

# **Phosphorus dynamics in Jessie Lake: mass flux across the sediment-water interface**

**Hong Wang <sup>a</sup>, Miki Hondzo <sup>a</sup> Bruce Wilson <sup>b</sup> and Brenda Stauffer <sup>c</sup>**

<sup>a</sup> St. Anthony Falls Laboratory, Department of Civil Engineering,

University of Minnesota, MN 55414, U.S.A.

<sup>b</sup> Minnesota Pollution Control Agency, 520 Lafayette Rd, St Paul, MN 55155

<sup>c</sup>USFS

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## **ABSTRACT**

Phosphorus dynamics and its release fluxes at the sediment-water interface in Jessie Lake were investigated by means of field, laboratory measurements and numerical simulations. It was found that the lake is highly dynamic with a high-energy dissipation rate and a turbulent flow at the sediment-water interface in the lake. The sediment-water interface was dominated with anoxic conditions in summers. Compared to other lakes, the lake has relatively low phosphorus-affinity element concentrations of Fe, Al, and Ca, indicating a low holding capacity of phosphorus in sediments. This conclusion is also supported by fractionation results of sediment phosphorus: inorganic phosphorus accounts for only a small portion of total phosphorus. There was a release flux of phosphorus observed from the sediments to the overlying water under anaerobic condition.

A sediment phosphorus dynamic model was used to conduct short and long-term predictions of phosphorus internal loadings in Jessie Lake. Close to laboratory measurement, the simulated phosphorus release flux across the sediment-water interface is 14.1 mg/m<sup>2</sup>/day. The long-term predictions indicate that if organic loading to the lake sediments continues at the rate observed in the past, the internal loading of phosphorus will increase in the next 30 years. The reduction in the organic loading of 1%, 5%, 10% and 25% will achieve reductions in the phosphorus internal loading from current 13.0 mg/m<sup>2</sup>/day to 9.7, 3.0, 0.7, and 0 mg/m<sup>2</sup>/day, respectively.

*Keywords:* Phosphorus, mobilization, release, sediments, fractionation, Jessie Lake

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## **1. Introduction**

Phosphorus is generally considered to be a major bio-growth limiting macro nutrient in aquatic ecosystems (Jorgensen, 1983; Ishikawa and Nishimura, 1989 and Fox, 1989). Cultural eutrophication of freshwater ecosystems due to anthropogenic sources of phosphorus is well documented (Wetzel, 2001; Lampert and Sommer, 1997; Stumm and Morgan, 1996; Schindler 1974). Studies have shown that in some situations eutrophication can continue even after external anthropogenic sources have stopped (Hu et al., 2001; Lemmin and Imboden, 1987). This has led researchers to examine other causes of eutrophication including the significance of internal loading of phosphorus released from the sediments (Petticrew and Arocena, 2001; Blais and Kalff, 1995).

Phosphorus may be released from the sediment to overlying water through its biogeochemical processes. In some lakes and reservoirs, it has been shown that the flux of phosphorus released from sediments to the overlying water is comparable to the external loading (Ishikawa and Nishimura, 1989). Decomposition of organic matter in sediments has been reported to be a driving force for the release of phosphorus from sediments to overlying water (Boers and Hese, 1988; Di Toro and Fitzpatrick, 1993). The organic matter, supplied by settling of dead biomass, is used as an energy source by sediment-living bacteria and fungi through their metabolism activities. One of the products, ortho-phosphorus is regenerated from the particulate organic matter during the metabolism activities and acts as a primary source for the internal loading of phosphorus. In addition, lake sediments can act not only as a sink but also a source for phosphorus due to their sorption properties. Phosphorus has a strong affinity to oxide iron, aluminum and manganese. Reduction and oxidation (redox) of these metals regulate the dynamics of phosphorus in sediments. The mechanisms of phosphorus mobilization are explained by the reductions of insoluble metal oxides such as Fe(III) to soluble Fe(II) in sediments or water whereby phosphorus bound to Fe(III) or adsorbed to iron complexes is returned to solution when system redox potentials change from aerobic to anaerobic conditions. The resultant concentration gradient between the sediment pore water and overlying water from phosphorus mobilization drives phosphorus flux into the overlying water.

A history of nuisance algal blooms, fluctuating phosphorus concentrations and trophic level values has been documented in Jessie Lake, USA (Reed and Watkins, 1999). Because of this erratic history there is a concern that Jessie Lake is approaching a hypereutrophic state. During last decades, phosphorus concentration has exhibited an

increase of 135% over 6 years from 24 ug/L in 1992 to 57.3 ug/L in 1998 (Reed and Watkins, 1999), placing Jessie Lake in the 90<sup>th</sup> percentile of total phosphorus concentration in its eco-region (Heiskary and Wilson, 1989). The Carlson Trophic Status evaluated in terms of Secchi disc, phosphorus, and chlorophyll-*a* concentrations suggested that the Jessie Lake ranged in the mesotrophic class in 1992 and in the eutrophic class in 1998 (Reed and Watkins, 1999). The increasing deterioration of water quality in the lake has impacted its ecological conditions, biological species, recreation potential and property value. During the summer of 1998 a fish kill occurred due to the low oxygen levels within the lake. A study was launched to investigate mobility of sediment phosphorus and its release flux from sediments to the overlying water in Jessie Lake. The objectives of this study are to address: a) lake dynamic conditions near the sediment-water interface in Jessie lake by field measurements; b) phosphorus mobility by phosphorus-affinity metal analysis and sediment phosphorus fractionations; c) phosphorus dynamics in sediments and release flux from sediments to the overlying water by laboratory measurement and numerical simulation.

## **2. Methods**

### 2.1. Site description

Jessie Lake is a 1,760-acre lake located in northwestern Itasca County, Minnesota, USA and entirely within the Chippewa National Forest (Fig. 1). The lake has a special layout of northwest-southeast orientation with a maximum fetch of 4.0 miles and shoreline length of 9.3 miles, which is in the line of the dominant wind direction. The

lake has a maximum depth of 42 ft with a mean depth of 22 ft and is stratified. The littoral zone (< 15 ft) is generally sandy and accounts for 26% of the surface area. The average elevation of Jessie Lake is 1,324.6 ft mean sea level, and has a recorded range from 1,327.00 to 1,323.57 ft msl. Monitoring equipment was positioned in the deepest area of the lake located in the northwest corner (Fig. 1). Substrate in this area consisted mostly of muck. Several sediment core samples were taken at this site.

The watershed of Jessie Lake is 15,834 acres and is within the larger Rainy River watershed, which flows north and empties into Hudson Bay. The watershed consists mostly of forest (60%) and wetland (24%), with some agricultural land (9%). Over 100 private residences and four resorts are located within the Jessie Lake watershed. Most of the homes are along the Jessie Lake shoreline, or within a short vicinity of the lake (Reed and Watkins, 1999). Weather data recorded from 1961 to 1990 show the area receives an annual average of 27.54 inches of rain with an average annual temperature of 38.8 °F and a growing season of 116 days.

## 2.2. Field measurement

In order to understand meteorological, water quality and hydraulic dynamics at the sediment-water interface of the Jessie Lake, a wind anemometer, a Sontek single-point acoustic-Doppler velocity probe (ADV) with a compass and tilt sensor, a Self-Contained Autonomous Microprofiler (SCAMP) and a Hydrolab multi-probe were used to measure wind velocity above water surface, three-component fluid velocity, temperature, dissolved oxygen, pH at about 20 cm above the sediment-water interface. The data were collected from July 24 to September 4, 2001.

### 2.3. Laboratory measurement

#### *Sediment core analysis*

Sediment samples were collected using a messenger-activated gravity core-sampler (Aquatic Research Instruments). The collected sediment cores were immediately transported to laboratory and sliced into small cakes with 1 and 2 cm vertical thickness for measurements of sediment physical properties, metal and phosphorus concentrations. To measure dissolved phosphorus in sediment pore water, the sliced sediment samples were immediately centrifuged at 3000 rpm for 20 minutes to separate the pore water from sediment particles. The pore water was then passed through 0.45  $\mu\text{m}$  polycarbonate membranes and the dissolved phosphorus concentration was measured using spectrophotometer at 880 nm according to Ascorbic Acid Method (Eaton et al., 1995).

To measure particular metal and phosphorus concentration, the sliced sediment samples were dried under forced air at 36°C/97°F, and ground in a mortar. Prepared sediment samples were stored in a desiccator. The analysis of metals was conducted by the Research Analytical Laboratory, University of Minnesota. After passing through plastic sieves, metals were extracted by shaking 3 g of sediment samples in a 30 mL of 1 N HNO<sub>3</sub> for 1 hour. The supernatants were centrifuged and then analyzed for Fe, Al, Mn, Cu, Zn, Cd, Ni, Pb, Cr and other metals by Inductively Coupled Plasma Emission Spectrometry (ICP-AES) (Dancer et al., 1998). To analysis the total phosphorus, the ground sediment samples were sieved through a 1.8 mm sieve, and 0.5 g of samples were then digested with a 10 mL concentrated HNO<sub>3</sub> in a 100 mL Teflon lined vessel. The vessels were heated for 5.5 min to 175 °C and then hold at 175- 180 °C for 4.6 min. The

digests were diluted to a final volume of 40 mL, centrifuged and analyzed for total phosphorus by Inductively Coupled Plasma Emission Spectrometry (ICP-AES) in the Research Analytical Laboratory, University of Minnesota (Dancer et al., 1998).

The fractionation of inorganic phosphorus was performed according to the chemical extraction method by Hieltjes and Lijklema (1980). Three categories of phosphorus with different mobile characteristics were measured. The method included two consecutive extractions for loosely bound phosphorus using a 50 mL 1M  $\text{NH}_4\text{Cl}$  for 2 hours. The residue was then extracted for Fe and Al bound phosphorus with a 50 mL 0.1 N NaOH for 17 hours, followed by a final extraction for Ca bound phosphorus with a 50 mL 0.5 N HCl for 24 hours. Each extractant was adjusted to pH 7.0, centrifuged at 3000 rpm for 30 minutes, and filtrated through a 0.45  $\mu\text{m}$  membrane. The concentration of phosphorus in each extractant was determined by Ascorbic Acid Method (Eaton et al, 1995). Organic phosphorus was roughly estimated by the difference between total and inorganic phosphorus.

### *Phosphorus flux simulation*

A laboratory setup (Fig. 2) consists of a sediment core with a water cylinder above the core. Both sides of the reaction chamber were sealed with rubber stoppers. At the top of the cylinder, inlet and outlet tubes provided manipulation ports for the oxygenation/de-oxygenation of water above the sediment cores. Sediment cores were collected at the sampling station in Jessie Lake on September 5, 2001. Water depth at the sampling site was about 12 m. The depth of sediment core collected was about 46 cm. Two simulation systems, reassembling aerobic and anaerobic conditions, were

investigated under the laboratory conditions. The lake water, which was collected at the sampling site, was filtered and loaded into the simulation systems. The cylinders were wrapped with an aluminum foil to prevent algal growth. The first simulation setup was oxygenated by bubbling air and the second simulation setup was deoxygenated by nitrogen gas. The setups were incubated at the room temperature of  $22 \pm 5$  °C for 17 days. During the incubation period, 5 mL water samples were collected at different intervals for dissolved phosphorus analysis (Eaton et al., 1995). The concentration of DO in the reaction systems was also monitored during the experimental procedure.

#### 2.4. Numerical simulation

A model consisting of six interrelated differential equations has been developed by Wang (1999) to study reactive phosphorus dynamics in aquatic sediments and to predict phosphorus release fluxes across the sediment-water interface. The model was validated by successful application to Chesapeake Bay, USA. As a case study for lake systems, the model is applied to Jessie Lake in this study. The model focused on the active sediment layer below the sediment-water interface, consisting of aerobic and anaerobic layers. The processes involved in the model include:

- the regeneration of phosphorus due to the decomposition of organic matter,
- the dynamic partitioning of phosphorus between the pore water and sediments due to sorption processes,
- the transportation of the dissolved and particulate phosphorus in sediments due to diffusion, bioturbation mixing and burial, and

- external regulating factors such as DO and temperature.

The general form of the Wang's model was expressed as:

$$\frac{d}{dt} [C_{ij}] = \frac{A_s}{V_s} \sum F_{ij}(C_{ij}, t) + \sum R_{ij} \quad (1)$$

where  $C_{ij}$  represents the concentrations of dissolved, exchangeable particulate and organic phosphorus ( $i = 1, 2,$  and  $3,$  respectively) in the aerobic and anaerobic layer ( $j = 1$  or  $2,$  respectively),  $t$  is time,  $F_{ij}$  represents the transport fluxes of individual phosphorus processes in and out of the defined aerobic and anaerobic layers, which are functions of  $C_{ij}$  and  $t,$  and  $R_{ij}$  represents the rates of decomposition and sorption reactions in the aerobic and anaerobic layers.

### 3. RESULTS

#### 3.1. Field measurements

The time series of the measured wind velocities at the lake surface displayed a diurnal variability ranged from 0 to 10 m/sec during July 24 to September 4, 2001. In response to the wind forcing, the water velocities above the sediment-water interface oscillated between  $-5$  cm/sec and 5 cm/sec. Small-scale (from a meter to a tenth of a millimeter) fluid motions and properties in Jessie lake were measured using the Self-Contained Autonomous Microprofiler (SCAMP). On deployment, the microprofiler descends at 0.1 m/s, while collecting temperature data at a rate of 100 samples per second from two pairs of sensors positioned 25 mm apart. The vertical temperature and microstructure measurements are given in Fig. 3. The temperatures at the sediment-water interface

ranged from 15°C to 18°C. The temperature oscillations in the water column were driven by the internal wave activities that were triggered by wind-forcing above the lake surface. The results indicate a stratified structure of temperature in the lake. A higher energy dissipation rate was observed at the epilimnion and hypolimnion zones.

pH measurements indicate a continuous increase from 7.4 to 8.2 above the sediment-water interface during the measurement period. DO concentrations measured were close to zero in most times, indicating an anoxic condition at the sediment-water interface during summers. Periodic fluctuations with maximum DO concentrations up to 2.2 mg/L were induced by intensive mixing events triggered by wind forcing above the lake surface.

### 3.2. Laboratory measurement

#### *Sediment core analysis*

Analysis of the sediment cores collected on August 14, 2001 indicates that Jessie Lake sediments have a relatively high water content, high porosity, and low density. The water content ranged from 89.21 to 94.29 %, while the porosity ranged from 88.82 to 93.74 %, and the density ranged 56.74 to 107.41 kg/m<sup>3</sup>. The concentration of metals in sediments versus sediment depth are shown Fig. 4. The metals measured included those have a strong affinity to phosphorus (Fe, Al, Mn, Mg and Ca), mineral nutrient metal (such as P, K), and trace metals. The concentrations of phosphorus-affinity metals ranged from 707.16 to 7326.0 mg/kg, the mineral nutrient metals ranged from 139.19 to 574.98 mg/kg, and trace metals ranged from 3.51 to 87.11 mg/kg.

### *Pore-water phosphorus*

The measurements of dissolved phosphorus in the sediments and at 5 cm above the sediment-water interface of Jessie Lake (Fig. 5) shows that pore water phosphorus concentrations decreased from the sediment surface to deep sediments. The highest concentrations were observed at the top 10 cm. The phosphorus concentrations in the top 10 cm remarkably increased from July to September 2001, showing a dynamic variation of phosphorus in the sediment pore water. Maximum concentrations ranged from 414.97 to 1092.02 ug/L. The observed overlying water phosphorus concentrations varied from 99.38 to 121.18 ug/L. As indicated in the figure, the resultant concentration gradients of phosphorus between the sediment and overlying water varied from 293.79 to 982.77 ug/L. The gradients drive a flux of phosphorus from sediments to the water column through pore water diffusion, bioturbation, and other transport processes.

### *Phosphorus fractionation*

The understanding of different species of phosphorus existing in sediments is important as it can provide information of phosphorus mobilization in sediments. The concentration profiles of obtained phosphorus fractions in Jessie Lake sediments is plotted in Fig. 6. The loosely bound phosphorus ranged from 0.75 to 22.21 ug/g DW. This fraction of phosphorus usually represents the labile form of readily releasable phosphorus. Fe and Al bound phosphorus ranged from 6.92 to 76.98 to ug/g DW, which is exchangeable between the particulate and dissolved phases through sorption processes. Ca bound phosphorus ranged from 41.94 to 70.77 ug/g DW, referring to the fraction that is fixed in sediments and may be lost into deep sediments through the burial process. The

total phosphorus concentrations ranged from 1179.1 to 2455.5 to ug/g DW. Remarkable spatial variability of these phosphorus fractions was evident in the top 10 cm of lake sediments.

Phosphorus fractions in the top 10 cm sediments of Jessie Lake (Fig. 7) show that the loosely bound labile phosphorus fraction accounts for only 0.8% of total phosphorus in Jessie Lake sediments, metal bound exchangeable phosphorus accounts for 2.9%, and Ca bound phosphorus accounts for 3.6%. The remaining 92.7 % is highly resistant insoluble phosphorus. The mobile inorganic phosphorus accounts very small portion in Jessie Lake and most of phosphorus is organic and resistant insoluble phosphorus.

#### *Phosphorus flux measurement*

Two experimental simulation systems with freshly collected sediment cores were incubated in laboratory over two weeks. The concentrations of dissolved reactive phosphorus (DRP) and DO in the water columns were monitored regularly (Fig.8). Under the aerobic condition, DRP in the water columns decreased from 37.17 to 19.30 ug/L and then kept relatively constant when DO was maintained in the range from 8.08 to 8.31 mg/L. After switching aeration gases (from oxygen to nitrogen), the DO in the aerobic chamber decreased from 8.24 to 0.38 mg/L. The corresponding DRP increased from 19.73 to 127.50 ug/L during the first 4 days. Under the anaerobic condition, however, DRP increased linearly during first 9 days from 52.33 to 632.07 ug/L when DO was kept at 0.69 to 0.26 mg/L and then appeared to increase slowly or keep constant. After switching aeration gases, DRP dropped from 619.69 to 165.81 ug/L when DO increased from 0.28 to 8.35 mg/L. The results indicate that DRP and its release flux from sediments

are sensitive to the DO concentration. Under the anaerobic conditions, DRP release from sediments was significant. Under the aerobic conditions, DRP in the water column settles to sediments. No DRP flux was observed under the aerobic condition.

The release flux of phosphorus were estimated according to the DRP concentration variations with time as:

$$J_{rel} = \frac{V_w}{A_s} \frac{\Delta(DP)_w}{\Delta t} \quad (2)$$

where  $J_{rel}$  is the phosphorus release flux ( $\text{mg}/\text{m}^2/\text{day}$ ),  $V_w$  is the total volume of the overlying water in the reaction chamber ( $\text{m}^3$ ),  $A_s$  is the area of the sediment-water interface of sediment cores ( $\text{m}^2$ ),  $\Delta(DP)_w$  is the concentration difference within a linear change, and  $\Delta t$  is the time span. The estimated flux of DRP from the sediment to the overlying water was  $16.93 \text{ mg}/\text{m}^2/\text{day}$  under the anaerobic condition.

### 3.3. Numerical modeling

#### *Model input and calibration*

The sediment phosphorus model developed by Wang (1999) was used to study phosphorus dynamics in Jessie Lake sediments and release fluxes across the sediment-water interface. The model input includes state parameters and external variables. The state parameters include those characterizing sediment properties, phosphorus transport, sorption and biodegradation coefficients in sediments. The external variables are forcing functions affecting the state of the sediment-water interaction, including depositional fluxes of organic matter from the overlying water onto sediments, dissolved phosphorus, oxygen concentrations and temperature at the sediment-water interface.

The state parameters input to the model are listed in Table 1, 2 and 3. Sediment porosity and density were measured based on the top 10 cm of sediment cores collected in Jessie Lake. The sediment oxygen consumption rate was determined according to the observed aerobic thickness at given DO concentrations (Wang, 1999). The organic depositional flux was measured according sediment accumulation using sediment cores in Center for Water and the Environment, University of Minnesota Duluth. The flux used in the model was  $12.6 \text{ mg P} / \text{m}^2/\text{day}$ , which was a average of measurements of 2000, 1997 and 1992 due to the fact that the value each year varied randomly. Other parameters were obtained either from literature or calibration. While the sorption partitioning parameters were calibrated, the sorption kinetic rates were obtained from the literature. The decomposition coefficients of organic phosphorus with different fractions were taken from the literature (Tables 2). The calibration was based on the organic phosphorus content, dissolved and exchangeable phosphorus concentrations measured in top 5 cm sediments. The Comparisons of the calibrated values of organic depositional flux and non-linear sorption partitioning parameters versus literature data are provided in Table 3.

#### *Short-term simulation*

Fig. 9 shows the simulated time-series of reactive phosphorus concentrations in Jessie Lake sediments from August 14 to September 6, 2001, including organic labile and refractory decomposable phosphorus (L-OP and R-OP), dissolved and exchangeable particulate phosphorus (DP and EP). The phosphorus concentrations simulated were relatively constant during the simulation period. The release flux of phosphorus across the sediment-water interface is a primary concern in modeling the water-sediment

interaction. Simulated phosphorus flux with measured DO concentrations are plotted in Fig. 10. During the three-week simulation period, the phosphorus flux ranged from 3.02 to 15.6 mg/m<sup>2</sup>/d. On August 25, 2001, the low flux corresponds to relatively high DO concentrations (1.09 mg/L) at sediment-water interface, caused by a windstorm. Increased DO concentration changed the redox potential of sediments from anaerobic to aerobic conditions. The magnitude of simulated phosphorus flux is close to 16.93 mg/m<sup>2</sup>/day that was obtained through experimental measurements under the laboratory conditions.

#### *Long-term prediction*

During a time span of decades, organic depositional loading is considered as a variable. The historic data were used to predict organic loading to Jessie Lake in next 30 years. This information is used as an input to the model for phosphorus internal loading simulation. The changes of the depositional loading with time was estimated according sediment accumulation rates measured using sediment cores in Center for Water and the Environment, University of Minnesota Duluth (Fig. 11) as

$$\text{From 1841 to 2000: } y = 0.0332 t + 5.9841 \quad (R^2 = 0.5616) \quad (3)$$

$$\text{From 1980 to 2000: } y = 0.2057 t - 19.627 \quad (R^2 = 0.6987) \quad (4)$$

where  $y$  is the organic depositional loading (mg/m<sup>2</sup>/d) at  $t$ , and  $t$  is time (year). The equations are based on about last 150 years and 20 years. Both cases were used for phosphorus internal loading prediction for next 30 years.

Fig. 12 shows the predictions of internal loading of phosphorus released from sediments to the overlying in Jessie Lake for the next 30 years. The predictions include the internal loadings according current condition I and II (based on Equation 3 and 4) and five hypothetical scenarios. The five scenarios assume the following conditions: a) organic loading remains unchanged, b) organic loading decreases annually by 1%, c) organic loading decreases annually by 5%, d) organic loading decreases annually by 10%, and e) organic loading decreases annually by 25%. The scenarios b) to e) reflect possible restoration measures in the Jessie Lake. Without any restoration initiative, the internal phosphorus loading in the next 30 years will increase from 13.0 to or 20.1  $\text{mg}/\text{m}^2/\text{d}$  if the organic loading was estimated based on about last 20 years, or from 13.0 to 13.8  $\text{mg}/\text{m}^2/\text{d}$  if the organic loading was estimated based on about last 150 years. The larger the reduction of organic loading the faster reduction in internal loading is evident. For example, the 25 % reduction in organic loading will reduce the phosphorus release flux almost to zero in the next 10 years.

## **4. Discussion**

### **4.1. Lake dynamic characteristics**

Jessie Lake has a northwest layout, which is in the line of the dominant wind direction. It is expected that the wind has an impact on lake water mixing. The measurements of wind velocities display a diurnal variability with a range from 0 to 10 m/sec. Meteorological forcing is the major mechanism that drives the lake dynamics

because the lake has no significant inflows and outflows. The measured water temperatures at 1, 3, 5, and 7 m located at the epilimnion layer respond directly to the diurnal heat and momentum input at the surface of the lake. The surface layer is considered to be an absorption layer that assimilates and redistributes the meteorological forcing in the entire lake. The water temperatures measured at 8 and 9 m in the region of strong stratification oscillate at different amplitudes and frequencies as the result of internal waves. Water temperatures below 10 m display uniform temperatures with episodic turbulent events. The vertical temperature and microstructure measurements indicate that a fluid mixing in a mean temperature gradient produces water temperature fluctuations because exported fluid particles retain their temperature during the overturn event.

Large two-sided temperature fluctuations indicate regions of vigorous mixing, and the sections with low temperature fluctuations indicate regions with a low activity in the water column. A higher energy dissipation rate was observed at the epilimnion and hypolimnion zones. For example, the energy dissipation rate of  $\varepsilon=1.3 \times 10^{-7} \text{ m}^2/\text{s}^3$  is estimated at the depth of 11.5 m. The high energy dissipation rates indicate significant mixing activities in these two zones, such as at water surface and above the sediment-water interface. Jessie Lake demonstrated an apparent stratified temperature structure, which prevent the mixing between epilimnion and hypolimnion. Therefore, energy and substance exchanges between two layers are low. This structure easily generates an anaerobic condition at the sediment-water interface. This characteristic is demonstrated by measurements of dissolved oxygen concentrations above the sediment-water interface, which were close to zero with periodic fluctuations up to 2.2 mg/L induced by periodic

mixing events due to wind-forcing above the lake surface. There is a turbulence existing at the sediment-water interface. The water velocities measured at this interface are in response to the wind forcing and oscillated between - 5 cm/sec and 5 cm/sec, which was generated by the internal waves in the lake. High fluctuations in the velocity field indicate intensive mixing activities at the sediment-water interface. The Jessie Lake is dynamics and easily forms an anaerobic condition due to its geographic and geomorphologic characteristics.

#### 4.2. Release potential of sediment phosphorus

In sediments, the concentrations of phosphorus-affinity metals ranged from 707.16 to 7326.0 mg/kg, the mineral nutrient metals ranged from 139.19 to 574.98 mg/kg, and trace metals ranged from 3.51 to 87.11 mg/kg. Table 4 provides a comparison of phosphorus-affinity metals in Jessie Lake versus other aquatic sediments worldwide. Jesse Lake has relatively low Fe, Al, and Ca concentrations in the sediments, indicating a low holding capacity of phosphorus in sediments. The phosphorus, regenerated in sediments from the decomposition of organic detritus of biomass, is easily released to the overlying water.

Jessie Lake sediments have a dynamic variation of pore water phosphorus concentration both temporally and spatially. Measured pore water phosphorus concentrations in the top 10 cm sediments remarkably increased from July to September. Maximum concentrations ranged from 414.97 to 1092.02 ug/L. One of the primary reasons responsible for the increase is the increasing temperatures from July to September, which enhanced biological processes. High dissolved phosphorus

concentrations were found at surface sediments. Low concentrations were in deep sediments and in the overlying water above sediment-water interface. The resultant concentration gradient of phosphorus between the sediment and overlying water varied from 293.79 to 982.77 ug/L. The gradients drive a flux of phosphorus from sediments to the water column through pore water diffusion, bioturbation, and other transport processes.

A loosely bound usually represents the labile form of readily releasable phosphorus. Fe and Al bound phosphorus is exchangeable between the particulate and dissolved phases through sorption processes. Ca bound phosphorus refers to the fraction that is fixed in sediments and may be lost into deep sediments through burial process. The residual phosphorus fraction, estimated as the difference between the total phosphorus and chemically extracted phosphorus, mostly consists of organic phosphorus (Ting and Appan, 1996). The Total phosphorus concentration in Jessie Lake sediments ranged from 1179.1 to 2455.5 to ug/g Dry Weight. The loosely bound phosphorus ranged from 0.75 to 22.21 ug/g DW. The Fe and Al bound phosphorus ranged from 6.92 to 76.98 to ug/g DW. The Ca bound phosphorus ranged from 41.94 to 70.77 ug/g DW. Those contents account for 0.8%, 2.9%, and 3.6% of total phosphorus, respectively. The remaining 92.7 % is highly resistant insoluble phosphorus, mostly consisting of organic phosphorus (Ting and Appan, 1996). The mobile inorganic phosphorus accounts very small portion in Jessie Lake and most of phosphorus is organic and resistant insoluble phosphorus. This organic phosphorus may generate labile inorganic phosphorus during the bio-decomposition processes (Wang, 1999).

Compared to other reported lake sediments (Table 5), Jessie Lake has an average total concentration of phosphorus in the sediments. However, the sediments have a high organic phosphorus content. The primary reason is primarily due to the low phosphorus-affinity metal concentrations such Fe and Al. The phosphorus regenerated in sediments from the decomposition of organic detritus of biomass is a continuous source for the internal loading in the lake. In sum, due to the low holding capacity of phosphorus and high storage of potential phosphorus sources in the sediments, Jessie Lake has a high potential for internal loading of phosphorus. There is a room to increase phosphorus-affinity metal concentrations so as to increase inorganic phosphorus fractions and reduce release flux in Jessie Lake. Sediment conditioning techniques such as chemical dosing of iron and aluminum salts can be a potential measure used to control the internal loading of phosphorus from the sediments.

#### 4.3. Simulation of phosphorus release fluxes

Laboratory simulations of phosphorus release from sediment to the overlying water using freshly collected sediment cores show that under the anaerobic conditions, phosphorus release from sediments was significant. The average release flux is 16.93 mg/m<sup>2</sup>/day. When the reaction system became aerobic, however, dissolved phosphorus in the water column settled to sediments. No release flux was observed under the aerobic condition. The release flux is sensitive to the dissolved oxygen concentration. The aeration technique can be, therefore, used to control the release flux of phosphorus in Jessie Lake during the summers.

Close to measured results of phosphorus from sediment cores, the numerical simulation of phosphorus dynamics also yielded relatively low reactive organic phosphorus concentrations compared with the total phosphorus. The main proportion of the organic phosphorus simulated in sediments is the non-degradable component. The comparisons of the simulated other phosphorus species with sediment core measurements are shown in Table 6. The results agree well with the measurements.

As a direct source for sediment phosphorus, the organic depositional loading from the overlying water to sediments sustains the release flux of the bio-available reactive phosphorus from the sediments to the overlying water. The long-term prediction shows that without any restoration initiative, the internal phosphorus loading in the next 30 years will increase from 13.0 to or 20.1 mg/m<sup>2</sup>/d if the organic loading was estimated based on about last 20 years, or from 13.0 to 13.8 mg/m<sup>2</sup>/d if the organic loading was estimated based on about last 150 years. However, if restoration initiatives are implemented to reduce overlying water biomass, the phosphorus internal loading will reduce corresponding to the reduction of the organic depositional flux. The larger the reduction of organic loading, the faster reduction in internal loading is evident. For example, the 25 % reduction in organic loading will reduce the phosphorus release flux almost to zero in the next 10 years.

Based on the study results, Jessie Lake has an average phosphorus release flux of 15.6 mg/m<sup>2</sup>/day under anaerobic conditions, a high potential source of internal phosphorus loading, a low phosphorus-affinity metal concentration, and a low holding capacity of phosphorus in sediments. We suggest a chemical and clay-dosing measure as a restoration method to increase phosphorus fixing capacity in sediments, and aeration

measure by diffused air to prevent anaerobic conditions at the sediment-water interface. Further studies are recommended to understand the efficiency of the chemical dosing in Jessie Lake.

#### **4. Conclusions**

1. Jessie Lake has a stratified temperature structure with high mixing at water surface and the sediment-water interface due to wind induced internal wave, which generated a fluid velocity fluctuated between  $\pm 5$  cm/sec during measurement period. The sediment-water interface was dominated with anaerobic condition in summer with occasional disruption by periodic mixing events induced by windstorm. During the measurement period, pH changed from 7.2 to 8.4.
2. Chemical analysis shows that the concentration of phosphorus-affinity metals ranged from 707.16 to 7326.0 mg/kg, represented by iron, aluminum, and calcium. In comparison to other lakes and reservoirs, Jessie Lake has relatively low phosphorus-affinity metal concentrations in the sediments, implying a low holding capacity of phosphorus in sediments.
3. The total phosphorus concentration ranged from 2455.5 to 1179.1 ug/g DW from the sediment-water interface to the 45 cm deep sediments. A loosely bound labile phosphorus fraction accounts for only 0.8% of the total phosphorus in Jessie Lake, while the metal bound exchangeable phosphorus accounts for 2.9%, and the Ca bound phosphorus accounts for 3.6%. The remaining 92.7% is organic phosphorus and highly resistant insoluble inorganic phosphorus. The Jessie Lake have a high potential

source of internal phosphorus loading due to low inorganic holding capacity and high organic pool in sediments.

4. The lake has dynamic dissolved phosphorus concentrations in sediments, varying temporally and spatially. Concentration gradients of phosphorus between the sediment and overlying water varied from 293.79 to 982.77 ug/L. The measured release flux of phosphorus from the sediments to the overlying water was 16.93 mg/m<sup>2</sup>/day under the anaerobic conditions. No release flux was observed under the aerobic conditions. This release flux is sensitive to the DO concentration in the water column.
5. Numerically simulated reactive organic and inorganic phosphorus concentrations are closed to measured values. The long-term simulation results indicate that if organic loading to the lake sediments continues at the rate observed in the past without any restoration initiative, the internal phosphorus loading in the next 30 years will increase from 13.0 to or 20.1 mg/m<sup>2</sup>/d if the organic loading was estimated based on about last 20 years, or from 13.0 to 13.8 mg/m<sup>2</sup>/d if the organic loading was estimated based on about last 150 years. However, if the organic loading is reduced with an implementation of restoration measures, the internal loading will decline gradually. The reduction in the organic loading of 1%, 5%, 10% and 25% will achieve reductions in the internal phosphorus to 13.0 mg/m<sup>2</sup>/d to 9.7, 3.0, 0.7, and 0 mg/m<sup>2</sup>/d, respectively in next 30 years.

## **Acknowledgments**

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Table 1

## Sediment characteristics and transport parameters used for model inputs

Parameters	Values
<u>sediment characteristics</u>	
<sup>1</sup> Density	71.44 kg/m <sup>3</sup>
<sup>1</sup> Porosity	92.84 %
<sup>2</sup> C/P ratio	41.0 mg C / mg P
<sup>2</sup> C/Chl <i>a</i> ratio	25 – 100 mg C / mg Chl <i>a</i>
<sup>1</sup> Sediment oxygen consumption rate	36.43 mg/m <sup>3</sup> /day
<u>Transport parameters</u>	
<sup>2</sup> Burial rate coefficients	1.37x10 <sup>-5</sup> m/day
<sup>3</sup> Effective diffusion rate coefficient at 20 °C	2.0x10 <sup>-4</sup> m <sup>2</sup> /day
<sup>4</sup> Temp. coefficient for diffusion	1.08
<sup>3</sup> Effective mixing rate coefficient at 20 °C	5.0x10 <sup>-5</sup> m <sup>2</sup> /day
<sup>4</sup> Temp. coefficient for mixing	1.117
<sup>4</sup> Ref. concentration of labile organic matter for mixing	50 g/m <sup>3</sup>
<sup>4</sup> Mixing half saturation coefficient for oxygen	4.0 g/m <sup>3</sup>

1. Measured
2. Di Toro (2001)
3. Wang (1999)
4. Di Toro and Fitzpatrick (1993).

Table 2

Literature parameters of Sorption and decomposition used for model inputs

Parameters	Values	
	Aerobic	Anaerobic
<sup>1</sup> Sorption rate constant (day <sup>-1</sup> )	22.8	1.4
<sup>2</sup> Labile fraction		0.65
Refractory fraction <sup>2</sup>		0.15
<sup>3</sup> Decomposition rate constants at 20 °C for labile fraction (day <sup>-1</sup> )	0.0378	0.0253
<sup>3</sup> Decomposition rate constants at 20 °C for refractory fraction (day <sup>-1</sup> )	0.0049	0.0037

1. Olila (1992)
2. Di Toro and Fitzpatrick (1993)
3. Wang (1999)

Table 3

Calibrated parameters of sorption partitioning for model inputs

Parameters	Calibrated	Estimated/literature values
Sorption isotherm constant	7.5	13**
(L/mg)	2.4	2.6**
Sorption capacity	0.90	0.7**
(mg/g)	0.13	0.4**

\* Estimated using field measurements of chlorophyll *a* concentration.

\*\* Furumai and Ohgaki.(1989)

Table 4

Comparison of phosphorus-affinity metals in Jessie Lake versus other aquatic sediments (g/kg)\*

Watersheds	Fe	Al	Mn	Ca	Mg	Reference
Lake Jessie, USA	6.53	1.61	1.50	16.09	5.98	This study
Okeechobee Basin, USA	1.62	1.11	2.94	-	0.34	Reddy et al., (1995)
14 Wisconsin lakes, USA	26.53	28.73	0.99	-	-	Williams et al., (1971)
Alton Water reservoir**, UK	95.50	-	-	133.25	-	Perkins & Underwood, (2000)
Lake Erie, Canada	38.22	-	0.87	-	-	Williams et al., (1976)
Kranji reservoir	34.73	-	0.23	-	-	Ting & Appan (1996)

\* The data are mean values.

\*\* The input water in reservoir was dosed with ferric sulfate to control extern phosphorus loading.

Table 5

Comparison of phosphorus composition between Jessie and other lakes (L-P is the labile phosphorus, Fe-P is the Fe & Al bound phosphorus, Ca-P is the Ca bound phosphorus and Res-P is the residual phosphorus)

Lake	Total P (mg/kg)	Chemical extraction fraction (%)				Reference
		L-P	Fe-P	Ca- P	Res-P	
Lake Jessie, USA	1579	0.8	2.9	3.6	92.7	This study
Okeechobee Basin, USA	72-1079	0.1-2.3	20.0- 70.1	13.0- 50.0	43-51	Reddy et al., (1995)
14 Wisconsin lakes, USA	580- 7000	-	-	-	20.3- 37.0*	Williams et al., (1971)
Lake Erie, Canada	188- 2863	-	-	-	0.8- 26.4*	Williams et al., (1976)
Kranji reservoir, Singapore	1885- 1640	0.4-0.5	53.0- 63.0	6.6-8.5	28.2- 39.2	Ting & Appan (1996)

\* Total organic fraction.

Table 6

Comparison of the model calibrations versus field measurements

Parameters	Calibrated using our model (Mean)	Estimated using our measurements
Reactive organic phosphorus ( $\text{g/m}^3$ )	23.0	14.4 – 20.8
Dissolved phosphorus ( $\text{g/m}^3$ )	1.0	0.4 – 1.1
Exchangeable particulate phosphorus ( $\text{g/kg}$ )	0.092	0.078 – 0.099
Release flux ( $\text{mg/m}^2/\text{d}$ )	15.6	16.9

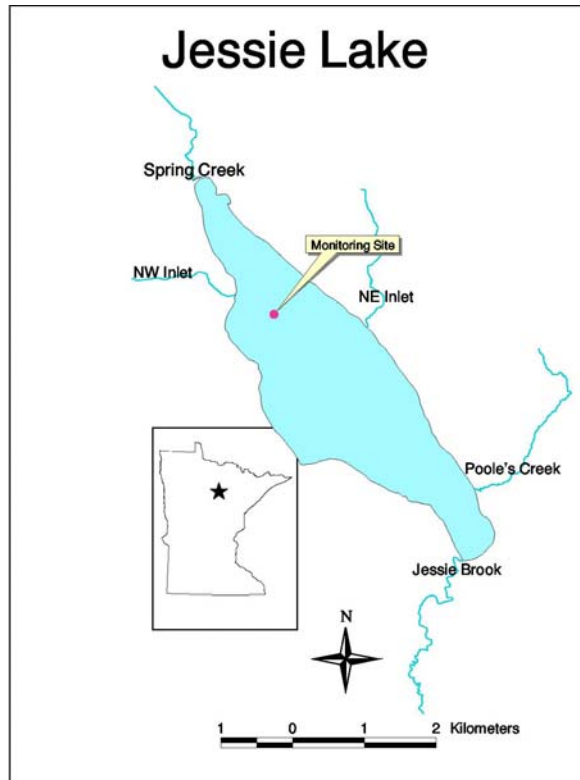


Fig. 1. Jessie Lake: Geographical location and monitoring site

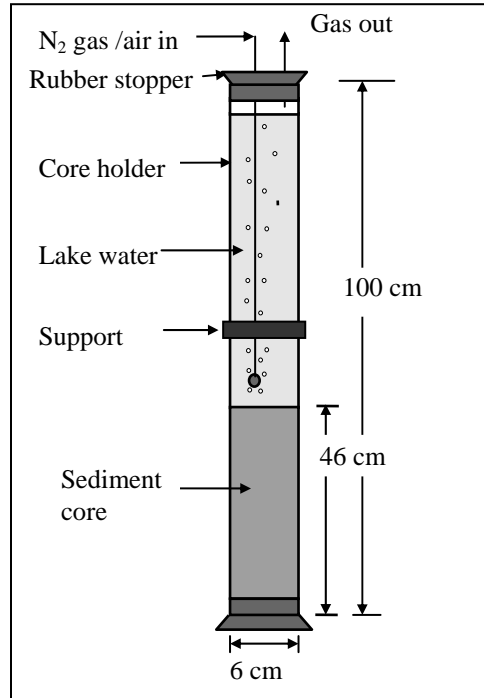


Fig. 2 Experimental setup

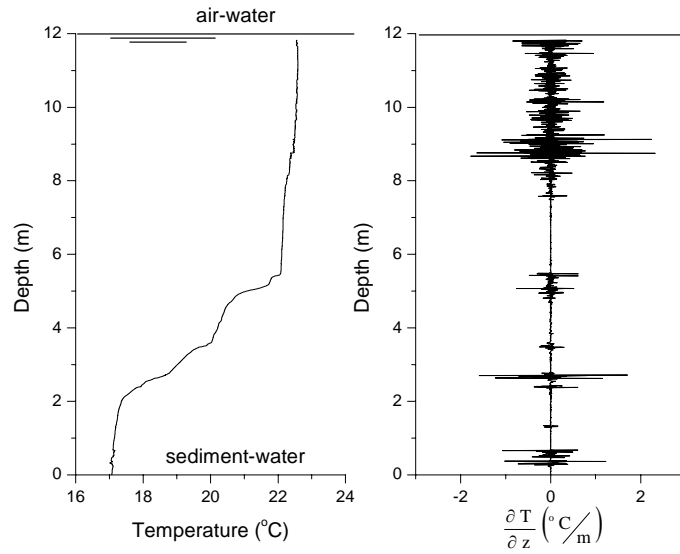


Fig. 3. Water temperature with water temperature gradients measured by the SCAMP in Jessie Lake on August 16, 2001 at 12:30 p.m.



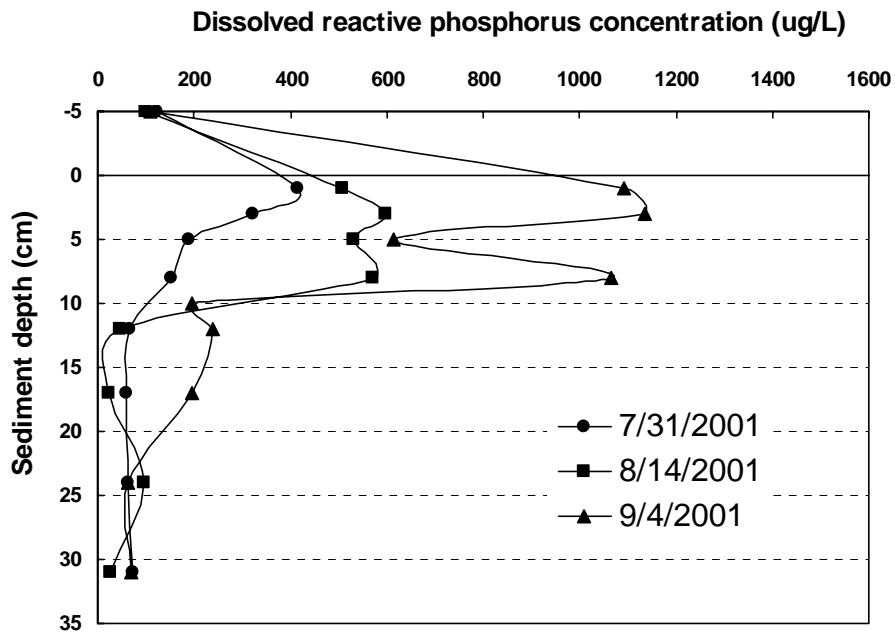


Fig. 5. Concentration profiles of dissolved phosphorus in Jessie Lake sediments

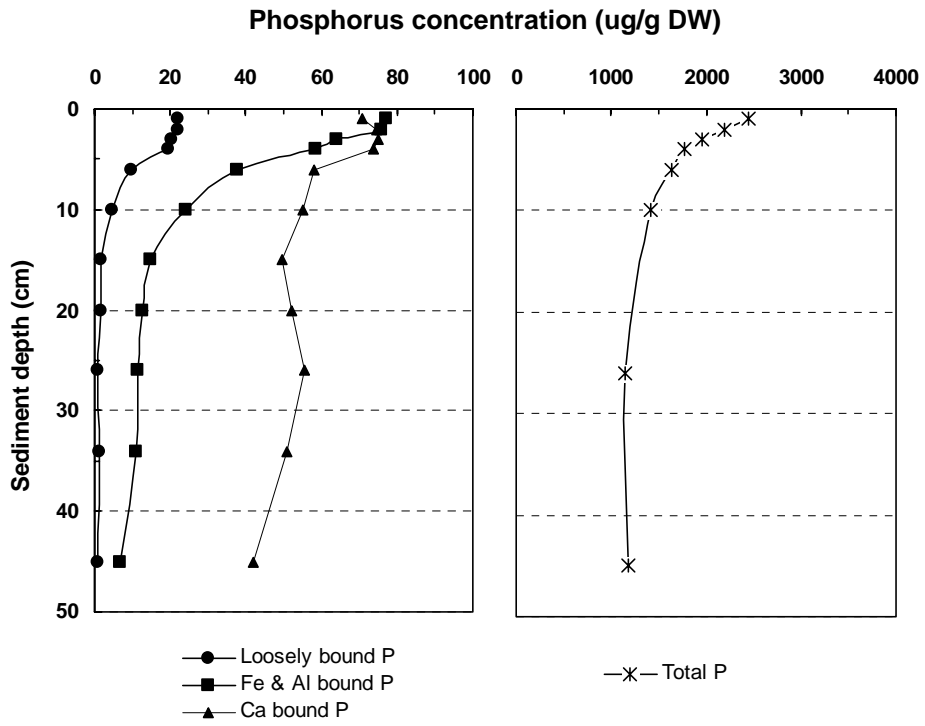


Fig. 6. Concentration profiles of particulate phosphorus fractions in Jessie Lake sediments

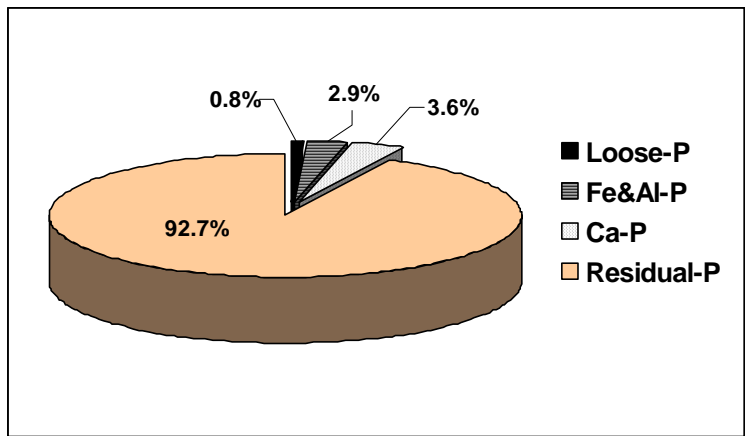


Fig. 7. Phosphorus species in Jessie Lake sediments

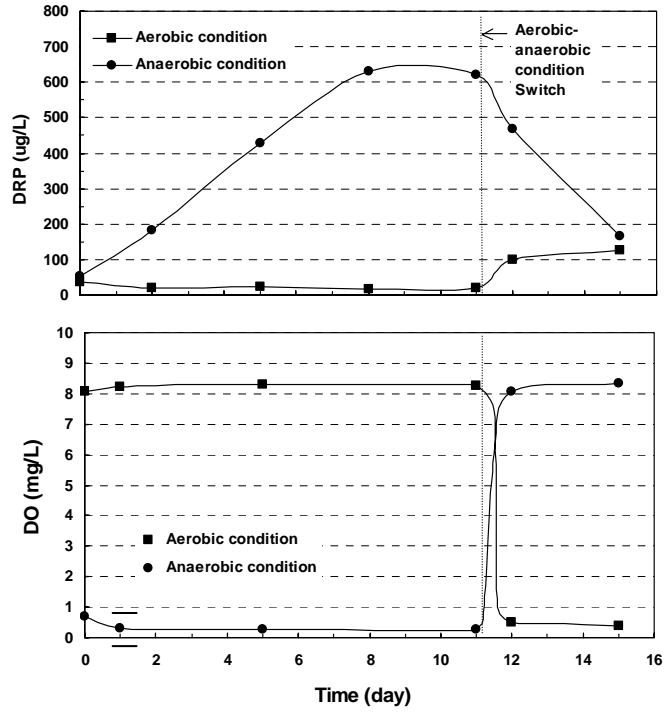


Fig. 8 Release processes of dissolved reactive phosphorus (DRP) from sediment cores to water column. The sediment cores were collected on September 5, 2001.

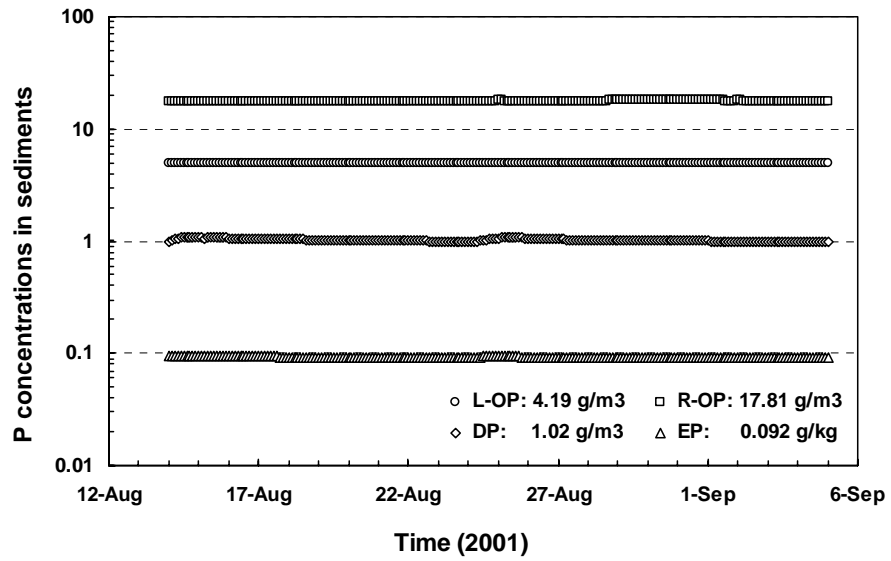


Fig. 9. Simulated reactive organic phosphorus concentrations of labile and refractory decomposition fractions (L-OP and R-OP), pore water and exchangeable particulate phosphorus concentrations (DP and EP).

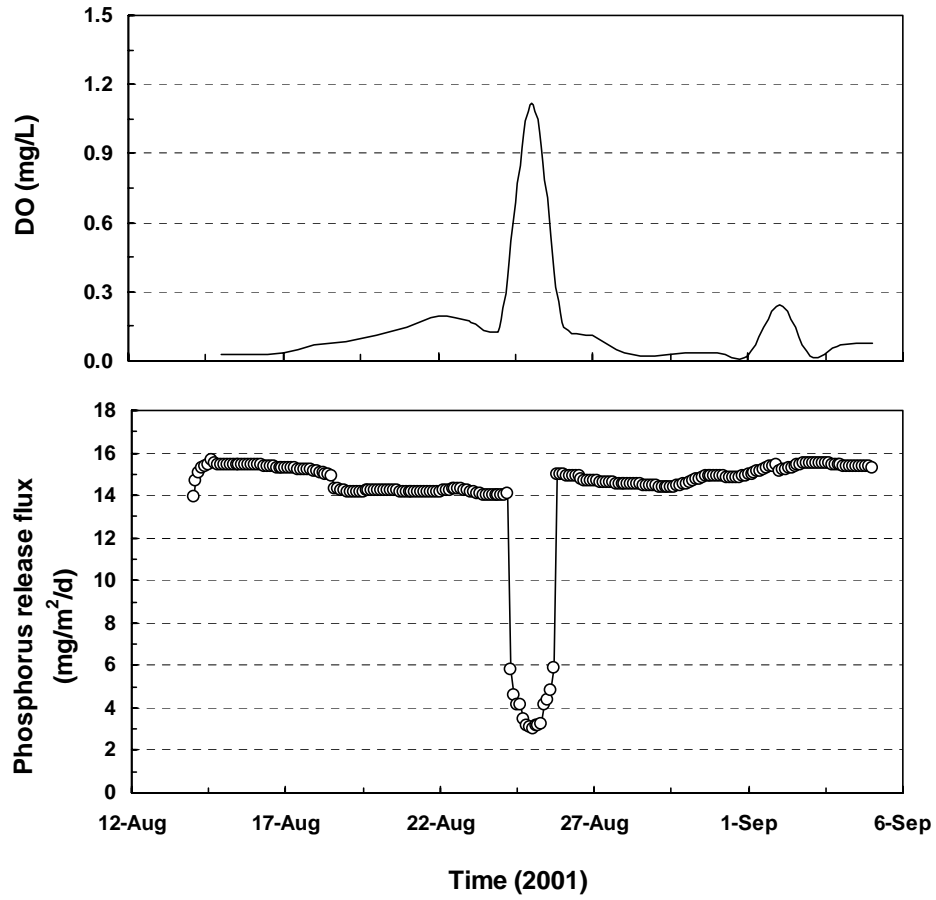


Fig. 10. Simulated release flux of phosphorus and measured DO concentrations from August 14 to September 6, 2001, Jessie Lake

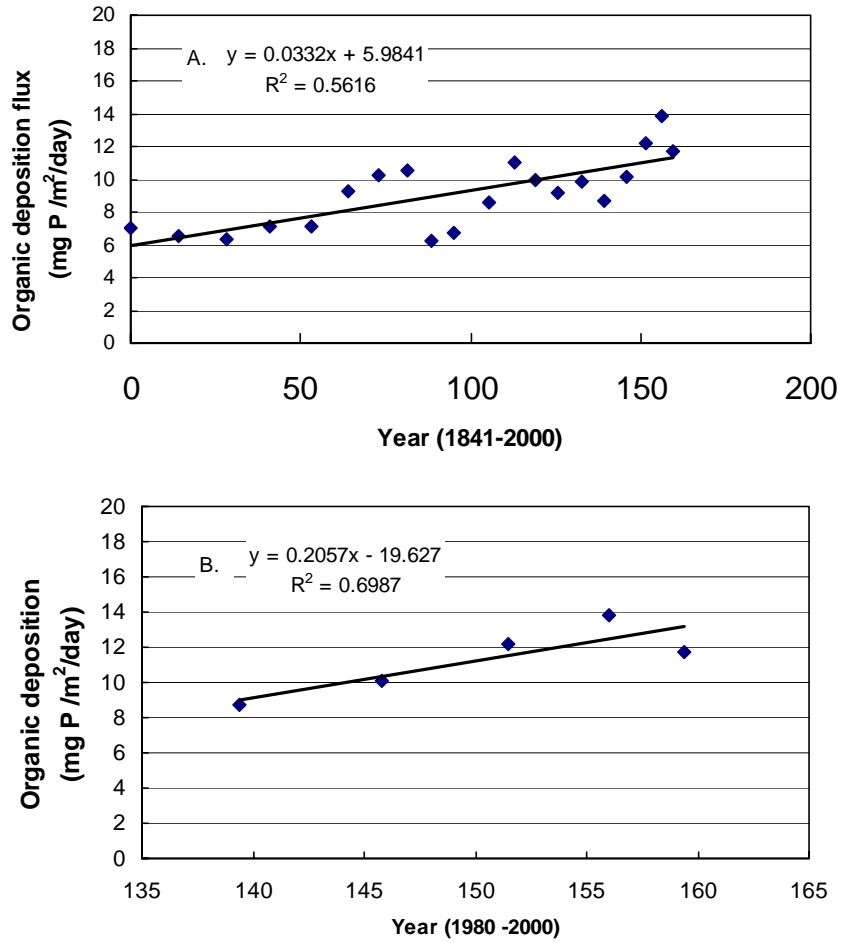


Fig 11. Changes of organic loading with time in Jessie Lake. A: Organic loadings from 1841 to 2000, B: organic loading from 1980 to 200.

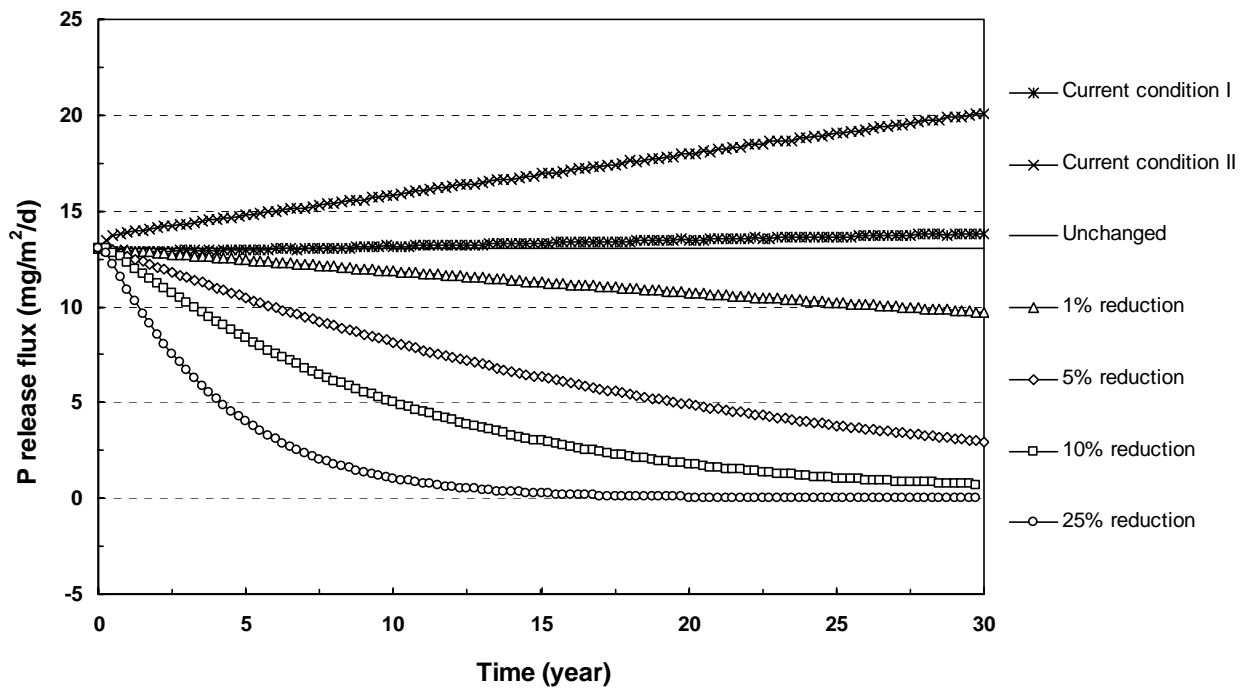


Fig. 12. Long-term predictions of internal loading of phosphorus released from sediments to the overlying in Jessie Lake for the next 30 years (Current condition I: organic deposition was estimated based last 20 years. Current condition II: organic deposition was estimated based last 150 years)

**University of Minnesota planned field measurements:**

Benthic boundary mixing and phosphorus dynamics will be investigated by conducting field measurements in Jessie Lake. In August, we will collect the following data:

- a) water temperatures, every 6 seconds, from the lake surface to lake bottom(10m);
- b) wind speeds, every 6 seconds, above the lake surface;
- c) 3-D velocity fields, every second, above the lake bottom;
- d) microstructure temperature, oxygen, and pH profiles measured with a self-contained microstructure profiler;
- e) and dissolved oxygen and pH, every 600 seconds, measured at the sediment water interface with the Hydrolab probe.

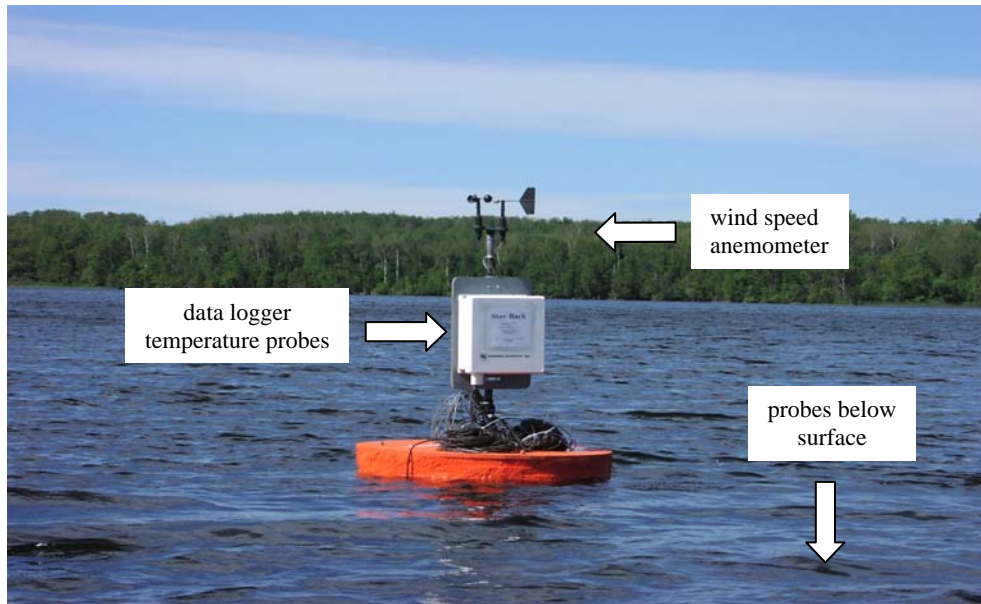


Fig. 1 Jessie Lake Experimental Setup.