Turbidity in Lake Carl Blackwell: Effects of Water Depth and Wind

Gregory L. Howick
Department of Systematics and Ecology, Kansas University, Lawrence, KS 66045

Jerry Wilhm
Department of Zoology, Oklahoma State University, Stillwater, OK 74078

Seasonal changes in turbidity were measured in Lake Carl Blackwell, Oklahoma, as part of an EPA Clean Lakes Project. Turbidity stratified with the onset of thermal stratification with the highest turbidities occurring in the hypolimnion. During winter, surface values were low and little variation existed among stations. In summer, values were high and increased from the dam to upstream. Resuspension of bottom sediments is a major cause of turbidity in the lake. Turbidity was highly correlated with the quantity of wind received ('wind value') for the two days preceding the sampling date. The inverse relationship between turbidity and depth had the highest level of significance when the average depth was determined for a 750-m-radius circle around each station. The best linear relationship between turbidity and the exposure/depth ratio was based on a 500-m circle with depth raised to the 1.5 power.

INTRODUCTION

Many reservoirs have been constructed in the southern Great Plains to provide water supply, flood control, and recreation. Many have high turbidity caused by suspended silts and clays. Turbidity affects the physical, chemical, and biological condition of lakes by varying water temperature (1); penetration of different wavelengths of light (2,3); the concentration of dissolved nutrients, heavy metals and organic contaminants (4,5,6); and biomass and productivity of phytoplankton (7,8). While naturally occurring levels of turbidity seldom exert direct lethal effects on fish (9), detrimental effects include a reduction in their ability to find prey (10,11), feeding rate (12), and productivity (13).

The major sources of inorganic turbidity are runoff, shoreline erosion, and resuspension of bottom sediments. In the southern Great Plains, turbidity in runoff is high because the soils contain large proportions of silts and clays, which are easily eroded (14,15). Improper land management also adds sediment to runoff (16,17). Shoreline erosion can increase turbidity if macrophytes in the littoral zone have been eliminated by fluctuating water levels. Although bottom sediments can be resuspended by thermal destratification and turnover (18) or the rooting activity of fish (19), the most common agents of resuspension are winddriven currents and wave action. Factors such as wind velocity, duration, and direction, fetch, water circulation patterns, water depth, sediment compaction, and lake bottom roughness are important in ultimately determining the extent of sediment resuspension (20,21).

Water movement across the surface of the sediments results in resuspension of sediments. The sources of water movement are the circular water motion under waves and large-scale currents (22). Both sources are a function of the amount of wind energy impinging on the lake surface, which in turn is a function of wind velocity and fetch. The amount of resuspension caused by circular water movements under waves is also a function of water depth, as the amplitudes of these movements decrease with increasing water depth. The objective of the present study was to quantify the relationship between turbidity and major factors known to influence turbidity in Lake Carl Blackwell, a southern Great Plains reservoir.

STUDY AREA

Lake Carl Blackwell (LCB), 13 km west of Stillwater, Oklahoma, impounds Stillwater Creek. The dam was constructed in 1938. At spillway elevation, the mean and maximum depth are 4.9 and 14.5 m, respectively, and surface area is 1300 ha. Since rainfall in the region is sporadic and the watershed is only 19,300 ha, the water level fluctuates considerably. Soils in the watershed are generally red-brown in color and have a high clay content (23). Land use in the watershed is 64% grassland, 31% forested to some degree, and 5% tilled for crops (23). The topography around the lake is gently rolling hills. The west end of the lake is particularly unprotected from the wind because few trees exist near the shore.

METHODS

Nine sampling stations were established. Stations 1 - 4 comprised a transect down the main body of the lake and stations 5 - 9 were located in the major arms (Fig. 1). Station 1 was located over the deepest point in the lake and was sampled at depths of 0. 5, 2, 5, 8, 11, and 14 m. This was the only station in which a hypolimnion existed. Stations 2 - 9 were sampled at 0.5 m. Stations were sampled monthly from late September 1980 to March 1981 and biweekly from April 1981 to September 1981. Samples were collected between 0855 and 1520 hr with an acrylic van Dorn water sampler. Turbidity was measured with a Hach model 16800 nephelometer and temperature with a model 4041 HydroLab instrument.

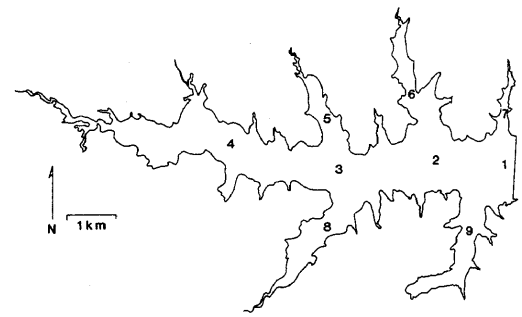

Figure 1. Sampling stations at Lake Carl Blackwell.

When turbidity was compared to depth, a form of average depth around each station was used to compensate for lack of measurement of horizontal transport by wind-driven currents. A bathymetric map with 2-m depth intervals was prepared from 28 bottom profiles made with a Lowrance LRG-1510B strip chart recording sonar. Each sampling station was located on the map and circles with radii equivalent to 250, 500, and 750 m were drawn around each station. Average depth around each station was calculated from the hypsographic curve for each circle.

Sediment resuspension also depends on wind velocity and duration. The equation of Ayers *et al*. (24) was used to obtain a weighted 'wind values', W_T. Daily 'wind values' W_i were obtained by integrating, over 24 hours, the instantaneous wind speed at a given point; each W_i was assigned a weight $g_i = e^{-0.693(i-1)}$ with i an integer designating the ordinal number of each 24-hr period *prior* to the sampling date. The equation for weighted 'wind value' is:

$$W_T = \sum_{i=1}^{n} W_i g_i \; ; \; i = 1,2,\ldots,n. \qquad (1)$$

In this study n ranged from 1 to 7. 'Wind values' and direction were measured at the weather station maintained at the Oklahoma State University Agricultural Experiamental Station in Stillwater because a weather station did not exist at LCB. We assumed that wind conditions at the two locations, which are 10 km apart, were similar. Wind data for December through March were unavailable because of anemometer malfunction.

To examine the relationship between wind and turbidity, effective fetch (25) and exposure were determined for each station. Exposure was defined as the percent of area that was water within circles around each station of 250 or 500-m radius. Regression analyses were performed using SAS statistical computer programs (27). Significant testing of the correlation coefficients were done by using Table Y in Rohlf and Sokal (26).

RESULTS AND DISCUSSION

Total precipitation during the study period was 81.5 cm; however, measurable runoff into LCB did not occur and lake elevation steadily decreased from 287.03 to 285.86 m msl. Therefore, increases in turbidity during the period were due primarily to resuspension of bottom sediments and shoreline erosion.

Considerable temporal and vertical changes in turbidity were observed at Station 1. In win-

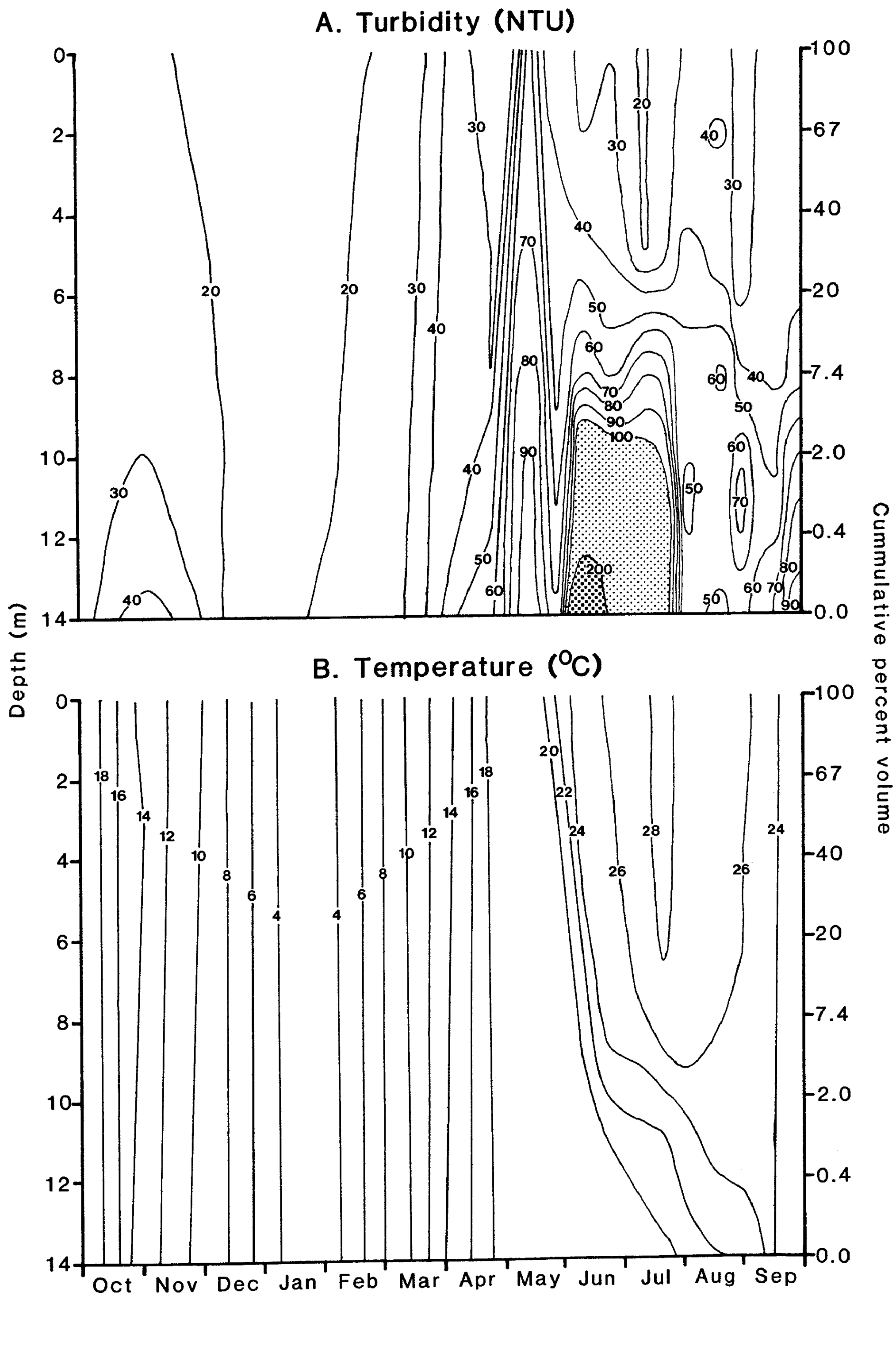

Figure 2. Temporal and vertical distributions of a) turbidity and b) temperature at Station 1.

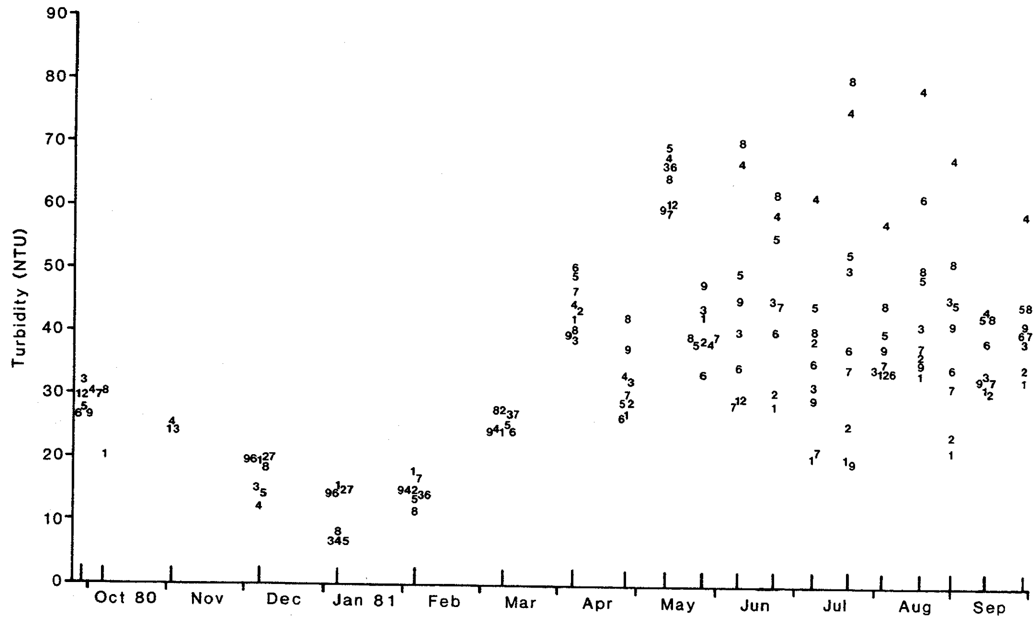

Figure 3. Temporal and horizontal changes in turbidity. The numbers correspond to stations.

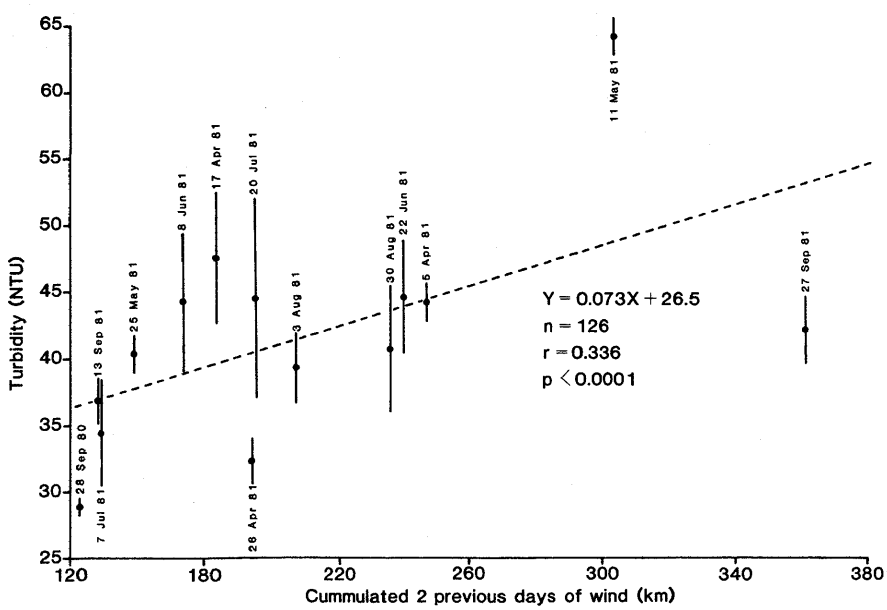

Figure 4. Relationship between turbidity and amount of wind. Only those dates for which all nine stations were sampled are shown. Points are the mean of the nine stations for the indicated date. Error bars indicate ± 1 standard error.

ter, turbidity was generally less than 20 nephelometric turbidity units (NTU) and little vertical variation existed (Fig. 2A). This relatively low level of turbidity occurred in the absence of ice cover. Turbidity increased during spring and values increased with depth in April. The greatest surface turbidity observed at Station 1 was 61 NTU in May. With the onset of thermal stratification in June (Fig. 2B), the vertical gradient in turbidity became pronounced (Fig. 2A). In June and July, surface turbidities were less than 30 NTU while turbidities in the hypolimnion exceeded 100 NTU. Since the hypolimnion was only 4% of the total lake volume (23), it is possible that turbulent water movements caused by internal seiches resuspended bottom sediments in the hypolimnion.

The surface turbidities across LCB ranged from 7 NTU at stations 3,4, and 5 in January to 81 NTU at Station 8 in July (Fig. 3). During fall and winter, turbidities were generally less than 30 NTU at all stations and relatively little variation existed among stations. From March through May surface turbidity increased uniformly at all stations. In June, the stations began to vary in turbidity. In general, stations 4, 5, and 8 had the highest turbidities, while stations 1, 2, 7, and 9 had the lowest. Stations 3 and 6 had intermediate levels of turbidity.

The development of the large horizontal gradients in turbidity (Fig. 3) coincided with the onset of thermal stratification (Fig. 2A). In winter and spring, when the lake was isothermal, the whole lake was probably well mixed horizontally and vertically. This would explain the small variations in surface turbidities (Fig. 3). However, after the lake stratified, the hypolimnion may have become a trap for turbidity-causing particles. Therefore, particles that settled out over relatively deep portions of the lake were not resuspended. In the shallow areas of the lake with no hypolimnion, resuspension of bottom sediments occurred all summer. The deep portions of the lake did not clear completely in summer because horizontal wind-driven currents supplied turbid water from the shallow portions of the lake.

Seasonal variations in turbidity was related to the quantity of wind received. Correlation coefficients were calculated for turbidity versus weighted 'wind value' W_T with $n = 1,2,\ldots,7$ in Eq. 1. When all stations are considered together, turbidity was most highly correlated with 'wind value' W_T when n was 2, i.e., when W_T was based on data for the 2 days preceding the sampling date (Fig. 4). The regression equation, $Y = 0.073\ X + 26.5$, where Y is turbidity (NTU) and X is W_T with $n = 2$, was highly significantly different from zero ($r = 0.336$, $df = 124$, $p < 0.01$); however, only 11.2% of the variance was explained by the regression. For individual stations, the value of n (i.e. the number of days of preceding wind) that showed the greatest correlation with turbidity ranged from 2 at the shallow stations to 7 at the deepest station. However, most of these correlations were not statistically significant (Table 1); therefore, the interactive effects of depth and wind on turbidity can only be weakly inferred.

The differences in turbidity among stations were partially explained by morphometric characteristics. An inverse relationship existed between turbidity and average depth around the sampling stations (Fig. 5A). This relationship had a higher level of significance when the average depth was determined for a 750-m-radius circle around each station than for 250-or 500-m circles. The relationship was particularly apparent for the stations in the main body of the lake (Fig. 5A). The arm stations appeared to have lower turbidities than main body stations of comparable average depth. Much of this variation seemed to be due to differences in exposure between arm and main body stations (Fig 5B). The lower exposures of the arm stations probably counteracted the effect of decreased depths.

Arm and main body stations were similar when turbidity was compared to the exposure depth ratio. The best linear relationship between turbidity and the exposure depth ratio was obtained using exposure based on the 500-m-radius circle instead of a 750-m-radius circle (average depth raised to the 1.5 power) (Fig. 5C). The amounts of resuspended sediments observed at Station 6 were lower than those that would have been predicted by the exposure depth ratio. This is probably due to differences in shoreline morphology. Most of the shoreline around LCB is gently sloping; this creates large expanses of shallow water where resuspension and shoreline erosion can occur. In contrast, much of the western shore around Station 6 is a bare rock cliff.

TABLE 1. Physical characteristics of the sampling stations and correlation coefficients for days of wind at each station that gave the best fit with turbidity.

Station	Average depth (750-m-radius circle)	Exposure (500-m-radius circle)	Days[a]	Correlation coefficient (DF)[b]	*P*
1	9.0	77.6	7	0.542(16)	<0.05
2	7.5	100	6	0.424(13)	NS
3	6.4	98.2	5	0.450(15)	NS
4	5.0	96.8	2	0.264(15)	NS
5	3.8	56.4	2	0.370(13)	NS
6	3.9	74.3	4	0.413(14)	NS
7	5.1	38.6	6	0.661(14)	<0.01
8	4.1	65.9	2	0.064(13)	NS
9	4.8	72.9	6	0.405(14)	NS

[a]Number of days of antecedent kilometers of wind that fit best with turbidity.
[b]DF = n − 2.
NS = Not significant, $P > 0.5$

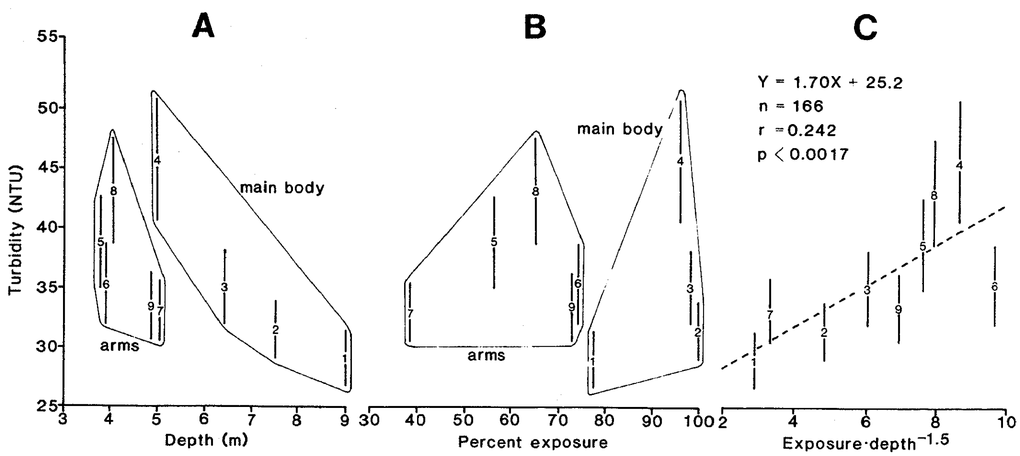

Figure 5. Relationship between turbidity and a) depth, b)percent exposure, and c) exposure • depth$^{-1.5}$. The numbers indicate stations. Error bars indicate ± 1 standard error. Depth was the average depth in a 750-m-radius circle drawn around each station. Percent exposure was the percent area in a 500-m-radius circle around each station that was water.

The amount of sediment resuspension by wave action is ultimately a function of how much wind energy is transmitted down through the water column to the bottom. We estimated cumulative wind energy at each station by combining effective fetch and cumulative wind into a formula similar to that used to calculate wave height. However, even when compensation was made for depth of the station, significant relationships with turbidity were not found. This is probably because we did not have a good measure of horizontal transport.

Despite the simplicity of the sampling scheme, a relationship between turbidity and other physical characteristics was found. The positive correlations between 'wind values' and turbidity and the interaction of turbidity with water depth and exposure to wind conform to concepts of the mechanics of wind, water, and sediment interactions.

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