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The Potential For Wave Disturbance in Shallow Florida Lakes

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ABSTRACT

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We applied wave theory to calculate the extent and frequency that we would expect wave-driven surface water movements to disturb the sediments in 36 Florida lakes covering a broad range of surface areas and mean depths. The calculated per cent of the lakebed subject to wave disturbance at one time or another ranged from 6 to 100% and the per cent of the time 50% of the lakebed was disturbed ranged from 0 to 65%. The large Florida lakes, Apopka, Okeechobee, and Istokpoga showed high levels of calculated wave disturbance, which was consistent with the conclusions of previous investigations. Historic water level fluctuations in Lake Apopka were calculated to have major effects on wave disturbance in that lake. The dynamic ratio (the square root of lake surface area in square kilometers divided by the mean depth in meters) was significantly related to various measures of wave disturbance in our sample lakes. For lakes with ratio values above about 0.8 the entire lakebed was subject to wave disturbance at least some of the time. The dynamic ratio was also related to lake water quality. We found that increases in the dynamic ratio were significantly related to decreases in water quality as measured by total phosphorus, total nitrogen, chlorophyll, and Secchi disk depth. Calculations of wind disturbance by waves need to be modified in lakes with extensive beds of macrophytes, where water levels change and in periods where climatic fluctuations result in changes in wind regimes.

Key Words: dynamic ratio, resuspension, shallow lakes, sediments, water quality, waves.

There are many examples of shallow lakes whose poor water quality can be attributed to resuspended sediments (Andersen and Lastein 1981, Bengtsson and Hellstrøm 1992, Ekholm et al, 1997, Evans 1994, Jackson and Starrett 1959, James, and Barko 1994, Kristensen et al. 1992, Lijklema et al, 1994, Luettich et al. 1990, Maceina and Soballe 1990). Sediment particles can be resuspended by shear stresses at the lakebed generated by wind-driven waves while the weaker circulatory currents can transport the particles to other parts of the lake (Luettich et al. 1990). In deep lakes fine particles will eventually settle out in the deeper portions of the lake and be protected from resuspension. In contrast, fine particles in shallow lakes can only settle in shallow waters where they are subject to resuspension by wind-drive waves again and again. This continual process may strongly influence the distribution of sediments in a lake and may also play a role in determining water quality. The resuspension process can facilitate the recycling of nutrients such as phosphorus from the sediments and the resuspended sediment particles and meroplankton cells (Carrick et al. 1993) themselves absorb and scatter light and decrease water transparency.

Previously, we documented the situation in Lake Apopka, a large, shallow lake in Florida (Bachmann et al. 1999) where the current limnology is dominated by sediment resuspension. In that study we applied wave theory to calculate the extent and frequency that we would expect wave-driven water movements to disturb the sediments in that lake. These calculations were summarized in a curve of lake area affected by waves versus per cent of time following a procedure used by Carper and Bachmann (1984) in Little Wall Lake, Iowa. In interpreting the significance of the curve for Lake Apopka we were hampered by the lack of comparable curves on other lakes. For that reason we saw a need for similar studies on other lakes in order to determine the relative importance of wave action in Lake Apopka or other lakes.

The first goal of this study was to calculate the potential for wind disturbance of sediments in a group of lakes of differing surface areas and depths. Because the calculations for this method are time consuming, a second goal was to find a simple morphometric index that could be used as a screening technique for management agencies responsible for large numbers of lakes. Third, we wanted to see if this index was related to water quality in a broad range of lakes of varying sizes and trophic states. Lastly, we wished to test the hypothesis that mixing patterns would be related to the distribution of sediments in shallow lakes using the results of previous investigations.

Methods

For our study we selected 36 Florida lakes with a broad range of surface areas and depths including all 6 of the largest lakes with available hydrographic maps (Lake Monroe has not been mapped and was not included). We excluded the extensive marshy areas on the west side of Lake Okeechobee (~200,000 ha) and only used that part of the lake area that had open water. For all other lakes we assumed that the macrophyte densities were not sufficient to interfere with wave action. This means that our results indicate the maximum potential for wave-induced sediment disturbance for each lake. We also included seven lakes that were the subject of a previous study (Whitemore et al. 1996) of sediment distribution patterns in shallow, wind-stressed lakes.

For each lake a contour map was overlain by a grid that had between 130 to 457 grid intersections within the lake area. For each of the grid intersections we calculated the effective wind fetch for 36 equally spaced compass directions following the methods described in Carper and Bachmann (1984) and Håkanson (1981). We also recorded the water depth at each gridpoint found by interpolation between the contour lines. The wavelength of a deepwater wave is related to its period by the equation:

$$L = \frac{gT^2}{2\pi}$$

where L is the wavelength (m), g is the gravitational constant (9.8 $m \cdot s^{-1} \cdot s^{-1}$), and T the wave period (s). Wave period is found with an empirical equation (U.S. Army Coastal Engineering Research Center 1977):

$$\frac{gT}{2\pi U} = 1.20 \tanh\left[0.077\left(\frac{gF}{U^2}\right)^{0.25}\right]$$

where U is the wind velocity ($m \cdot s^{-1}$) and F is the effective fetch (m). For each of the 36 directions we calculated the minimum wind velocity that would be needed to generate surface waves with a wavelength equal to twice the water depth using the procedures in Carper and Bachmann (1984). According to theory and supported by empirical measurements on Little Wall Lake, Iowa, when the water depth is less than half the wavelength the horizontal water movements at the lakebed may be sufficient to resuspend sediments (Carper and Bachmann 1984). We assembled tables of wind frequencies and directions for 5-year periods for 5 stations in Florida. The South Florida Water Management District operated one on a tower in Lake Okeechobee and another was located on a tower in the center of Lake Apopka that was operated by the St. Johns River Water Management District. Wind data published by the National Oceanic and Atmospheric Administration were obtained for Gainesville (NOAA 1990-94a), Tampa (NOAA 1990-94b), and Orlando (NOAA 1989-93c). We combined the wind frequency data from the nearest recording station with the calculated minimum velocities to find the fraction of the time that surface waves would disturb the sediments for each of the gridpoints in the lake. We then used these data to construct a curve of the per cent of the lakebed disturbed versus the per cent of the time. To describe the curves we found the per cent of the lakebed area that was disturbed at any time, the per cent of the lakebed area that was disturbed 50% of the time, the per cent of the time that 50% of the lakebed area was disturbed, and the per cent of the time that 100% of the lakebed was disturbed.

In addition to looking at a series of lakes we also applied the model to Lake Apopka at several different water levels. We ran the model with elevations at 25-cm intervals from -75 to +75 cm deviation from the map elevation.

Previously Håkanson (1982) defined the dynamic ratio of a lake as the square root of the lake surface area in square kilometers divided by the mean depth in meters. His original purpose was to relate the ratio to the areas of a lake where fine sediments were eroded or transported by wave movements. We hypothesized that lakes with higher dynamic ratios would show a greater extent and frequency of wave disturbance to the lakebed. The dynamic ratio was tested using correlation and regression analyses with the various points from the frequency-time curves.

We examined water quality effects of wave disturbance by running correlation analyses between the dynamic ratio and water quality measures in 64 Florida lakes of varying trophic status that we had previously used to examine relationships between fish and trophic state (Bachmann et al. 1996). Similar analyses were run with the Osgood index (Osgood 1988) which is the mean depth in meters divided by the lake surface area in square kilometers.

A recent study (Battoe et al. 1999) noted improvements in water quality in Lake Apopka since July 1995. To determine if a changes in wind patterns might be responsible for these changes, we obtained monthly average wind velocity data from the Orlando International Airport (NOAA 1987-1998) for the time period January, 1987 through July, 1995 and for August 1995 through July, 1998 and used t-tests to test for differences in the mean values for winds for the two periods before and after mid-1995. A previous study (Carrick et al. 1993) had shown that the Orlando winds were representative of the winds at Lake Apopka.

Results

The morphometry, mixing frequency, and dynamic ratio ranged widely among the 36 lakes (Table 1). The per cents of the lake areas subject to resuspension some of the time range from 6.4 to 100%, the per cent of lake area disturbed 50% of the time ranges from 0 to 90.0 %, the per cent of the time 50% of the lakebed is disturbed from 0 to 68.3 % and the per cent of the time 100% of the lakebed is disturbed ranges from 0 to 22.7%. These data indicate that lakes Apopka, Okeechobee, and Istokpoga are frequently subject to extensive wave disturbances of their lakebeds, which is in agreement with the findings of independent studies on these lakes (Brezonik et al. 1978, James et al. 1997, Lamb 2000).

We illustrated the results of our calculations for two contrasting types of lakes in Figure 1. In smaller and deeper Lake Thonotosassa (Fig. 1A) greatest wave disturbances are expected in near-shore regions versus relatively low frequencies estimated for the central deeper area. Hence, greater long-term deposition is typically expected in the deep basin zone. Lake Istokpoga (Fig. 1B) estimated wave distribution frequencies are relatively high at all points in this large, shallow lake with the entire basin subject to disturbance. Accordingly, the frequency distribution curves for these contrasting lakes (Fig. 1C) show that Lake Istokpoga has a greater per cent of the area disturbed 50% of the time and has a higher frequency of disturbance for 50% and 100 % of the lake area.

Water level alterations in Lake Apopka were shown to have significant effects on the estimated mixing frequencies (Fig. 2). The per cent of the time that 50% of the lakebed was disturbed ranged from a low of 34% when the lake level was elevated by 75 cm to a high of 78% when the lake level was lowered by 75 cm from the normal level. These approximate water level fluctuations from 1935 through 1972 (Bush 1974) with a positive deviation of 82 cm in 1936 and a minimum of minus 75 cm in 1956.

The dynamic ratio was significantly related to each of the 4 measures of wave disturbance noted in Table 1. The most distinct relationship was found between the dynamic ratio and the per cent of the lakebed disturbed at least some of the time (Fig. 3). For lakes with ratio values above about 0.8 the entire lakebed was subject to wave disturbance at least some of the time. Below dynamic ratio values of 0.8 there was a linear relationship (R^2=0.78, $p<0.001$) between % area disturbed and the dynamic ratio. The fitted regression line for the portion of the curve where the dynamic ratio was equal to or less than 0.8 was:

Per cent lakebed disturbed some of the time =
12.4 + 109 x dynamic ratio

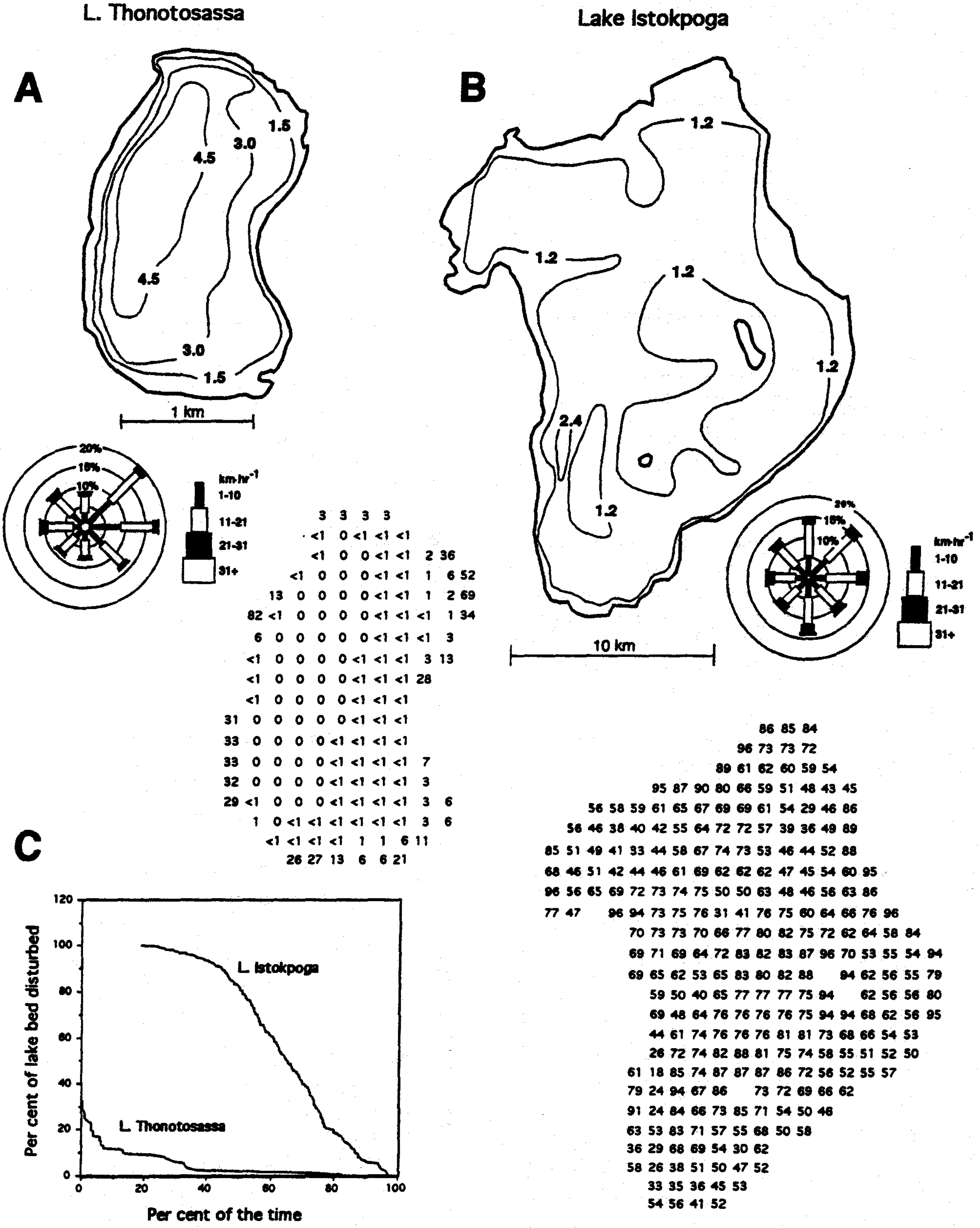
Each of the other variables used to describe the frequency and extent of wave disturbance in these lakes was also significantly correlated (R^2= 0.81 to 0.93) with the dynamic ratio, though the best fit lines were often polynomials (Fig. 4). In each case an increase in the value of the dynamic ratio corresponded to an increase in the frequency and extent of wave disturbance of the lakebed. The Osgood index was also related to the frequency and extent of wave disturbance, however, we preferred the dynamic ratio because it gave a linear relationship with the per cent of the lakebed disturbed at one time or another and also because it increased rather than decreased with increases in the extent and frequency of wave disturbance.

We also found that the dynamic ratio was related to the four water quality variables we examined from a group of 62 Florida lakes (Fig 5). Increases in the dynamic ratio were generally associated with decreases in water quality as measured by total phosphorus, total nitrogen, chlorophyll, and Secchi depth, however, the index only explained about one-third of the variance (R^2 =0.37 to 0.26, $p<0.001$).

In a previous study Whitmore et al. (1996) examined the distribution of fine sediments in seven Florida lakes and found three different distribution patterns. These were uniform distribution, distribution to deeper areas, or distribution to peripheral areas and embayments. We found that these sediment distribution patterns for the seven lakes (eight lake basins) studied by Whitmore et al. (1996) were related to the dynamic ratio. The three lakes (Clear, Thonotosassa, and Marianna) with their fine organic sediments confined to central deeper areas had ratio values less that 0.8 (Table 1), while the five lakes (Seminole south, Seminole north, Hollingsworth, Maggiore, and Parker)

Table 1.–The 36 study lakes with surface area, mean depth, dynamic ratio (square root of surface area in km^2/ mean depth in m), % of lakebed subject to resuspension at one time or another, % of lakebed subject to resuspension 50% of the time, % of time that 50% of lakebed is subject to resuspension, and % of time that 100% of the lakebed is subject to resuspension. Lakes are ranked according to the value of the dynamic ratio. To show effects of water level changes, Lake Apopka is also listed for water levels 75-cm above and below the map datum.

Lake	Surface Area km^2	Mean depth m	Dynamic ratio km/m	% Area subject to resuspension	% Area dist. 50% of time	% Time 50% area disturbed	%Time 100% area disturbed
Keystone	0.1	5.8	0.04	6.41	0.0	0.0	0.0
Denton	0.2	6.8	0.07	30.7	9.3	0.0	0.0
Magnolia	0.8	7.8	0.12	13.7	0.0	0.0	0.0
Clear	0.8	4.5	0.20	67	0.0	0.08	0.0
Apthorp	0.9	4.4	0.22	17.2	0.0	0.0	0.0
Conine	1.0	3.3	0.29	39.6	0.0	0.0	0.0
Kingsley	6.7	7.4	0.35	28.9	1.5	0.0	0.0
Carlton	1.5	3.3	0.37	65.4	0.0	0.01	0.0
Grandin	1.4	2.4	0.48	85.6	1.6	0.02	0.0
Marianna	2.1	2.8	0.51	68.5	0.6	0.1	0.0
Thonotosassa	3.5	3.0	0.63	67.3	2	0.03	0.0
Center	1.7	1.9	0.69	100	7.4	1.02	0.01
Brick	3.5	2.6	0.72	85	8.3	0.8	0.0
Dora East	5.3	2.9	0.80	98.8	0.0	0.2	0.0
Seminole South	1.5	1.5	0.84	100	7.2	0.5	0.39
Seminole North	1.0	1.1	0.93	100	7.5	8.7	5.31
Yale	16.0	4.2	0.94	100	0.0	0.74	0.1
Hollingsworth	1.3	1.2	0.99	100	17.3	8.06	0.49
Beauclair	4.5	1.9	1.10	100	5.4	3.96	0.34
Dora West	12.2	2.8	1.22	100	0.0	0.12	0.0
Tarpon	10.3	2.5	1.26	100	0.9	0.32	0.01
Maggiore	1.5	0.8	1.59	100	15.2	28.4	2.5
Parker	8.6	1.8	1.64	100	3.6	8.72	0.42
Eustis	31.8	3.1	1.82	100	2.9	5.3	0.11
Harris	58.9	3.7	2.10	100	0.3	1.7	0.33
E. Tohopekaliga	49.2	2.8	2.52	100	14	9.2	0.24
Griffin	37.9	2.2	2.79	99.5	8.5	9.7	0.0
Hatchineha	27.0	1.7	3.03	100	12.7	15.5	0.39
Orange	34.2	1.8	3.25	100	8.9	10.4	0.79
Newnans	24.4	1.1	4.35	100	21	42.1	1.89
Apopka +75 cm	124.1	2.4	4.74	100	0.75	34.3	1.41
Kissimmee	151.6	2.5	4.96	100	15.5	24.7	0.81
George	161.3	2.4	5.34	100	8.4	23.2	9.39
Tohopekaliga	77.0	1.5	5.83	100	27.7	35.5	5.53
Apopka	124.1	1.6	6.96	100	68.3	57	2.99
Istokpoga	116.1	1.2	8.62	100	80	65.1	18.9
Apopka - 75 cm	124.1	0.9	13.11	100	93.6	78.6	5.9
Okeechobee	1292.0	2.4	14.98	100	90	66.9	39.3



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                              96 73 73 72
                           89 61 62 60 59 54
                  95 87 90 80 66 59 51 48 43 45
         56 58 59 61 65 67 69 69 61 54 29 46 86
      56 46 38 40 42 55 64 72 72 57 39 36 49 89
   85 51 49 41 33 44 58 67 74 73 53 46 44 52 88
   68 46 51 42 44 46 61 69 62 62 62 47 45 54 60 95
   96 56 65 69 72 73 74 75 50 50 63 48 46 56 63 86
   77 47    96 94 73 75 76 31 41 76 75 60 64 66 76 96
               70 73 73 70 66 77 80 82 75 72 62 64 58 84
               69 71 69 64 72 83 82 83 87 96 70 53 55 54 94
               69 65 62 53 65 83 80 82 88    94 62 56 55 79
                  59 50 40 65 77 77 77 75 94    62 56 56 80
                  69 48 64 76 76 76 76 75 94 94 68 62 56 95
                  44 61 74 76 76 76 81 81 73 68 66 54 53
                  26 72 74 82 88 81 75 74 58 55 51 52 50
               61 18 85 74 87 87 87 86 72 56 52 55 57
               79 24 94 67 86    73 72 69 66 62
               91 24 84 66 73 85 71 54 50 46
               63 53 83 71 57 55 68 50 58
               36 29 68 69 54 30 62
               58 26 38 51 50 47 52
                  33 35 36 45 53
                  54 56 41 52
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Figure 1.–A. Contour map and wind rose for Lake Thonotosassa and calculated per cent of the time that waves are expected to disturb the sediments at each of the grid intersections. Values listed as <1 are disturbed less than 1 but more than 0% of the time. B. Similar maps for Lake Istokpoga. C. The per cent of the lakebed subject to wave disturbance for different percentages of time for Lake Thonotosassa and Lake Istokpoga.

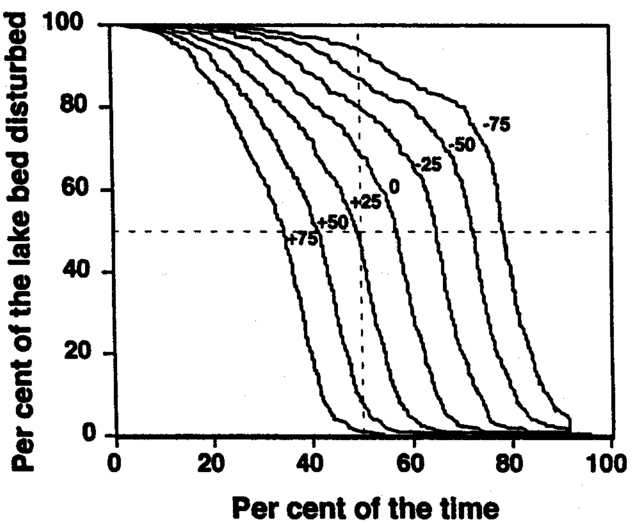

Figure 2.–The calculated per cent of the lakebed subject to wave disturbance for different percentages of time for Lake Apopka based on deviations (in cm) in water levels from the map datum of 66.5 feet. Dashed lines are shown for reference at 50% on each axis.

with fine sediments distributed either uniformly or in peripheral areas or embayments had dynamic ratio values greater than 0.8. In addition Lake Apopka with a dynamic ratio of 6.96 has been found in other studies (Schneider and Little 1969, Reddy and Graetz 1991, Schelske 1997) to have fine organic sediments uniformly distributed across the lakebed.

The average wind velocity at Orlando, FL (Fig. 6A) in the period January 1987 through July 1995 was 15.7 (SE± 0.21) km · hr^{-1} and for the period August 1995

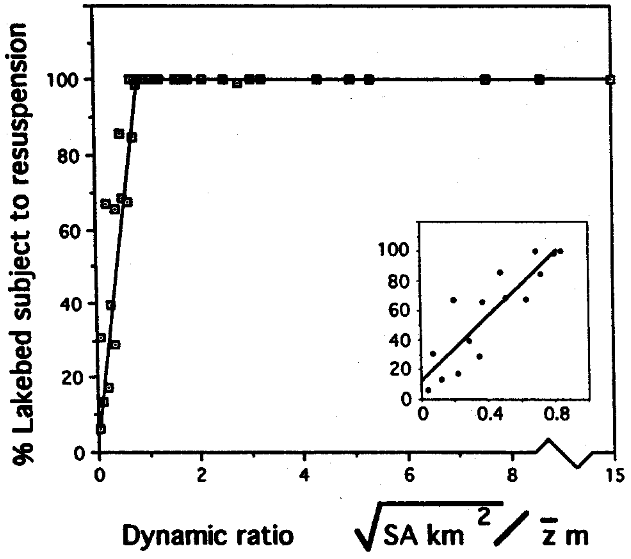

Figure 3.–Per cent of the lakebed subject to disturbance by wind-driven waves some of the time as a function of the dynamic ratio based on the 36 lakes in this study. The linear portion where the dynamic index is 0.8 or less is shown in the inset.

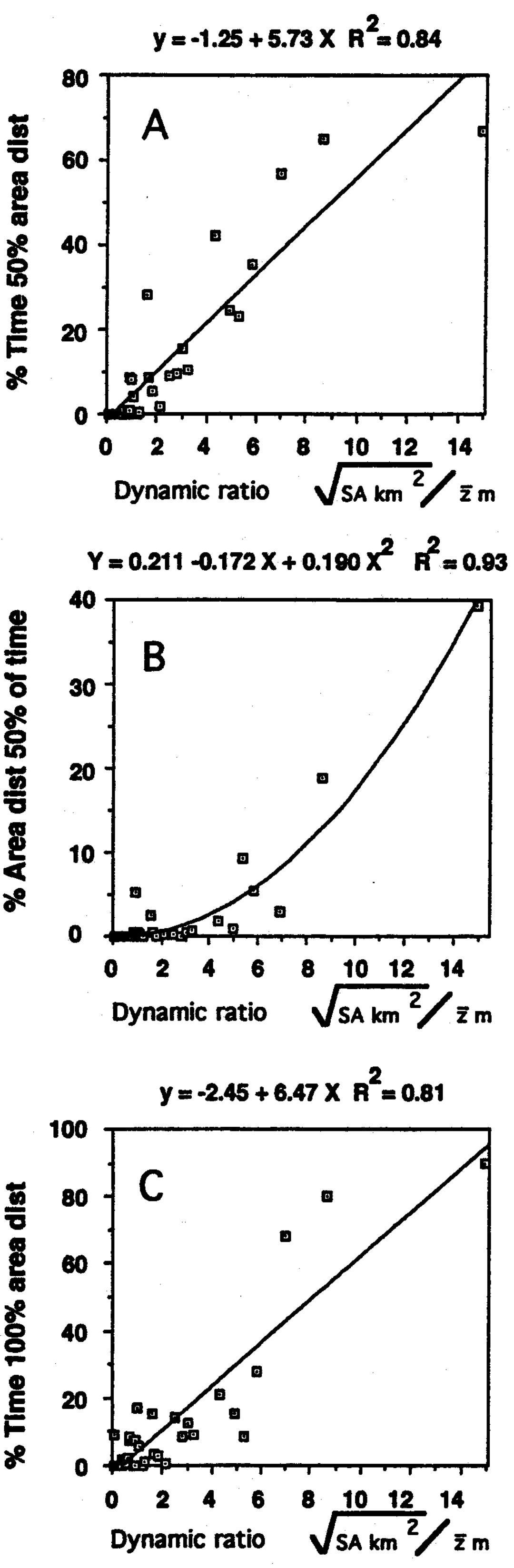

Figure 4.–Best fit analysis of the per cent of the time that 50% of the lakebed is disturbed, per cent of the time that 100% of the lakebed is disturbed, and the per cent of the lake area that is disturbed 50% of the time versus the dynamic ratio for the 36 lakes in this study.

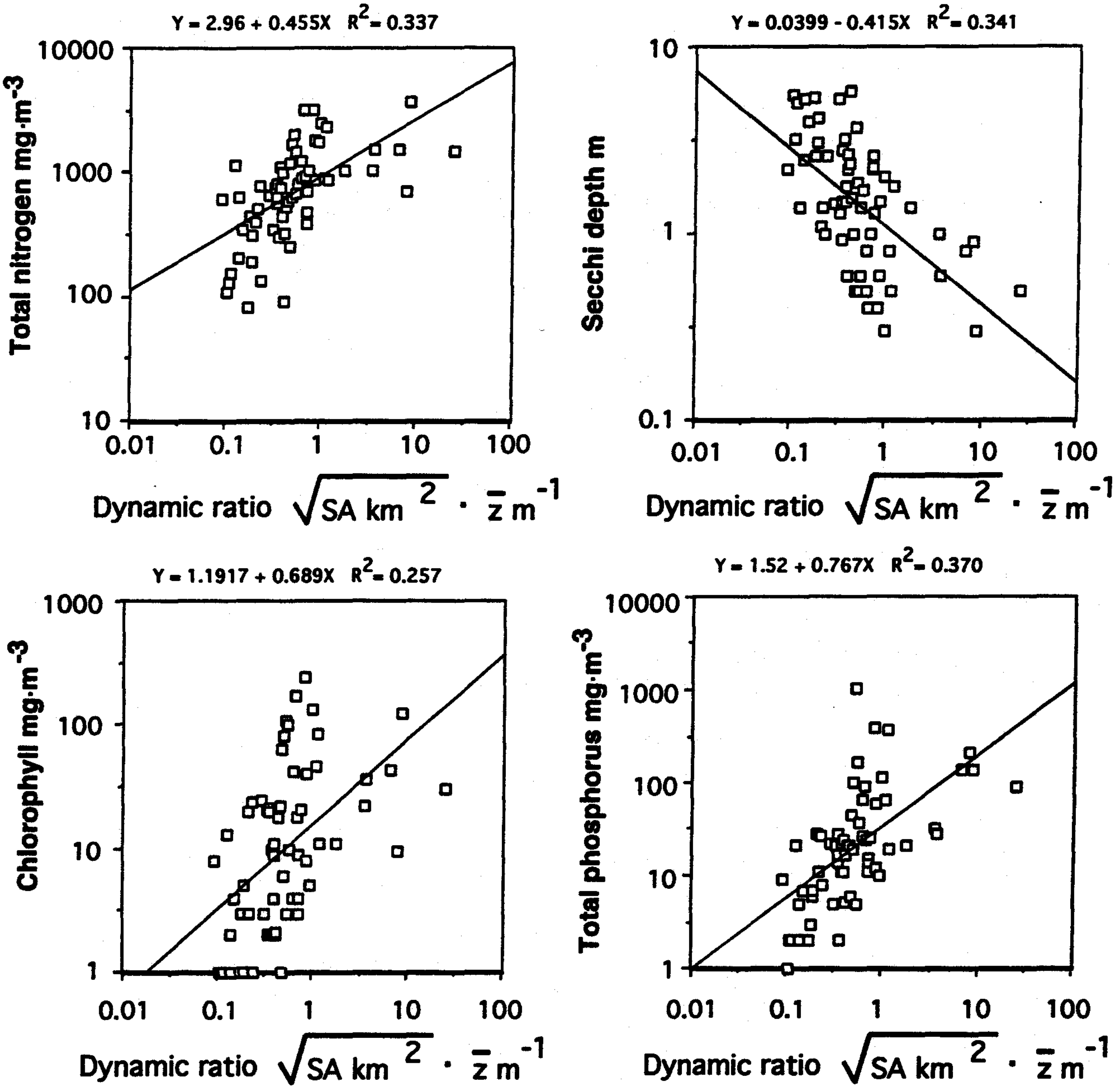

Figure 5.–Double logarithmic regressions of total nitrogen, Secchi disk transparency, chlorophyll, and total phosphorus on the dynamic ratio for 62 Florida lakes studied by Bachmann et al. (1997).

through July 1998 was 14.2 (SE± 0.27) km · hr^{-1}. The difference was statistically significant ($p<.001$).

Discussion

We investigated the potential for wave disturbance of sediments and its inferred connection to water quality measures in a wide range of Florida lakes. While some lakes had deep areas where sediments could accumulate undisturbed by surface waves, many of them had their entire lakebed subject to wave disturbance at one time or another. Many Florida lakes are shallow relative to their surface areas and thus have the potential for significant sediment resuspension. The extent that particles are actually moved into the water column will depend on the magnitude of mixing energy that is available at the lake sediment boundary and the susceptibility of the particles to resuspension.

According to our calculations, sediments in Lake Apopka are very susceptible to disturbance by wind-driven waves. All areas of the lakebed were susceptible

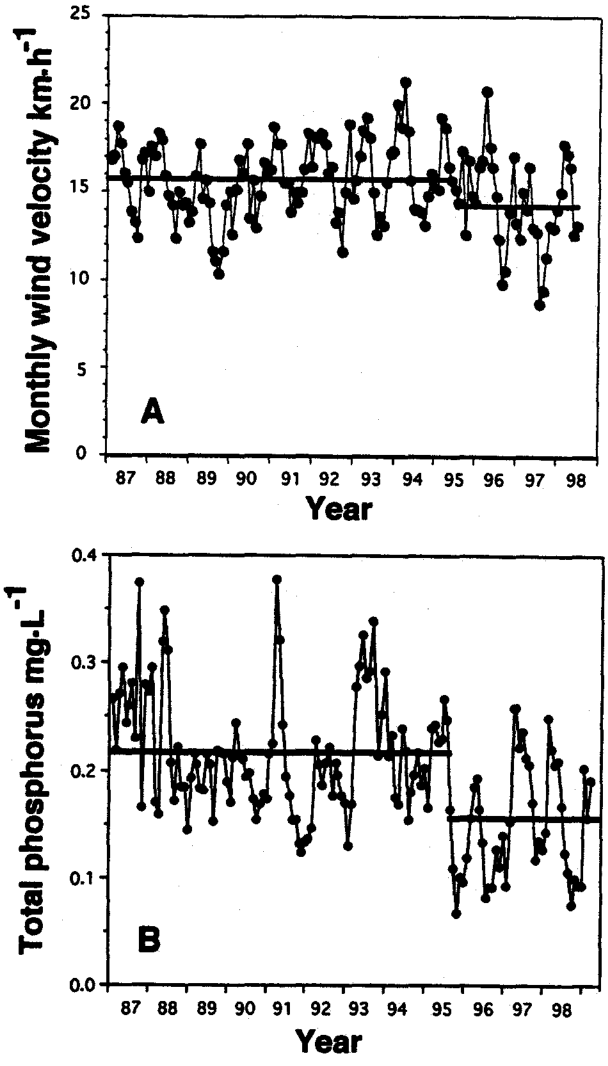

Figure 6.–A. Wind velocities at the Orlando International Airport. The horizontal lines represent the average velocities for the periods before and after July 1995. B. Total phosphorus concentrations in Lake Apopka, FL (Battoe et al. 1999). The horizontal lines represent the average concentrations for periods before and after July 1995.

to wave disturbance at one time or another and the frequencies of disturbance were among the highest in Florida. This finding is consistent with the field observations of Pollman (1983) who described the effects of an afternoon storm on the lake. "As the storm swept across the lake surface, bottom sediments were immediately resuspended to the surface. The visual change was rather remarkable; for example, sediment resuspension was observed as a sharp front normal to and moving across the lake in the same direction as the wind. Behind the front the water surface assumed a muddy brown appearance from entrained sediments while on the leeward side, a characteristic greenish cast typical of the highly productive water column was observed." He calculated that the storm resuspended the top 4 cm of sediments in the lake. These findings and observations support our previous hypothesis (Bachmann et al. 1999) that wind resuspended sediments dominate the limnology of this lake and that water clarity cannot be significantly improved in Lake Apopka until this problem is solved. Two other large Florida lakes, Okeechobee and Istokpoga, have similar calculated sensitivity to wave disturbance (e.g. having the highest per cent of the lake area disturbed 50% of the time and in having the largest per cent of the lakebed disturbed 50% of the time) and are noted for having problems with sediment resuspension (James et al. 1997, Lamb 2000), Maceina and Soballe 1990).

The dynamic ratio of Håkanson (1982) promises to be a useful tool to screen lakes to determine which water bodies might be susceptible to sediment disturbance by wind-driven waves. Estimating wave disturbance frequencies is time consuming and requires a large data set of morphometric and wind information. Hence, a less labor-intensive wind-mixing calculation based on surface area and mean depth may be of greater utility. Strong correlations between this ratio and all of our various measures of the calculated extent and frequency of sediment disturbance by surface waves reinforce its usefulness. The strongest relationship was with the per cent of the lakebed subject to wave disturbance at one time or another. Lakes with a dynamic ratio or 0.8 or higher have no portion of the lakebed that is completely undisturbed over time and would thus be most likely to have problems with sediment resuspension. For dynamic ratio values below 0.8 there was a linear decrease in the area disturbed one time or another. We also had a preference for an index whose value increased rather than decreased with increases in the extent and frequency of wave disturbance, hence the use of the dynamic ratio rather than the Osgood index (Osgood 1988).

The dynamic ratio was also related to water quality. In general those lakes that were most susceptible to sediment resuspension by wave action had the poorest water quality in terms of Secchi disk transparency, phosphorus and nitrogen concentrations, and total chlorophyll. Detailed studies of individual lakes have shown correlations between wind velocities and water clarity, nutrient concentrations, and algal chlorophylls (Hamilton and Mitchell 1996, James et al. 1997, Carrick et al. 1993). Associations between water transparency and resuspended particles that would directly influence light scattering and absorption would be most important. Phosphorus and nitrogen could be attached to sediment particles, or the disruption of the surface sediments and wind-driven water movements could release dissolved nutrients from the interstitial waters that would otherwise be released only very slowly by diffusion. While increases in phytoplankton chlorophylls could be related to increases in plant nutrient concentrations, they could also result from the resuspension of benthic algae on the sediment surface. Such a phenomenon has been described for Lake Apopka where a layer of meroplankton on the sediment surface is resuspended during wind events (Carrick et al. 1993) and results in a linear relationship between wind velocity and chlorophyll concentration in this lake.

Some caution is necessary in interpreting the correlations between the dynamic ratio and water quality in these lakes. The dynamic ratio explains only about 26 to 34% of the variance in water quality measures, so other factors are more important for this group of lakes. Further there can also be factors other than wave action associated with large surface areas or shallow depths that could lead to reduced water quality. For example in comparing deep and shallow lakes with the same areal nutrient loadings, the shallow lakes would have the higher concentrations because there would be less dilution even if wave actions would not reach the sediments. Further the well-known relationships between lake productivity and mean depth (Rawson 1952) extend to a large group of lakes that have little exposure to sediment resuspension. The relationships between lake water quality and shallowness extend beyond sediment resuspension.

In addition to relating the dynamic ratio to short-term water quality measures, we also found that the mixing frequency curves and the dynamic ratio were related to long term patterns of sedimentation. In lakes with low dynamic ratio values, sediments were concentrated in central deeper areas. This confirmed pervious ideas that sediments will tend to move until they end up in an undisturbed area where they can accumulate. On the other hand, if such areas do not exist, the sediments will continue to resuspended and will be widely distributed over the lakebed.

There are situations where the calculations of frequencies of wave mixing need to be modified. These include lakes with extensive beds of macrophytes, lakes with water level changes, and periods of climatic fluctuations when the wind regime changes. The calculations in this study did not take into account the presence of macrophytes. Macrophytes can interfere with the development of surface waves and reduce water movements within their beds (Jackson and Starrett 1959, Hamilton and Mitchell 1996). This is one of the reasons that the limnological character of shallow lakes with and without macrophytes can vary so much (Scheffer 1998). For example in Lake Apopka where resuspended sediments currently account for much of the light extinction, the water was reported to be clear in much of the lake in the 1940s when the lake was dominated by macrophytes (Clugston 1963). The calculations for wind mixing described in this study represent the potential for sediment disturbance only in the absence of substantial beds of macrophytes.

Water level changes can also play an important role in shallow lakes. Lind et al. (1994) showed in Lake Chapela, Mexico that a drop in the water level caused a resuspension of clay particles and increased turbidities. This paper demonstrated that the range of water levels encountered in Lake Apopka between 1935 and the present could account for significant differences in the frequency and extent of wave action on the lake's bottom (Fig. 2). During the low water period in 1956 when the elevation was 75 cm below the map datum, there were massive fishkills noted during windstorms that were coincident with observations of massive sediment resuspensions. Oxidation of resuspended organic sediments may have led to oxygen depletions (Bachmann et al. 1999). This was one of the reasons that a water control structure was built to prevent the occurrence of low water periods (U. S. Environmental Protection Agency 1978). Water level changes may have played a role in setting up the current resuspension problem in Lake Apopka. According to early reports (Delta Canal Company 1895, Shofner 1982) a canal constructed in 1883 to connect Lake Apopka with downstream lakes dropped the water level in the lake by about 1 m. While the precise elevation changes are not known, if this means that early water levels were even 75 cm higher than the current map level, then the calculated potential for sediment resuspension in the lake was much less prior to 1883 than at present (Fig. 2).

Our calculations of potential wind resuspension in Lake Apopka were based on of a 5-years series of wind data from a nearby wind gage. The assumption is made that these are representative of the wind regime for that location, however this might not always be the case. For example in an analysis of water quality fluctuations over time at Lake Okeechobee it was found that there were changes in annual wind velocities that were correlated with changes in water quality that may be due in part to resuspension effects (Maceina and Soballe 1990). This might have happened in Lake Apopka. Battoe et al. (1999) compared averages of monthly measurements of total phosphorus, phytoplankton chlorophyll, total suspended solids, and Secchi disk depths for the periods before and after mid-1995. They found significant decreases in the concentrations of total phosphorus, phytoplankton chlorophyll, and total suspended solids and a significant increase in Secchi disk depth after mid-1995. They attributed the changes to regulatory actions designed to reduce nutrient inputs, however we found that average wind velocities also decreased in the period after mid-1995 when compared to the period before mid-1995. Thus the differences in water quality variables such as total phosphorus (Fig. 6B) noted by Battoe et al. (1999) before and after mid-1995 could have been due to decreased wind velocities rather than changes in nutrient loading. We had previously found that there was no correlation between annual nutrient loading and average annual total phosphorus concentrations in lake Apopka (Canfield 2000), supporting our hypothesis that changes in wind velocities rather than loading changes are responsible for the observed changes in water quality. Since we are dealing with correlations rather than controlled experiments, however, neither explanation is proved nor disproved by these analyses.

The field of limnology has developed with a prevalence of deep lake studies such as lakes Geneva, Mendota, Washington, etc. where surface waves did not influence a large fraction of the lakebed. Recently it has been recognized that there are important differences between how deep and shallow lakes function and that these differences have to be taken into account in the formulation of management plans (Moss et al. 1996, Scheffer 1998). We suggest that calculations of wave disturbance frequencies and the dynamic ratio can be useful tools in the diagnosis and management of shallow lakes in Florida and elsewhere.

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