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Suspended Sediment Dynamics and Light Attenuation Characteristics in Peoria Lake, Illinois: Can Submersed Macrophyte Communities Improve Water Quality in this Shallow System?

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Contents

List of Figures

List of Tables

Preface

The work reported herein was conducted as part of the Aquatic Plant Control Research Program (APCRP). The APCRP Program is sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), and is assigned to the U.S. Army Engineer Research and Development Center (ERDC) under the purview of the Environmental Laboratory (EL). Funding was provided under the Department of the Army Appropriation 96X3122, Construction General. The APCRP is managed under the Center for Aquatic Plant Research and Technology (CAPRT), Dr. John W. Barko, Director. Mr. Robert C. Gunkel, Jr., was Assistant Director, CAPRT. Technical Monitor during the study was Mr. Timothy Toplisek, HQUSACE.

This study was conducted and the report written by Mr. William F. James, Eau Galle Aquatic Ecosystem Research Facility, Spring Valley, WI, Dr. Elly P. H. Best, and Dr. John W. Barko, Ecosystem Processes and Effects Division (EPED), EL, ERDC. Dr. Barko is also affiliated with Eau Galle Facility. We gratefully acknowledge Ms. Susan Fox and Mr. Dale Dressel, American Scientists (AScI) Corp.; Mses. Laura Blegen, Alyssa Boock, Emily Gillis, Kelly LaBlanc, Emily Schnieder, and Stephanie Sweeney and Messrs. Harry L. Eakin, Charles Gruber, Ben Heinzen, Alan Lamphere, Phil Newman, Matthew Pommier, and Eric Secrist, Eau Galle Aquatic Ecosystem Research Facility, for field and laboratory analyses; and Messrs. Jay Dexter and Jeff Arnold, Illinois Natural History Survey, Havana, IL, for field operations on Peoria Lake.

This investigation was conducted under the general supervision of Dr. Ed Theriot, Director, EL, and under the direct supervision of Dr. Richard E. Price, Chief, EPED, EL.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC and COL John W. Morris III, EN, was Commander and Executive Director.

1 Introduction

Shallow lakes are very susceptible to wind-generated sediment resuspension which, in turn, promotes nutrient recycling, high light attenuation, and excessive algal growth (Hellström 1991; Bengtsson and Hellström 1992; Søndergaard, Kirstensen, and Jeppesen 1992). Although submersed macrophytes can greatly improve water quality by dampening wave activity and reducing sediment resuspension (James and Barko 1994, Koch 1996), reestablishment of macrophytes in shallow lakes that have lost these communities is often difficult because light conditions are no longer favorable for their persistence and growth (Kimber, Owens, and Crumpton 1995; Kimber, Korschgen, and Van der Valk 1995; Korschgen, Green, and Kenow 1997; Scheffer 1998; Doyle and Smart in preparation). Rehabilitation of these lakes to promote macrophyte growth, thus, requires a knowledge of factors contributing to resuspension and poor light levels and a means of predicting the success of macrophyte reestablishment under different management scenarios to improve the underwater light climate (Best, Boyd, and James in preparation; Blom, Van Duin, and Lijklema 1994; Blom, Van Duin, and Vermaat 1994; Van Duin 1992; Van Duin et al. 1992).

The objectives of this research were to examine sediment resuspension dynamics and light attenuation characteristics in Peoria Lake, Illinois, for future use in evaluating via model explorations. These studies involved: (a) the potential for macrophyte growth under different management scenarios to improve light characteristics and (b) the potential impact that established macrophyte communities will have on improving water quality in this system by reducing sediment resuspension and, thus, suspended sediment concentrations in the water column. Peoria Lake is a very large and shallow impoundment of the Illinois River; and it exhibits frequent periods of wind-generated sediment resuspension. Excessive suspended sediment loading over the last several decades has resulted in significant losses in both lake volume and mean depth (Demissie and Bhowmik 1986), exacerbating the potential for total suspended sediment (TSS) resuspension. Macrophytes, once present in the lakes, have been gone since the 1950's (Best et al. in preparation).

2 Methods

Study Site

Peoria Lake is part of a navigation pool located in central Illinois on the Illinois River. The Illinois River enters Peoria Lake at river mile 182 and the Peoria Lock and Dam system is located at river mile 158 (Figure 1). There are also numerous smaller tributaries entering the lake at various points around its perimeter (Bhowmik et al. 1993). As a result of construction of the lock and dam system in the 1930's and increased agricultural row cropping in the 1940's and 1950's, the lake has filled with sediment at a rapid rate, losing over 60 percent of its original 1903 volume by the mid 1980's (Bhowmik et al. 1993). Currently, the lake has a surface area of 5,270 hectares below a nominal pool elevation of 134.1 m, a volume of 14.6×10^7 m^3, and an average depth of less than about 0.6 m . A narrow navigation channel is maintained at a depth of 2 to 3 m via dredging.

Suspended Particles and Light Attenuation Characteristics

Five stations were established in Peoria Lake for water sampling purposes and suspended particle analysis (Figure 1). Stations 2 and 4 were located in the deeper thalweg (navigation channel) and Stations 1, 3, and 5 were located in shallow reaches of the lake. Water column depths near nominal pool elevation (134.1-m mean sea level (MSL) were 0.75, 5.25, 0.75, 0.75, and 0.75 m for Stations 1 through 5, respectively. An inflow and outflow sampling station was established on the Illinois River upstream of the lake near Chillicothe, IL, and immediately downstream of the Peoria Lock and Dam near Pekin, IL, respectively (Figure 1). We did not establish sampling stations at the smaller tributary inflows. Flow was obtained for the Illinois River at the Henry, IL (i.e., ~ 23 km upstream of Chillicothe), via a gaging station established by the U.S. Geological Survey. Discharge flow from Peoria Lake was obtained from a gaging station established at the lock and dam near Pekin, IL, by the U.S. Army Engineer District (USAED), Rock Island. Daily and annual loading was estimated via regression analysis using the software program FLUX (Walker 1996).

At biweekly intervals between April and November 2000, underwater photosynthetically active radiation (PAR) was measured at 10-cm intervals in the

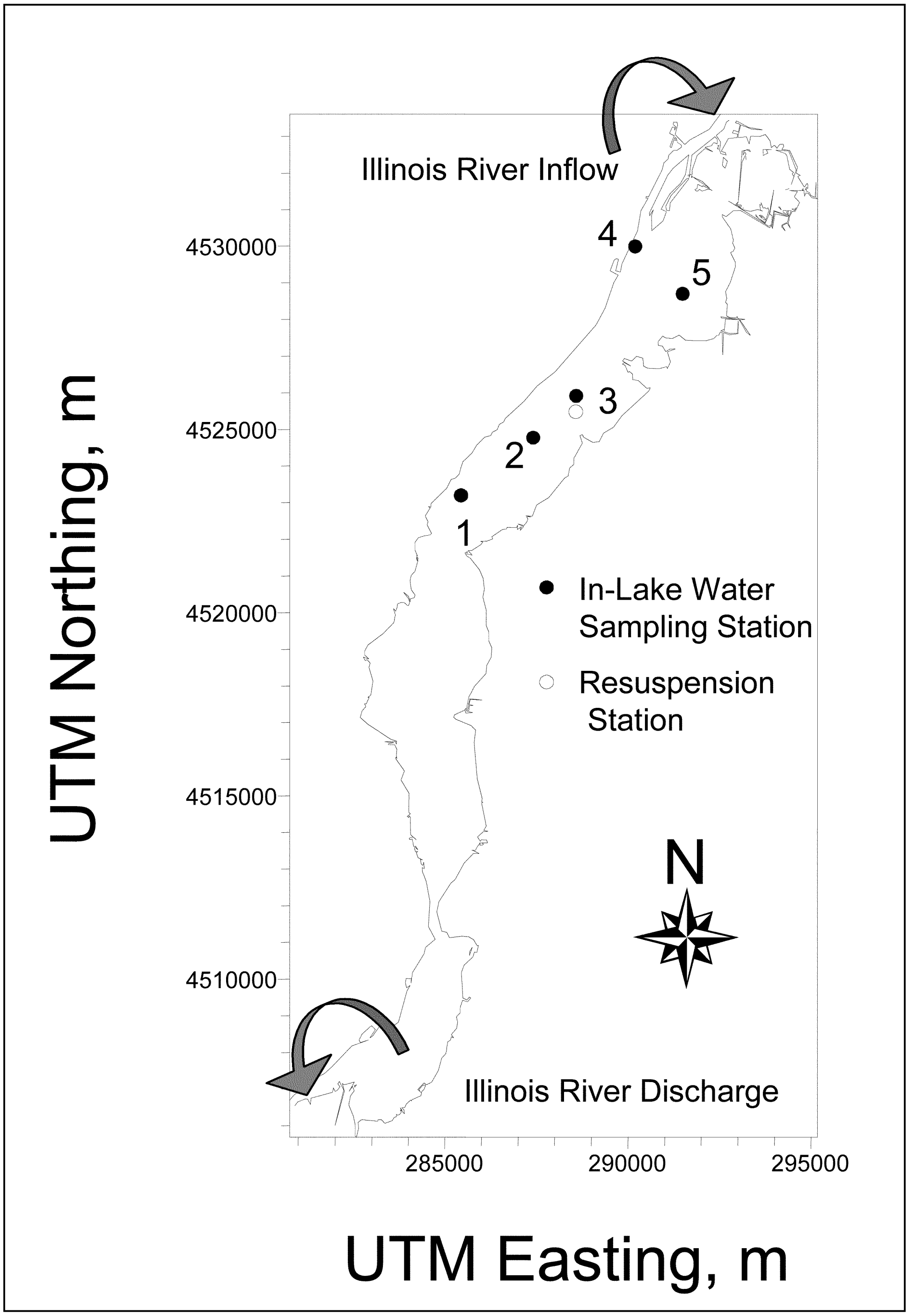

Figure 1. Map of Peoria Lake showing sampling stations

upper 1 m of the water column at each in-lake station using a cosine quantum radiometer (Licor Model LI1000). Measurements were typically collected between 10:00 am and 3:00 pm. The attenuation coefficient (K_d) for PAR was calculated over the upper 0.5-m water column as,

$$K_d = \frac{\{\ln Ez_1 - \ln Ez_2\}}{z_1 - z_2} \quad (1)$$

where

E = PAR, μE m^{-2} s^{-1}

z = Depth, m.

This depth range was chosen because nearly all of the light is attenuated beyond 0.5 m. Secchi transparency was determined to the nearest 1 cm using a 10-cm diam, alternating black and white, disk. *In situ* characteristics (temperature, dissolved oxygen, pH, and specific conductance) were monitored at 0.5-m intervals using a Hydrolab Surveyor III (Hydrolab Corp., Lincoln, NE) that was calibrated against known buffers and Winkler titrations (American Public Health Association (APHA) 1992).

Water samples, integrated over the upper 0.5-m water column, were collected at all in-lake stations and the Illinois River inflow and outflow stations for suspended particle and chlorophyll analysis at biweekly intervals using an integrated water sampler as described in Barko et al. (1984). Turbidity was determined using a nephalometric turbidometer (Hach 2100N) and a YSI 6000 data sonde equipped with a nephalometric turbidity probe (Model 6026, YSI Incorporated, Yellow Springs, Ohio). Samples for TSS were filtered onto preweighed glass fiber filters (Gelman Metricel A/E), dried at 105 °C., and weighed to the nearest 0.1 mg. The particle-size distribution of TSS in the water column was determined using a combination sieving and pipet technique as described in Plumb (1981). Three particle-size fractions were determined: sand (> 62.5 μm), silt (1.95 to 62.5 μm), and clay (<1.95 μm). Samples of lake water were sieved through a # 230 sieve to remove particles greater than 62.5 μm for mass determination. The remaining water was homogenized by shaking and 1 L was placed in a glass settling column measuring 35.5 cm in length by 6.5 cm in diameter. A 20-mL water sample was pipetted at a withdrawal depth of 20 cm from the water surface at ~ 20 s after homogenization for determination of particles < 62.5 μm. A second sample was withdrawn from a depth of 5 cm from the water surface at ~ 4 hr after homogenization to determine particles < 1.95 μm. The mass of particles for each fraction was determined by filtering pipetted material onto preweighed glass fiber filters and drying at 105 °C. The mass of particles finer than 1.95 μm was subtracted from the mass particles finer than 62.5 μm to calculate the mass of silt. Very fine clay particles may have passed through the glass fiber filters in our attempt to determine mass. Thus, we may have underestimated the clay fraction. Settling velocities (cm s^{-1}) for the silt and clay particle size fractions were determined concurrently as the vertical distance settled divided by the time of sample collection. From a subset of water samples collected during the summer low-flow period (16 August and 12 October), we determined the percentage of particles finer than 31.2, 15.6, and 3.9 μm in an effort to provide greater resolution to the overall size distribution and settling velocity of the silt fraction.

For TSS and the portion of TSS constituting the sand, silt, and clay size fractions, a beam attenuation coefficient (ε) was determined in the laboratory over the 400- to 700-nm wavelength ranges according to Van Duin (1992) to ascertain the relative importance of different particle-size fractions to overall light attenuation characteristics in Peoria Lake. Beam attenuation through a 1-cm quartz cuvette was measured on a Perkin-Elmer (Model Lambda 20) UV-vis spectrophotometer. Light absorption characteristics, measured at 50-nm intervals for each size fraction, were averaged over the 400- to 700-nm range to calculate ε. Relationships between ε and K_d were examined via regression analysis. K_d' was calculated as the sum of K_{dsand}', K_{dsilt}', and K_{dclay}', after conversion of ε to K_d for individual fractions.

Samples for chlorophyll analysis were filtered onto a glass fiber filter and extracted at < 0 ^{o}C in a 50:50 solution of acetone:dimethyl sulfoxide for a minimum of 12 hr. Viable chlorophyll *a* concentration was determined fluorometrically from this extraction procedure using a Turner TD-700 fluorometer according to Welschmeyer (1994). Additional samples for chlorophyll, filtered onto glass fiber filters, were extracted in 90 percent acetone after grinding in a mortar and pestle. Chlorophyll *a* concentrations from this extraction procedure were determined using the trichromatic equation (APHA 1992). A beam attenuation coefficient for chlorophyll was determined over the 400- to 700-nm range (50-nm intervals) using the clarified, 90-percent acetone extract. The coefficient was corrected to account for concentrating chlorophyll in the water onto a glass fiber filter. A chlorophyll:ash-free dry mass conversion factor of 70 was used to convert chorophyll to an organic matter dry mass equivalent (Van Duin 1992; p 92).

Sediment Resuspension

A sampling platform, anchored to the lake bottom with steel pipe, was established in a shallow, exposed region of Peoria Lake between 1998 and 2000 for examination of sediment resuspension under a variety of wind conditions (near Station 3; Figure 1). Wind speed and direction (Wescor, Inc., Logan, UT; Model 824) were recorded at 15-min intervals (i.e., the average of 5-min intervals over a 15-min period) approximately 2 m above the nominal pool elevation. Turbidity was measured at 0.25 m above the sediment surface at 15-min intervals at each station using Yellow Springs Instruments (YSI) 6000 data sondes. The probes were pre- and postcalibrated with standard turbidity solutions (range of 0 to 100 Nephelometric Turbidity Units) purchased from YSI (YSI 6073, YSI, Incorporated, Yellow Springs, Ohio). At weekly-to-biweekly intervals, the data sondes were serviced, cleaned, recalibrated, and redeployed. In 1998 and 99, water samples were collected at hourly intervals during wind resuspension events using automated techniques (ISCO 2700 automated water samplers). Samples were analyzed for TSS and turbidity (YSI 6000). Linear relationships between TSS and turbidity were used to estimate TSS from *in situ* turbidity measurements during periods when only turbidity was measured in the water column.

The wave models developed by Coastal Engineering Research Center (1984), Carper and Bachmann (1986), Hamilton and Mitchell (1996), and Bailey and Hamilton (1997) were used to calculate effective fetches and bottom shear stresses (dynes cm^{-2}) at the resuspension platform using continuous records of wind speed and direction. The bottom shear stress was calculated as:

$$\tau = H\left[\frac{\rho\left(\upsilon(2\pi/T)^3\right)^{0.5}}{2\sinh(2kh)}\right] \qquad (2)$$

where

τ = calculated bottom shear stress

H= wave height (cm)

ρ = density of water (1 g cm^{-3})

T = wave period (s)

ν = kinematic viscosity

k = wave number ($2\pi/L$ where L = wave length, cm)

h = water depth (cm)

The critical bottom shear stress (τ_c) of sediments in the vicinity of the resuspension platform was determined experimentally using a particle entrainment simulator (PES) designed exactly as described by Tsai and Lick (1986). The PES consisted of a vertically oscillating, perforated acrylic grid driven by a computer-controlled motor (Figure 2). The grid was positioned so that the bottom of its oscillation cycle occurred exactly 5.08 cm (2 in.) above the interface of an intact sediment core. A cam on the motor shaft allowed the grid to oscillate up and down for a distance of 2.54 cm (1 in.).

In March, 1999, three replicate intact sediment cores, 10 cm in depth, were collected using a 15- by 15-cm box corer (Wildco Wildlife Supply Co., Saginaw, MI) for determination of τ_c. The sediment contained in the box corer was transferred to a 13-cm (5-in.) diam by 20-cm acrylic cylinder by carefully slipping the cylinder over the sediment enclosed by the box core sleeve and sliding a thin plexiglass disk underneath the cylinder to contain the sediment. Cores were transferred to the laboratory with water overlying the sediment to minimize changes in physical characteristics (moisture content and density) that would have occurred because of desiccation. In the laboratory, the overlying water was removed and 1.36 L (to a height of 13 cm (5 in.)) of filtered lake water was then carefully siphoned onto the sediment surface of the sediment core system to prevent sediment resuspension.

To determine τ_c, the motor of the PES was programmed to oscillate above the sediment interface in a stepwise manner from 0 to 800 revolutions per minute (RPM) at 100-RPM increments at 10-min intervals. At 8 min into each RPM

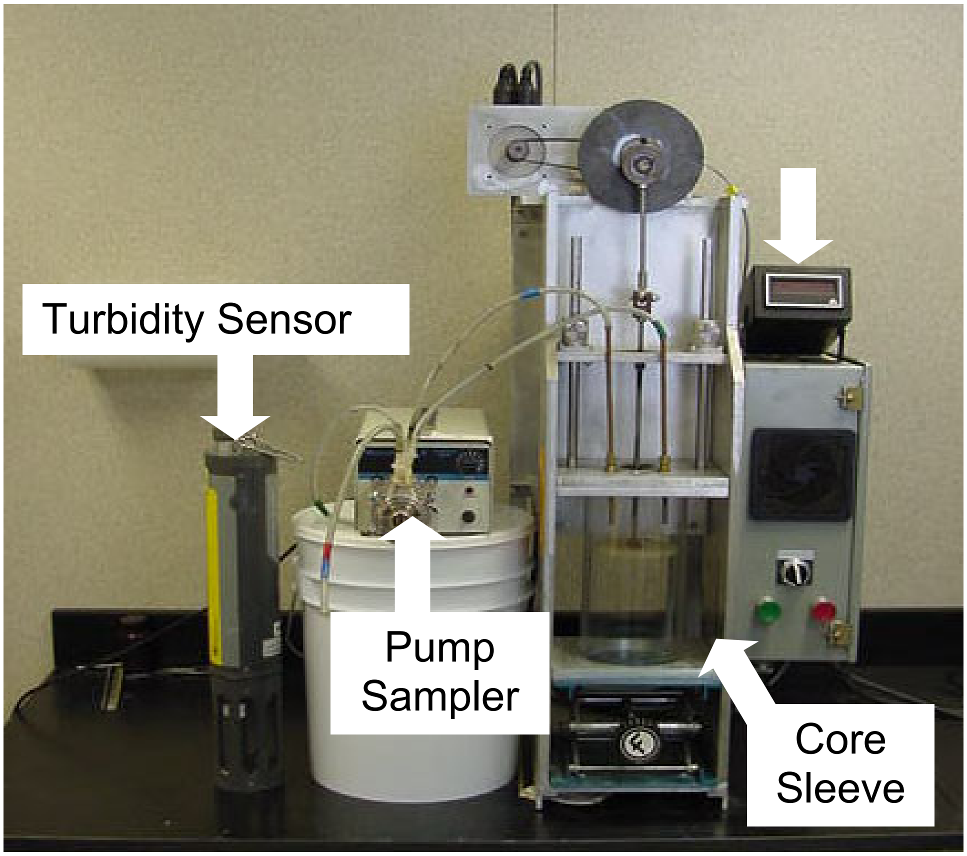

Figure 2. Photograph of the particle entrainment simulator used to estimate critical shear stress of sediment collected in Peoria Lake

cycle, a 50-mL sample was collected 2.54 cm below the water surface using a peristaltic pump. Water removed as a result of sampling was simultaneously replaced with filtered lake water using a peristaltic pump. Samples were analyzed for TSS and turbidity. RPM was converted to τ using the calibration curve developed by Tsai and Lick (1986; Figure 5, p 317) for levels ranging between 430 and 750 RPM. We used linear interpolation to estimate τ for levels that occurred below 450 RPM and above 750 RPM. Thus, τ ranged from 0 to nearly 6 dynes cm^{-2}. The τ_c was estimated as the inflection point where TSS and turbidity increased in the water column above background conditions. Sediment resuspension was predicted to occur at this station when calculated bottom τ exceeded τ_c.

The concentration of TSS (C_{TSS}; mg L^{-1}) in the water column at the resuspension station during September was predicted using the equation (Bengtsson and Hellström 1992; Hamilton and Mitchell 1996; Bailey and Hamilton 1997):

$$C_{TSS} = C_e + C_{background} + (C_i - C_e - C_{background}) \bullet \exp\left(\frac{w_s}{h} t\right) \tag{3}$$

where

C_e = TSS equilibrium concentration when sediment resuspension balances sediment deposition

$C_{background}$ = TSS concentration under quiescent periods

C_i = initial TSS concentration

W_s = depth-averaged settling velocity (cm s^{-1})

h = depth of the water column (cm)

t = time step (sec)

C_e was estimated from the following equation:

$$C_e = 0 \qquad \text{when } \tau_c < \tau$$

$$C_e = A\left(\frac{\tau - \tau_c}{\tau_{ref}}\right)^n \qquad \text{when } \tau_c > \tau \tag{4}$$

where

τ_{ref} = 1 dyne cm^{-2}

A and n = constants determined via regression analysis

The W_s of particles was determined via particle size analysis (see methods above).

Sediment Characteristics

Three replicate sediment cores were collected using a Wildco KB sediment corer (Wildco Wildlife Supply Co.) equipped with an acrylic core liner (6.5-cm ID and 50-cm length) for determination of physical and chemical sediment characteristics. The upper 10 cm of sediment was dried at 105 ^{o}C to a constant weight for determination of moisture content and sediment density (Håkanson 1977). A portion of the sediment sample was combusted at 500 ^{o}C for determination of percent organic matter (Håkanson 1977). The particle-size distribution of the sediment was determined using a combination sieving and pipet technique for sand (> 62.5 µm), silt (1.95 to 62.5 µm), and clay (<1.95 µm).

3 Results

Suspended Sediment Loadings and Discharge

Mean daily inflows to Peoria Lake from the Illinois River were elevated between mid-April and mid-July in conjunction with storm runoff (Figure 3). Major peaks in mean daily flow occurred in mid-April, late May, mid-June, and early July. The greatest mean daily inflow peak (1,136 cms) occurred on 12 July. Pool elevation increased substantially above 135 m MSL during these periods of high inflow (Figure 3). During January through mid-April and August through December, mean daily inflow from the Illinois River was much lower and pool elevation fluctuated around a mean of 134.3 m MSL.

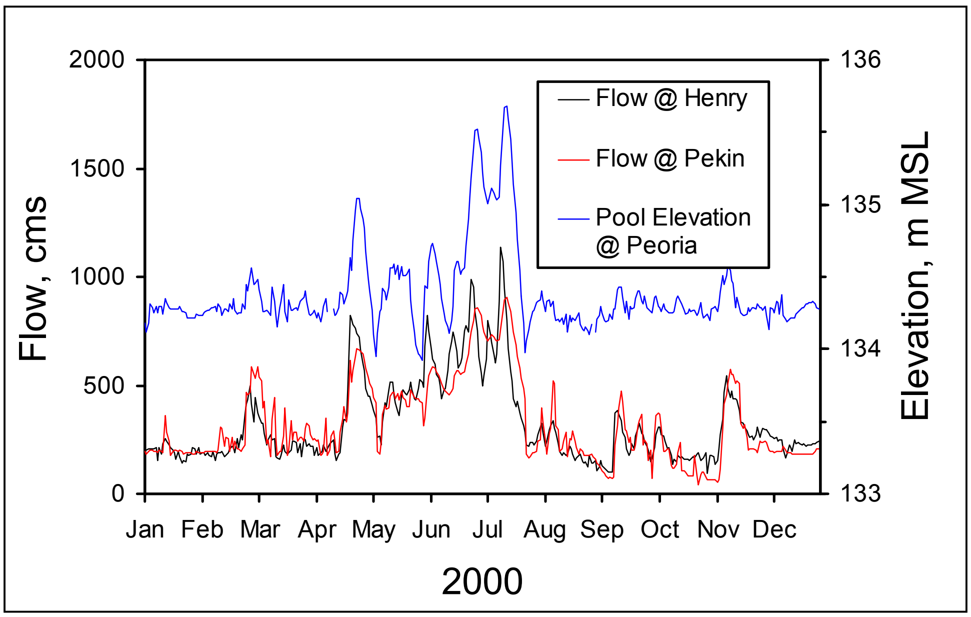

Figure 3. Variations in flow from the Illinois River at Henry, IL, and Pekin, IL, and pool elevation measured at Peoria, IL, in 2000

A positive linear relationship existed between TSS concentrations and mean daily inflows from the Illinois River (Figure 4). Thus, TSS loading from the Illinois River increased markedly during periods of high flow (Figure 5). TSS discharge from Peoria Lake also increased during peaks in inflow (Figure 5). During periods of high TSS loading from the Illinois River in April through early

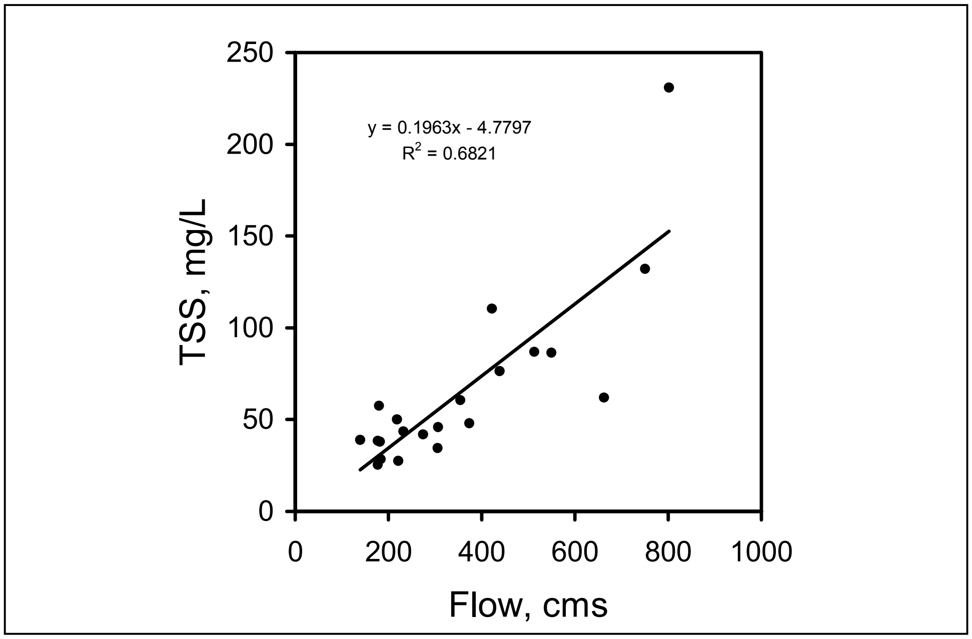

Figure 4. Regression relationships between flow and total suspended sediment (TSS) concentrations for the Illinois River at Henry, IL

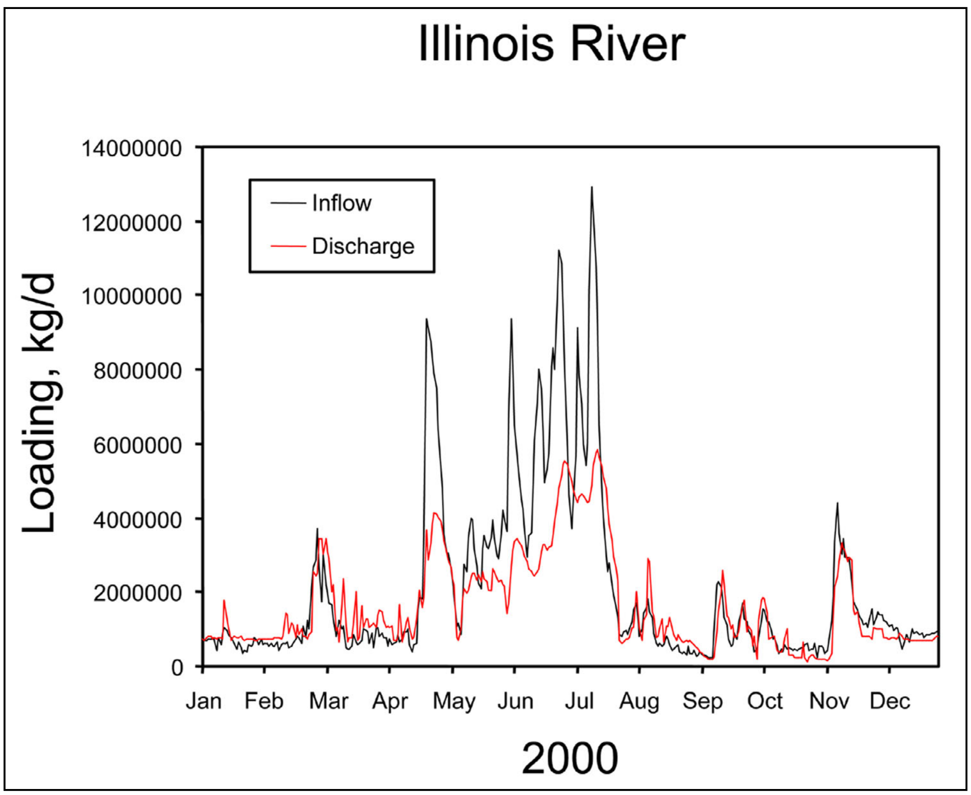

Figure 5. Variations in TSS loading from the Illinois River at Henry, IL, and the Illinois River at Pekin, IL, in 2000

July, apparent net TSS retention occurred, indicating some sedimentation of TSS originating from storm inflows. During periods of lower inflow and lower pool elevation, it appeared that there was some net export of TSS from the system in relation to TSS loading from the Illinois River resulting, most likely, from frequent periods of resuspension (see below).

Annual retention of TSS loadings (Table 1) were calculated using year 2000 estimates of TSS loading from the Illinois River and the discharge, and TSS loading estimates from the other tributary inflows determined for the year 1989 by Bhowmik et al. (1993). Flows and TSS loadings for the Illinois River were similar for the years 1989 and 2000; thus, we assumed that TSS loadings from other tributary sources to Peoria Lake were similar as well. Under this assumption, Peoria Lake retained a net ~ 70 percent of the measured TSS loadings.

Table 1
Mean (Coefficient of Variation, CV, in parentheses) Annual Total Suspended Sediment (TSS) Loading, Discharge, and Retention in Peoria Lake

Tributary		TSS, kg/y
Inputs		
	Illinois River @ Henry, IL, 2000	771,091,900 (0.12)[1]
	Other Tributaries, 1989	91,209,287[2]
Outputs		
	Illinois River @ Pekin, IL, 2000	598,271,900 (0.10)
Net Retention		264,029,287
Percent Retention of inflow		69 percent

[1] Annual TSS loading estimate for the Illinois River was 726,292,311 kg in 1989 and 1,104,951,330 in 1990 (Bhowmik et al. 1993).
[2] Annual TSS loading estimate for other tributary inputs in 1989 (Bhowmik et al. 1993).

The silt (i.e., ≤ 62.5 μm and > 1.95 μm) fraction dominated the particle-size distribution of TSS loadings from the Illinois River in 2000 (Figure 6). Although sand (i.e., > 62.5 μm) represented a minor component of the particle-size distribution of the TSS load from the Illinois River, loading of this fraction increased during periods of high flow between April and July. Overall, annual TSS loadings from the Illinois River were composed of 11 percent sand, 78 percent silt, and 11 percent clay (i.e., ≤ 1.95 μm; Table 2). Although silt comprised most of the TSS discharge from Peoria Lake (Figure 7), the percent clay fraction was elevated relative to loadings from the Illinois River. In contrast, the percent sand fraction was less in the discharge versus in the Illinois River (Figures 6 and 7).

Sediment Resuspension Dynamics

Variations in the effective fetch as a function of wind direction are shown in Figure 8 for the resuspension station located in Peoria Lake (Figure 1). Greatest effective fetches (i.e., up to 4,000 m) occurred for winds blowing out of the southwest (SW). The effective fetch was also high (i.e., up to 3,000 m) for winds blowing out of the northeast (NE). It was much lower along the northwest (NW) and southeast (SE) wind rose. Winds blew most frequently out of the south southwest (SSW) (30 percent of the time; Figure 9) and average wind

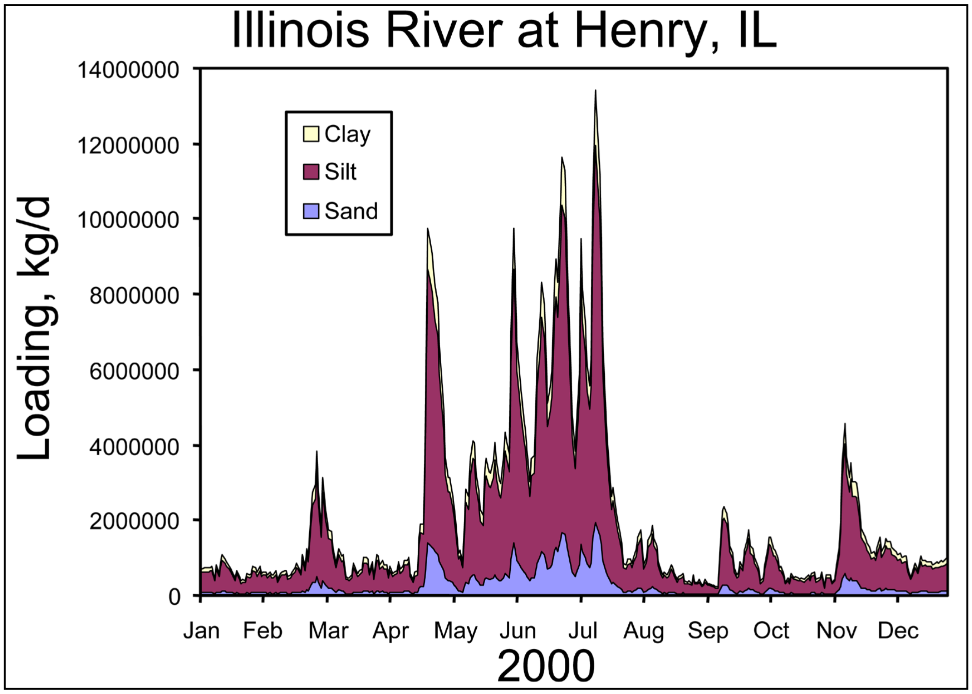

Figure 6. Variations in loading of sand, silt, and clay fractions from the Illinois River at Henry, IL, in 2000

Table 2
Mean (1S.E.; n=20) Percent Sands Silt, and Clay Content of Total Suspended Sediment in Water Column of Inflow (i.e., Illinois River), outflow (i.e., Discharge at Peoria Lock and Dam), and Various In-lake Stations (Mean ±1 S.E., n=3) Sand, silt, and clay content of surface sediment (i.e., upper 10 cm) at Station 3 is shown in the last row)

	% Sand	% Silt	% Clay
Inflow	9.2 (1.3)	76.8 (1.9)	14.1 (2.1)
Station 1	7.1 (0.8)	76.5 (2.6)	16.5 (2.8)
Station 2	7.5 (0.8)	76.7 (2.2)	15.7 (2.2)
Station 3	6.5 (0.6)	70.9 (3.4)	22.5 (3.1)
Station 4	9.6 (1.3)	76.0 (1.9)	14.4 (1.6)
Station 5	5.3 (0.6)	73.0 (2.8)	21.7 (2.4)
Outflow	7.3 (1.0)	70.7 (2.3)	21.9 (2.6)
Sediment at Station 3	8.3 (0.7)	86.9 (2.5)	4.8 (1.8)

speeds for the study period were greatest out of the west southwest (WSW) and SSW wind rose (i.e., the region of greatest effective fetch; Figure 10). Thus, high effective fetch and prevailing winds out of the SW indicated a high potential for sediment resuspension at this station.

Intact sediment cores from the resuspension station that were subjected to varying applied τ in the laboratory exhibited low relative turbidity in the water column at low τ (i.e., $\leq$ 2.3 dynes cm^{-2}; Figure 11). Relative turbidity increased substantially as applied τ increased above 2.3 dynes cm^{-2}. From these patterns, we estimated a τ_c of ~2.3 dynes cm^{-2} for sediments located in the vicinity of the resuspension station.

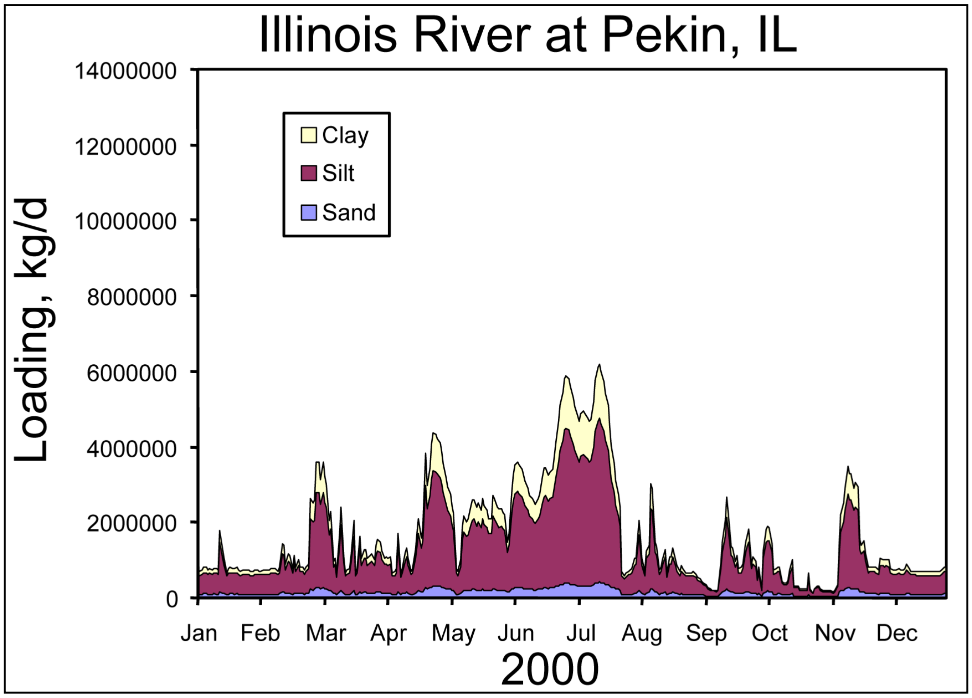

Figure 7. Variations in loading of sand, silt, and clay fractions from the Illinois River at Pekin, IL, in 2000

An example of sediment resuspension dynamics at nominal pool elevation (i.e., no storm inflows) is shown for the month of September in Figure 12. During that period, wind speeds exceeding 30 km h^{-1} out of the S and SSW occurred on 7 through 9, 11, and 17 through 19 September. High wind speeds (i.e., > 30 km h^{-1}) out of the NE occurred on 4 September. Wind speeds exceeding 25 km h^{-1} primarily out of the N occurred on 14, 15, and 24 September. Calculated bottom τ, estimated as a function of wind velocity, effective fetch, and wind direction (i.e., Equation 2), exceeded ~ 2.3 dynes cm^{-2}, determined experimentally in the laboratory using intact sediment cores, 27 percent of the time during the study period in September. Turbidity increased substantially in the water column as calculated bottom τ exceeded τ_c. Overall, relationships between turbidity, measured at the resuspension station during September, and calculated bottom τ (Figure 13) suggested that resuspension occurred when calculated bottom τ exceeded ~ 2.5 dynes cm^{-2}. This value was similar to the τ_c estimated in the laboratory using the PES.

Since a strong relationship existed between turbidity and TSS (Figure 14), we estimated net areal TSS resuspension for the month of September (Figure 15). To estimate this mass, we subtracted the concentration estimated in the water column by a baseline TSS (i.e., $C_{background}$; Equation 3). $C_{background}$ was estimated as the mean concentration when τ was less than τ_c during September (i.e., ~165 mg L^{-1}). Positive differences in the concentration (i.e., $C - C_{background} > 0$; mg L^{-1}), representing net resuspended TSS, were multiplied by the depth of the water column to estimate net areal TSS resuspension (g m^{-2}; Figure 15). Overall,

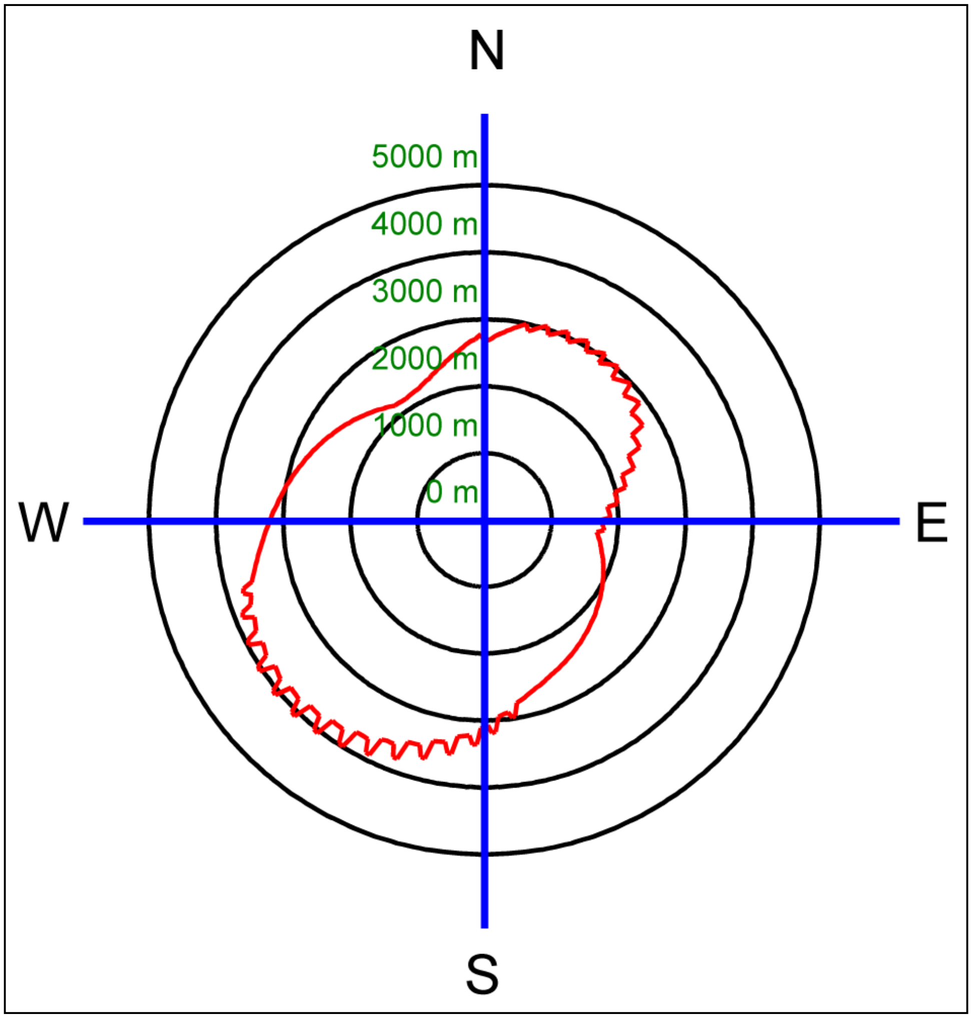

Figure 8. Variations in the effective fetch at the resuspension station (Figure 1) as a function of wind direction

110 kg m^{-2}/month $^{-1}$ TSS were resuspended via wind activity versus 0.5 kg m^{-2}/month $^{-1}$ TSS inputted to the lake from the Illinois River during September.

Particle Settling Velocities

Silt dominated the particle-size distribution of TSS at in-lake stations in Peoria Lake (Table 2). Mean percent sand was significantly greater ($p < 0.05$; Analysis of Variance (ANOVA); Statistical Analysis System (SAS) 1994), while mean percent clay was significantly less, for in-lake stations located in the thalweg (i.e., Stations 2 and 4) versus those located at shallow sites (i.e., Stations 1, 3, and 5). However, mean sand and clay collectively accounted for < 25 percent of the particle-size distribution in Peoria Lake.

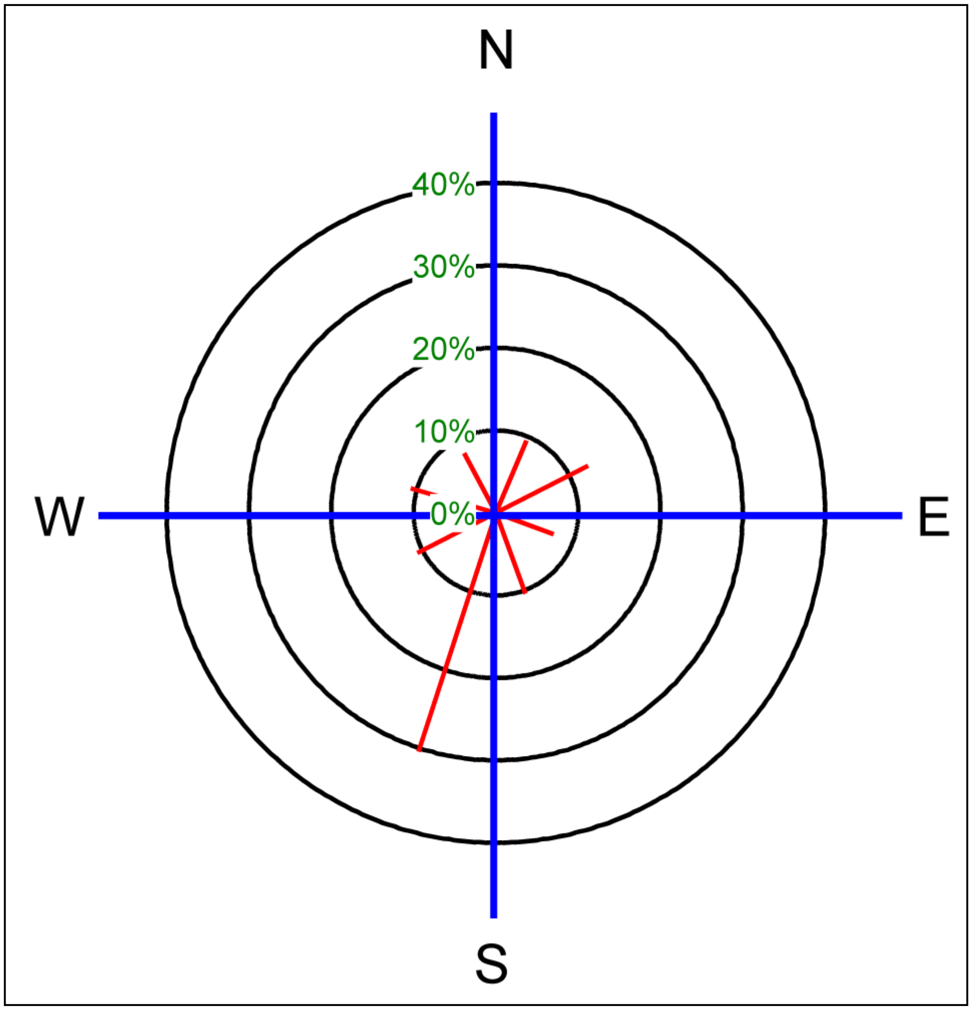

Figure 9. Variations in the frequency of occurrence of winds blowing out of the north northeastern (NNE), east northeast (ENE), east southeast (ESE), south southeast (SSE), SSW, WSW, west northwest (WNW), and north northwest (NNW) at the resuspension station, Peoria Lake

Since the silt fraction represented a large range in both particle diameter and settling velocity, we examined a finer range of size classes and settling velocities for lake samples collected on 16 August and 12 October (Table 3). Particles with an average diameter less than 15.6 μm represented 59.2 percent of the particle-size distribution in the silt fraction (Table 3). The dominant size class in the silt fraction were those particles with average diameters ranging between 3.9 and 1.95 μm (Table 3). The average settling velocity for those dates, weighted with respect to the particle-size distribution, was ~0.04 mm s^{-1}. Overall, sand, silt, and clay fractions on those dates represented 7.1, 74.1, and 18.9 percent of the TSS (Table 3), which was very similar to the mean particle-size distribution determined for the five in-lake stations during the summer (Table 2).

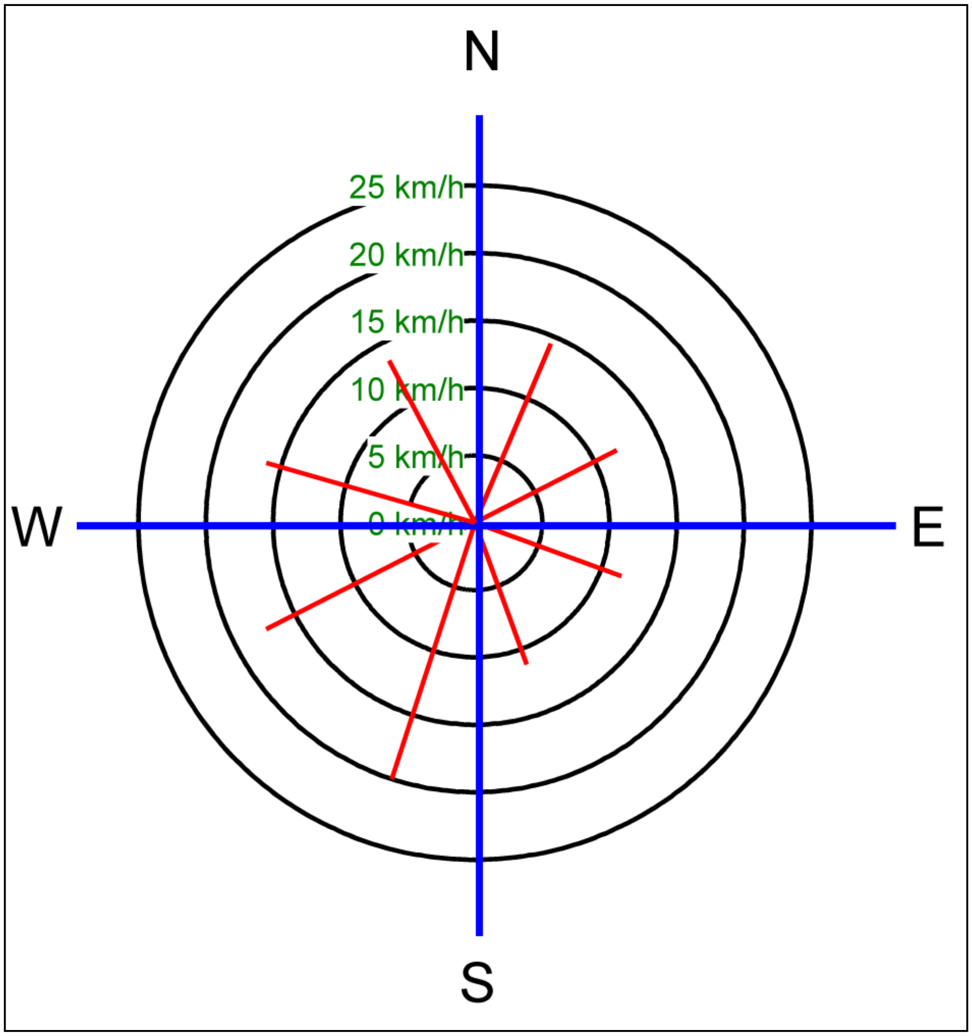

Figure 10. Variations in the average wind speed of winds blowing out of the NNE, ENE, ESE, SSE, SSW, WSW, WNW, and NNW at the resuspension station, Peoria Lake

Bottom Sediment Characteristics

Surface sediment at the resuspension station exhibited a mean moisture content of 53 percent (± 1.0 standard error (S.E.)), a mean bulk density of 0.59 g/mL (± 0.03 S.E.), and a mean particulate organic matter content of 7.5 percent (± 0.1 S.E.). The silt fraction dominated the particle-size distribution of the sediment, representing a greater percentage of the sediment content than that observed for the water column (Table 2). Conversely, the clay fraction comprised a lower percentage of the sediment content compared to the water column. The sand fraction comprised a similar percentage in the sediment and the water column (Table 2).

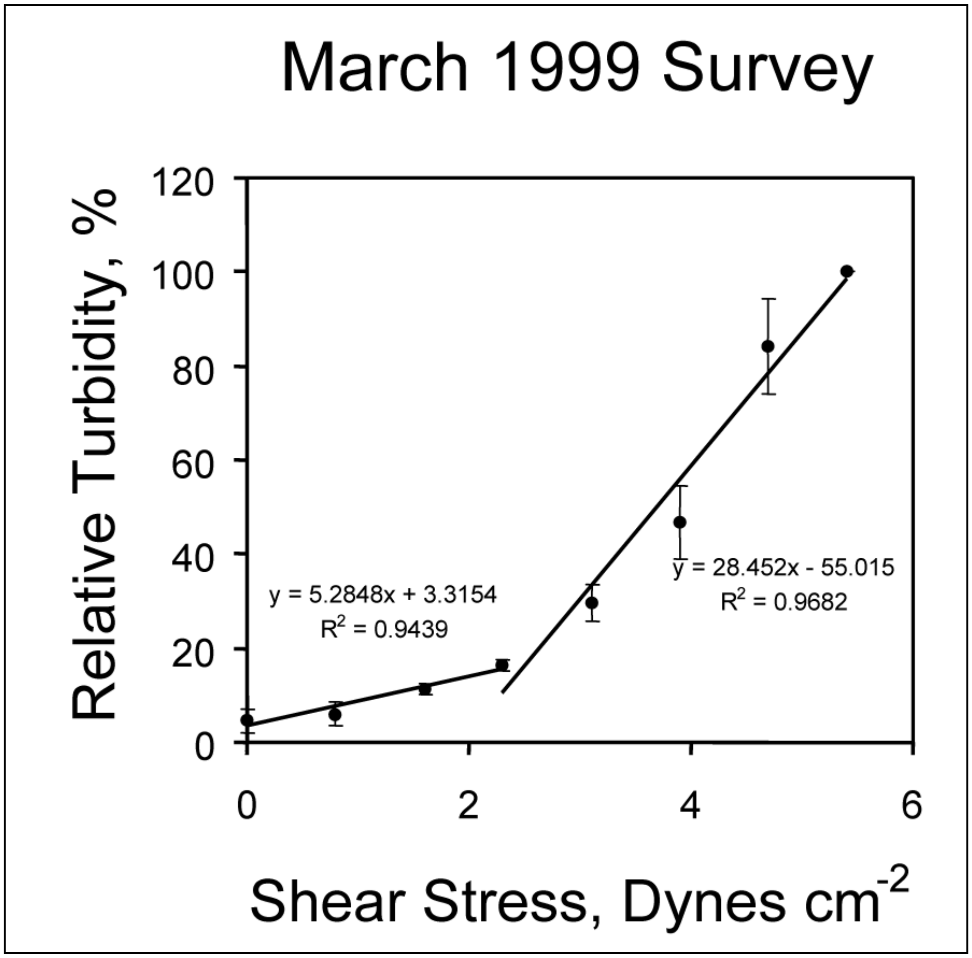

Figure 11. Relationships between relative turbidity (i.e., percentage of maximum turbidity) and applied shear stress for sediments collected at the resuspension station. Shear stress was applied to the sediments using the particle entrainment simulator

Estimation of TSS Resuspension in the Water Column

The parameters used to estimate TSS in the water column of Peoria Lake at the resuspension station (i.e., Equations 2 through 4) are listed in Table 4. The constants A and n were estimated from the relationship between the variable $\tau - \tau_c$ (i.e., normalized shear stress) and C_e (Figure 16; Lick, Xu, and McNeil 1995). Predicted versus measured TSS for the month of September are shown in Figure 17. In general, predicted TSS was similar to measured TSS for a number of large peaks caused by sediment resuspension (i.e., 4, 8, 9, 10, 11,17, 19, 20, 23 September). There were also instances (i.e., early and late September) where the model did not predict peaks in TSS.

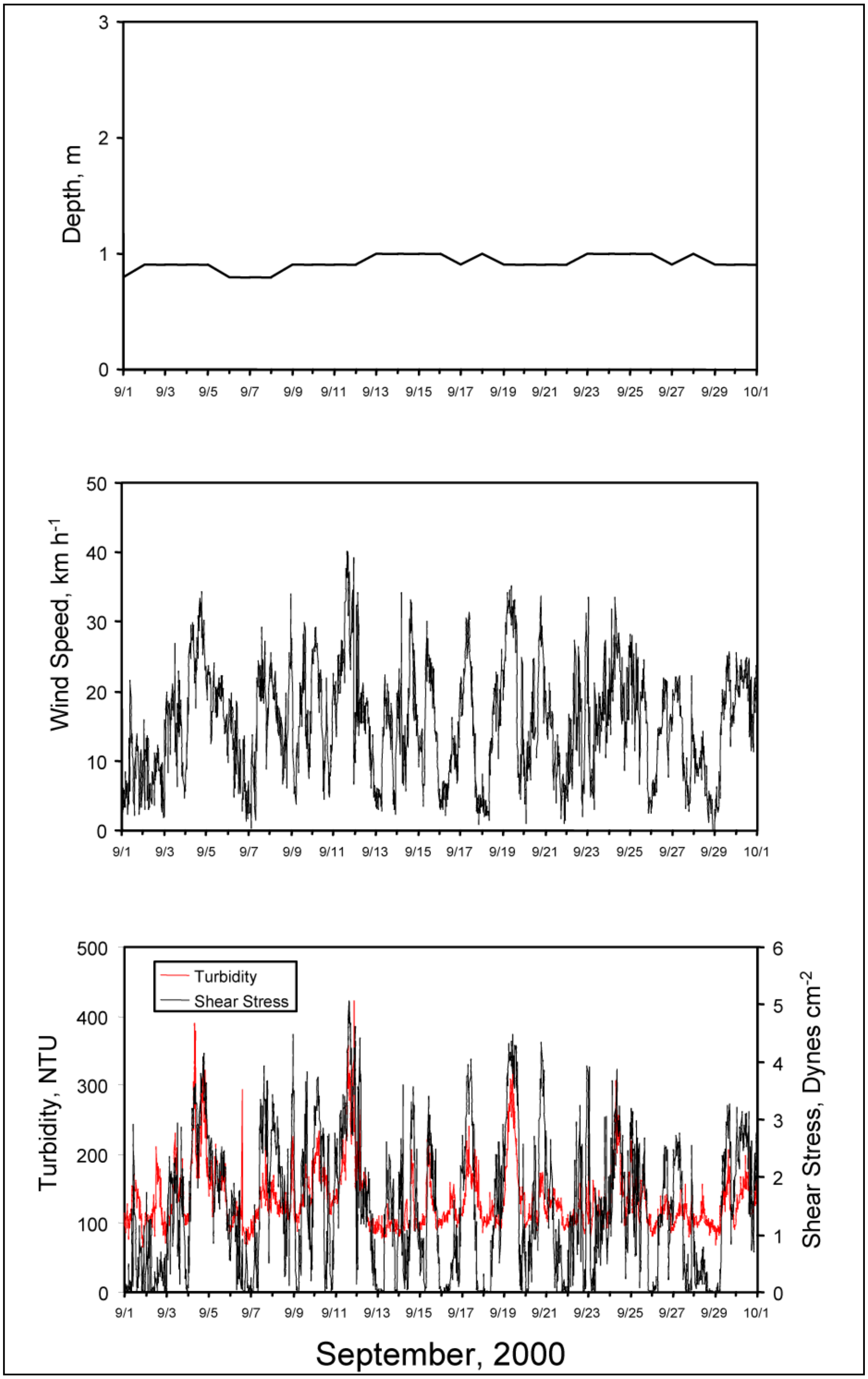

Figure 12. Variations in water column depth (upper), wind speed measured at 15-min intervals (middle), and turbidity and calculated shear stress (lower) at the resuspension station in Peoria Lake. Shear stress was calculated using Equation 2

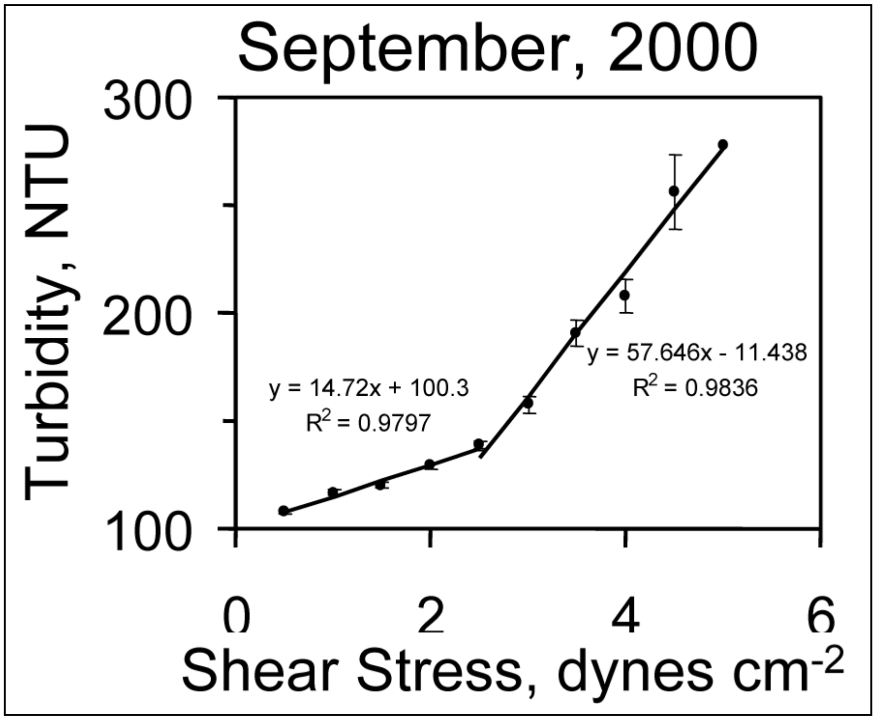

Figure 13. Relationships between mean turbidity (± 1 S.E.) and calculated shear stress at the resuspension station for September 2000. Shear stress was calculated using Equation 3

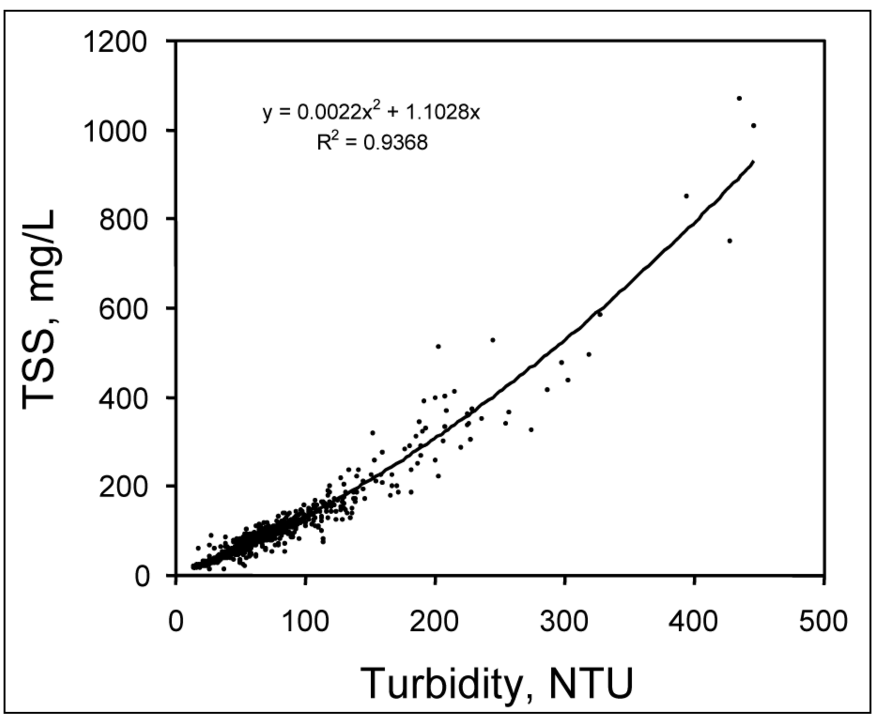

Figure 14. Relationships between turbidity and TSS

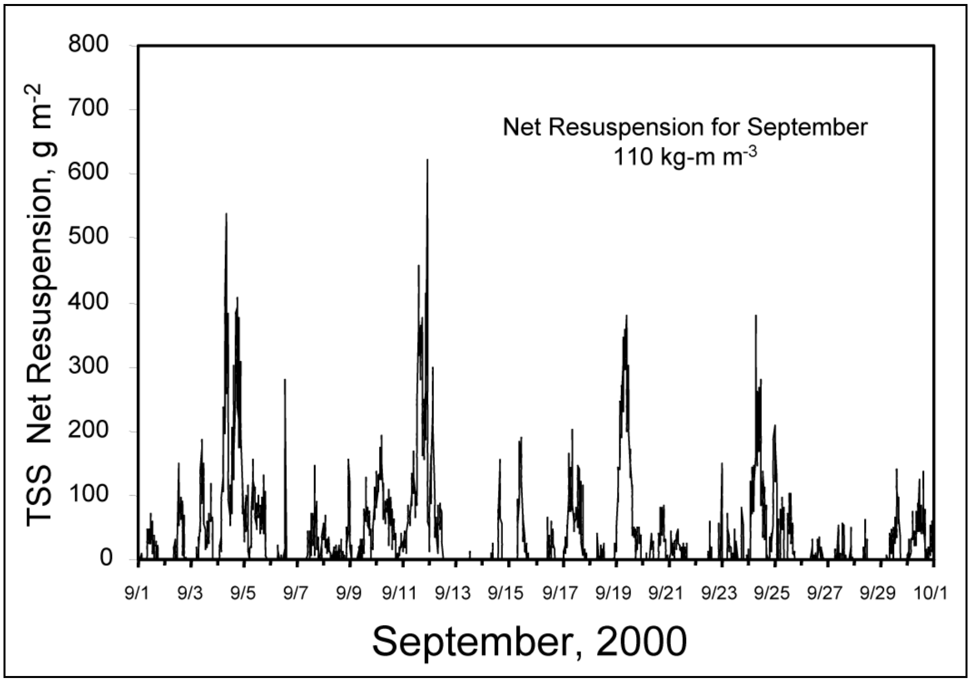

Figure 15. Variations in net TSS resuspension during September. See text for explanation of calculation of net TSS resuspension

Table 3
Mean (±1 S.E.; n=4) Percent Distribution of Various Particle-Size Classes for Data Collected on 16 August and 12 October 2000, at Stations 3 and 5 in Peoria Lake

Diameter Range	Settling Velocity Range, mm s^{-1}	Percent Distribution (±1 S.E.)
> 62.5	> 10	7.1 (1.0)
62.5 µ - 31.2 µ	10 - 0.877	2.8 (1.6)
31.2 µ - 15.6 µ	0.877 - 0.219	12.1 (4.7)
15.6 µ - 3.9 µ	0.219 - 0.0136	25.5 (15.6)
3.9 µ - 1.95 µ	0.0136 - 0.0034	33.7 (14.0)
< 1.95 µ	< 0.0034	18.9 (2.0)

Light Attenuation Characteristics

TSS concentrations at in-lake stations exhibited numerous peaks during March through November in conjunction with periods of high external TSS loading (i.e., April through July) and during periods of lower pool elevation and high resuspension potential (i.e., August through October; Figure 18). Overall, TSS concentrations, comprised primarily of silt fractions, were high throughout the study period, averaging 76 mg L^{-1} (± 3.9 S.E.) between March and November. Chlorophyll concentrations ranged between 5 mg m^{-3} and 136 mg m^{-3} between March and October for all stations (Figure 19). Peaks in chlorophyll occurred in early April, mid-May, and early September. In general, Station 5 exhibited the greatest in-lake concentrations of chlorophyll.

Table 4
Values Used as Model Parameters for Estimation of TSS in the Water Column of Peoria Lake

Parameter	Value	Comments
τ, shear stress	0 - 5.07, dynes cm^{-2}	Figure 12
τ_c, critical shear stress	2.3 dynes cm^{-2}	Figure 11
A, constant	9.12 mg cm^{-2}	Figure 16
N, constant	3.01	Figure 16
ω_s, settling velocity	0.004 cm s^{-1}	Table 3
H, water column depth	0.8 - 1.0 m	Figure 12
t, time step	900 s	
$C_{background}$, Background TSS	164.6 mg/L	See Chapter 3 for results
C_p, Initial TSS	156 - 822 mg/L	C_{TSS-1}

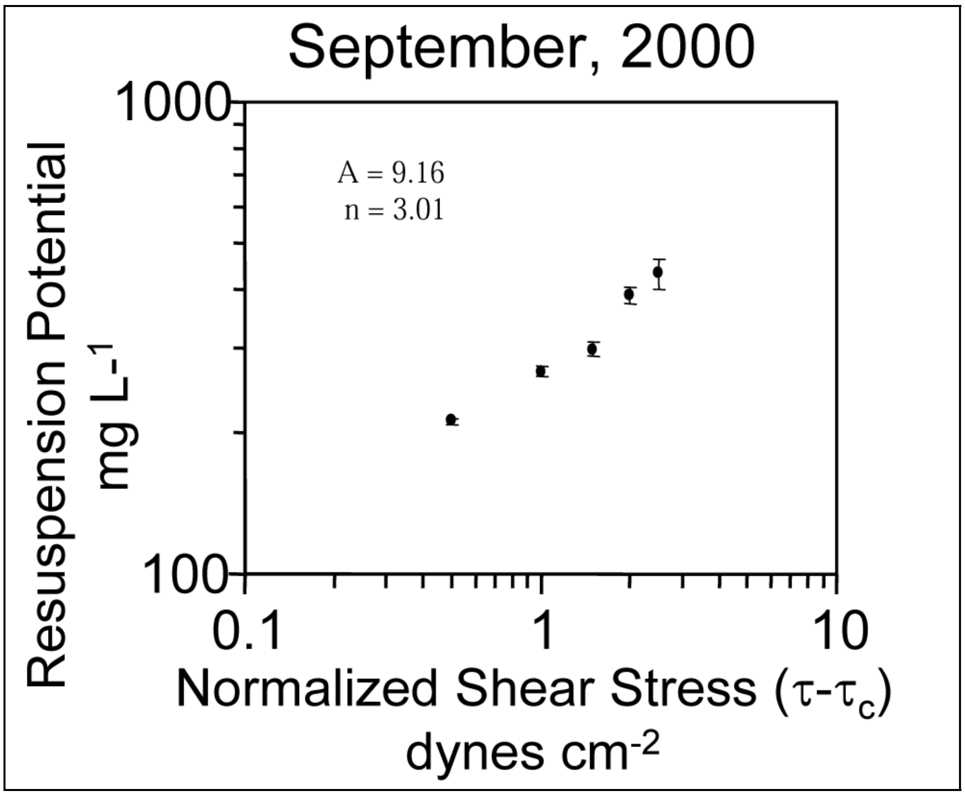

Figure 16. Relationships between calculated shear stress minus critical shear stress (τ_c) and net TSS resuspension. See text for explanation of calculation of net TSS resuspension

K_d was high, while Secchi transparency low, at all in-lake stations during the study period (Figures 20 and 21). There was a positive linear relationship between TSS and K_d (Figure 22) and a negative linear relationship between TSS and Secchi transparency (Figure 23) indicating that particulate components (versus soluble components) in the lake were most likely dominating light attenuation. The ε (i.e., beam attenuation coefficient) for TSS was also positively related to K_d (Figure 24), allowing for empirical conversion of ε to K_d' (i.e., calculated K_d) for specific fractions of TSS and for chlorophyll. In general, the ε and specific K_d'

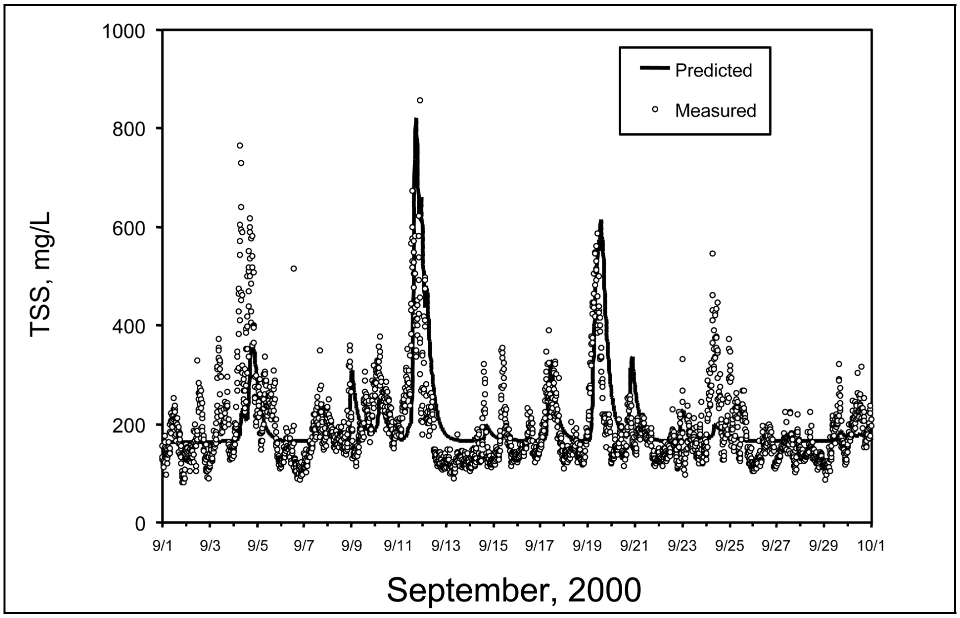

Figure 17. Seasonal variations in simulated versus measured TSS concentrations at the resuspension station, Peoria Lake, during September 2000

were greatest for chlorophyll, followed by the clay, silt, and sand fraction (Table 5). However, the chlorophyll contribution to K_d' was negligible compared to contributions by other sediment fractions (Table 5). Overall, the silt fraction exhibited the greatest K_d', followed by clay > sand > chlorophyll. The sum of K_d' from the sand, silt, clay, and chlorophyll fractions (i.e., $K_d' = K_d'_{sand} + K_d'_{silt+chla} + K_d'_{clay}$) was very close to K_d , measured in the field (Figure 25), suggesting that empirically derived K_d' was accurately reflecting measured K_d.

We estimated a daily K_d' for the resuspension station during the month of September (Figure 26). Daily TSS was estimated using *in situ* turbidity (Figure 12) and the conversion equation shown in Figure 14. We assumed that the sand, silt, and clay fraction represented a constant percentage of the TSS concentration in the water column at this station (i.e., 6.5 percent sand; 70.0 percent silt; 22.5 percent clay measured for TSS collected at the resuspension station. These percentages are slightly different than the averages determined for all stations; Table 2). We calculated the contribution of the sand, silt, and clay fractions to K_d' using the ε measured for each fraction (Table 5) and relationships between ε and K_d (Figure 24). Since the chlorophyll contribution to K_d' was negligible (not shown) compared to other fractions, it was not included as a separate component in the calculation. Since algal cells generally fall in the > 1.95-µm size range, we assumed that chlorophyll impacts were included in the K_d' estimated for the silt fraction. Overall, K_d' was most strongly impacted by the silt fraction (Figure 25), exhibiting marked peaks (i.e., > 25 m^{-1}) in conjunction with wind-generated resuspension events on 4, 11, 17, 19, and 24 September. Sand and clay contributions to K_d' were much less. During less windy conditions, K_d' was also high (> 10 m^{-1}), indicating that background TSS was contributing substantially to K_d', as well.

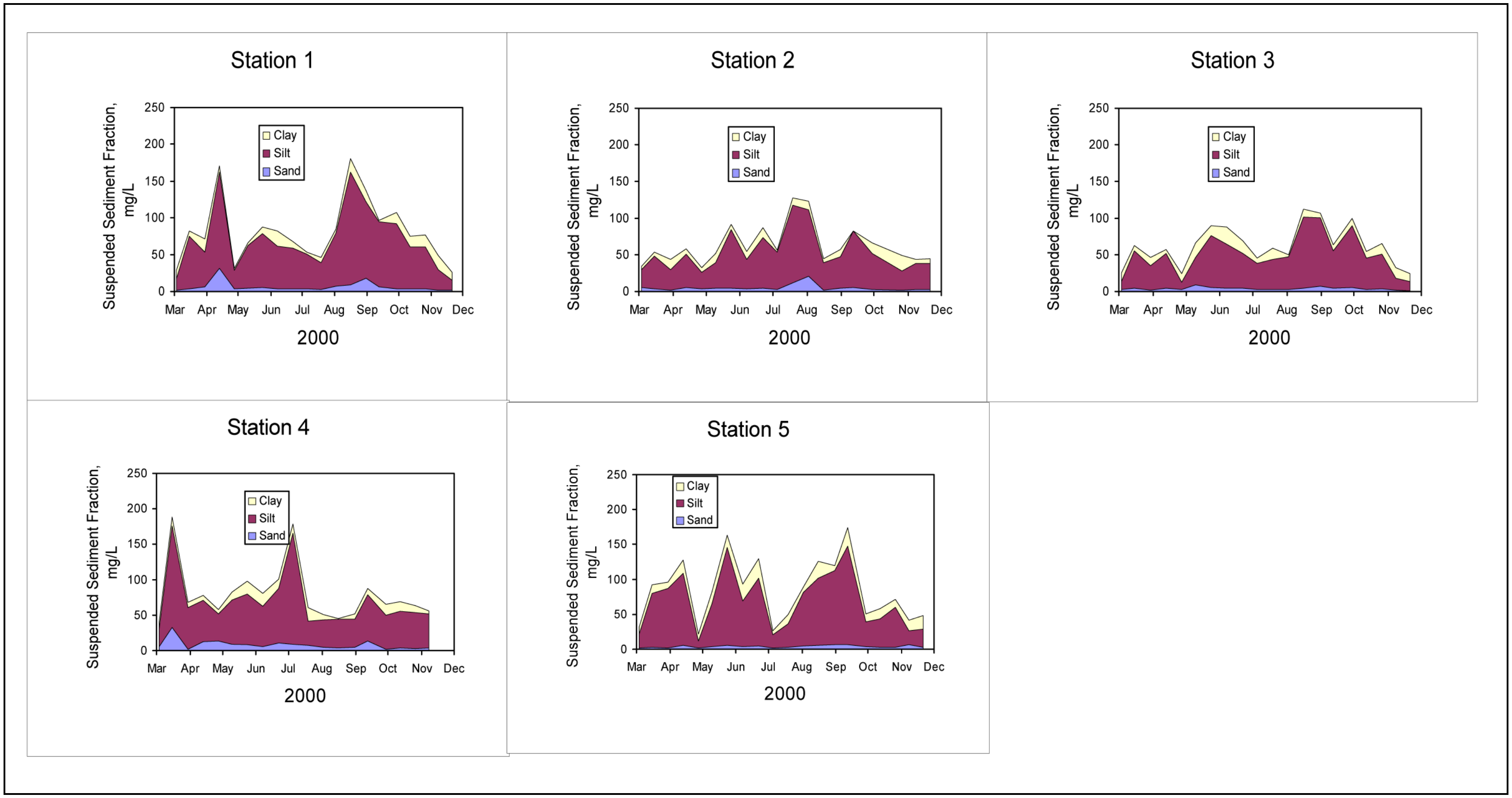

Figure 18. Seasonal variations in the sand, silt, and clay content of total suspended sediment at stations 1 through 5, Peoria Lake, in 2000

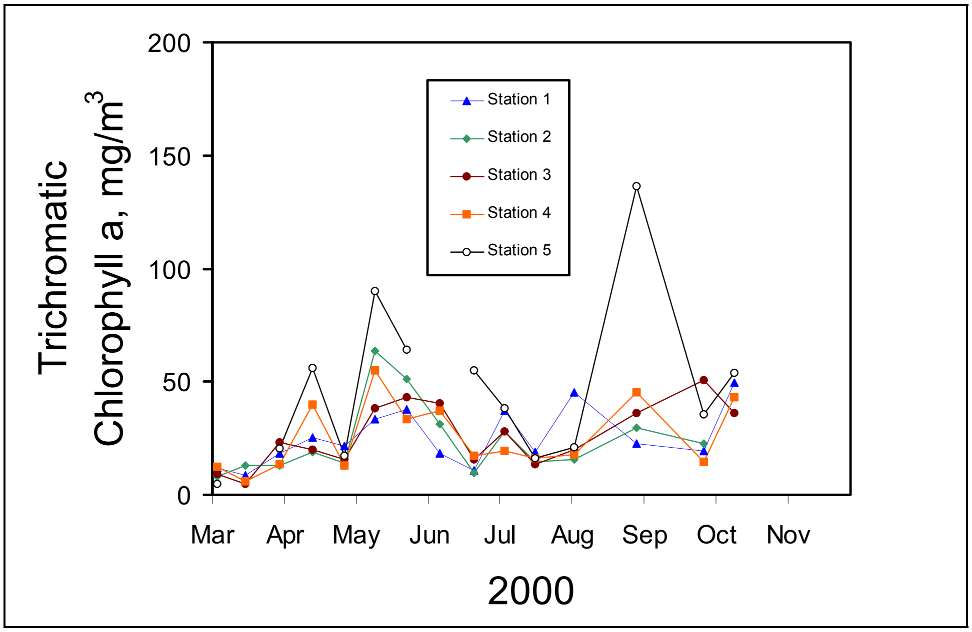

Figure 19. Seasonal variations in chlorophyll *a* at Stations 1 through 5, Peoria Lake, in 2000

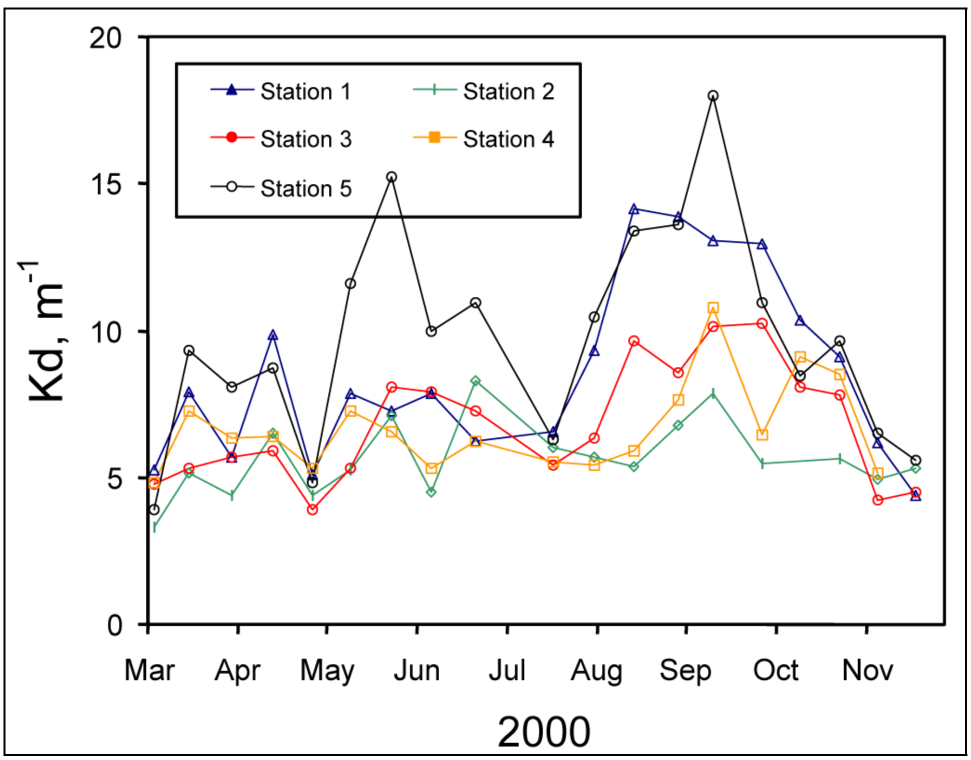

Figure 20. Seasonal variations in the light attenuation coefficient (K_d) at Stations 1 through 5, Peoria Lake, in 2000

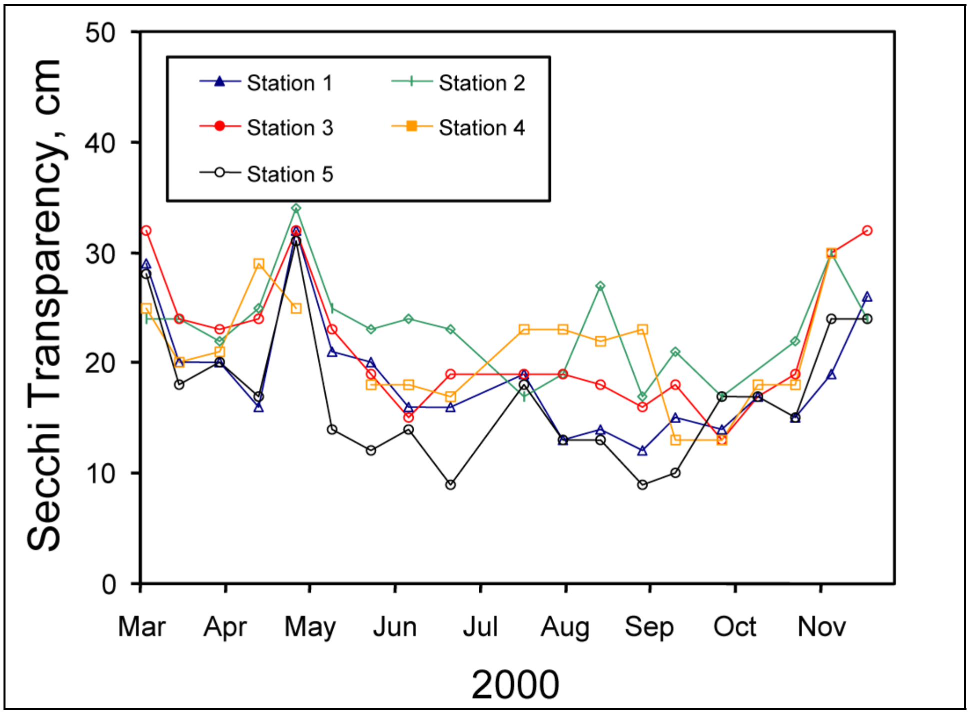

Figure 21. Seasonal variations in Secchi disk transparency at Stations 1 through 5, Peoria Lake, in 2000

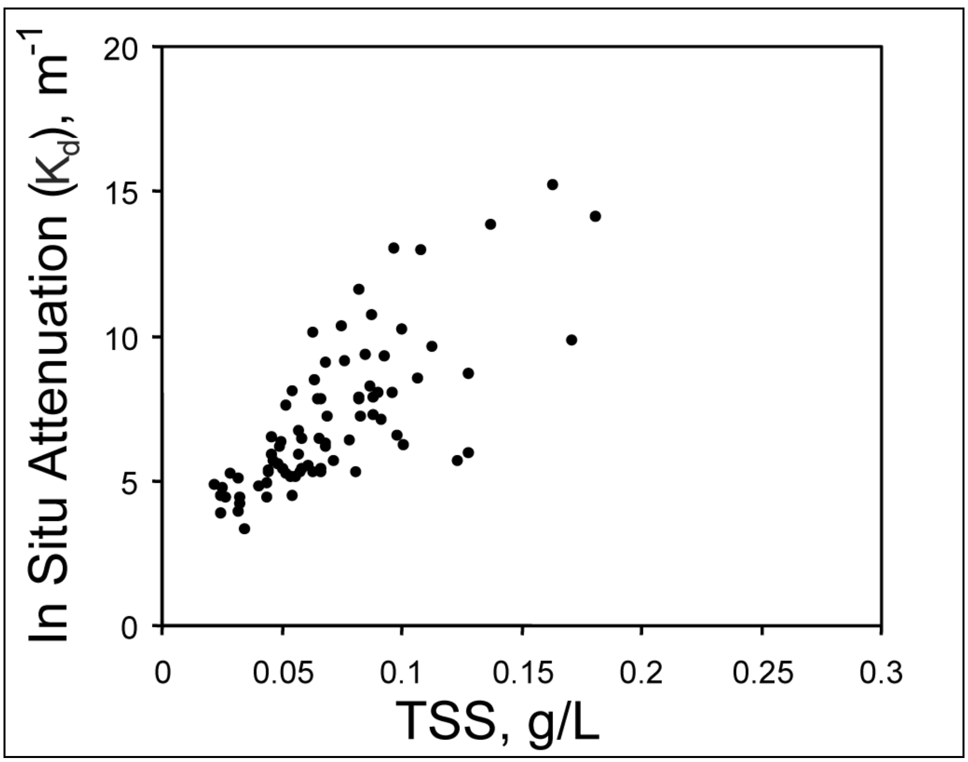

Figure 22. Regression relationships between TSS and the *in situ* light attenuation coefficient

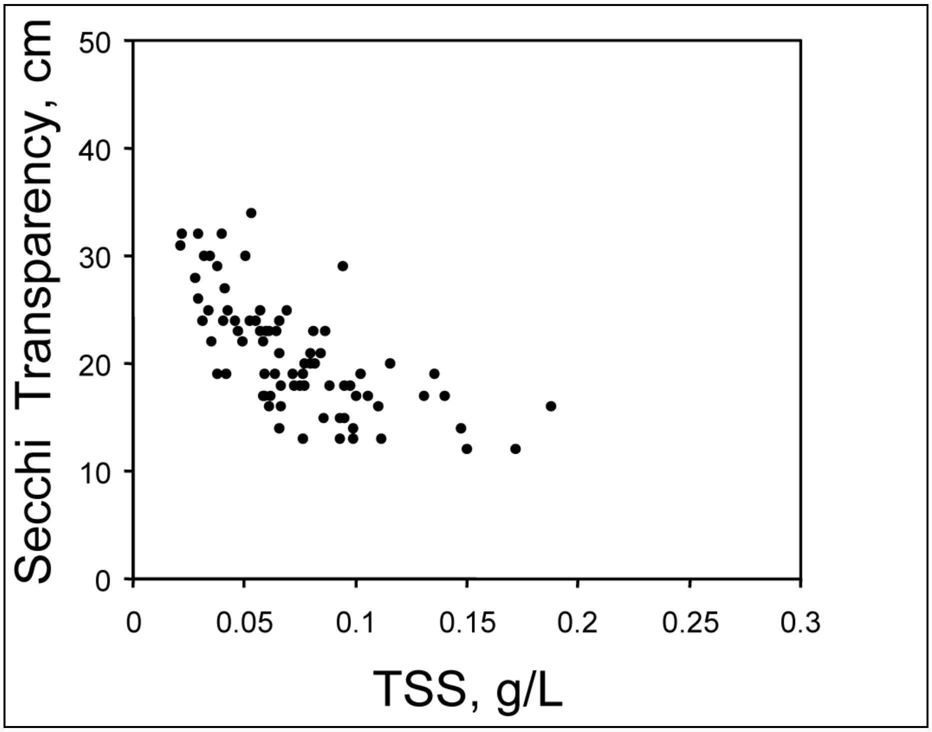

Figure 23. Regression relationships between TSS and Secchi disk transparency

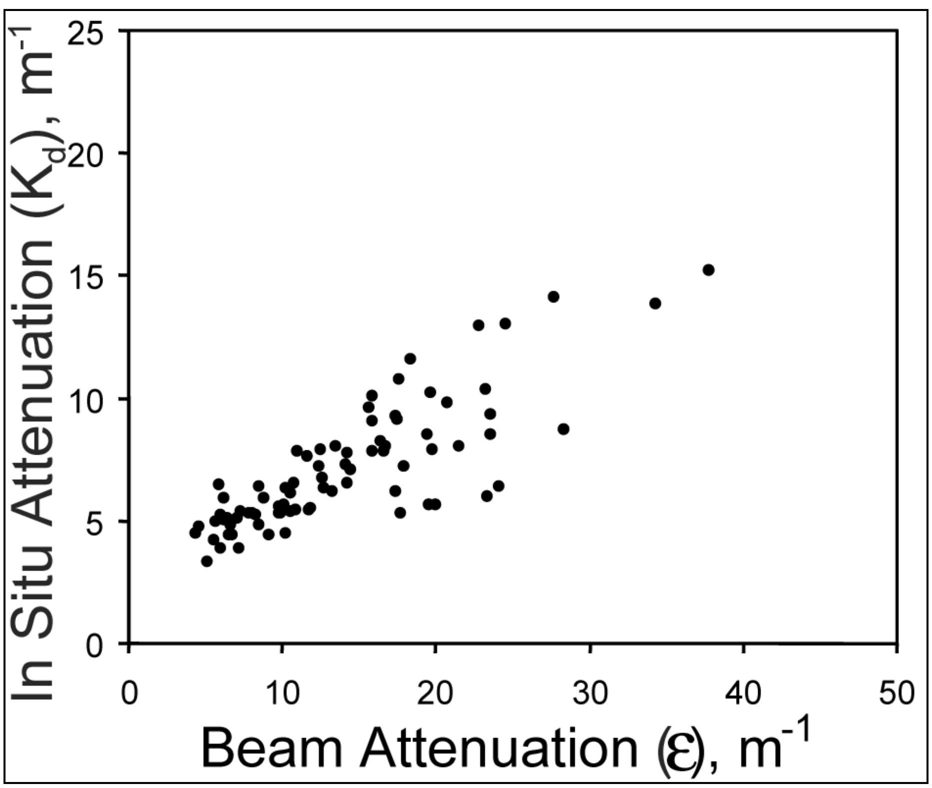

Figure 24. Regression relationships between the beam attenuation and *in situ* light attenuation coefficient

Table 5
Mean (±1 S.E., n=11-137) Concentrations of Sand, Silt, Clay, and Chlorophyll, Beam Attenuation Coefficient, Light Attenuation Coefficient (K_d') Estimated via Regression Relationships Between K_d' and the Beam Attenuation Coefficient (Figure 24), and the Specific Light Attenuation Coefficient (K_d' normalized with respect to dry mass)

Component	Mean Concentration(g m^{-3})	ε^1(m^{-1})	Estimated K_d'(m^{-1})	Estimated Specific K_d'(m^2 g^{-1})
Sand[2]	12.5 (0.7; n=30)	0.17 (0.02; n=11)	1.0 (0.05; n=30)	0.079 (<0.001; n=30)
Silt[2,3]	136.6 (7.7; n=30)	0.23 (0.01; n=137)	13.7 (0.77; n=30)	0.101 (<0.001; n=30)
Clay[2]	43.2 (2.4; n=30)	0.40 (0.03; n=71)	7.9 (0.45; n=30)	0.183 (<0.001; n=30)
Chlorophyll[4]	0.024 (0.002, n=84)	0.14 (0.01; n=84)	0.063 (0.004 n=84)	2.65 (<0.001; n=84)
AFDW Equivalent Chlorophyll[5]	1.72 (0.13, n=84)	0.14 (0.01; n=84)	0.063 (0.004; n=84)	0.036 (<0.001; n=84)

[1] Epsilon (beam attenuation coefficient).
[2] Mean for the month of September at the resuspension station. Values were estimated from relationships between *in situ* turbidity and TSS, assuming a constant percentage composition of sand, silt, and clay in the water column (i.e., 6.5, 71.0, and 22.5 percent).
[3] Estimated K_d and specific K_d are not corrected for K_d by chlorophyll (i.e., $K_{d\text{-silt}}$ -$K_{d\text{-chla}}$).
[4] The trichromatic equation was used to determine chlorophyll *a*. Expressed as chlorophyll.
[5] A conversion factor of 70 (ash-free dry mass:chlorophyll) was used to convert chlorophyll to organic matter.

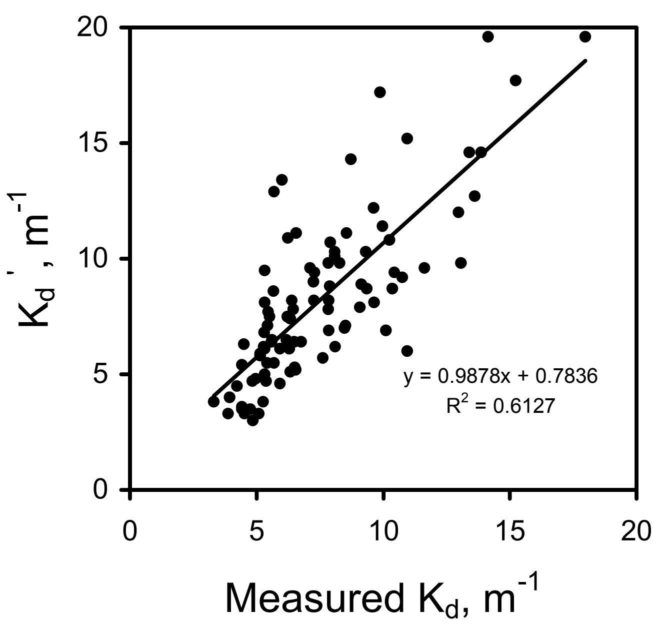

Figure 25. Regression relationships between the *in situ* light attenuation coefficient (K_d) and the predicted light attenuation coefficient (K_d'). K_d' (representing the sum of the sand, silt, and clay fractions) was determined via empirical conversion of the beam attenuation coefficient (ε, m^{-1}; Figure 24) for the sand, silt, and clay fractions

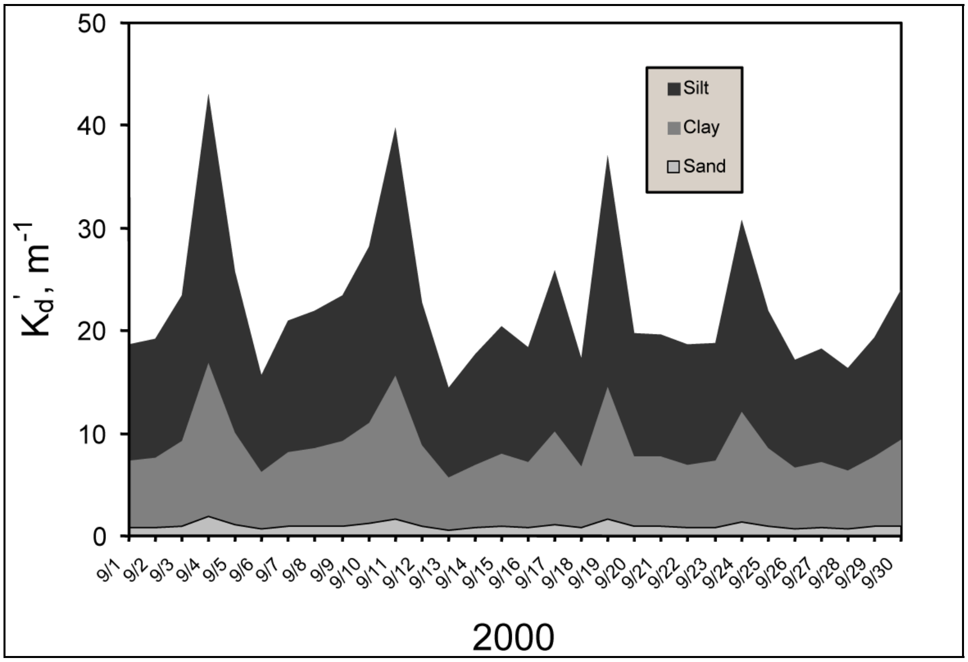

Figure 26. Variations in the daily calculated light attenuation coefficient (K_d') for the month of September. K_d' (representing the sum of the sand, silt, and clay fractions) was determined via empirical conversion of the beam attenuation coefficient (ε, m^{-1}; Figure 24) for the sand, silt, and clay fractions.

Discussion

Annual TSS loading from the Illinois River in 2000 was comparable to loading estimates computed by Bhowmik et al. (1993) for the year 1989, which was a relatively dry year. These results suggested that TSS loading to Peoria Lake is probably much higher during years of average and above average precipitation. For instance, Bhowmik et al. (1993) reported a much higher annual TSS loading from the Illinois River of ~ $1{,}100 \times 10^6$ kg during 1990, a year exhibiting near average precipitation conditions, compared to our annual estimate for 2000. Nevertheless, our estimated annual TSS input from the Illinois River for 2000 was nearly equivalent to TSS loadings to Pools 2, 3, and 4, and Lake Pepin, Upper Mississippi River, during periods of average flow conditions (James, Barko, and Eakin 1999), suggesting that TSS loading to Peoria Lake is comparable to other large river systems. In addition, much of the TSS load in 2000 was retained in Peoria Lake as fined-grained (i.e., < 63-μm) sediment, indicating it was an efficient trap for sediment that could be later resuspended during wind events.

As a result of step-wise increases in RPM and thus, applied τ, turbidity in the overlying water increased in a biphasic manner for intact sediment cores collected from the vicinity of the resuspension station and subjected to the PES. The slope of the turbidity increase was small at low applied τ, but it increased substantially as τ increased above 2.3 dynes cm^{-2}, implying a τ_c for these sediments of ~ 2.3 dynes cm^{-2}. By comparison, relationships between τ, estimated via wave theory, and turbidity, measured *in situ* at the resuspension station in September, yielded a similar pattern of marked increases in turbidity as shear stress exceeded ~2.5 dynes cm^{-2}. The marked similarity between the two methods of determining τ_c suggested that the PES may a useful tool for estimating τ_c for modeling resuspension of sediments that respond to a critical τ threshold (Lavelle and Mofjeld 1987). In general, our overall estimated τ_c for sediments was high relative to τ_c values suggested by Sheng and Lick (1979), Lick, Xu, and McNeil (1995), and Hamilton and Mitchell (1996). However, there is a need for more research regarding the experimental determination of τ_c using mechanical τ simulators (McNeil, Taylor, and Lick 1996; Jepsen, McNeil, and Lick 2000).

It appeared that as calculated τ determined in September increased above τ_c (estimated in the laboratory), resuspension was substantial in Peoria Lake. These patterns suggested that τ, in combination with τ_c, was a good predictor of the occurrence of TSS resuspension at the monitoring station in Peoria Lake. Hamilton and Mitchell (1996) and Bailey and Hamilton (1997) found that τ provided better estimates of changes in TSS in several shallow Australian Lakes versus other variables such as wave height^2, depth^{-1}, or wavelength depth^{-1} (Carper and Bachmann 1986). In addition, the resuspension potential (i.e., C_e; Equation 2) of sediments located at the monitoring station (i.e., Figure 16) was very high compared to river sediments (Lick, Xu, McNeil 1995; i.e., Buffalo, Fox, and Saginaw Rivers; HydroQual 1996; Pools 2, 3, and 4, Upper Mississippi River). This contrasting pattern was mostly likely a result of the high silt content of sediments located in the vicinity of the resuspension station versus the more sand-dominated riverine sediments.

Model simulations of TSS appeared to reasonably predict measured TSS at the resuspension station for the month of September, suggesting that parameter estimates such as setting velocity determined from particle size analysis and τ_c measured in the laboratory using the PES were acceptable for model input. We did not consider other factors such as circulation patterns and τ generated by other means such as advective flow and motor boat activity (Barge traffic through Peoria Lake can be heavy) which could greatly improve the accuracy of the model (Bailey and Hamilton 1997).

We explored the possible impacts that a canopy-forming population of submersed macrophytes might have on TSS concentrations at the resuspension station, using information reported by James, Barko, Butler (2001) on apparent τ adjusted for macrophyte influences. Using gypsum sphere dissolution to measure τ near the sediment surface, they found that at low biomass levels (i.e., <20g m^{-2}) of *Myriophyllum sibericum* (a canopy-forming native aquatic macrophyte), apparent measured τ was lower by nearly one-half ($0.46 \bullet \tau$) than τ calculated using wave theory. At high biomass levels and associated surface canopy structure (> 200 g m^{-2}), they found that apparent measured τ was ~ zero for all levels of calculated τ as the result of almost complete dampening of wave activity, even at high wind speeds. Thus, we adjusted the τ_c of 2.3 dynes cm^{-2} in Equation 2 to 3.4 dynes cm^{-2}. This was accomplished by using the following equation: 2.3 dynes cm^{-2} + (2.3 dynes cm^{-2} • 0.46) = 3.4 dynes cm^{-2} to simulate the resistance that a canopy-forming submersed macrophyte population like *M.*

sibericum might have on τ at low biomass levels. For high biomass levels, we assumed that τ_c was higher than all calculated τ at the resuspension station in Peoria Lake. Simulated results indicated that TSS concentrations declined markedly during wind-generated sediment resuspension at low macrophyte biomass levels (Figure 27).

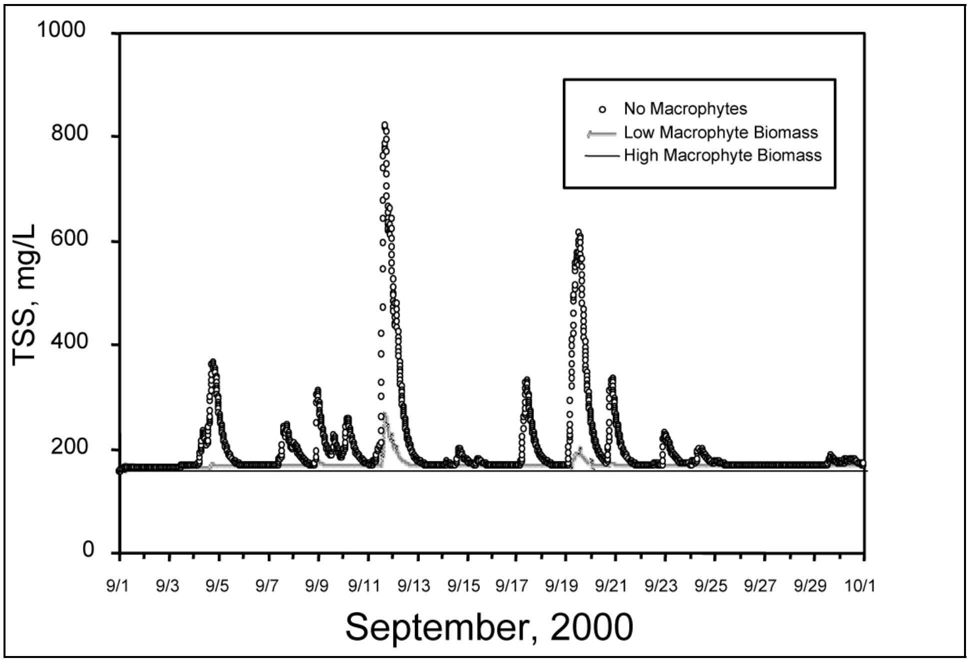

Figure 27. Variations in simulated TSS concentrations at the resuspension station, Peoria Lake, in the absence of submersed macrophytes and in the presence of low (< 20 g m^{-2}) and high (> 200 g m^{-2}) macrophyte biomass

These model simulations for the resuspension station suggest that the establishment of submersed macrophytes, even at low biomass levels, could have a marked impact on reducing TSS in the water column caused by sediment resuspension. James and Barko (1994) and Barko and James (1998) observed an almost complete absence of sediment resuspension, even at wind speeds exceeding 25 km h^{-1}, in Marsh Lake, Minnesota, when it was densely covered by submersed macrophytes. But during years when submersed macrophytes were absent from the system, TSS increased frequently as a result of wind-generated resuspension. Others (James and Barko 2000; Dieter 1990; Scheffer 1990; Scheffer et al. 1993; Scheffer et al. 1994) have shown that macrophytes can have a marked influence on reducing sediment resuspension in shallow lakes by dampening wave activity and, thereby, shear stress near the sediment surface.

One factor we did not consider in our simulation of resuspension was the potential impact that submersed macrophytes may have on $C_{background}$, which is very high in Peoria Lake. In conjunction with the low settling velocities of the silt and clay fractions, high loading of TSS from the Illinois River and other tributaries most likely contribute to high background TSS concentrations during quiescent periods. Other factors such as high-density benthic fish populations may also play an important role in sustaining high TSS in the water column. Submersed macrophytes may also be influential in lowering background TSS by promoting deposition in plant beds (James and Barko 1990; Barko and James 1998). However, more information is needed regarding deposition rates inside versus outside plant beds to improve models to address this question in future simulations.

K_d was very high at the resuspension station in Peoria Lake relative to some reported values for other shallow lakes (Van Duin 1992; Van Duin et al. 1992; Scheffer 1998), primarily a result of very high TSS concentrations in the water column that were predominantly < 62.5 µm. For inorganic suspended particles, the clay and silt fractions exhibited the greatest specific K_d' values and, thus, had the greatest impact on the underwater light regime. As indicated by Van Duin (1992), ε (and, thus, K_d') is typically greater for smaller particles because, in large part, of more numerous particles per gram as size class decreases. Since smaller particles had much lower fall velocities (Table 4), the light field in Peoria Lake was likely impacted for longer periods of time (versus sand settling velocity) in response to resuspension events.

One management option for improving water quality conditions in Peoria Lake, as suggested by model simulations, is reestablishment of submersed aquatic vegetation in various regions to dampen wave activity and reduce sediment resuspension. Areas in the shallow northeastern region of Peoria Lake were once inhabited by *Vallisneria americana* between 1948 and 1954 (Best et al. in preparation). However, current underwater light conditions are not favorable for reestablishment of submersed macrophytes in this lake. For instance, Doyle and Smart (2001) demonstrated in experimental mesocosms that survival and growth of *V. americana* was greatly diminished at high sustained turbidity and K_d levels (i.e., 45 NTU and 4 m^{-1}). K_d in Peoria Lake was much greater than the highest level of 4 m^{-1} used in the experimental systems of Doyle and Smart (in preparation). Others have found negative relationships between high K_d and tuber production for *V. americana* (Kimber, Owens, and Crumpton 1995; Kimber, Korschgen, and Van der Valk 1995), implying that a poor light environment may suppress this plant's ability to persist over the winter months.

If reestablishment of submersed vegetation is considered for Peoria Lake, the underwater light regime will have to, at least temporarily, be modified to allow for successful establishment of aquatic plants. Construction of islands to reduce fetch and resuspension may provide for both improved light penetration and refuge from wave activity for submersed macrophyte establishment (Smart and Dick 1999). Compacting sediments via drawdown and dessication may lower the resuspension potential and raise the τ_c required to initiate resuspension (Sheffer 1998), thereby, improving both light penetration and the rooting medium. For a large lake like Peoria, where whole-lake drawdown is impractical, small areas could be diked and pumped to temporarily desicate sediment. Finally, reduction in TSS loading should be considered in concert with in-lake techniques to reduce sediment resuspension.

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14. ABSTRACT

We examined sediment resuspension dynamics and light availability in relation to the potential for macrophytes to improve water quality conditions in Peoria Lake, Illinois. The lake exhibited high total suspended sediment (TSS) loading and retention of predominantly fine-grained particles during 2000. Large fetches along the prevailing wind rose, coupled with shallow morphometry and sediment particles composed of >90 percent silt and clay, resulted in frequent periods of sediment resuspension in September. The τ_c of sediment in the vicinity of the resuspension monitoring station, determined experimentally using a particle entrainment simulator, was 2.3 dynes cm^{-2}. This value was in close agreement with τ_c, determined by direct examination of variations in *in situ* turbidity as a function of τ, calculated using wave theory, at the resuspension monitoring station during the month of September. As calculated τ increased above τ_c, turbidity increased substantially at the resuspension monitoring station during the month of September. Net TSS resuspension was very high in relation to TSS loading from the Illinois River during September. The settling velocity of particles in the water column was estimated as 0.004 cm s^{-1}, based on analysis of five particle-size fractions ranging between <1.95 and >62.5 µm. Using a resuspension model, we reasonably predicted resuspension events that occurred in September at the resuspension station. Model explorations suggested that establishment of submersed aquatic macrophytes could substantially reduce sediment resuspension in Peoria Lake. However, K_d was very high, while Secchi transparency was low at in-lake stations, and the silt fraction (i.e., <62.5 and >1.95 µm) strongly influenced K_d. Thus, in order to establish a persistent macrohpyte population in the lake to control resuspension, the underwater light regime must initially improve quite dramatically.

15. SUBJECT TERMS

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Macrophytes	Suspended sediment
Resuspension	

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