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THE SIGNIFICANCE OF PHOSPHORUS RELEASED FROM THE SEDIMENT UNDER ANOXIC CONDITIONS IN SODUS BAY, N.Y.

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Summary

The goal of this study was to evaluate the loss of phosphorus from the sediment to the anoxic hypolimnion of Sodus Bay, New York. Total phosphorus (TP) and soluble reactive phosphorus (SRP) concentrations were monitored weekly throughout the water column in Sodus Bay from 16 May 2001 to 22 September 2001. Increased amounts of TP and SRP into the hypolimnion, during periods of hypolimnetic anoxia, indicated that phosphorus was being released from the sediment. On an annual basis, the sediments contributed 600 kg of phosphorus to Sodus Bay (24 kg/d x 25 days, from 8/18 to 9/12) in 2001. This is 7.5% of the annual input of phosphorus to Sodus Bay from the watershed (8,004 kg P, annual average from 1989 to 1994). If the period of anoxia in the hypolimnion is considered (25 days in the late summer), the amount of phosphorus released by the sediments into the hypolimnion is still 600 kg but the amount entering from the watershed is 123 kg of P. That is, phosphorus release into the hypolimnion is 488% greater than the amount entering from the watershed during this period of the year. Since the sediment is releasing phosphorus at a time when inputs from the watershed are minimal, phosphorus inputs from the sediments may prove to be a more important factor in the stimulation of late summer algal blooms than inputs from the watershed.

Introduction

Sodus Bay, located 24 miles southwest of Oswego and 28 miles east of Rochester, is one of Lake Ontario's few natural harbors. Sodus Bay has a surface area of 13.79 km^2 (Makarewicz and Lewis, 1990). The bay has extensive development along much of its shoreline, and is currently in a eutrophic state (Wayne County, 1993). During late summer, Sodus Bay often experiences impressive algal blooms, inconveniencing those who use the bay for recreation.

Phosphorus is generally realized as the limiting nutrient controlling algal growth in most freshwater systems (Wetzel, 2001). In freshwater lakes, the most effective means of reducing productivity is usually obtained by decreasing algal growth through the reduction of phosphorus inputs (Wetzel, 2001). During stratification, lakes with anoxic hypolimnia often accumulate total phosphorus in the hypolimnion (Nurnberg, 1984, 1987). That high concentrations of reduced substances are usually present in the hypolimnion under such conditions suggest that much of this phosphorus is released from the anoxic sediment surface, through redox reactions (Nurnberg, 1987). Laboratory release experiments have also suggested that under anoxic condition, lake sediments will release significant amounts of phosphorus into the water column (Nurnberg, 1984; Mortimer 1941). If this surplus of hypolimnetic phosphorus is transported vertically to the euphotic zone it may stimulate algal growth (Cooke *et al.*, 1977).

From past studies, it is known that during late summer stratification the hypolimnion of Sodus Bay becomes anoxic with elevated concentrations of phosphorus (Makarewicz and Lewis, 1990) (Wayne County, 1993). However, the relative importance of phosphorus regeneration from the sediment compared to inputs of phosphorus from the watershed was not known. The purpose of this study was to quantitatively evaluate the level of release of phosphorus from sediments to the hypolimnion and, if possible, any transfer from the hypolimnion to the epilimnion.

Methods

General

Samples were taken weekly at Sodus Bay from May 16, 2001 through September 22, 2001. A SUNY Brockport research vessel, docked at the private residence of David Scudder of LeRoy Island, was used to gain access to the sampling location.

Water samples were taken from the deepest part of the central basin of Sodus Bay at meter intervals from a moored boat. Within one meter of the sediment, samples were taken at one-half meter intervals in order to provide higher resolution near the water-sediment interface. Samples were collected with a horizontal Van Dorn water bottle and stored in dark polyethylene bottles. Immediately after sampling, a sub-sample was filtered through a 0.45-micron filter for soluble reactive phosphorus and nitrate + nitrite analyses.

Water Chemistry

Dissolved Oxygen: Dissolved oxygen was measured in the field, at meter intervals using the azide modification of the Winkler method (APHA, 1999).

Temperature/Conductivity: Temperature and conductivity were measured *in situ* at meter intervals with a YSI temperature-conductivity probe.

Transparency: Secchi disk readings were taken before sampling from the shaded side of the boat.

pH: Within six hours of sampling, samples were analyzed for pH using a Beckman meter standardized daily using two buffers (4.01 and 9.18)

Chlorophyll-a: Within six hours of sampling, chlorophyll-*a* was determined by extract and/or raw water fluorometric methods (APHA, 1999).

Soluble Reactive Phosphorus: Analysis was performed using the automated (Technicon) colorimetric ascorbic acid method (APHA, 1999).

Total Phosphorus: The persulfate digestion procedure was used prior to analysis by the automated (Technicon) colorimetric ascorbic acid method (APHA, 1999).

Nitrate + Nitrite: Dissolved nitrate + nitrite nitrogen analyses were performed by the automated (Technicon) colorimetric cadmium reduction method (APHA, 1999).

Physical Measurements

Basin Area: Isopleth area data was taken from a previous study (Makarewicz and Lewis, 1990) to construct a hypsographic curve (Figure 1). Areas were read directly off the hypsographic curve.

Results and Discussion

Thermal Stratification and Dissolved Oxygen

Two periods of thermal stratification were observed is Sodus Bay during the summer 16 May until 11 July, and 25 July until 15 September. The summer thermal stratification of the water column that normally sets up in Sodus Bay is often overcome by energy from winds that cause the Bay to partially or completely mix. When calmer conditions return thermal stratification is re-established until eroded by again by wind energy or cooler temperatures in the fall. Consequently, Sodus Bay may be stratified and mixed a number of times during a warm weather season depending on the weather conditions.

From 16 May until 6 June abundant dissolved oxygen (DO) concentrations (> 8 mg/L) were observed throughout the hypolimnion (Figure 2). After 6 June, hypolimnion levels decrease reaching a minimum observed concentration of 2.1 mg/L of DO at 13m on 18 July. Between 18 July and 25 July, an increase of 4.1 mg/L of DO was observed at the 13m depth (Figure 2). Between 11 July and 18 July, a mixing event eroded the thermocline resulting in nearly isothermal conditions throughout the water column (Figure 2). The weakening of thermal stratification allowed oxygen rich water from the upper levels of the water column to be mixed into the oxygen poor water of the hypolimnion.

After 25 July, Sodus Bay once again became thermally stratified and DO concentrations in the hypolimnion decreased until anoxia was observed in the hypolimnion on 22 August (Figure 2). After 22 August the hypolimnion gradually decreased in area as the thermocline moved down in the water column. The erosion of the hypolimnion accelerates after 25 August, and by 15 September temperatures and DO concentrations are nearly even throughout the water column (Figure 2).

Stratification Period 1 (16 May to 25 July)

Between 11 July and 18 July, when the lowest DO concentration of the first stratification period was observed, there is a sudden increase in hypolimnion total phosphorus (TP) concentrations (Figure 3). After 18 July, TP concentrations in the hypolimnion increase (Figure 3).Soluble reactive phosphorus (SRP) profiles show this trend even more clearly (Figure 4). On 3 July when dissolved oxygen concentrations fall below 3 mg/L in the hypolimnion, SRP concentrations in the hypolimnion begin steadily increasing (Figure 4). Concentrations of SRP in the hypolimnion continue to increase reaching an observed maximum on 18 July (Figure 4). Between 18 July and 25 July, when a sudden increase was observed in DO concentrations in the hypolimnion, there is a decline in the concentrations of SRP in the hypolimnion (Figure 4). By 1 August SRP concentrations are nearly even throughout the water column (Figure 4).

As DO concentrations in the hypolimnion decrease, both TP and SRP concentrations in the hypolimnion increase. This observation indicates that phosphorus is being released into the hypolimnion from the sediment during periods of low DO content in the hypolimnion.

Stratification Period 2 (25 July to 15 September)

The correlation between DO and phosphorus concentrations in the hypolimnion is even more apparent during the second period of thermal stratification when DO fell to very levels in the hypolimnion from 15 August until 8 September (Figure 4). During this period, an increase in SRP and TP concentrations is observed (Figures 3 and 4). TP and SRP concentrations in the hypolimnion reach an observed maximum on 8 September (Figure 3 and 4) of 648.9 µg/L and 265.2 µg/L, respectively. Between 8 September and

15 September the bay mixes and a dramatic decrease in hypolimnetic phosphorus concentrations is observed (Figures 3 and 4).

During the second stratification period there is an increase of average epilimnion TP concentrations from 16.5 µg P/L on 8 August to 34.5 µg P/L on 8 September (Figure 3). From 8 August to 8 September SRP concentrations decrease to non-detectable levels in the epilimnion (Figure 4) due to uptake by phytoplankton. After 25 August the hypolimnion begins to erode causing increasing SRP concentrations in the epilimnion until an average epilimnion SRP concentration of 6.0 µg P/L is observed on 8 September (Figure 4).

Phosphorus Content

The phosphorus content (kg) of Sodus Bay was calculated by dividing the basin into 1-meter horizontal strata and multiplying the phosphorus concentration of each stratum by its volume. Similarly, amounts of phosphorus in the hypolimnion, metalimnion, and epilimnion were calculated in a similar manner using appropriate depth intervals.

The time interval (8 August to 8 September) represents a period where oxygen values began to decrease in the hypolimnion to the mixing period where oxygen levels are elevated again (Figure 2). During this period, the TP content of the entire lake increased by 1,097 kg (Figure 5). After 25 August, the thermocline gradually moves further down the water column until complete mixing occurs (Figure 2). Since precipitation was minimal during the period and input from the watershed was not large enough to account for the increase, we infer that nutrient rich water from the lower depths of the bay was circulated into the epilimnion (Figure 3).

The entire TP content of the bay increased from a minimum value of 1,406 kg P on 8 August to a maximum value of 2503 kg P on 8 September (Figure 5).

Estimating the Loss of Phosphorus from the Sediments to Sodus Bay

After 22 August the hypolimnion begins to slowly erode, exporting its phosphorus rich waters to the upper levels of the bay (Figures 3 and 4). The increase in the hypolimnion TP content from the week previous to the decline in hypolimnion DO (15

August) to the peak hypolimnion content (25 August) is considered to be the amount of phosphorus released by the sediments into the hypolimnion during the interval between the two dates. Similar calculations were done for various time periods (Table 1) and averaged to yield a phosphorus release rate from the sediment of 24.00 kg P/d (Table 1). The annual amount of phosphorus released by the sediments into the hypolimnion was calculated as 600 kg P by multiplying the phosphorus release rate by the 25 days that anoxia was observed in the hypolimnion this summer (Table 2). The annual TP loading from the watershed based on the average for 1989 to 1994 was calculated as 8,004 kg P by multiplying the watershed release rate (Table 1) by 365 days (Table 2, Makarewicz and Lewis 1990).

In order to compare internal loading from the sediment with external loading from the watershed, areal weighted phosphorus release rate was calculated to be 0.36 mg TP/m^2/d for the summer stratification period and 1.59 mg TP/m^2/d on an annual basis (Table 2). This rate reflects the amount of phosphorus released from the
sediment per square meter of the basin's surface area per day of stratification. An annual release rate was determined to be 0.05 mg TP/m^2/d (Table 2). This rate reflects the annual release of phosphorus from the sediment per square meter of the basin's surface area over 365 days.

Mass Balance

A mass-balance analysis for phosphorus was performed for the Sodus Bay ecosystem both on an annual basis and during the summer stratification period. Annual phosphorus loss from the Sodus Bay watershed was monitored from 1989 to 1994. During the period 1992 to 1994 only Sodus Creek East was monitored, but this creek provided 94% of the total phosphorus from the entire watershed during 1990 to 1992 (Makarewicz and Lewis 1989, 1990, 1991 Makarewicz *et al*. 1992, 1993 and 1994).

Summer Mass Balance:

Sodus Bay's phosphorus content increased at a rate of 38.0 kg P/d from 8 August to 8 September 2001 (Figure 5). This value is represents the sum of the loss of

Table 1: Sources of phosphorus entering the Sodus Bay. TP = total phosphorus. Watershed total phosphorus loading data was taken from Makarewicz and Lewis 1989, 1990, 1991 Makarewicz *et al*. 1992, 1993 and 1994. * = only Sodus Creek – East was monitored. The areal release rate is normalized by the surface are of the top of the hypolimnion.

Source and Period	Release Rate (kg TP/d)	Areal Release Rate (mg TP/m^2/d)
P loss from sediment to Sodus Bay		
8/15 – 8/22 2001	25.12	5.93
8/22 – 8/25 2001	22.53	6.41
8/15 – 8/25 2001	24.34	6.61
Average	24.00	6.32
Loss from the watershed	Annual (kg/d)	Summer (kg/d)
Annual 1989-90	7.98	0.68
Annual 1990-91	23.22	0.33
Annual 1991-92	27.59	1.03
Annual 1992-93*	34.58	18.40
Annual 1993-94*	16.27	4.07
Average	21.93	4.90

Table 2. Loss of phosphorus from the sediment to the hypolimnion and from the watershed of Sodus Bay. The areal rates are normalized by the surface area of Sodus Bay.

		Weighted Release Rate	
	Annual P Release (kg TP)	During Stratification (mg TP/m^2/d)	Annual Rate (mg TP/m^2/d)
Sediment	600	6.32	0.05
Watershed	8,004	O.36	1.59

phosphorus from the sediment to the water column, the loss of P from the watershed, direct drainage (including septic systems) and direct deposition through rainfall. We estimate the rate of phosphorus release from the sediments to the water column is 24.0 kg P/d during the period of hypolimnetic anoxia (Table 1). Phosphorus input from the watershed is estimated at 4.9 kg/d for the summer period over six consecutive years (1989-1994) (range = 0.68 to 18.4 kg/d) (Table 1, Figure 6). The difference (9.1 kg/d) between the increase in phosphorus content in the lake minus the input from sediment and the watersheds represents a crude estimate of phosphorus entering the Bay from direct drainage, septic systems, rainfall, etc.

On an annual basis, the sediments contributed 600 kg of phosphorus to Sodus Bay (24 kg/d x 25 days, from 8/18 to 9/12) in 2001. This is 7.5% of the annual input of phosphorus to Sodus Bay from the watershed (8,004 kg P, annual average from 1989 to 1994). If the only the period of decreased oxygen in the hypolimnion is considered (25 days in the late summer), the amount of phosphorus released by the sediments into the hypolimnion is still 600kg but the amount entering from the watershed is 123 kg of P. That is, phosphorus release into the hypolimnion is 488% greater than the amount entering from the watershed during this period of the year. Since the sediment is releasing phosphorus at a time when inputs from the watershed are minimal, phosphorus inputs from the sediments may prove to be a more important factor in the stimulation of late summer algal blooms than inputs from the watershed.

Comparison to Other Lakes

A weighted release rate was calculated (6.32 $mg/m^2/d$) for Sodus Bay reflecting the amount of phosphorus released from the sediment per square meter of the hypolimnion surface area per day to allow comparisons with release rates compiled by Nurnberg (1984) (Table 3).

The phosphorus release rates in Table 3 were estimated from *in situ* phosphorus studies in a manner similar to how the Sodus Bay phosphorus release rates were estimated. Sodus Bay has a phosphorus release rate in the lower range of internal loading compared to other lakes (e.g., West Twin, East Twin, Erie; Table 3).

Table 4 gives phosphorus release rates estimated from sediment core tube samples (containers used to hold sediment samples under experimental conditions) from both anoxic and oxic sediments in various lakes (Nurnberg, 1984). Again internal loading of phosphorus occurs in Sodus Bay is greater than or comparable to St. Gribsoe Lake, Grand Langose Lake, Trummen Lake, Vombjoen and Mohegon Lake (Table 4). To summarize, Sodus Bay release rates (P/m^2/day) from the sediments to the hypolimnion are in the low range when compared to other lakes whether calculated by the whole-lake method or by the core-tube method.

Table 3: Estimates of phosphorus release rates from lakes of the world with anoxic hypolimnions. Release rates are calculated in a manner similar to this study. Negative release rates indicate absorption of phosphorus by sediment. Data are reproduced from Nurnberg, 1984.

Lake	Release Rate (mg P/m^2/d)
Shagawa	12.1
Mendota	10.8
West Twin	6.5
East Twin	6.0
Erie	7.4
White Lake	19.0
Barten Broad	9.6
Alderfen Broad	20.0
Baldeggersee	9.7
Rotsee	28.0
Norrviken	9.2
Bergundasjoen	24.5
Esrom	11.5
Byoesjoen	20.0
Magog	13.5
Sodus Bay	6.3
Mean	13.4
Standard Error	1.8
Median	11.2
n	21

Epilimnetic Phosphorus and Chlorophyll

Clearly, epilimnetic levels of phosphorus start to increase with the onset of hypolimnetic deoxygenation (Figure 7). Although not a strong relation, levels of phytoplankton increase in the Bay as soluble reactive phosphorus increase (Figure 8). This suggests that phytoplankton blooms in Sodus Bay are probably related to release of phosphorus from sediments during anoxic conditions in the hypolimnion.

Table 4: Estimates of phosphorus release rates from lakes of the world. Release rates are estimated from core tubes. Negative release rates indicate absorption of phosphorus by sediment. Data are reproduced from Nurnberg, 1984.

Lake	Release Rate	
	Anoxic ($mg/m^2/d$)	Oxic ($mg/m^2/d$)
White	34.3	-
Ursee	11	-
Furosoe	17.3	-4.5
Esrom	12.3	-1.4
St. Gribsoe	1.2	0.2
Grand Langsoe	0.8	0.6
Bergundasjoen	34	-
Alderfen Broad	20	0
Mohegon	3	0
Glanningen	18	2
Ramsjoen	20	0.3
Ryssbysjoen	20	0.7
Charles East	31	-16
Stone	32	-
Trummen	1.5	0.3
Arungen	16	1.0
Vombsjoen	6	2.6
Byoesjoen	27	7
Norrviken	10	5
Ontario	-	0.2
Memphremagog	10	-
Mean	16	-0.01
Standard Error	2.5	1.32
Median	15	0.3
n	20	15

Treatment Potential

Application of alum to deep water sediments has been used to “permanently” trap sediment phosphorus, and thereby reduce the release of phosphorus from the sediments. The Monroe County Environmental Health Lab reported a 77% reduction in hypolimnetic phosphorus accumulation rates since the treatment of deep water sediments with alum in Irondequoit Bay (Monroe County Environmental Health Lab, 2001). Polymictic lakes such as Sodus Bay often benefit significantly from alum treatment

(Cooke, 1993). Rapid siltation rates can decrease the effectiveness of alum treatment by covering the trapped sediments with new materials from which internal loading can resume (Gilman, 2001). Careful attention must be paid to the dosage of alum used, since high concentrations of alum can have toxic side effects (Gilman, 2001). Oxygen supplementation was also used to reduce the release of phosphorus from the sediments, increase precipitation of phosphorus from the water column, and to create a zooplankton protection zone (Monroe County Environmental Health Lab, 2001).

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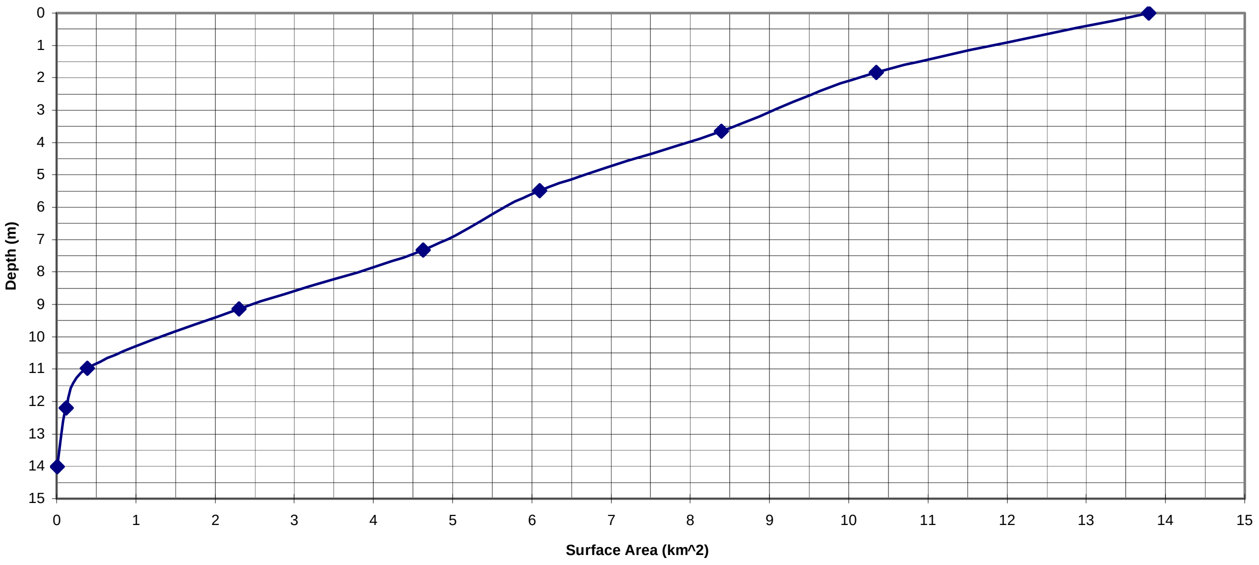
Figure 1: Hypsographic Curve of Sodus Bay Basin

Isopleth Area data taken from Makarewicz and Lewis, 1990



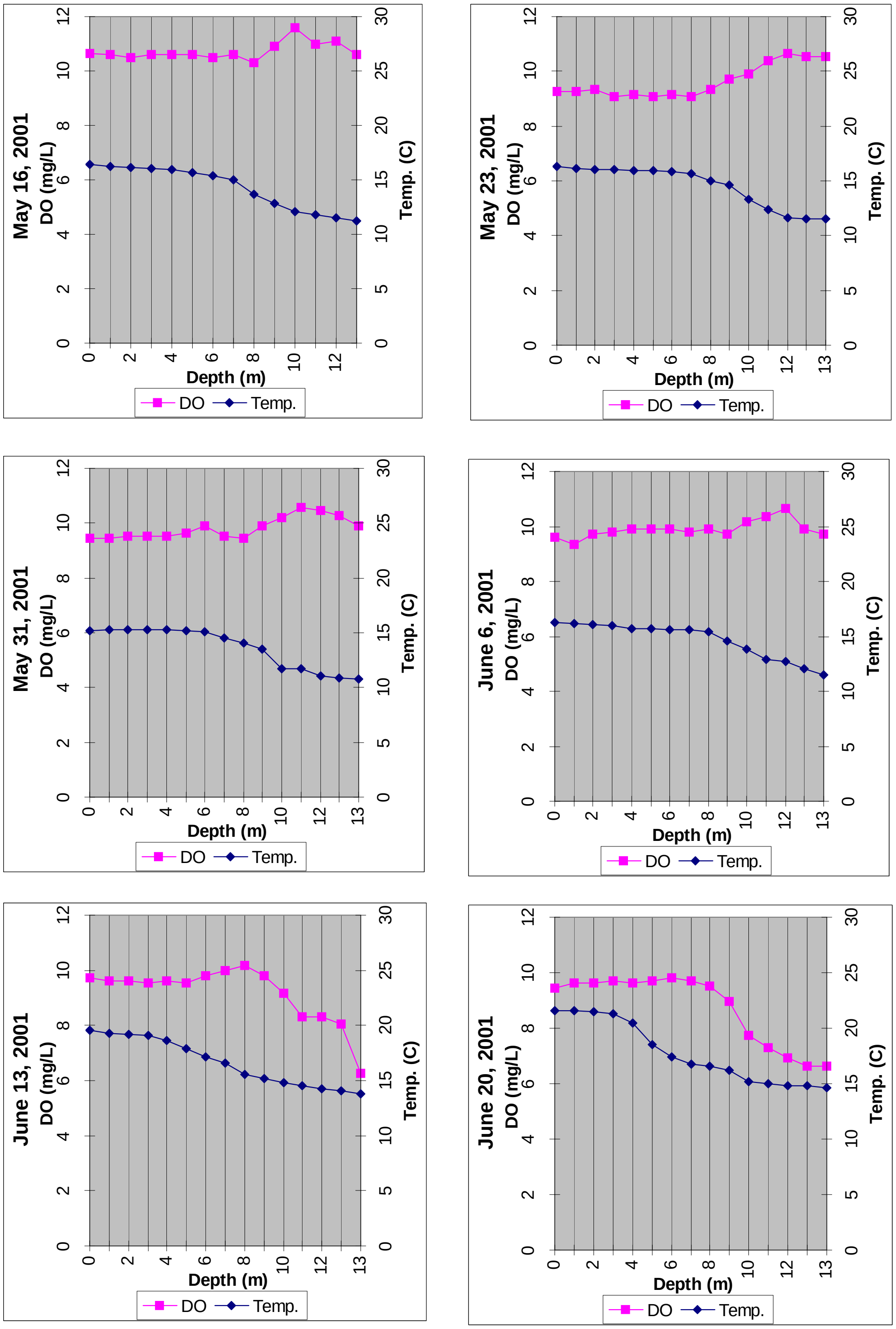
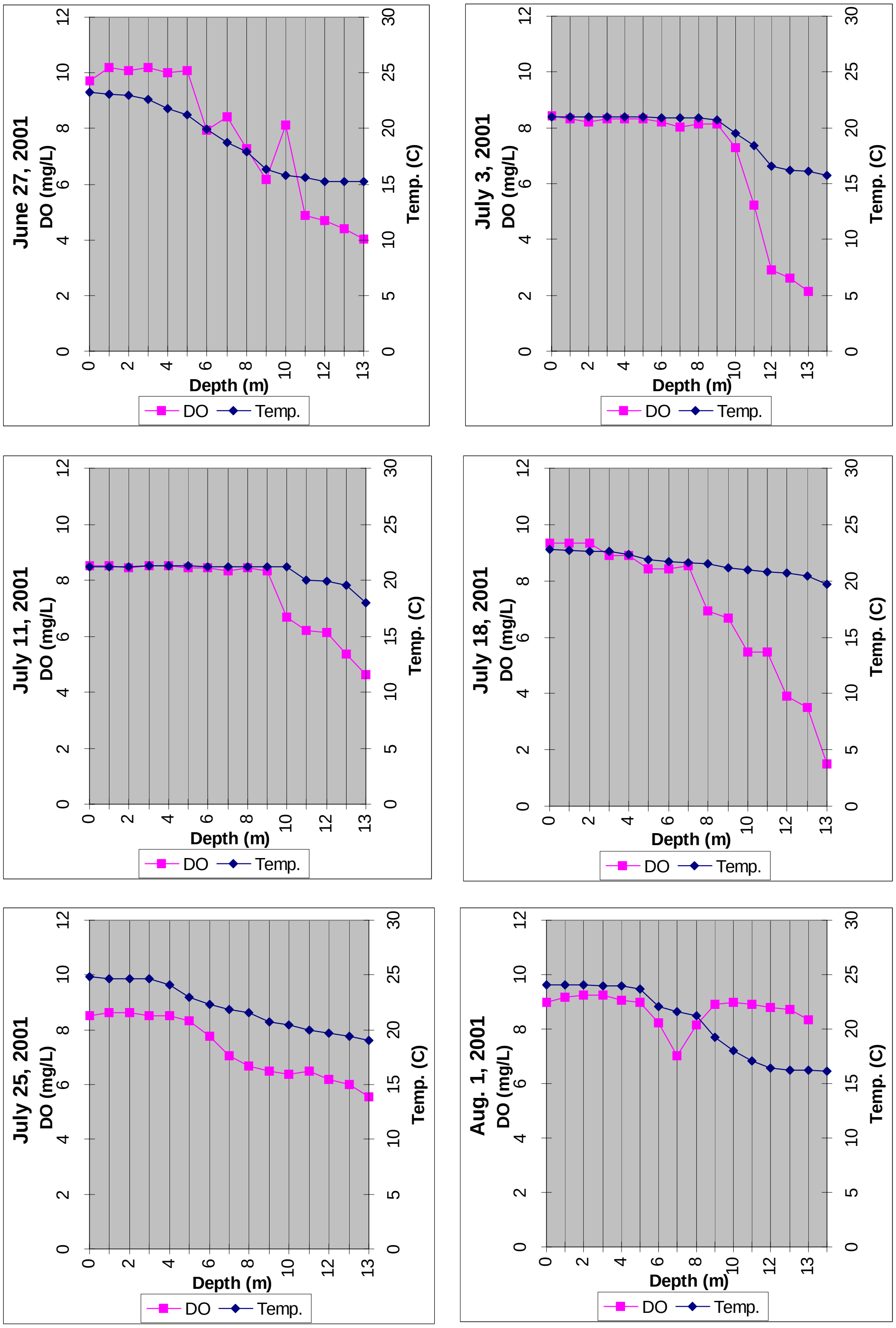


Figure 2. Dissolved oxygen and temperature profiles, Sodus Bay. 16 May 2001 to 22 September 2001.



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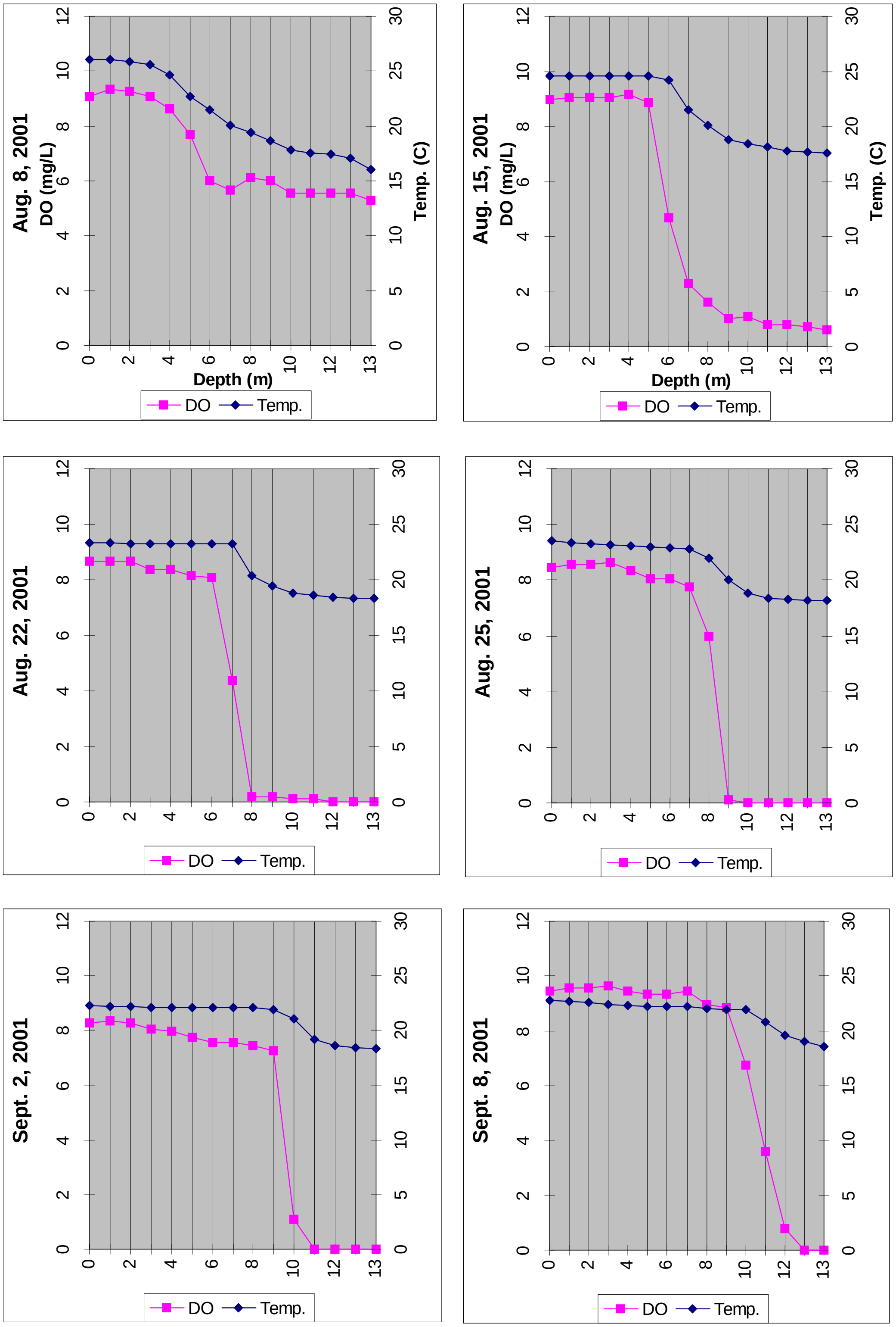

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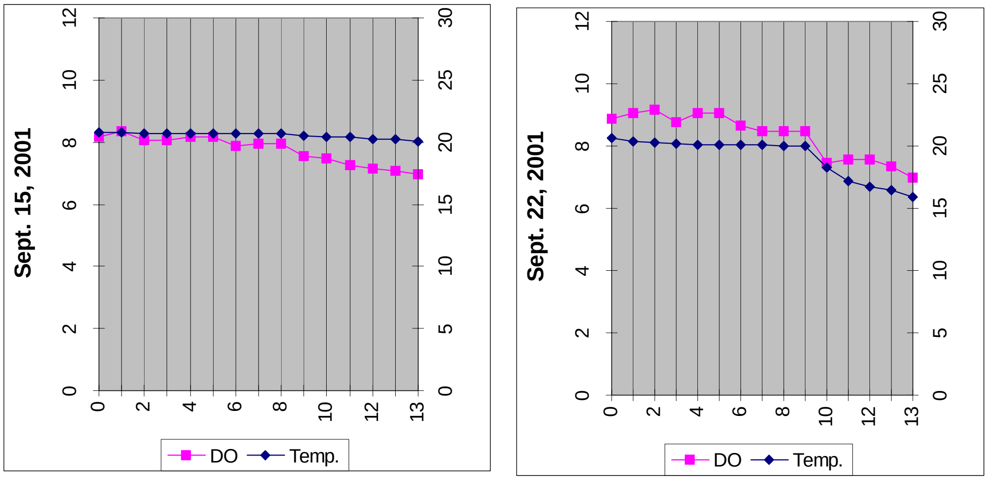

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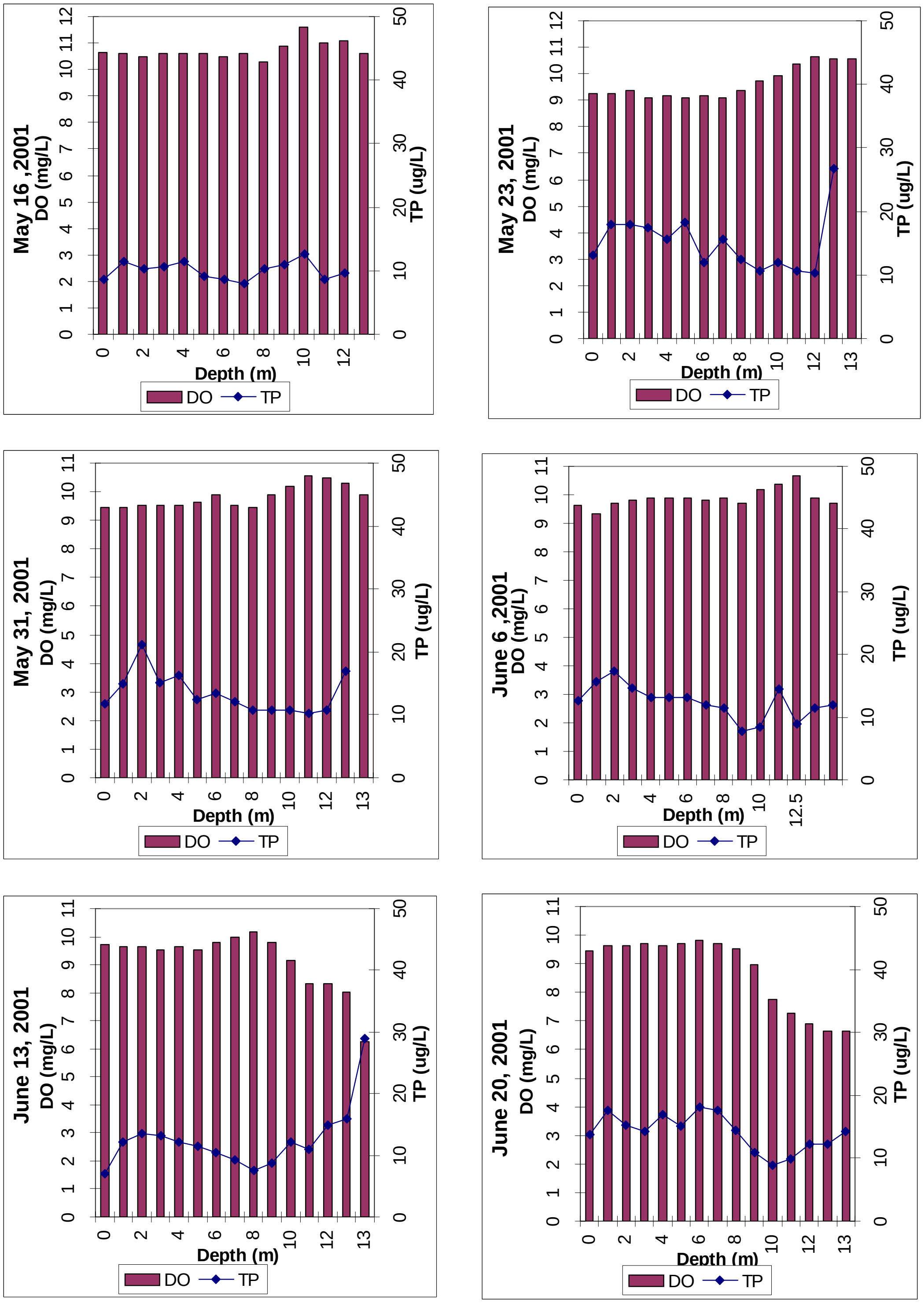


Figure 3. Dissolved oxygen and total phosphorus profiles, Sodus Bay. 16 May 2001 to 22 September 2001.

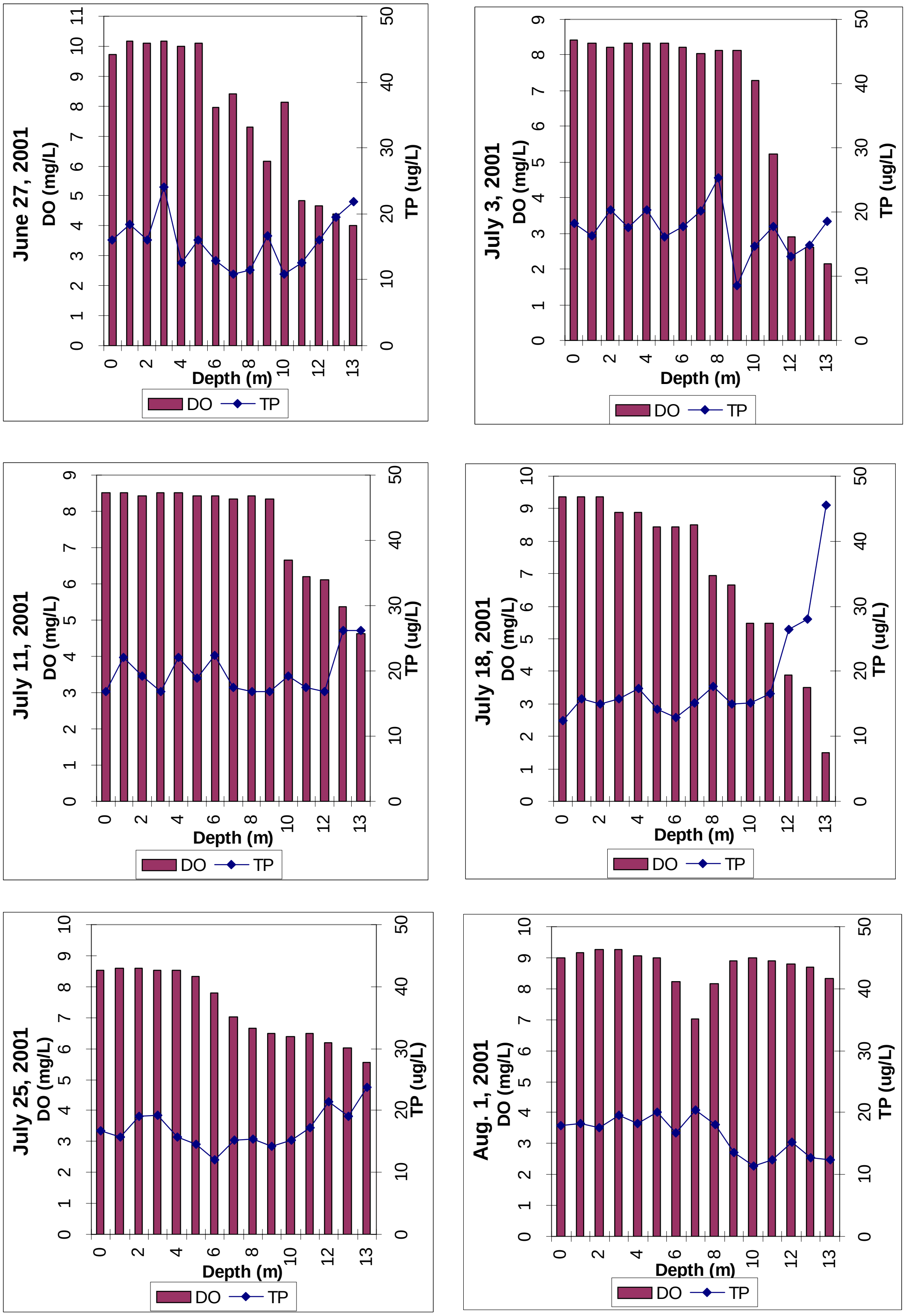
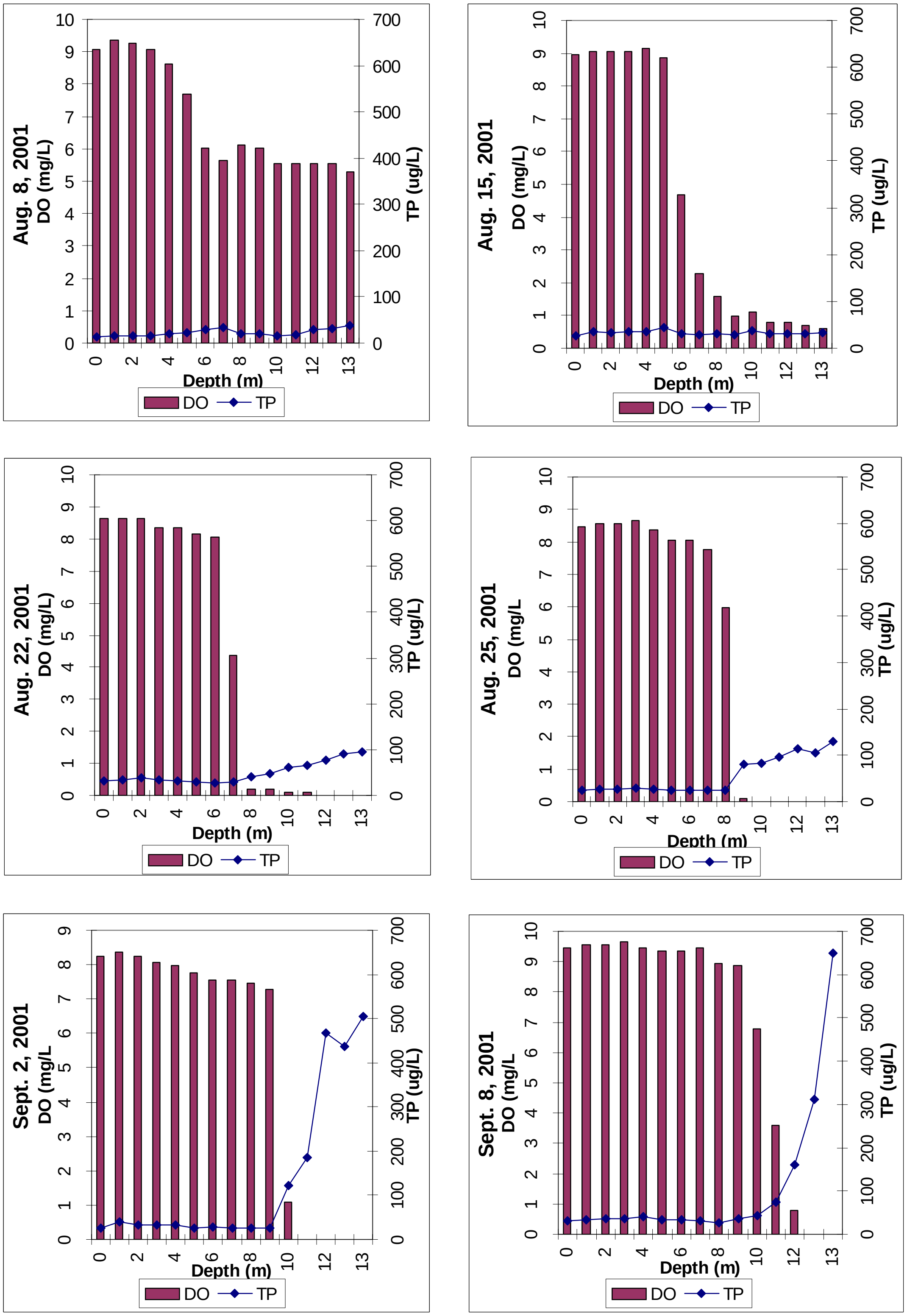


Figure 3. Dissolved oxygen and total phosphorus profiles, Sodus Bay. 16 May 2001 to 22 September 2001.



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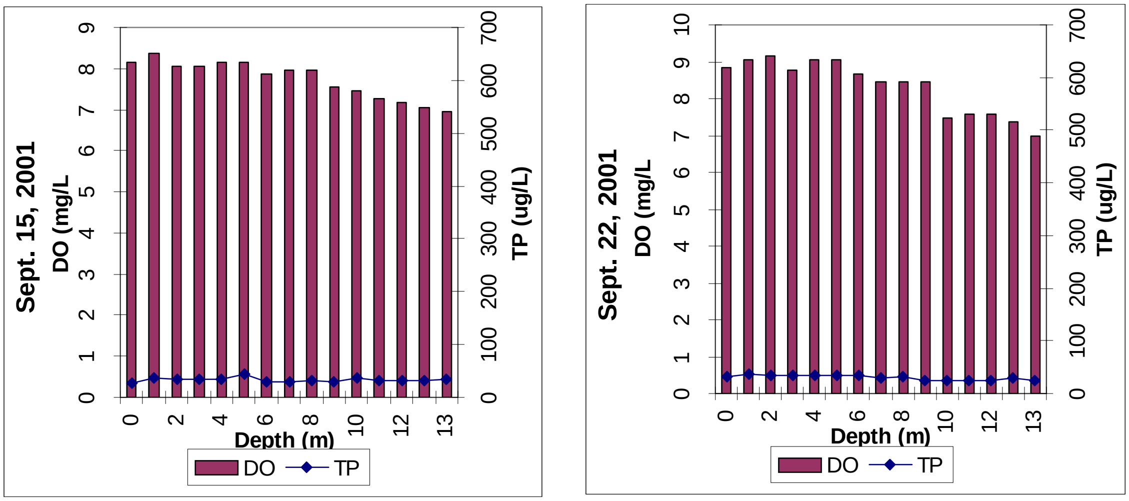

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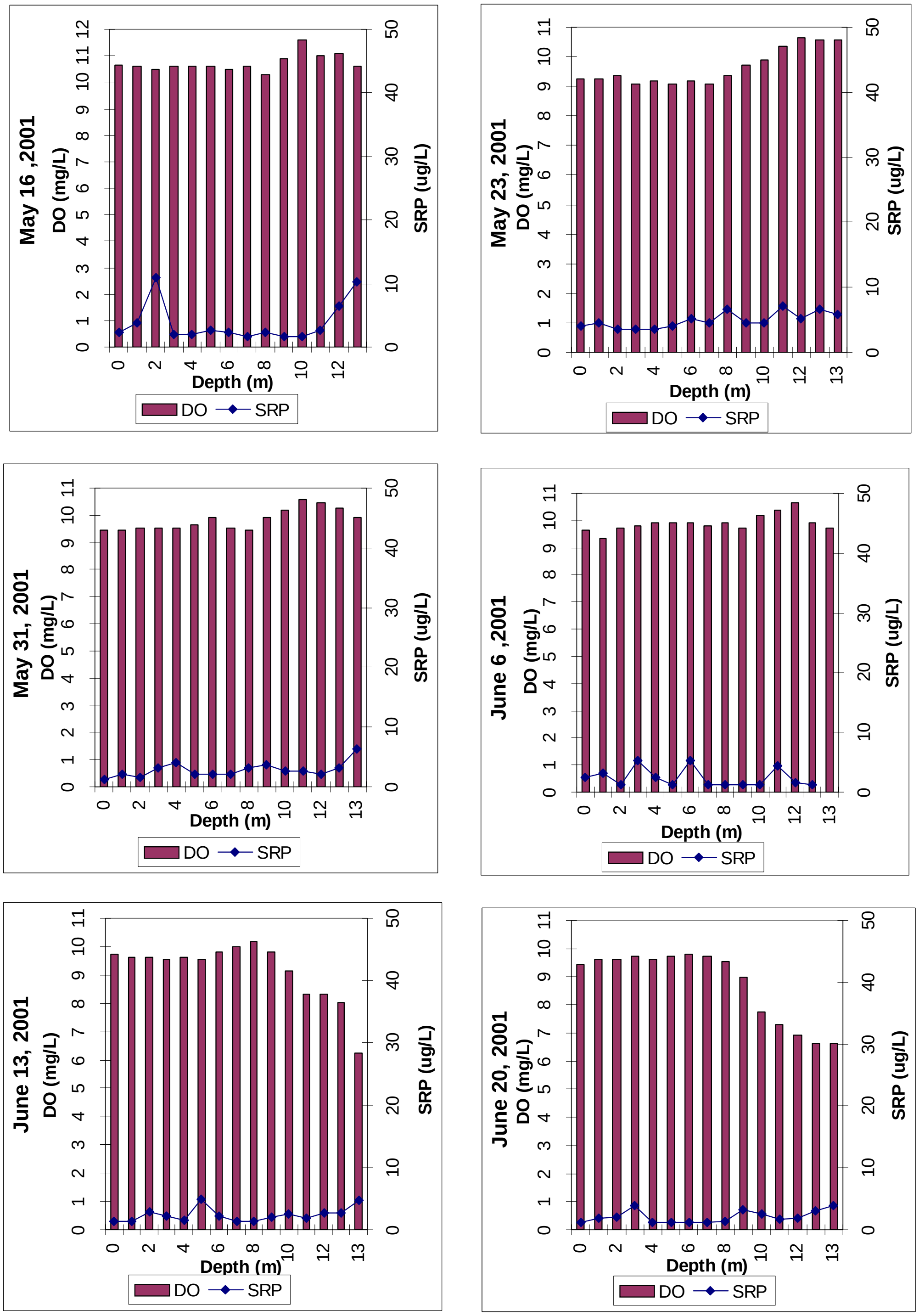
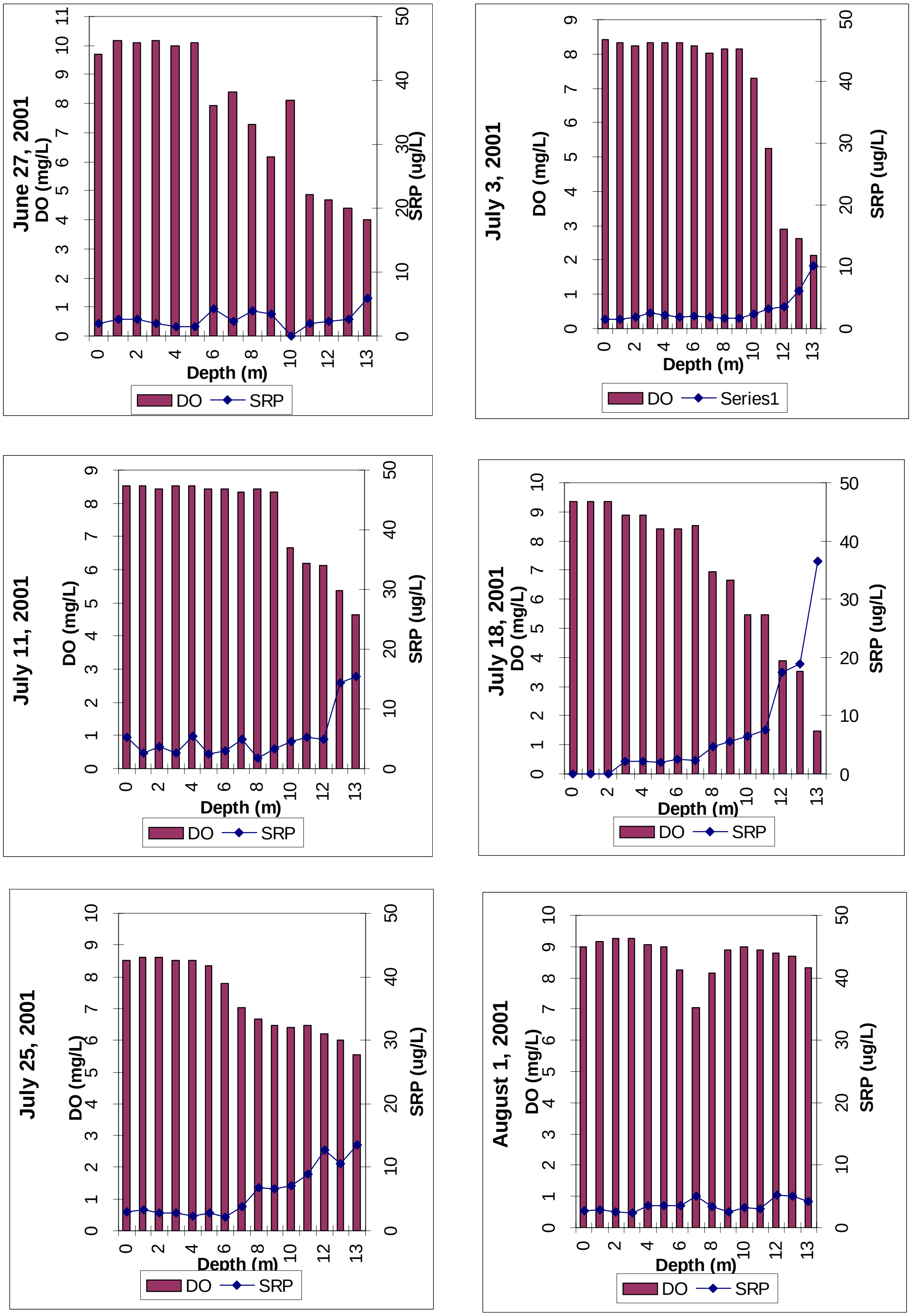


Figure 4. Dissolved oxygen and soluble phosphorus profiles, Sodus Bay. 16 May 2001 to 22 September 2001.



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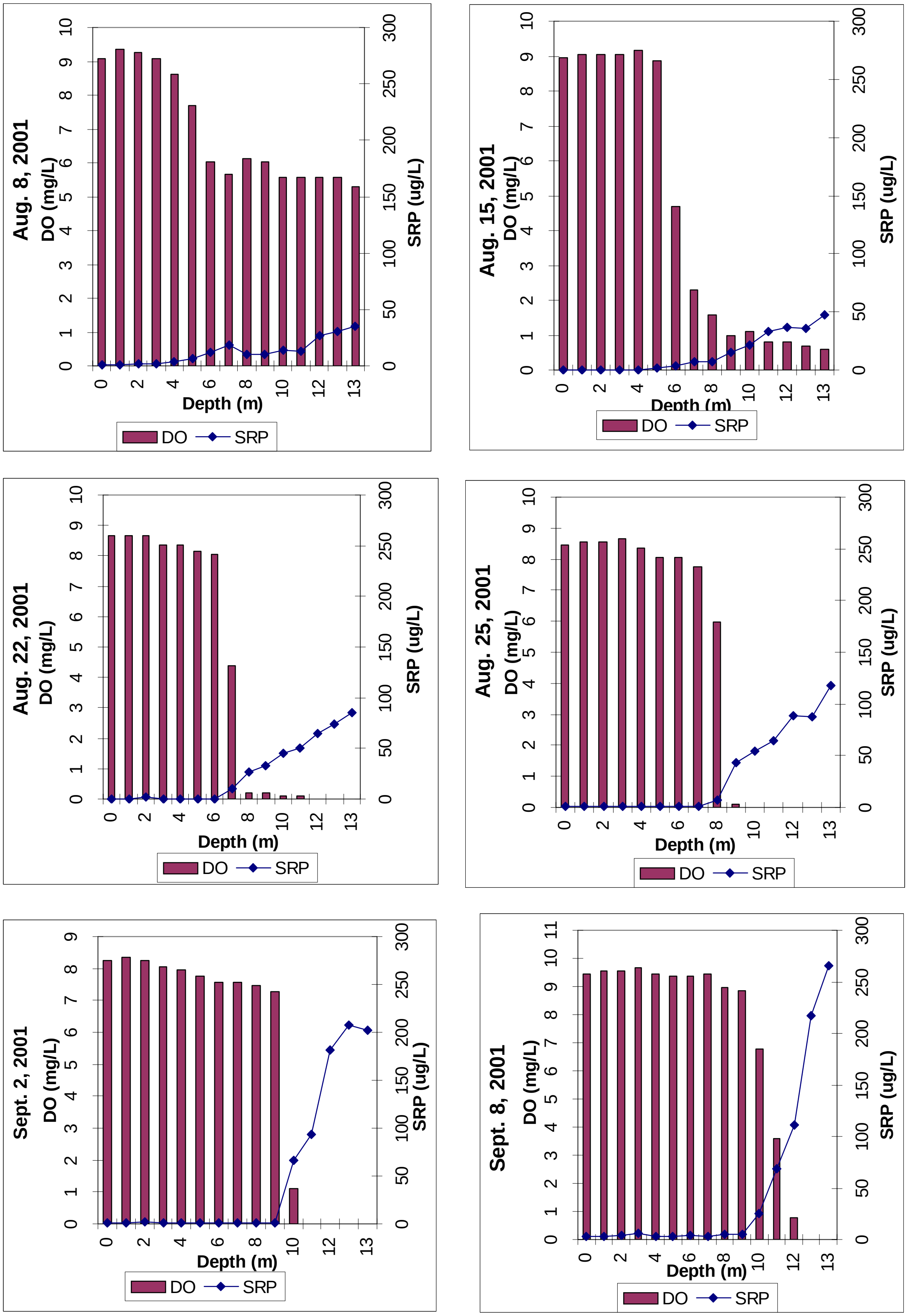

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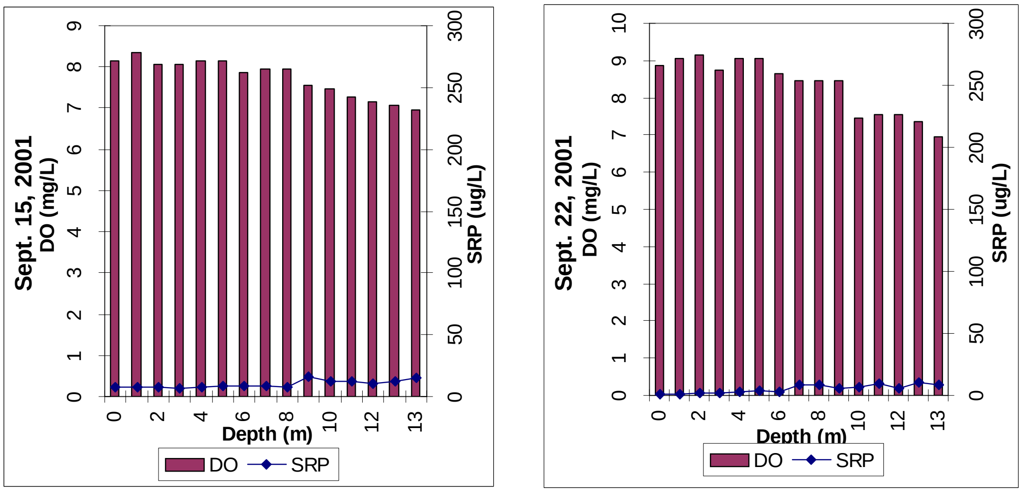


Figure 4. Dissolved oxygen and soluble phosphorus profiles, Sodus Bay. 16 May 2001 to 22 September 2001.

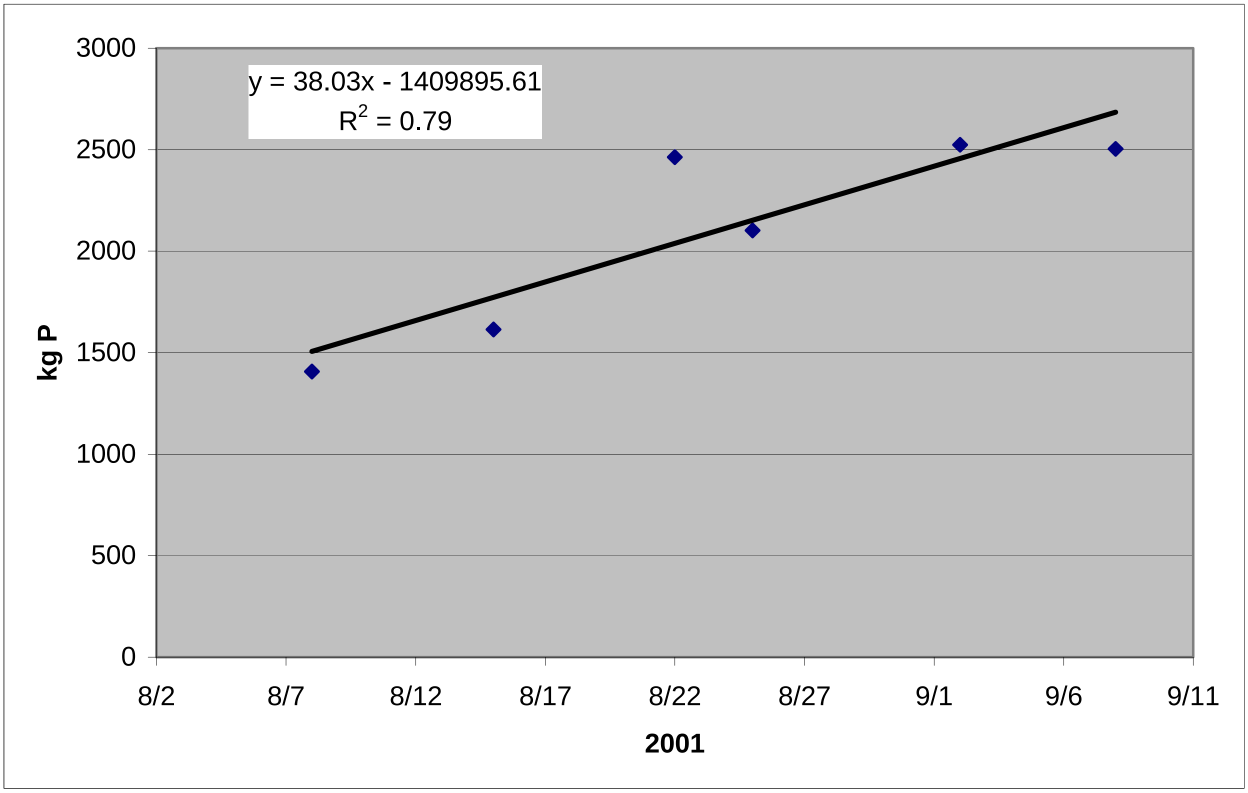


Figure 5. The increase in total phosphorus (kg P) for the entire volume of Sodus Bay during the period of depressed hypolimnetic oxygen conditions. The rate of phosphorus increase was estimated at 38.0 kg P/d.

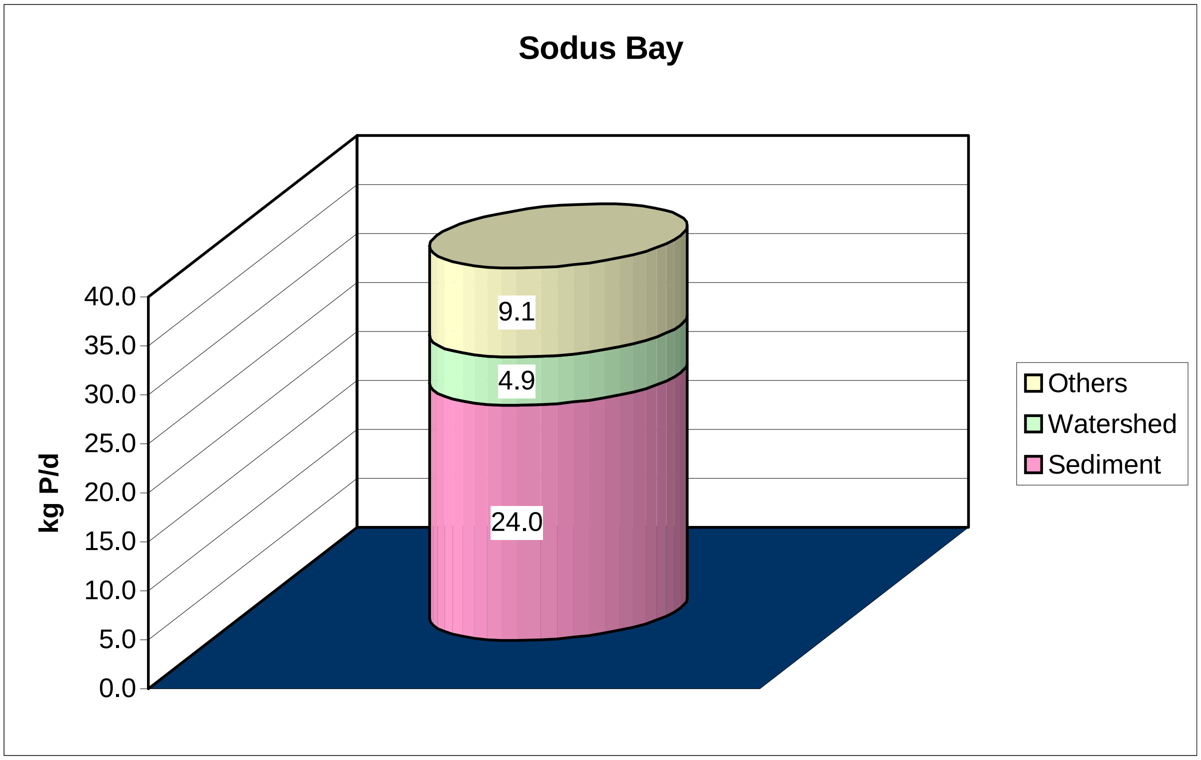


Figure 6. Sources of total phosphorus to Sodus Bay for the period 8 August to 8 September 2001.

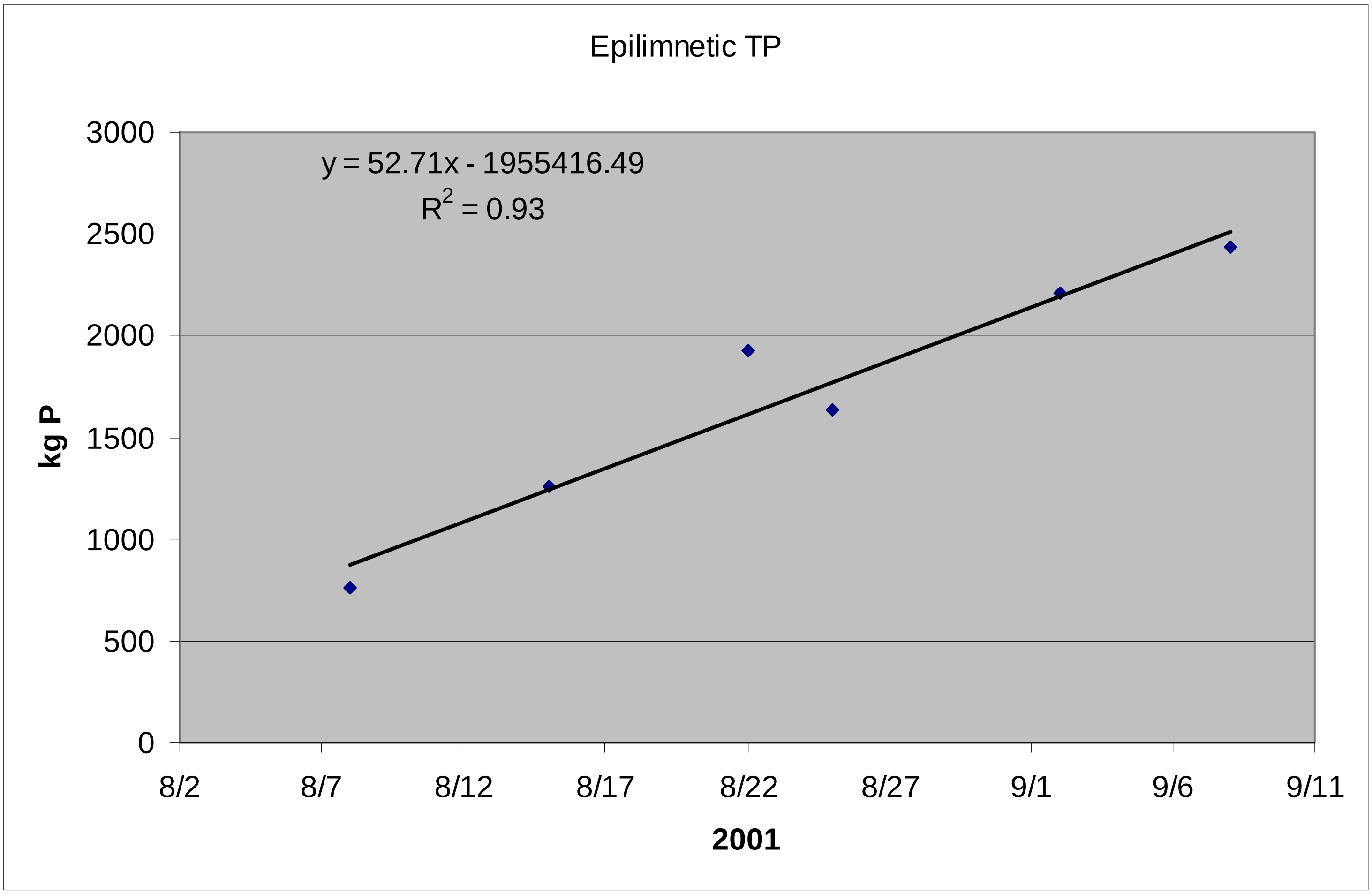


Figure 7. The increase in epilimnetic total phosphorus (kg P) during the period of depressed hypolimnetic oxygen conditions in Sodus Bay. The rate of phosphorus increase was estimated at 52.7 kg P/d.

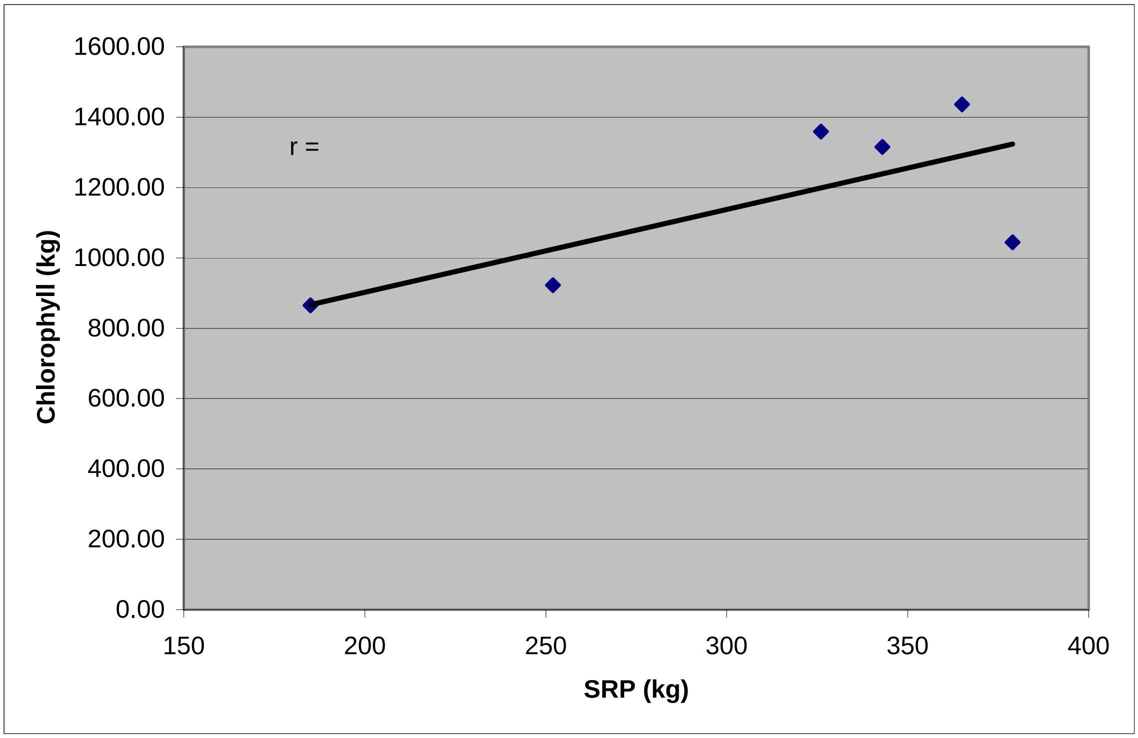


Figure 8. The relationship between SRP content and chlorophyll content of the waters of Sodus Bay, during the anoxic period of 2001.

Appendicies

Figure A: The amount of Total Phosphorus in the epilimnion, metalimnion, hypolimnion and the entire basin of Sodus Bay from 1 August, 2001 to 22 September, 2001.

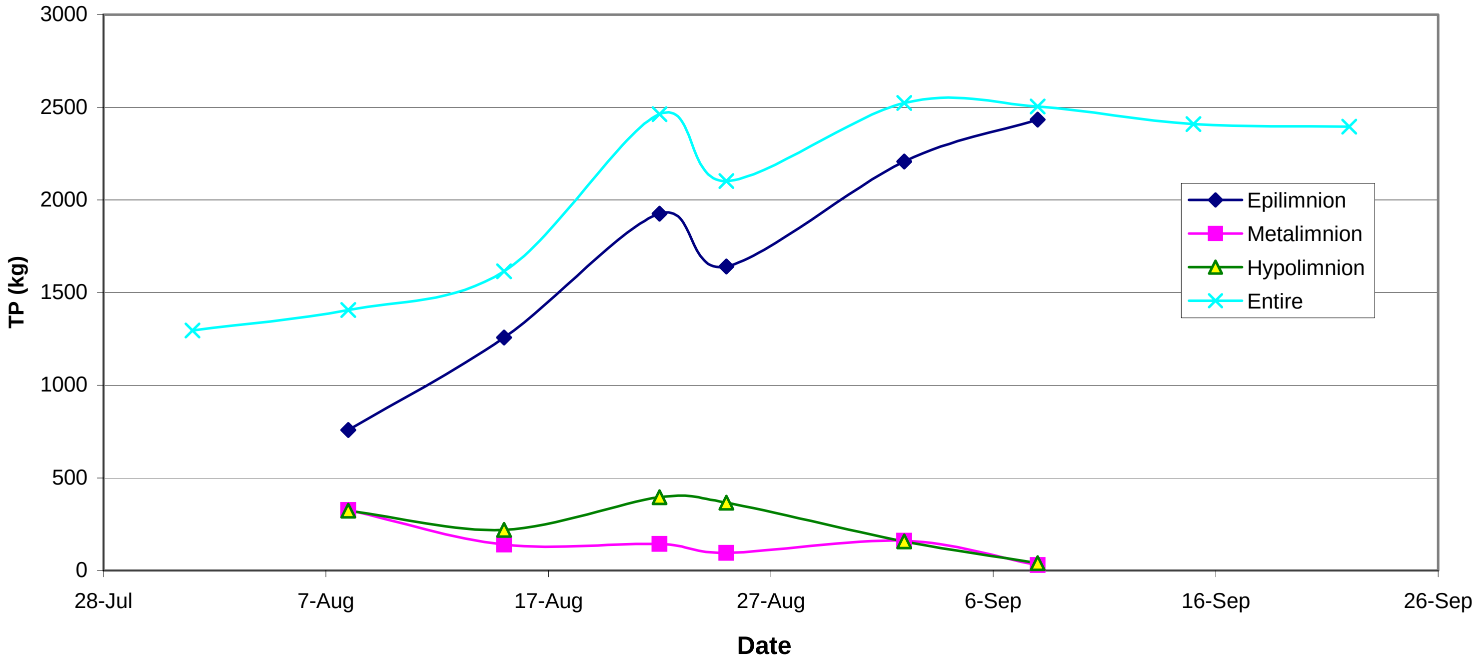
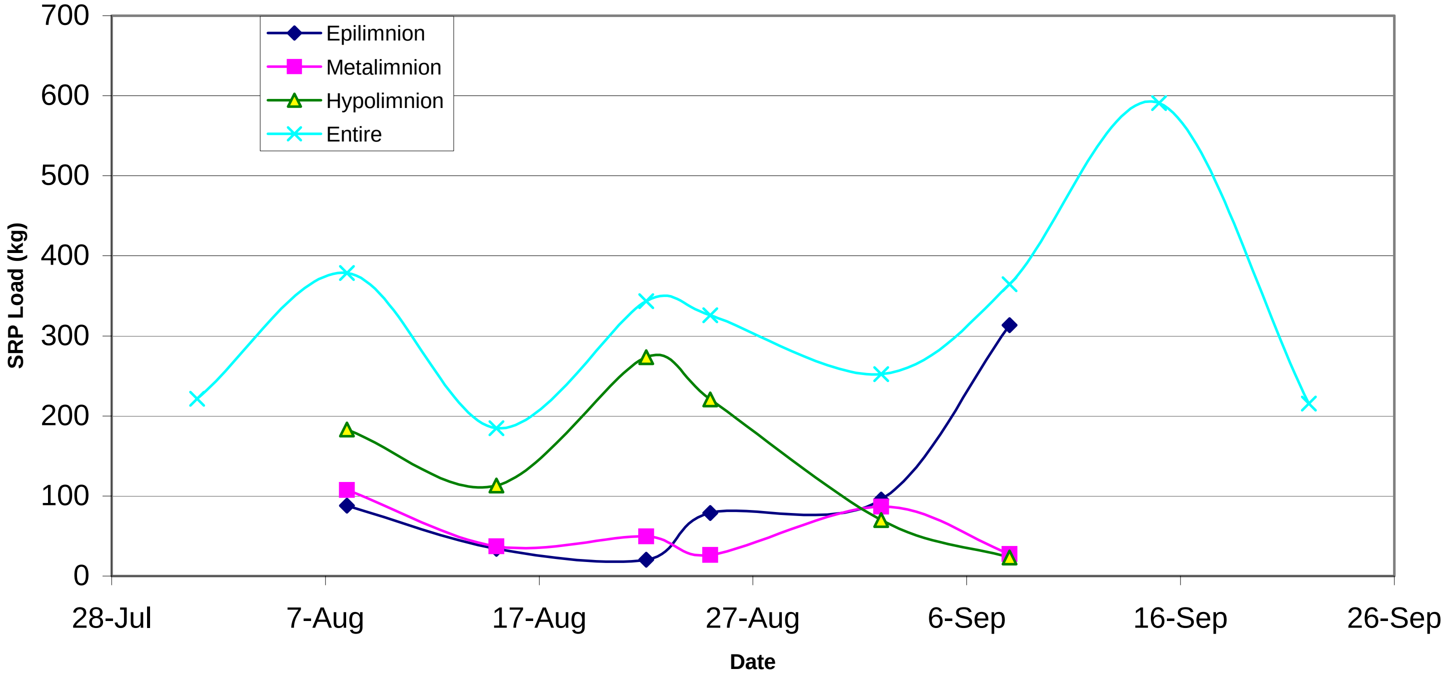
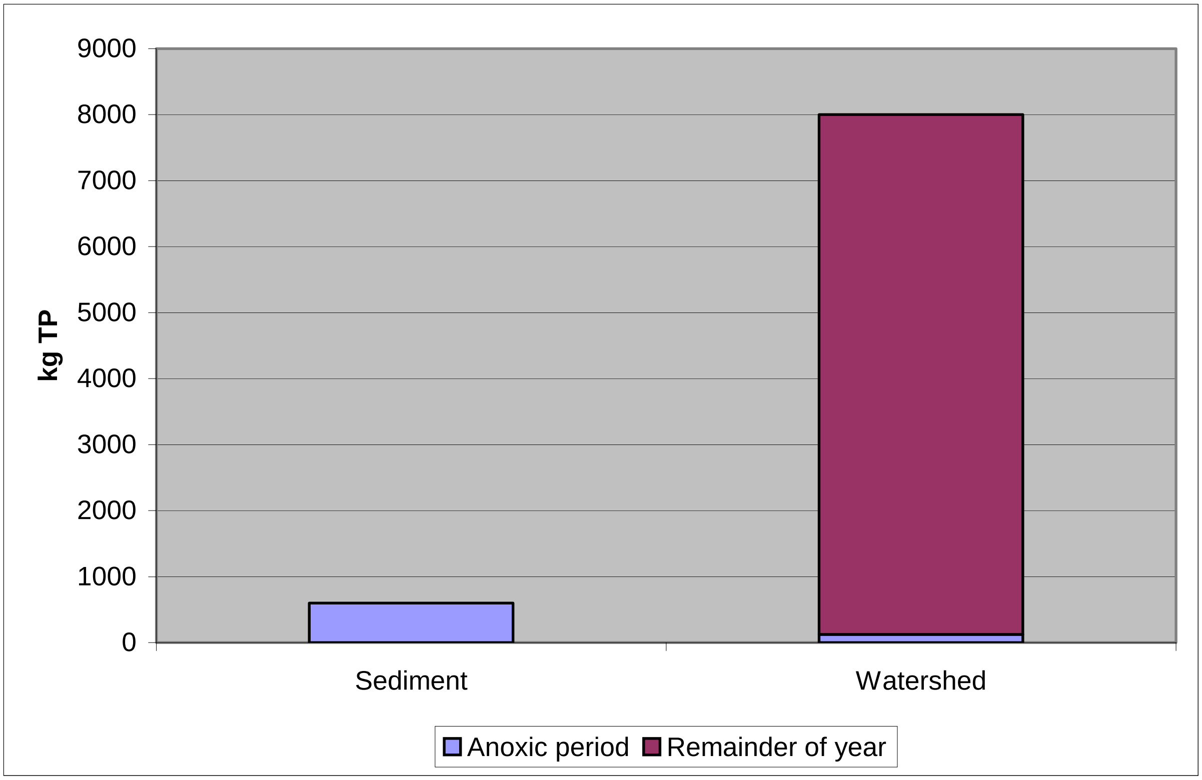
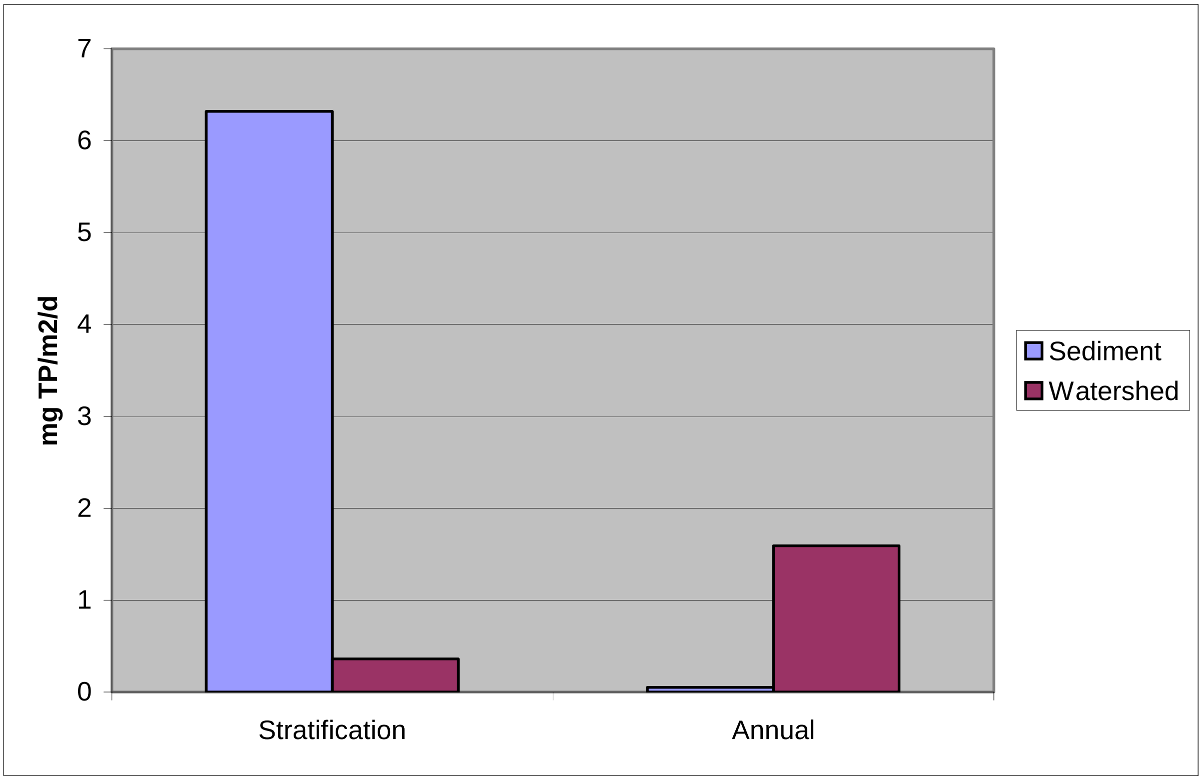


Figure B: The amount of Soluble Reactive Phosphorus in the epilimnion, metalimnion, hypolimnion and the entire basin of Sodus Bay from 1 August, 2001 to 22 September, 2001.





Appendix C. Annual loss of total phosphorus from the sediment and the watershed of Sodus Bay during 2001. The blue shade represents the amount of total phosphorus lost during the anoxic period (18 August to 12 September 2001).



Appendix D. Total phosphorus loss rates from the sediments and the watershed to Sodus Bay during the stratification period and on an annual basis for 2001. The areal loss rate is normalized by the surface area of Sodus Bay.

Figure E: Total phosphorus (TP) and Soluble Reactive Phosphorus (SRP) content of the top 5 meters of Sodus Bay during a mixing event.