Int. J. Environ. Res. Public Health **2007**, *4(2)*, 185-192

International Journal of
Environmental Research and Public Health
ISSN 1661-7827
www.ijerph.org

Effects of Prevailing Winds on Turbidity of a Shallow Estuary

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Received: 19 January 2007 / Accepted: 30 April 2007 / Published: 30 June 2007

Abstract: Estuarine waters are generally more turbid than lakes or marine waters due to greater algal mass and continual re-suspension of sediments. The varying effects of diurnal and seasonal prevailing winds on the turbidity condition of a wind-dominated estuary were investigated by spatial and statistical analyses of wind direction, water level, turbidity, chlorophyll *a*, and PAR (Photosynthetically Active Radiation) collected in Lake Pontchartrain, Louisiana, USA. The prolonged prevailing winds were responsible for the long-term, large-scale turbidity pattern of the estuary, whereas the short-term changes in wind direction had differential effects on turbidity and water level in varying locations. There were temporal and spatial changes in the relationship between vertical light attenuation coefficient (K_d) and turbidity, which indicate difference in phytoplankton and color also affect K_d. This study demonstrates that the effect of wind on turbidity and water level on different shores can be identified through system-specific analyses of turbidity patterns.

Keywords*:* Wind direction, turbidity, water level, estuary, Lake Pontchartrain

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Introduction

Estuaries are coastal indentations that receive freshwater flows and have restricted connections with the open sea [8, 20]. In general, estuaries are physically dominated ecosystems with complex water movements including gravitational, tidal, and wind-driven circulations [8]. Dissolved plant nutrients (N and P) and sediment nutrients have greater roles in the energy flow in estuarine ecosystems than in freshwater or marine ecosystems [23]. Due to continual re-suspension of sediments and higher algal mass, light availability is generally lower in estuaries than at comparable depths in lakes or marine waters [24].

Incident light attenuates as it travels through water because it is absorbed by pure water, dissolved organic material, chlorophyll *a*, and scattered by suspended particulate matter [7]. Turbidity is defined as a decrease in the transparency of a solution due to light attenuation from scattering and reflection of incident light primarily caused by suspended particulate matter [13]. Turbidity causing materials include organic seston (phytoplankton and non-living detritus) and re-suspended inorganic sediments (silts and clays). At a given TSS (total suspended solids) level, water with finer suspended particles transmits less light than water with coarse suspended particles because smaller particles have a larger surface area to scatter light [2]. Light attenuation in the water column is, therefore, not only influenced by the amount of total suspended sediment, but also by the types of turbidity causing matters that differ in composition and particle size.

Inherent color, also called true color of the water, also reduces the amount of light penetrating through the water column [7]. Inherent color is caused by the dissolved organic carbon (DOC), the pigmented material in natural waters which passes through a 0.22 um filter [12]. An increase in the concentration of DOC, particularly humic acids, results in shifts of spectral regions of light absorption in addition to reduction of light transmission [27]. Absorption of short wavelengths (blue and green) by DOC can affect photosynthesis by underwater vegetation in deep water by restricting light to the green region of the electromagnetic spectrum that is not used in photosynthesis by most macrophytes.

Light penetration in a water column is additionally affected by surface conditions including water surface roughness, surface algal blooms, or other surface contamination such as oil spills**.** Wind is an important factor in moving water in and out of an estuary, affecting water level, water movement, and surface conditions. Therefore, wind direction, duration, and wind-generated waves can significantly influence turbidity and underwater light condition in an estuary. An individual estuarine system can be influenced predominantly by particular wind directions due to its unique large-scale geologic and geographic settings; and the prevailing winds may cause particular shores to experience higher turbidities and water level fluctuations than the rest of the system. The wind-driven-wave-stressed shores may not serve as a favorable habitat or a restoration site for many estuarine-dependent organisms, especially for submerged aquatic vegetation that requires conditions of high light and relatively low wave energy [6]. Thus, there is a need to identify the system-specific, multi-scale turbidity patterns that are caused by physical stresses (i.e. wind-driven waves, water currents), prior to planning for an environment management or a restoration project.

In this paper, I present how diurnal, seasonal, and prevailing winds affect turbidity conditions at selected shores and areas differently in a shallow, large, wind-dominated estuary. The research approach included: (1) analyses on the effects of daily resultant winds on turbidity and water level at selected shores; (2) GIS visualization of the system-wide turbidity patterns; (3) analyses on the seasonal and spatial turbidity and chlorophyll *a* distribution; and (4) regression analyses on turbidity-light attenuation relationships and its temporal variation.

Materials and Methods

Study Area

Lake Pontchartrain is a wind-dominated estuary, located in southeastern Louisiana, USA (Fig. 1). Its water level is influenced by a combination of the Gulf tides and the easterly winds that drive water into the lake [15]. Tidal ranges of Lake Pontchartrain are small, ranging from 10 cm to 20 cm [25]. Lake turbidity is influenced by salinity and wind [10]. Since Lake Pontchartrain is shallow (a mean depth of 3.7 m) and large (a surface area of 1,631 km^2), winds blowing at 6.8 m/s (15 mph) over the Lake are sufficient to stir and mix bottom sediments throughout the water column [26].

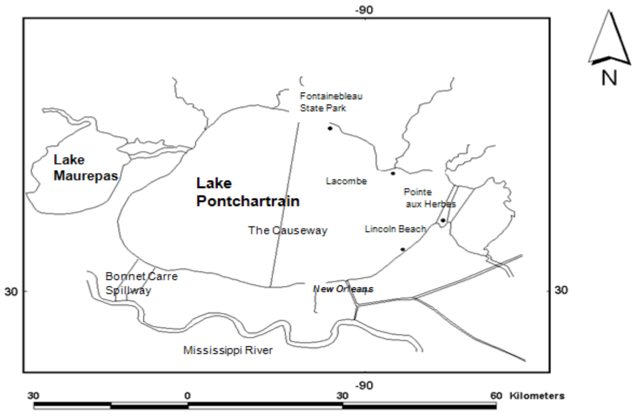

Figure 1: The map of Lake Pontchartrain, Louisiana, USA. Monthly PAR-turbidity monitoring sites are indicated.

Turbidity and PAR monitoring

Turbidity and Photosynthetically Active Radiation (PAR) was monitored monthly at Fontainebleau State Park (Fontainebleau), Lacombe, and Pointe aux Herbes from September 1996 through August 2002 (Fig.1; Table 1). Two sites at Lincoln Beach were added in January 2000 and monitored through August 2002 (Fig.1; Table 1).

Table 1: Geographic coordinates for turbidity-PAR monitoring sites and the stations for the hydrologic state.

	Site	*Latitude*	*Longitude*
Monthly turbidity and PAR monitoring sites	Fontainebleau State Park	30^{o} 20’ 12.7”	90^{o} 02’ 46.1”
	Lacombe	30^{o} 15’ 42.9” – 43.9”	89^{o} 57’ 25.1” – 26.9”
	Pointe aux Herbes	30^{o} 09’ 12.5” – 13.3”	89^{o} 51’ 27.0” – 28.0”
	Lincoln Beach	30^{o} 04’ 20.0”	89^{o} 56’ 56.9”
Stations of hydrologic state (lake level)	Mandeville	30^{o} 21’ 31” N	90^{o} 05’ 45” W
	Irish Bayou	30^{o} 08’ 46” N	89^{o} 51’ 41” W
	Chef Menteur	30^{o} 04’ 04” N	89^{o} 48’ 25” W
	Frenier	30^{o} 06’ 22” N	90^{o} 24’ 01” W
	Manchac	30^{o} 16’ 53” N	90^{o} 24’ 01” W

Water samples and PAR (umols^{-1}m^{-2}) measurements were taken in the field between 9:00 A.M. and 3:00 P.M. Turbidity (NTU) was measured in the laboratory with a HACH Pocket Turbidimeter (Cat. No. 52600-00) using water samples taken at a depth of 1 m. PAR was measured at the surface and at a depth of 1 m with a Li-Cor quantum sensor and photometer. First, radiation was measured just below the surface, and then the sensor was lowered to read the PAR at 1.0-meter depth. Surface radiation was read again to determine if changes occurred due to cloud cover. If the two surface measurements differed by more than 10%, they were discarded and PAR was measured again. The two surface PAR readings were averaged, and then the readings at 1 meter were expressed as percentage of the average surface PAR. The vertical absorption coefficient (K_d) was calculated from Beer-Lambert Law, $K_d = (\ln I_0 - \ln I_z) / Z$, where I_0 is PAR at water surface and I_z is PAR at a depth of Z. All sampling and analytical methods followed general recommendations by Standard Methods [1] and manufacturer’s manuals for each instrument.

Wind Data

Wind data from October 21, 1996 through May 21, 2001 were obtained from the Southern Regional Climate Center. These data were collected at New Orleans International Airport (Lat 29^{o} 59’ N; Long $90^{o}15$’W) on a daily basis (metadata published at www.srh.noaa.gov/LIX/html/new/apr98new.html). Wind direction was recorded in degrees to the nearest tenth, clockwise from true north. Daily resultant wind directions were used in the analyses.

Lake Level Data

Hydrologic data were obtained from U.S. Army Corps of Engineers (http://www.mvn.usace.army.mil/cgi-bin/watercontrol.pl). Daily readings of lake level recorded at 8 A.M. at five stations during September 1996 through January 2002 were used for the analyses. Lake levels were recorded in feet relative to the mean sea level (MSL). The five stations were at Mandeville, Irish Bayou, Chef Menteur, Frenier Beach and Manchac (Table 1).

Lake-wide Turbidity Data

In order to evaluate the spatial distributions of turbidity and chlorophyll *a* in the lake, monthly samplings were made at 18 sampling stations from February 1999 through January 2000 (Fig. 2). Water samples were taken from a boat using a Kemmerer water sampler within the photic zone (0.3-0.5 m below water surface) at each station. Turbidity was measured with a HACH Pocket Turbidimeter.

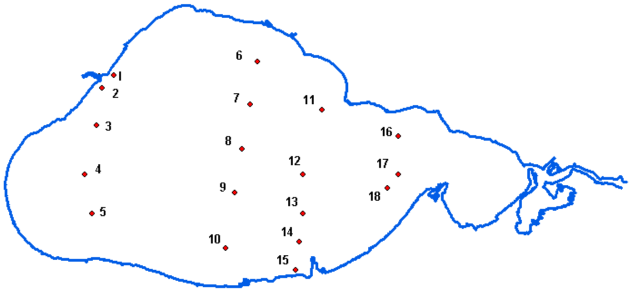

Figure 2: Turbidity and chlorophyll *a* sampling sites.

Chlorophyll *a* expressed in ug/L was measured with a Turner Design Fluorometer (Model 10-AU) Pigment extraction procedure followed Nusch [18] using 90% ethanol. Measurements of chlorophyll *a* concentration are widely used as an indirect method to estimate phytoplankton biomass [1].

Data Analyses

Wind Direction and Lake Level

Wind direction was grouped into 45^{o} intervals: 337.5^{o}-22.5^{o} (N); 22.5^{o} -67.5^{o} (NE); 67.5^{o} -112.5^{o} (E); 112.5^{o} -157.5^{o} (SE); 157.5^{o} -202.5^{o} (S); 202.5^{o} -247.5^{o} (SW); 247.5^{o} -292.5^{o} (W); and 292.5^{o} -337.5^{o} (NW). The number of days that the wind was from a given direction was determined. The effect of the daily resultant wind direction on the daily change in lake level was analyzed by using one-way ANOVA with wind direction as a fixed variable.

Wind Direction and Turbidity

The effect of daily resultant wind direction on turbidity at Fontainebleau, Lacombe, Pointe aux Herbes and Lincoln Beach was tested using one-way ANOVA. Wind direction on the day before the each turbidity measurement was used as a fixed variable. After-ANOVA unplanned contrasts were used to compare each pair of wind directions for their effects on turbidity at the study sites.

Lake-wide Analysis of Turbidity and Chlorophyll a

The 18 lake-wide turbidity sampling stations (Fig. 2) were grouped into four: stations 1-5 (Transect 1); stations 6-10 (Transect 2); stations 11-15 (Transect 3); and stations 16-18 (Transect 4). Stations on transect 1 are located in the western part of the lake, transect 2 is the Causeway Bridge, transect 3 was located in mid-east of the lake and transect 4 was in the eastern part of the Lake. The stations were grouped along the transects in order to display the W-E gradients in the turbidity-causing constituents. The twelve-month period of turbidity measurements were compared among the transects using one-way ANOVA. The turbidity values at the 18 sites were spatially interpolated using the Kriging Interpolation method with a variable radius in ArcMap 8.1.

Chlorophyll *a* concentration (ug/L) collected monthly at the 18 sites (Fig. 2) from February 1999 through January 2000 was analyzed using two-way ANOVA with fixed variables of site and month to test if there is seasonal or spatial variation in relative contribution of phytoplankton to light attenuation.

Turbidity and Light Attenuation

Regression analyses were used to find relationships between turbidity and vertical absorption coefficient (K_d). Combined data from the study sites at Fontainebleau, Lacombe, and Pointe aux Herbes were regressed with *ln* turbidity (natural log transformed turbidity) as an independent variable and *ln* K_d (natural log transformed K_d) as a dependent variable. Residuals from the linear fit line derived from the analysis were calculated and the mean residuals were plotted against annual time periods (September through August of the year after for each time period) to assess the relative contribution of turbidity on light attenuation among different years.

The first two time periods (September 1996-August 1998) were excluded in order to eliminate the effects of surface algal blooms that occurred during the summer of 1997 [19]. Separate regression analyses were conducted for datasets (September 1998 to August 2002) from all three sites, and also from each study site. Residuals were calculated as above. Analysis of covariance tested homogeneity of the slopes.

Results

Wind Direction and Lake Level

As shown in Fig. 3, easterly winds over Lake Pontchartrain occurred more often than westerly winds. Overall, north winds dominated the winter months (December-February). Then the prevailing wind direction switched to south-southeast during March through June. West winds dominated during July and August, but became northeast from September through November.

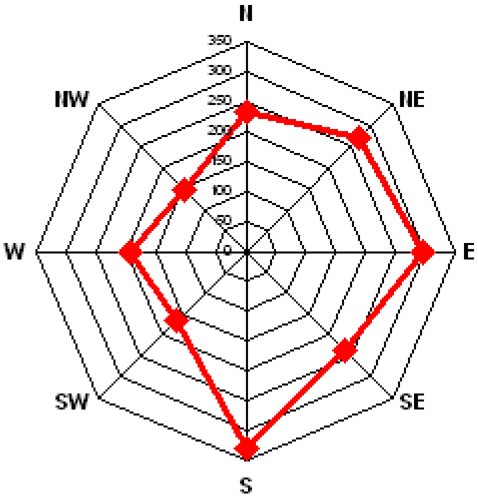

Figure 3: Number of days with each daily resultant wind direction data (Oct 21, 1996 through May 21, 2001) obtained at the Southern Regional Climate Center.

Table 2: Mean daily change in lake level for eight resultant wind directions. The presented P values are the results of the one-way ANOVA comparing the water level changes for different wind directions.

Wind direction	*Stations*			
	Mandeville	*Irish Bayou*	*Chef Menteur*	*Frenier Beach*
N	-0.15	-0.17	-0.01	-0.06
NE	0.11	0.12	0.01	0.04
E	0.22	0.20	0.14	0.16
SE	0.15	0.15	0.07	0.10
S	0.04	0.06	0.03	0.01
SW	-0.19	-0.13	-0.13	-0.14
W	-0.22	-0.19	-0.16	-0.18
NW	-0.26	-0.23	-0.06	-0.14
P value	<0.001	<0.001	<0.001	<0.001

Diurnal changes in lake level under different wind directions are presented in Table 2. There were significant differences among the effects of the wind direction on lake level. Easterly winds (NE, E, and SE) and south wind resulted in positive values at all stations, indicating that these winds force water into the basin. Westerly winds (SW, W, and NW) and north winds result in negative values, indicating these winds drive water out of the basin.

Wind Direction and Turbidity

The effect of wind direction on turbidity values at the four shores are presented in Table 3. Generally south to westerly winds result in higher turbidity at Fontainebleau and Lacombe which are located in the northeastern sector of the lake (Fig. 1). Turbidity at Pointe aux Herbes, located in eastern sector of the lake, was strongly influenced by west winds. North and south winds turbidity effects oppose each other at Lincoln Beach. Turbidity at this south shore site was highest with north winds and lowest with south winds.

Table 3: Mean turbidity values (NTU) for different wind directions at four turbidity-PAR monitoring sites. Data on resultant wind direction were obtained from Southern Regional Climate Center. Turbidity was compared using one-way ANOVA for each study site with wind direction as a fixed variable. The difference between values with the same superscript letter(s) is not statistically significant (P>0.05).

Direction	*Fontainebleau State Park*	*Lacombe*	*Pointe aux Herbes*	*Lincoln Beach*
N	8.04^{A}	8.16^{AB}	13.83^{AB}	29.20^{A}
NE	5.08^{A}	9.59^{AB}	13.88^{AB}	17.20^{AB}
E	4.81^{A}	5.92^{A}	14.09^{AB}	12.22^{AB}
SE	8.12^{A}	8.54^{AB}	11.68^{A}	14.15^{AB}
S	17.34^{B}	14.07^{B}	16.55^{AB}	9.32^{B}
SW	11.11^{A}	16.61^{B}	12.55^{AB}	18.37^{AB}
W	19.52^{B}	18.12^{B}	27.46^{B}	26.30^{AB}
NW	No data	No data	No data	No data

Spatial Analyses of Turbidity

Results of the one-way ANOVA on turbidity data measured at 18 sampling stations during 12 months (February 1999-January 2000) are presented in Table 4. Turbidity on transect 1 in western part of the lake was significantly higher than other areas. The interpolated turbidity values at the 18 sites (February – December 1999) are presented in Fig. 4.

Table 4: One-way Analysis of Variance comparing turbidity (NTU) measured monthly at 18 sites in Lake Pontchartrain between January 1999 and December 1999. Transect 1 includes sites 1-5, transect 2 for sites 6-10, transect 3 for sites 11-15 and transect 4 comprises sites 15-18. For the expression of significance by One-way ANOVA, different letters indicate the significant difference at a P value of 0.05.

Transect	*Data Count*	*Mean Turbidity (NTU)*	*Standard Error*	*Significance*
1	60	11.47	1.68	A
2	60	6.73	0.86	B
3	60	6.78	0.97	B
4	36	5.66	0.60	B

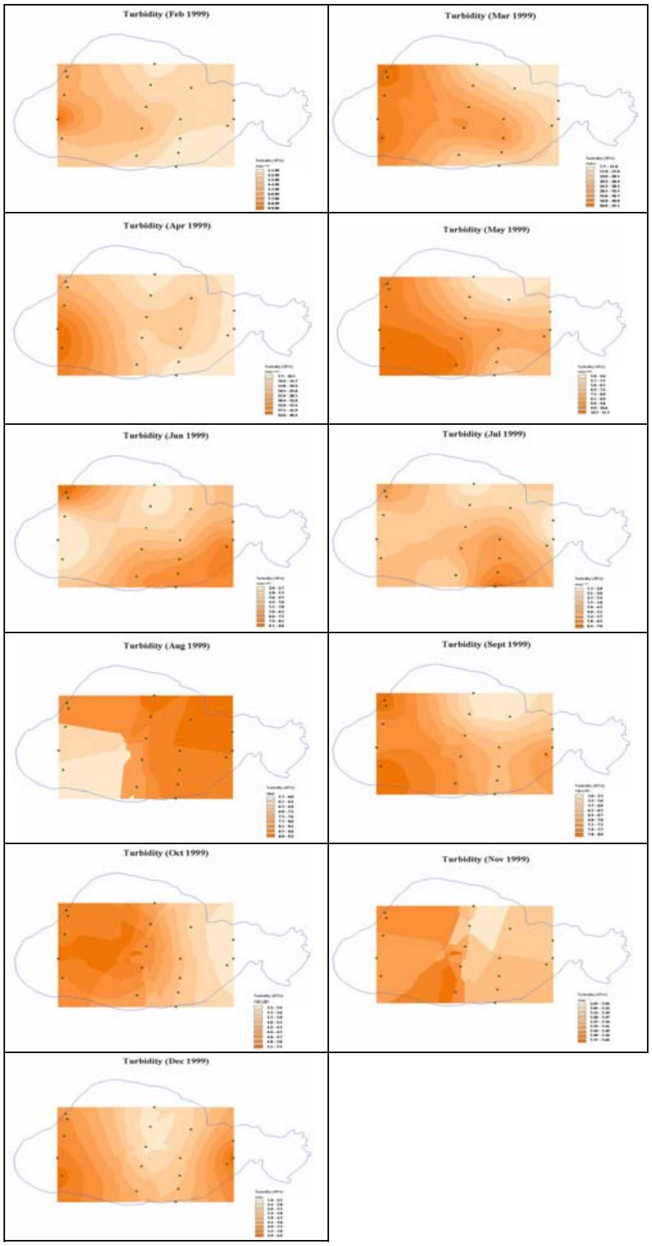

Figure 4: Interpolated (Kriging interpolation method) monthly turbidity values measured at the 18 sampling sites in 1999. The darker the color, the higher the turbidity.

Patterns of Chlorophyll a Concentration

The mean of chlorophyll *a* concentration collected monthly at the 18 sampling sites (Fig. 2) between February 1999 and January 2000 was 4.11 ug/L, with a standard error of 0.22. There was no significant difference in chlorophyll *a* concentration among the sampling sites (Table 5). Monthly differences were nearly significant at the 5% level (Table 5). The combined effect of month and site on chlorophyll *a* was not significant.

Table 5: Results of two-way ANOVA comparing chlorophyll *a* concentration at the 18 sampling sites. Data from site 7 (Fig. 2) were excluded from the analysis due to the smaller number of data (location of site 7 was changed during the sampling period, July 1999).

	DF	*SS*	*MS*	*F*	*P value*
Month	11	148.553	13.505	2.667	0.053
Site	16	121.301	7.581	1.497	0.242
Month*Site	176	1936.588	11.003	2.173	0.065
Error	12	60.755	5.063		
Total	216	5927.457			

Establishment of Relationships between K_d and Turbidity

The linear regression equation for *ln* turbidity and *ln* K_d for all three sites (Fontainebleau, Lacombe and Pointe aux Herbes) that were monitored for water quality between September 1996 and August 2002 is shown in Eq. 1,

$$\ln K_d = -0.478 + 0.460 \ln \text{Turb} \qquad \text{(Eq. 1)}$$

The slope was statistically ($P<0.001$) different from 0, and the coefficient of determination (R^2) was 0.41.

Residuals from the regression line of equation 11 are presented in Fig. 5. Positive residuals were shown in September 1996 through August 1998; residuals were negative between September 1998 and August 2002.

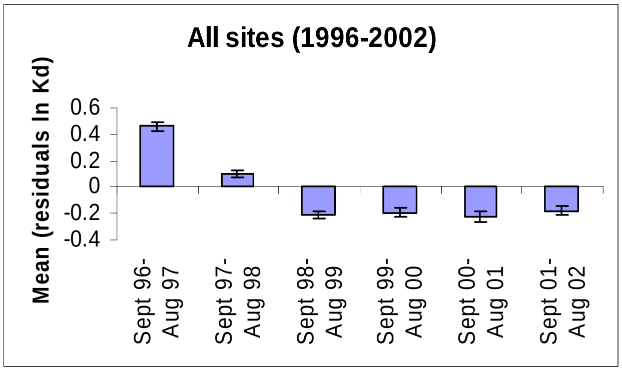

Figure 5: Residuals from the K_d-turbidity relationship ($\ln K_d = -0.478 + 0.460 \ln \text{Turb}$) (data collected at Fontainebleau, Lacombe and Pointe aux Herbes) were plotted against the survey periods.

To eliminate the effect of algal blooms that occurred in summer of 1997 [19] from the K_d-turbidity relationship, data from periods 1 and 2 (September 1996-August 1998) were excluded. The R square of the regression of the new dataset increased to 0.54. The equation for the September 1998 to August 2002 dataset is shown in Eq. 2,

$$ln\ K_d = -0.727 + 0.485\ ln\ \text{Turb} \qquad \text{(Eq. 2)}$$

The residuals of the regression line 12 (Eq. 2) were not significantly different to each other. Linear regression representing relationships between turbidity and K_d for individual sites are presented in equations 3, 4 and 5. Data from periods 3 through 6 (August 1998-September 2002) were included in these analyses. Eq. 3 is for Fontainebleau State Park, Eq. 14 for Lacombe and Eq. 15 represents the relationship at Pointe aux Herbes.

$$ln\ K_d = -0.666 + 0.510\ ln\ \text{Turb} \qquad \text{(Eq. 3)}$$
$$ln\ K_d = -0.676 + 0.463\ ln\ \text{Turb} \qquad \text{(Eq. 4)}$$
$$ln\ K_d = -1.037 + 0.576\ ln\ \text{Turb} \qquad \text{(Eq. 5)}$$

Coefficients of Determination for the regression lines were 0.71 for Fontainebleau, 0.48 for Lacombe and 0.50 for Pointe aux Herbes.

Discussion

Effects of Winds on Turbidity and Water Level

Water column light extinction is caused by several factors such as the pure water effect, dissolved matter, and suspended inorganic/organic matter including phytoplankton [7]. In a physically dominated large, shallow water body, the system-wide water transparency condition and pattern can significantly be changed with wind-driven resuspension of sediment. The effects of wind-induced resuspension on Secchi depth readings have been demonstrated in a shallow lake in Denmark [14]. Sediment resuspension caused by winds also increased the phosphorus flux between sediment and the water column, which can further contributed to turbidity increases through inducing phytoplankton growth [21].

In this study, I attempted to relate the daily resultant wind direction, water level, and turbidity patterns at varying locations in the shallow estuary, Lake Pontchartrain. Winds significantly increased the turbidity of littoral areas at the study sites (Table 3) as Swenson [26] stated that winds as low as 15 mhp can resuspend bottom sediments in this large and shallow lake. Within the wave-stressed shores, turbidity increases due to the scoring effects of waves that makes the bottom unstable and water-level fluctuation is greater.

The high correlation between lake wind, currents, and water clarity has been demonstrated in the lake [10]. Although use of the wind data from a single source can produce errors in the effects of small-scale weather systems, this study demonstrates that information on prevalent wind direction is important to understand the large-scale water clarity pattern and to identify shores with relatively high physical stresses. The results also indicate that prolonged unidirectional winds can affect particular shore by increasing turbidity and wave energy. Turbid conditions affect survival of submerged macrophytes and many fish larvae. Mitzner [17] also speculated that wind-driven energy and turbidity make certain shores inhospitable conditions for juvenile crappies.

The south to east winds are the force that drives Gulf water into the lake (Table 2), which is the counterpart of the gravitational force derived from the freshwater inputs (Fig. 1). In the western part of the lake, the dominant easterly wind-driven waves (Fig. 3) make the bottom unstable. Under these conditions the sediments are easily suspended. As a result, turbidity is higher (Table 4) and wave energy is stronger [15]. Maps of Lake Pontchartrain showing sediment texture [9, 16] show a higher proportion of sand at the northeastern part of the lake and at Lincoln Beach on south shore. Sandy sediments within the eastern area of the lake have originated from Pleistocene terrace deposits and Holocene relic beaches [9]. The westward long shore drifts along the north and south shores are responsible for the transport and deposition of the sand [22].

Once disturbed, the finer sediment in the western area remains suspended for longer periods and transmits less light than coarse suspended particles [2] which also contributed to the overall higher turbidity in the western area (Table 4). The large-scale turbidity pattern was changed with changes in seasonal prevailing winds (Fig. 4). The lack of the significant difference in Chlorophyll *a* concentration among the 18 sites (Table 5) indicates that the varying amount of wind-suspended inorganic and organic sediment were the primary factor for the seasonal spatial changes in turbidity in this lake during the study period (Table 4; Fig. 4). However, it should be noted that the lake-wide turbidity and chlorophyll a measurements presented in this study (Fig. 4) were made during the La Nina-related drought [5]. The drought significantly reduced the freshwater/nutrients inputs into the lake in 1999 and 2000 [5]; the seasonal turbidity pattern can be more significantly correlated with phytoplankton abundance if studies are done in years with high rainfalls that will increase freshwater runoff from the streams, rivers, bayous, as well as from surrounding urban/agricultural areas.

Turbidity and Water Column Light Attenuation

When the residuals of the K_d-Turbidity regression line were grouped by sampling period, positive deviations from the predicted values were found during sampling periods of 1 through 2 (September 1996-August 1998), and negative deviations were found during the periods of 3 through 6 (September 1998-August 2000) (Fig. 5). The results indicate that light attenuation was considerably higher at upper layer of the water column during the algal blooms so that turbidity measured in water column (at a depth of 1 m) underestimates light attenuation.

The intercept in a K_d-Turbidity relationship can be used as an indicator of light attenuation caused by factors other than turbidity, whereas the slope in the relationship that indicates the type of turbidity causing materials. The equation 1 is the K_d-Turbidity relationship developed from the data collected between September 1996 and August 2002 and includes effects of the 1997 algal blooms that occurred after the Mississippi River diversion through Bonnet Carre Spillway opening [19]. Equation 2 is the relationship for periods when surface algal blooms were absent (September 1998 through August 2002). The significant increase ($P<0.05$) in the intercept (from -0.478 to -0.727) between equations 1 and 2 also indicates relatively high contribution of the algal blooms on light attenuation.

Light Extinction Caused by Inherent Water Color

Since light absorption by pure water was constant among study sites and algal blooms were absent during September 1998-August 2002, the differences among the equations 3, 4 and 5 were probably due to suspended particles or water color. The differences in the intercepts of the regression lines (Equations 3, 4 and 5) are probably due to the difference in water color among the sites at Fontainebleau, Lacombe and Pointe aux Herbes. The intercept of the regression line for Pointe aux Herbes was considerably lower ($P < 0.05$) than Fontainebleau or Lacombe. Fontainebleau and Lacombe, located on the north shore of Lake Pontchartrain, are influenced by freshwater inflow from the north shore streams that are highly colored [4, 3]. The intensity of the color is often related to fresh water flow and can be used as an indication of freshwater because color decreases as freshwater mixes with brackish water [11].

Summary

The spatial and statistical analyses on the wind direction, water level, turbidity, chlorophyll a, PAR (Photosynthetically Active Radiation) data were used to present the effects of diurnal and seasonal prevailing winds on the turbidity condition of a large, shallow, wind-dominated estuary, Lake Pontchartrain, Louisiana, USA. Prevailing wind direction is important to understand the large-scale water clarity pattern and to identify shores with relatively high physical stresses. Prolonged unidirectional winds can make particular shores inhospitable for aquatic plants and animals by increasing turbidity and wave energy. Short-term changes in wind direction had differential effects on turbidity and water level in varying locations. The relative contribution of surface algal mass and inherent water color on water column light attenuation varied annually and spatially, which was evidenced by the changes in the relationships between K_d and turbidity. As demonstrated in this study, system-wide analyses on multi-scale turbidity patterns of an estuary help identify wave-stressed shores which need to be considered in habitat management and restoration plans.

Acknowledgments: Funding for this study was provided by the NOAA, EPA through the Lake Pontchartrain Basin Foundation, FREEPORT McMoRan Inc., Louisiana Department of Wildlife and Fisheries, and National Fish and Wildlife Foundation. The author thanks Estuarine Research Laboratory of the University of New Orleans for make this study possible by providing boats, instruments, and help in field work, as well as professional advice.

References

1. APHA. Standard methods for the examination of water and wastewater, 19th Edition. *American Public Health Association, Inc., New York*, **1997**
2. Bhargava, D. S.; Mariam, D. W.: Light penetration depth, turbidity and reflectance related relationships and models. ISPRS *J. of Photogrammetric Engineering and Remote Sensing* **1991**, *46*, 217-230.
3. Bordelon, B. R.: Environmental factors affecting the properties and precipitation of coloring colloids in aquatic habitats. *Master's Thesis. University of New Orleans. New Orleans, Louisiana*, **1973**.
4. Brick, G. H.; Hornuff L. E.; Lambremont, E. N.: An ecological reconnaissance of a naturally acid stream in southern Louisiana. *J. of Tennessee Academy of Science*, **1953**, *28*, 221-231.
5. Cho, H. J.; Poirrier, M. A.: Response of Submersed Aquatic Vegetation (SAV) to the 1997-2001 El Niño Southern Oscillation Shifts in Lake Pontchartrain, Louisiana. *Estuaries*, **2005**, *28 (2)*, 215-225.
6. Cho, H. J.; May C. A.: An Initial Restoration Tool for Submersed Aquatic Vegetation. *National Wetland Newsletter*, **2006**, *28*, 10-12 and 20.
7. Cole, G. A.: Textbook of Limnology. 4th Ed. *Waveland Press, Inc. P. O. Box 400, Prospect Heights, Illinois 60070*. **1994**.
8. Day, J. W.; Hall, C. A. S.; Kemp, W. M.; Yanez-Arancibia, A.: Estuarine Ecology. *John Wiley & Sons, Inc. New York. Chichester, Brisbane, Toronto, Singapore*, **1989**.
9. Flowers, G. C.; Isphording, W. C.: Environmental sedimentology of the Pontchartrain estuary. *Transactions of the Gulf Coast Association of Geological Societies*, **1990***; Vol. XL*: 237-249.
10. Francis, J. C.; Poirrier, M. A.; Barbe, D. E.; Wijesundera, V.; Mulino, M. M.: Historic trends in the Secchi disk transparency of Lake Pontchartrain. *Gulf Coast Research Reports*, **1994**, *9*, 1-16.
11. Jerlov, N. G.: Influence of Suspended and Dissolved Matter on the Transparency of Sea Water. *Tellus*, **1952**, *V*, 59-65.
12. Kirk, J. T. O.: Yellow Substance (Gelbstoff) and its Contribution to the Attenuation of Photosynthetically Active Radiation in some Inland and Coastal South-Eastern Australian Waters. *Australian Journal of Marine and Freshwater Research*, **1976**, *27*, 61-71.
13. Kirk, J. T. O. Light and photosynthesis in aquatic ecosystems. 2nd edition, *Cambridge University Press, New York*, **1994**, 401 pp.

14. Kristensen, P.; Sondergaard, M.; Jeppesen, Erik: Resuspension in a shallow eutrophic lake. *Hydrobiologica*, **1992**, *228 (1)*, 101-109.
15. List, J.; Signell, R.: Long-term near-bottom velocity in Lake Pontchartrain. *In* Penland, S., A. Beall and J. Waters (Eds.), Environmental Atlas of the Lake Pontchartrain Basin. *Lake Pontchartrain Basin Foundation, University of New Orleans, USGS, EPA, New Orleans, LA*. **2001**, p 43.
16. Manheim, F. T.; Hayes, L.; McIntire, A. G.: Sediment Database and Preliminary Interpretations, URL: http://pubs.usgs.gov/of/of98-805/html/manheim.htm. **1998**.
17. Mitzner, L. Effect of Environmental variables upon crappie young, year-class strength, and the sport fishery. *North American Journal of Fisheries Management* **1991**, 11, 534-542.
18. Nusch, E. A.: Comparison of different methods for chlorophyll and phaeopigments determination. *Ergebnisse der Limnologia*, **1980**, *14*, 14-36.
19. Poirrier, M. A.; Maglic, B.; Francis, J. C.; Franze, C. D.; Cho, H. J.: Effects of the 1997 Bonnet Carre Spillway Opening on Lake Pontchartrain Submersed Aquatic Vegetation. *Recent Research In Coastal Louisiana*, **1999**, 123-133.
20. Pritchard, D.: Observations of circulations in coastal plain estuaries. In: G. Lauff (ed.), Estuaries. *American Association for the Advancement of Science. Publ. No. 83, Washington, D.C.,* **1967**, pp.37-44.
21. Sondergaard, M.; Kristensen, P.; Erik, J.: Phosphorus relase from resuspended sediment in the shallow and wind-exposed Lake Arreso, Denmark. *Hydrobiologia*, **1992**, *228*, 91-99.
22. Steinmeyer, R. A.: Bottom Sediments of Lake Pontchartrain, Louisiana. *American Association of Petroleum Geologists Bulletin*, **1939**, *23*: 1-23.
23. Stevenson, J. C.: Comparative ecology of submersed grass beds in freshwater, estuarine, and marine environments. *Limnology and Oceanography*. **1988**, 33, 867-893.
24. Stevenson, J. C.; Staver, L. W.; Staver, K. W.: Water quality associated with survival of submersed aquatic vegetation along an estuarine gradient. *Estuaries*, **1993**, *16*, 346-361.
25. Stone, J. H.: Environmental analysis of Lake Pontchartrain, Louisiana, its surrounding wetlands, and selected land uses. CEL, CWR, LSU, BR, LA 70803. Prepared for U.S. Army Engineer District, New Orleans. *Contract No. DACW 29-77-C-0253.* **1980**.
26. Swenson, E. M.: General hydrography of Lake Pontchartrain, Louisiana. Pages 57-155 *In* J.H. Stone (Ed) Environmental analysis of Lake Pontchartrain, Louisiana, its surrounding wetlands, and selected land uses. CEL, CWR, LSU, BR, LA 70803. Prepared for U.S. Army Engineer District, New Orleans, *Contract No. DACW29-77-C-0253*, **1988**.
27. Wetzel, R. G.: Limnology. 2nd edition. *CBS College Publishing. New York, NY.,* **1983**.