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August 1995

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Waterways Experiment Station

Water Quality Research Program

Wind-Induced Sediment Resuspension and Export in Marsh Lake, Western Minnesota

by William F. James, John W. Barko

WES

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Prepared for U.S. Army Engineer District, St. Paul
and Headquarters, U.S. Army Corps of Engineers

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3909 Halls Ferry Road
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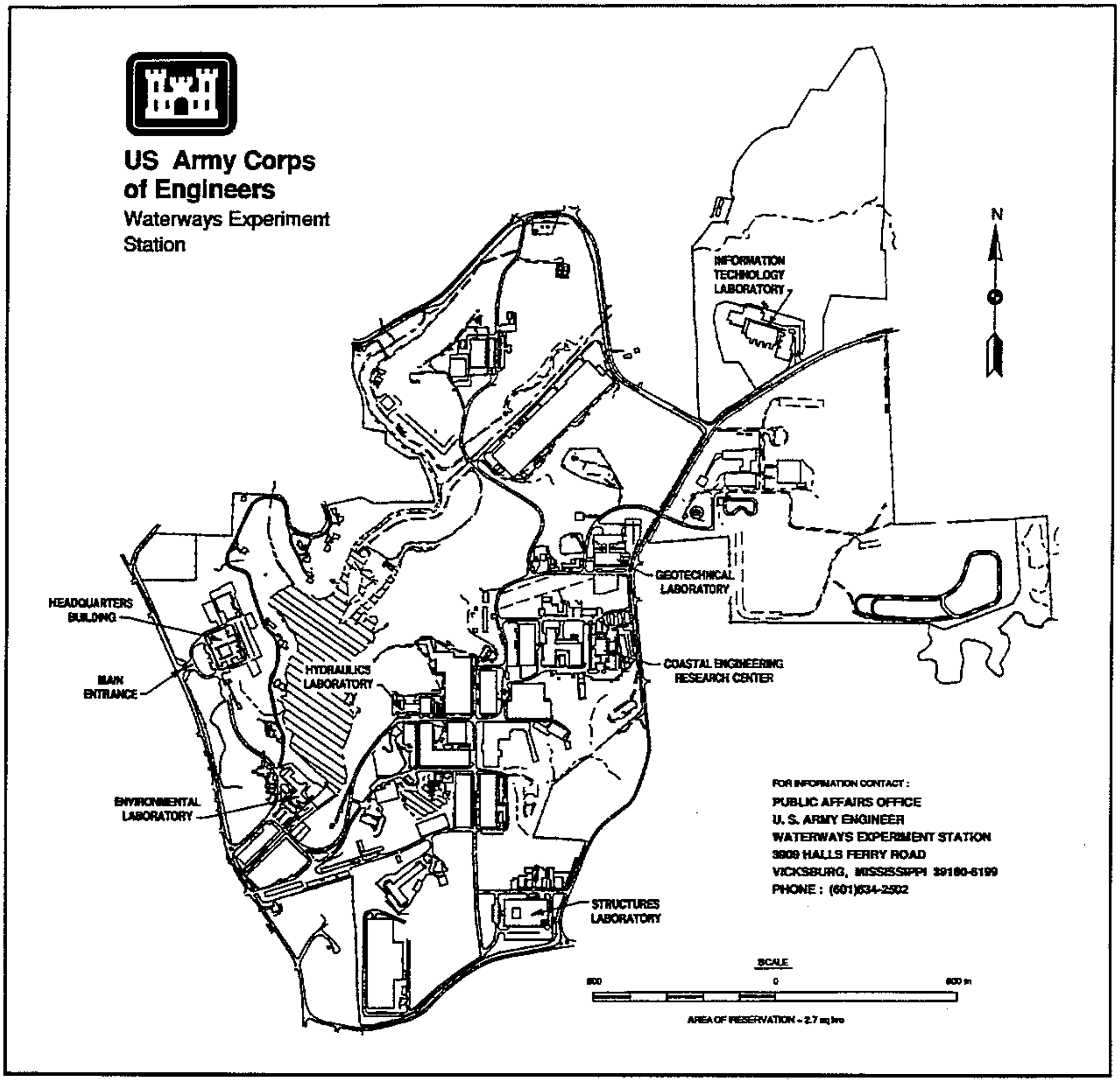

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Contents

List of Figures

Preface

This study was conducted for the U.S. Army Engineer District (USAED), St. Paul, to evaluate options for improving wetland and aquatic habitat conditions in Marsh Lake under Section 1135 of the Federal Water Resources Development Act of 1986. Funding was provided by the USAED, St. Paul, the Water Quality Research Program (WQRP), and the Water Operations Technical Support (WOTS) Program. The WQRP and WOTS Program are sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), and are assigned to the Waterways Experiment Station (WES) under the purview of the Environmental Laboratory (EL). The WQRP and WOTS Program are managed under the Environmental Resources Research and Assistance Programs (ERRAP), Mr. J. Lewis Decell, Manager. Mr. Robert C. Gunkel, Jr., was Assistant Manager, ERRAP, for the WQRP and WOTS Program. Program Monitors during this study were Mr. Frederick B. Juhle, Mr. Rixie Hardy, and Dr. John Bushman, HQUSACE.

This study was conducted and the report was prepared by Mr. William F. James and Dr. John W. Barko, Environmental Processes and Effects Division (EPED), EL, WES. Messrs. Dennis D. Holme and James D. Sentz, USAED, St. Paul, and Mr. Kurt Hanson, resource manager, Lac Qui Parle Flood Control Project, provided valuable logistical support for the study. Messrs. Don Hatfield, Paul Adams, and Wayne Gustufson, Lac Qui Parle Flood Control Project, conducted the field sampling. Mr. Lance Albrightson, Ms. Sarah Dixon, Mr. Dale Dressel, AScI, Vicksburg, MS, and Mses. Angela Niccum and Ellen Zimmer, Eau Galle Aquatic Ecology Laboratory, Spring Valley, WI, provided chemical analyses of the water samples. Dr. David M. Soballe, Environmental Management Technical Center, U.S. Fish and Wildlife Service, Onalaska, WI, and Mr. Daniel B. Wilcox, USAED, St. Paul, provided reviews of this report.

The investigation was conducted under the general supervision of Dr. John W. Keeley, Director, EL, and Mr. Donald L. Robey, Chief, EPED, and under the direct supervision of Dr. Richard E. Price, Acting Chief, Ecosystem Processes and Effects Branch.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

This report should be cited as follows:

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1 Introduction

Shallow lakes and reservoirs are often dominated by wind-induced sediment resuspension leading to sediment-related water quality problems, such as enhanced nutrient recycling and reduced water clarity (Dillon, Evans, and Molot 1990; Maceina and Soballe 1990; Hellström 1991; Søndergaard, Kristensen, and Jeppesen 1992). Sediment resuspension depends on a variety of factors, including the length of the maximum effective fetch under prevailing wind conditions, lake bathymetry, shear stress at the sediment surface, and sediment composition (Håkanson 1977; Carper and Bachmann 1984; Bengtsson and Hellström 1990, 1992; Kristensen, Søndergaard, and Jeppesen 1992). Sediment resuspension may occur frequently in shallow lakes, particularly if a large proportion of the lake is shallower than one-half the wave length of deepwater waves (Carper and Bachmann 1984). Concentrations of sediment, nutrients, contaminants, and oxygen-demanding materials can increase substantially in the water column with increasing wind velocity, as more of the lake's bed is subjected to sediment resuspension (Bengtsson and Hellström 1992). Thus, an understanding of sediment resuspension dynamics is essential for developing management plans to improve water quality conditions in shallow impoundments.

By reducing sediment resuspension, wetland and submersed aquatic vegetation can have beneficial effects on the water quality of shallow impoundments and lakes. For example, Dieter (1990) showed that sediment resuspension was reduced in regions colonized by emergent vegetation in Sand Lake, South Dakota. Similarly, James and Barko (1990) demonstrated that submersed vegetation reduced sediment erosion in the littoral zone of Eau Galle Reservoir, Wisconsin. Thus, aquatic vegetation may play an important role in mitigating water quality problems in shallow lakes subjected to frequent winds.

This study examined sediment resuspension in Marsh Lake, Minnesota, and the discharge of sediment from the system to downstream Lac Qui Parle Reservoir, Minnesota. Sediment resuspension was examined under a variety of wind conditions in Marsh Lake to determine critical thresholds of wind velocity that resulted in high concentrations of suspended sediment (i.e., seston) in the water column. Sediment resuspension was examined during a year when submersed aquatic vegetation in Marsh Lake was densely established (1991) and during a year when it was almost completely absent (1992), thus providing information on the influence of aquatic vegetation on sediment dynamics in a shallow reservoir.

2 Study Area

Marsh Lake, a flood control impoundment located near the headwaters of the Minnesota River in western Minnesota, is large (a surface area of 1,862 ha) and very shallow (mean depth, 0.9 m, and maximum depth, 1.5 m, Figure 1). Tributaries to Marsh Lake include the Pomme De Terre River, which enters the lake near the dam and outlet structure, and the Minnesota River (Figure 1). Both tributaries drain a mostly agricultural watershed. Discharges from Marsh lake occur over an uncontrolled fixed crest overflow structure located at an elevation of 285.78 m NGVD.[1] Discharge also occurs through a sluice gate located at 284.26 NGVD. Discharges from Marsh Lake travel approximately 20 km downstream before entering the headwaters of Lac Qui Parle Reservoir.

[1] All elevations cited herein are in meters as referred to in National Geodetic Vertical Datum (NGVD) of 1929.

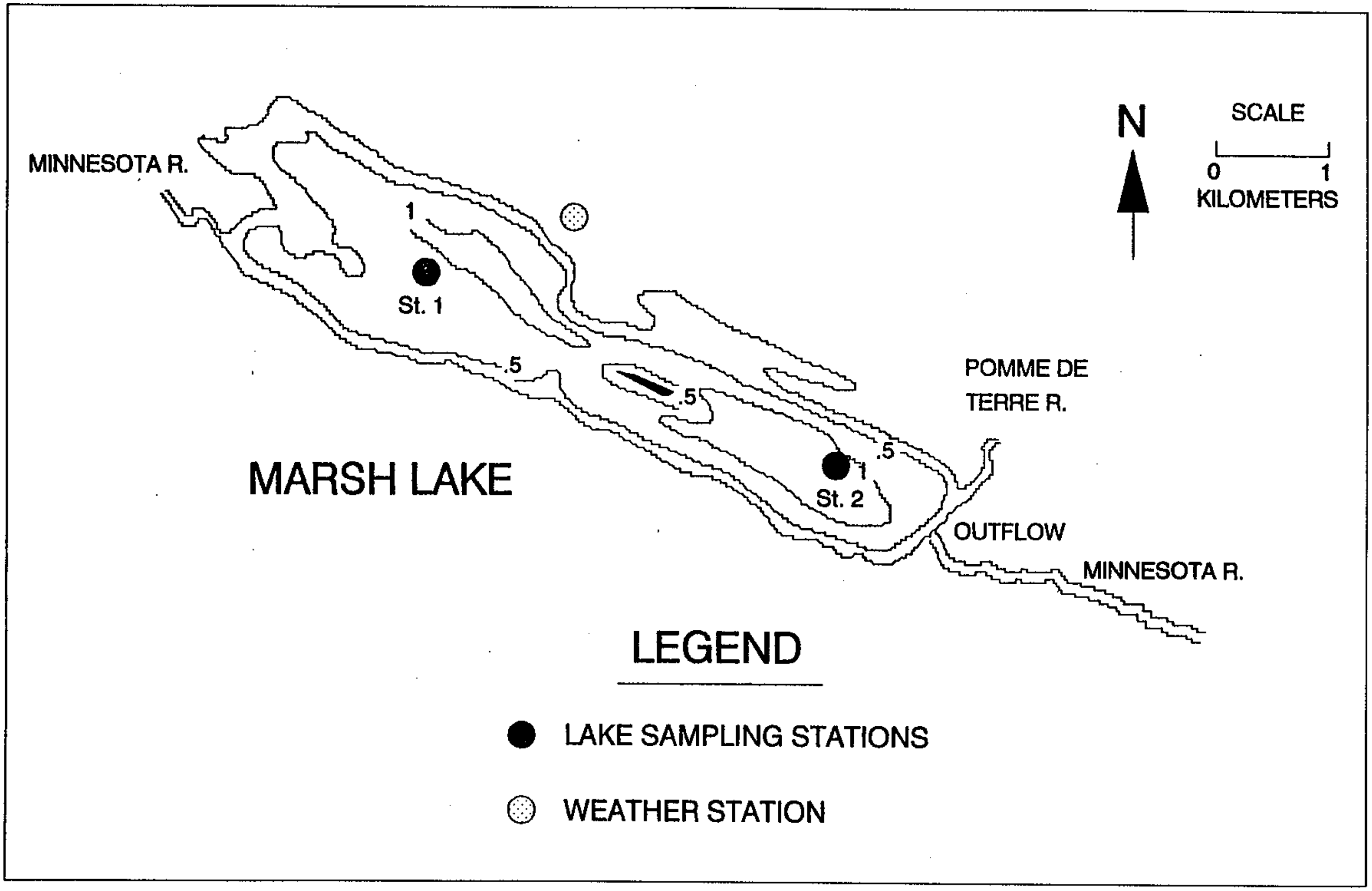

Figure 1. Morphometric map and station locations in Marsh Lake. Depth contours are in meters

3 Methods

Sediment loading and resuspension were examined in Marsh Lake during June through September, 1991, and during May through September, 1992. During the summer and autumn of 1991, the entire reservoir was densely populated by *Potamogeton* sp., with surface coverages > 90 percent.[1] Submersed macrophyte densities diminished greatly in 1992 to the point where plants could not be observed visually in the water column throughout most of the reservoir. Differences in macrophyte coverage were not quantified, since we did not anticipate such a marked contrast in abundance between the two study years. The cause of this macrophyte decline has not been determined.

In 1991, two midchannel stations (0.7 to 0.8 m deep) were established in the lake, with water sampling (integrated water column) attempted by boat every Monday, Wednesday, and Friday. However, strong winds and high waves prevented manual collection of water samples on many dates. In 1992, automated water samplers (ISCO) were placed on permanently anchored platforms at these same lake stations (Figure 1). The samplers were programmed to composite three water samples, collected at 8-hr intervals at a depth of 0.3 m below the lake surface, on a daily basis. Thus, water samples could be collected even under severe wind conditions.

River water samples were collected daily (automated water samplers) or weekly (grab samples) at fixed stations located on the Minnesota River upstream of Marsh Lake, on the Pomme De Terre River, and at the outflow of Marsh Lake during both years. Flows were gauged continuously using continuous recording gauges or stage height recorders. The water level of Marsh Lake was measured daily with a recording gauge.

All lake and river samples were analyzed for seston (i.e., total suspended solids), particulate organic matter (POM), and total phosphorus (total P) concentrations. Samples for seston and POM were filtered onto precombusted glass fiber filters. The filters were dried at 105 °C for seston analysis and then combusted at 550 °C for 2 hr for determination of POM (i.e., loss on ignition;

[1] Personal Observation, 10 February 1992, D. Hatfield and K. Bonema, U.S. Army Engineer District, St. Paul, MN.

APHA 1985). Total P of unfiltered samples was determined colorimetrically on a Technicon Autoanalyzer II following persulfate oxidation (APHA 1985).

Daily external loadings and discharges of seston, POM, and total P in Marsh Lake were calculated by multiplying the daily volumetric flow rate by the measured concentration. Linear interpolation was used to estimate concentrations on dates when water samples were not collected. Retention (kg/d) of these constituents in Marsh Lake was estimated according to the following equation: Retention = External Load - Outflow. The external load represented the sum of daily loading estimates from the Minnesota and Pomme De Terre Rivers, while the outflow represented the daily discharge load from Marsh Lake.

A weather station was established on the northern shoreline of Marsh Lake for wind monitoring (Figure 1). The average of data collected at 5-min intervals was recorded every 15 to 30 min for wind velocity and direction using an automated data logger (Omnidata International). Mean daily wind velocities were computed from these data for comparison with trends in water quality variables, because mean daily velocity reflects sustained winds. Daily wind vectors were calculated as the wind direction weighted with respect to wind velocity and averaged over a 24-hr period. Statistical analysis of the wind data were performed using SAS (1988).

The ability of waves, generated by wind activity, to disturb and resuspend the sediment surface in Marsh Lake was estimated for a variety of wind directions using the wave model developed by Carper and Bachmann (1984). In general, the model calculates wavelengths (L) of surface waves using mathematical wave theory as applied by the U.S. Army Coastal Engineering Research Center (1977), and compares 1/2L to the water column depth. If 1/2L is greater than the water column depth, the wave is assumed to touch the lake bottom and resuspend sediment. The wave model assumes that there are no obstructions in the water column such as submersed or emergent aquatic macrophytes that might create drag or redirect currents and wave activity.

4 Results

Hydrological Conditions and Loading Estimates

High inflows to Marsh Lake, due to heavy precipitation, occurred in mid-June, early July, and early August, 1991, and late June and early July, 1992 (Figures 2a and 3a), causing the pool elevation to often exceed the elevation of the weir outlet structure by 0.5 to 1.0 m (Figures 2b and 3b). The Minnesota River accounted for the majority of the gauged inflow (> 80 percent) during these storm periods. Flows and pool elevations were nominal during May through early June of 1992 and during September of both years.

External loadings of seston, POM, and total P to Marsh Lake generally increased to maxima in conjunction with peaks in the flow record during both years (Figures 4 and 5). During high inflow periods, the Minnesota River usually exhibited substantially higher loading rates of these constituents than the Pomme De Terre River. Overall, the Minnesota and Pomme De Terre Rivers each contributed about 50 percent of the average daily seston load to Marsh Lake during both years (Table 1). However, the Minnesota River accounted for over 65 and 75 percent of the average daily POM and total P load to the lake, respectively, during both years (Table 1).

Wind and Wave Activity

During both 1991 and 1992, winds blew most frequently out of the southeast (40 percent) and southwest (39 percent), followed by winds blowing out of the northwest (18 percent; Tables 2 and 3). Relatively low mean daily wind velocities of 5-10 km/h were most frequent (47 percent) during both years, followed by greater wind velocities of 10-15 km/h and 15-20 km/h, occurring 28 and 11 percent of the time, respectively. Although winds blowing from the northwest were less frequent than from other wind directions, mean daily wind velocities from this particular direction exceeded 10 km/h on 77 percent of the measured days. In general, mean daily wind velocities for all directions were ~ 10 km/h on 44 percent of the days and ~ 20 km/h on 5 percent of the days during both years.

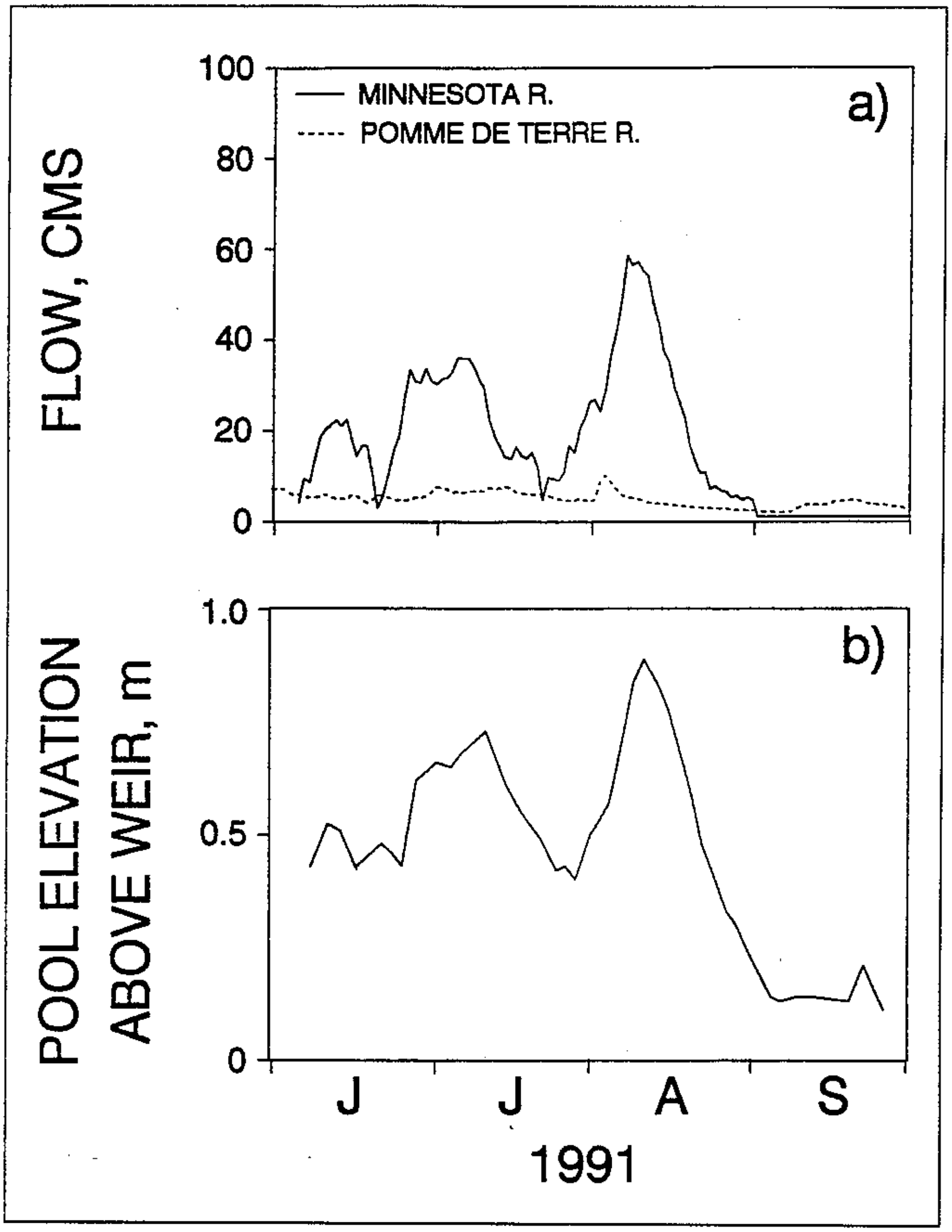

Figure 2. Variations in: a) flow from the Minnesota and Pomme De Terre Rivers and b) the height of Marsh Lake's pool elevation above the weir outlet structure during June through September, 1991

Areas of Marsh Lake that were potentially affected by sediment resuspension at different wind velocities and directions are shown in Figures 6 to 9. At low wind velocities (i.e. ≤ 5 km/h), only 17 to 22 percent of the lakebed was potentially affected by waves (Table 4). However, at wind velocities of 10 km/h, the percentage of the lakebed affected by waves increased markedly, particularly for winds blowing in the direction of maximum effective fetch (i.e, SE and NW winds; Figures 7 and 9). Virtually 100 percent of the lakebed was potentially affected by waves at wind velocities of 10 to 15 km/h blowing

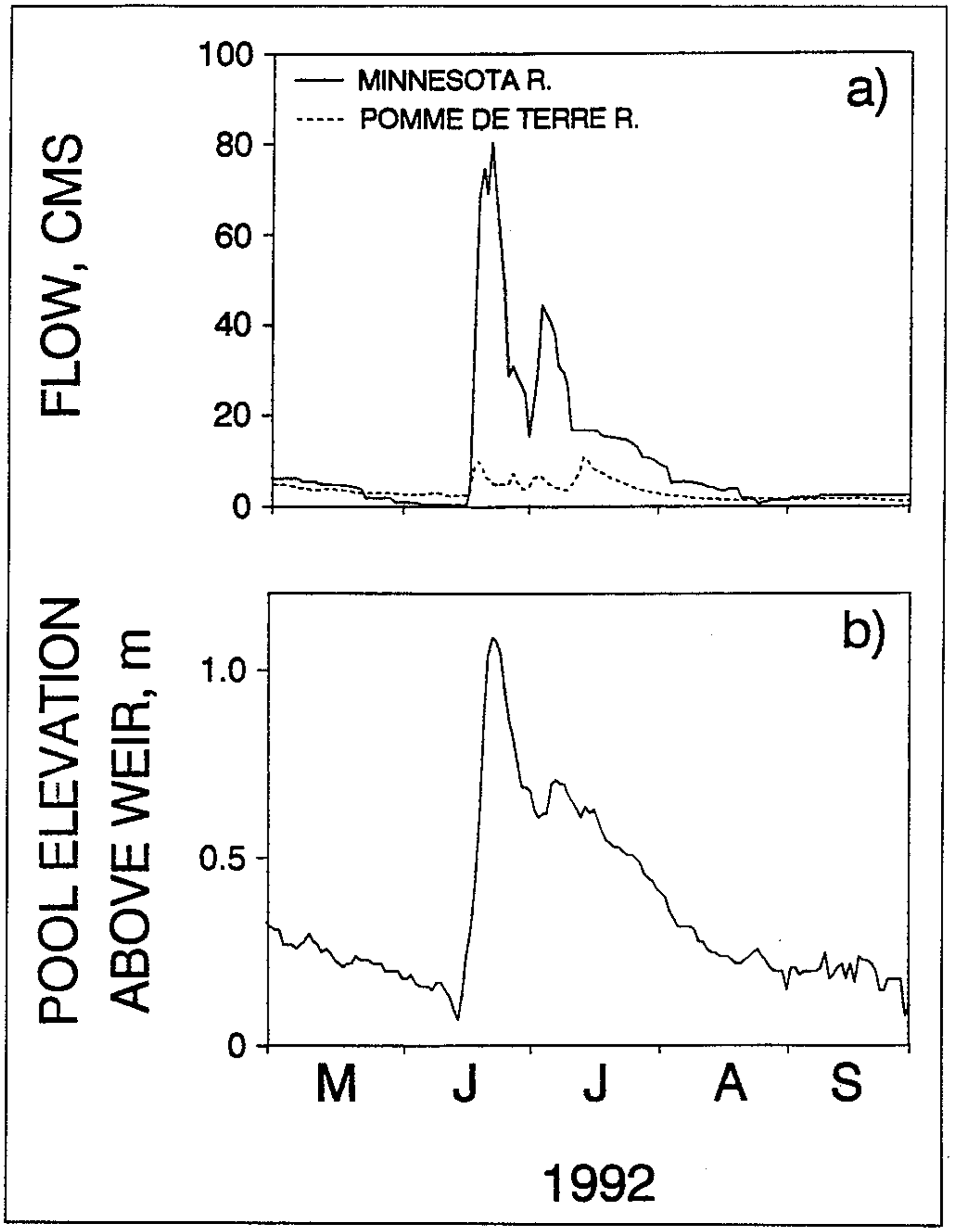

Figure 3. Variations in: a) flow from the Minnesota and Pomme De Terre Rivers and b) the height of Marsh Lake's pool elevation above the weir outlet structure during May through September, 1992

from any direction. Water sampling stations in Marsh Lake were potentially affected by wind velocities ranging between 10 and 15 km/h for all wind directions, when the pool was at normal elevation (Table 5). As pool elevation increased during storm inflows in the summer (Figures 2b and 3b), the wind velocity required to resuspend sediment potentially increased at these stations (Figure 10).

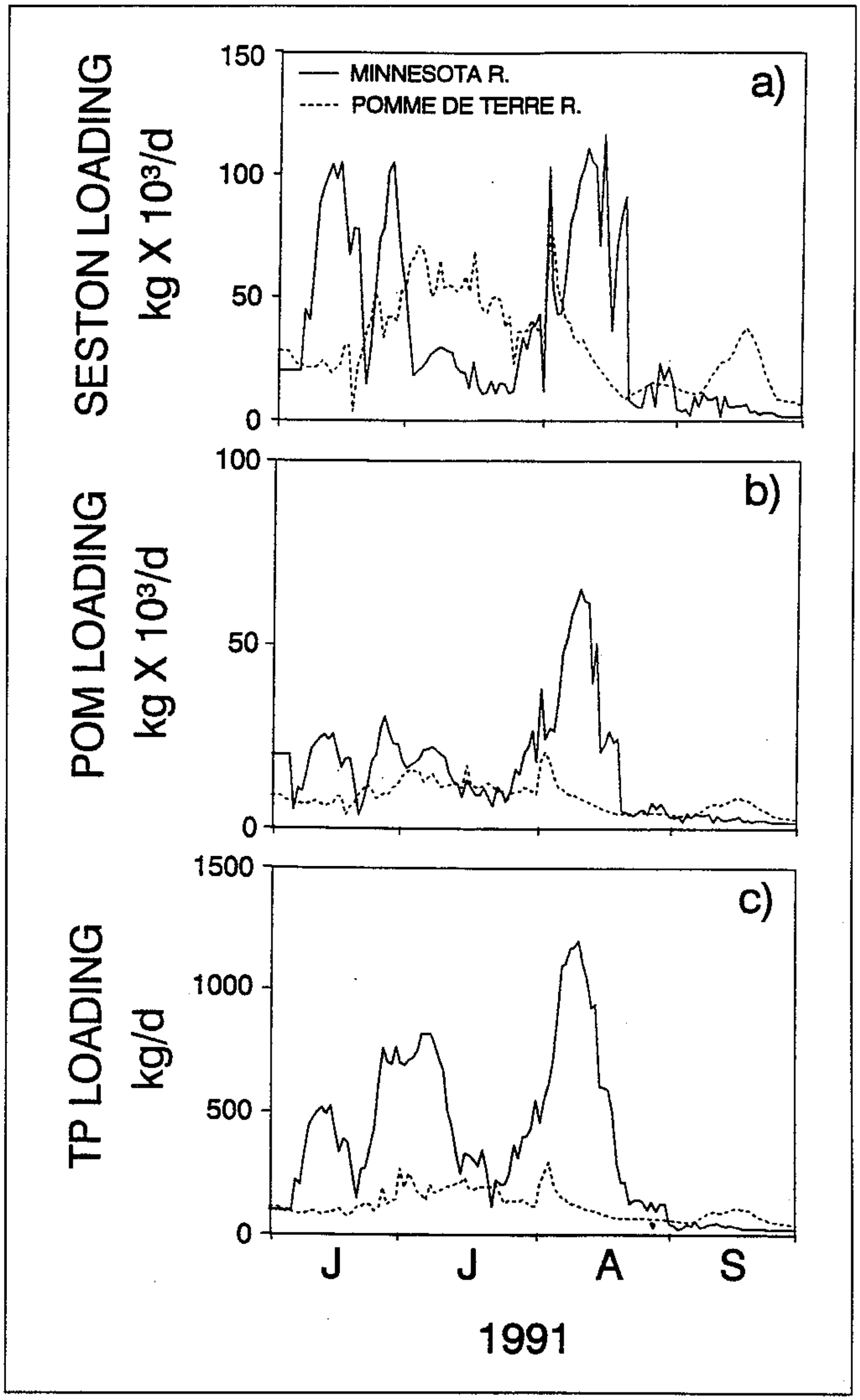

Figure 4. Variations in estimated daily loadings for: a) seston, b) particulate organic matter, and c) total phosphorus from the Minnesota and Pomme De Terre Rivers during June through September, 1991

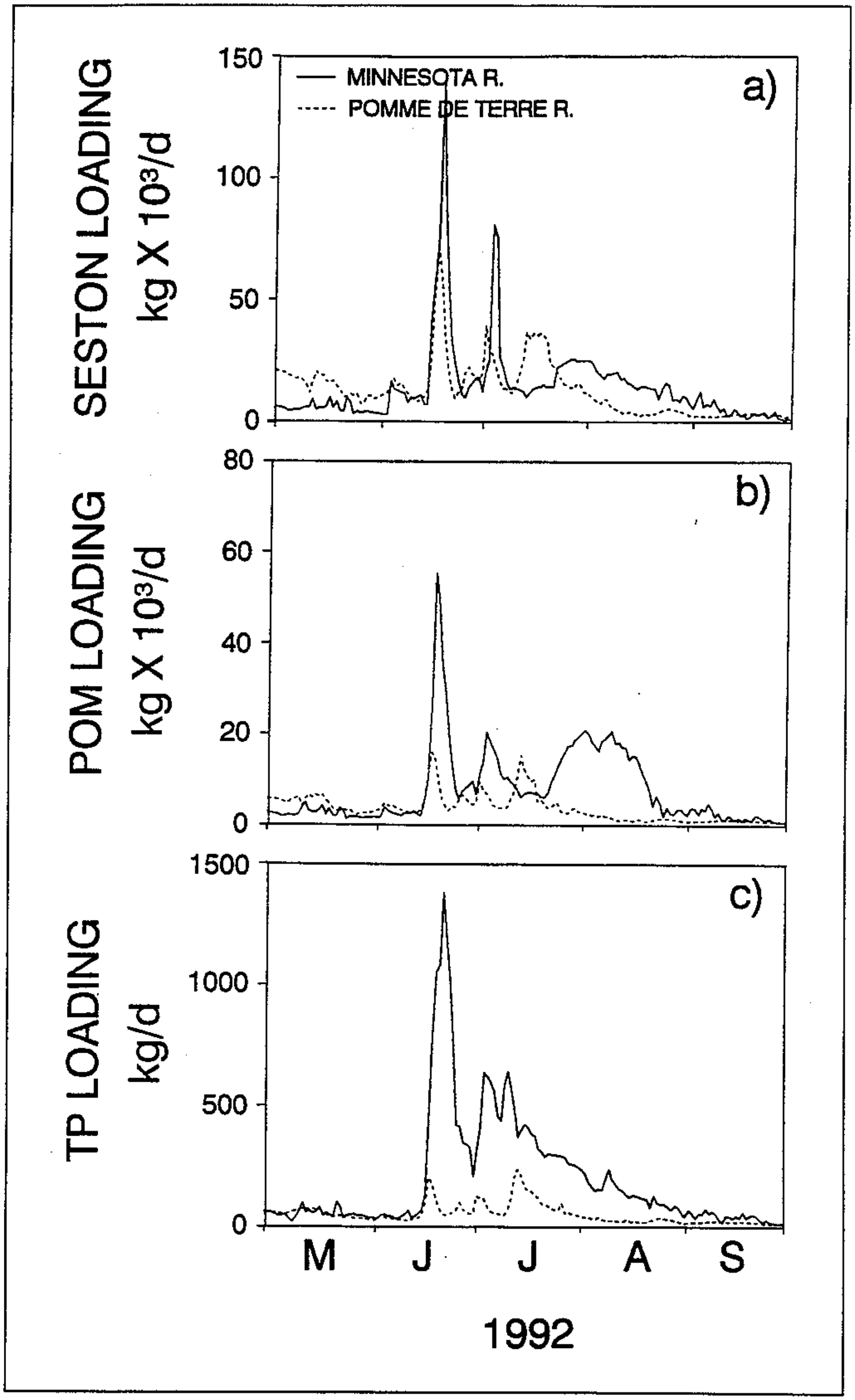

Figure 5. Variations in estimated daily loadings for: a) seston, b) particulate organic matter, and c) total phosphorus from the Minnesota and Pomme De Terre Rivers during May through September, 1992

Table 1
Average Daily Loadings of Seston, POM, and Total P from the Minnesota and Pomme De Terre Rivers

Constituent	1991 June - September		1992 May - September	
	Minnesota R. kg/d	Pomme De Terre R. kg/d	Minnesota R. kg/d	Pomme De Terre R. kg/d
Seston	36,000	31,000	14,500	13,000
POM	16,000	8,300	7,847	3,600
Total P	360	120	200	50

Table 2
Frequency of Occurrence of Daily Average Wind Speeds Blowing in Various Directions During Summer and Autumn, 1991 (i.e., June Through September)

Wind Speed km/h	Wind Direction				
	NE	SE	SW	NW	Total
< 5	0	2	4	0	6
5-10	3	29	17	5	54
10-15	0	17	9	5	31
15-20	0	2	5	4	11
20-25	0	0	1	3	4
Total	3	50	36	17	106

Table 3
Frequency of Occurrence of Daily Average Wind Speeds Blowing in Various Directions During the Summer and Autumn, 1992 (i.e., May Through September)

Wind Speed km/h	Wind Direction				
	NE	SE	SW	NW	Total
< 5	1	10	5	0	16
5-10	3	23	35	5	66
10-15	1	12	15	12	40
15-20	0	4	5	8	17
20-25	0	2	3	3	8
Total	5	51	63	28	147

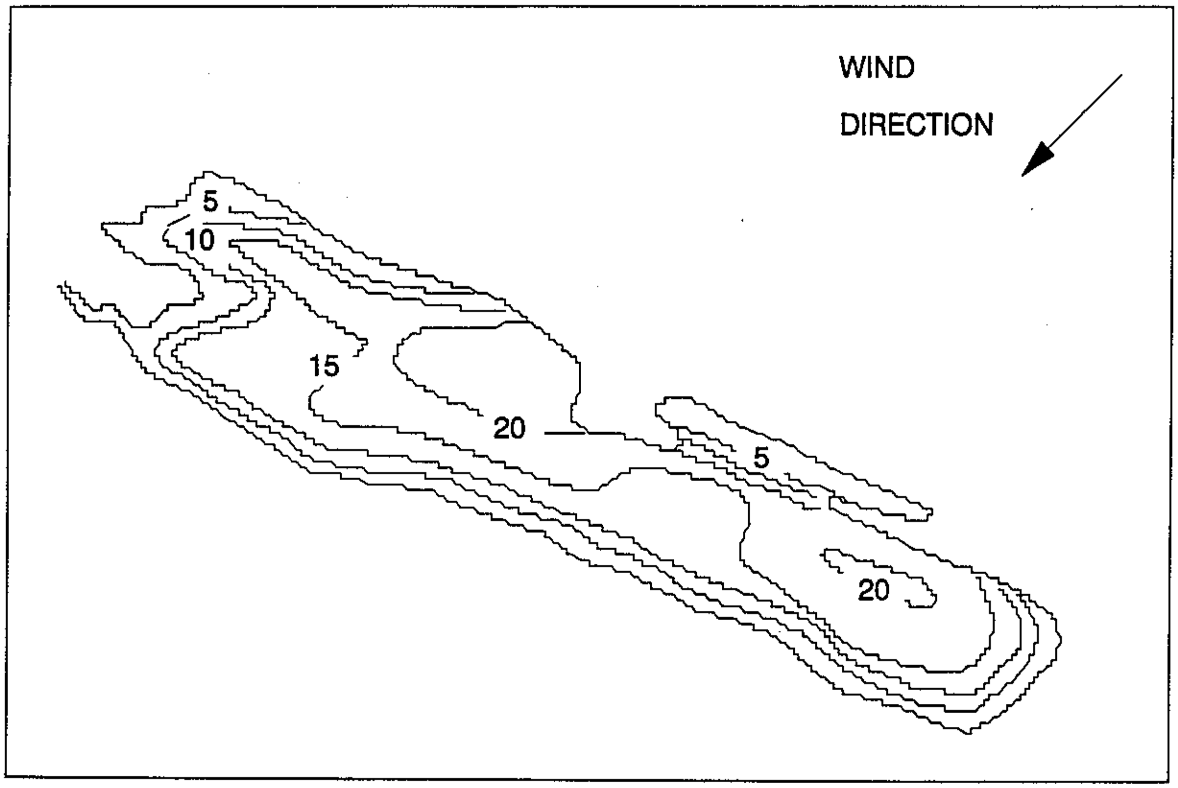

Figure 6. Contour map of wind velocities (km/h) from the northeast required to resuspend sediment in Marsh Lake

Sediment Resuspension and Seston Concentration

In 1991, mean daily wind velocities fluctuated between about 5 and 19 km/h from June through mid-September (Figure 11). Peaks in mean daily wind velocity of ≥ 19 km/h occurred in late September (Figure 11). Wind direction during these periods of high wind velocity was predominantly from the northwest. Seston concentrations were relatively low (i.e., < 50 mg/L) in Marsh Lake from June through mid-September (Figure 11), coincident with lower mean daily wind velocities and higher pool elevations (Figure 2b). However, concentrations of seston increased markedly in late September (i.e. > 100 mg/L) in association with high, mean daily wind velocities of ≥ 19 km/h.

A similar seasonal pattern was observed for seston concentrations in the outflow of Marsh Lake. During periods when mean daily wind velocity was relatively low (i.e., June through mid-September), concentrations of seston in the outflow were relatively low (Figure 11); however, they increased substantially in the outflow (i.e., > 100 mg/L) during late September. Increases coincided with both high mean daily wind velocities and high mean seston concentrations in the lake, suggesting the discharge of resuspended sediment (Figure 11).

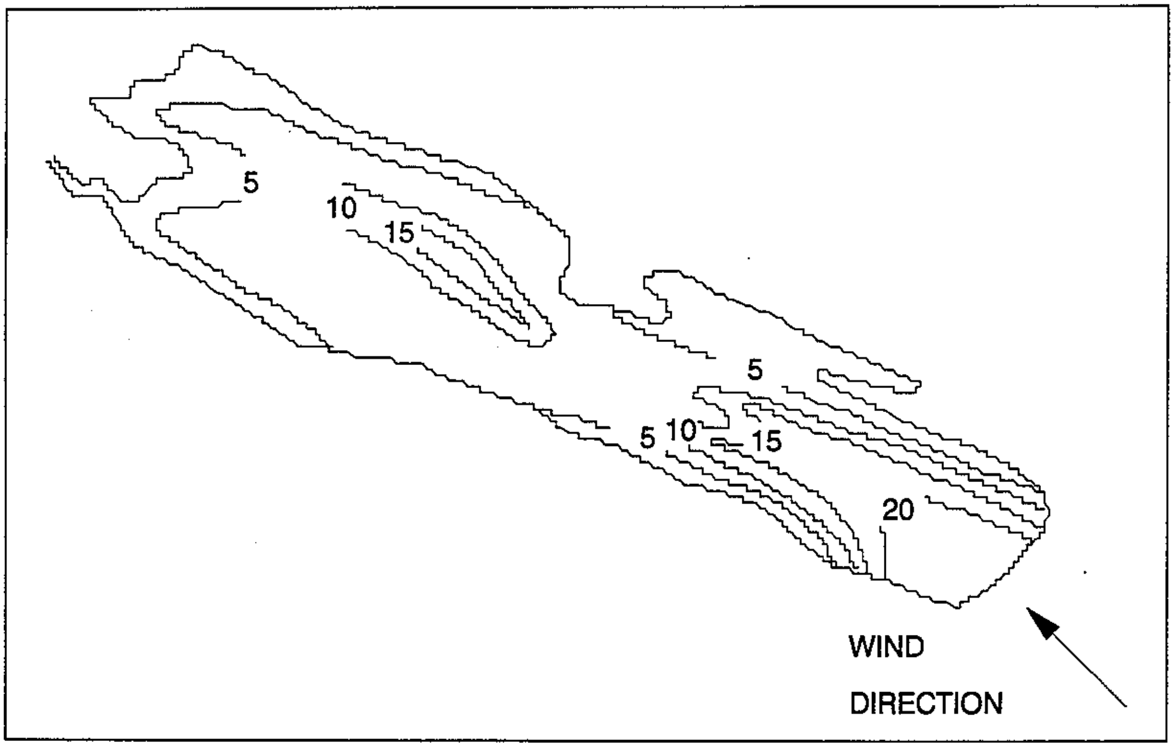

Figure 7. Contour map of wind velocities (km/h) from the southeast required to resuspend sediment in Marsh Lake

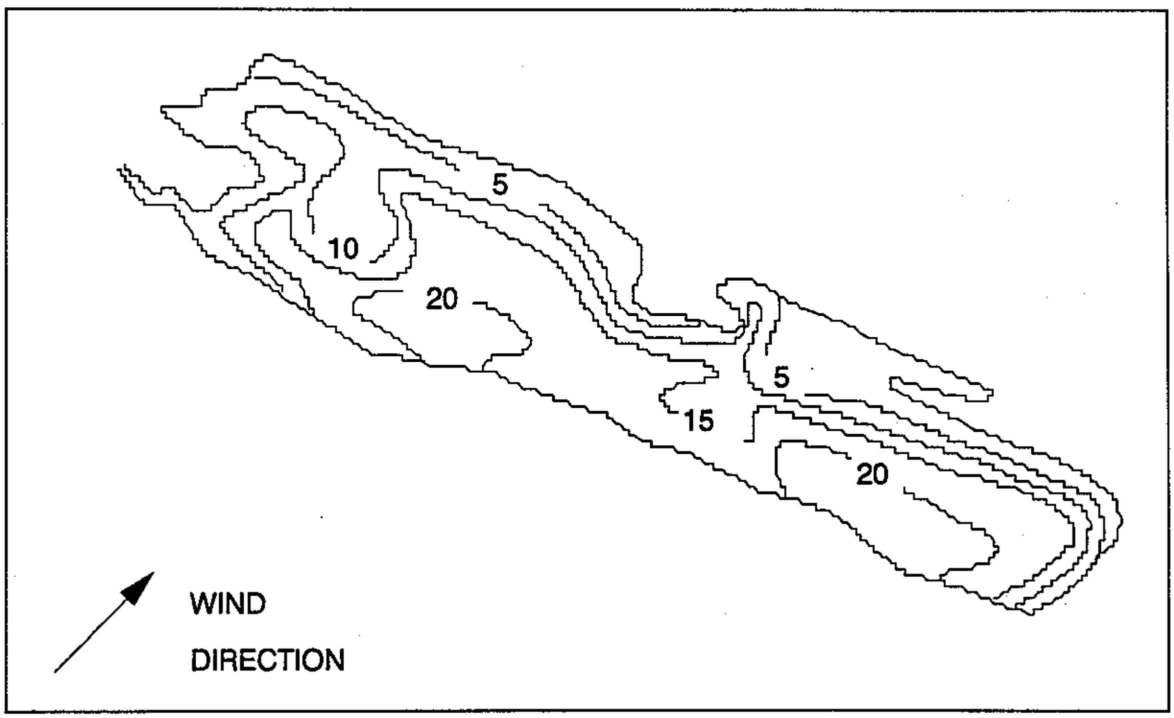

Figure 8. Contour map of wind velocities (km/h) from the southwest required to resuspend sediment in Marsh Lake

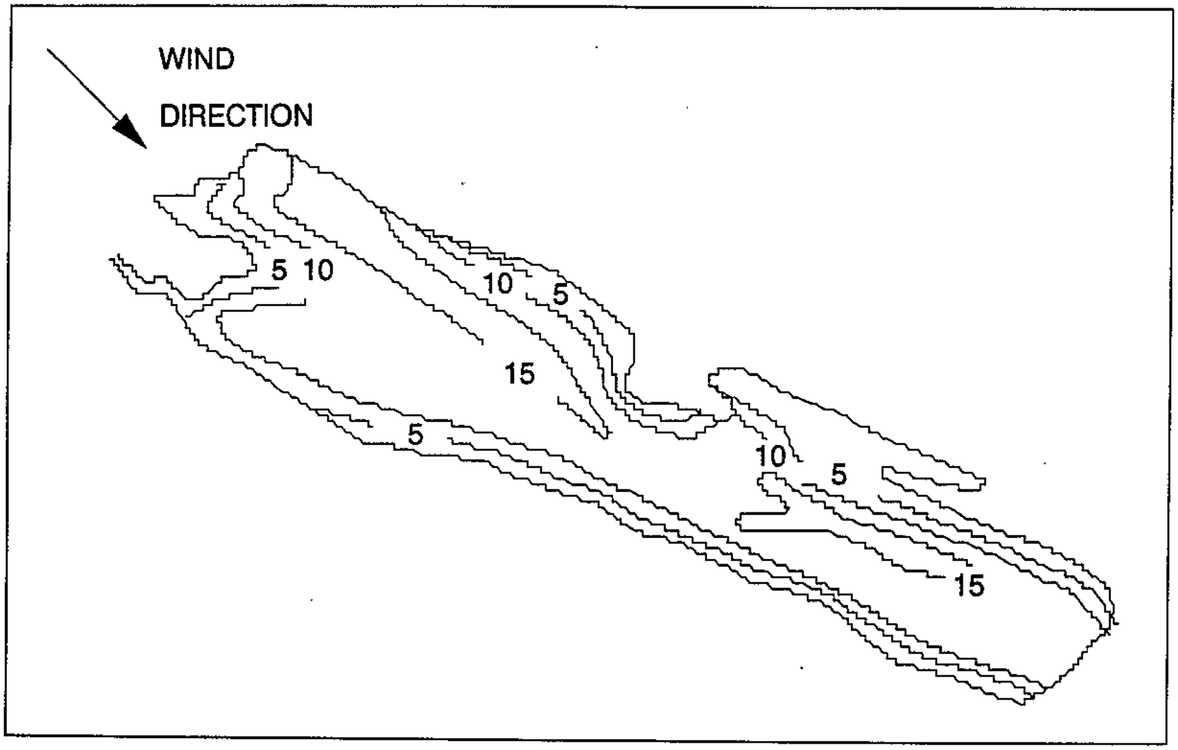

Figure 9. Contour map of wind velocities (km/h) from the northwest required to resuspend sediment in Marsh Lake

Table 4
Percent of the Lakebed Disturbed by Waves at Various Wind Speeds and Directions

Wind Speed km/h	Wind Direction			
	NE	SE	SW	NW
5	22	22	17	17
10	49	67	37	75
15	86	95	81	100
20	100	100	100	100

Although we predicted from the wave model (Carper and Bachmann 1984) that sediment resuspension would occur at wind velocities of only 10.5 to 15 km/h, depending on wind direction (Table 5), the actual critical wind velocity for sediment resuspension was about 20 km/h in 1991, based on relationships between mean daily wind speed and Marsh Lake seston concentrations (Figure 12). At these wind velocities from the northwest, seston concentrations were elevated in the outflow in 1991, and the seston retention rate was high and extremely negative (i.e., $< -100 \times 10^3$ kg/d; Figure 12), indicating a net loss of sediment from the system during sediment resuspension events (Figure 13). The discrepancy between predicted and observed critical wind

Table 5
Comparison of Effective Fetches and Wind Velocities Required to Resuspend Sediment at Stations 1 and 2 for Various Wind Directions at Nominal Water Column Depths (i.e., ~ 0.8 m)

Wind Direction	Effective Fetch m	Wind Velocity Required for Sediment Resuspension km/h
Station 1		
NE	1,100	15.0
SE	1,200	14.5
SW	1,100	15.0
NW	2,900	10.5
Station 2		
NE	1,150	15.5
SE	2,500	11.0
SW	1,200	14.5
NW	1,900	12.0

velocities may be attributed to the presence of high densities of submersed aquatic macrophytes which potentially dampened wave activity and sediment resuspension in 1991.

During 1992, mean daily wind velocities were generally greatest in May and late August through September and much lower during late June through mid-August (Figure 14). However, the highest mean daily wind velocity of 24 km/h occurred in mid-June. Mean seston concentrations (100 to 200 mg/L) increased substantially in both Marsh Lake and the outflow during these windy periods in 1992 (Figure 14). In contrast, seston concentrations (< 50 mg/L) were much lower during the calmer summer months.

Relationships between mean daily wind speed and seston concentrations in Marsh Lake suggested that a critical wind velocity of about 12 km/h was required for sediment resuspension in 1992 (Figure 15). Above this critical wind velocity, seston concentrations increased in a linear fashion with increasing wind velocity ($p < 0.05$; $r = 0.58$), regardless of wind direction. Below this critical wind velocity, seston concentrations were usually < 50 mg/L. Anomalously high seston concentrations (i.e., between 50 and 100 mg/L) below this critical wind speed were representative of seston samples collected 1 day after the occurrence of a sediment resuspension event (wind speeds > 15 km/h). This pattern in 1992 suggested a time lag of at least 1 day for the recovery of seston concentrations to nominal values following wind-generated sediment resuspension.

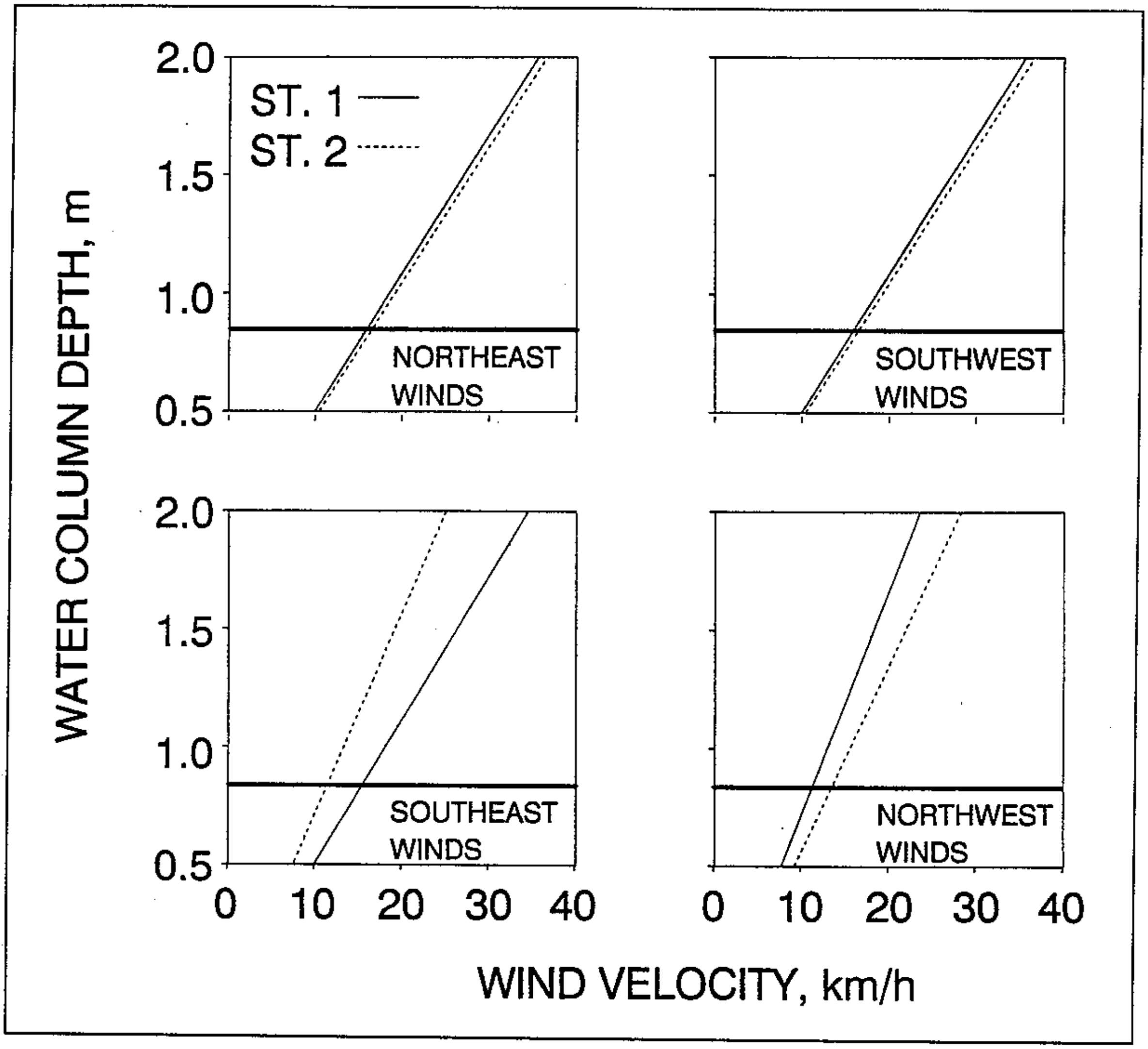

Figure 10. The relationship between wind velocity and the depth where wavelengths will resuspend sediment at stations 1 and 2 for different wind directions. For instance, if the water column depth at station 1 is 2 m, due to storm inflows, the wind velocity required to resuspension the sediment is 36 km/h for winds blowing from the northeast. The bold horizontal line represents the depth (0.8 m) of stations 1 and 2 at normal pool elevation. Add 0.8 m to the pool elevation above the weir (shown in Figures 2b and 3b) to determine actual sample station depth

The critical wind velocity required to resuspend sediment in Marsh Lake in 1992 more closely coincided with predicted values determined from the wave model (Figure 15 and Table 5), which contrasted markedly with the higher critical wind velocity required in 1991. This apparent decline in the critical wind velocity in 1992 coincided with an almost complete absence of submersed aquatic macrophytes in Marsh Lake during that year.

Wind direction, in addition to wind speed, appeared to be an important factor regulating the discharge of resuspended seston from Marsh Lake in 1992

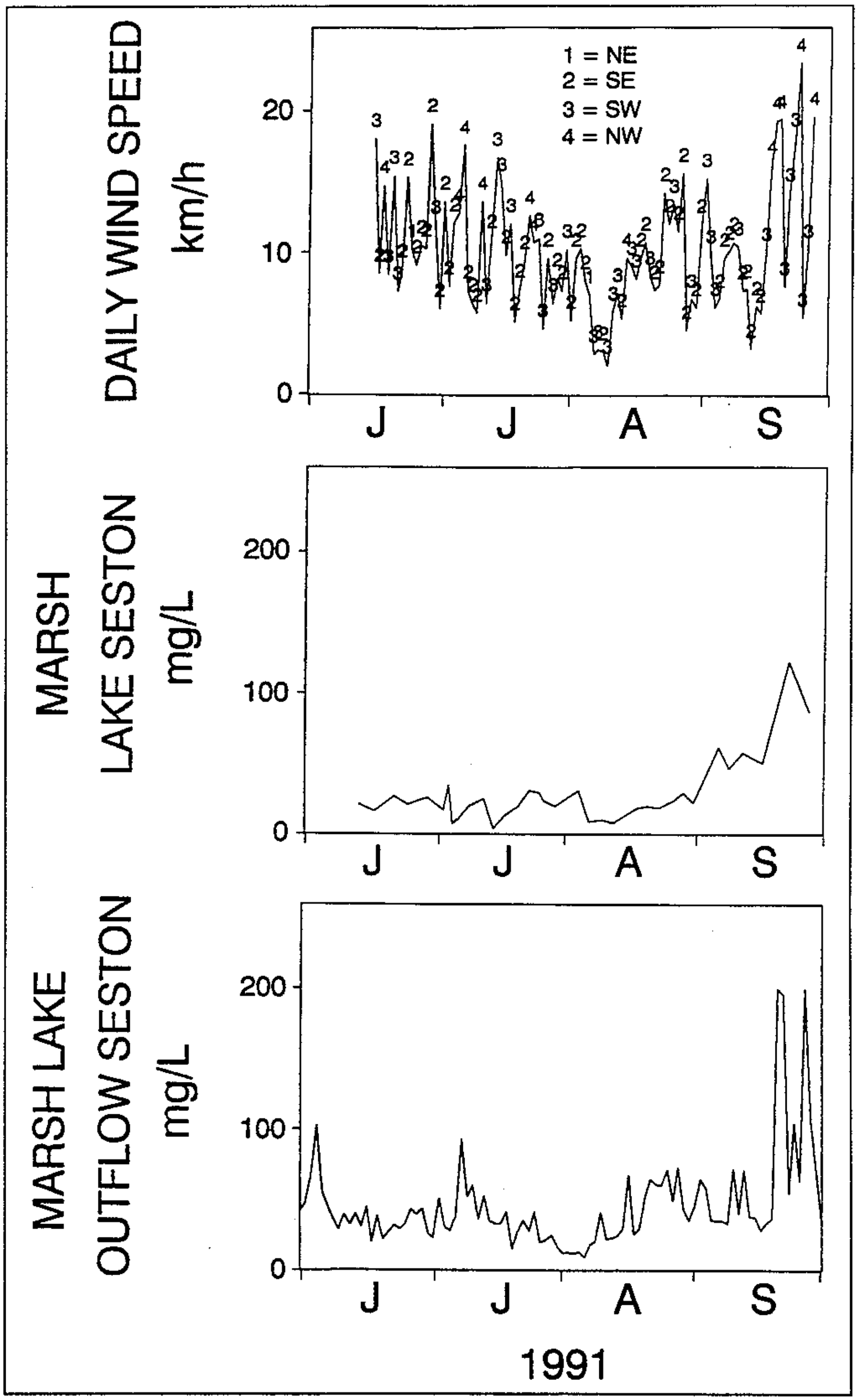

Figure 11. Variations in mean daily wind velocity (upper panel); seston concentrations in Marsh lake (middle panel) and in the outflow (lower panel) during June through September, 1991

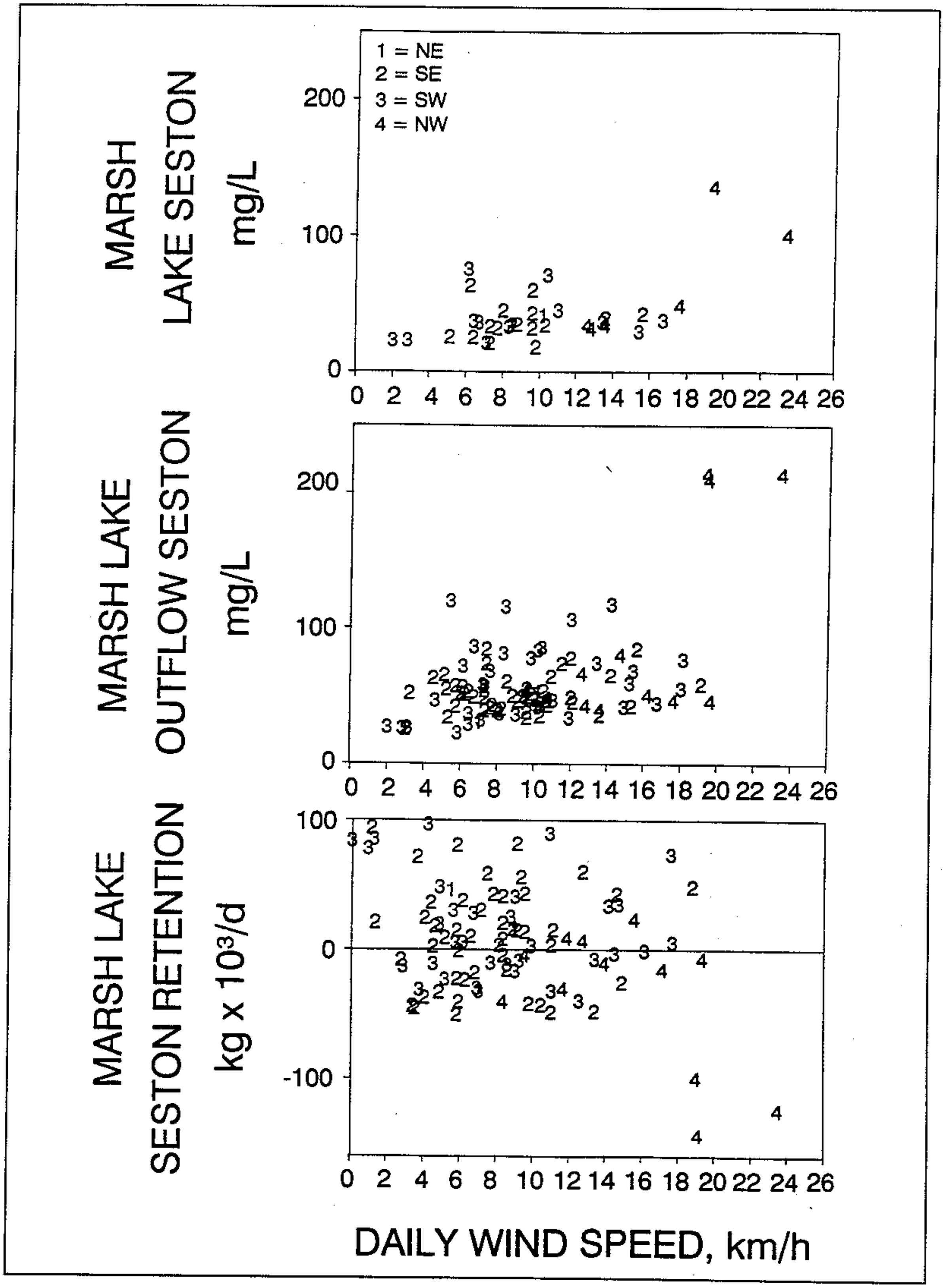

Figure 12. Relationships between mean daily wind velocity and seston concentrations in Marsh Lake (upper panel) and in the outflow (middle panel); daily retention of seston (lower panel) in the lake during June through September, 1991

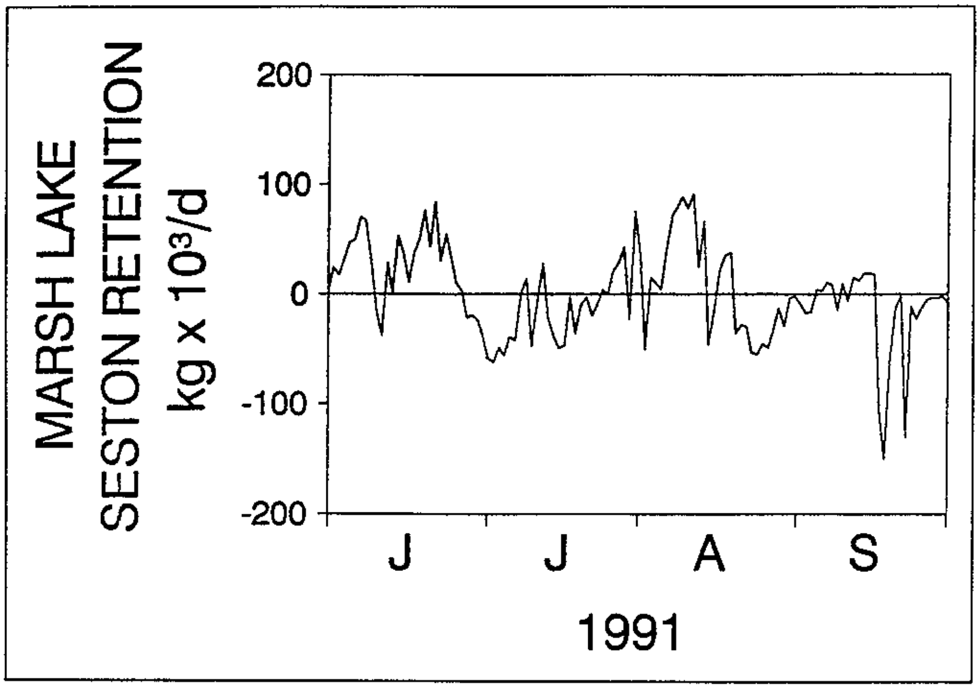

Figure 13. Variations in daily retention of seston in Marsh Lake during June through September, 1991

(Figure 15). Although seston concentrations generally increased in the outflow above a critical wind velocity of about 12 km/h, concentration increases appeared to be greatest when strong winds were blowing from the northwest toward the outlet weir. When winds (above about 12 km/h) were blowing from southerly directions (i.e., away from the outlet weir), outflow concentrations remained low even though Marsh Lake exhibited high seston concentrations due to sediment resuspension (Figure 14).

During 1992, seston retention was usually negative when mean daily wind velocities exceeded about 12 km/h, particularly when winds were blowing from the northwest, indicating discharge of resuspended sediment (Figure 15). Negative seston retention rates generally occurred during high winds in May and late August through September (Figure 16). In contrast, Marsh Lake retained seston during the midsummer months (i.e., June and July; Figure 16), coincident with the occurrence of high external loadings during storm inflows (Figure 3).

Water Quality

POM and total P concentrations exhibited the same general trends as seston during both years. During 1991, POM and total P concentrations were relatively low in Marsh Lake from June through August. Mean daily wind velocities did not exceed 19 km/h (Figures 17 and 18) during this period, and the

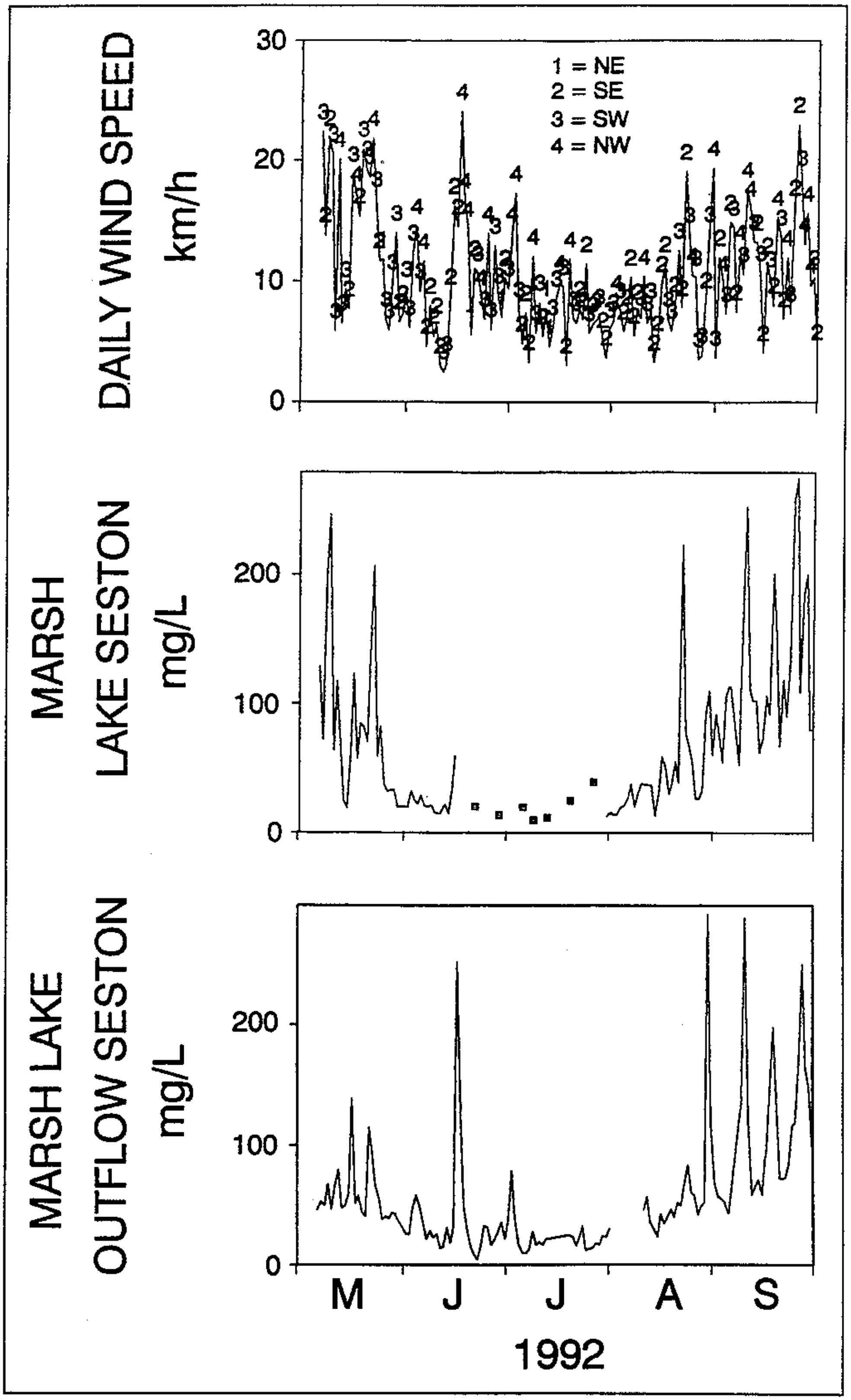

Figure 14. Variations in mean daily wind velocity (upper panel); seston concentrations in Marsh lake (middle panel) and in the outflow (lower panel) during May through September, 1992

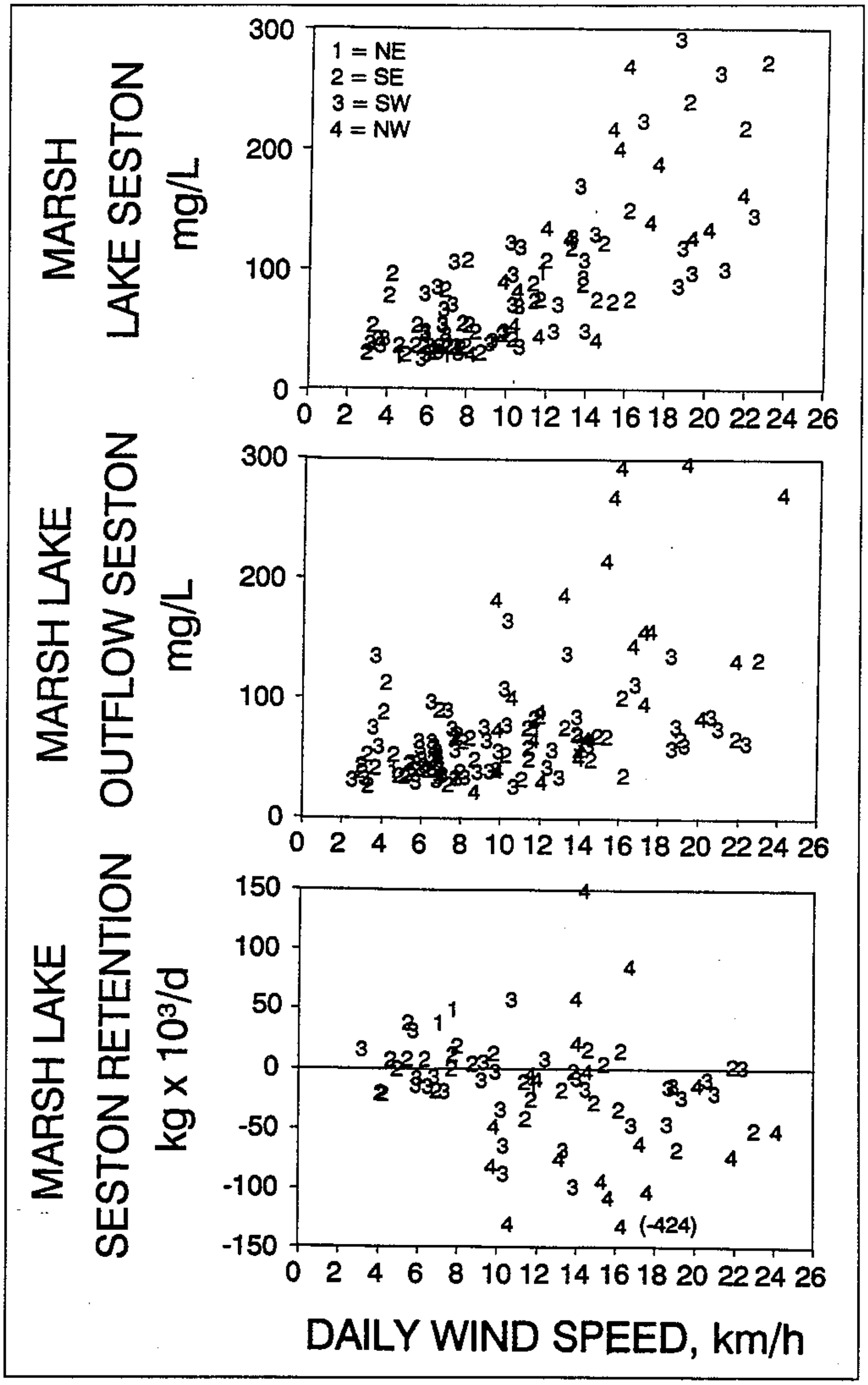

Figure 15. Relationships between mean daily wind velocity and seston concentrations in Marsh Lake (upper panel) and in the outflow (middle panel); daily retention of seston (lower panel) in the lake during May through September, 1992

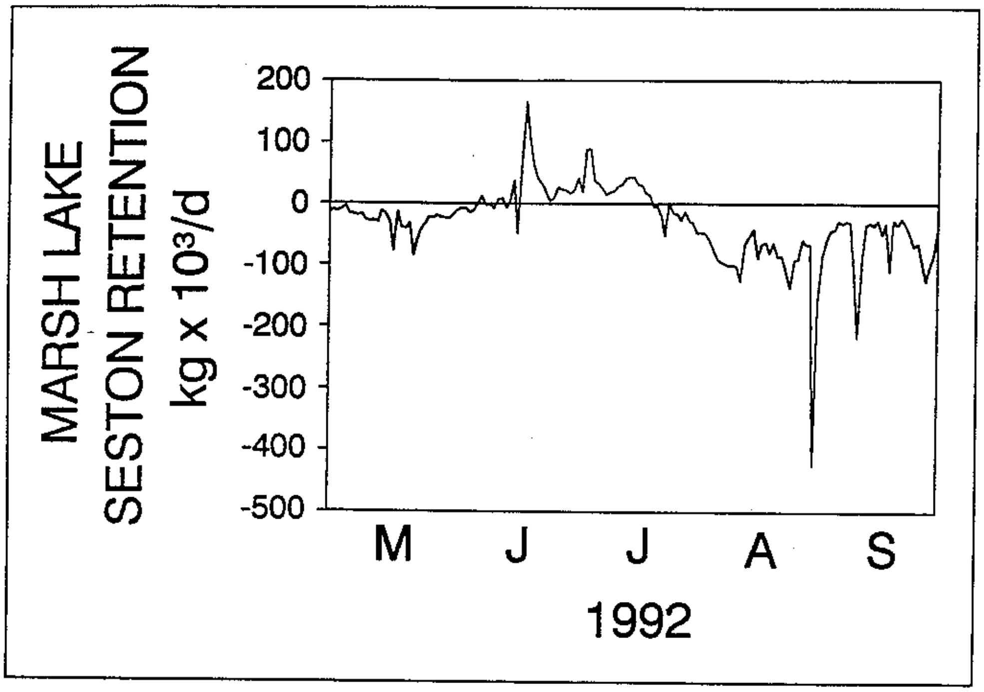

Figure 16. Variations in daily retention of seston in Marsh Lake during May through September, 1992

water column depth was deeper due to storm inflows. In September of 1991, POM and total P concentrations increased substantially in Marsh Lake and the outflow, as mean daily wind velocities exceeded 19 km/h (Figures 17 and 18).

As with seston, the critical wind velocity required to cause resuspension and discharge of POM and total P in Marsh Lake during 1991 was approximately 20 km/h (Figures 19 and 20). Highest net losses of POM and total P from Marsh Lake during 1991 also occurred above a critical wind velocity of 20 km/h (Figures 19 and 20). Marsh Lake retained POM and TP, when external loading was high in 1991, and exhibited a net loss of these constituents during high winds in September (Figures 21 and 22).

In 1992, POM and total P concentrations increased markedly in Marsh Lake and in the discharge in response to high mean daily wind velocities occurring in May and late August through September (Figures 23 and 24). Similar to the patterns observed in seston concentration during 1992, the critical wind velocity required to resuspend POM and total P in Marsh Lake declined to about 12 km/h (Figures 25 and 26).

As with patterns of seston discharge during sediment resuspension events, the greatest discharges of resuspended POM and total P from Marsh Lake occurred when high winds were blowing from the northwest toward the outflow structure (Figures 25 and 26). Discharge of relatively high concentrations of POM and total P from the outflow structure did not occur when high winds were blowing from southerly directions. In general, Marsh Lake retained POM

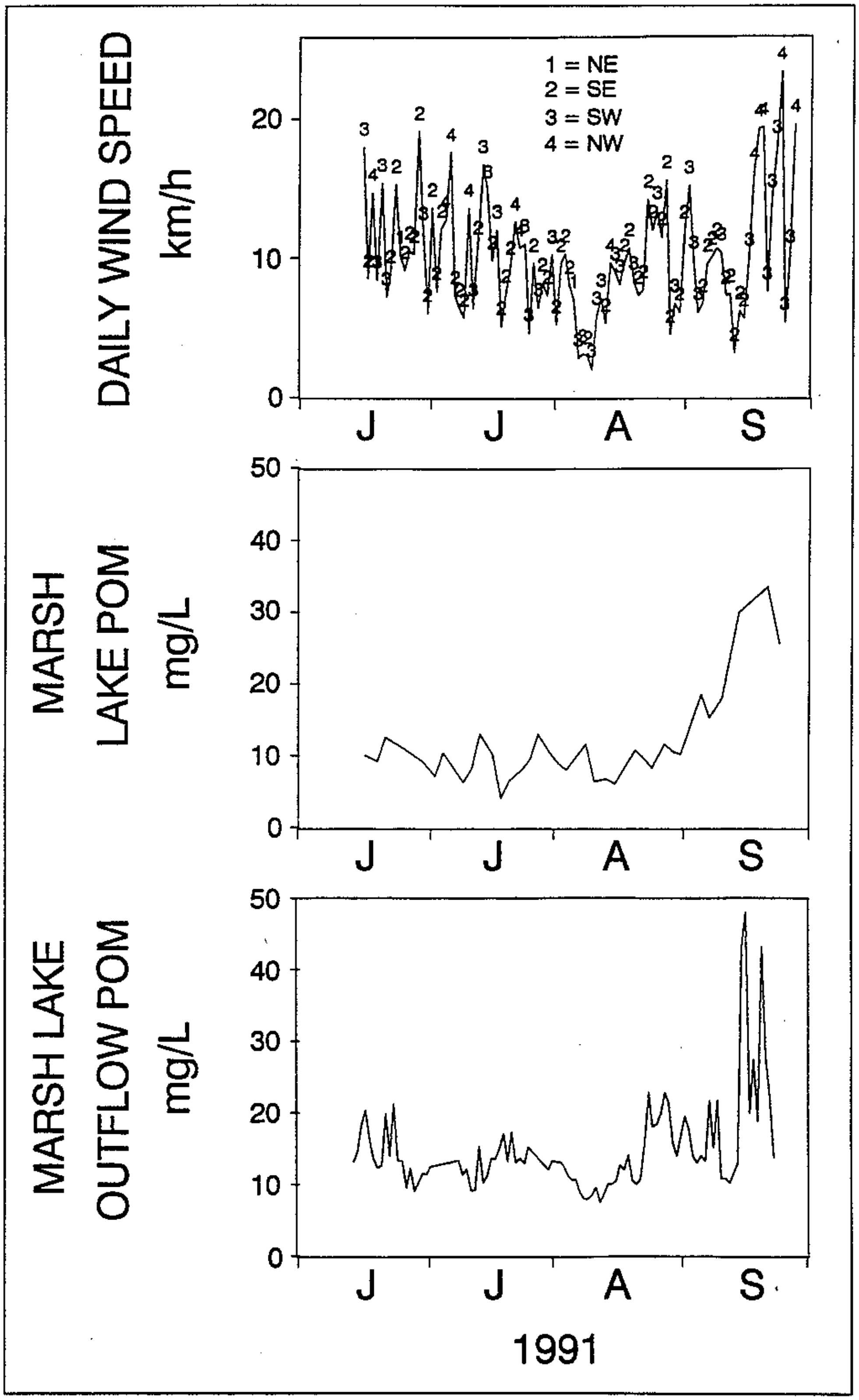

Figure 17. Variations in mean daily wind velocity (upper panel); particulate organic matter concentrations in Marsh Lake (middle panel) and in the outflow (lower panel) during June through September, 1991

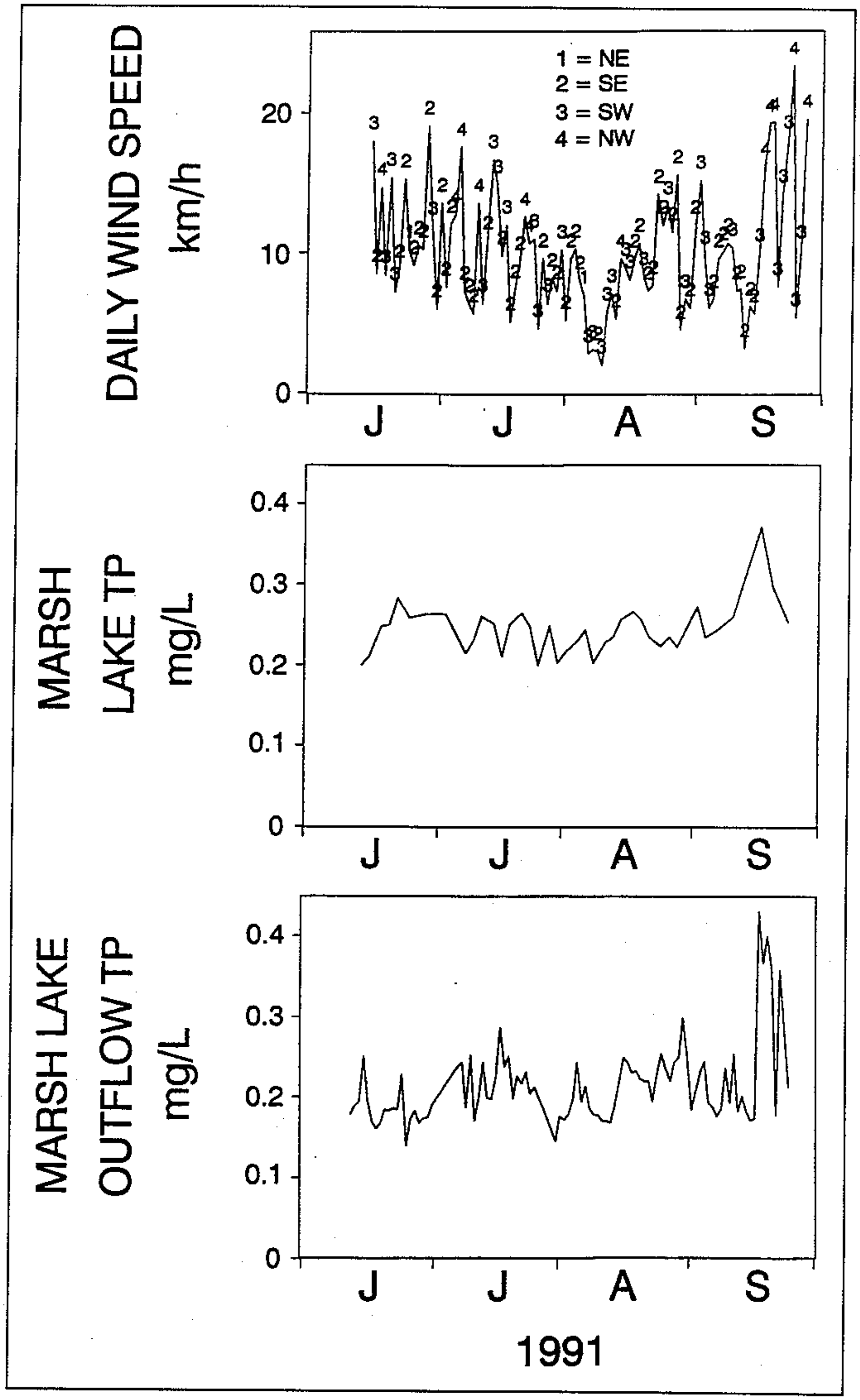

Figure 18. Variations in mean daily wind velocity (upper panel); total phosphorus concentrations in Marsh Lake (middle panel) and in the outflow (lower panel) during June through September, 1991

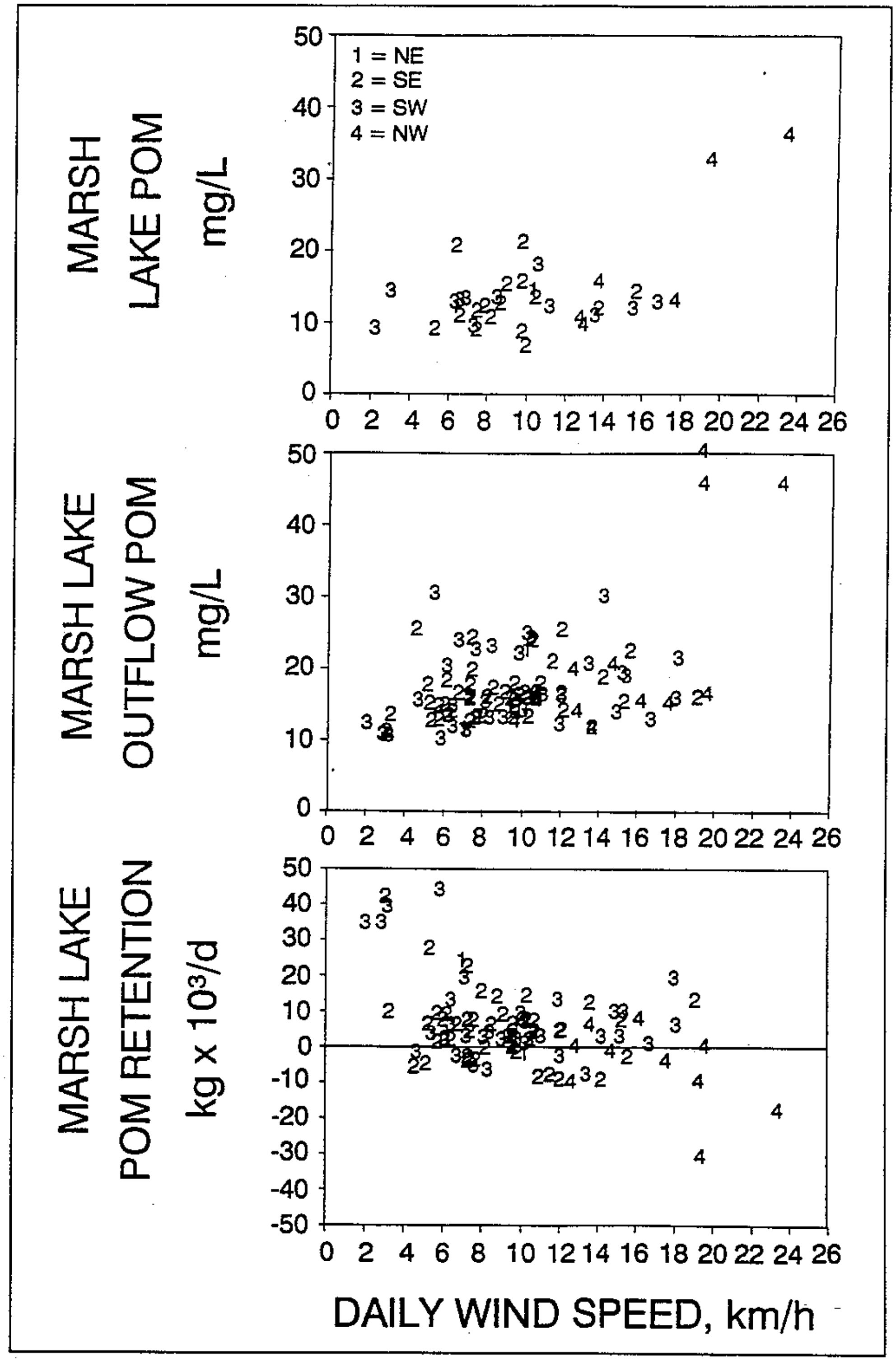

Figure 19. Relationships between mean daily wind velocity and particulate organic matter concentrations in Marsh Lake (upper panel) and in the outflow (middle panel); daily retention of particulate organic matter in the lake (lower panel) during June through September, 1991

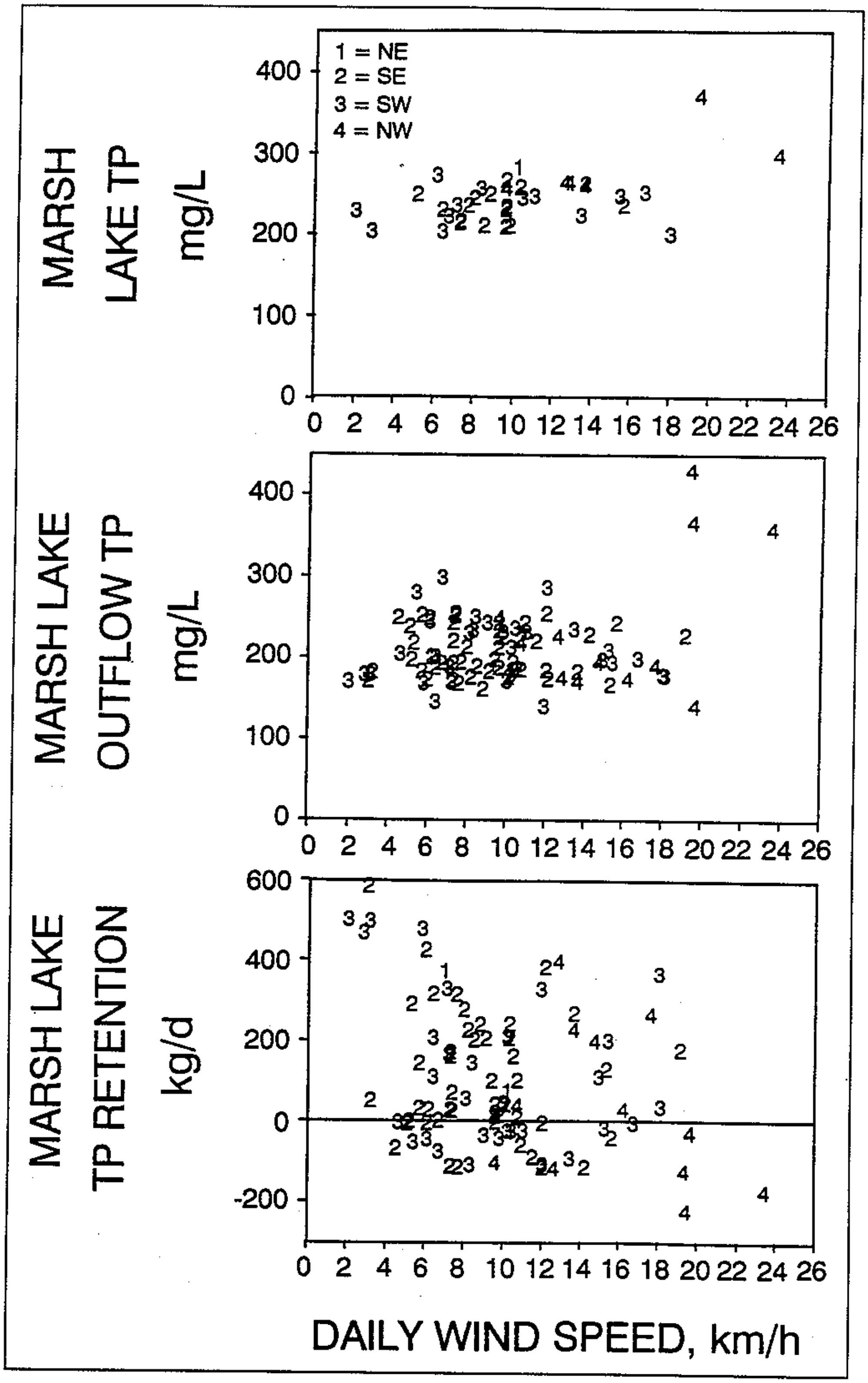

Figure 20. Relationships between mean daily wind velocity and total phosphorus concentrations in Marsh Lake (upper panel) and in the outflow (middle panel); daily retention of total phosphorus in the lake (lower panel) during June through September, 1991

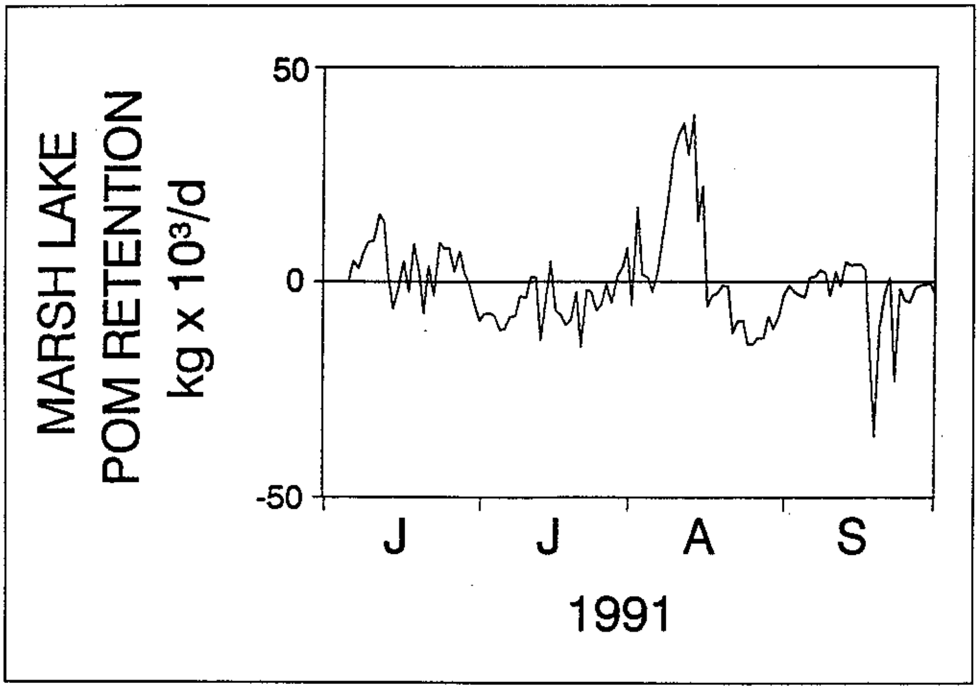

Figure 21. Variations in daily retention of particulate organic matter in Marsh Lake during June through September, 1991

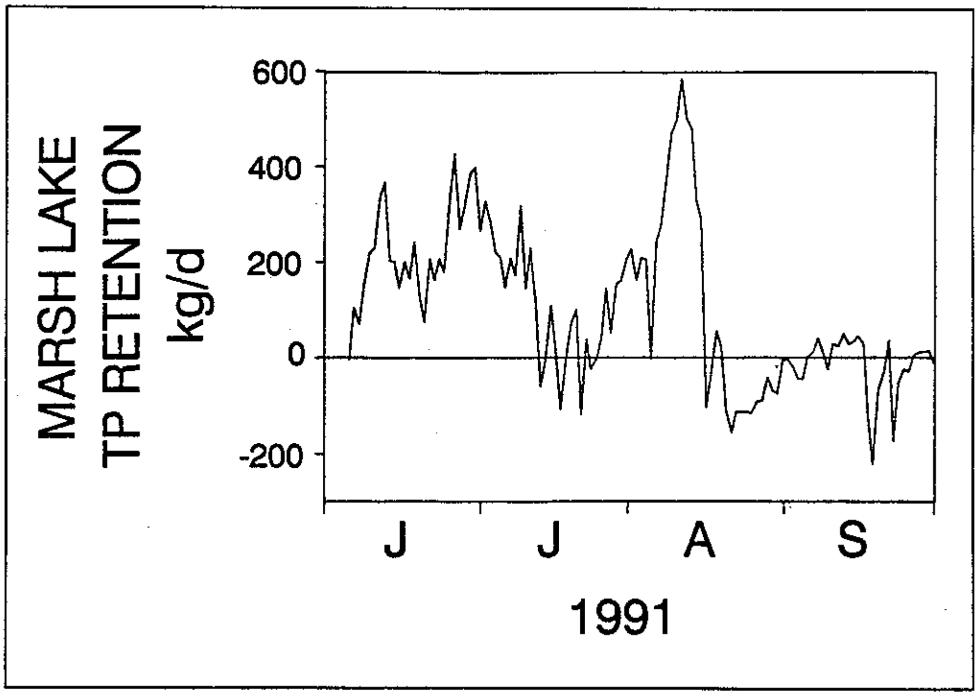

Figure 22. Variations in daily retention of total phosphorus in Marsh Lake during June through September, 1991

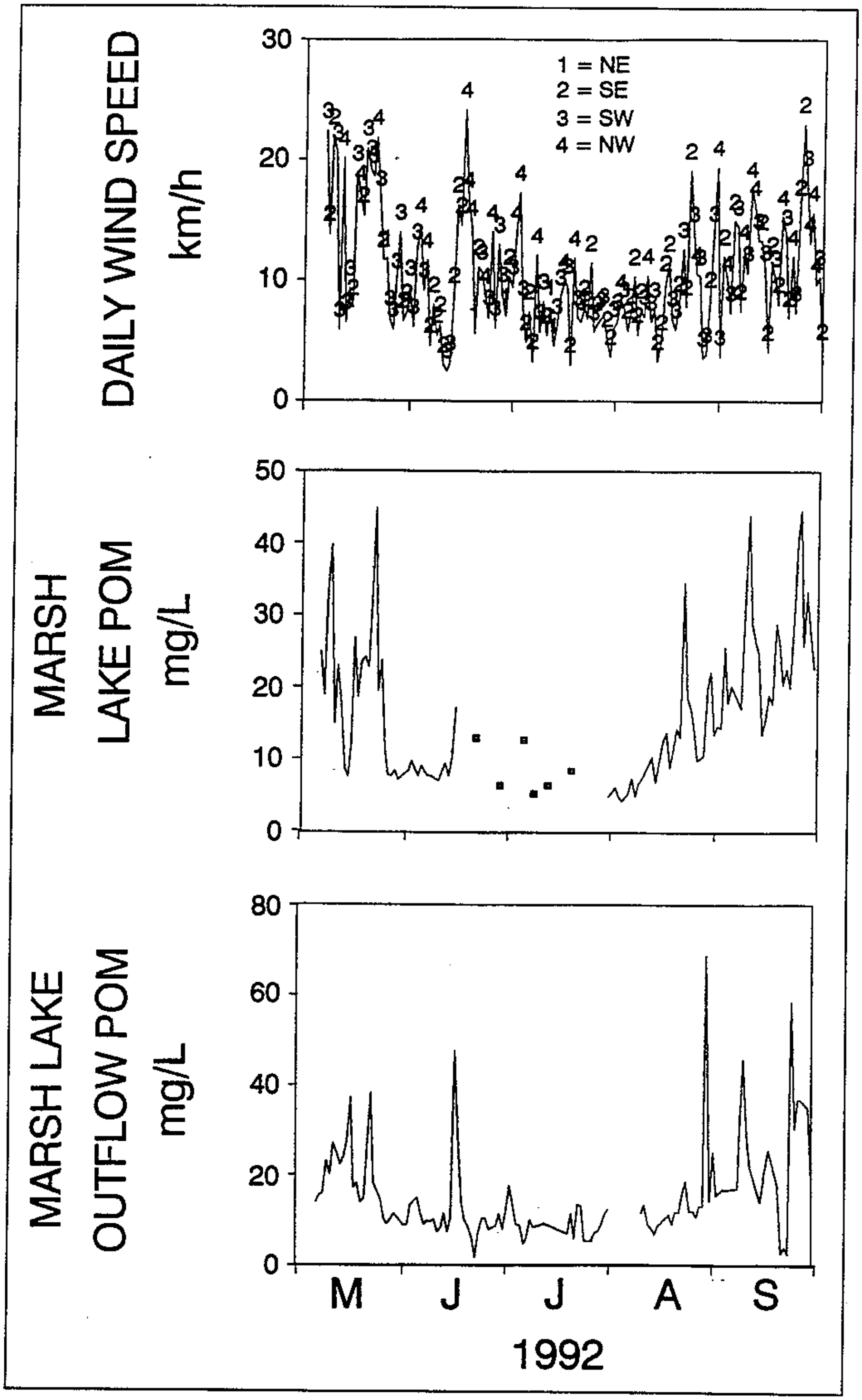

Figure 23. Variations in mean daily wind velocity (upper panel); particulate organic matter concentrations in Marsh Lake (middle panel) and in the outflow (lower panel) during May through September, 1992

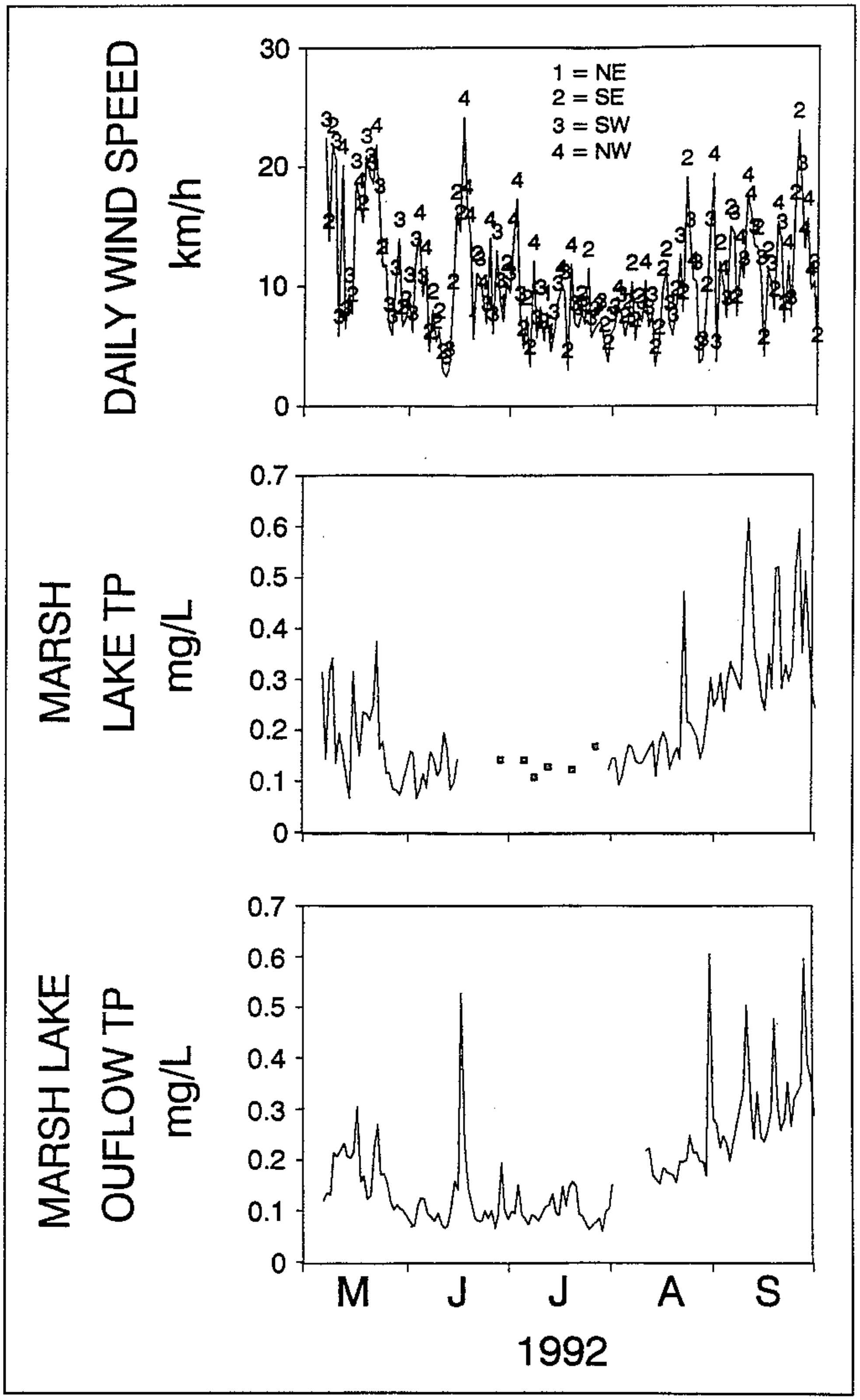

Figure 24. Variations in mean daily wind velocity (upper panel); total phosphorus concentrations in Marsh Lake (middle panel) and in the outflow (lower panel) during May through September, 1992

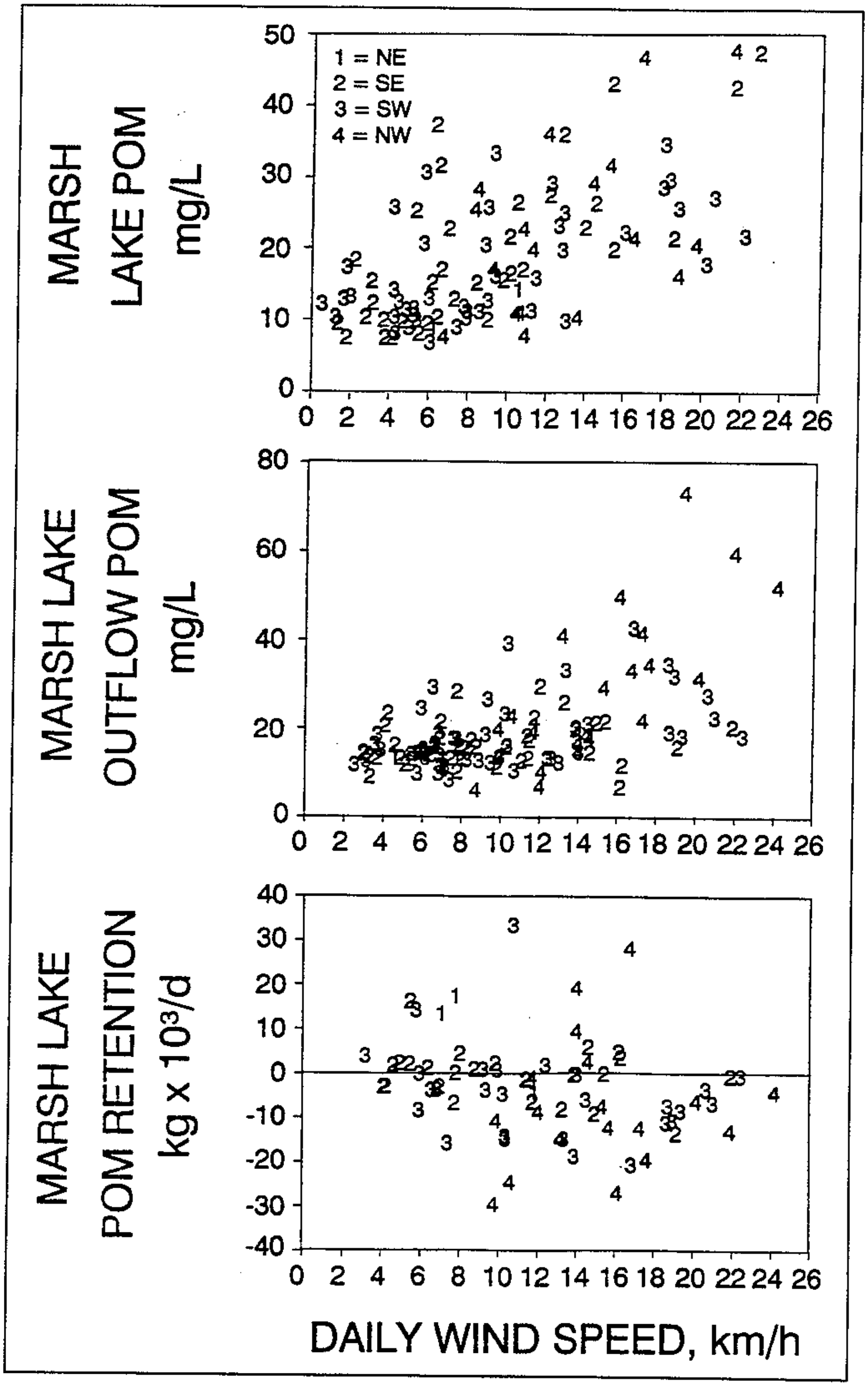

Figure 25. Relationships between mean daily wind velocity and particulate organic matter concentrations in Marsh Lake (upper panel) and in the outflow (middle panel); daily retention of particulate organic matter in the lake during May through September, 1992

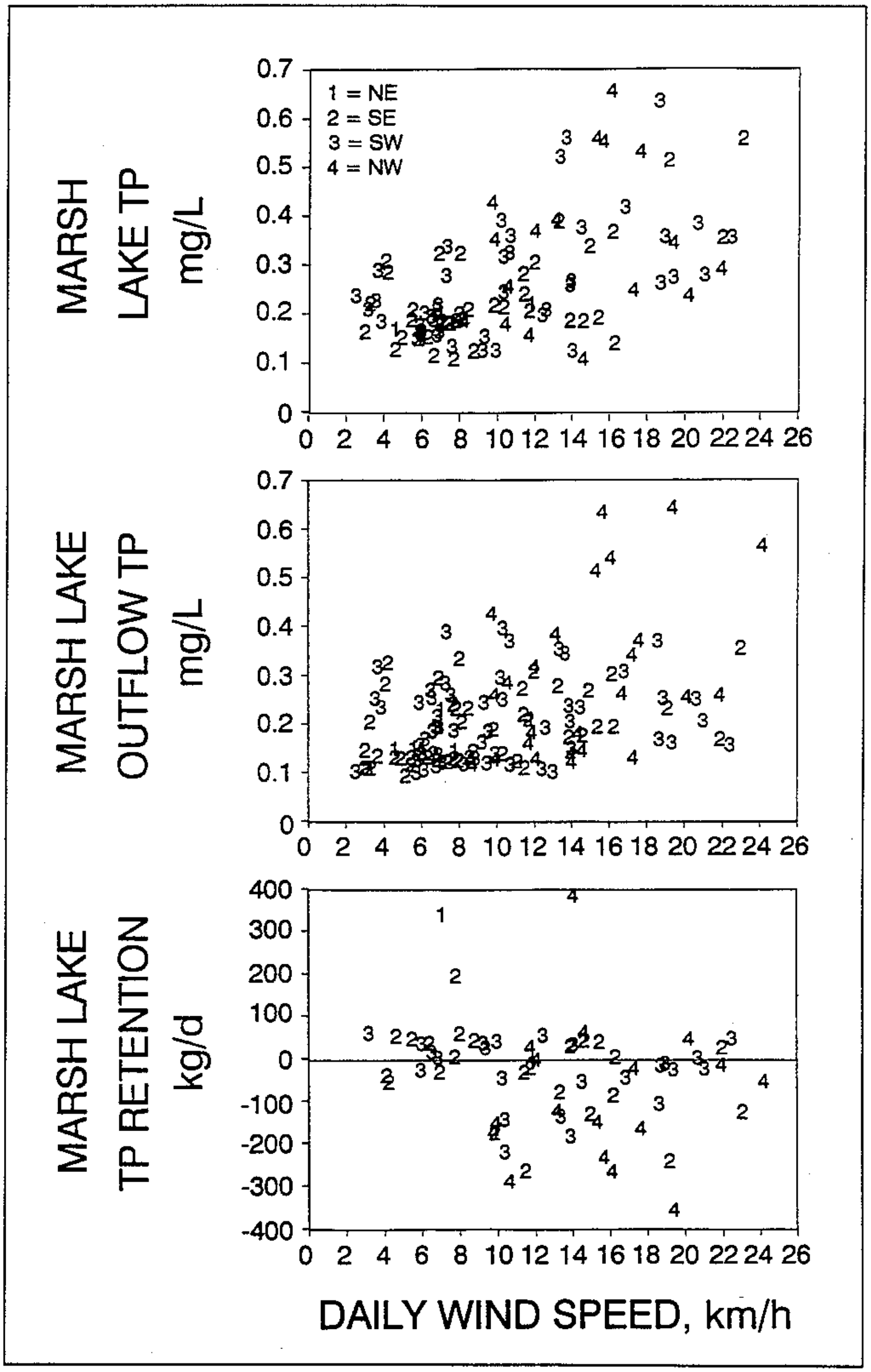

Figure 26. Relationships between mean daily wind velocity and total phosphorus concentrations in Marsh Lake (upper panel) and in the outflow (middle panel); daily retention of total phosphorus in the lake during May through September, 1992

and total P during periods of high external loadings in 1992, and exhibited a net loss of these constituents during May and August through September during periods of high mean daily wind velocities and sediment resuspension (Figures 27 and 28).

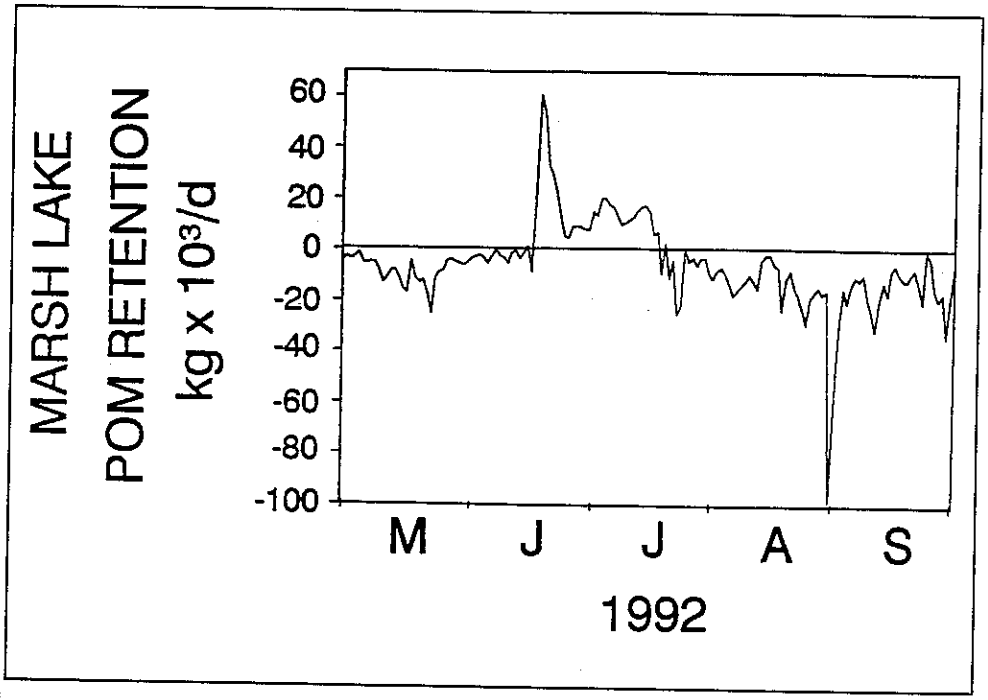

Figure 27. Variations in daily retention of particulate organic matter in Marsh Lake during May through September, 1992

Algal biomass in Marsh Lake, represented by chlorophyll concentrations, appeared to be affected by high wind velocities during both years. In particular, chlorophyll concentrations increased substantially (i.e., > 50 mg/m^3) during high winds in September of both years (Figures 29 and 30), coinciding with concomitant increases in total P concentrations in the water column. In contrast, chlorophyll concentrations were < 50 mg/m^3 during the calmer summer months of both years.

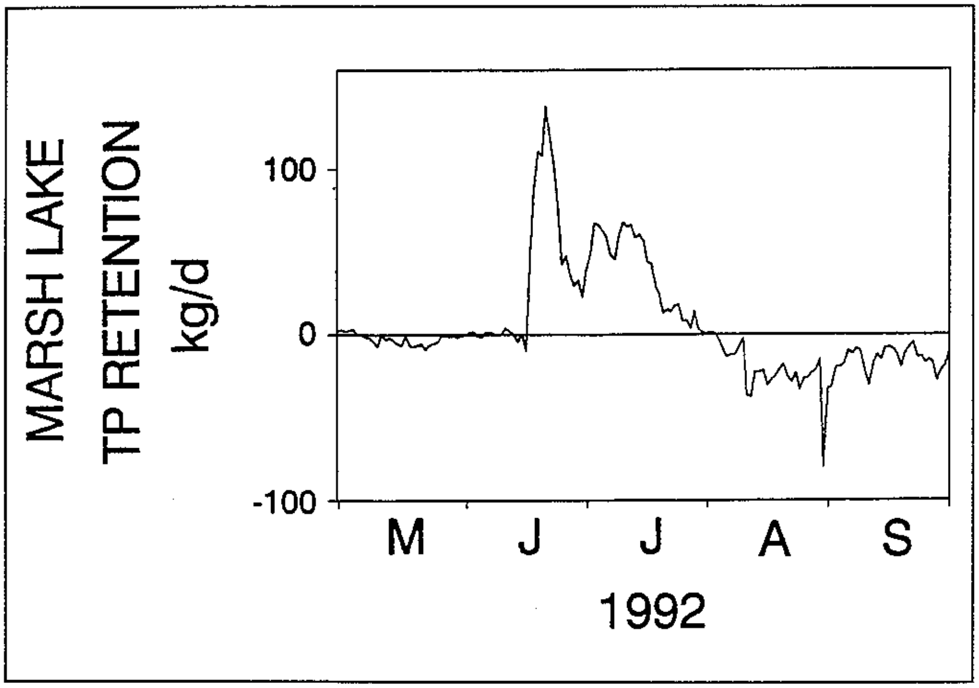

Figure 28. Variations in daily retention of total phosphorus in Marsh Lake during May through September, 1992

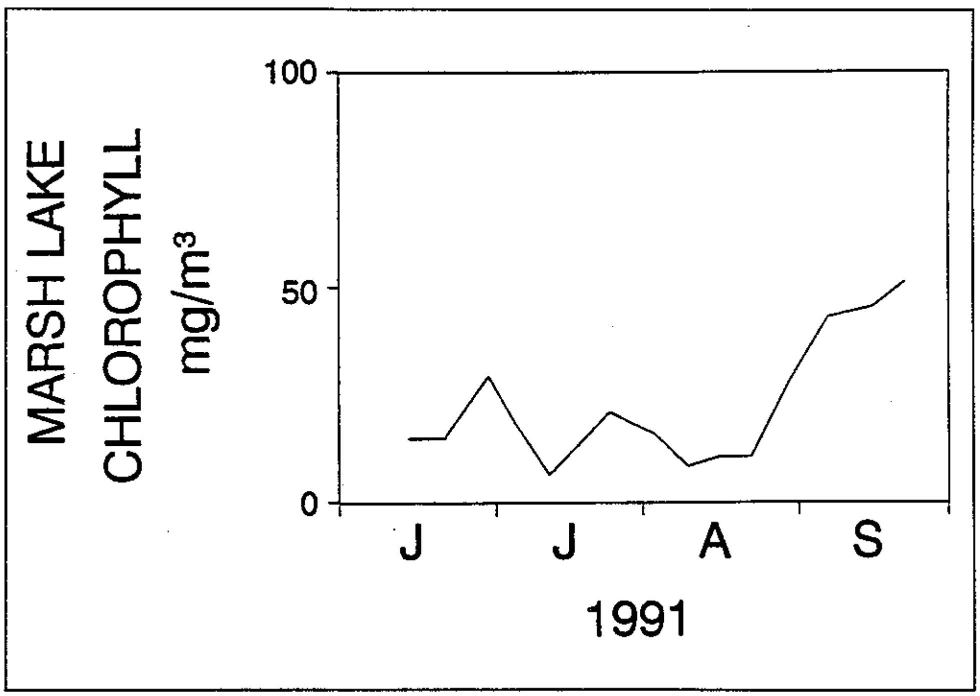

Figure 29. Variations in chlorophyll a concentrations in Marsh Lake during June through September, 1991

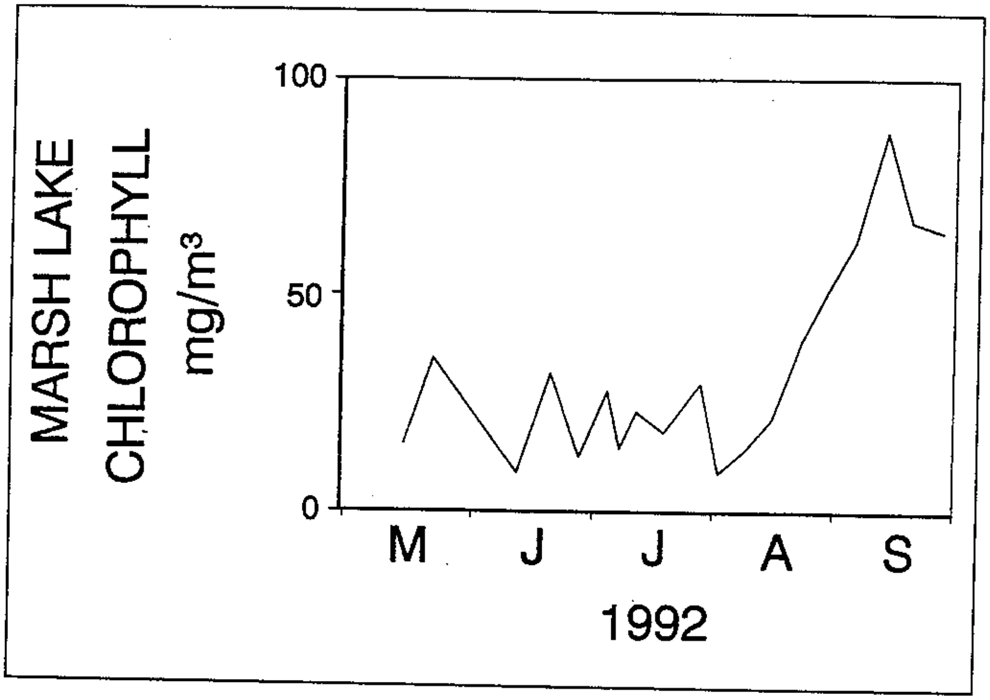

Figure 30. Variations in chlorophyll a concentrations in Marsh Lake during May through September, 1992

5 Discussion

The presence or absence of aquatic vegetation appears to play an important role in sediment resuspension dynamics in Marsh Lake. As an apparent result of the presence of aquatic vegetation in 1991, the critical wind velocity required to cause sediment resuspension was 5 to nearly 10 km/h higher than the values predicted from the wave model. In contrast, the critical wind velocity was much lower in 1992, owing to the absence of aquatic macrophytes. This change in the critical wind velocity from about 20 km/h in 1991 to 12 km/h in 1992 resulted in a > 25-percent increase in the frequency of occurrence of sediment resuspension. These results strongly suggest that aquatic vegetation was beneficial in reducing the occurrence of sediment resuspension in Marsh Lake by dampening wave activity.

Several studies have shown that emergent and submersed macrophytes can reduce and/or redirect currents and wave activity that promote sediment resuspension (Fonseca et al. 1982; Gregg and Rose 1982; Madson and Warnke 1983; Eckman, Duggins, and Sewell 1989). Others have shown that sediment resuspension and erosion are reduced in shallow regions of lakes occupied by aquatic vegetation (Moeller and Wetzel 1988; Deiter 1990; James and Barko 1990; Anderson 1990). In particular, although nearly 80 percent of the sediment surface area of shallow Lake Tämnaren (mean depth = 1.5 m) is potentially suspended as a result of wind and wave activity, all vegetated regions along the shoreline represent zones where sediments accumulate (Hellström 1991).

Seston concentrations in Marsh Lake, as well as POM and total P concentrations, increased in a fairly linear fashion with increasing wind velocity during 1992, when the critical wind velocity was exceeded (i.e., 12 km/h). Others have found similar relationships between wind velocity and seston concentrations in the water column (Bengtsson and Hellstrom 1990 and 1992; Kristensen, Søndergaard, Jeppesen 1992). Bengtsson and Hellstrom (1992) indicated that this linear pattern is strongly related to the fraction of the lakebed that was eroded during wind activity. As waves erode an increasingly larger fraction of the lakebed, more sediment mass is resuspended and homogeneously mixed into the water column, resulting in linearly increasing seston concentration as a function of increasing wind velocity.

In general, a seasonal pattern in sediment resuspension was observed in Marsh Lake during 1991 and 1992. Sediment resuspension was much reduced during the June through August of each year in the lake as a result of two factors. First, storm inflows during the summer of both years caused increases in the pool elevation and, thus, the wavelength required to resuspend the sediment surface. Second, mean daily wind velocities were also generally lower during June through August, further reducing the potential for sediment resuspension. In contrast, mean daily wind velocities and sediment resuspension were generally greatest in Marsh Lake during the late spring (i.e., May and early June) and the autumn (i.e., late August and September) of both years.

Although high wind velocities from virtually any direction caused sediment resuspension in Marsh Lake, the discharge of resuspended seston, POM, and total P from the lake generally occurred only when winds were blowing from the northwest toward the weir outlet structure. This pattern may have been due to the discharge of water and resuspended sediment that was physically piling up at the dam and spilling over the weir outlet structure during high northwest wind periods. During periods of strong winds blowing from the southeast or southwest (i.e., in the opposite direction of the dam), water and resuspended sediment in Marsh Lake was apparently pushed away from the weir outlet structure, thereby reducing the discharge of resuspended sediment from Marsh Lake. Thus, while sediment resuspension occurred relatively frequently in Marsh Lake during 1992 (i.e., 32 percent), discharge of resuspended sediment occurred much less frequently (i.e., 15 percent), due to the role of wind direction in regulating discharges.

Sediment transport from Marsh Lake during periods of resuspension could have an important impact on downstream locations by both exacerbating accretion rates and accelerating the reduction in water storage capacity in these regions. In addition, discharges of POM associated with resuspended sediment from Marsh Lake could have a later impact on dissolved oxygen conditions at downstream locations during ice formation. For instance, Gunnison and Barko (1988) and James et al. (1992) suggested that resuspension of sediment and associated high chemical oxygen-demanding materials in the headwaters and downstream transport was responsible for the rapid development of anoxia during winter drawdown in Big Eau Pleine Reservoir, Wisconsin. Discharge of resuspended phosphorus and other nutrients could also accelerate eutrophication and algal productivity in impoundments located downstream of Marsh Lake.

Chlorophyll concentrations exhibited peaks during the autumn when sediment resuspension was frequent in Marsh Lake. We currently do not know precisely the processes responsible for this apparent stimulation of algal growth. Perhaps wind-induced disturbances resulted in the resuspension of dormant algal cells from the sediments into the water column. However, Søndergaard, Kristensen, and Jeppesen (1992) found that a substantial amount of phosphorus was released from resuspended sediments (i.e., 20 to 30 times more than is released from undisturbed sediment) in Lake Arresø, suggesting a mechanism of nutrient recycling which may stimulate algal growth. We found elevated concentrations of total P during periods of sediment resuspension and high chlorophyll in Marsh Lake, suggesting possible phosphorus recycling which may have stimulated algal growth.

6 Conclusions

Because Marsh Lake is very shallow and large, wave theory predicts that virtually 100 percent of the sediment surface area can be resuspended by waves at relatively low wind velocities from any direction.

The critical wind velocity required to cause wave-induced sediment resuspension in Marsh Lake appears to be regulated, in part, by the presence or absence of aquatic vegetation. During 1991 when aquatic vegetation was present, the critical wind velocity was high (20 km/h), resulting in a lower frequency of sediment resuspension events. During 1992 when aquatic vegetation was minimal in Marsh Lake, the critical wind velocity was much lower and, thus, the frequency of occurrence for sediment resuspension was much higher than in 1991. Thus, aquatic vegetation appears to be beneficial in reducing sediment resuspension in Marsh Lake by dampening wave activity.

In general, sediment resuspension was frequent in Marsh Lake during 1992, occurring predominantly during the spring and autumn months when wind velocities were typically greatest.

During periods of high wind velocity in 1992, seston concentrations and associated POM and total P increased in a linear fashion with increasing wind velocity above a threshold critical wind velocity. The linearity of this pattern is probably associated with an increasing percentage of the lakebed becoming subjected to sediment resuspension as wind velocity increases.

Wind direction appears to be an important factor in regulating the discharge of resuspended seston, POM, and total P from Marsh Lake. Discharge of high concentrations of these constituents from Marsh Lake occurs only when winds are blowing from the north, suggesting that water is physically piling up on the dam and splashing over the weir.

Chlorophyll a biomass increases substantially in Marsh Lake when sediment resuspension is frequent during autumn. Concomitant increases of total P in the water column during resuspension events suggest a mechanism of nutrient recycling that may stimulate algal growth in Marsh Lake.

The redistribution of sediment, organic matter, phosphorus, and other sediment constituents via sediment resuspension has strong implications for water quality conditions in both Marsh Lake and neighboring Lac Qui Parle Reservoir.

7 Recommendations

An important finding of the present investigation is that sediment resuspended in Marsh Lake can be transported downstream in large quantities, particularly when the wind is blowing out of the northerly direction. To determine the effects of sediment transport on downstream water quality conditions, it will be necessary to investigate the fate of sediment and associated constituents exiting Marsh Lake.

Relationships between sediment resuspension, phosphorus availability, and phytoplankton growth dynamics need to be determined, since algal blooms (based on chlorophyll data) are common during the summer months in Marsh Lake. As part of this effort, it would be desirable to determine species composition of the algal community, since some algal groups (e.g., blue-greens) create more significant water quality problems than others.

Given the apparent depression of sediment resuspension in Marsh Lake, owing to the abundance in 1991 of aquatic macrophytes, techniques to maintain their abundance need to be developed. These might include, but would not necessarily be limited to: drawdown (for sediment consolidation and seed germination); construction of artificial islands (to reduce turbidity associated with sediment resuspension); and macrophyte transplanting (to promote an increased abundance of emergent/wetland macrophytes).

In combination with the development of techniques to maintain macrophyte abundance (previous paragraph), factors contributing to the wax and wane need to be better understood. Notably, we have no clear explanation for the loss of aquatic macrophytes that occurred between 1991 and 1992 in Marsh Lake. Studies should focus on effects of sediment composition, light, sediment scouring, etc., on both submersed and emergent macrophytes in Marsh Lake.

Assuming that drawdown would be an operationally viable technique for maintaining aquatic macrophytes in Marsh Lake, it would be desirable to conduct seed bank studies to better anticipate vegetation response. Here, it would be important to examine effects of sediment characteristics (e.g., sediment density, redox status, and moisture content) on seed germination and macrophyte species composition.

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13. ABSTRACT *(Maximum 200 words)*

Budgetary information and sediment resuspension dynamics were determined in Marsh Lake, located on the Minnesota River in western Minnesota. Resuspension and discharge of seston, particulate organic matter (POM), and total phosphorus (total P) were examined in Marsh Lake during June through September 1991 and May through September 1992. Based on a theoretical wave model, lakebed sediments at water sampling stations in Marsh Lake were susceptible to sediment resuspension at wind velocities as low as 10.5 km/h, depending on wind direction. Mean daily wind speeds were > 10 km/h on over 40 percent of the days during both study years, suggesting a strong potential for frequent sediment resuspension at these stations. Measured resuspension of seston, POM, and total P was much lower in Marsh Lake in 1991 than in 1992 as an apparent result of dense aquatic macrophyte beds that in 1991 covered nearly the entire lake. In 1992, when aquatic vegetation was absent from Marsh Lake, seston, POM, and total P concentrations increased substantially in the water column as a result of sediment resuspension. The discharge of high concentrations of resuspended sediment and associated constituents from Marsh Lake occurred primarily when strong winds were blowing from the northwest toward the outlet weir of Marsh Lake. The critical wind velocity for the discharge of resuspended seston, POM, and total P was 20 km/h in 1991, when aquatic plants

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were present, and only 12 km/h in 1992, when aquatic plants were absent. Thus, discharge of resuspended sediment occurred only 2 percent of the time in 1991 and 15 percent of the time in 1992. The results of these studies were used to critically evaluate management alternatives for habitat and water quality improvements in Marsh Lake.