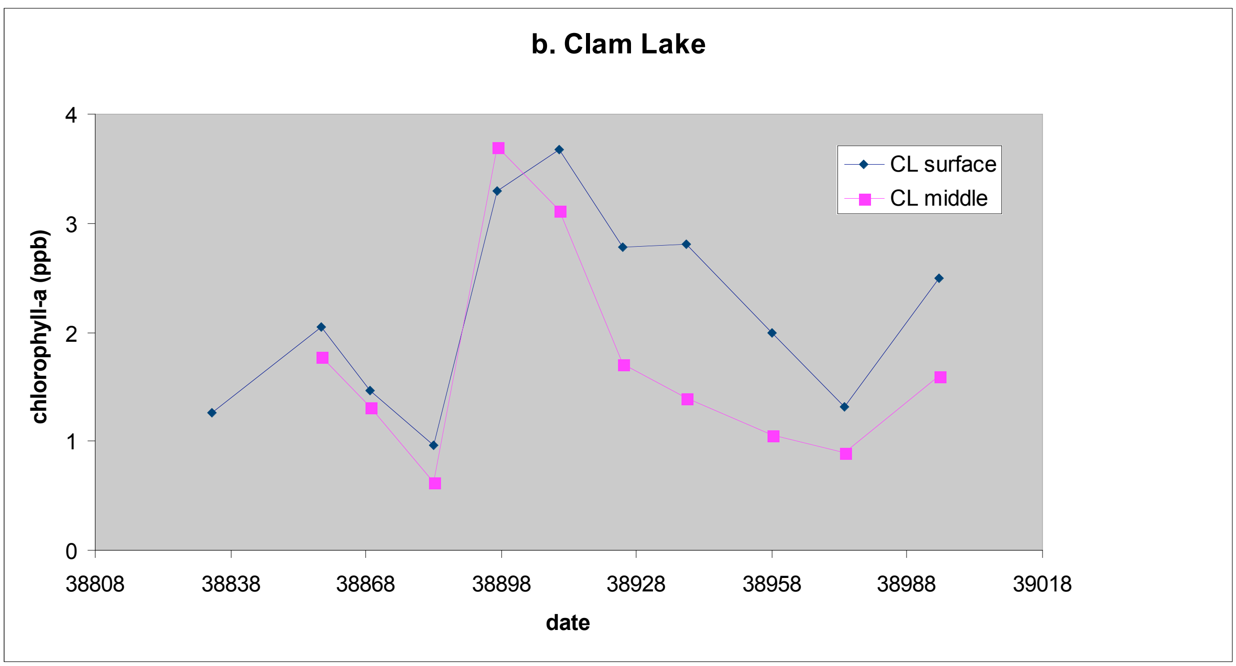



Fig. 13b  Measurements of chlorophyll-a concentrations in Clam Lake.

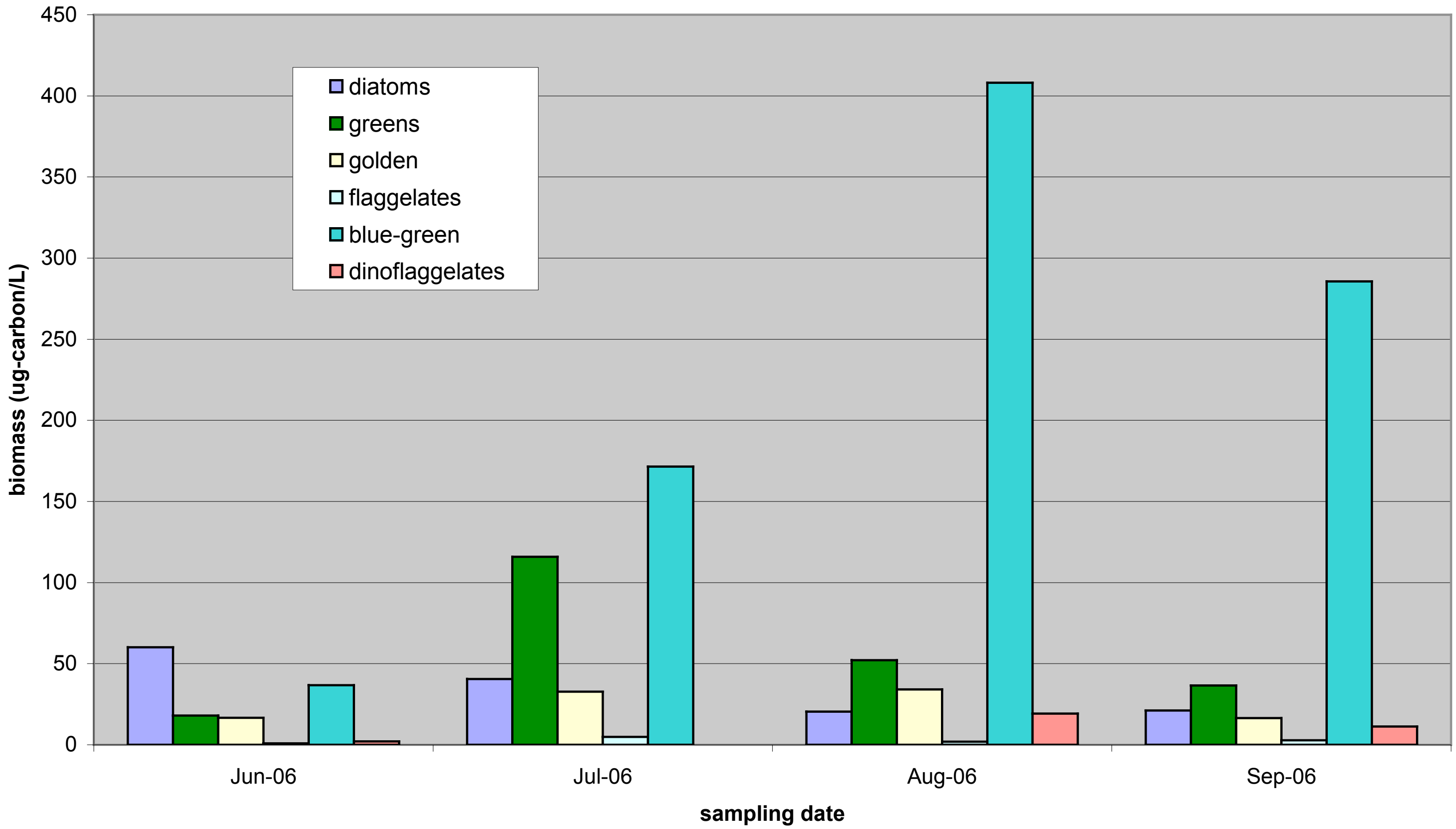



Fig. 14 Phytoplankton functional group biomass estimated from cell counts measured in the surface layer of Lake Bellaire.

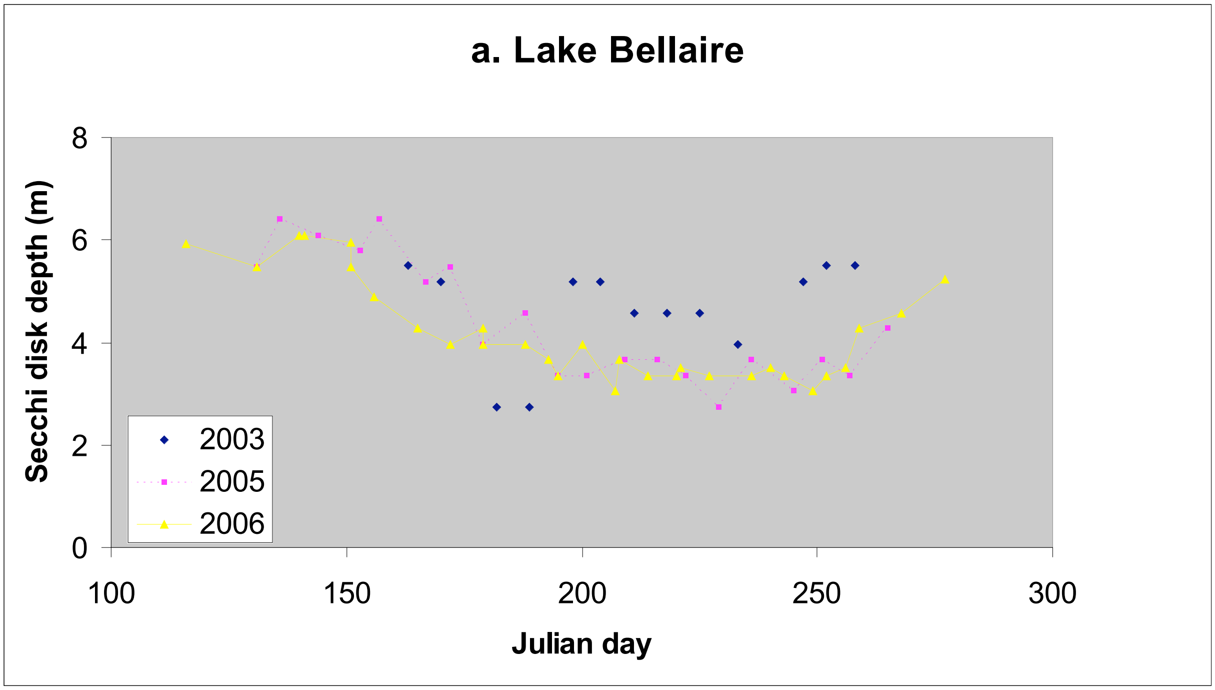



Fig. 15a  Secchi disk depths measured in Lake Bellaire by TLA, Michigan Lakes and Streams Association (MLSA) volunteers and TOM Watershed Center.

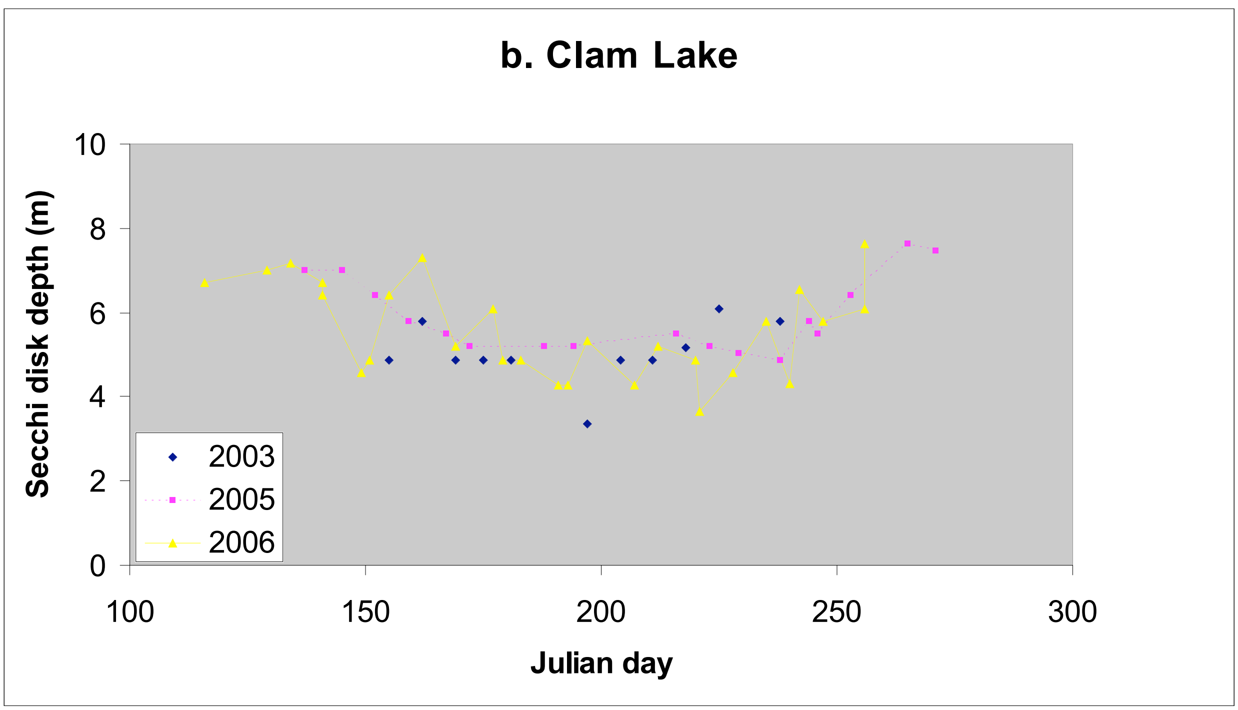



Fig. 15b  Secchi disk depths measured in Clam Lake by TLA, Michigan Lakes and Streams Association (MLSA) volunteers and TOM Watershed Center.

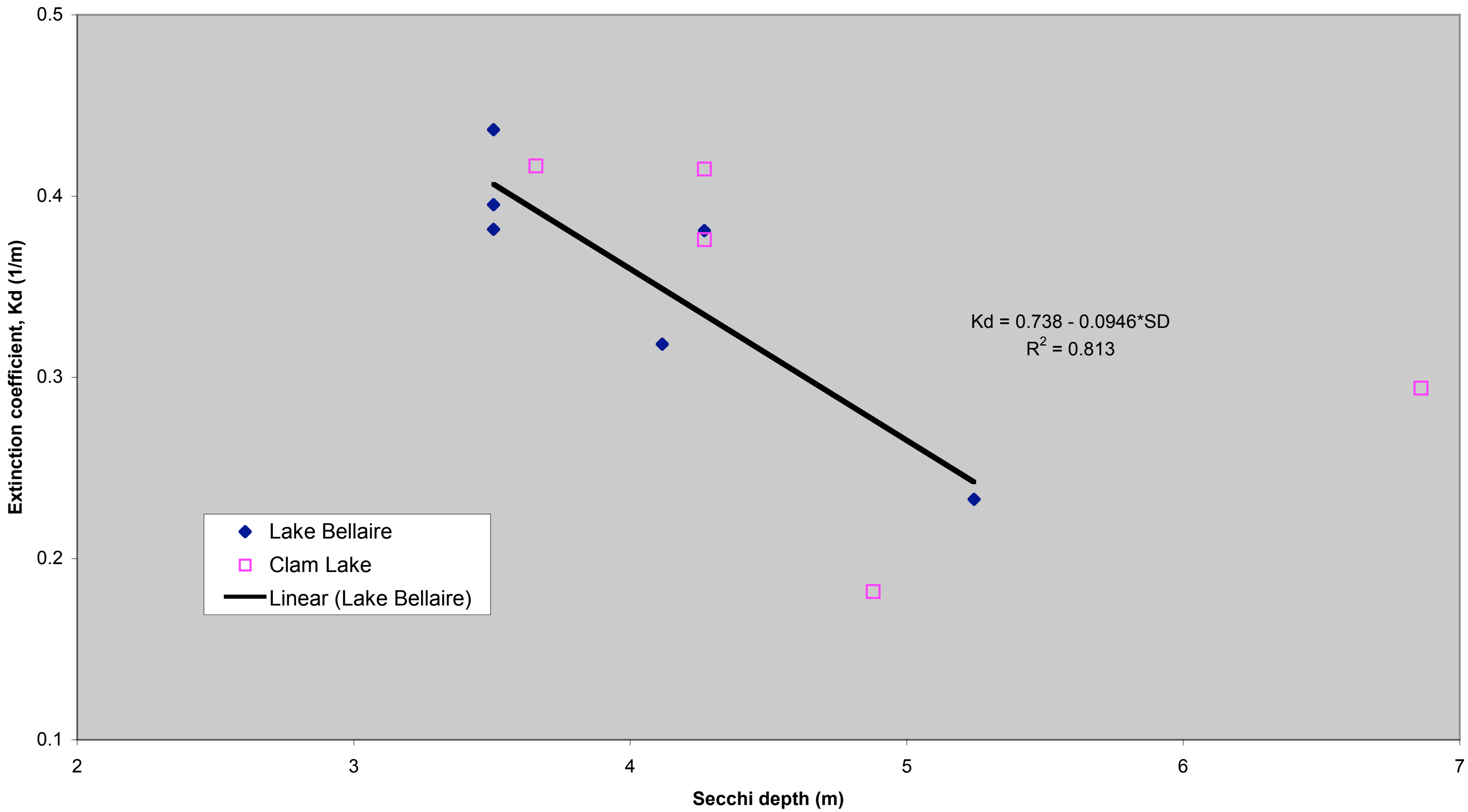



Fig. 16 Correlation between light extinction coefficients (Kd) and Secchi depths in Lake Bellaire and Clam Lake; regression (Kd = 0.738 – 0.0946 * SD) based on Lake Bellaire data only.

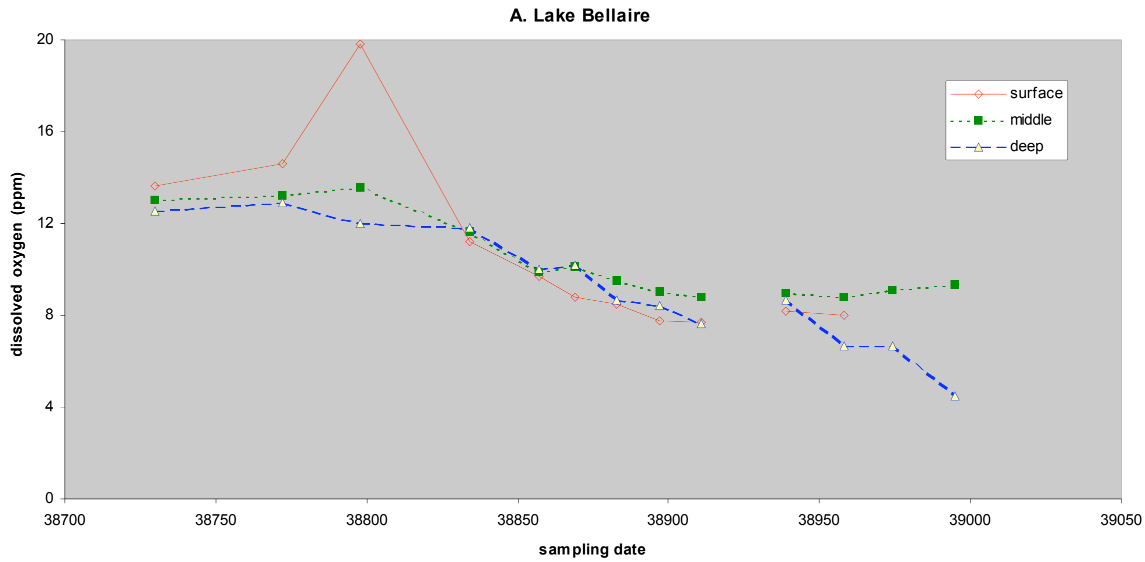



Fig. 17a  Average dissolved oxygen concentrations in each layer of Lake Bellaire calculated from HydroLab profile data.

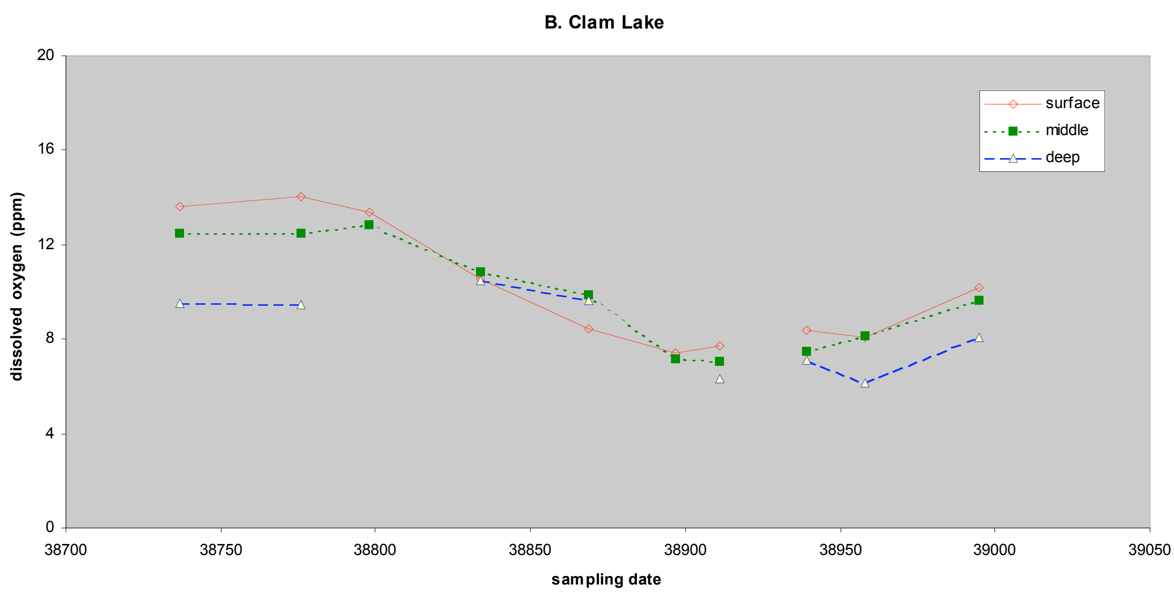



Fig. 17b  Average dissolved oxygen concentrations in each layer of Clam Lake calculated from HydroLab profile data.

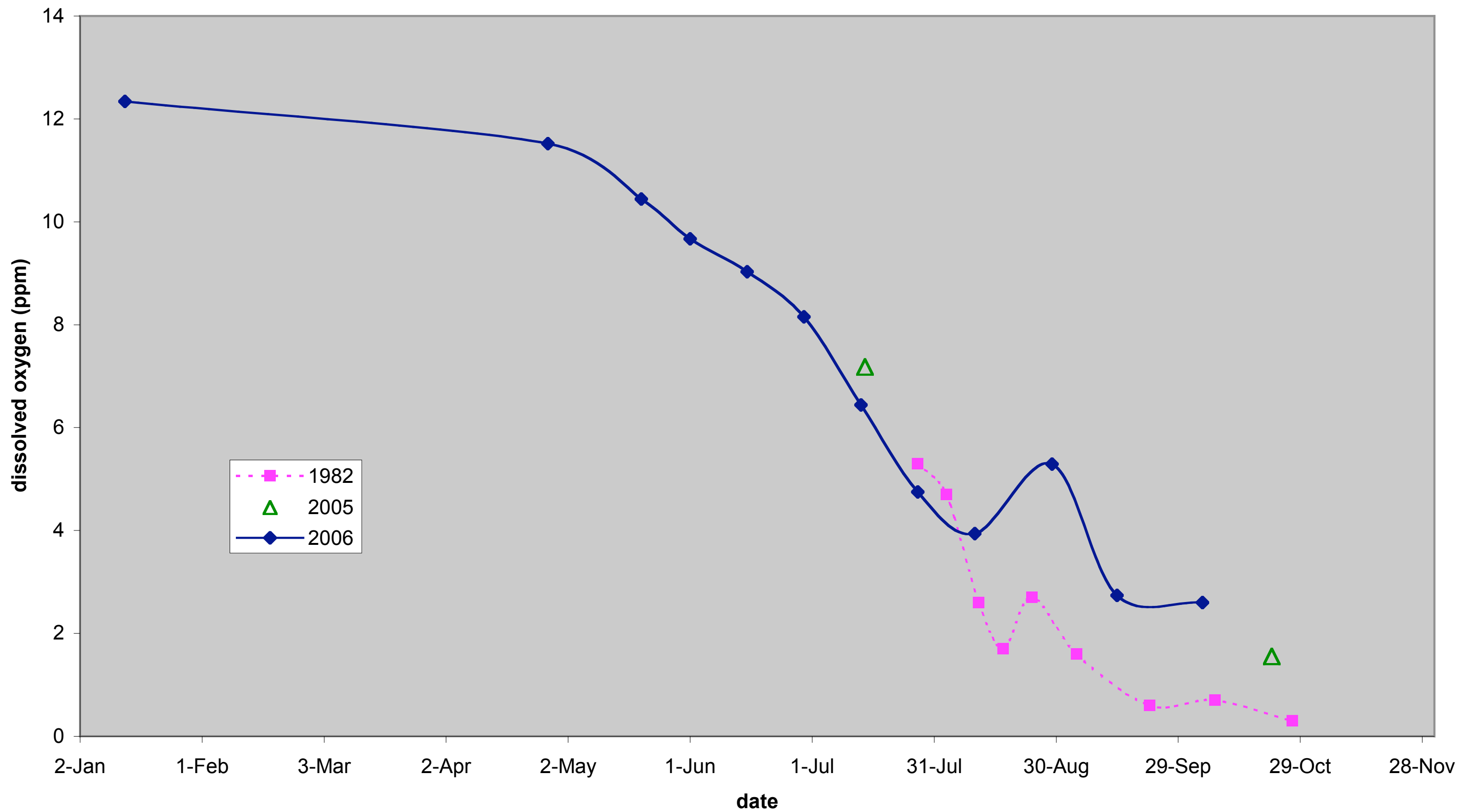



Fig. 18 . Lake Bellaire near-bottom dissolved oxygen concentration timeseries measured in this project (2005/2006) and comparison to Canale et al. data for 1982. The sampling locations and water column depths are nearly equivalent.

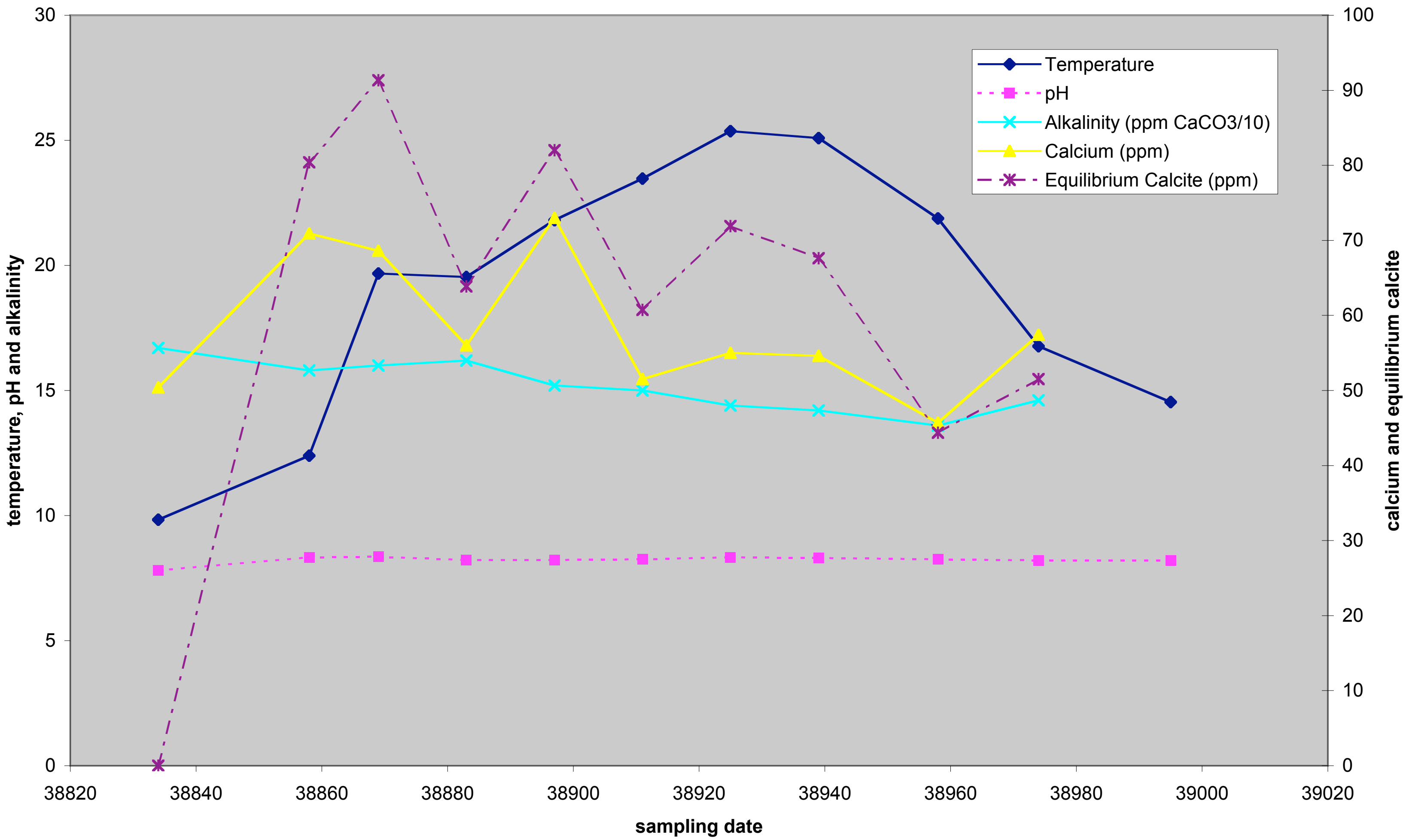



Fig. 19 Plot of surface water temperature, pH and calcium and alkalinity concentrations in Lake Bellaire along with the Visual MINTEQ predictions of the corresponding equilibrium calcite concentrations.

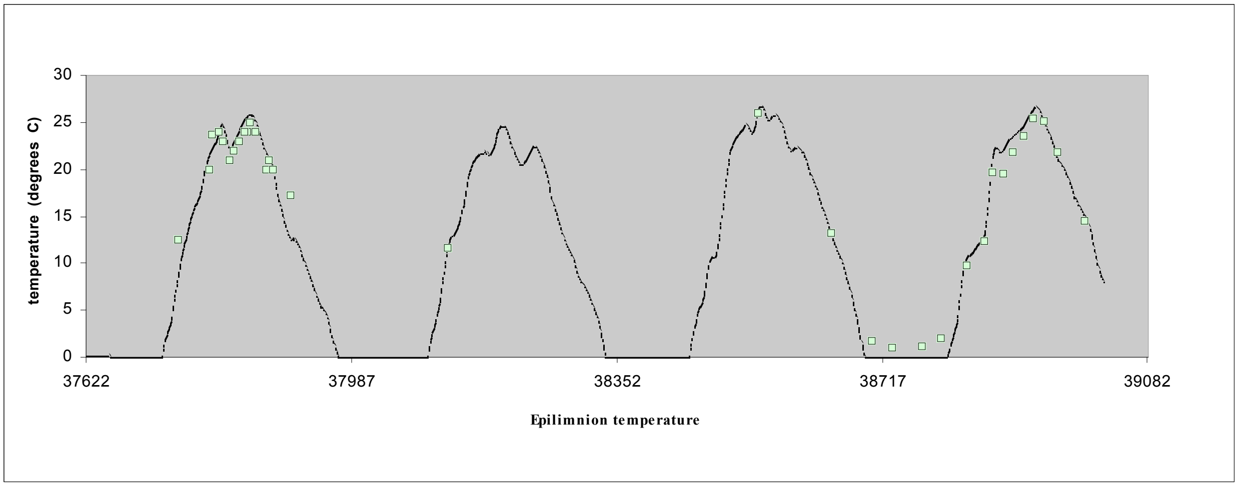



Fig. 20a Simulation of temperature by the Lake Bellaire model and average data in the epilimnion.

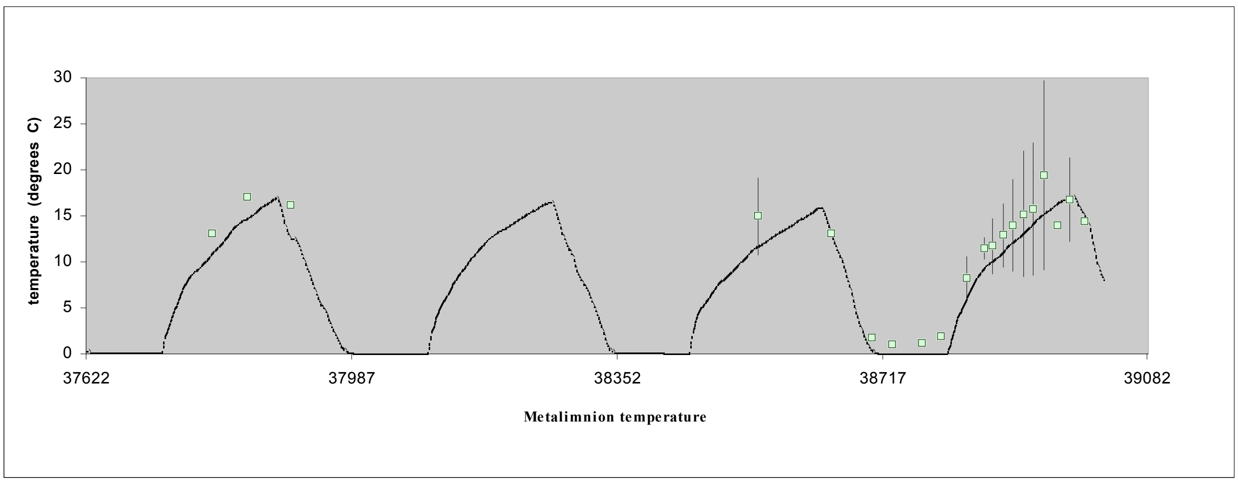



Fig. 20b Simulation of temperature by the Lake Bellaire model and average data in the metalimnion.

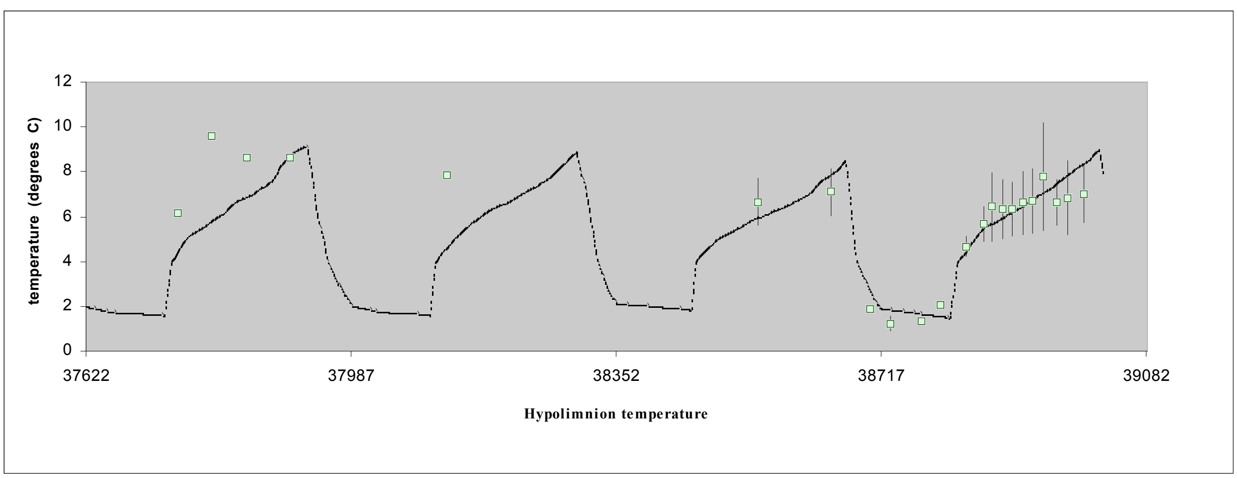



Fig. 20c Simulation of temperature by the Lake Bellaire model and average data in the hypolimnion.

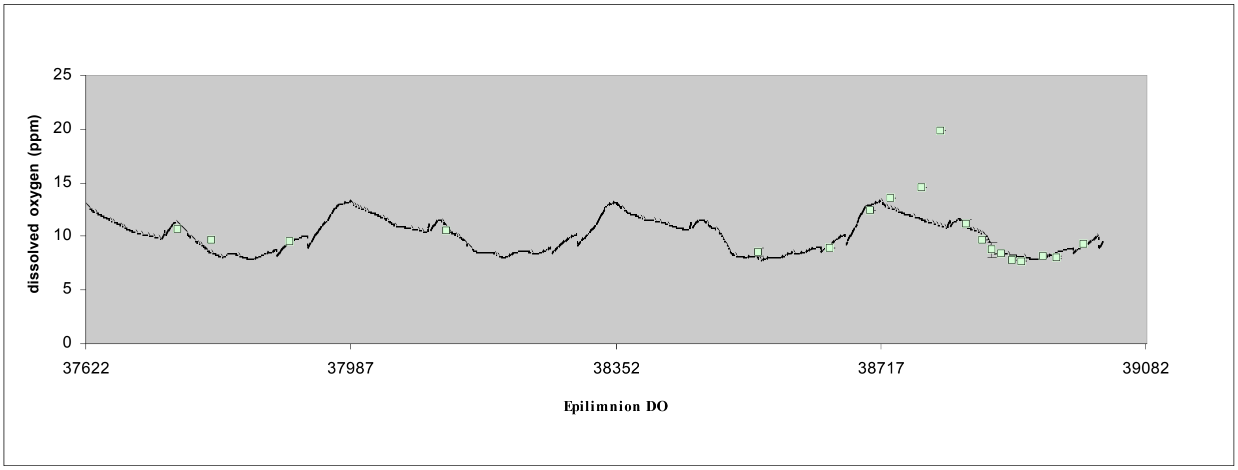



Fig. 20d Simulation of DO concentrations by the Lake Bellaire model and average data in the epilimnion.

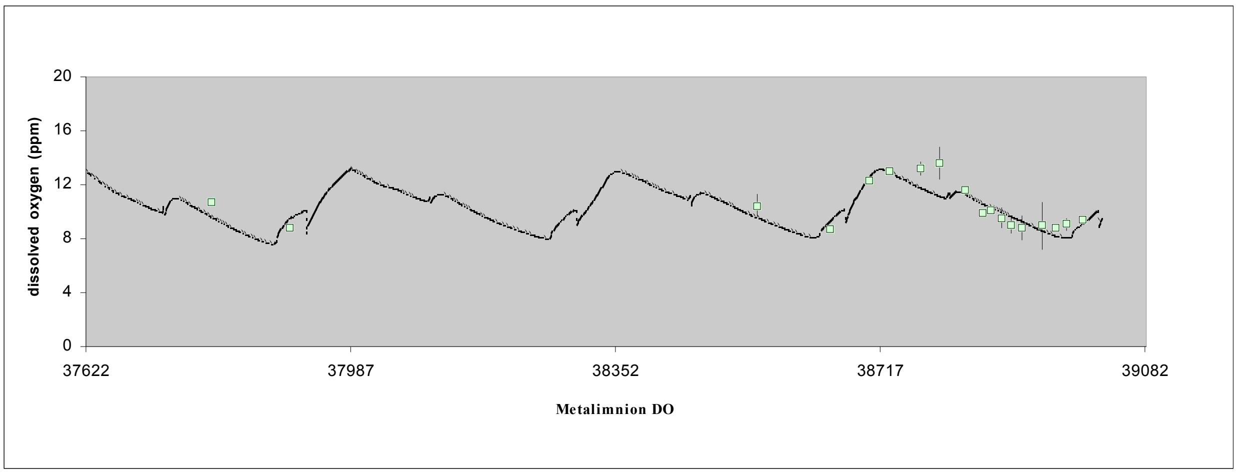



Fig. 20e Simulation of DO concentrations by the Lake Bellaire model and average data in the metalimnion.

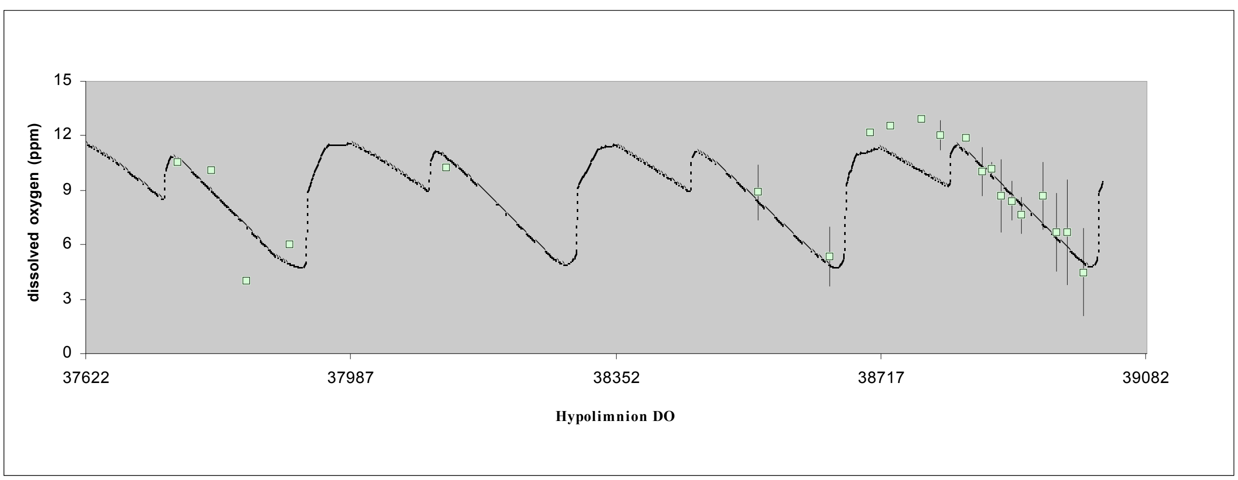



Fig. 20f Simulation of DO concentrations by the Lake Bellaire model and average data in the hypolimnion.

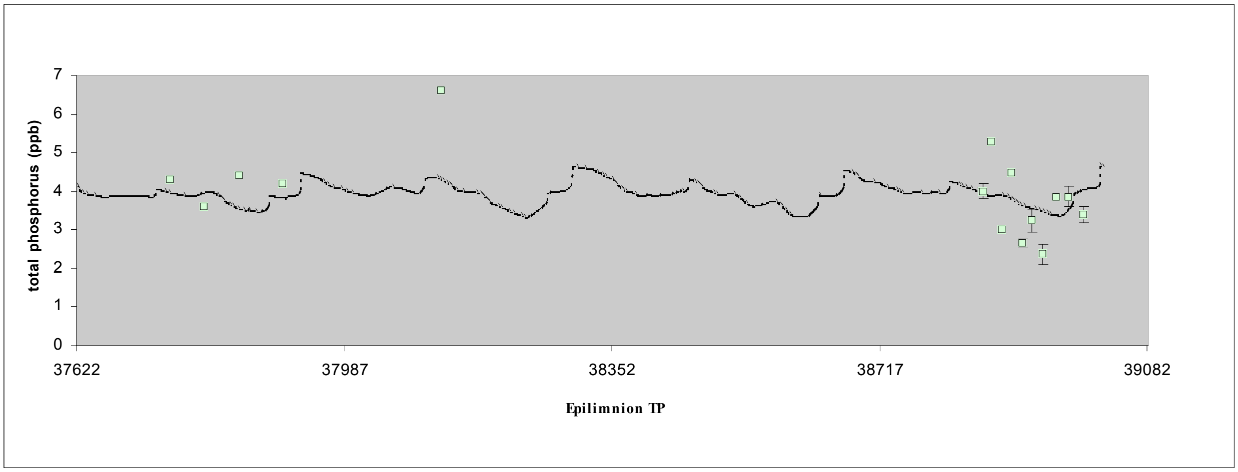
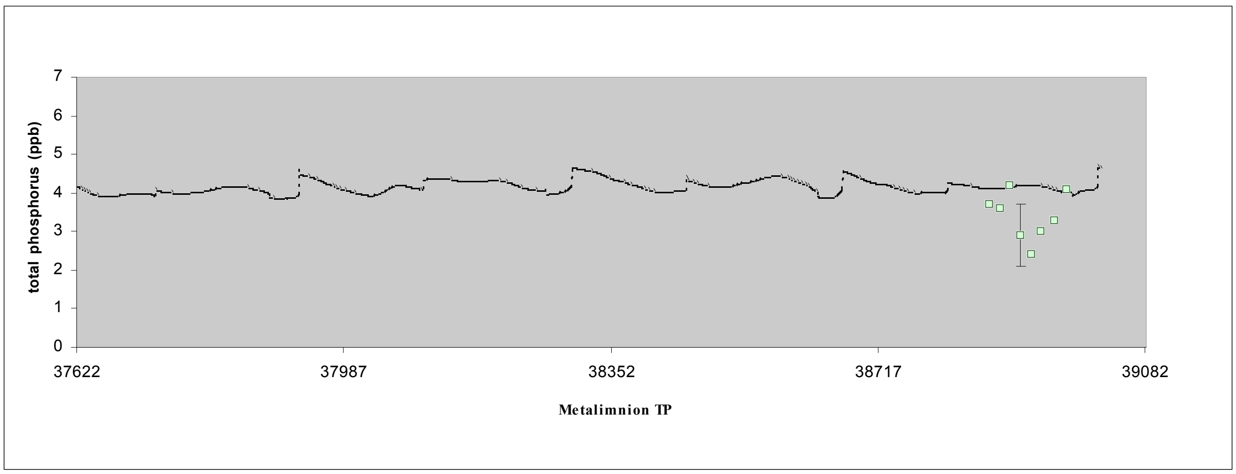



Fig. 21a  Simulation of total phosphorus concentrations by the Lake Bellaire model and average data for total and dissolved phosphorus in the epilimnion.




\Fig. 21b  Simulation of total phosphorus concentrations by the Lake Bellaire model and average data for total and dissolved phosphorus in the metalimnion.

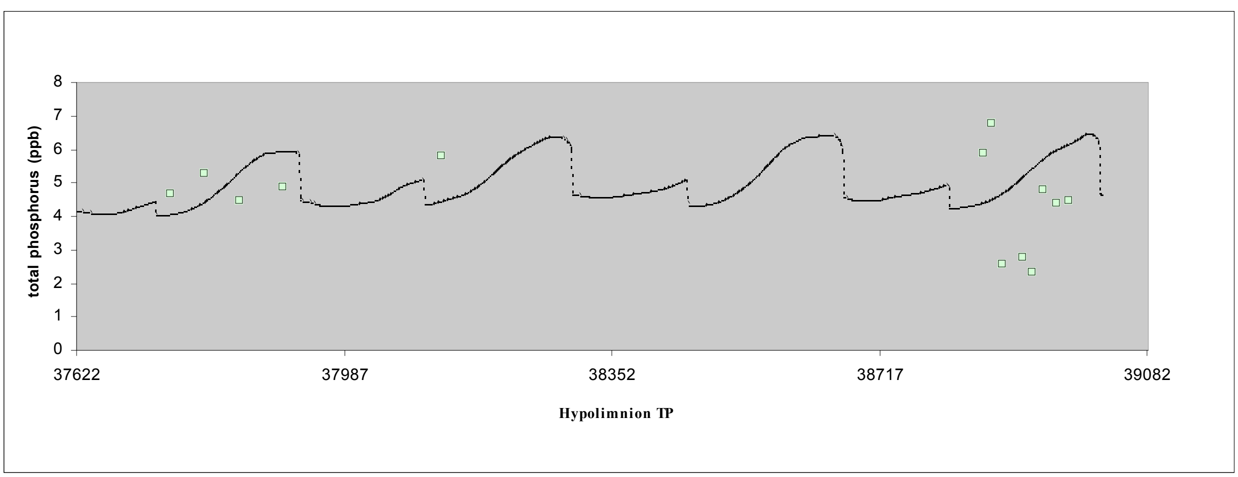



Fig. 21c  Simulation of total phosphorus concentrations by the Lake Bellaire model and average data for total and dissolved phosphorus in the hypolimnion.

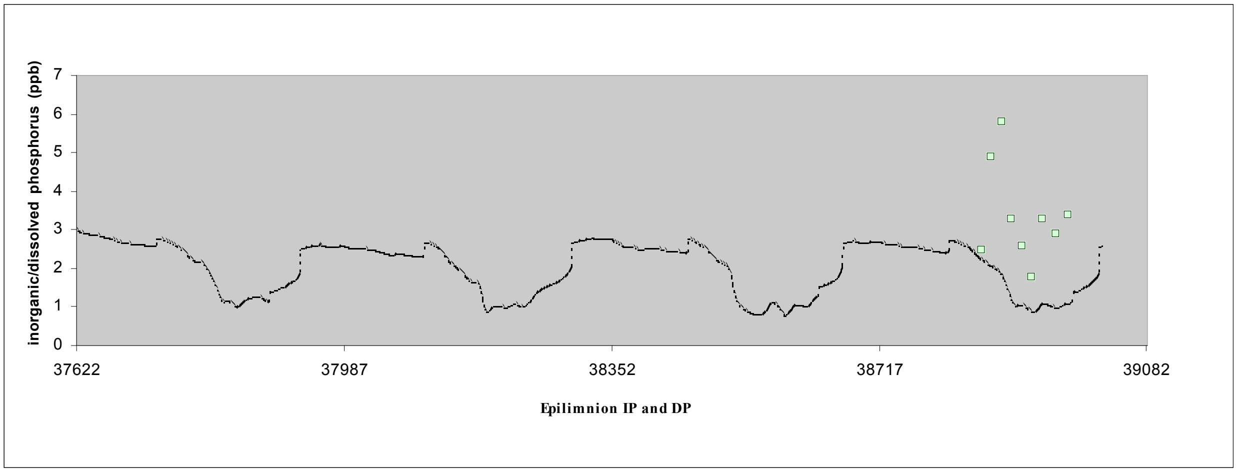



Fig. 21d  Simulation of inorganic phosphorus concentrations by the Lake Bellaire model and average data for total and dissolved phosphorus in the epilimnion.

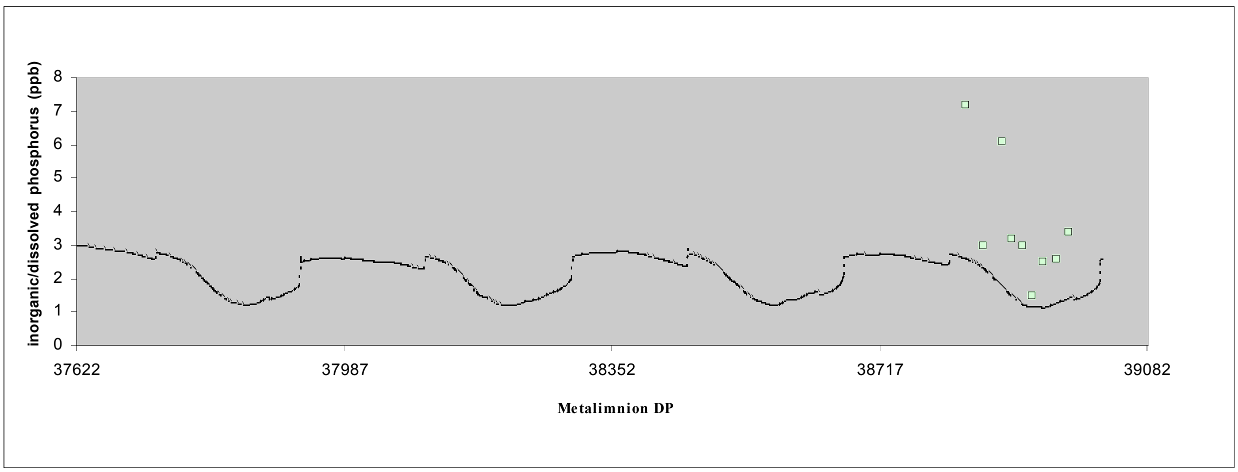



Fig. 21e  Simulation of inorganic phosphorus concentrations by the Lake Bellaire model and average data for total and dissolved phosphorus in the metalimnion.

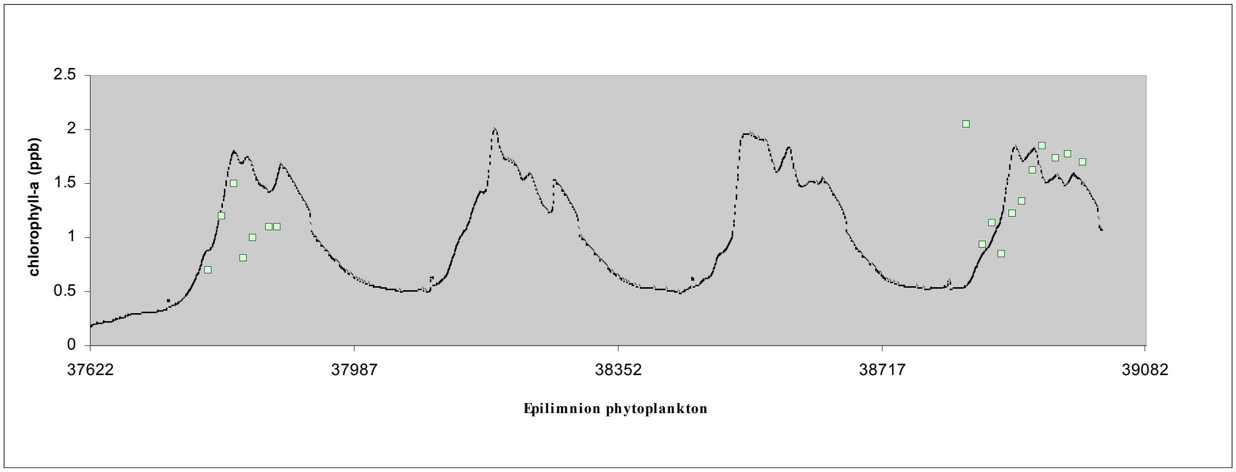



Fig. 22a Simulation of epilimnion chlorophyll-a concentrations in the Lake Bellaire model and data from the lake.

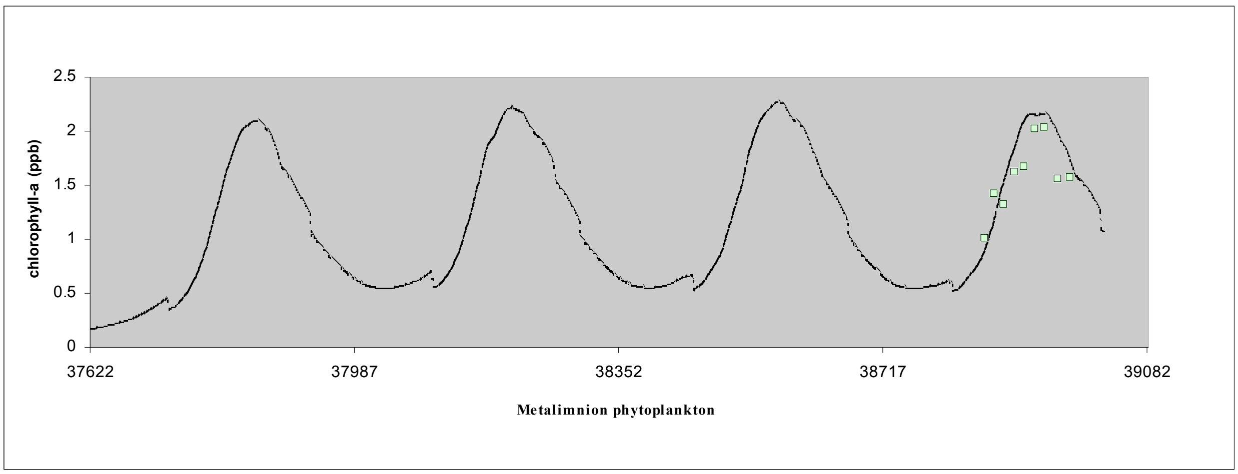



Fig. 22b Simulation of metalimnion chlorophyll-a concentrations in the Lake Bellaire model and data from the lake.

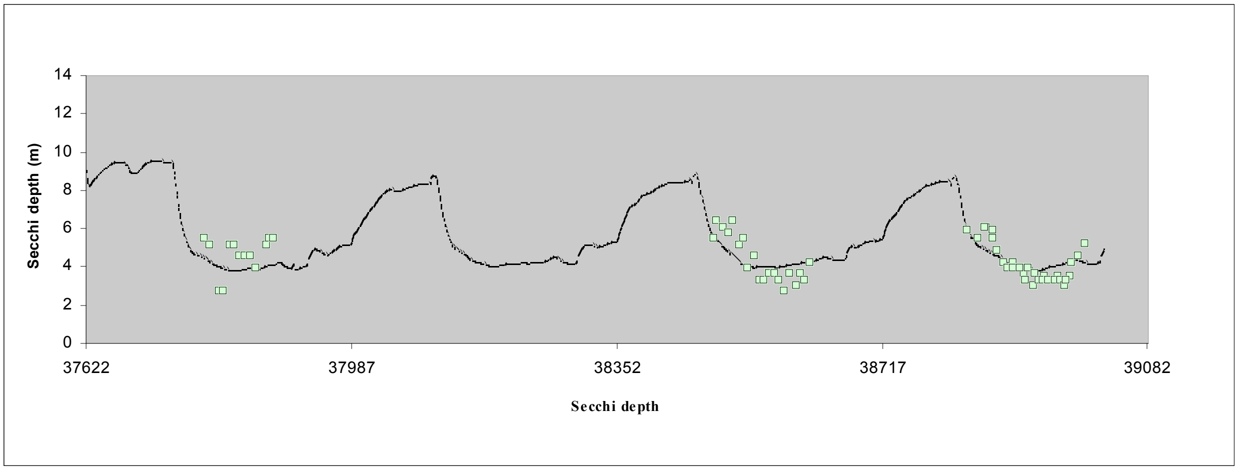



Fig. 22c  Simulation of Secchi depths in the Lake Bellaire model and data from the lake.

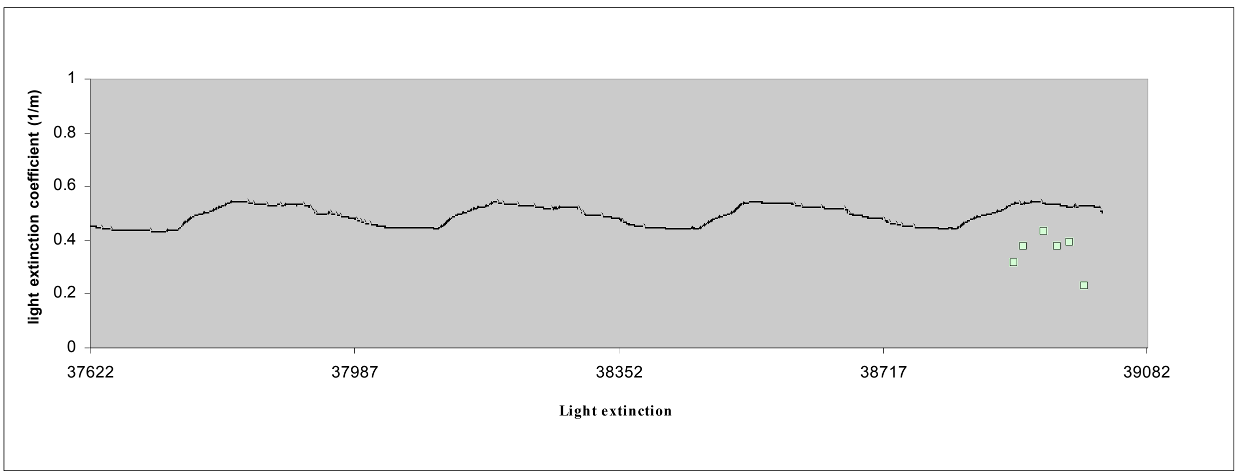



Fig. 22d  Simulation of light extinction in the Lake Bellaire model and data from the lake.

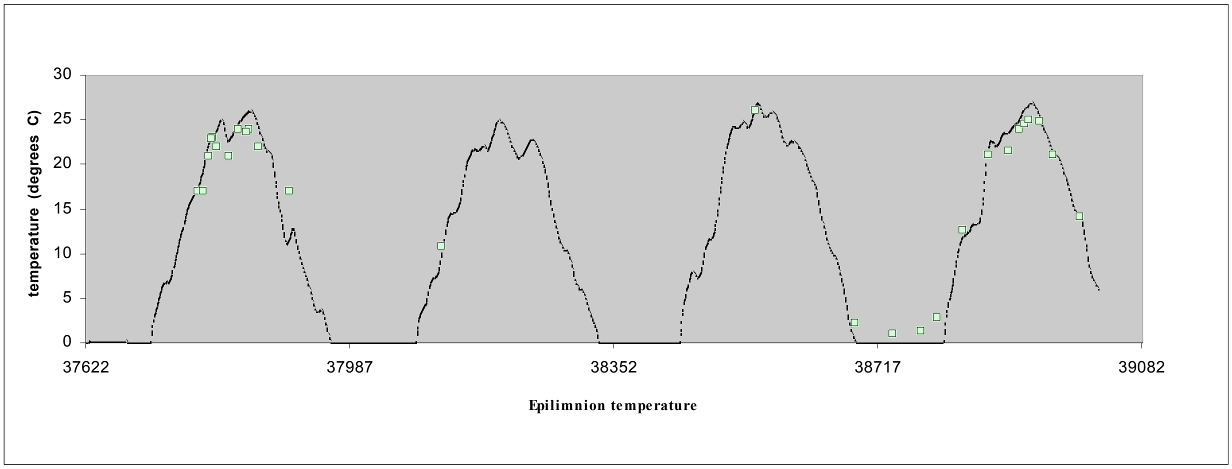



Fig. 23a Simulation of temperature by the Clam Lake model and average data in the epilimnion.

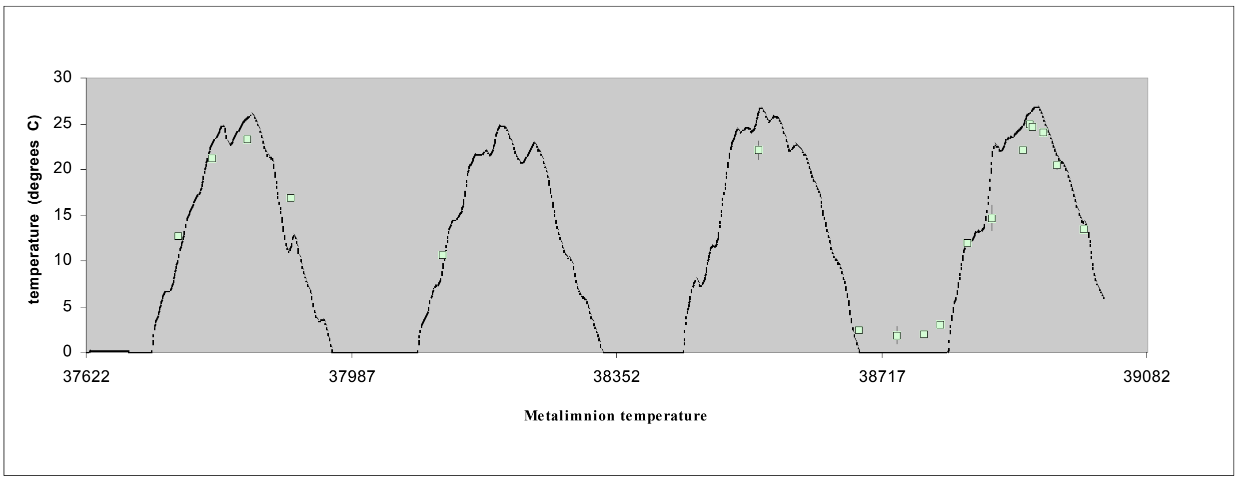



Fig. 23b Simulation of temperature by the Clam Lake model and average data in the metalimnion.

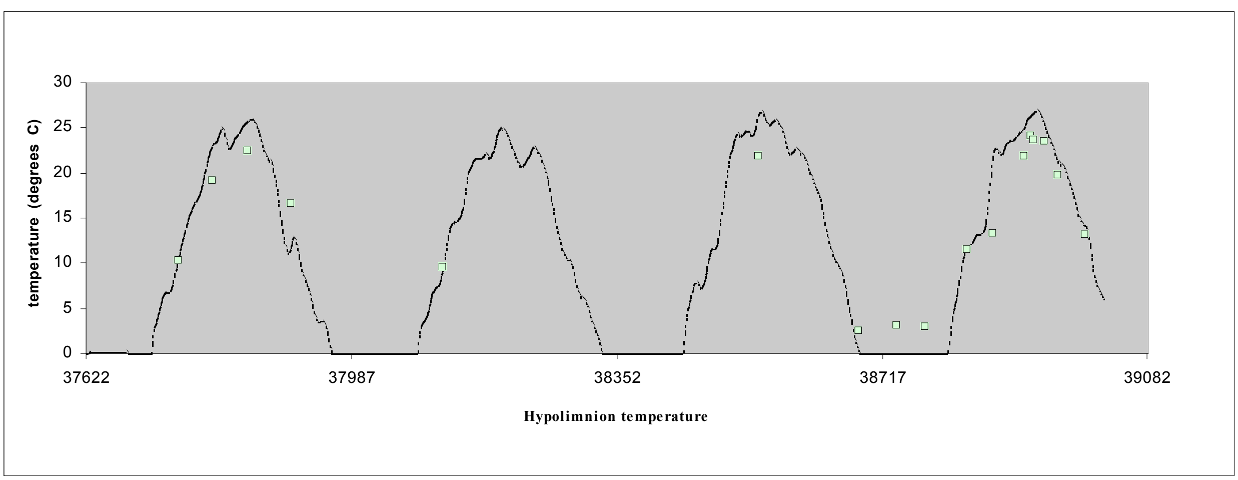



Fig. 23c Simulation of temperature by the Clam Lake model and average data in the hypolimnion.

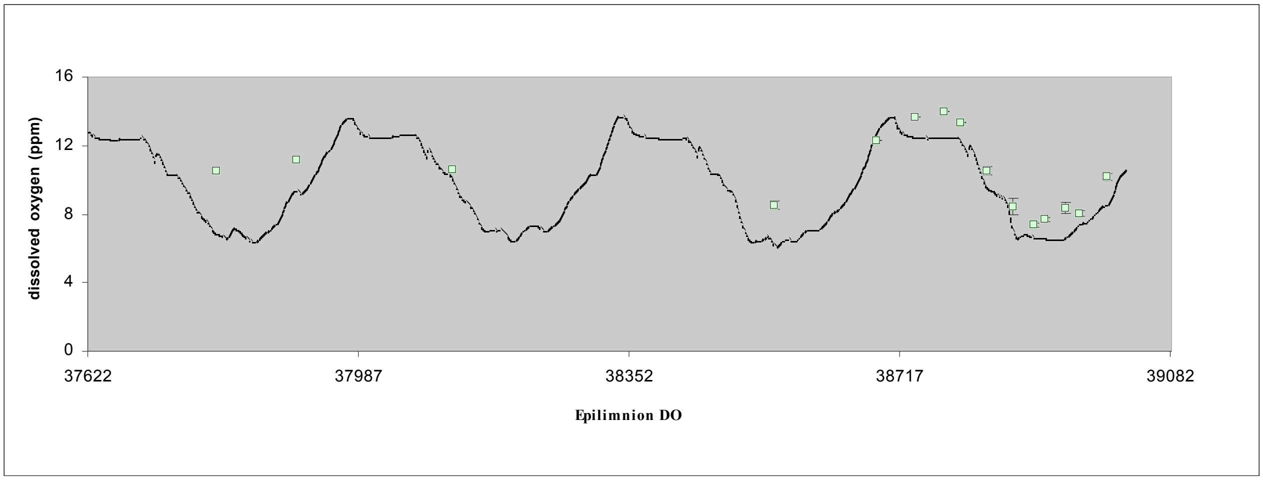



Fig. 23d  Simulation of DO concentrations by the Clam Lake model and average data in the epilimnion.

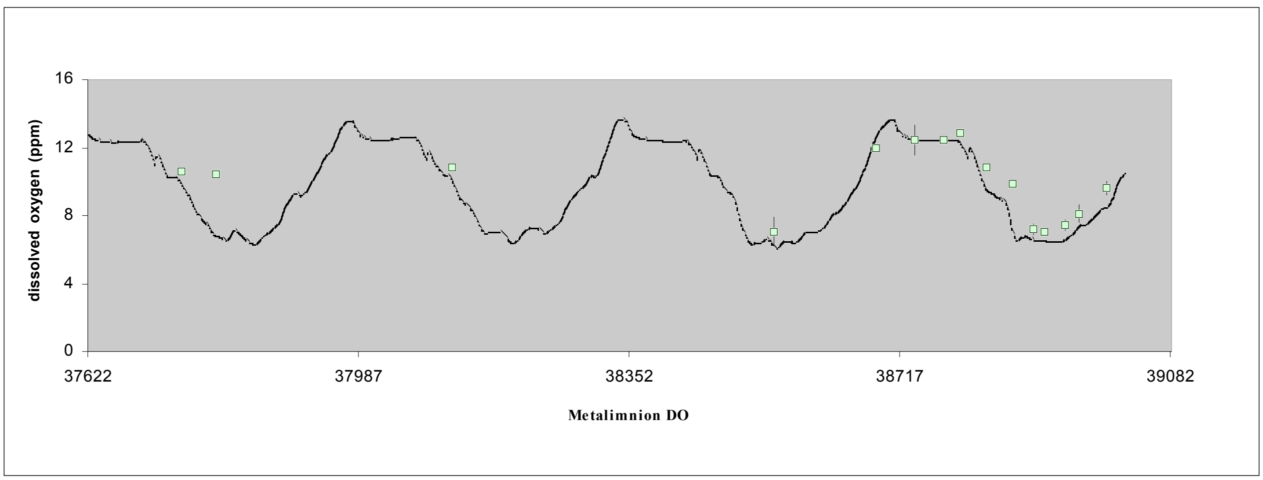



Fig. 23e  Simulation of DO concentrations by the Clam Lake model and average data in the metalimnion.

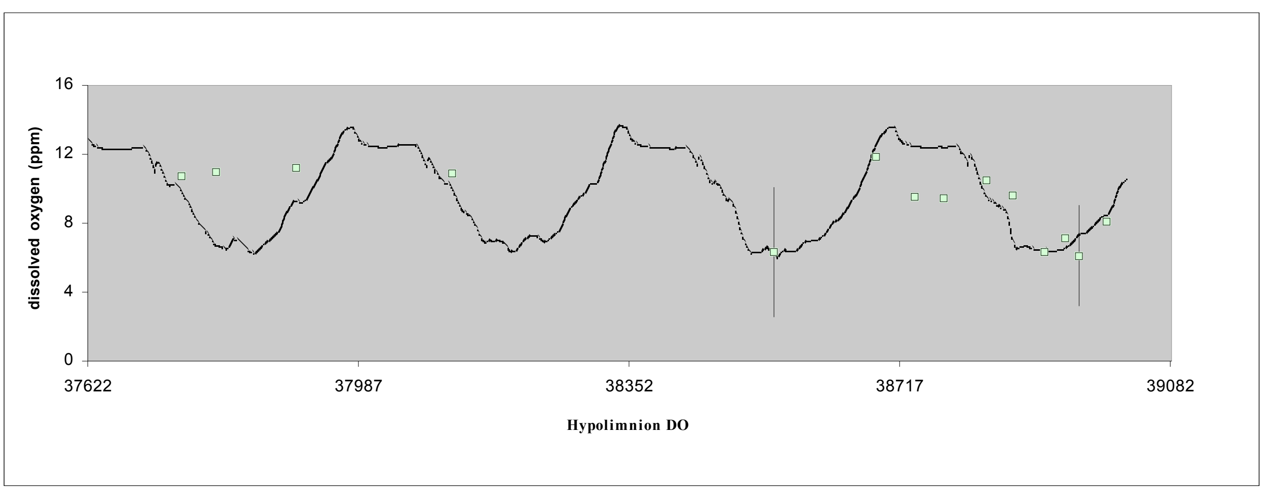



Fig. 23f  Simulation of DO concentrations by the Clam Lake model and average data in the hypolimnion.

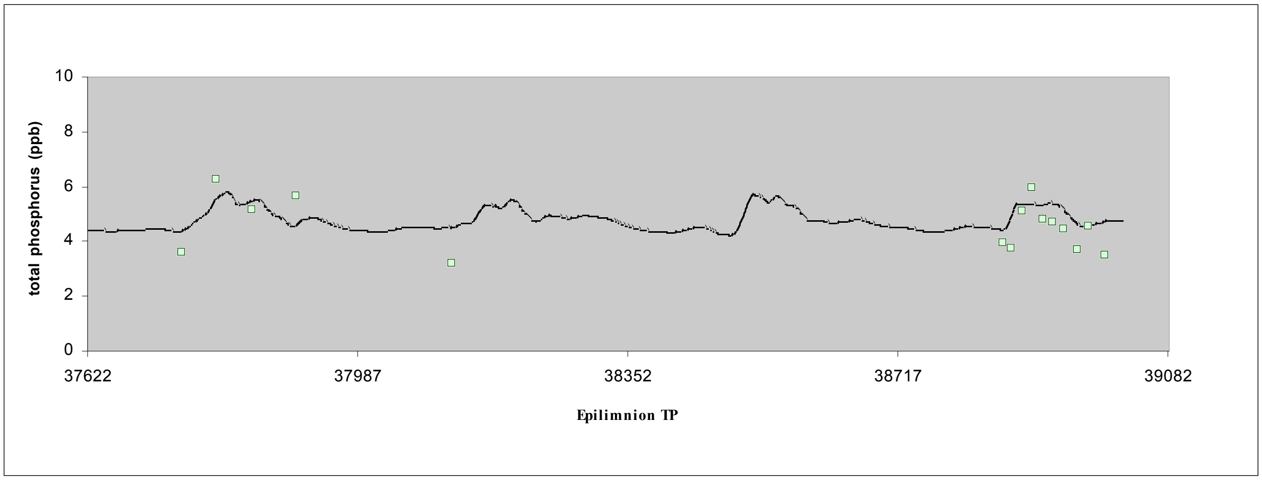



Fig. 24a Simulation of total phosphorus concentrations by the Clam Lake model and average data for total phosphorus in the epilimnion.

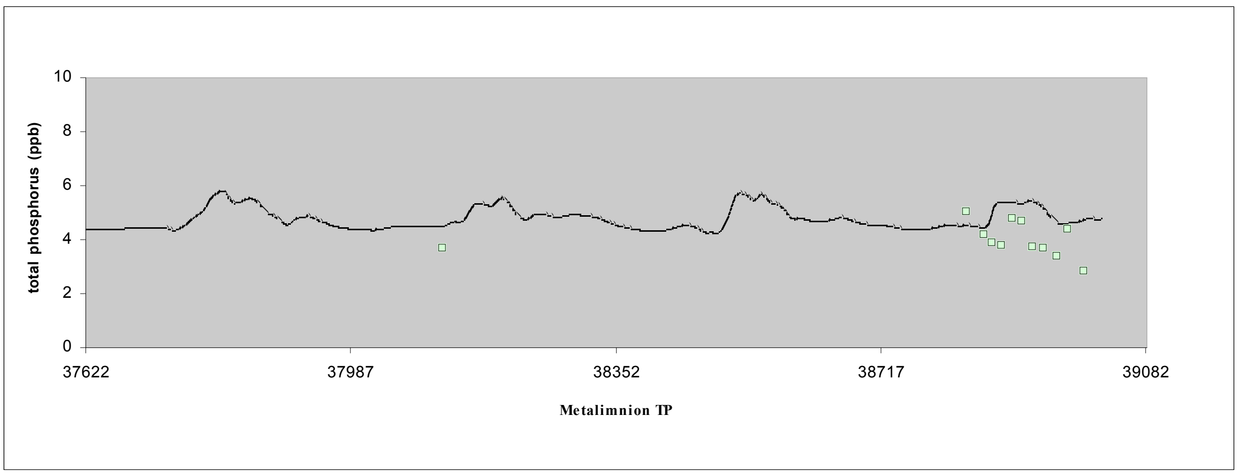



Fig. 24b Simulation of total phosphorus concentrations by the Clam Lake model and average data for total phosphorus in the metalimnion.

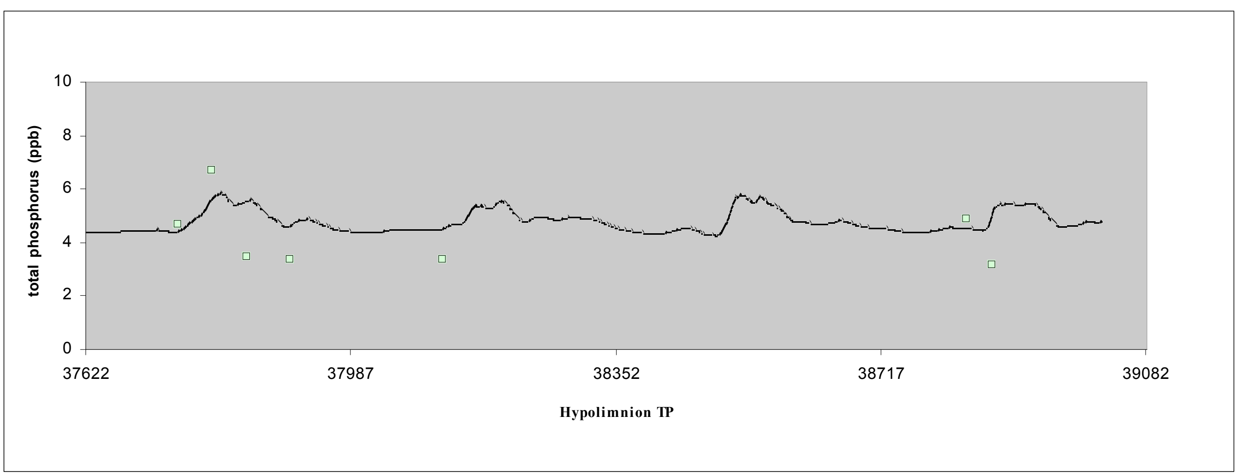



Fig. 24c Simulation of total phosphorus concentrations by the Clam Lake model and average data for total phosphorus in the hypolimnion.

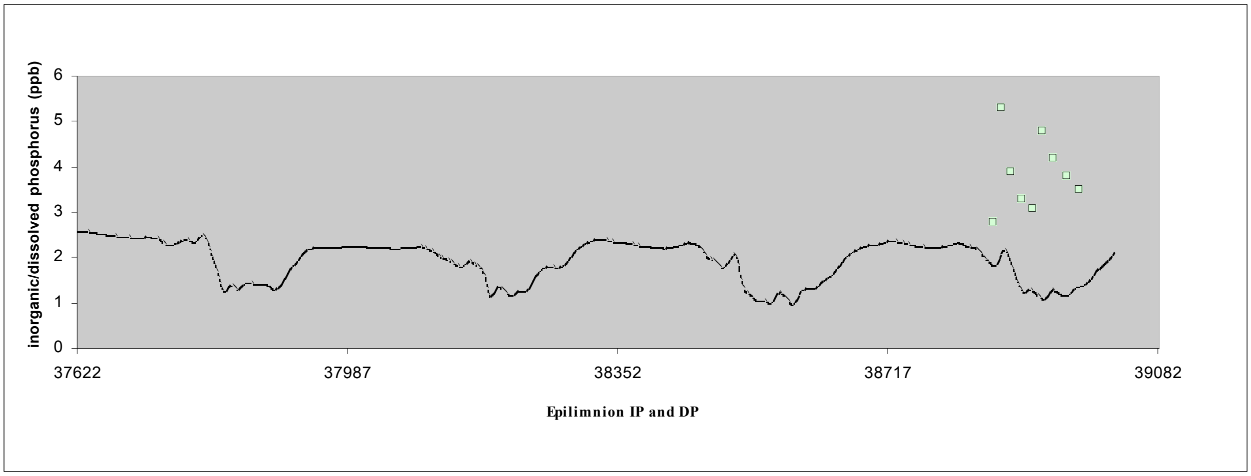



Fig. 24d Simulation of inorganic phosphorus concentrations by the Clam Lake model and average data for dissolved phosphorus in the epilimnion.

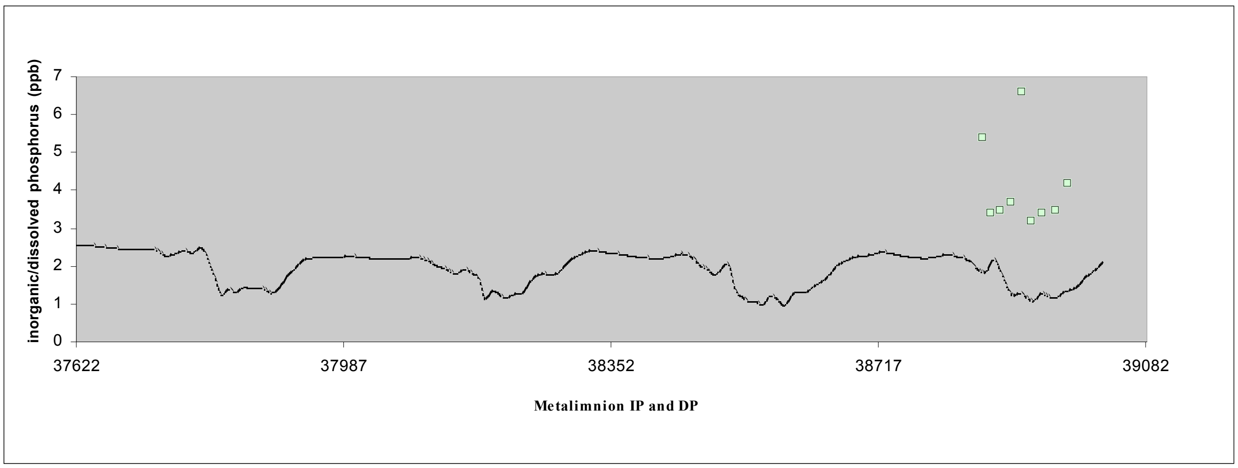



Fig. 24e Simulation of inorganic phosphorus concentrations by the Clam Lake model and average data for dissolved phosphorus in the metalimnion.

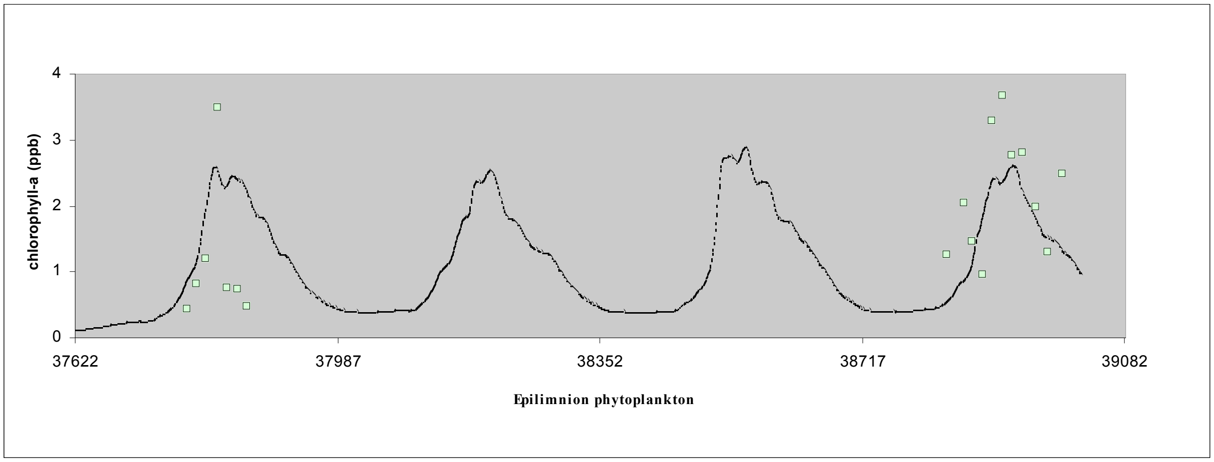



Fig. 25a  Simulation of epilimnion chlorophyll-a concentrations by the Clam Lake model and data from the lake.

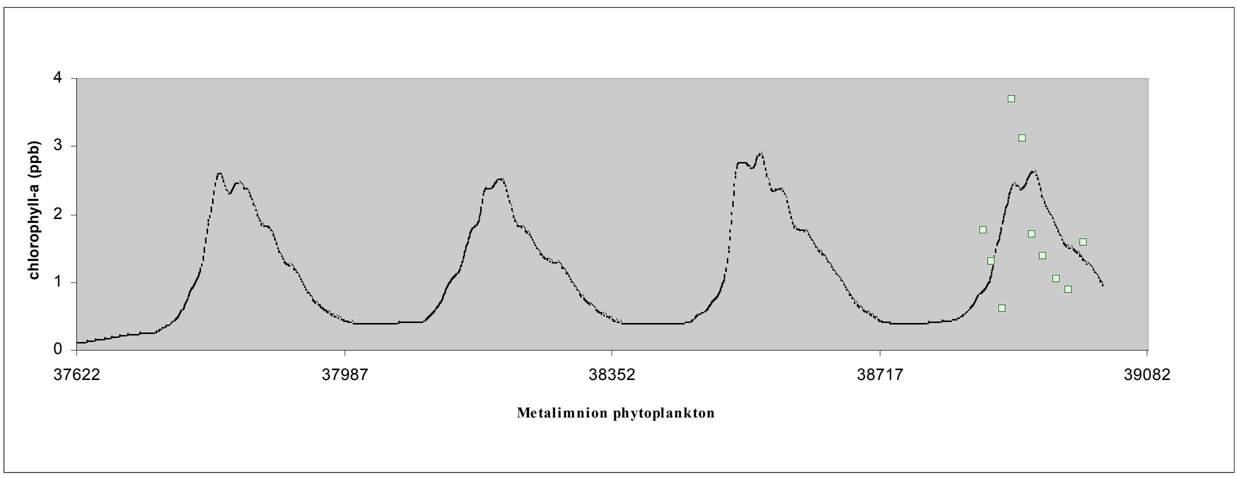



Fig. 25b  Simulation of metalimnion chlorophyll-a concentrations by the Clam Lake model and data from the lake.

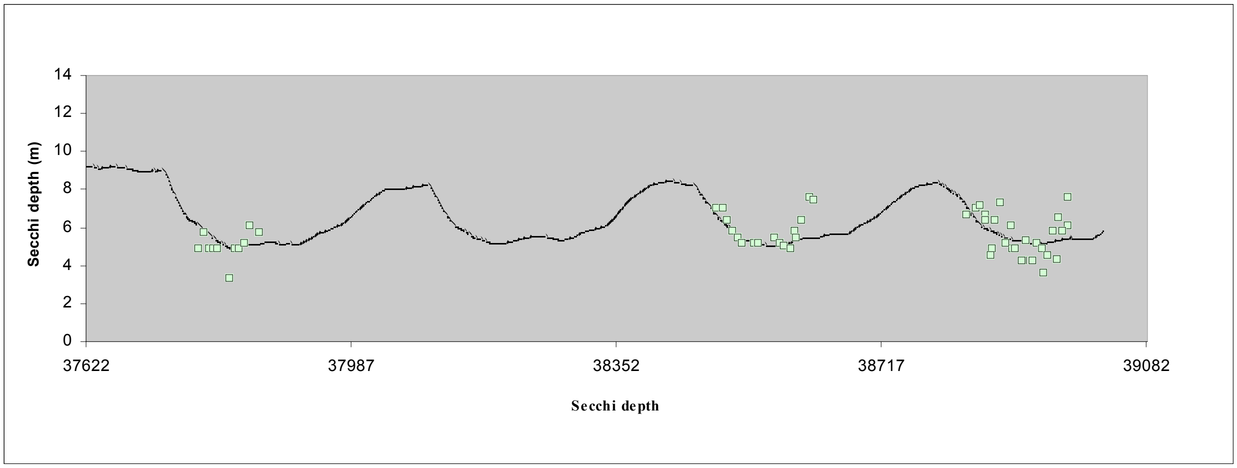



Fig. 25c  Simulation of Secchi depths by the Clam Lake model and data from the lake.

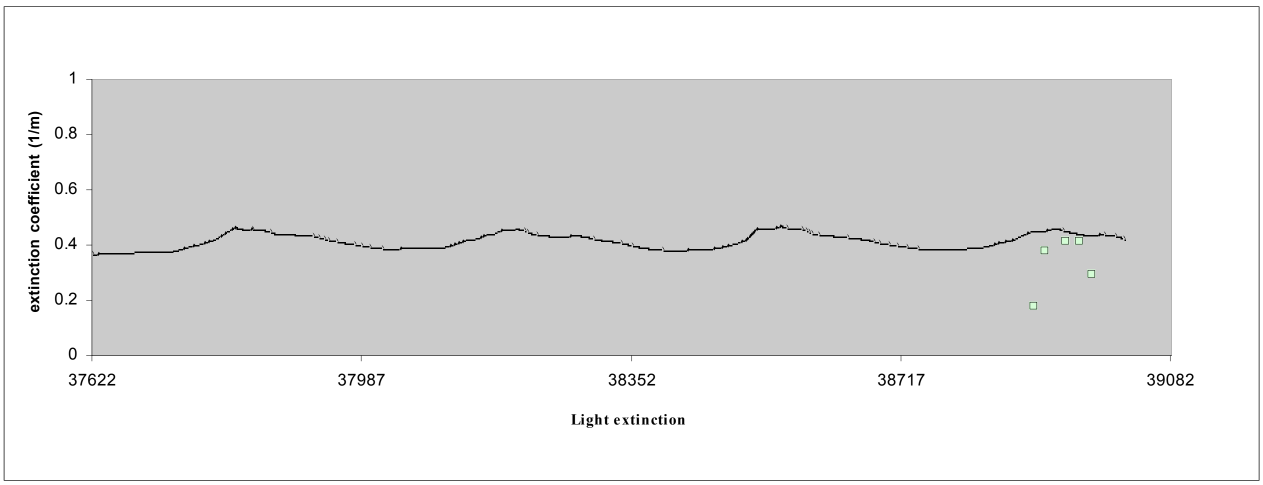



Fig. 25d  Simulation of the light extinction by the Clam Lake model and data from the lake.

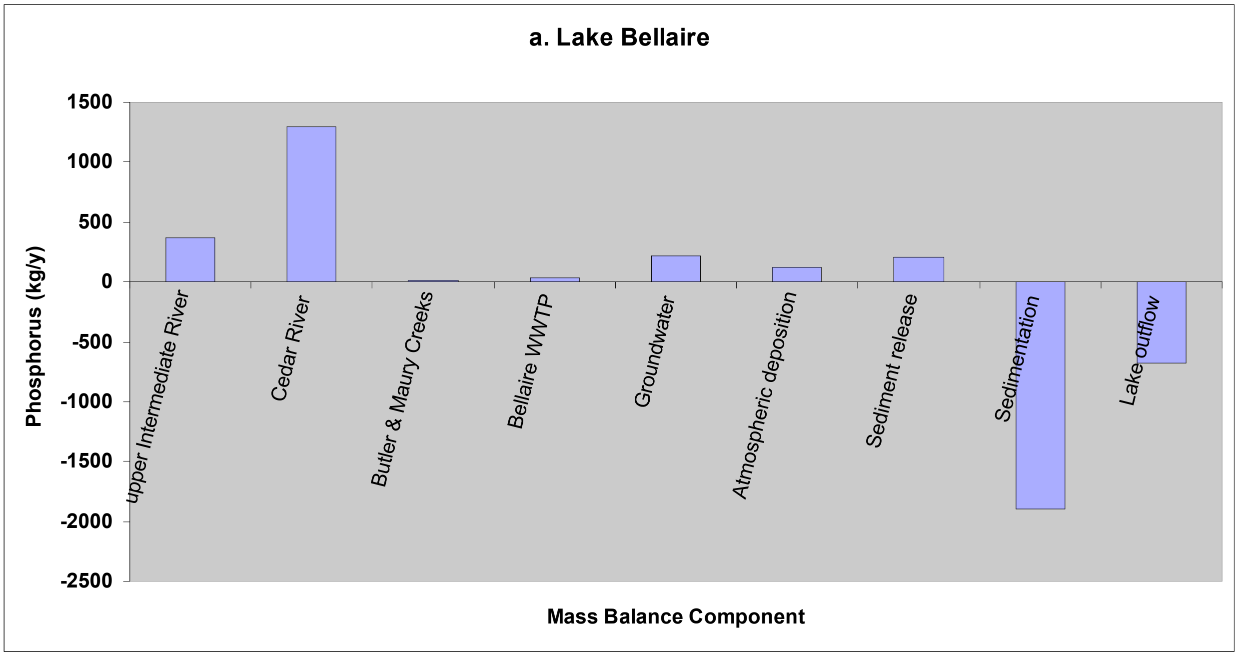



Fig. 26a Phosphorus mass balances for Lake Bellaire. Loadings are plotted as positive kilograms; losses are negative.

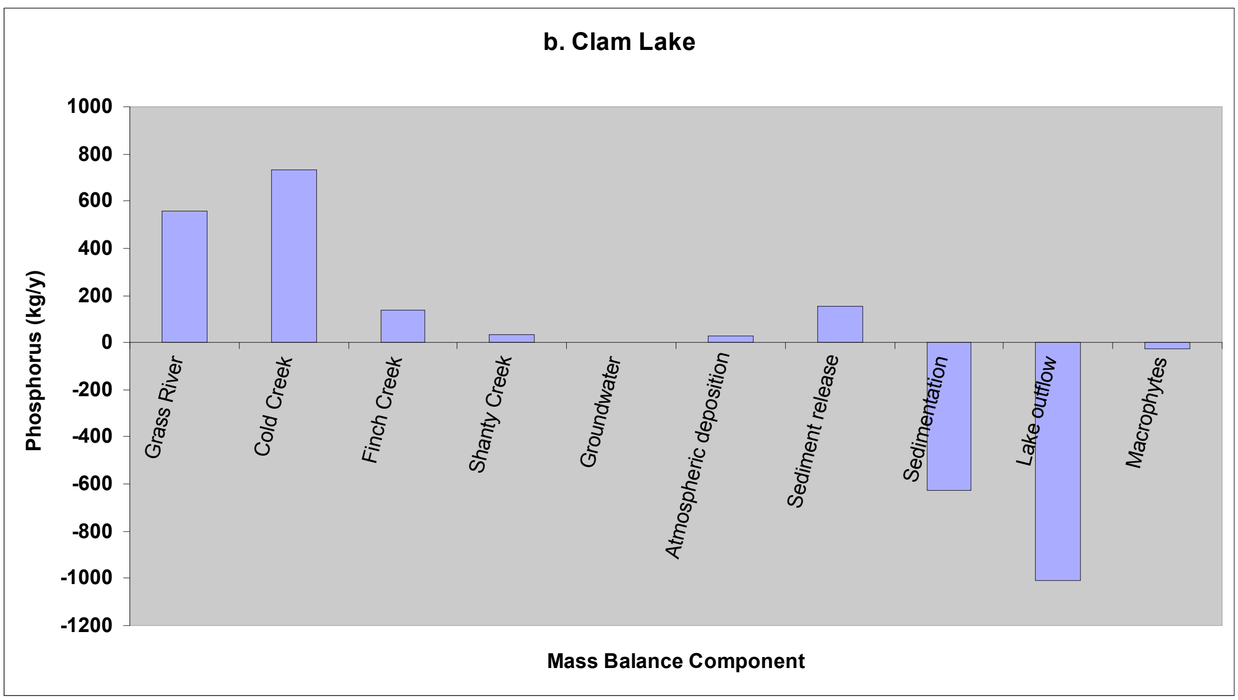



Fig. 26b Phosphorus mass balances for Clam Lake. Loadings are plotted as positive kilograms; losses are negative.

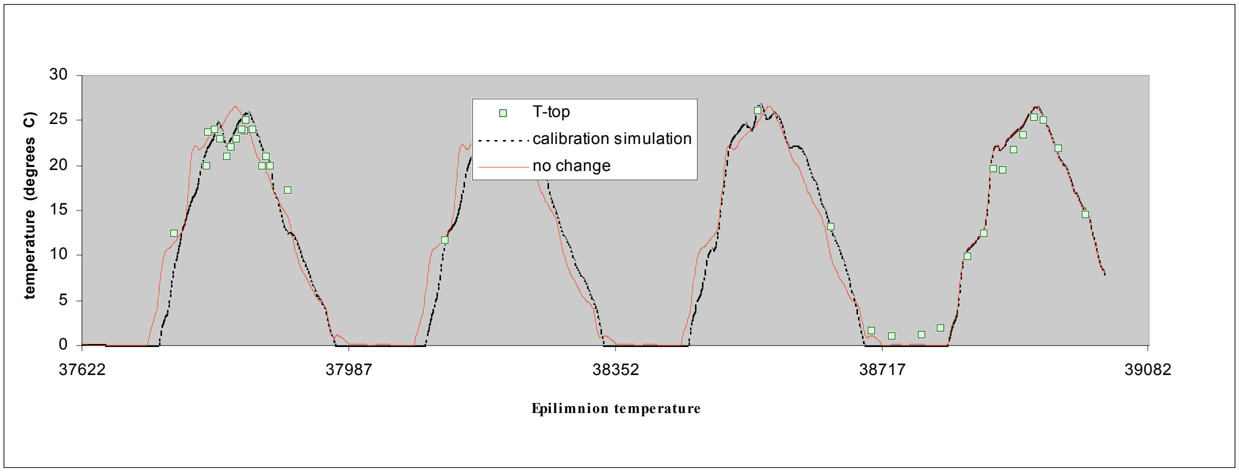



Fig. 27a  Lake Bellaire model simulation of epilimnion water temperature for "No change" scenario; also plotted are the calibration simulations.

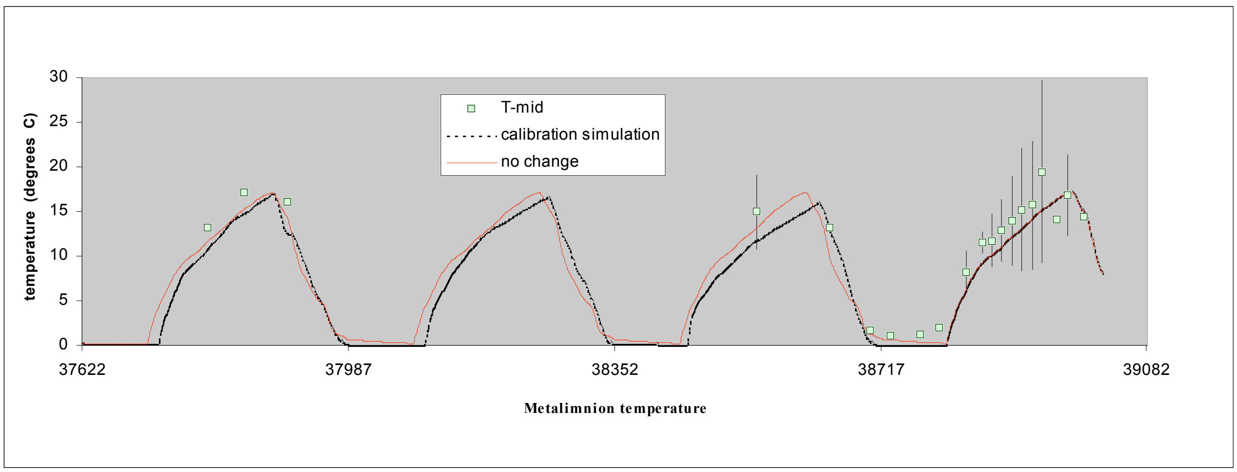



Fig. 27b  Lake Bellaire model simulation of metalimnion water temperature for "No change" scenario; also plotted are the calibration simulations.

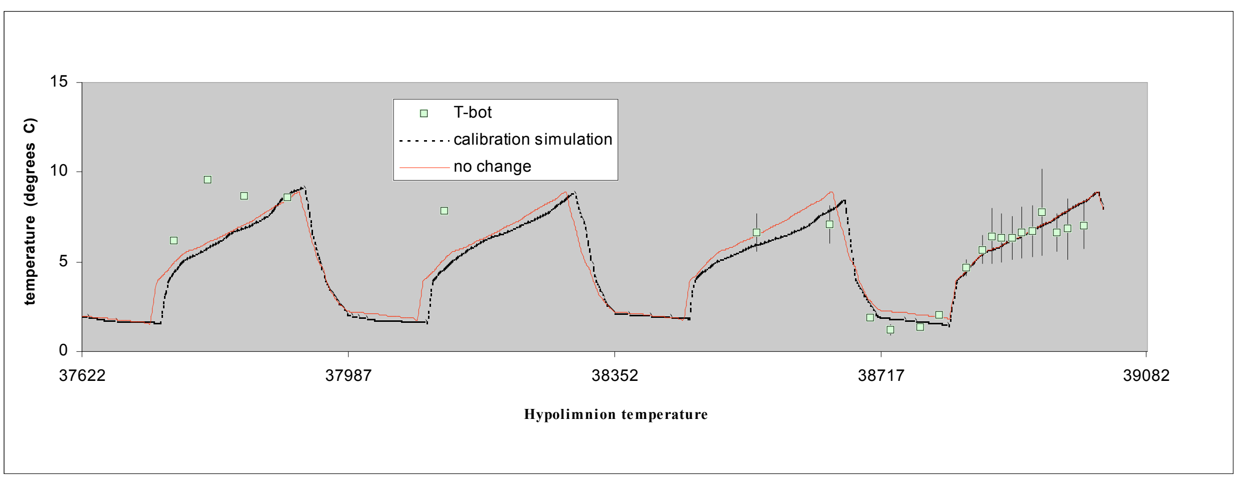



Fig. 27c  Lake Bellaire model simulation of hypolimnion water temperature for "No change" scenario; also plotted are the calibration simulations.

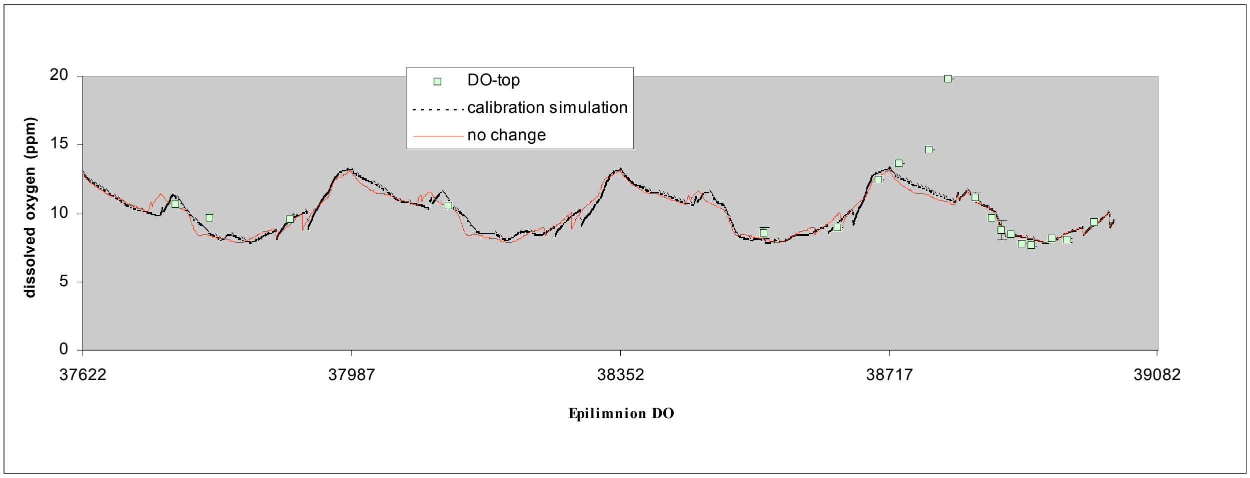



Fig. 27d Lake Bellaire model simulation of epilimnion DO concentration for “No change” scenario; also plotted are the calibration simulations.

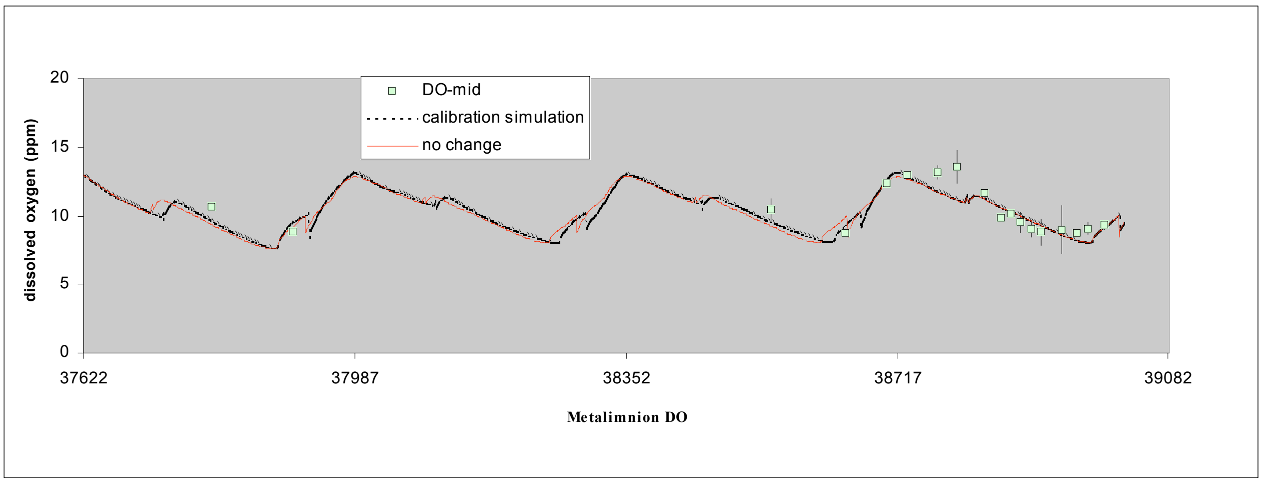



Fig. 27e Lake Bellaire model simulation of metalimnion DO concentration for “No change” scenario; also plotted are the calibration simulations.

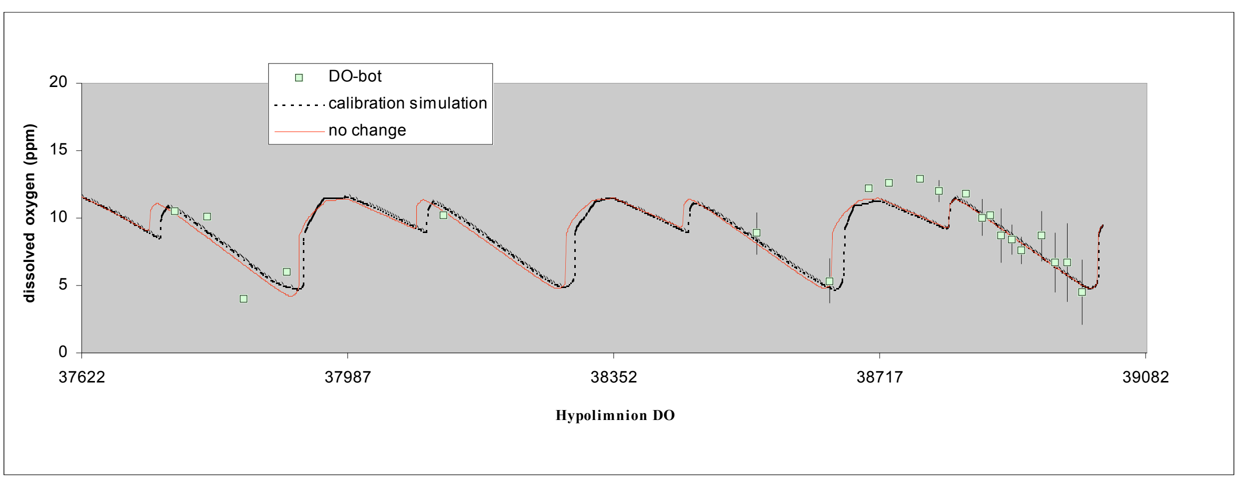



Fig. 27f Lake Bellaire model simulation of hypolimnion DO concentration for “No change” scenario; also plotted are the calibration simulations.

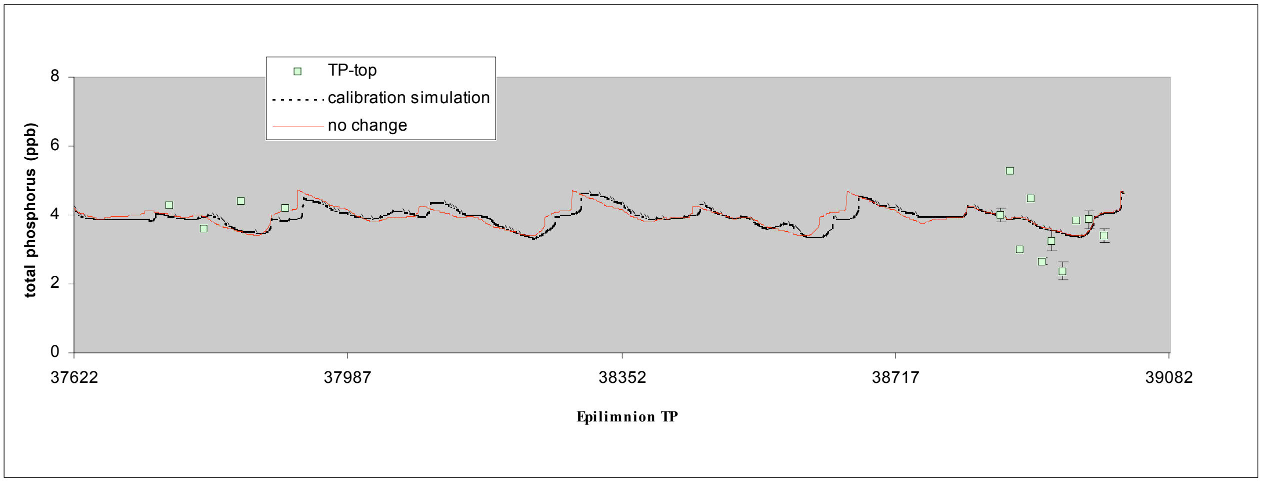



Fig. 28a Lake Bellaire model simulation of epilimnion total phosphorus for "No change" scenario; also plotted are the calibration simulations.

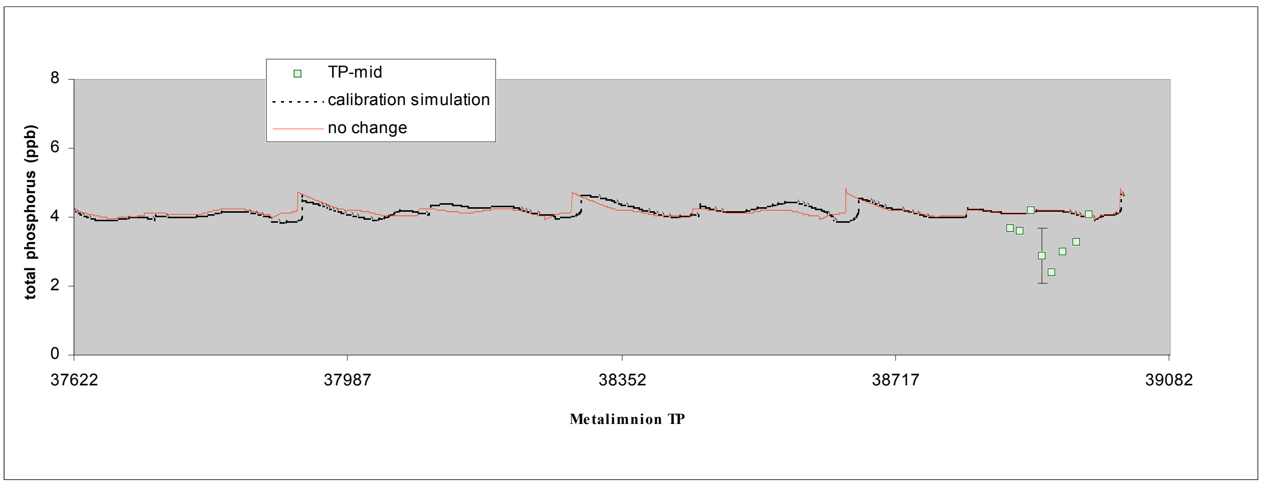



Fig. 28b Lake Bellaire model simulation of metalimnion total phosphorus for "No change" scenario; also plotted are the calibration simulations.

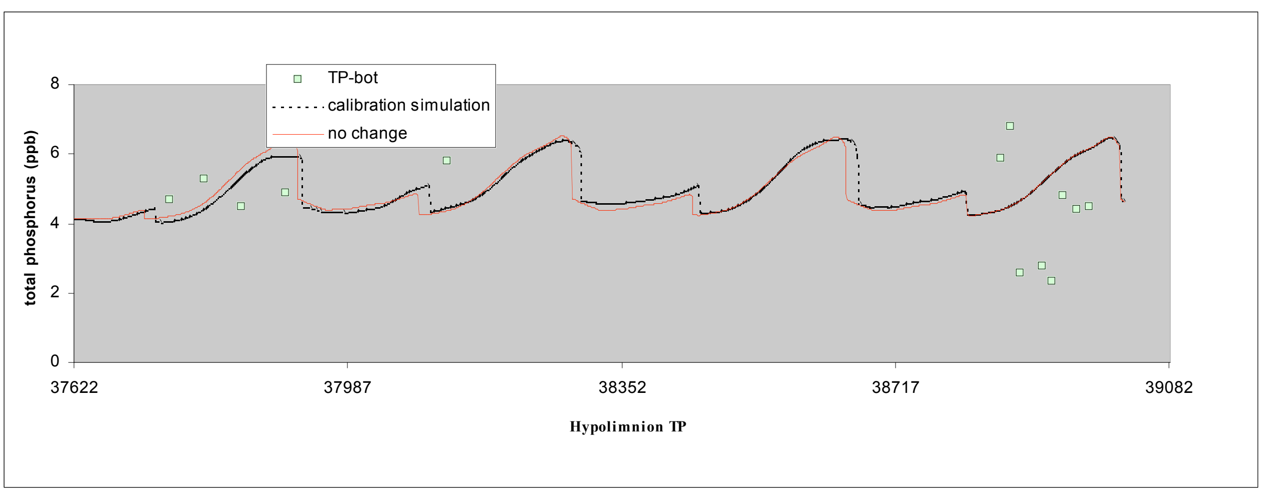



Fig. 28c Lake Bellaire model simulation of hypolimnion total phosphorus for "No change" scenario; also plotted are the calibration simulations.

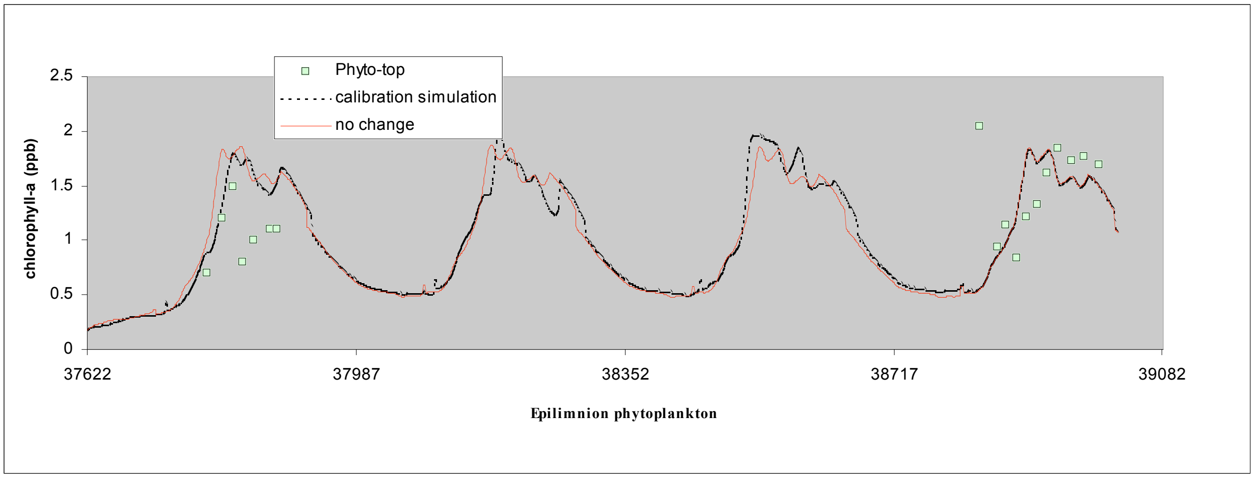



Fig. 28d Lake Bellaire model simulation of epilimnion chlorophyll-a for "No change" scenario; also plotted are the calibration simulations.

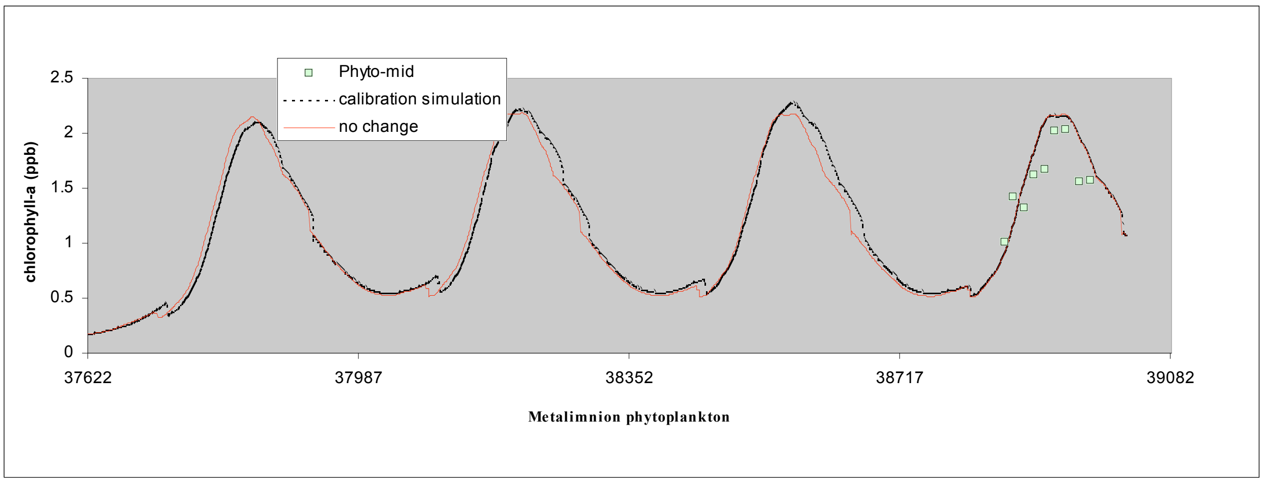



Fig. 28e Lake Bellaire model simulation of metalimnion chlorophyll-a for "No change" scenario; also plotted are the calibration simulations.

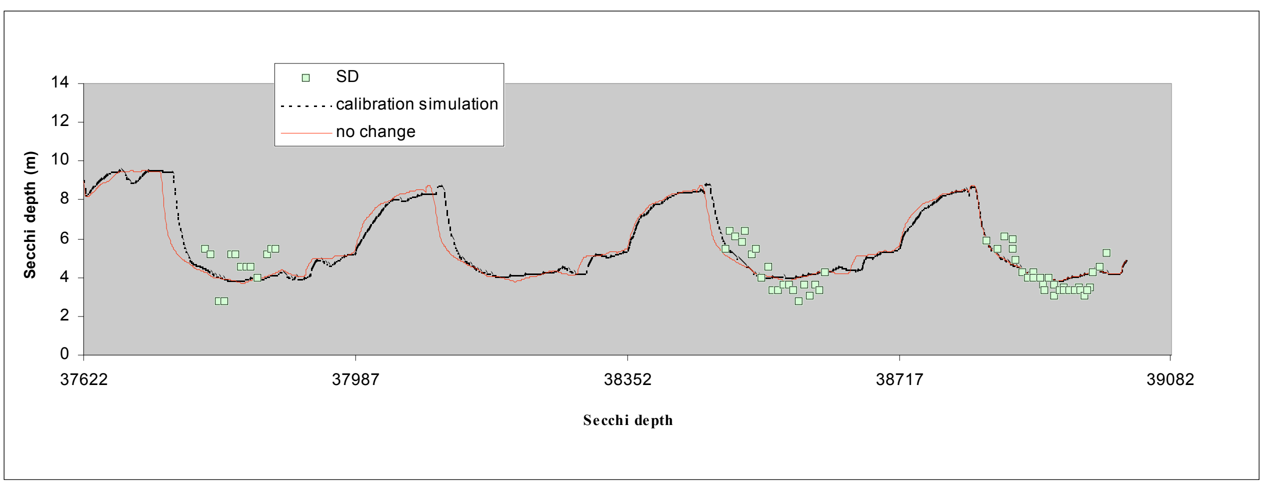



Fig. 28f Lake Bellaire model simulation of Secchi depth for "No change" scenario; also plotted are the calibration simulations.

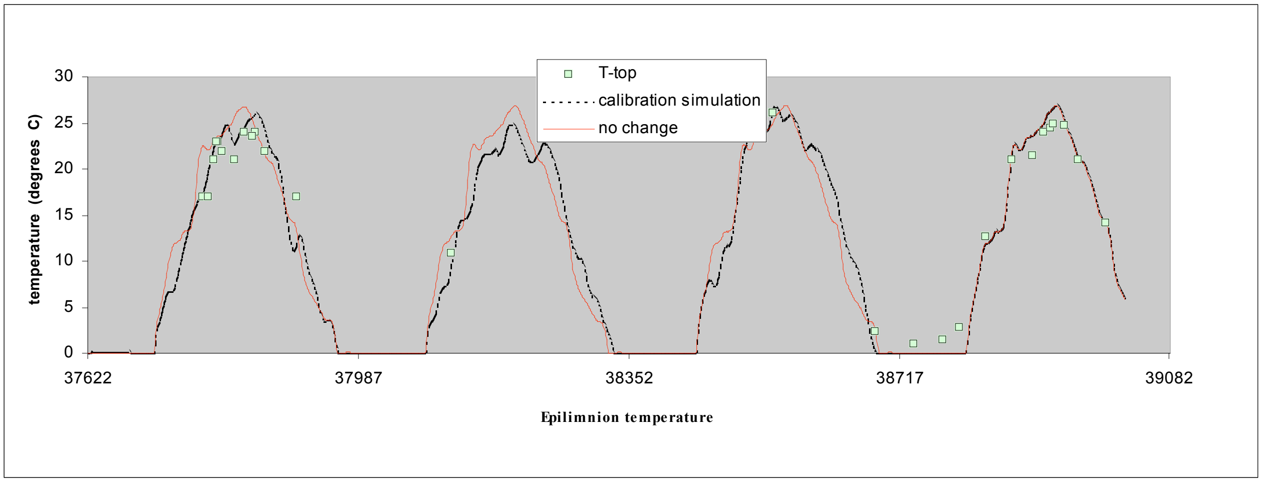



Fig. 29a Clam Lake model simulation of epilimnion water temperature for “No change” scenario; also plotted are the calibration simulations.

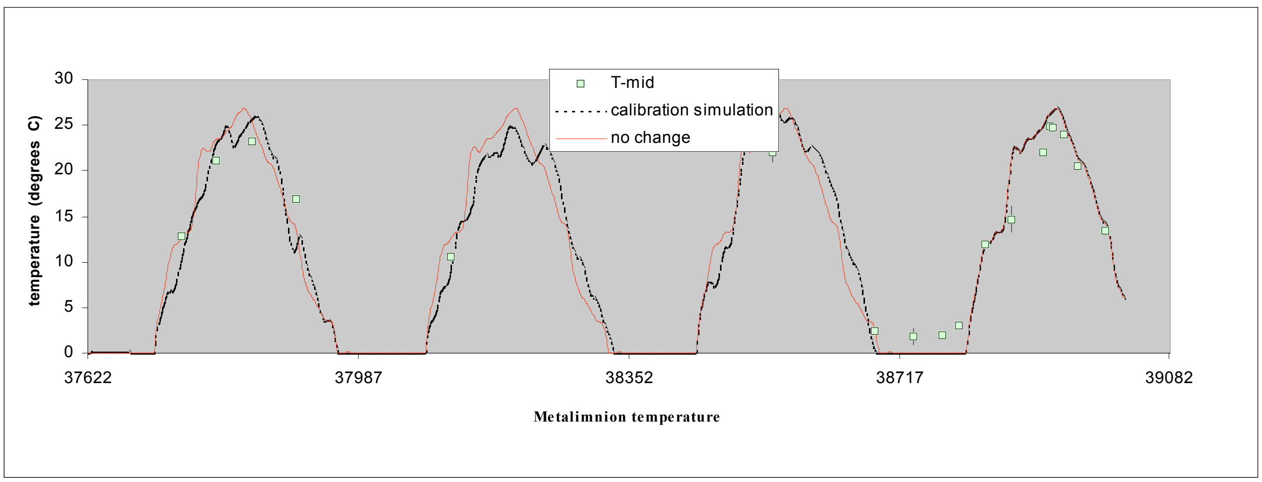



Fig. 29b Clam Lake model simulation of metalimnion water temperature for “No change” scenario; also plotted are the calibration simulations.

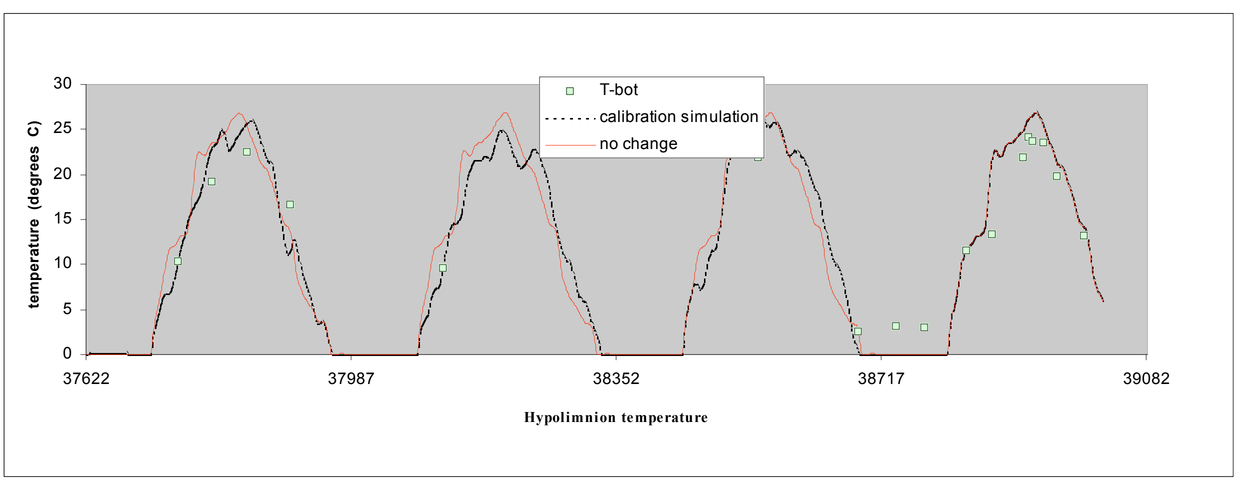



Fig. 29c Clam Lake model simulation of hypolimnion water temperature for “No change” scenario; also plotted are the calibration simulations.

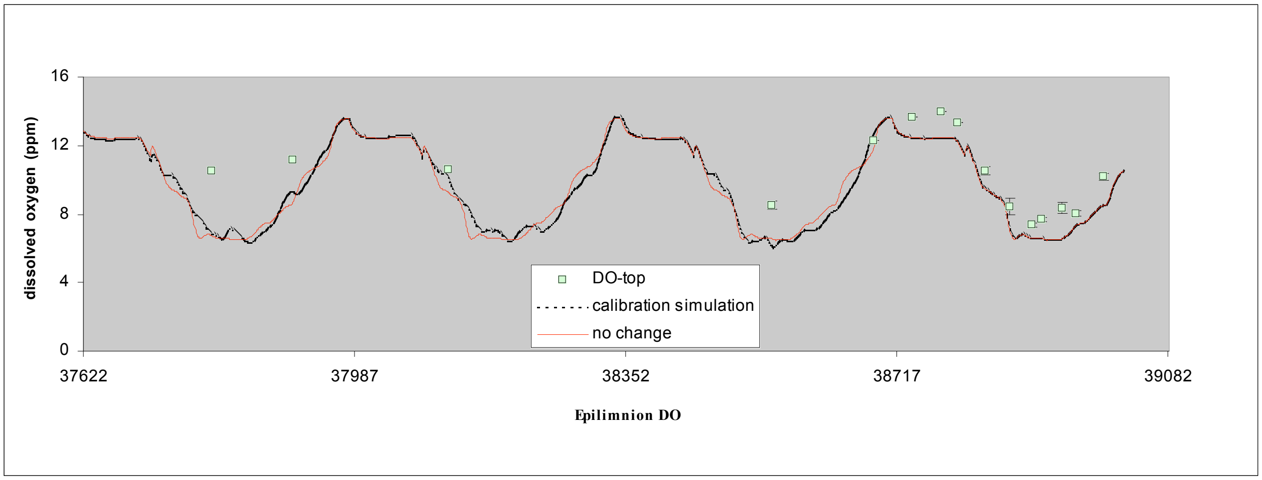



Fig. 29d Clam Lake model simulation of epilimnion DO concentration for "No change" scenario; also plotted are the calibration simulations.

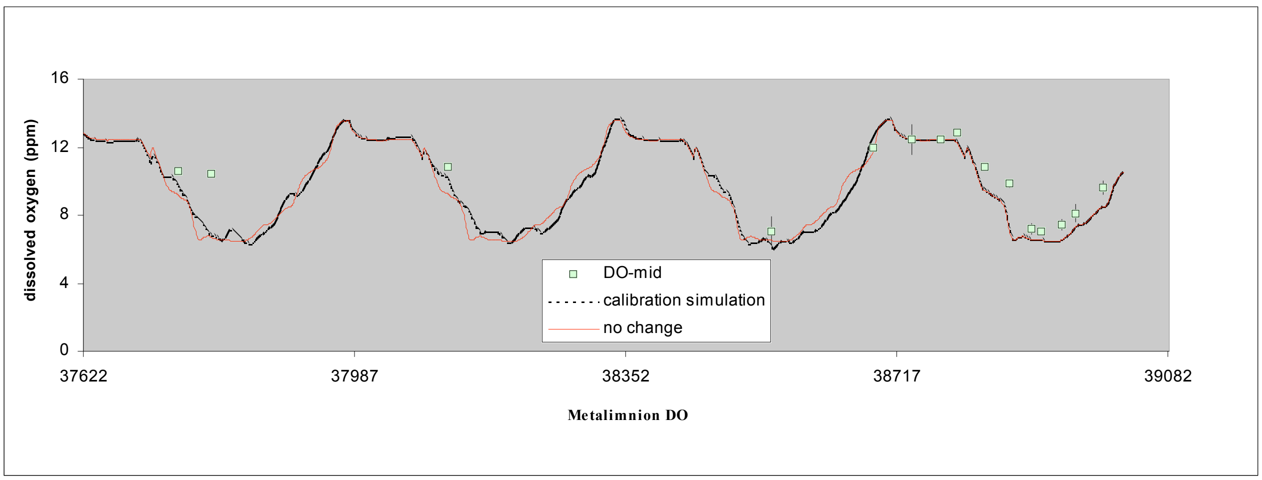



Fig. 29e Clam Lake model simulation of metalimnion DO concentration for "No change" scenario; also plotted are the calibration simulations.

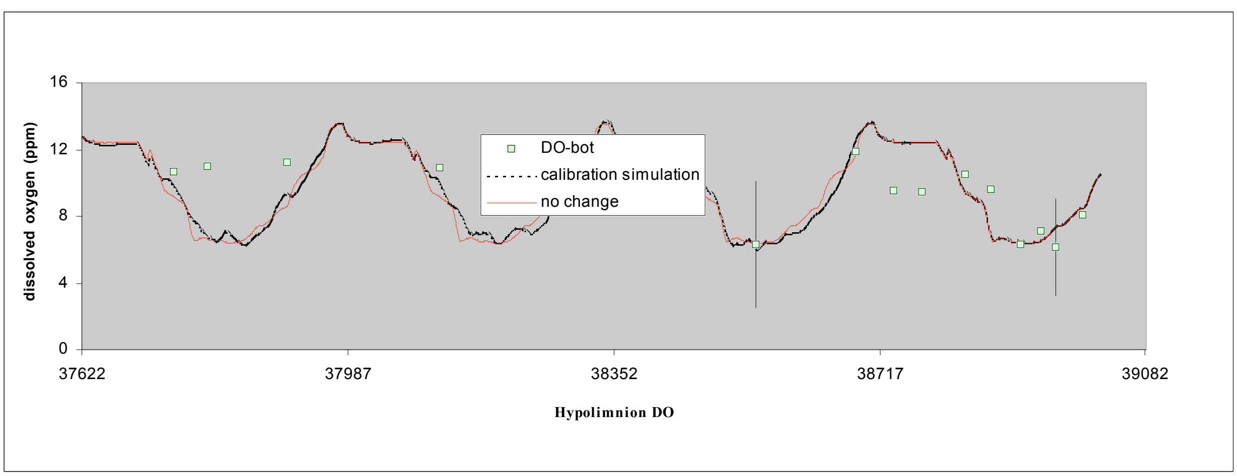



Fig. 29f Clam Lake model simulation of hypolimnion DO concentration for "No change" scenario; also plotted are the calibration simulations.

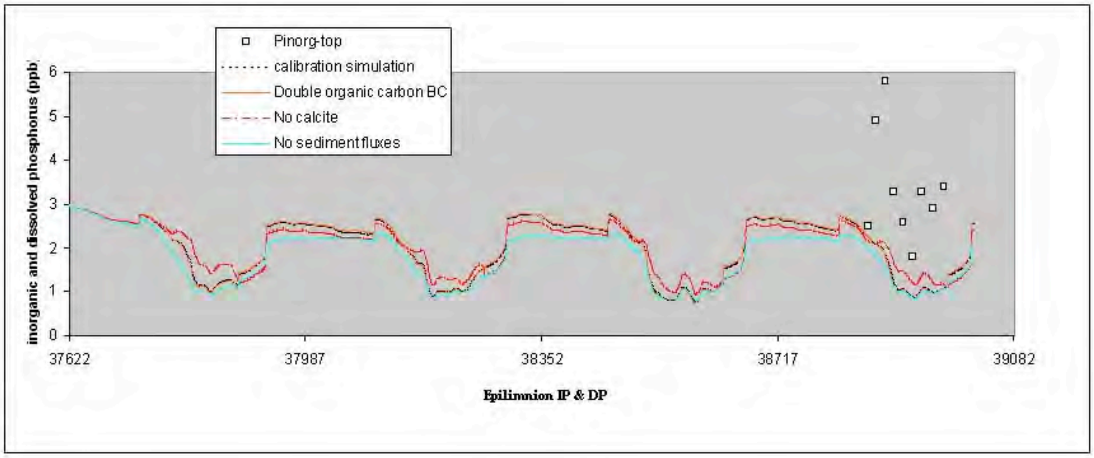



Fig. 30a Clam Lake model simulation of epilimnion inorganic and dissolved phosphorus for "No change" scenario; also plotted are the calibration simulations.

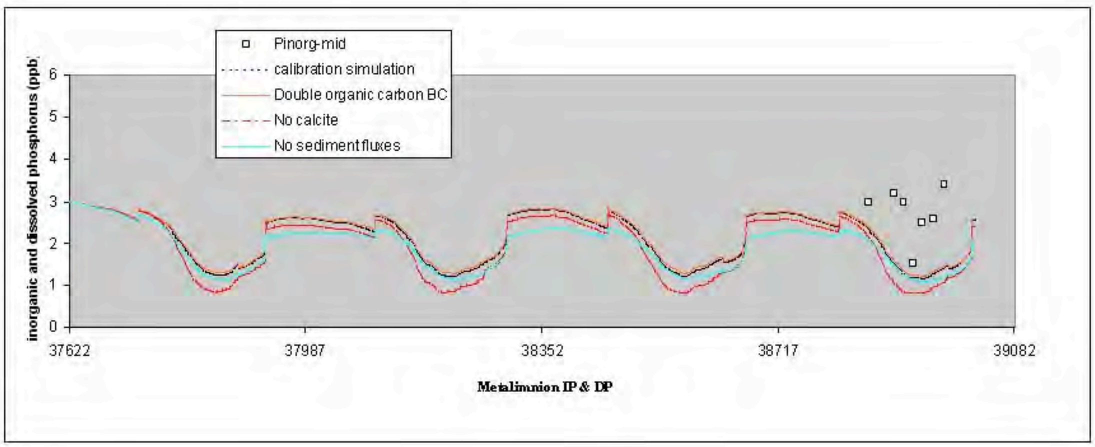



Fig. 30b Clam Lake model simulation of metalimnion inorganic and dissolved phosphorus for "No change" scenario; also plotted are the calibration simulations.

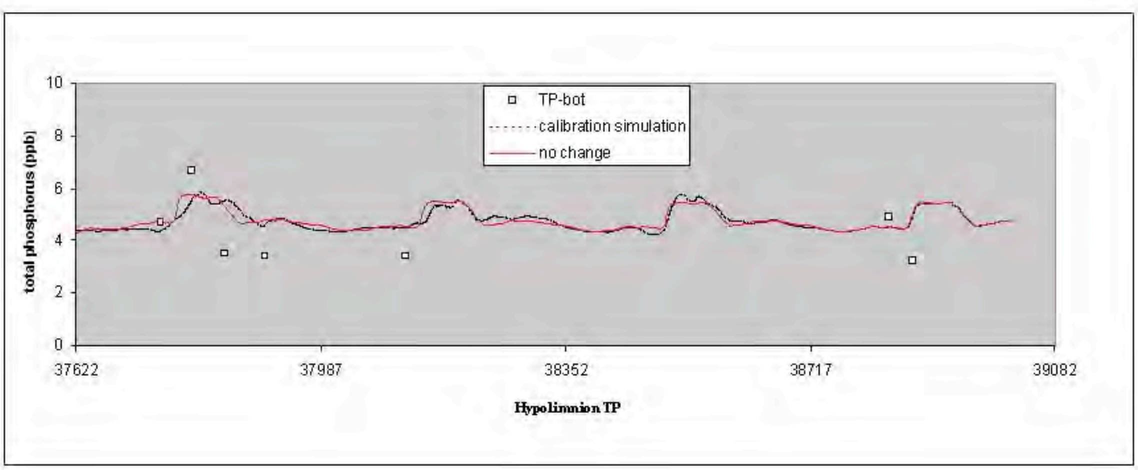



Fig. 30c Clam Lake model simulation of hypolimnion inorganic and dissolved phosphorus for "No change" scenario; also plotted are the calibration simulations.

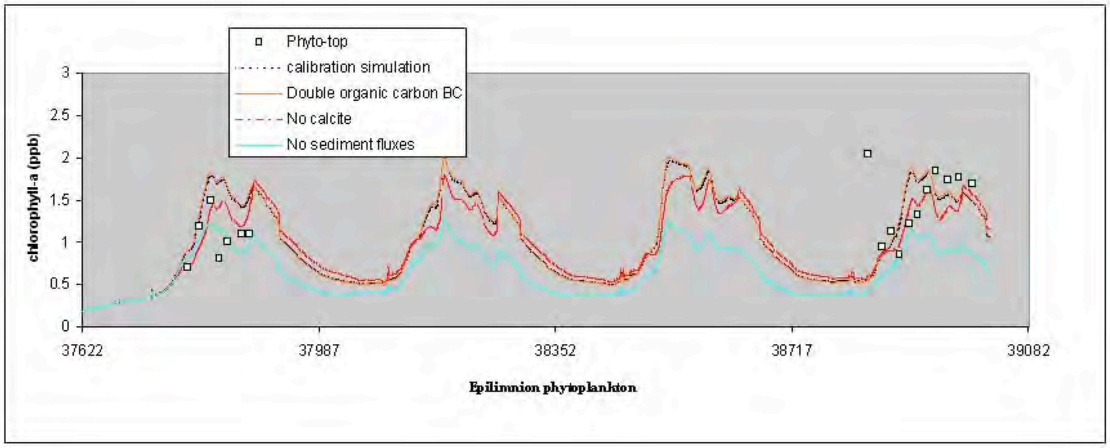



Fig.30d Clam Lake model simulation of epilimnion chlorophyll-a for “No change” scenario; also plotted are the calibration simulations.

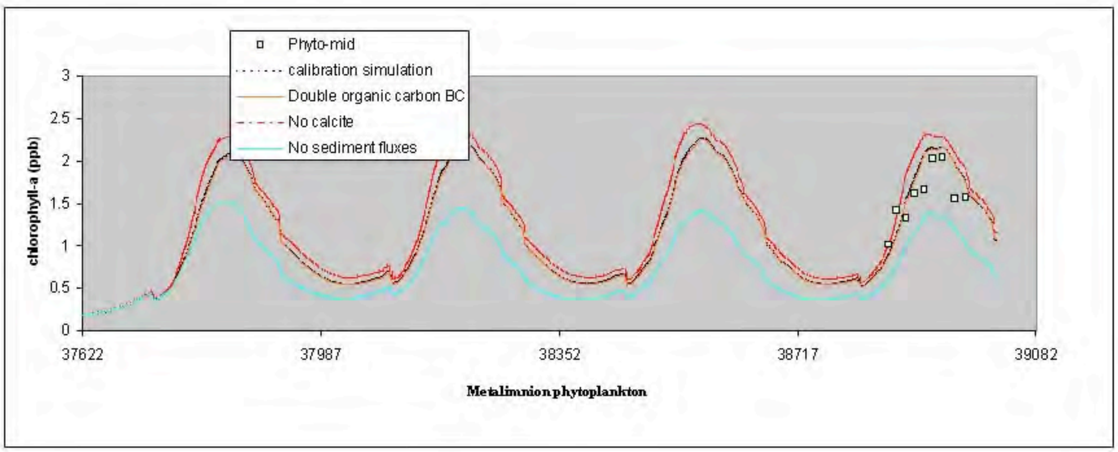



Fig.30e Clam Lake model simulation of metalimnion chlorophyll-a for “No change” scenario; also plotted are the calibration simulations.

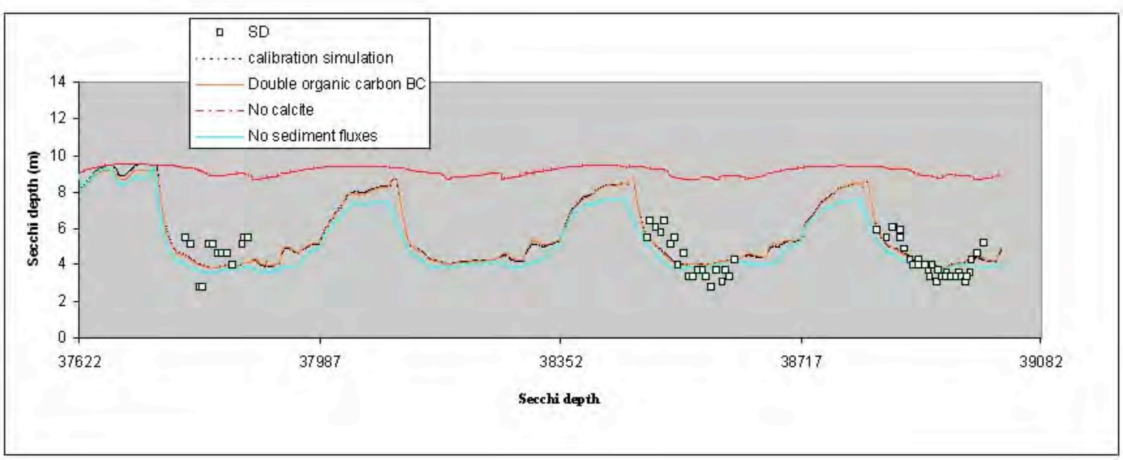



Fig. 30f Clam Lake model simulation of Secchi depth for “No change” scenario; also plotted are the calibration simulations.

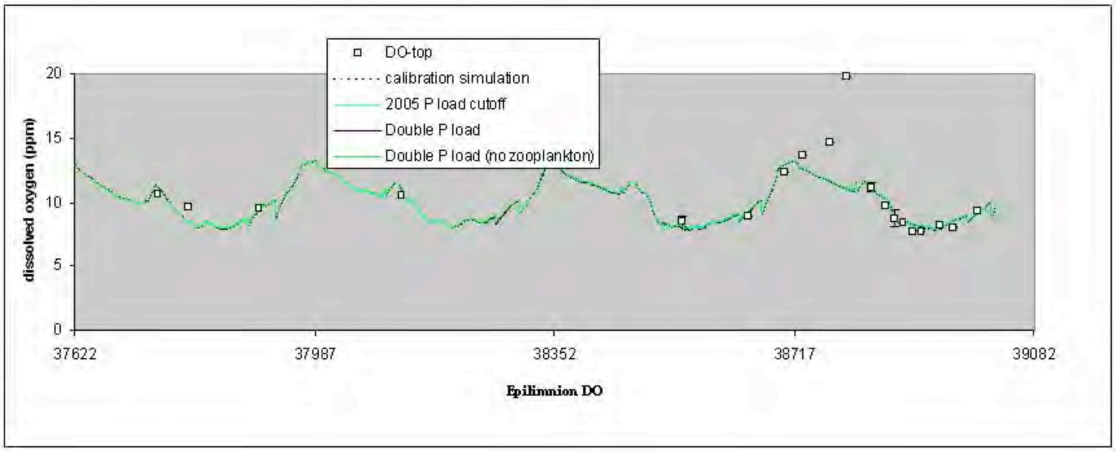



Fig. 31a

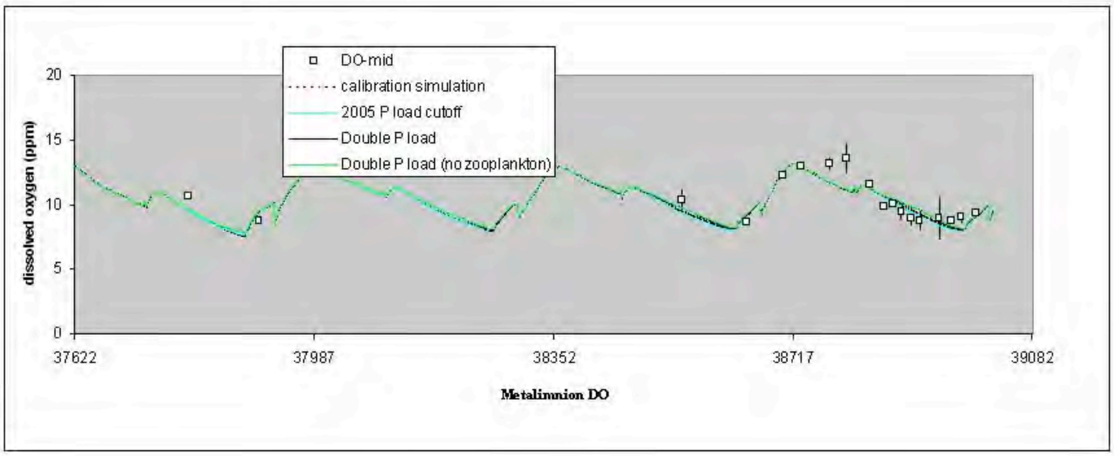



Fig. 31b

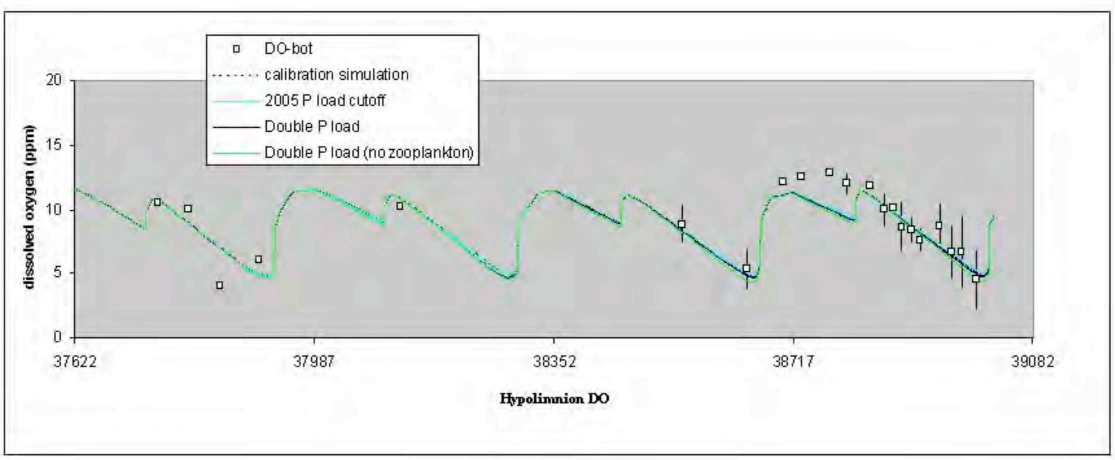



Fig. 31c

Lake Bellaire model simulation of (a) epilimnion, (b) metalimnion, and (c) hypolimnion DO for phosphorus load cutoff (2005 P load cutoff), double phosphorus load (Double P load) and double phosphorus load without zooplankton (Double P load no zooplankton) scenarios; also plotted for comparison are the calibration simulations.

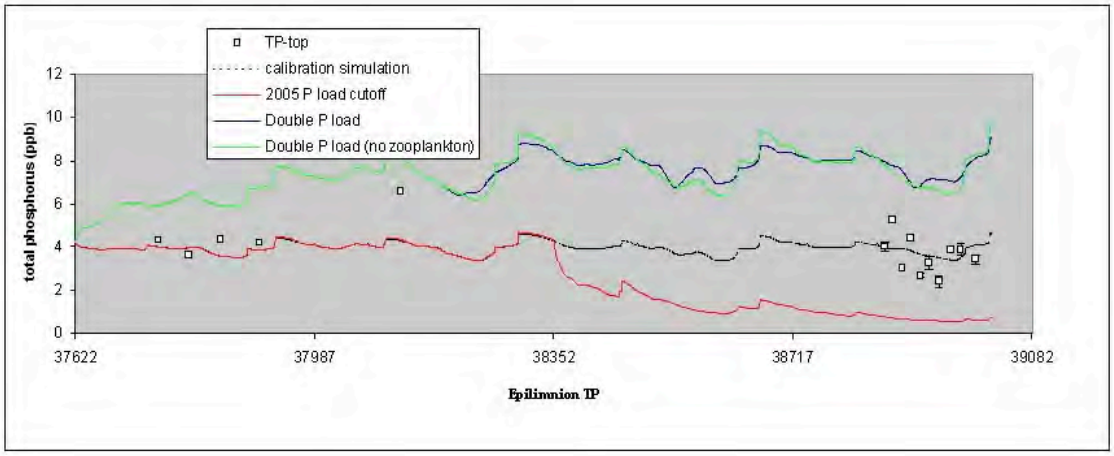



Fig. 31d

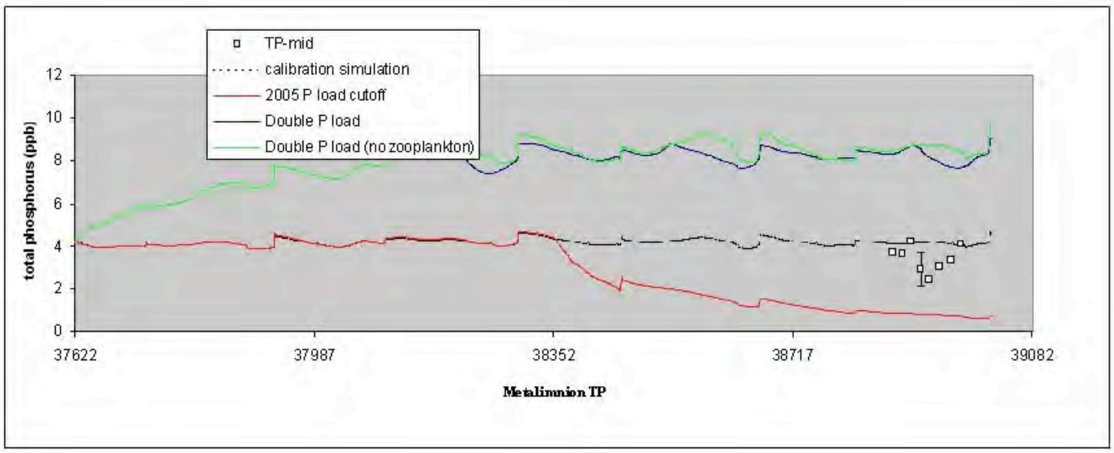



Fig. 31e.

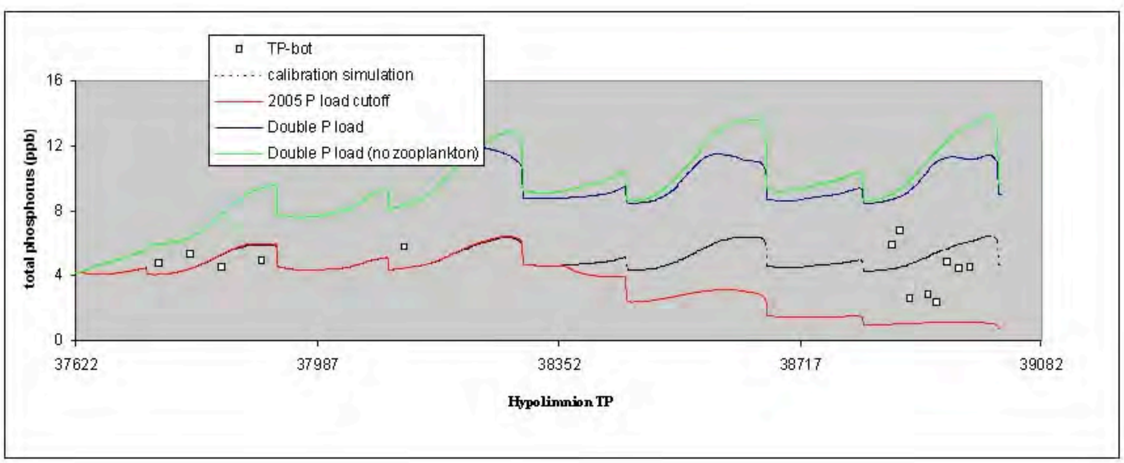



Fig. 31f

Lake Bellaire model simulation of total (d) epilimnion, (e) metalimnion, and (f) hypolimnion phosphorus concentration for phosphorus load cutoff (2005 P load cutoff), double phosphorus load (Double P load) and double phosphorus load without zooplankton (Double P load no zooplankton) scenarios; also plotted for comparison are the calibration simulations.

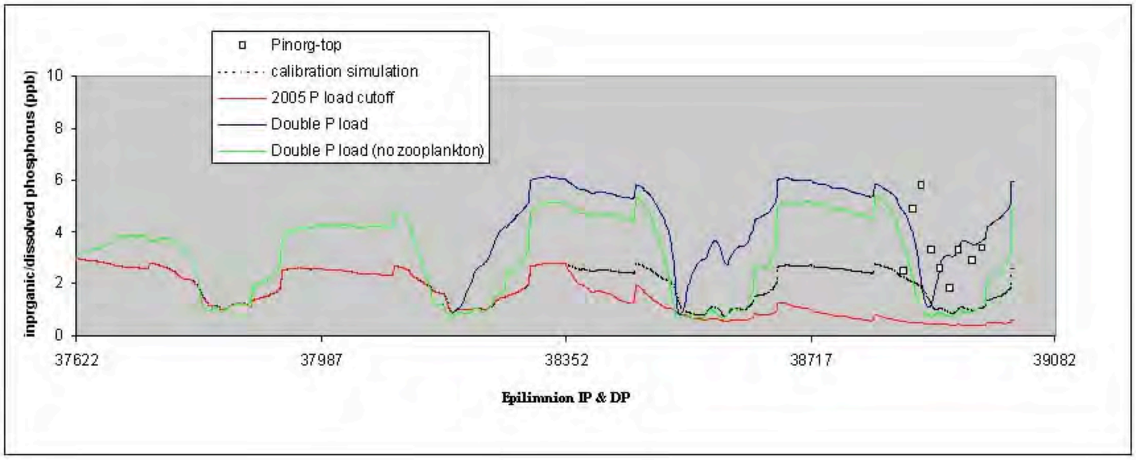



Fig. 32a

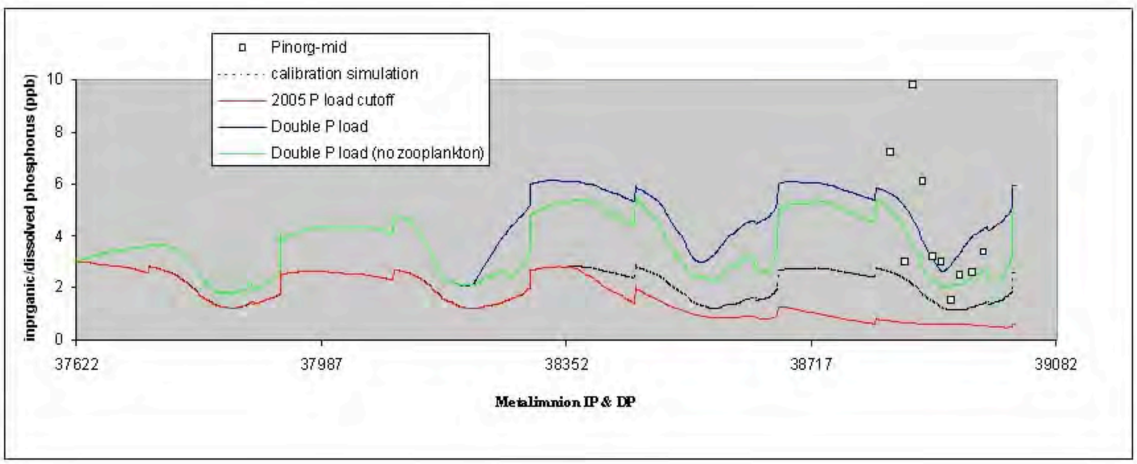



Fig. 32b

Lake Bellaire model simulation of (a) epilimnion and (b) metalimnion inorganic phosphorus for phosphorus load cutoff (2005 P load cutoff), double phosphorus load (Double P load) and double phosphorus load without zooplankton (Double P load no zooplankton) scenarios; also plotted for comparison are the calibration simulations.

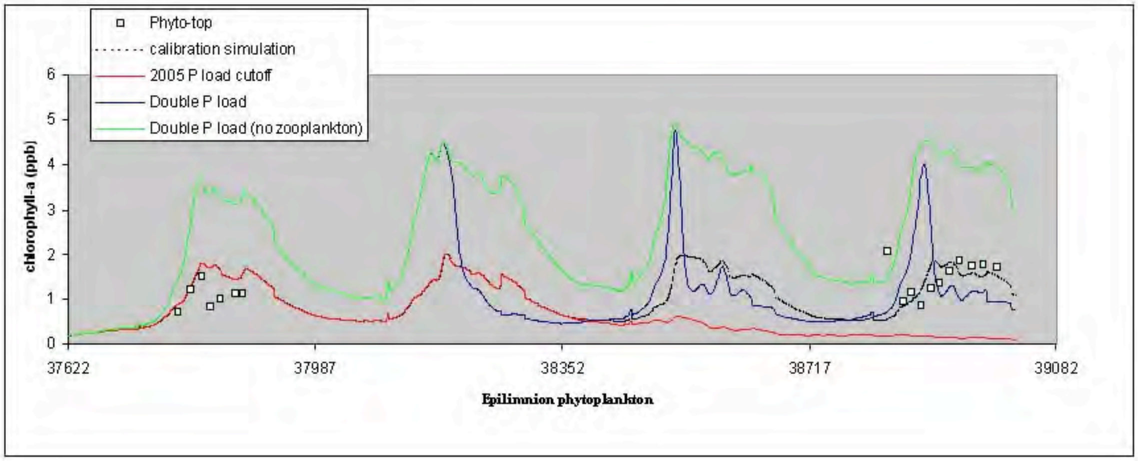



Fig. 32c

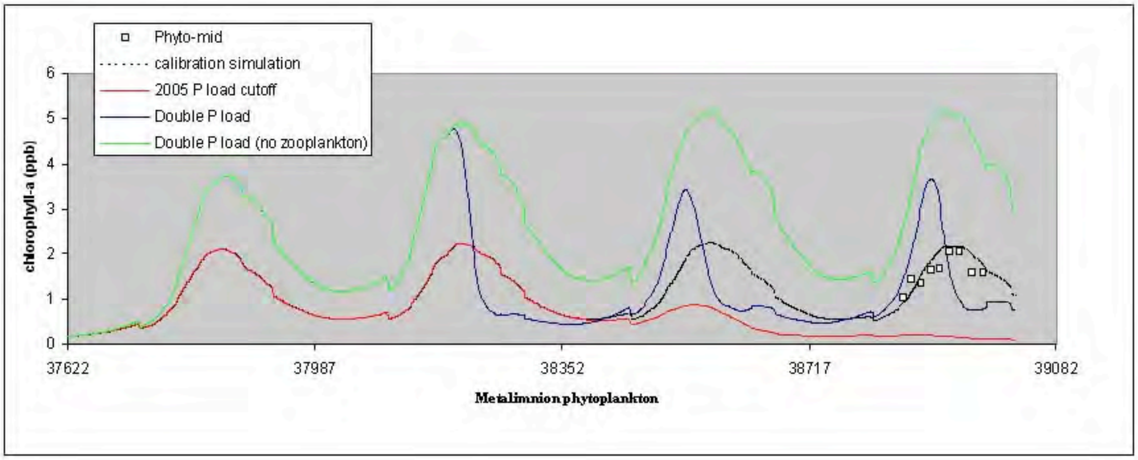



Fig. 32d

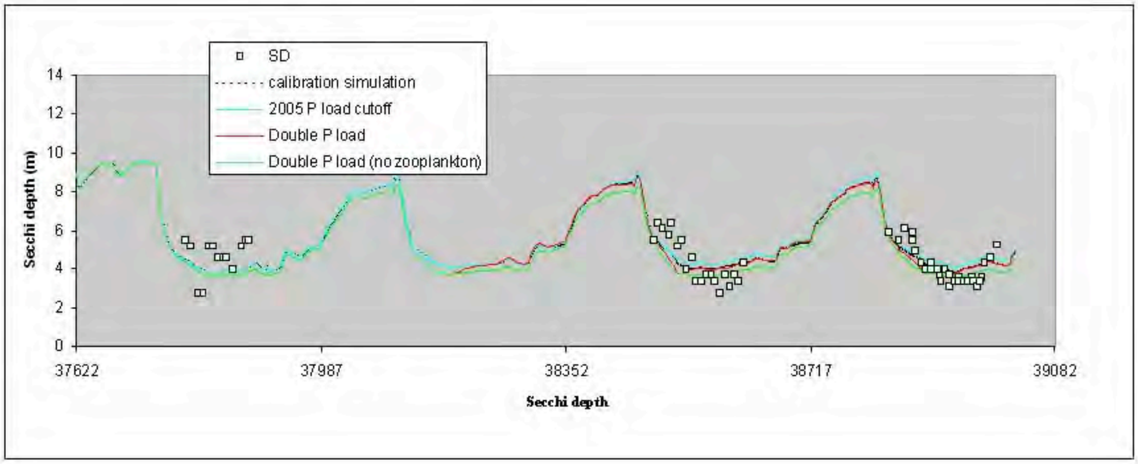



Fig. 32e

Lake Bellaire model simulation of (c) epilimnion phytoplankton, (d) metalimnion phytoplankton, and (e) Secchi depth for phosphorus load cutoff (2005 P load cutoff), double phosphorus load (Double P load) and double phosphorus load without zooplankton (Double P load no zooplankton) scenarios; also plotted for comparison are the calibration simulations.

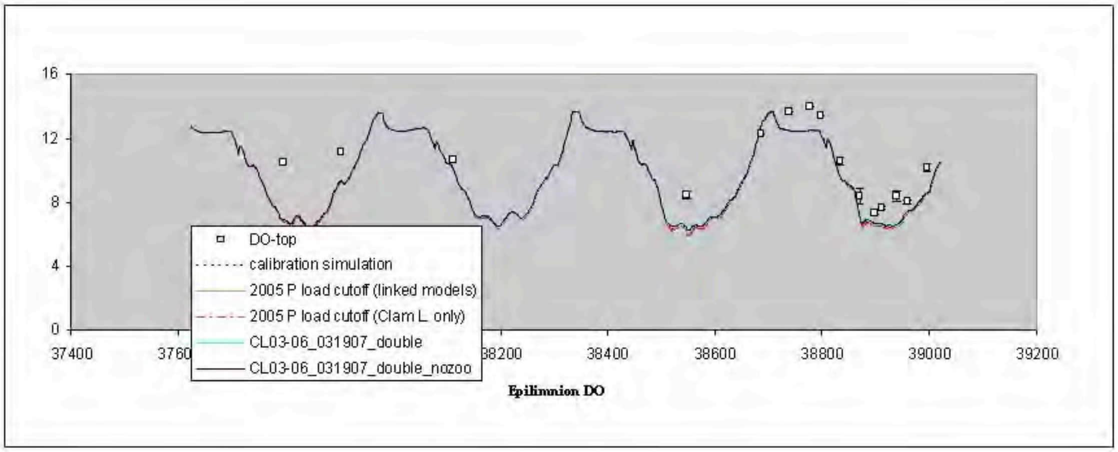



Fig.33a

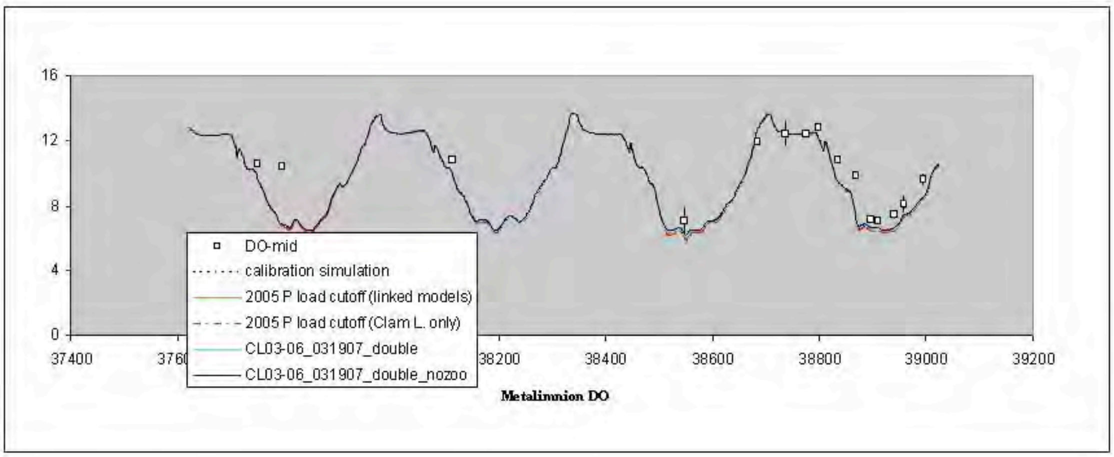



Fig. 33b

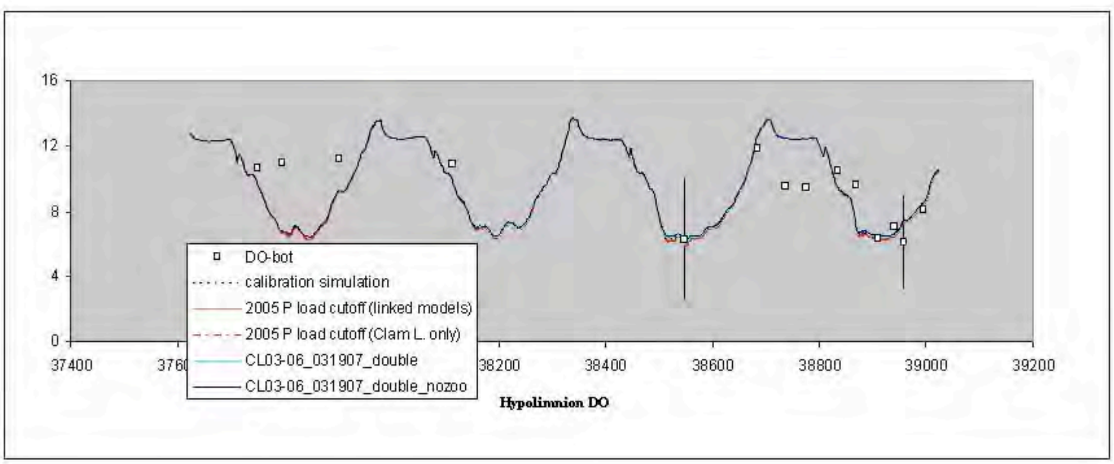



Fig. 33c

Clam Lake model simulation of (a) epilimnion, (b) metalimnion, and (c) hypolimnion DO concentration for phosphorus load cutoff (2005 P load cutoff), double phosphorus load (Double P load) and double phosphorus load without zooplankton (Double P load no zooplankton) scenarios; also plotted for comparison are the calibration simulations.

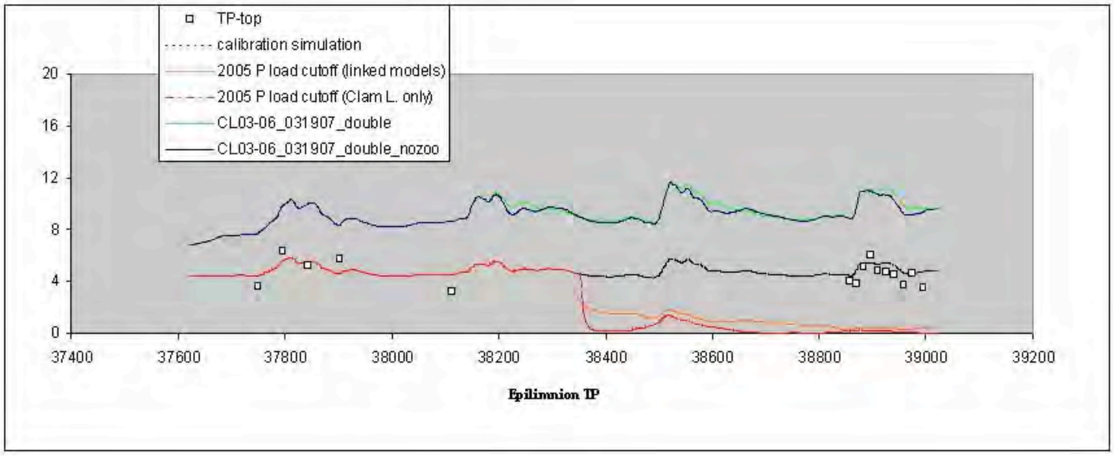



Fig. 33d

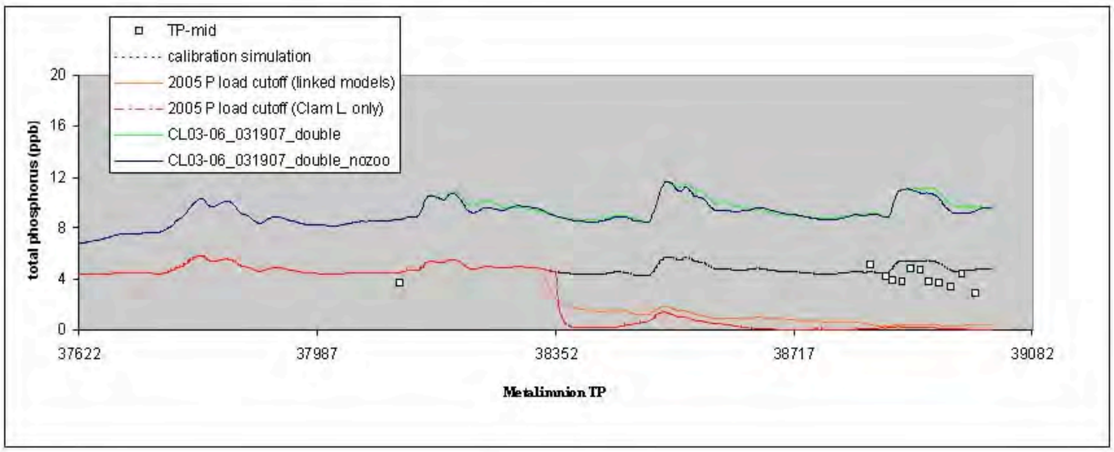



Fig. 33e

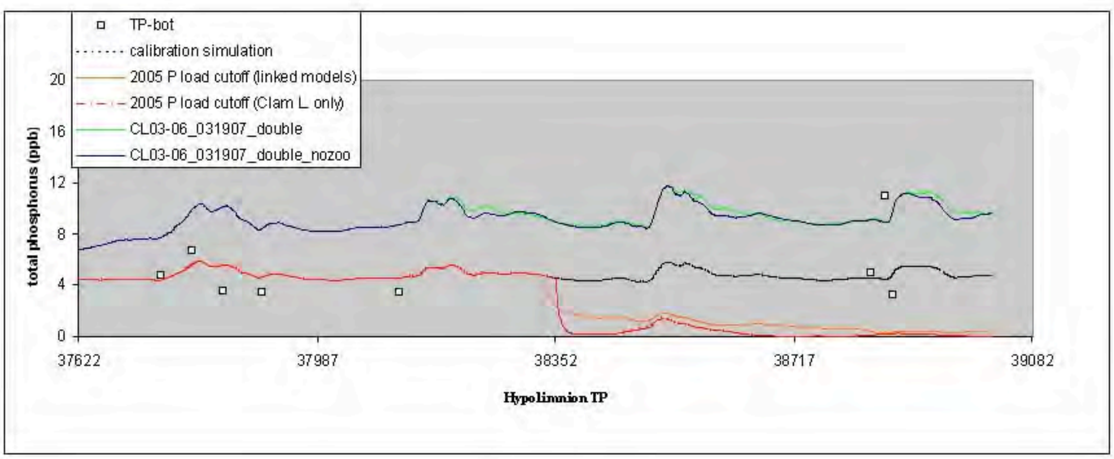



Fig. 33f

Clam Lake model simulation of (d) epilimnion, (e) metalimnion, and (f) hypolimnion total phosphorus concentration for phosphorus load cutoff (2005 P load cutoff), double phosphorus load (Double P load) and double phosphorus load without zooplankton (Double P load no zooplankton) scenarios; also plotted for comparison are the calibration simulations.

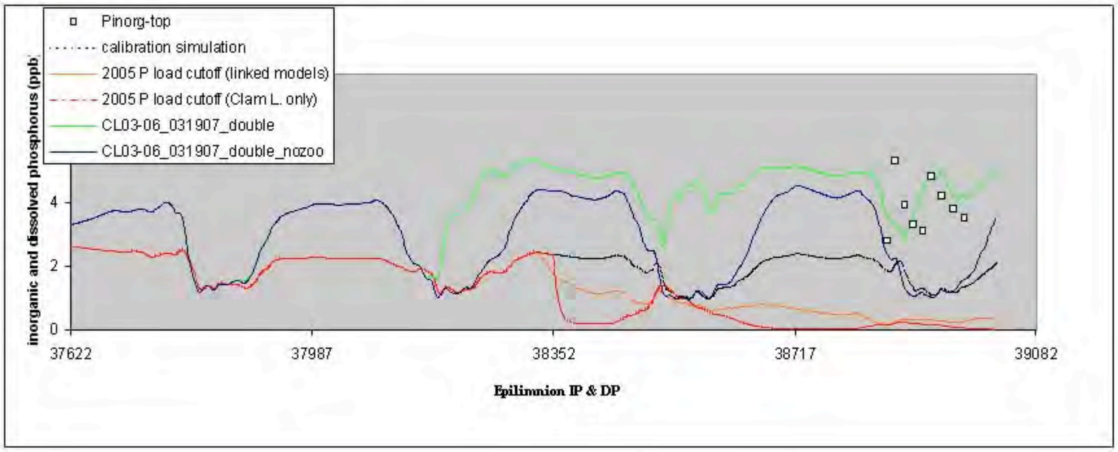



Fig. 34a

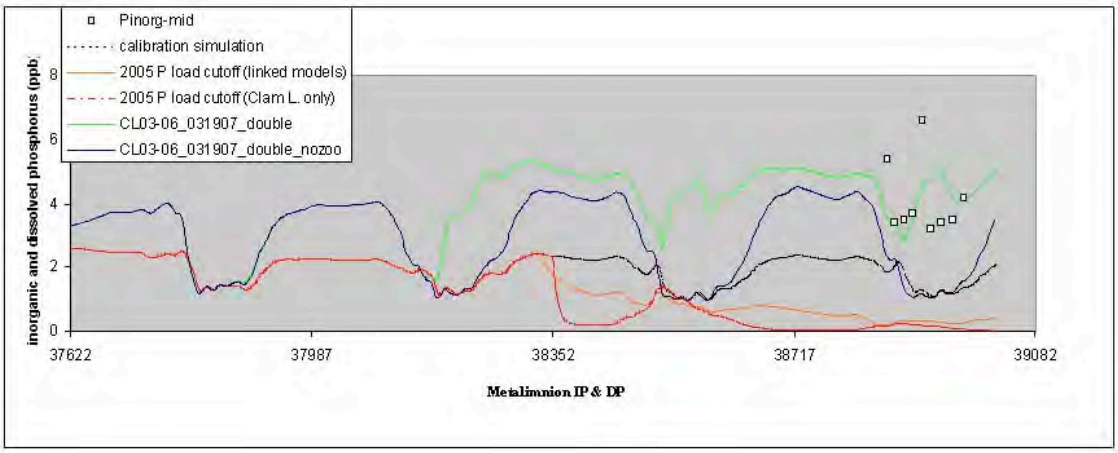



Fig. 34b

Clam Lake model simulation of (a) epilimnion and (b) metalimnion for phosphorus load cutoff (2005 P load cutoff), double phosphorus load (Double P load) and double phosphorus load without zooplankton (Double P load no zooplankton) scenarios; also plotted for comparison are the calibration simulations.

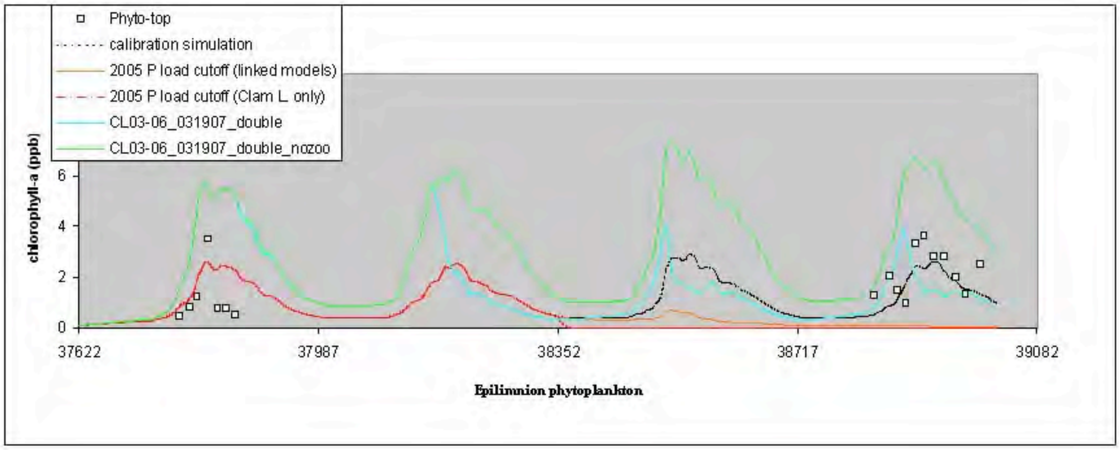



Fig. 34c

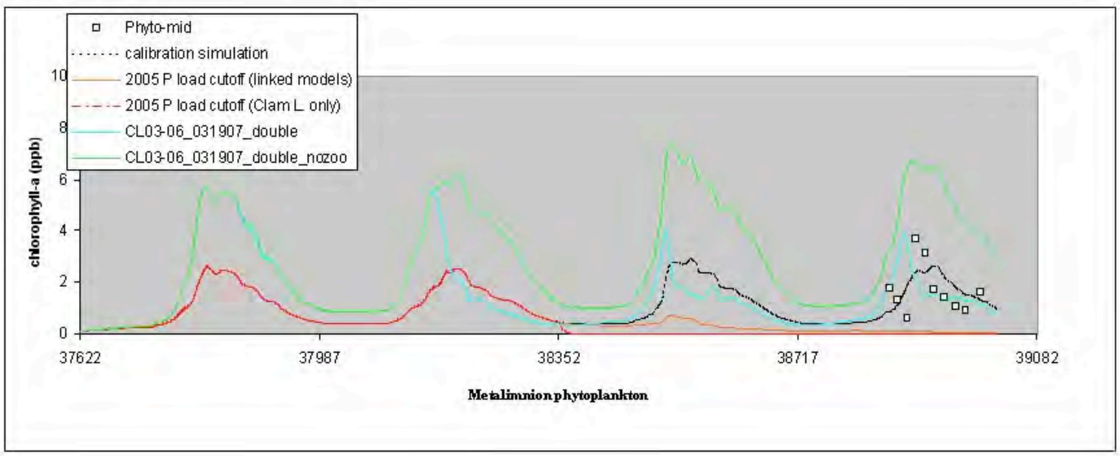



Fig. 34d

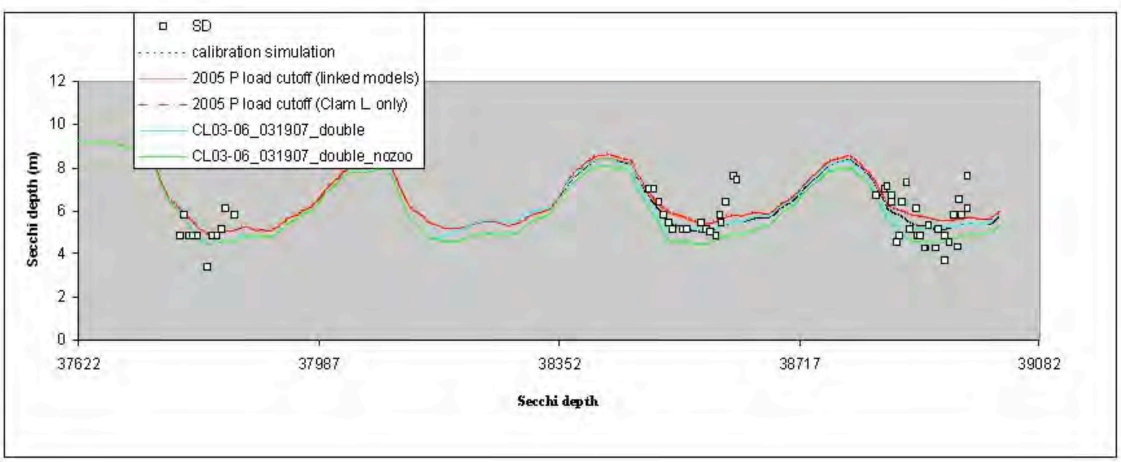



Fig. 34e

Clam Lake model simulation of (c) epilimnion, (d) metalimnion chlorophyll-a concentrations, and (e) Secchi depth for phosphorus load cutoff (2005 P load cutoff), double phosphorus load (Double P load) and double phosphorus load without zooplankton (Double P load no zooplankton) scenarios; also plotted for comparison are the calibration simulations.

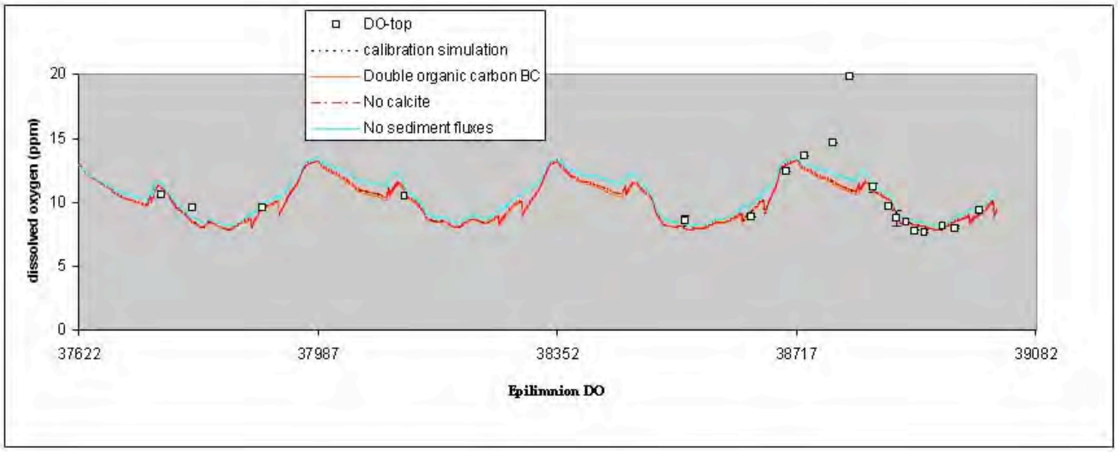



Fig. 35a

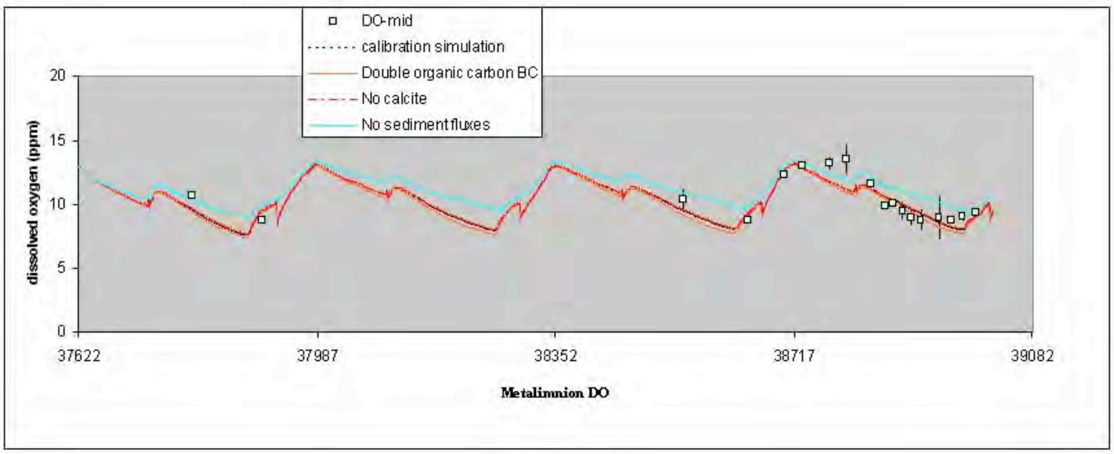



Fig 35b

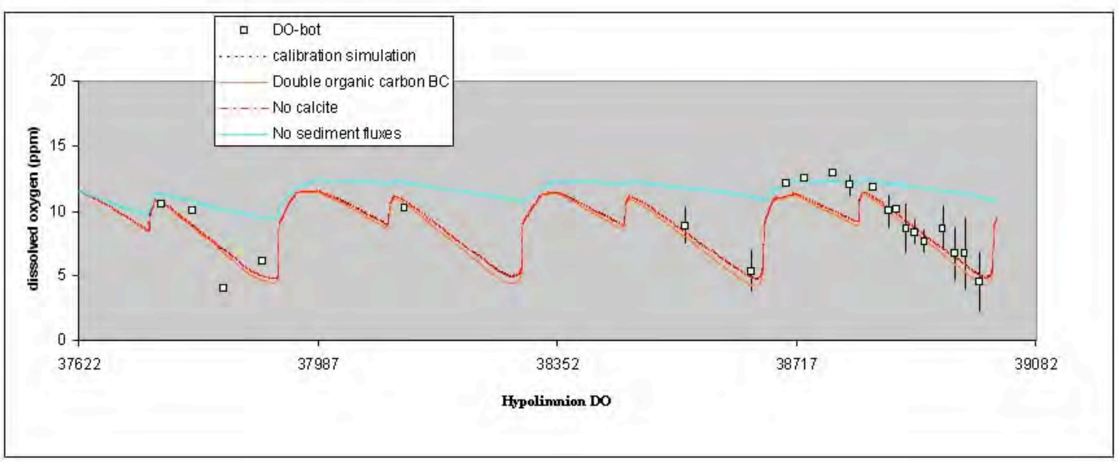



Fig. 35c

Lake Bellaire model simulation of (a) epilimnion, (b) metalimnion, and (c) hypolimnion DO concentration for double organic carbon boundary condition (double organic carbon BC), no calcite formation (no calcite) and no sediment flux scenarios; for comparison, the calibration simulations are also plotted.

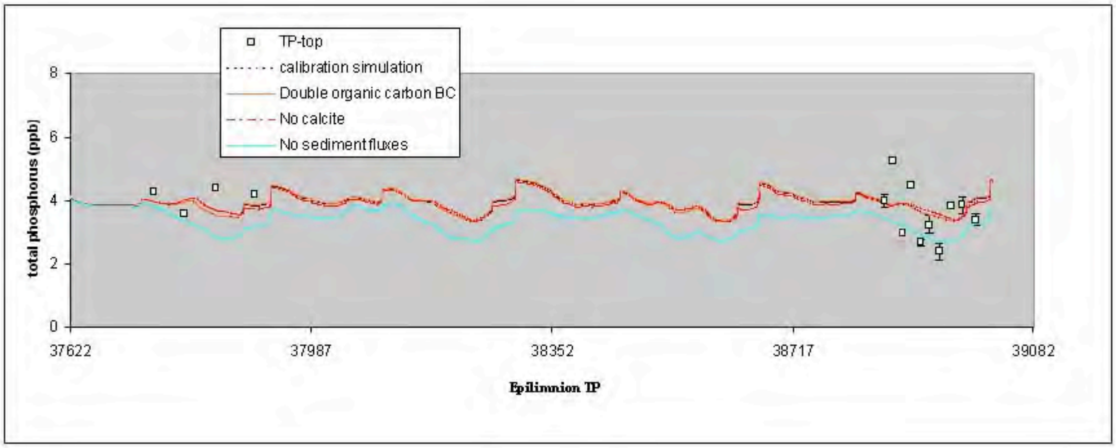



Fig. 35d

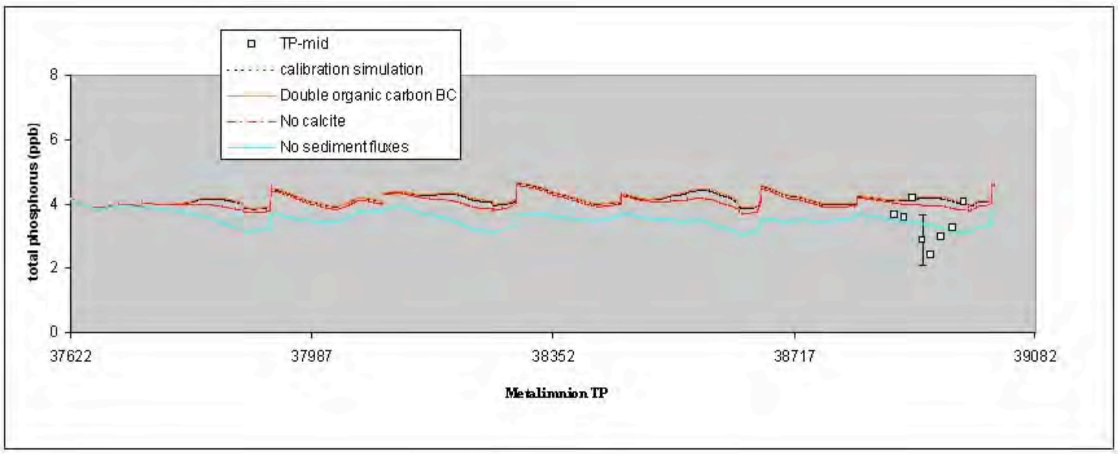



Fig. 35e

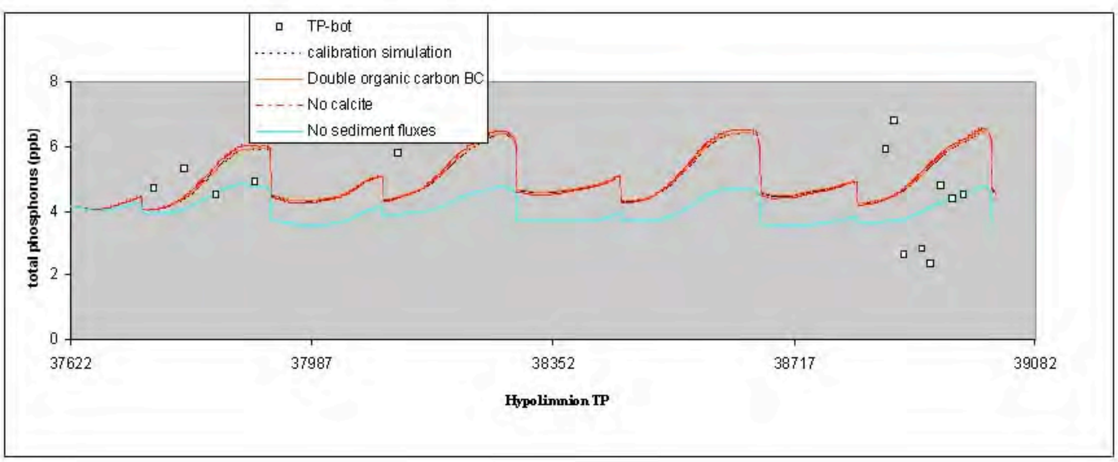



Fig. 35f

Lake Bellaire model simulation of (d) epilimnion, (e) metalimnion, and (f) hypolimnion total phosphorus concentration for double organic carbon boundary condition (double organic carbon BC), no calcite formation (no calcite) and no sediment flux scenarios; for comparison, the calibration simulations are also plotted.

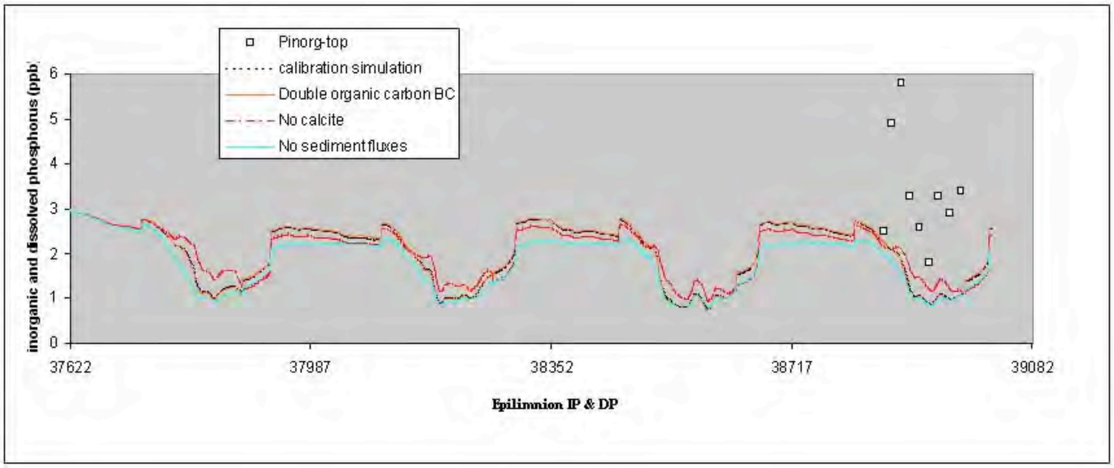



Fig. 36a

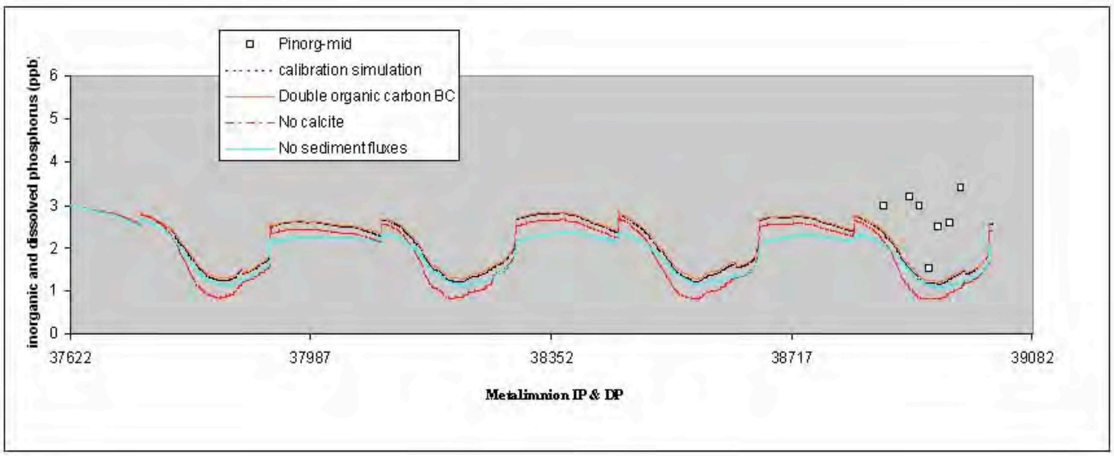



Fig. 36b

Lake Bellaire model simulation of (a) epilimnion and (b) metalimnion inorganic and dissolved phosphorus for double organic carbon boundary condition (double organic carbon BC), no calcite formation (no calcite) and no sediment flux scenarios; for comparison, the calibration simulations are also plotted.

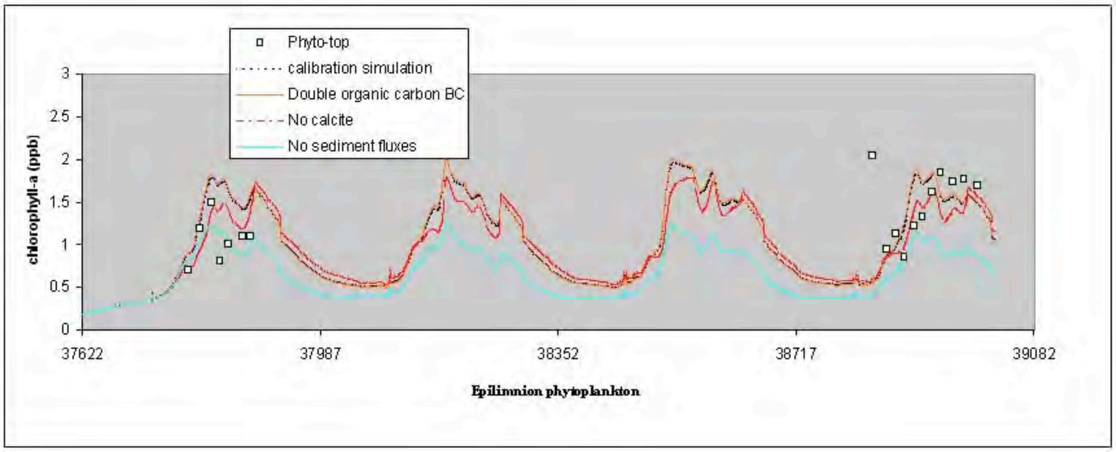



Fig. 36c

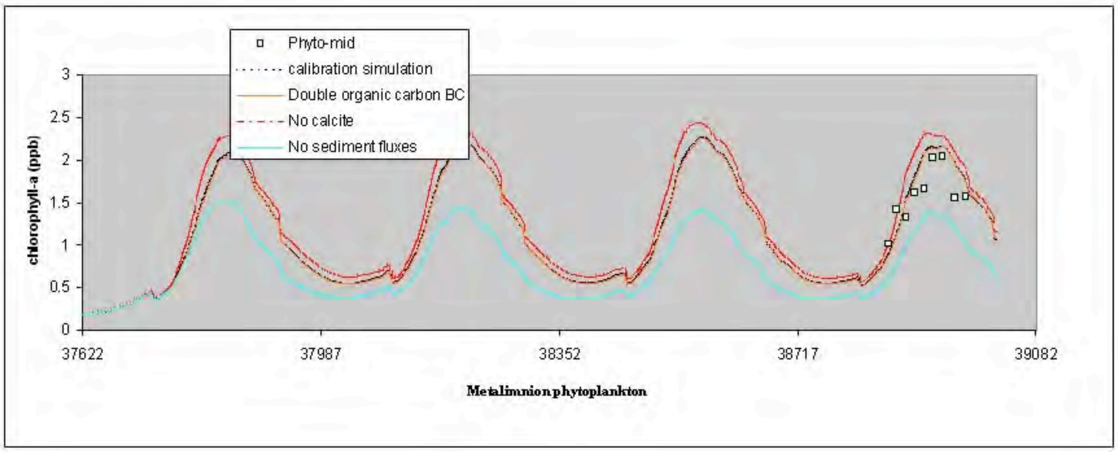



Fig. 36d

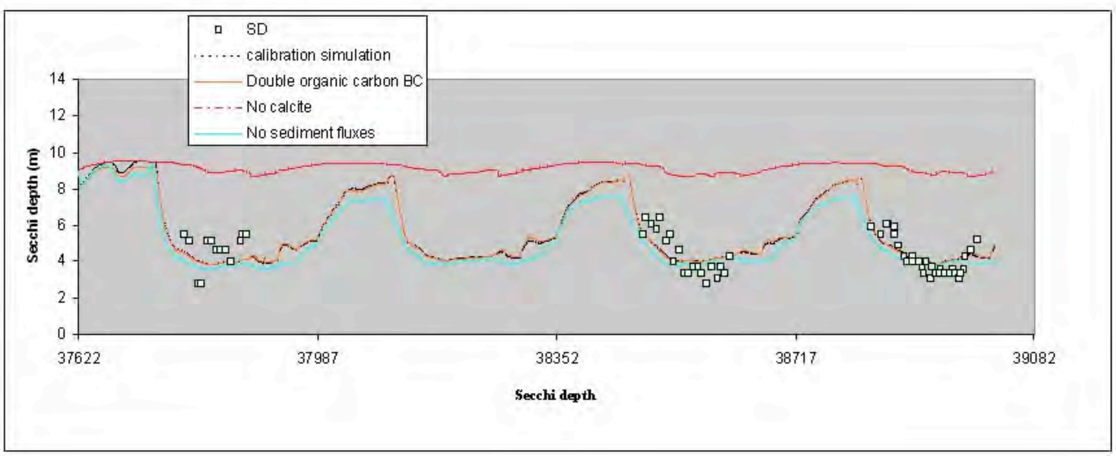



Fig. 36e

Lake Bellaire model simulation (c) epilimnion chlorophyll-a, (d) metalimnion chlorophyll-a, and (e) Secchi depth for double organic carbon boundary condition (double organic carbon BC), no calcite formation (no calcite) and no sediment flux scenarios; for comparison, the calibration simulations are also plotted.

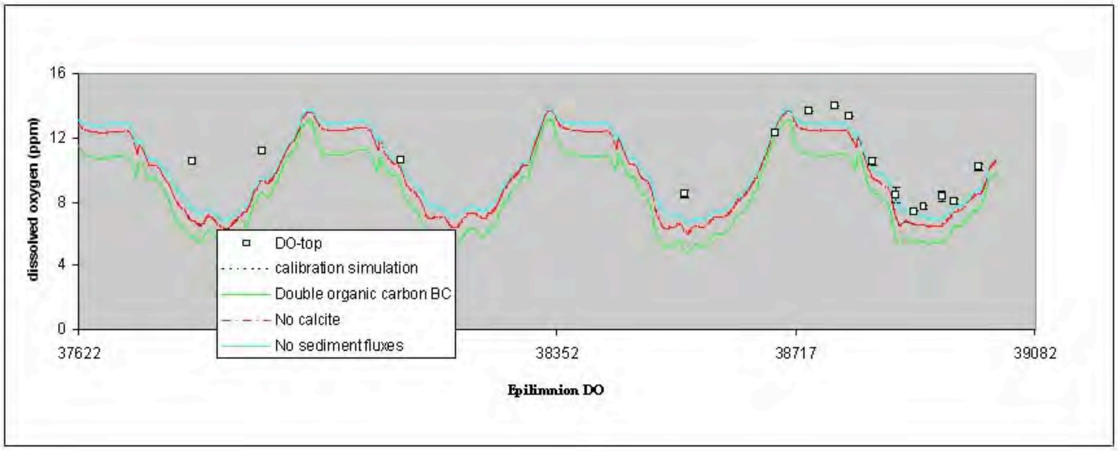



Fig. 37a

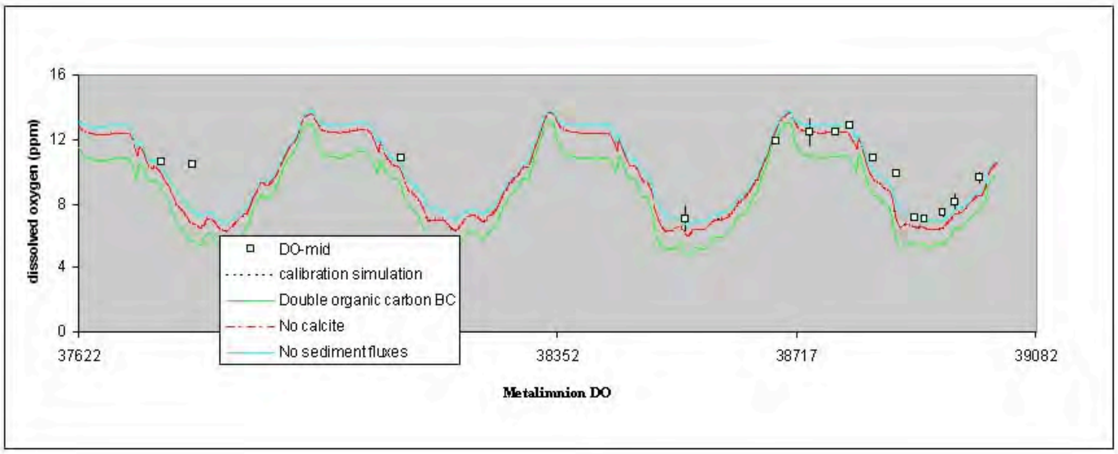



Fig. 37b

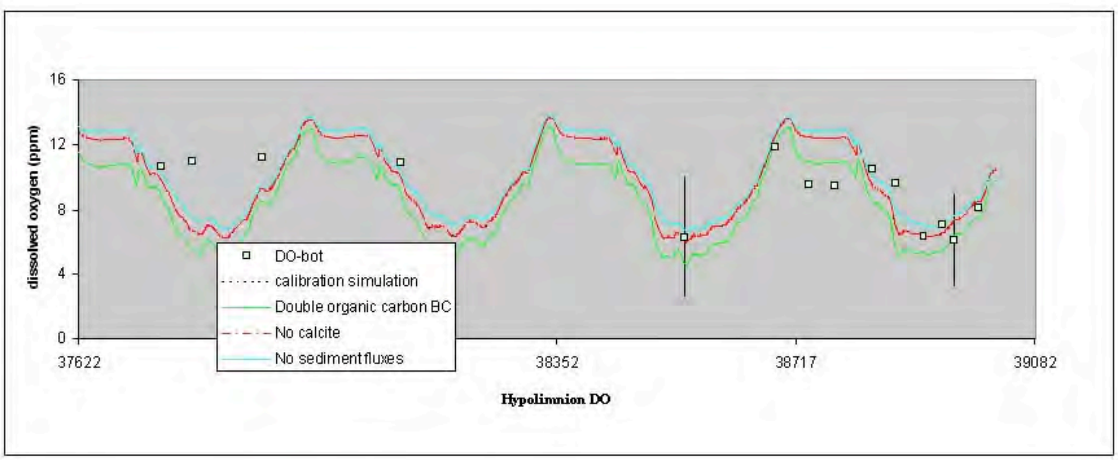



Fig. 37c

Clam Lake model simulation of (a) epilimnion, (b) metalimnion, and (c) hypolimnion DO concentration for double organic carbon boundary condition (double organic carbon BC), no calcite formation (no calcite) and no sediment flux scenarios; for comparison, the calibration simulations are also plotted.

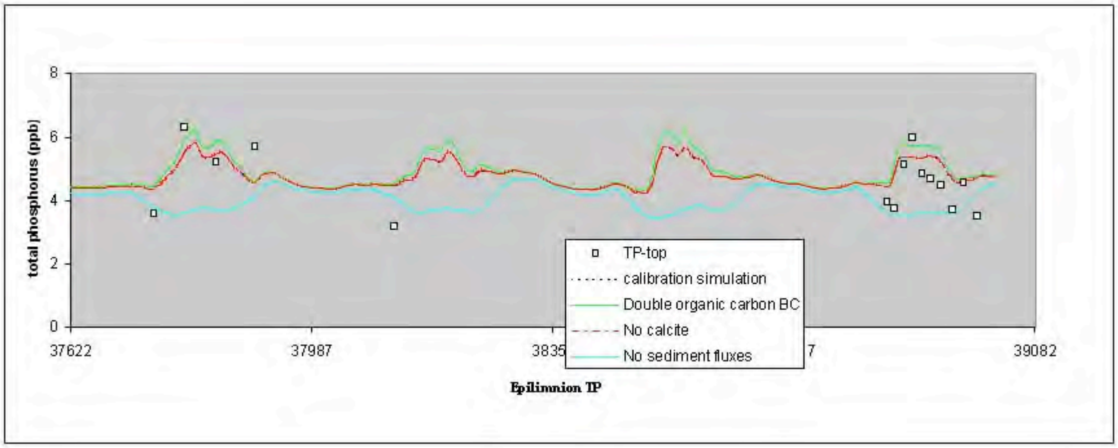



Fig. 37d

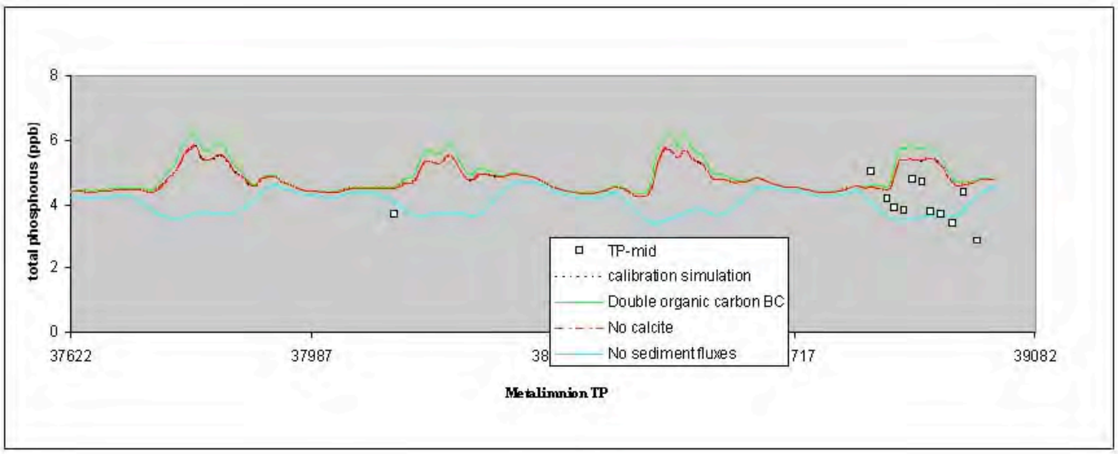



Fig. 37e

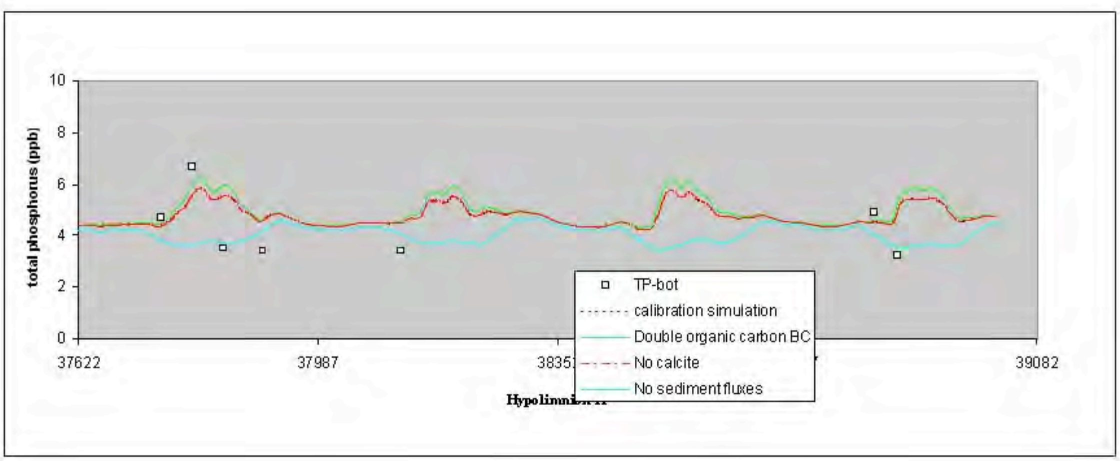



Fig. 37f

Clam Lake model simulation of (d) epilimnion, (e) metalimnion, and (f) hypolimnion total phosphorus concentration for double organic carbon boundary condition (double organic carbon BC), no calcite formation (no calcite) and no sediment flux scenarios; for comparison, the calibration simulations are also plotted.

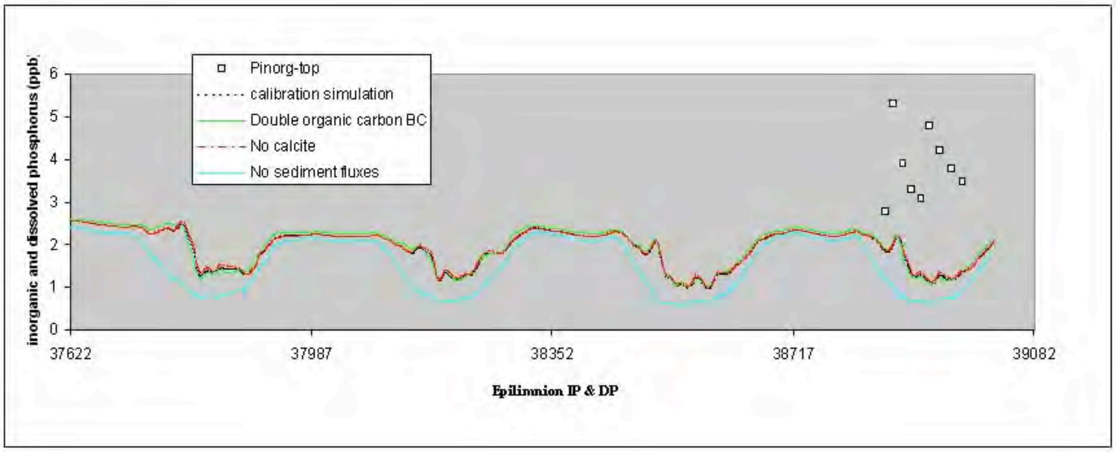



Fig. 38a

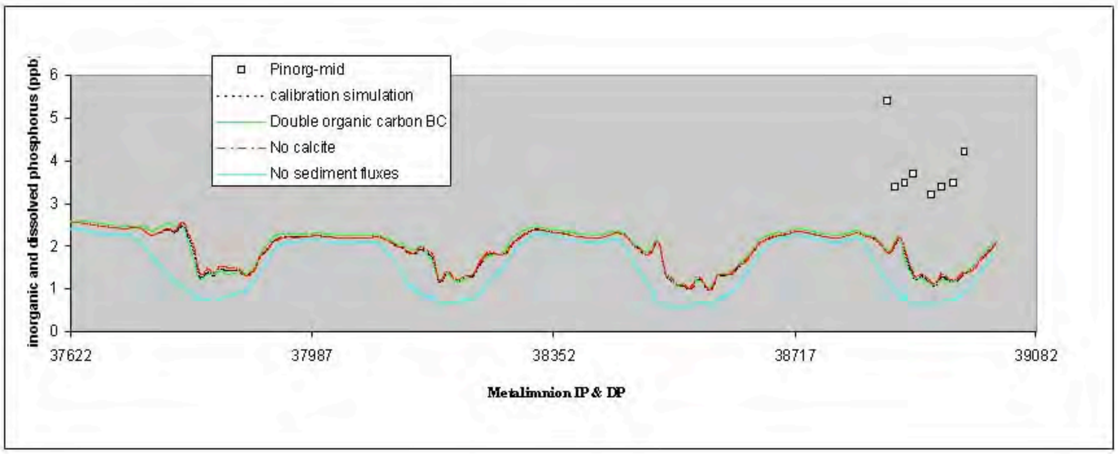



Fig. 38b

Clam Lake model simulation of (a) epilimnion and (b) metalimnion inorganic and dissolved phosphorus for double organic carbon boundary condition (double organic carbon BC), no calcite formation (no calcite) and no sediment flux scenarios; for comparison, the calibration simulations are also plotted.

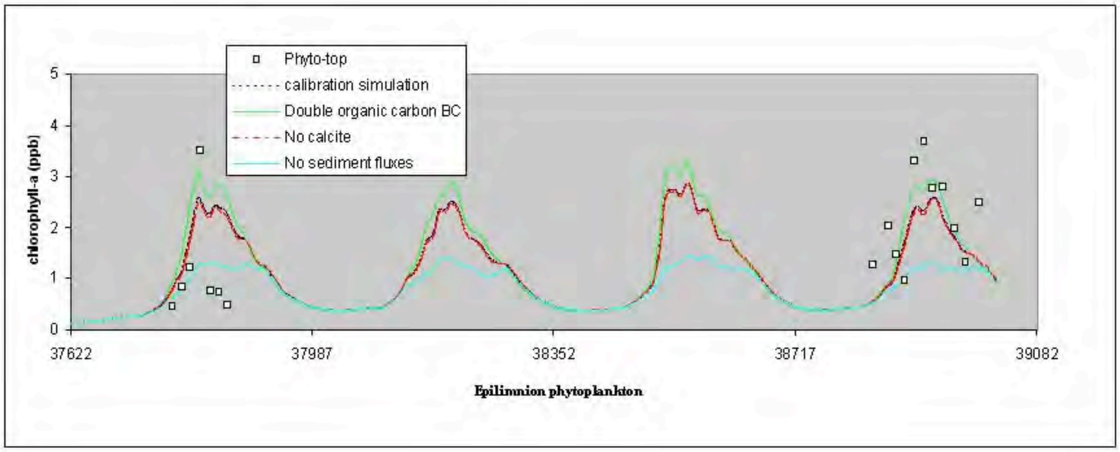



Fig. 38c

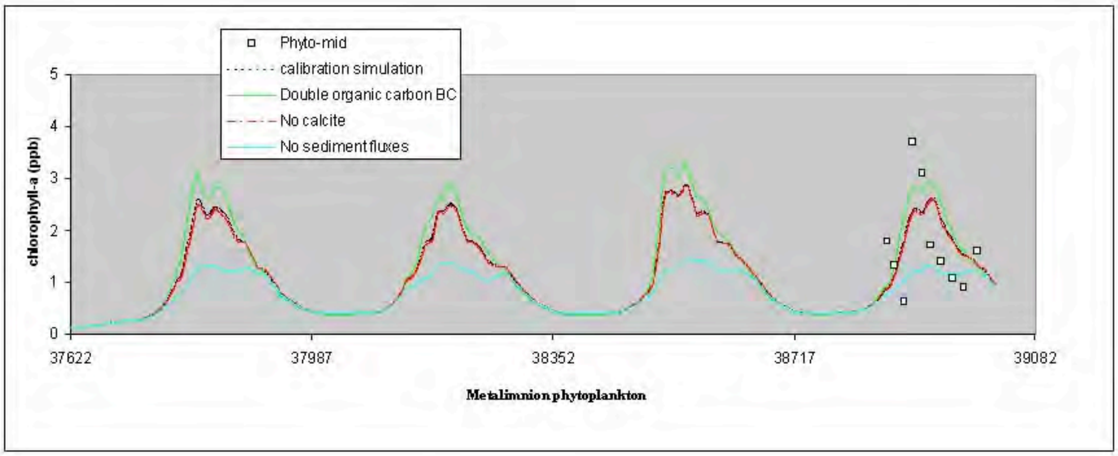



Fig. 38d

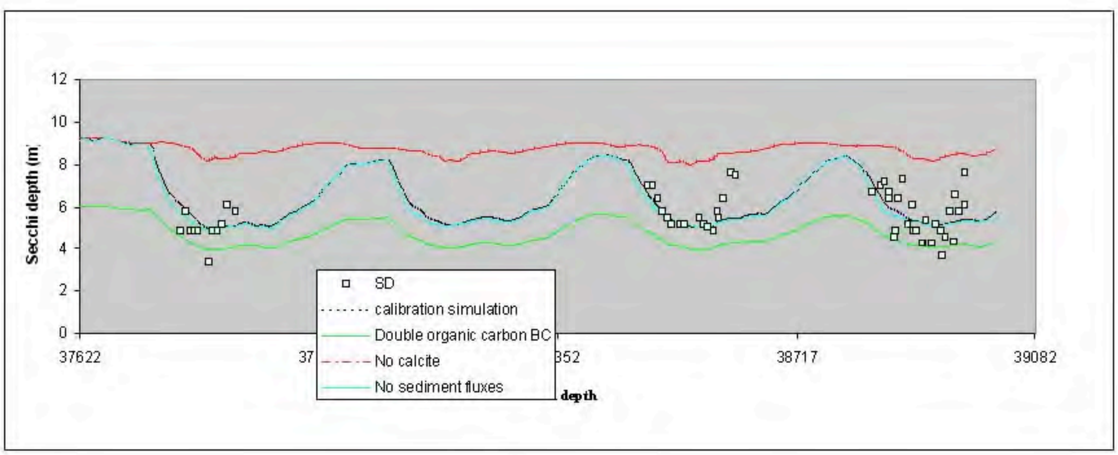



Fig. 38e

Clam Lake model simulation of (c) epilimnion chlorophyll-a concentrations, (d) metalimnion chlorophyll-a concentrations and (e) Secchi depth for double organic carbon boundary condition (double organic carbon BC), no calcite formation (no calcite) and no sediment flux scenarios; for comparison, the calibration simulations are also plotted.

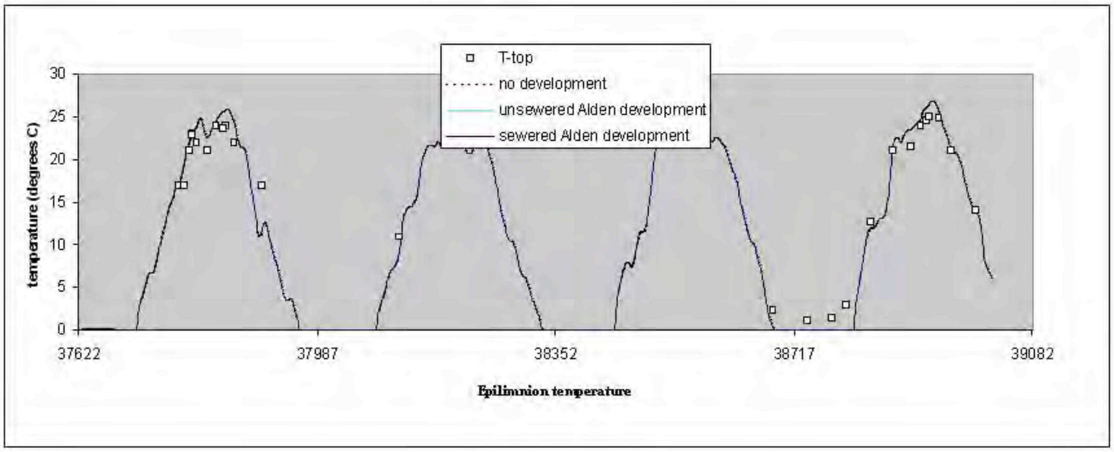



Fig. 39a

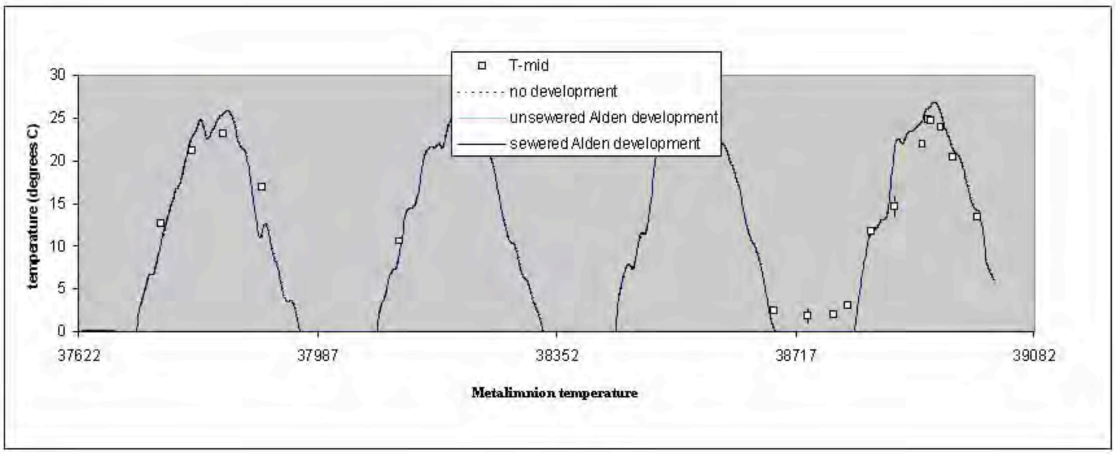



Fig. 39b

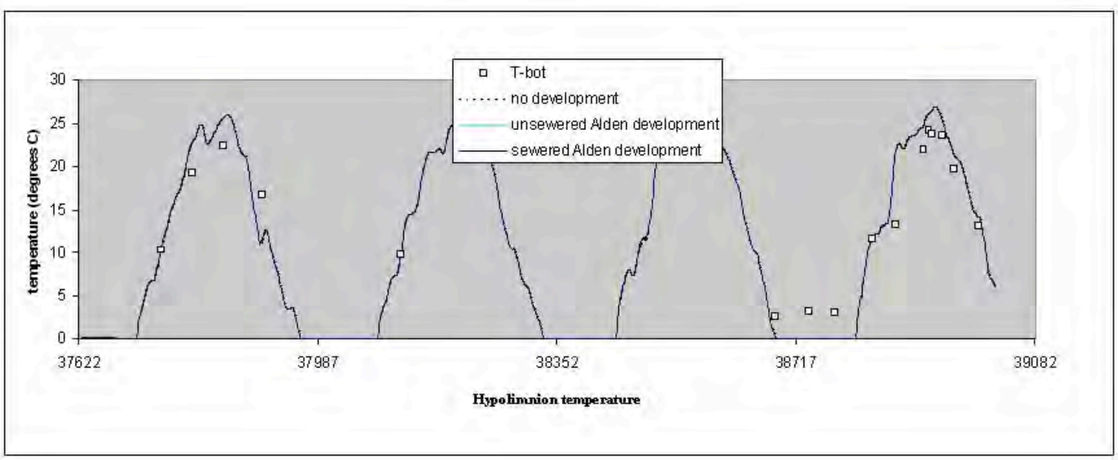



Fig. 39c

Clam Lake model simulation of (a) epilimnion, (b) metalimnion, and (c) hypolimnion water temperature for the sewered and unsewered Alden development scenario; for comparison, the calibration simulations are also plotted.

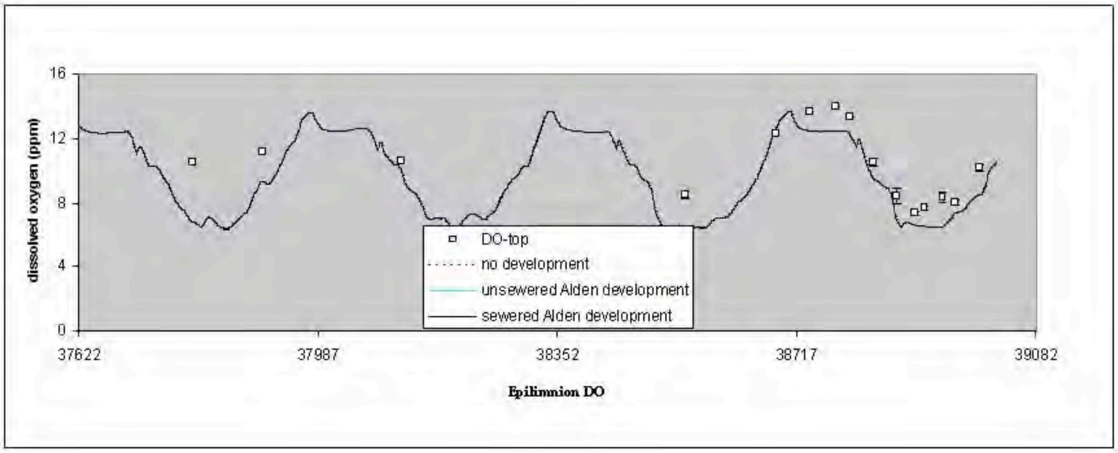



Fig. 39d

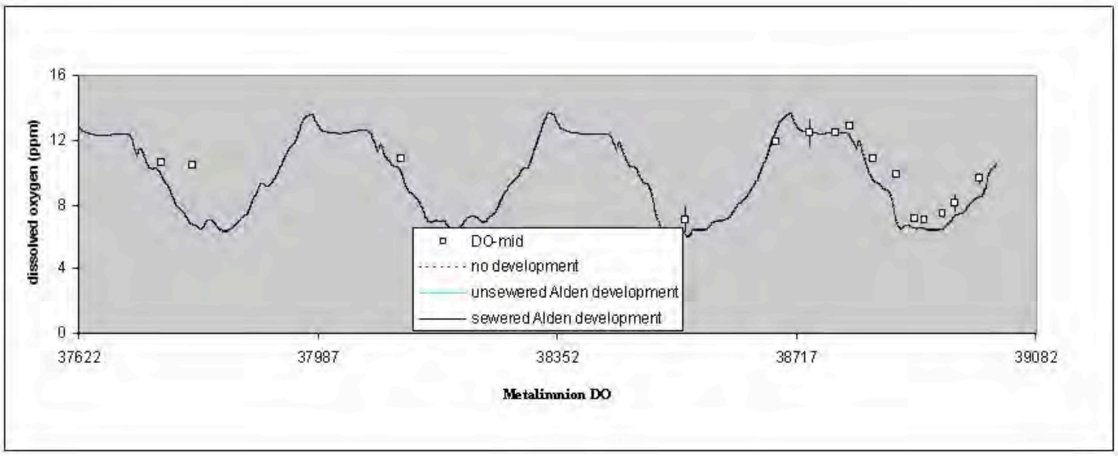



Fig. 39e

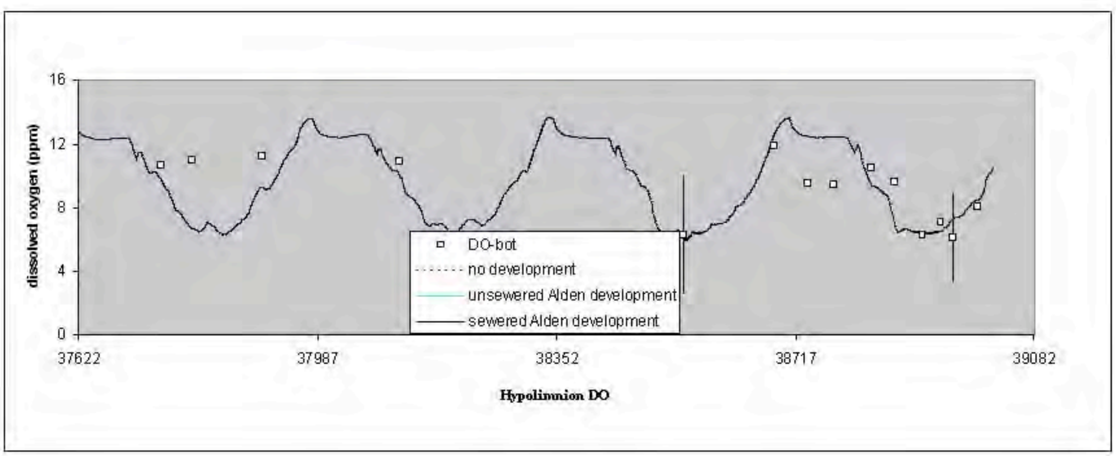



Fig. 39f

Clam Lake model simulation of (d) epilimnion, (e) metalimnion, and (f) hypoliminon DO concentration for the sewered and unsewered Alden development scenario; for comparison, the calibration simulations are also plotted.

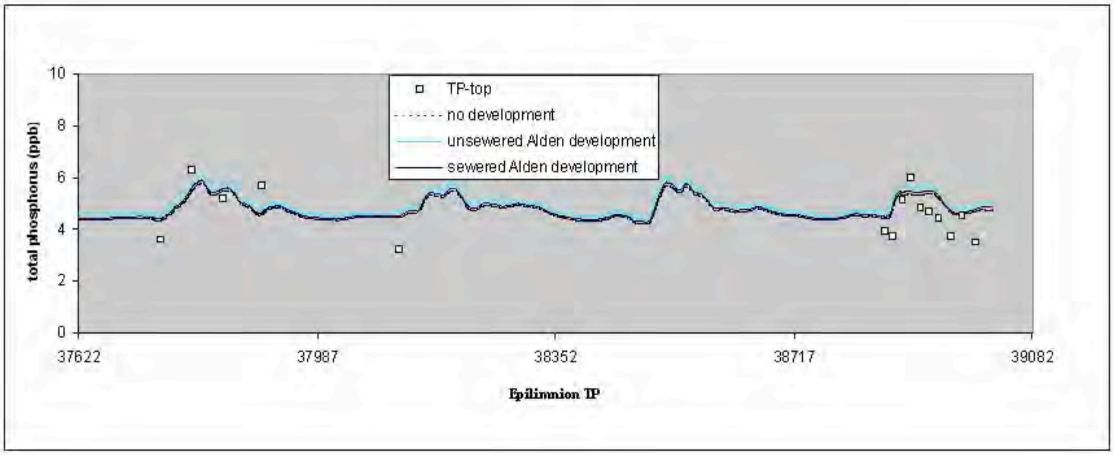



Fig. 40a

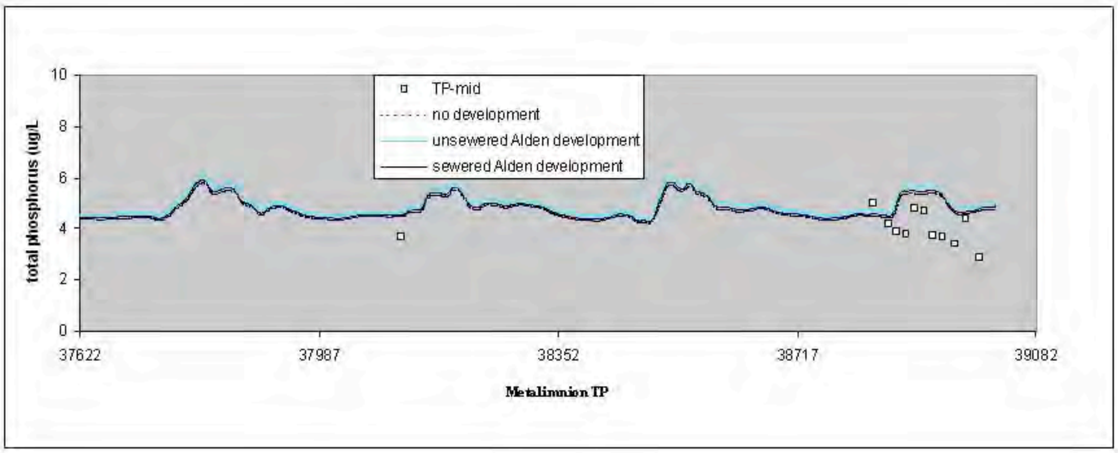



Fig. 40b

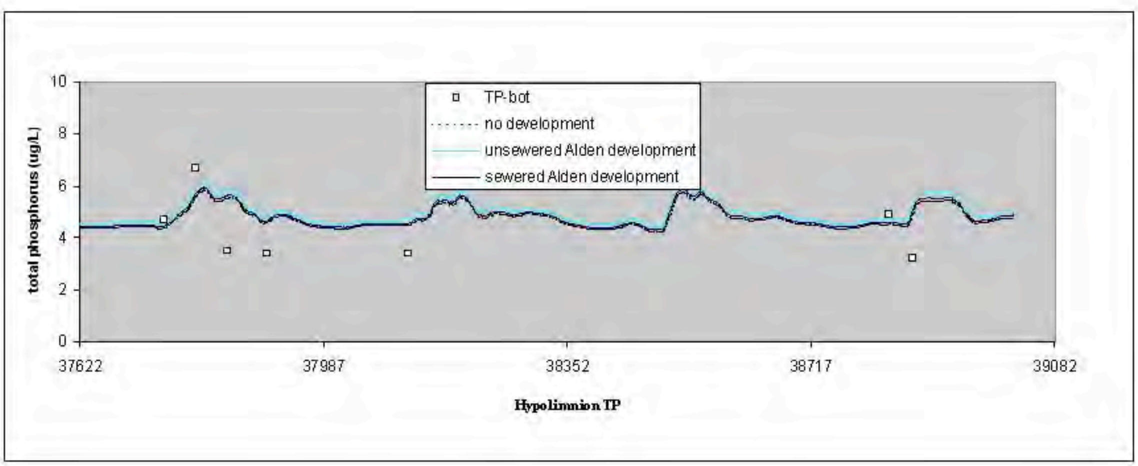



Fig. 40c Clam Lake model simulation of (a) epilimnion, (b) metalimnion, and (c) hypolimnion total phosphorus for the sewered and unsewered Alden development scenario; for comparison, the calibration simulations are also plotted.

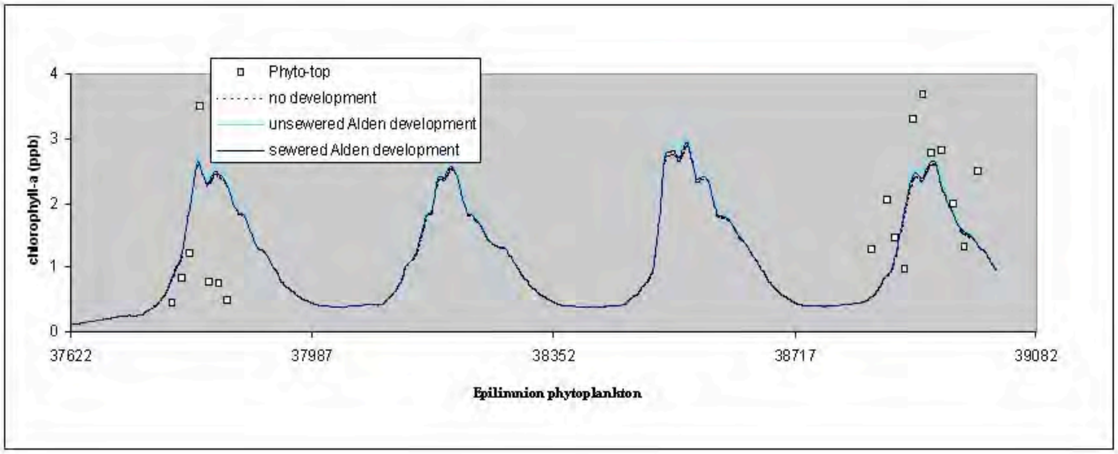



Fig. 40d

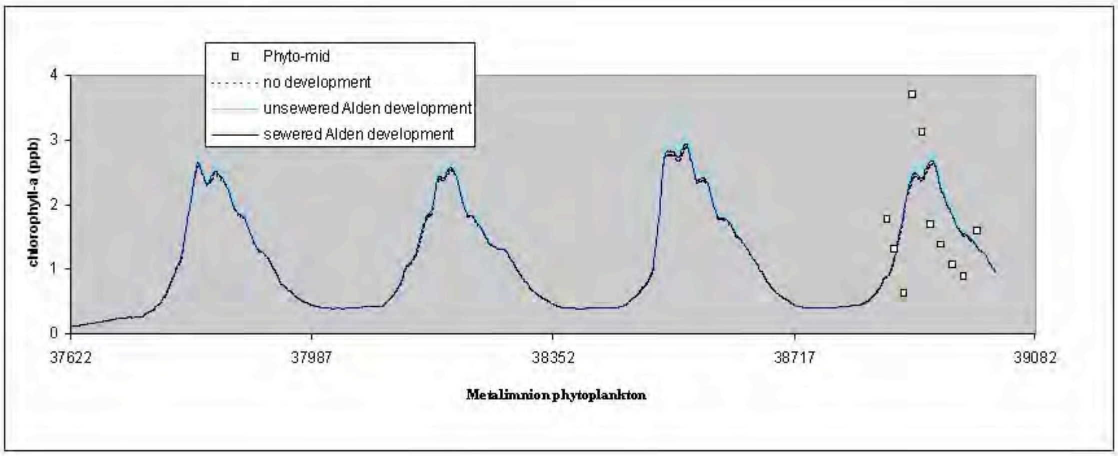



Fig. 40e

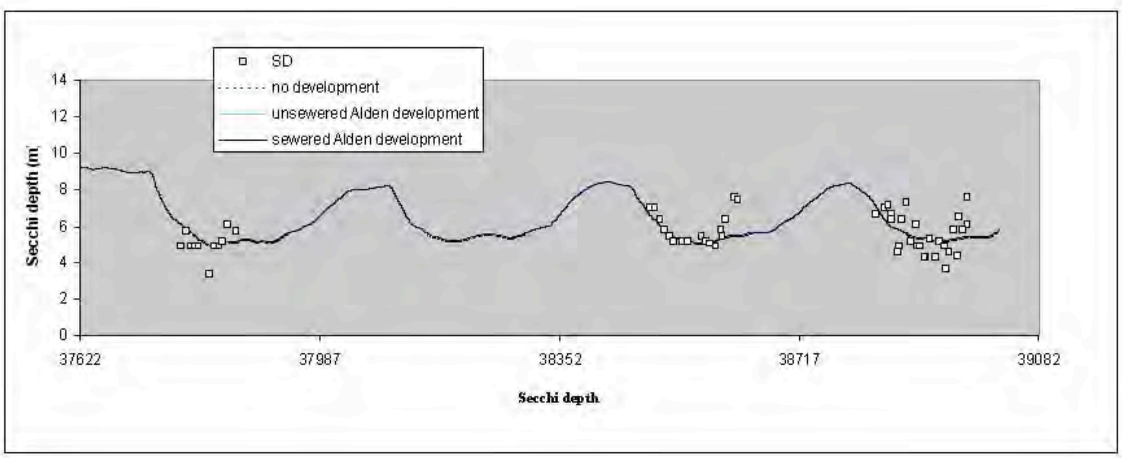



Fig. 40f

Clam Lake model simulation of (d) epilimnion chlorophyll-a, (e) metalimnion chlorophyll-a, and (f) Secchi depth for the sewered and unsewered Alden development scenario; for comparison, the calibration simulations are also plotted.

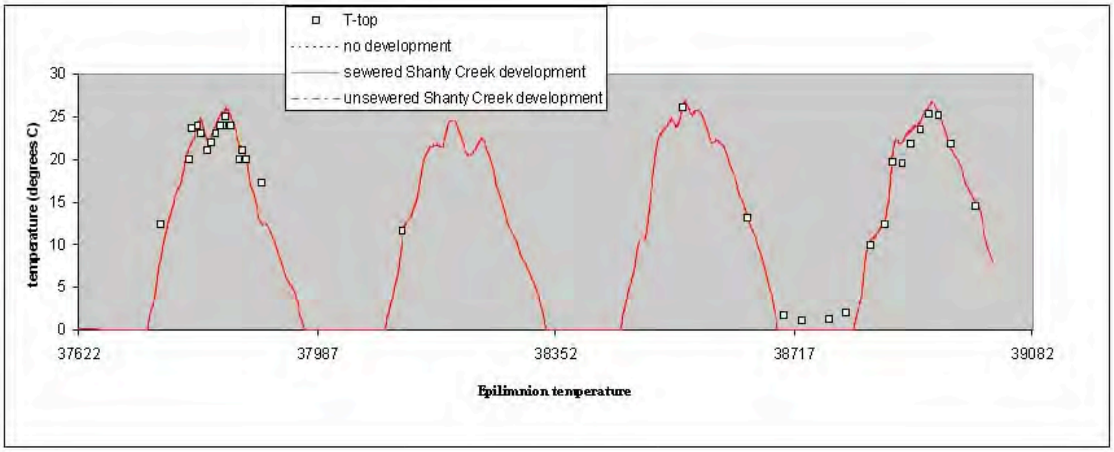



Fig. 41a

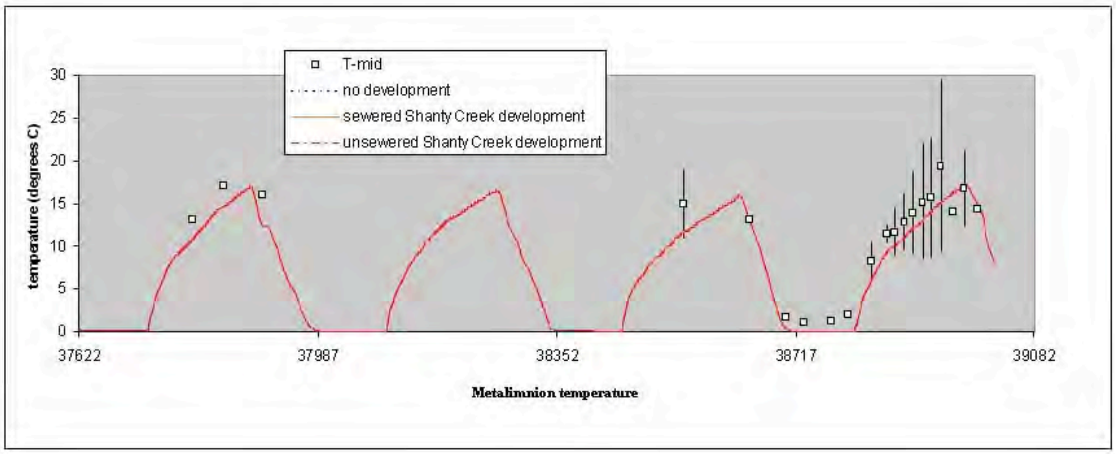



Fig. 41b

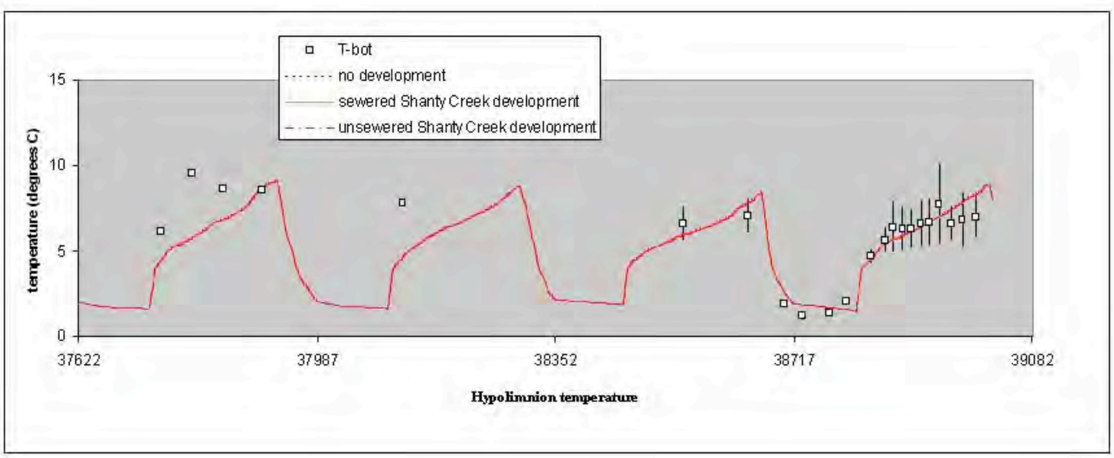



Fig. 41c

Lake Bellaire model simulation of (a) epilimnion, (b) metalimnion, and (c) hypolimnion temperature for the sewered and unsewered Shanty Creek development scenario; for comparison, the calibration simulations are also plotted.

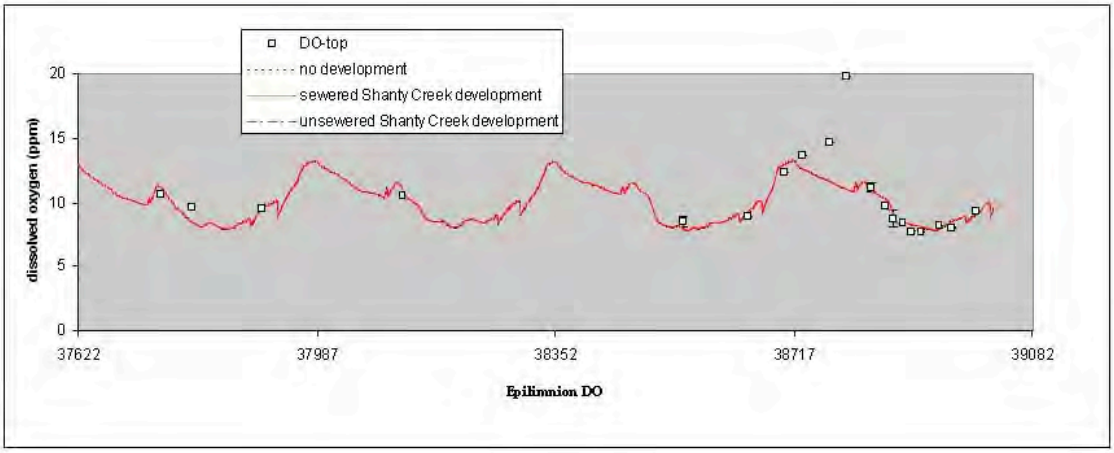



Fig. 41d

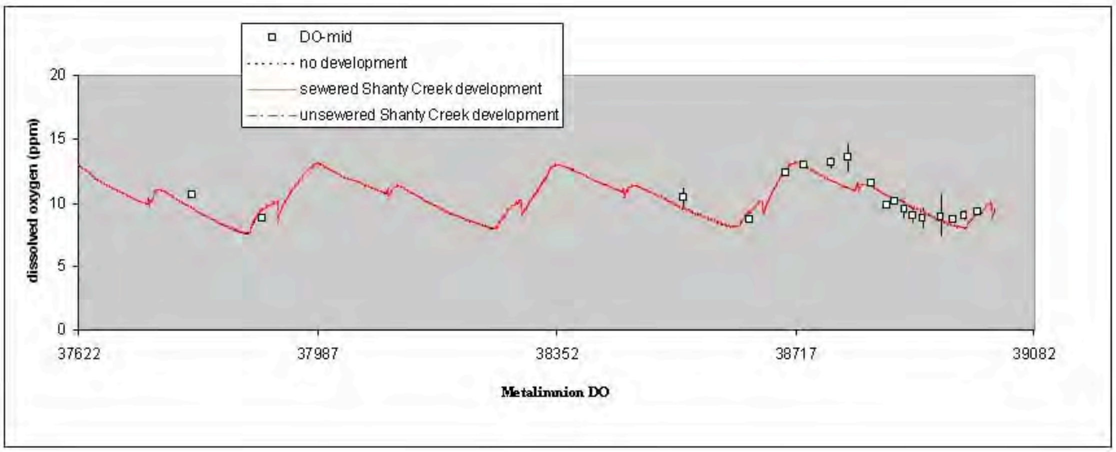



Fig. 41e

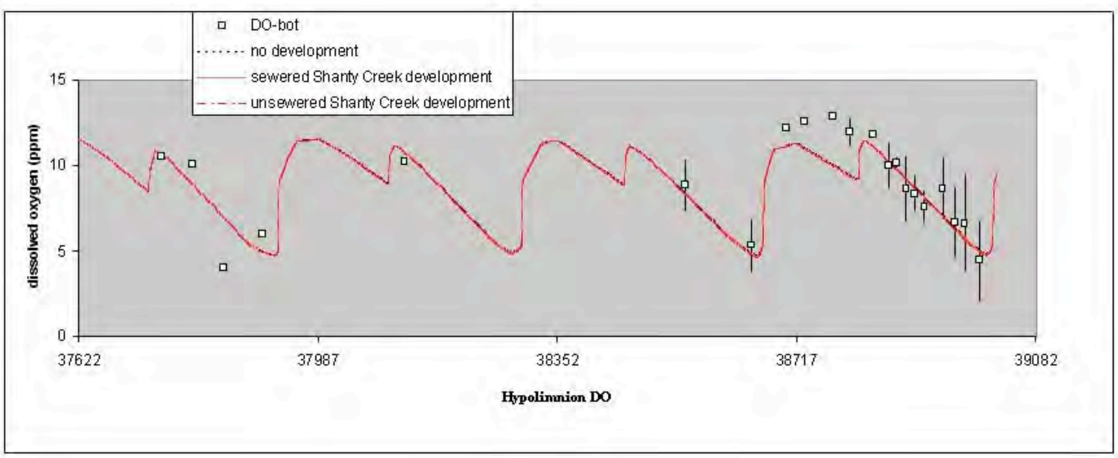



Fig. 41f

Lake Bellaire model simulation of (d) epilimnion, (e) metalimnion, and (f) hypolimnion DO concentration for the sewered and unsewered Shanty Creek development scenario; for comparison, the calibration simulations are also plotted.

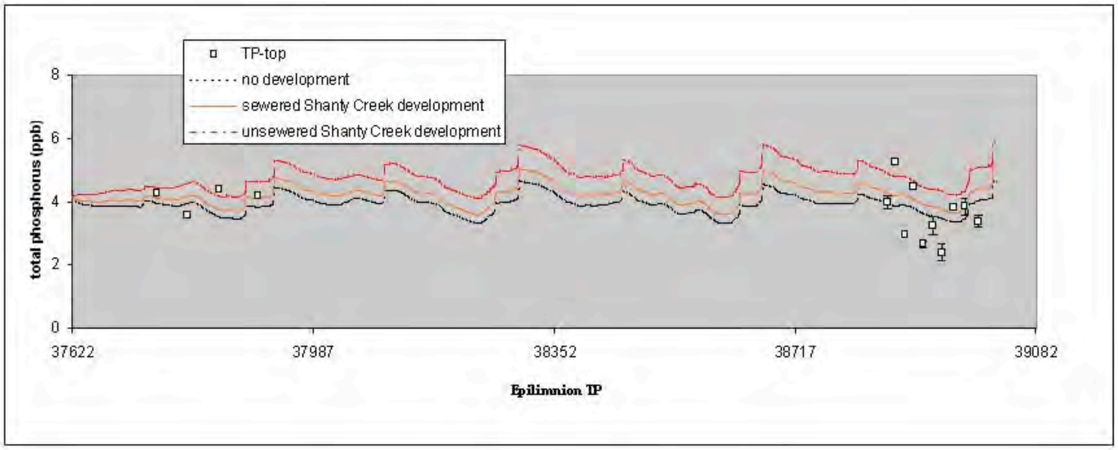



Fig. 42a

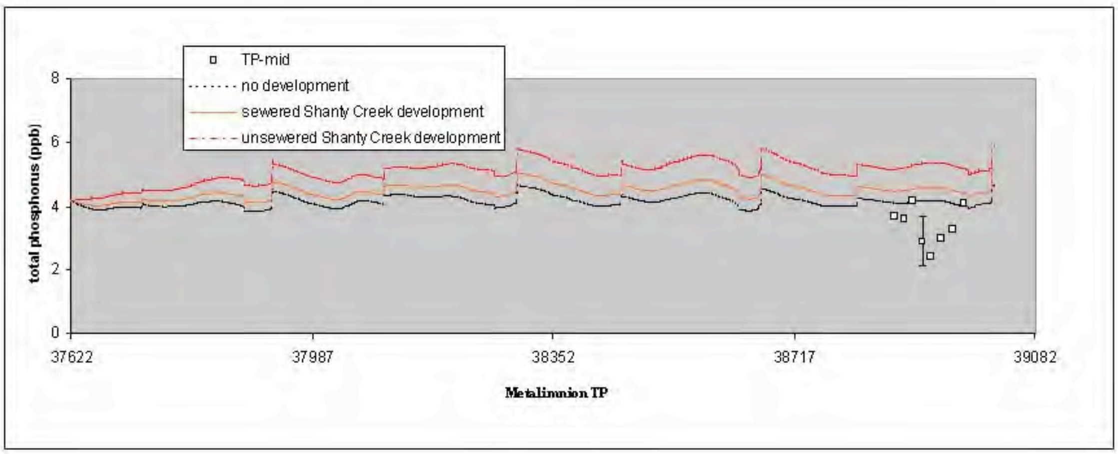



Fig. 42b

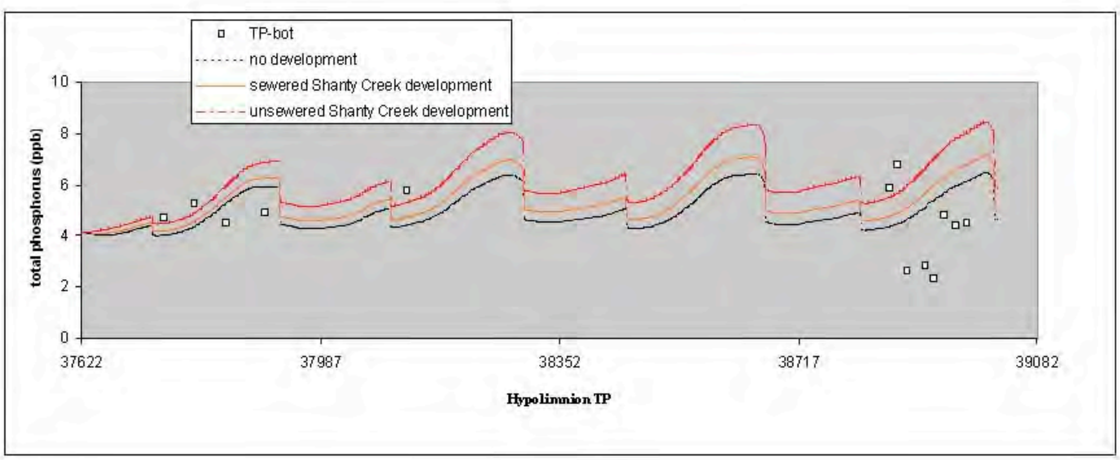



Fig. 42c

Lake Bellaire model simulation of (a) epilimnion, (b) metalimnion, and (c) hypolimnion total phosphorus for the sewered and unsewered Shanty Creek development scenario; for comparison, the calibration simulations are also plotted.

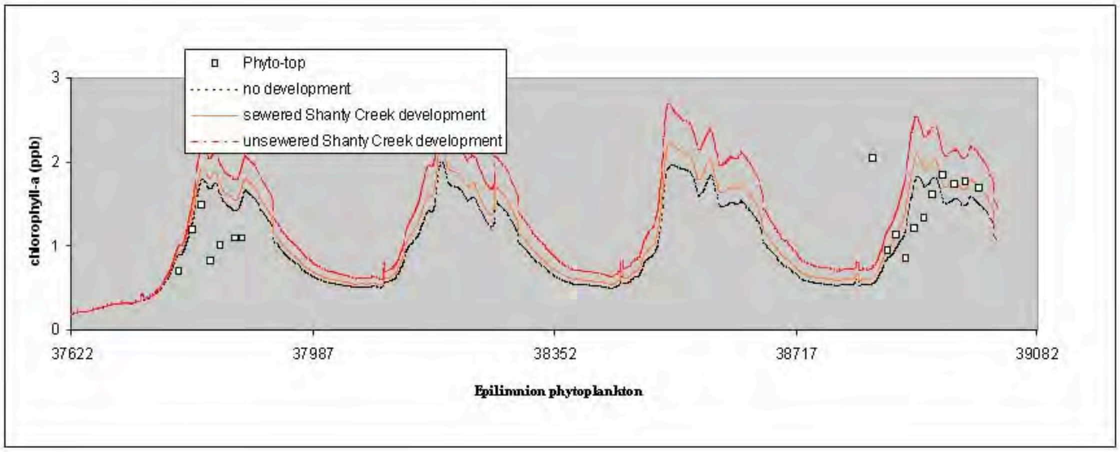



Fig. 42d

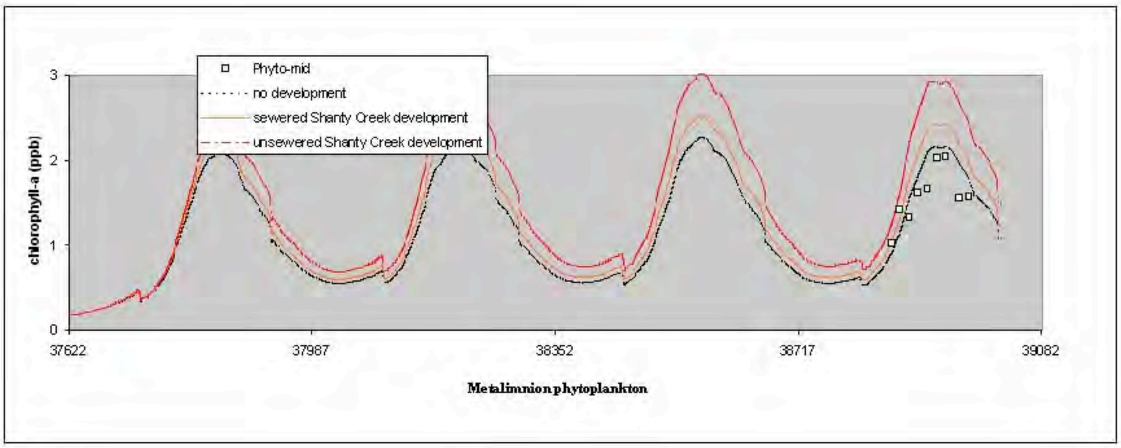



Fig. 42e

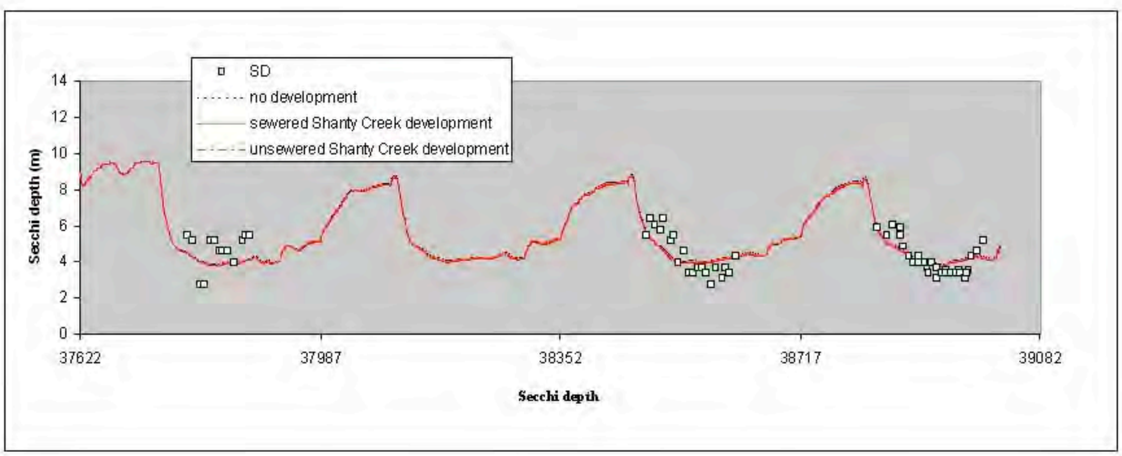



Fig. 42f

Lake Bellaire model simulation of (d) epilimnion chlorophyll-a concentration, (e) metalimnion chlorophyll-a concentration and (f) Secchi depth for the sewered and unsewered Shanty Creek development scenario; for comparison, the calibration simulations are also plotted.

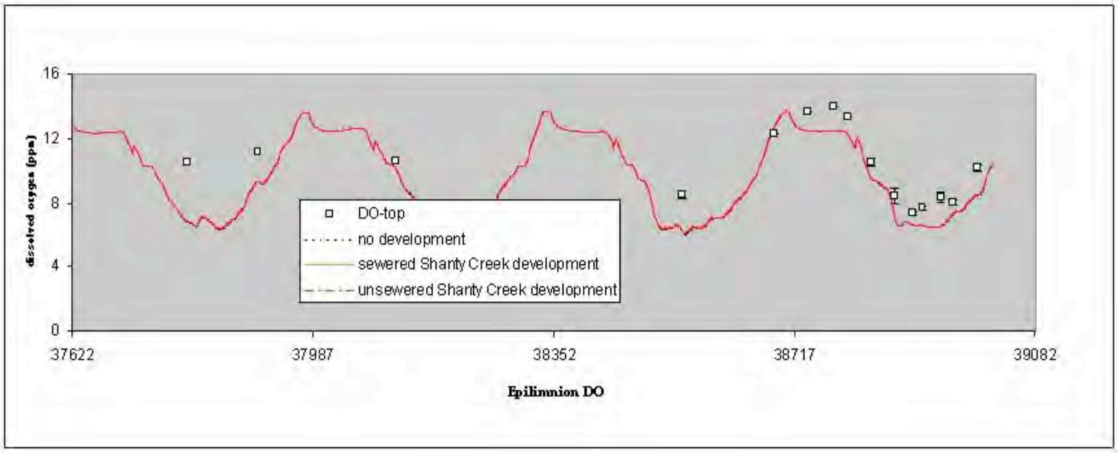



Fig. 43a

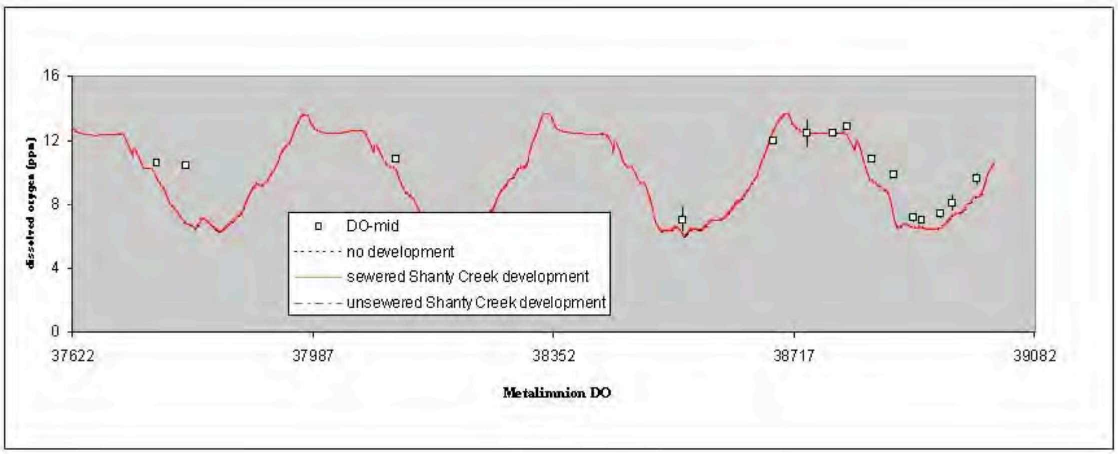



Fig. 43b

Clam Lake model simulation of (a) epilimnion and (b) metalimnion DO concentration for the sewered and unsewered Shanty Creek development scenario; for comparison, the calibration simulations are also plotted.

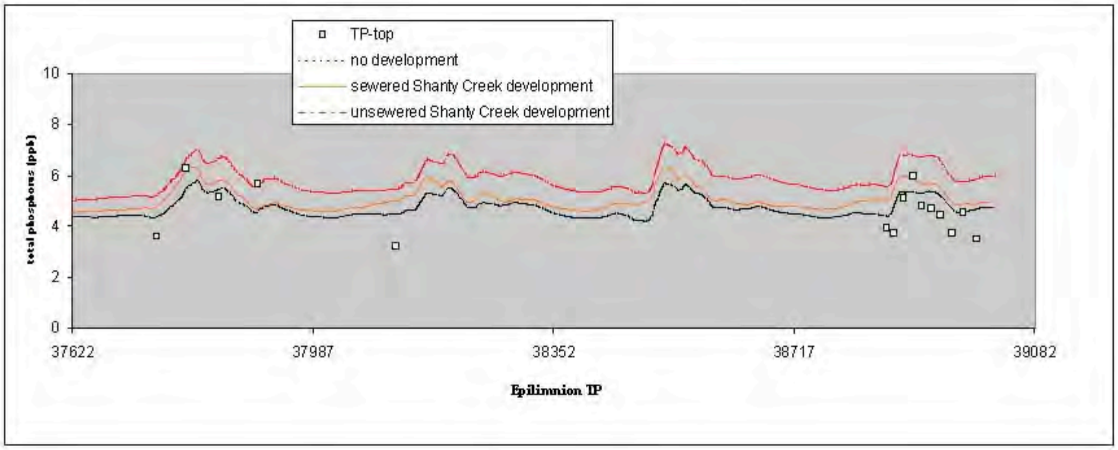



Fig. 43c

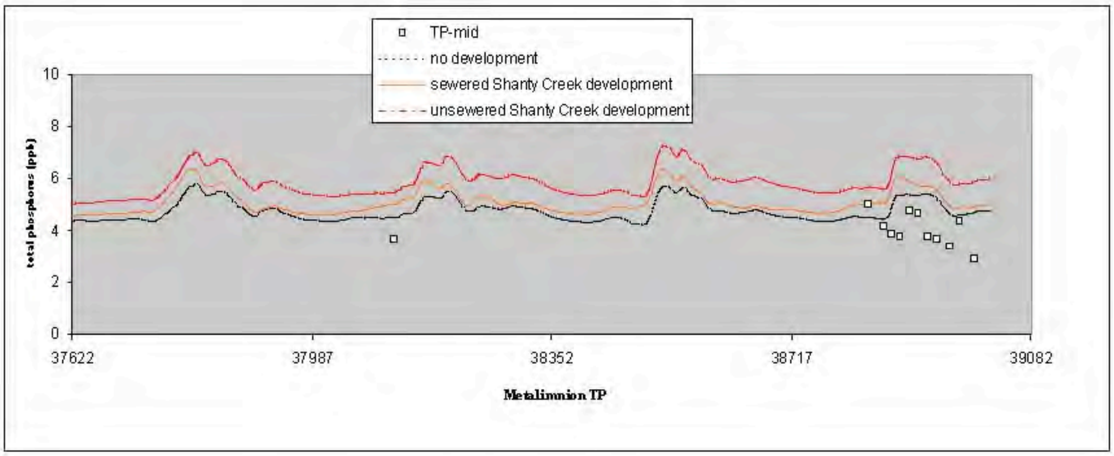



Fig. 43d

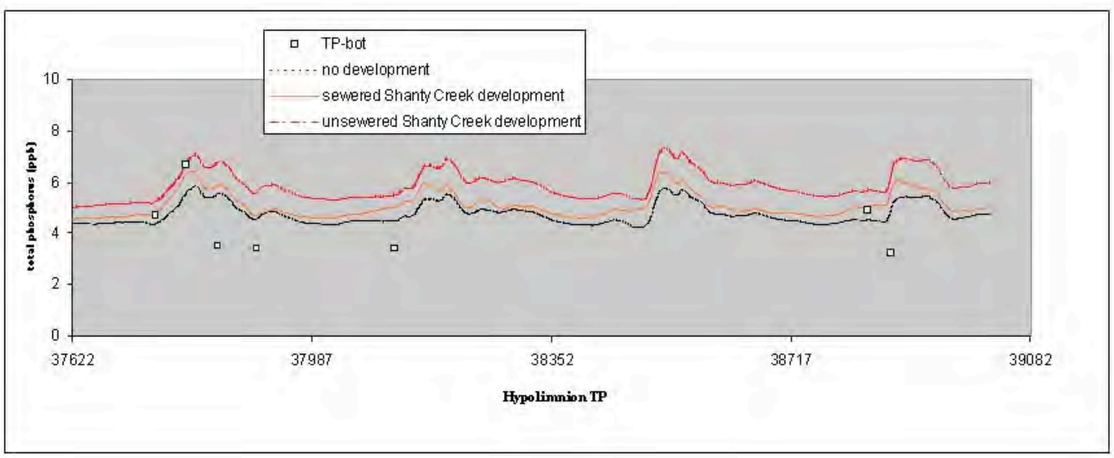



Fig. 43e

Clam Lake model simulation of (c) epilimnion, (d) metalimnion, and (e) hypolimnion total phosphorus concentration for the sewered and unsewered Shanty Creek development scenario; for comparison, the calibration simulations are also plotted.

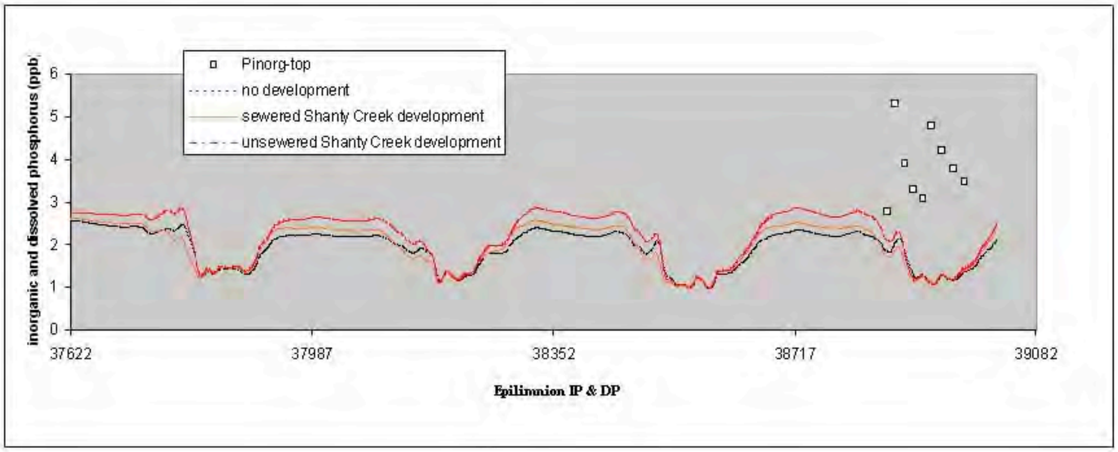



Fig. 44a

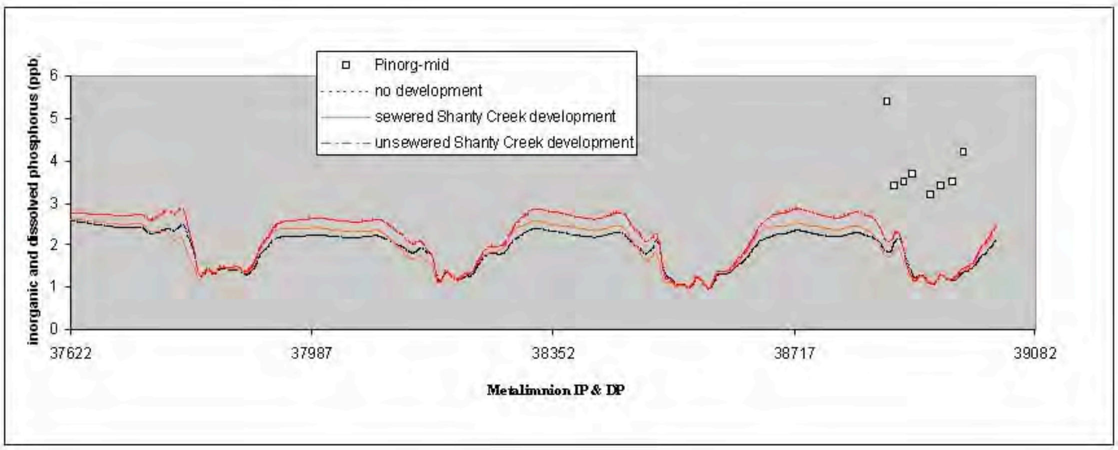



Fig. 44b

Clam Lake model simulation of (a) epilimnion and (b) metalimnion inorganic and dissolved phosphorus for the sewered and unsewered Shanty Creek development scenario; for comparison, the calibration simulations are also plotted.

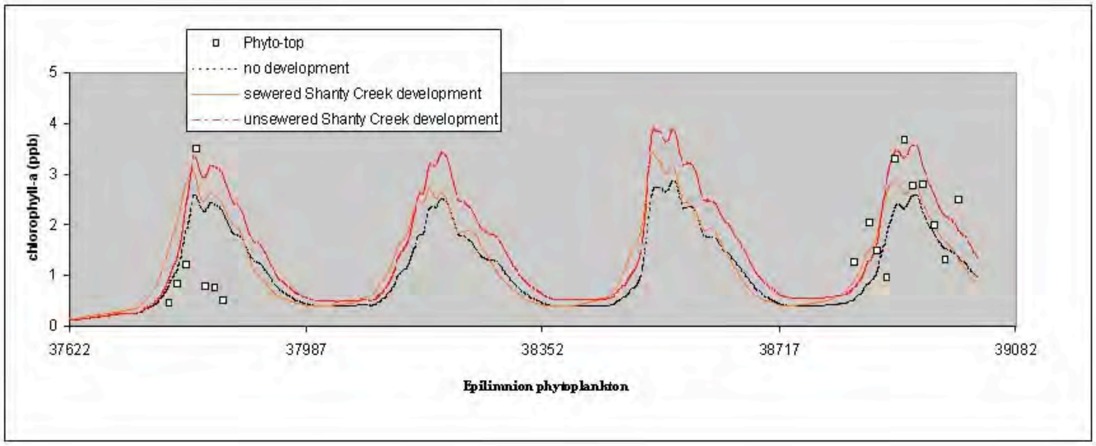



Fig. 44c

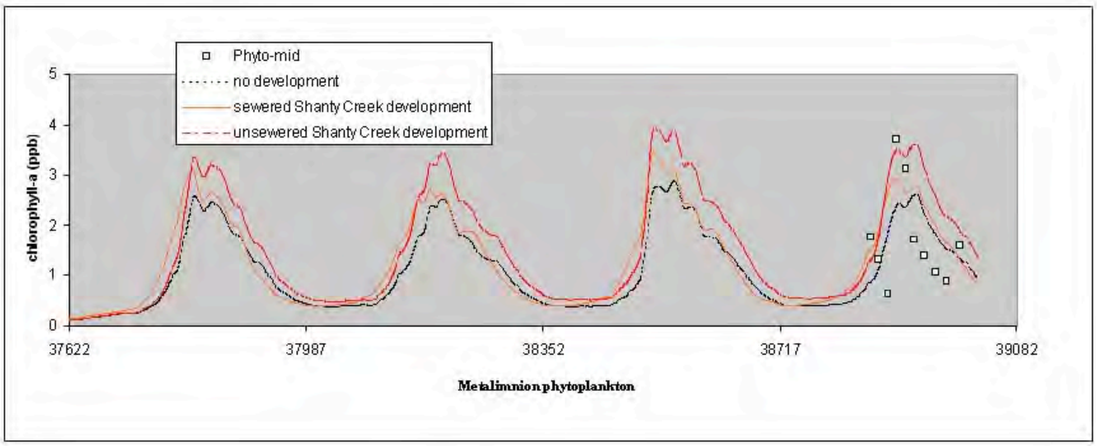



Fig. 44d

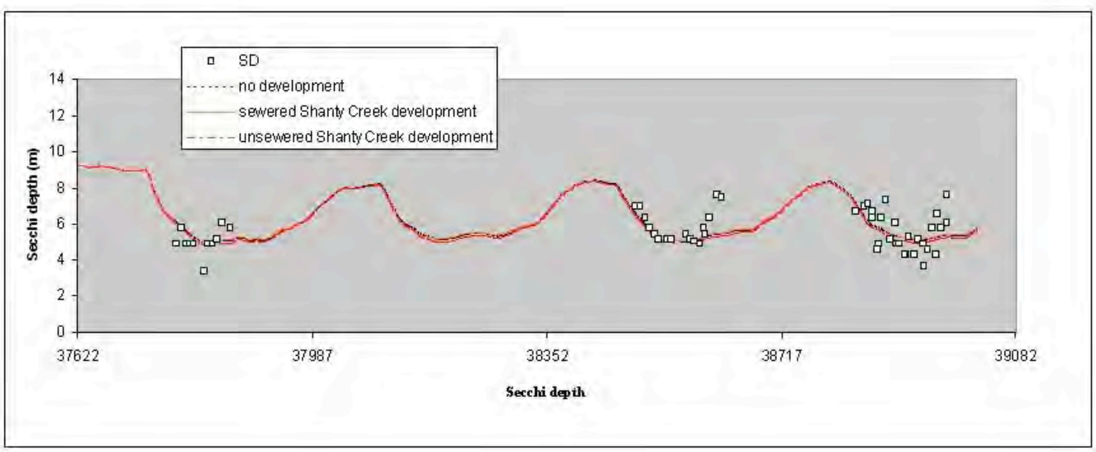



Fig. 44e

Clam Lake model simulation of (c) Epilimnion chlorophyll-a, (d) metalimnion chlorophyll-a, and (e) Secchi depth for the sewered and unsewered Shanty Creek development scenario; for comparison, the calibration simulations are also plotted.