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Recent Paleolimnology of Devils Lake, Oregon

Abstract

A study of the sediments in an eutrophic Oregon coastal lake, Devils Lake, was initiated to assist in management decisions regarding lake restoration. Recent limnologic changes in the lake were determined through examination of the sediments and measurement of lake bathymetry. A 1.5 m long core, collected near the lake center, was analyzed for percent water, loss-on-ignition, nitrogen, phosphorus, and diatoms. The age of the sediments was measured using ^{210}Pb for the upper sediments and ^{14}C for the lower sediments on a total of three cores. The upper 40 cm of sediment represented 140 years of accumulation. The age of sediments at the base of three cores ranged in age from 2030 (± 80) b.p. (core D 1.5 m) to 2870 (± 80) b.p. (core A 1.0 m) in the lake center. Marine sand was present at the base of core A, which was most likely derived from a tsunami. The analysis of diatoms in the sediments showed a very diverse flora with almost 250 taxa identified. The dominant diatom taxa changed relatively little throughout most of the last 140 yrs, suggesting that the lake was productive prior to recent development. Most of the changes in diatom taxa occurred in the last several decades and involved subtle changes in the less abundant taxa. A major erosional event occurred about 1912 (± 8 yr) causing a 5-fold increase in sedimentation rate based on ^{210}Pb dating. Sediment accumulation rates returned to pre-1900 rates in the 1920's and 1930's, but increased again in the last several decades. The major increase in sedimentation rate in the early part of the century corresponded to periods of intense storms which coincided with early development activities. The more recent increases in sedimentation rate which caused a loss in lake volume apparently resulted from a combination of urbanization and logging.

Introduction

Devils Lake is an eutrophic lake located in Lincoln County, on the central Oregon coast. Coastal lakes, such as Devils Lake, have been popular sites for residential and recreational development. The lake was formed by natural accumulation of beach sand impounding water at the outlet of the D River. Physical properties of the lake and watershed and water quality characteristics of the lake are summarized in Table 1. Surface water concentrations of total phosphorus and chlorophyll *a* averaged 60 and 41 μg/L, respectively in recent years (CH2M HILL 1992). Additional descriptions of the lake are available in Johnson et al. (1985). The lake exhibits abundant growths of macrophytes and occasional phytoplankton blooms. The lake has been the subject of several investigations over the previous 20 years (Kavanaugh 1973, Larson 1974, Shulters 1974, Meyerhoff 1977, Kramer, Chin, and Mayo 1983, Thomas et al. 1990, CH2M Hill 1992). Perceived water quality problems in Devils Lake, in addition to the visible growths of aquatic plants (especially *Myriophylum spicatum*), include occasional depletion of dissolved oxygen in the deeper waters, high nutrient concentrations, and an accelerated sedimentation rate. The primary action taken in response to these conditions has been to stock the lake with triploid (sterile) grass carp (*Ctenopharyngodon idella*) in 1986, 1987, and 1993 in an effort to control the excessive growth of macrophytes. Only modest reductions in the macrophytes occurred through 1992 (CH2M Hill 1992); however, major reductions in macrophyte biomass were observed in 1994 and 1995 (Dave Wagner, Devils Lake Water Improvement district, pers. comm.).

Although there was a strong perception by local residents that conditions in the lake had recently deteriorated, there were few historic data to support this view. The purpose of the study reported here was to satisfy the need for historical information on Devils Lake to aid in decisions regarding restoration efforts.

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TABLE 1. Devils Lake physical and water quality characteristics.

Physical Characteristics			
Lake Area (ha)	270.7	Lake elevation (m, msl)	3.05
Watershed area (km^2)	60	Lake volume (m^3 x 10^6)	6.14
Mean depth (m)	2.3	Annual Precipitation (m)	2.3-2.8
Maximum depth (m)	5.8		
Water Quality Characteristics (Units are in µM except as noted)			
pH (s.u.)[a]	8.09	Alkalinity[a]	448
Ca[b]	117	TP[a]	60
Mg[b]	128	SO_4[b]	33
Na[b]	461	Cl[b]	440
K[b]	8	NO_3[a]	1.3
Transparency (m)	2.1	SiO_2[a]	95
Chlorophyll *a* (µg/L)[a]	41.4	Conductivity (µS)[a]	103

[a] CH2M Hill 1992
[b] Johnson et al. 1985

Methods

Sediment samples were collected from Devils Lake using a 5-cm diameter piston corer with a tube length of 2.5 m. The cores were collected from anchored rafts by placing the corer above the sediments and forcing the cylinder into the sediments using push rods until resistance prevented further penetration. This resulted in retrieval of sediment cores of about 1.5 m. Each core was inspected immediately for signs of disturbance caused by failure to capture the topmost sediment and for possible loss of sediment from the bottom of the core during core extraction. Four cores (A-D) were collected from several locations in the lake (Figure 1). Cores A, B, and C were collected on 14 February, 1993, and core D was collected on 30 May, 1993. Based on the quality of the initial analyses of the cores, core D was selected for more intensive analysis.

In addition to percent water and loss-on-ignition (LOI), subsamples of the sediment from core D were analyzed for lead-210 (^{210}Pb), total Kjeldahl nitrogen (TKN), total phosphorus (TP), and diatom species composition. Material from selected intervals was first analyzed for ^{210}Pb to ensure that the age of the sediments could be determined with confidence and to assess what portions of the core to analyze in greater detail. This procedure was necessary to ensure that the pre- and post-settlement periods were adequately represented in the core. Once the preliminary ^{210}Pb results were obtained, additional sediment intervals were analyzed to refine the sediment dating. ^{210}Pb activity was measured through its granddaughter product ^{210}Po, with ^{208}Po added as an internal yield tracer. The polonium isotopes were distilled from 0.2-1.3 g dry sediment at 550° C following pretreatment with concentrated HCl and plated directly (without HNO_3 oxidation) onto silver planchettes from a 0.5 N HCl solution (modified from Eakins and Morrison 1978). Activity was measured for 1-6 x 10^5 s with Si-depleted surface barrier detectors and an Ortec Adcam® alpha spectroscopy system. Unsupported ^{210}Pb, which is the ^{210}Pb derived from atmospheric sources, was calculated by subtracting supported activity, which is the ^{210}Pb produced from ^{226}Ra in the sediment, from the total activity measured at each level; supported ^{210}Pb was estimated from the asymptotic activity at depth (the mean of the lowermost samples in a core). Dates and sedimentation rates were determined according to the constant rate of supply model (Appleby and Oldfield 1978) with confidence intervals calculated by first-order error analysis of counting uncertainty (Binford 1990).

Sediment intervals from the base of cores A, C, and D were analyzed using ^{14}C techniques to estimate the overall sedimentation rate. Sample preparation and analyses were performed by Beta Analytic, Inc. using methodology described by Tamers (1975). Sediment from the following intervals was analyzed to achieve sufficient carbon for measurement: core A (92-100 cm); core C (146-154 cm); and core D (144-150 cm). The sediments were dispersed in deionized water, sieved to remove rootlets, and rinsed in hot acid. Neither rootlets nor carbonates were observed in any of the samples. After drying and final inspection, the portions of each were repeatedly combusted until adequate

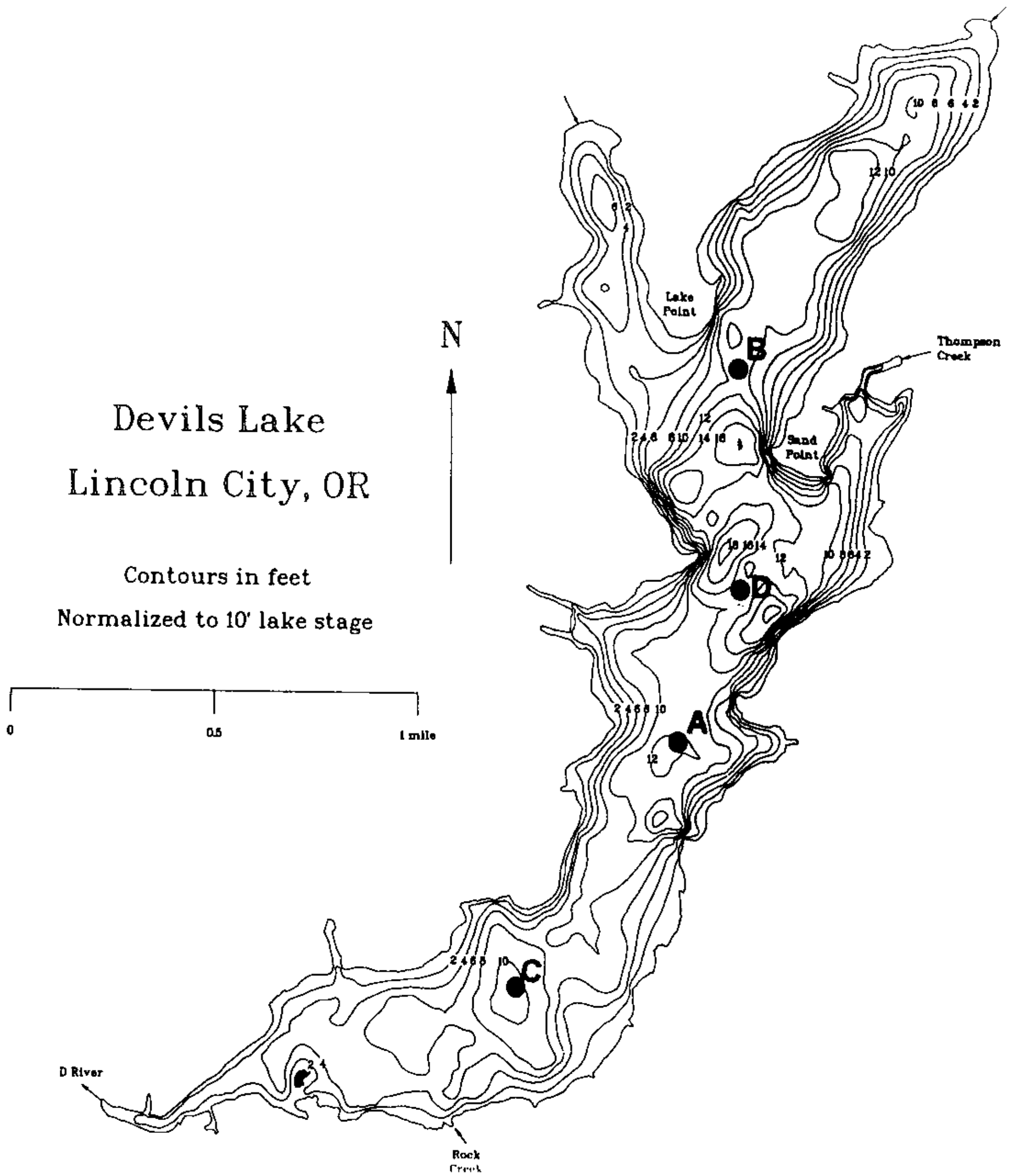

Figure 1. Bathymetric map of Devils Lake measured on 28 January 1994 using the methodology of Gubala et al. (1994). Coring sites (A-D) are located on the map. Lake area is 270.7 ha.

carbon dioxide was collected for analysis. All carbon in the sediment was assumed to be type C3 (terrestrial wood) for the purposes of dating.

Nitrogen in sediments was analyzed using a modified total Kjeldahl nitrogen (TKN) digestion (Method 351.1, EPA 1979) except that copper sulfate and sodium sulfate were substituted as catalysts in place of mercuric sulfate and potassium sulfate. Total phosphorus (TP) was measured using an ascorbic acid reaction spectrophotometrically in a 1 cm cell (Method 365.1, EPA 1979). Organic matter was estimated by LOI (Dean 1974).

The preparation of sediment samples for analysis of diatom fossils required special measures because of the poor preservation of diatoms. Meyerhoff (1977) was unable to find a sufficient number of adequately preserved diatom frustules to complete his historical reconstruction of Devils Lake. Sediments from multiple cores and intervals were used to test for the presence of diatoms at various sediment intervals and to develop methods for slide preparation. One cubic centimeter of sediment was digested in a microwave oven with nitric acid. Diatom suspensions were settled onto cover slips in Battarbee trays and analyzed using a light microscope at 1000X magnification. A counting goal of 500 diatom valves per slide was established and achieved for most intervals. Counts of less than 500 valves were obtained for intervals 27, 30, 33, 39, and 42 cm. An insufficient number of diatoms in these intervals was attributed to an abundance of inorganic particles that "diluted" the diatom remains, although silica dissolution reactions involving aluminum and ferric oxyhydroxide reactions cannot be ruled out (cf, Nriagu 1978). Diatoms were identified to the lowest possible taxa using taxonomic protocols established in the PIRLA (Paleoecological Investigation of Recent Lake Acidification) project (cf, Charles et al. 1990).

A revised bathymetric map was prepared using a SONAR-GPS methodology developed by Gubala et al. (1994). Data for the creation of a bathymetric map for Devils Lake was collected on 28 January 1994; the staff gage height at the outlet was 3.018 m. A 200 kHz, 3.5° transducer was configured to acquire data at 3-second intervals. Average boat speed during data collections was about 5 to 6 m/s. All data were normalized by lake stage and expressed as depth relative to a lake stage of 3.048 m. Measurements of bottom reflectivity from the SONAR measurements also were recorded to provide an indication of changes in relative hardness of the sediment.

Results

Bathymetry and Reflectively

The bathymetric map of Devils Lake completed for this study shows a complex bottom profile with several depressions not previously identified (Figure 1). The maximum depth measured in Devils Lake was 5.8 m. The SONAR signal used to record lake depth also was evaluated with respect to signal strength, referred to as reflectively. Changes in lake bottom reflectivity can be used to evaluate spatial patterns in sediment composition such as differences between sand and organic sediments. The reflectivity values for Devils Lake ranged from 13 to 16 (relative intensity) throughout the lake. The values are indicative of relative signal strength and vary among lakes depending on the initial instrument settings used in optimizing the SONAR signal for a given application. The relatively small difference in reflectivity was considered insignificant. No spatial patterns were observed in these data, indicating that the physical properties of the surface sediments were relatively uniform.

Physical Characteristics of the Sediments

Cores B, C, and D were visually similar to one another and were about 1.5 m long. Core A, collected from the deepest location near the center of the lake, was only 1.0 m long but was noteworthy because of the distinct layer of sand present at the base of the core. The sand was relatively uniform and light tan, giving it the appearance and consistency of marine-derived sand. Although the sediments lacked varves, there were visible differences in sediment composition. All four cores had similar consistency at the top (~ 12 cm) with flocculent, brown organic-rich material, grading into sediment with greater plasticity and firmness. Sediment below 110 cm could usually be separated into non-cohesive portions. The sediment from 12 cm to 24 cm appeared brown (iron colored). The sediment had a distinct grey-green appearance from about 24 cm to the base of the cores, becoming darker green with increasing depth. Unidentified plant rhizomes were abundant in the cores below 100 cm. The water content in core D decreased down through the sediment from 93% at the surface to 79% at 150 cm; however, this trend was punctuated by portions of the core that showed minor reversals of 3 to 4% in the overall pattern.

Sediment Dating

The activity values of ^{210}Pb in core D were at supported (background) levels below 40 cm with an average supported activity of 0.60 pCi/g (Figure 2a). Although a core of 150 cm length was collected, the dating shows that the upper 39 cm of sediment represents the last 140 years of lake history (Figure 2b). The sediment interval from 33 to 39 cm represents the pre-settlement period from about 1850 to 1880. Sediment accumulation in

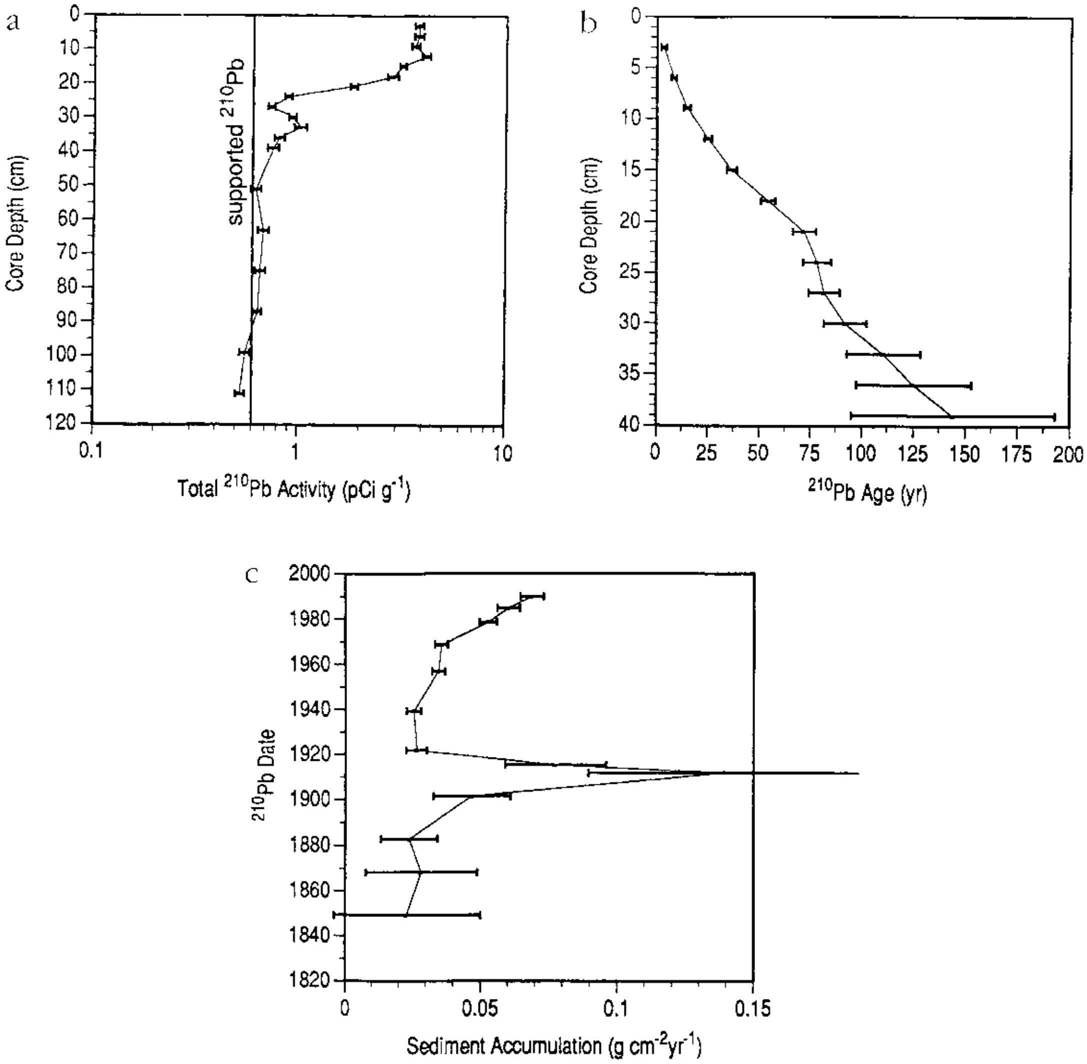

Figure 2. (a) Total ^{210}Pb activity (pCi/g) for Devils Lake core D; (b) Age of sediments estimated from ^{210}Pb activity versus sediment depth in Devils Lake, core D. The horizontal lines associated with each observation represent the uncertainty (1 sd) in the age of the sediments; c) Sediment accumulation rate (g/cm^2/yr) in Devils Lake, core D, versus sediment date. The horizontal lines associated with each observation represent the uncertainty (1 sd) in the sediment accumulation rate.

this period was about 0.025 g/cm^2/yr, increasing to a maximum of 0.14 g/cm^2/yr around 1912 ($\pm$7.6 yrs), which was over five times the pre-settlement rate (Figure 2c). Sediment accumulation rates decreased to near pre-development sediment accumulation rates of 0.026 g/cm^2/yr during the 1920's to 1940's. In the 1950's, the sediment accumulation rate began increasing again to values which are currently about 2 1/2 times the pre-settlement rate.

The long-term age at the base of the cores was determined by ^{14}C measurements on three of the four cores. The bottom of the cores ranged from about 2000 to 3000 years of age (Table 2). If we examine the sediment accumulation rate below 33 cm in core D, the average rate of sedimentation would be 0.0113 g/cm^2/yr, or about one-half of the minimum sedimentation rate measured in the upper portion of the core. Sedimentation rates below 33 cm in Devils Lake of 56 cm/per thousand

TABLE 2. Radiocarbon dating of sediments in Devils Lake, Oregon.

Core	Sediment Depth (cm)	Radiocarbon Date (Years BP)	Analytical Precision[a] (Yr)	Calendar Equivalent Ages[b]	Average Accumulation Rate (cm/kyr)
A	92-100	2870	± 80	1270 BC to 830 BC	33.4
C	146-154	2600	± 70	850 BC to 530 BC	57.7
D	144-150	2030	± 80	200 BC to 140 AD	72.4

[a] 1 standard deviation
[b] assuming type C3 carbon (terrestrial wood)

years (cm/kyr) are comparable to two cores collected from Lake Washington which showed linear accumulation rates of 51 cm/kyr and 55 cm/kyr (Karlin and Abella 1992). The ^{14}C results provide additional confirmation that current sedimentation rates are considerably greater than natural rates and could range from 2 to 5 times pre-development rates depending on whether the ^{210}Pb or ^{14}C dates are used.

Sediment Chemistry

Loss-on-ignition (LOI) provides a gross measure of sediment composition, particularly organic matter. Sediments high in inorganic materials such as clay will exhibit low LOI values, whereas sediments with a high proportion of decomposing organic matter will exhibit high LOI values. A comparison of four cores (A-D) collected in Devils Lake shows that cores A, B, and D are quite similar for the past 150 years, but deviate from one another below 50 cm (Figure 3). Core C collected closest to the boat launch on the south end of the lake, has a much higher organic content than the other three cores. Whereas cores A, B, and D reach local minima in LOI near 27 cm, sediment from core C tends to increase in LOI below 27 cm. These results indicate that core D is reasonably representative of the general stratigraphy (as represented by LOI) in the northern two-thirds of the lake, but core D may not be indicative of changes occurring in the southern portion of the lake.

Major trends in the nutrient status of Devils Lake were investigated by measuring the nitrogen and phosphorus content of the sediment. Both total Kjeldahl nitrogen (TKN) and total phosphorus (TP) concentrations reached a maximum at 24 cm and exhibited fairly stable values down to 39 cm (Table 3). Two deep sediment samples showed much greater concentration of TKN, possibly because of the rhizomes present. TP concentrations in the pre-settlement era were only about 20% of the maximum values observed at 24 cm. Thus, both TKN and TP concentrations in the sediments have decreased from the peak at 24 cm which corresponds to a date of 1915 (± 6.9 yrs). The ratio of TKN/TP shows three distinct periods whereby the ratios from 0 to 15 cm (from present to 1957 ± 2.4 yrs) are between 3-4, the ratios from 18 to 30 cm (1939 ± 3.5 yrs to 1882 ± 17.9 yrs) are between 1-2, and the values to 42 cm are between 4-9. Most of the changes in the TKN/TP ratio can be attributed to changes in TP which showed a major increase in phosphorus that corresponds with the first records of modern settlement in the county (Steere 1951).

Diatoms

The sediment diatom assemblages are remarkably diverse. Up to 86 taxa were present in specific sediment intervals, with a total of 243 taxa recorded in the fourteen intervals analyzed from core D. The number of taxa decreased from 85 taxa in the surface sediments to 51 taxa at 42 cm, although this was largely an artifact of the total diatoms counted per interval. When the prescribed number of diatoms (≥ 500) were counted, the number of taxa recorded was significantly ($p \leq 0.05$) greater than those intervals with counts less than 500. Several sections had an insufficient number of diatoms available for counting because of either dilution from sediment particles or possible dissolution reactions occurring in the sediments. When the observed number of diatom taxa are normalized to a standard number of valves counted, the expected number of taxa differs relatively little from the number of observed taxa for sections with ≥ 500 diatoms counted.

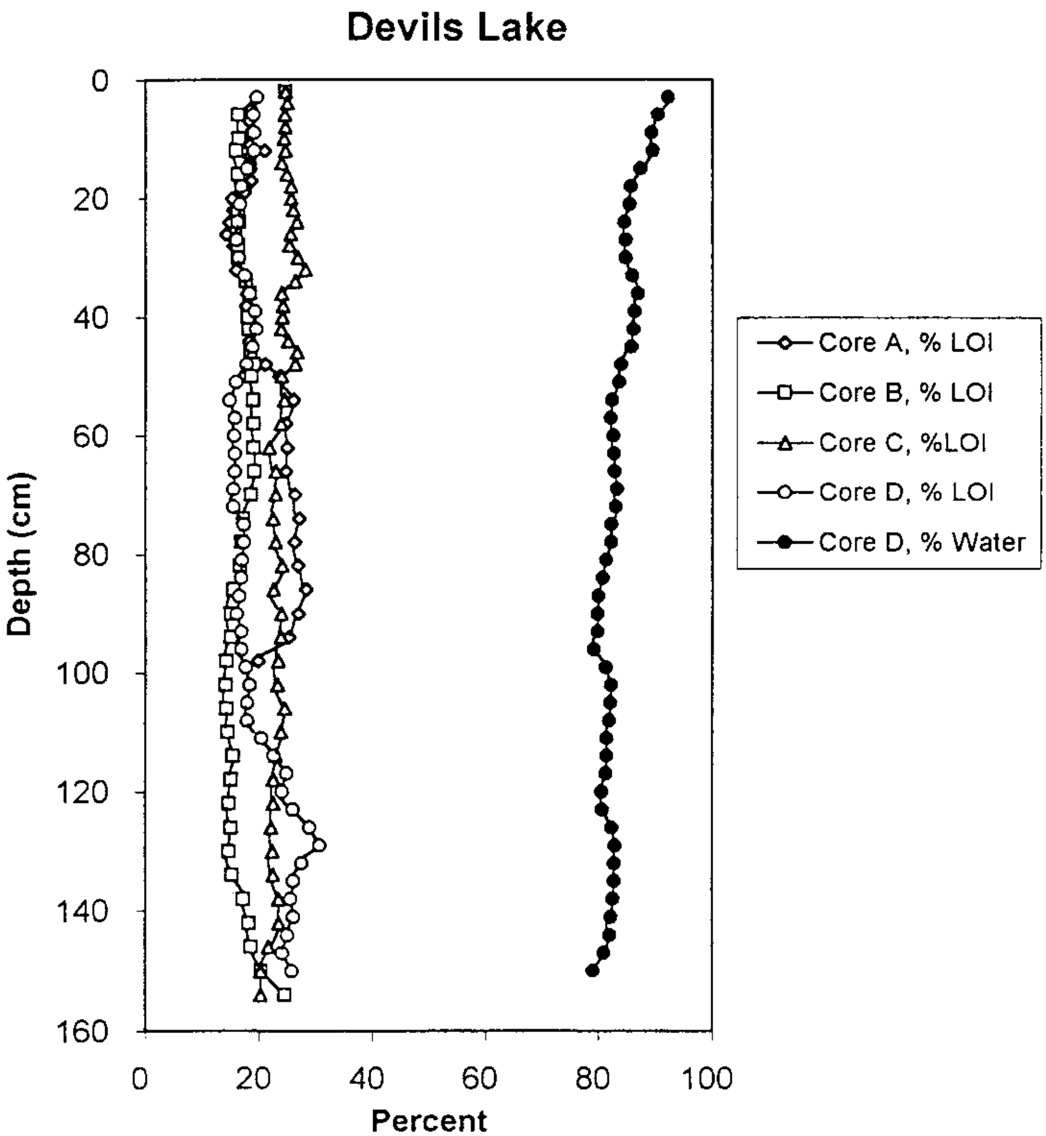

Figure 3. Percent water and loss-on-ignition (LOI) versus sediment depth (cm) in core D. LOI values are also shown for cores A, B, and C.

The most abundant seven taxa present in the sediments show only modest changes in relative abundance through the core (Figure 4). The most abundant taxon, *Cocconeis placentula* var. *lineata* shows a slight decline from 18-33 cm, but two intervals at 24 and 30 cm have relative abundances near 20%, which casts doubt on the significance of the apparent decline. *Fragilaria construens* var. *venter* is most abundant at intervals 18 and 21 (1939 and 1922, respectively), at a period when the sedimentation rate had decreased to near pre-industrial levels. *Fragilaria crotonensis* exhibited a trimodal distribution with peaks at 3, 12, and 39 cm. The major decline of *F. crotonensis* beginning at 33 cm precedes the accelerated sedimentation which begins at 30 cm.

Asterionella formosa is a species commonly found in highly productive lakes. With the exception of the observations from 39 cm, the species appears to display a gradual increase in abundance from historical times to present. *A. formosa* was the principal species associated with increasing

TABLE 3. Total Kjeldahl nitrogen (TKN), total phosphorus (TP), and the ratio of TKN/TP in Devils Lake, core D.

Sediment Depth (bottom of interval, cm)	Total Kjeldahl Nitrogen (TKN) (mg/g, dry wt)	Total Phosphorus (TP) (mg/g, dry wt)	TKN/TP
3	2.7	0.7	3.8
6	9.1	2.5	3.6
9	11.9	3.2	3.7
12	8.2	2.2	3.8
15	8.5	2.7	3.2
18	7.0	1.9	3.6
21	7.3	3.6	2.0
24	7.4	4.8	1.5
27	5.6	4.5	1.2
30	5.9	3.8	1.6
33	6.1	1.0	5.8
36	8.8	1.0	8.5
39	7.1	1.4	5.1
42	7.3	1.6	4.6
72	6.3	1.1	5.7
102	5.4	0.6	8.4
123	8.8	0.5	17.4
150	7.8	0.3	22.4

watershed disturbance for lakes in western Washington (Brugam and Vallarino 1989). In some of their study lakes, relative abundance of *A. formosa* increased from 0 to over 60%. The relatively small changes in abundance for *A. formosa* observed in Devils Lake suggest only slight changes in productivity during the last century.

Navicula radiosa shows a general decrease through the period of record. As observed with *A. formosa*, the interval that is a major exception to the overall trend occurs at 39 cm. *Fragilaria construens* var. *pumila* also exhibits a slight decrease, most of it occurring in the most recent sediments. In contrast, *Fragilaria pinnata* exhibits a slight increase in relative abundance. Whatever changes may have occurred in water quality in Devils Lake in the last century have not been great enough to cause pronounced changes in the dominant diatom species.

The information regarding the less abundant diatom species was assessed through multivariate statistical techniques. A principal component analysis (PCA) using all taxa present showed that the recent sediment samples (0-12 cm) were distinct from the diatom community in the deeper sediment samples (Figure 5). When cluster analyses (FASTCLUS, SAS 1988) is used to group the sediment intervals according to statistical similarity, we observe that the top interval (3) forms its own cluster (I) as do intervals 6, 9, and 12 (Cluster III). The remaining intervals form clusters that show little relationship to other sediment characteristics such as sedimentation rate or sediment nutrient concentrations. These data for the dominant diatom taxa suggest that the water quality in the lake, at least in the northern half of the lake, has not changed radically in the last century. However, the community composition shows more subtle changes among the less common species that may reflect some water quality change in the last three to four decades.

Discussion

There is local concern regarding accelerated watershed erosion and sedimentation in Devils Lake (Kramer, Chin, and Mayo 1983). The sediment accumulation since creation of the 1953 bathymetric map (Oregon State Game Commission

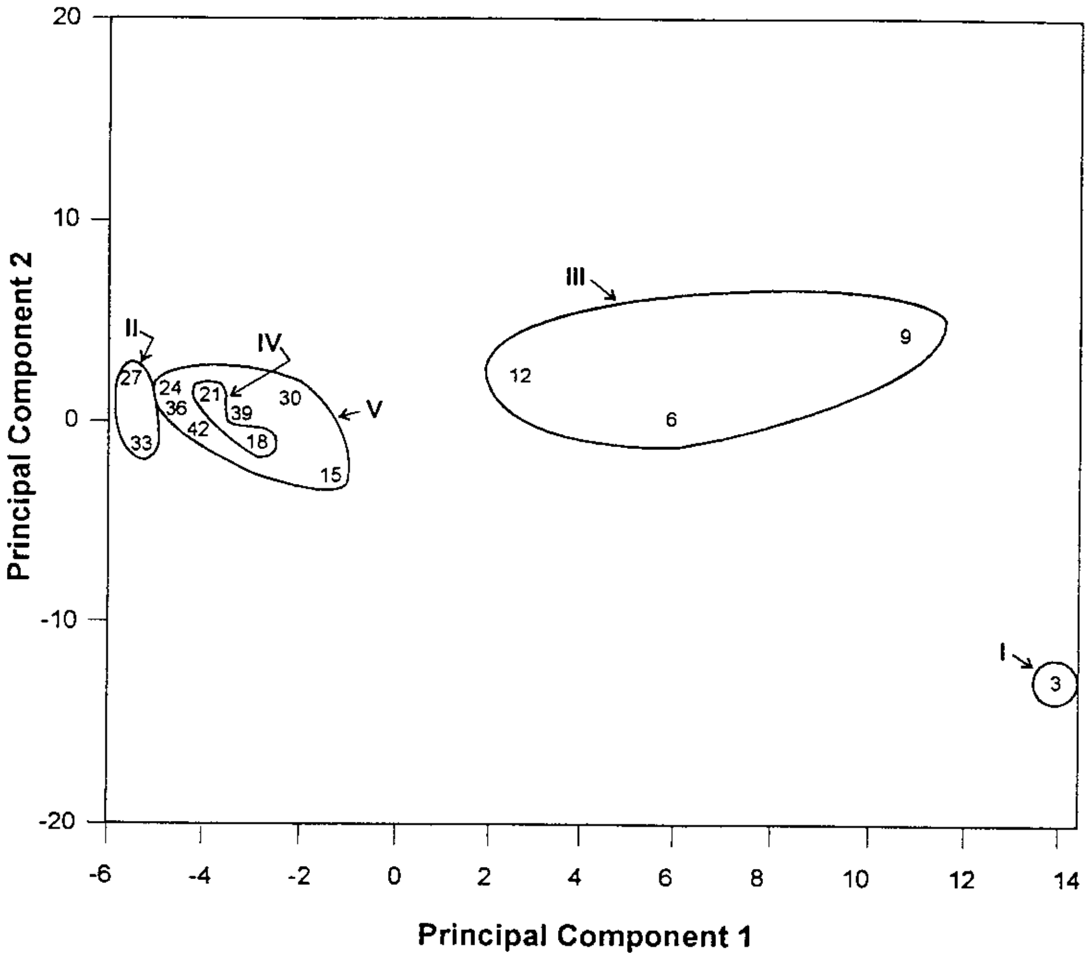

Figure 5. Principal component classification of diatom species composition in Devils Lake, core D for the first two principal components. The numbers refer to the sediment interval. Related diatom communities are indicated by the five clusters (I-V) encompassing the numbered individual sediment intervals. All 243 diatom taxa were included in the classification.

1953), computed on the basis of ^{210}Pb dating for core D, is only about 15 cm. If this estimate represents a reasonable lake-wide accumulation rate, the lake has lost about 4 x 10^5 m^3 or 6% of the previous lake volume over the last 40 years. However, the actual reduction in lake volume could be considerably different than that estimated on the basis of sediment accumulation at one site. Reports of shoaling in embayments following major storm events (see Johnson et al. 1985) suggest that deposition rates adjacent to inlets are greater than in the lake center. Thus, a 6% reduction in lake volume over the last 40 yrs may be an underestimate. Alternatively, if sediment focusing is occurring at this site, then the actual lake-wide sediment accumulation could be less than this estimate. An upper-bound estimate for loss of lake volume based on comparison of the current bathymetry with 1953 bathymetry is 26%.

The sediment reconstruction for Devils Lake is based largely on the results of one core, raising some concerns about the homogeneity of the sediments and the representativeness of core D. Both the SONAR reflectivity results and the LOI results from three other cores indicate relatively little variation in the physical composition of the sediments. However, some difference was noted in the LOI values between core C from the southern portion of the lake and the remaining cores. The apparent lack of synchronism between core C and the remaining cores could be due, in part, to different influences in the southern portion of the lake. The decreases of LOI in core C near 40 and 60 cm may correspond with the decreases observed at 24 cm in cores A, B, and D. Site C favors a high sedimentation rate because of its proximity to Rock Creek which drains most of Devils Lake watershed. The southern end of the lake also was the discharge site for the Oceanlake sewage treatment plant from 1951-1970. Meyerhoff (1977) analyzed four 50-cm long sediment cores collected from 3 m to 6 m depths in Devils Lake. Sediments from the 6 m site (located near site D in this study) were analyzed in the greatest detail. There were only small variations in percent organic matter (LOI) and profiles were uniform ranging from 22 to 25% LOI in three of the four cores. This compares reasonably well with the values measured in this study which ranged from 15 to 25% in the upper 50 cm. Meyerhoff (1977) measured LOI values of 10% in one core collected from a lake depth of 3.5 m. This site appeared to be close to shore and may have received greater erosional inputs than the deeper sites.

Whether the differences in TKN/TP ratios among the intervals correspond to differences in *inputs* of nutrients or differences in *retention* of the nutrients cannot be determined with these data. It is possible that the apparent changes in the TKN/TP ratio are an artifact caused by differences in nutrient mobility in the sediments, rather than serving as an unaltered record of nutrient deposition (cf, Carignan and Flett 1981). Both N and P are mobile to some degree in sediment and their peak concentrations at 24 cm may reflect redox gradients rather than depositional history. The accumulation rates of TKN and TP peak in the early portion of the century, corresponding to the major depositional event. These data suggest that TKN and TP accumulation rates are associated with erosional inputs. Assuming that this is the cause, it is likely that most of these nutrients entered the lake in particulate form and were generally unavailable for uptake by aquatic macrophytes or phytoplankton. Regardless, the sediment profile provides dramatic evidence of the potential importance of major hydrologic events, not only on sedimentation, but on nutrient accumulation as well.

Meyerhoff (1977) also measured increased TP and TKN above 30 cm in the sediments. The increase in sediment TP concentrations peaked at 22 cm with values about three-fold greater than values measured near the base of the core. The increase in TKN was more gradual up to 6 cm, where a five-fold increase over base values was observed. Meyerhoff (1977) attributed the higher nutrient concentrations in the surface sediments to watershed activities which increased nutrient loads.

The ^{14}C dates for the three sediment cores show that long-term average sediment accumulation rates in Devils Lake are low, and appear to be greatest in the northern part of the lake. This is unexpected considering that the primary tributary discharges into the southern portion of the lake. However, the proximity of Rock Creek to the outlet may result in much of the sediment load depositing closer to the outlet or being transported to the ocean. Core C, collected near the southern end of the lake, exhibits a long-term average sedimentation rate about 25% less than core D. The core collected from the lake center, core A, is the shortest core, and exhibits the lowest sedimentation rate. The sand layer at the bottom of core A (and observed at the base of several other incomplete cores that were discarded) was noteworthy because of its distinctly marine appearance. Heusser (1960) collected a 7 m-long core through peat adjacent to the west shore of Devils Lake and estimated the age of the lake at 6,300 (± 275) BP using ^{14}C dating. Heusser (1985) also noticed that sand was interbedded in the lake sediments, which he viewed as an indication the lake became estuarine at times. More recent studies of lake and estuaries along coastal Washington (Atwater 1987, 1992; Jacoby et al. 1992; Karlin and Abella 1992; Schuster et al. 1992) and Oregon (Darienzo and Peterson 1990, Nelson 1992, Nelson et al. 1994, Darienzo et al. 1994) indicate that at least some of these lake sediment sand layers were derived from tsunamis generated by earthquakes.

Devils Lake has received numerous inputs from anthropogenic activities in the last 100 years including erosion from logging and development, poorly treated effluent from a sewage treatment plant, and runoff from livestock and urban areas. In addition, the lake was treated with rotenone and stocked with warm-water fish species, trout, and herbivorous carp (Dave Wagner, Devils Lake Water Improvement District, pers. comm.). The population of the area has grown from a small group of native tribes in the 1800's to the current community of Lincoln City with a population over 5000.

We were unable to identify conclusive evidence of anthropogenic disturbance in the early part of the century that might explain the dramatic increase in sedimentation observed between 1900 and 1920. There is evidence that the settlement of the Devils Lake area began in the 1890's, but it is unclear what the major activity associated with the early settlements was in this watershed. There are accounts of homesteaders with livestock present in the area as early as 1909. Logging was beginning along the Oregon Coast during this period and the timber industry was greatly stimulated by demand for lumber products following the 1906 earthquake in San Francisco. However, specific evidence for intensive logging in the Devils Lake watershed is somewhat conflicting. Examination of the nearshore area shows only a small number of extremely large stumps, suggesting that little old growth forest was present in the watershed in the late 1800's. A review of the 1900 forest cover maps (scale 1" = 2 mi.) for the area shows the Devils Lake watershed classified primarily as recently burned. The 1914 forest classification map (scale 1" = 6 mi) also shows most of the watershed as "burnt with restocking." However, a more detailed 1936 (scale 1" = 0.66 mi.) classification represents the shoreline and lowland area of the watershed as large spruce hemlock (forests containing >50% by volume either western hemlock or Sitka spruce, trees from 20 to 24 in diameter). Much of the upland portion of the watershed is classified on this map as large second growth Douglas fir (forests, not yet mature, containing >60% Douglas fir where the majority of volume in trees 20-40 in. diameter). The immature Douglas fir stands are consistent with the earlier forest fire history, but the lowland spruce/hemlock forest suggests a different situation than that represented on the 1900 and 1914 small-scale maps.

Historical precipitation records earlier than 1928 are unavailable for this area. Precipitation records for Corvallis, located about 70 km southeast from Devils Lake, indicate that the largest three-day precipitation event recorded for the region occurred 17-19 January 1911 when 16.5 cm was recorded (Office of State Climatologist, Corvallis). Precipitation at the coast averages about 40-60% greater than in Corvallis, suggesting that this event could have been in excess of 25 cm at Devils Lake. Precipitation in 1909 also appears to have been well above normal, at least for October and November (Steere 1951).

The high precipitation events in 1909 and 1911 provided opportunities for accelerated erosional inputs into Devils Lake. The possibility that the erosion which occurred circa 1910 was entirely natural is low in view of the low long-term sediment accumulation rate based on the ^{14}C measurement and the absence of periodic erosional events that might have been associated with high precipitation events. Furthermore, the greatest floods in western Oregon in modern history (1861, 1890, 1943, 1945, and 1964) do not correspond with the high sedimentation periods observed in the Devils Lake sediment. We conclude that the high sedimentation rate in the early 20th century was caused, in large part, by watershed activities.

Although the historical peak in sediment accumulation is dramatic, the sediment accumulation rate quickly returned to pre-settlement rates. Of greatest interest with respect to current management of Devils Lake is the trend in the last three to four decades which shows a steady increase in the rate of sediment accumulation (Figure 6). The cumulative sediment accumulation in the last three decades exceeds the total sediment accumulation from 1900-1920. The results of this paleolimnological reconstruction suggest that lake management efforts should focus on identifying important land use contributions to watershed erosion and controlling these erosional inputs. This appears to be consistent with plans being implemented by the Devils Lake Watershed Improvement District (Wagner 1994).

The biological history of the lake, as reflected in the sediment diatoms, shows a more subtle pattern. The major diatom species have shown only minor changes in relative abundance, although several species display apparent trends. Judging from the diatom species composition, it appears that the lake has been productive for at least the last 150 years and probably much longer. A statistical analysis of the diatom community shows that the species composition in the most recent sediments (i.e. last 25 years) differs, particularly among the less common species, from diatoms in the deeper sediments.

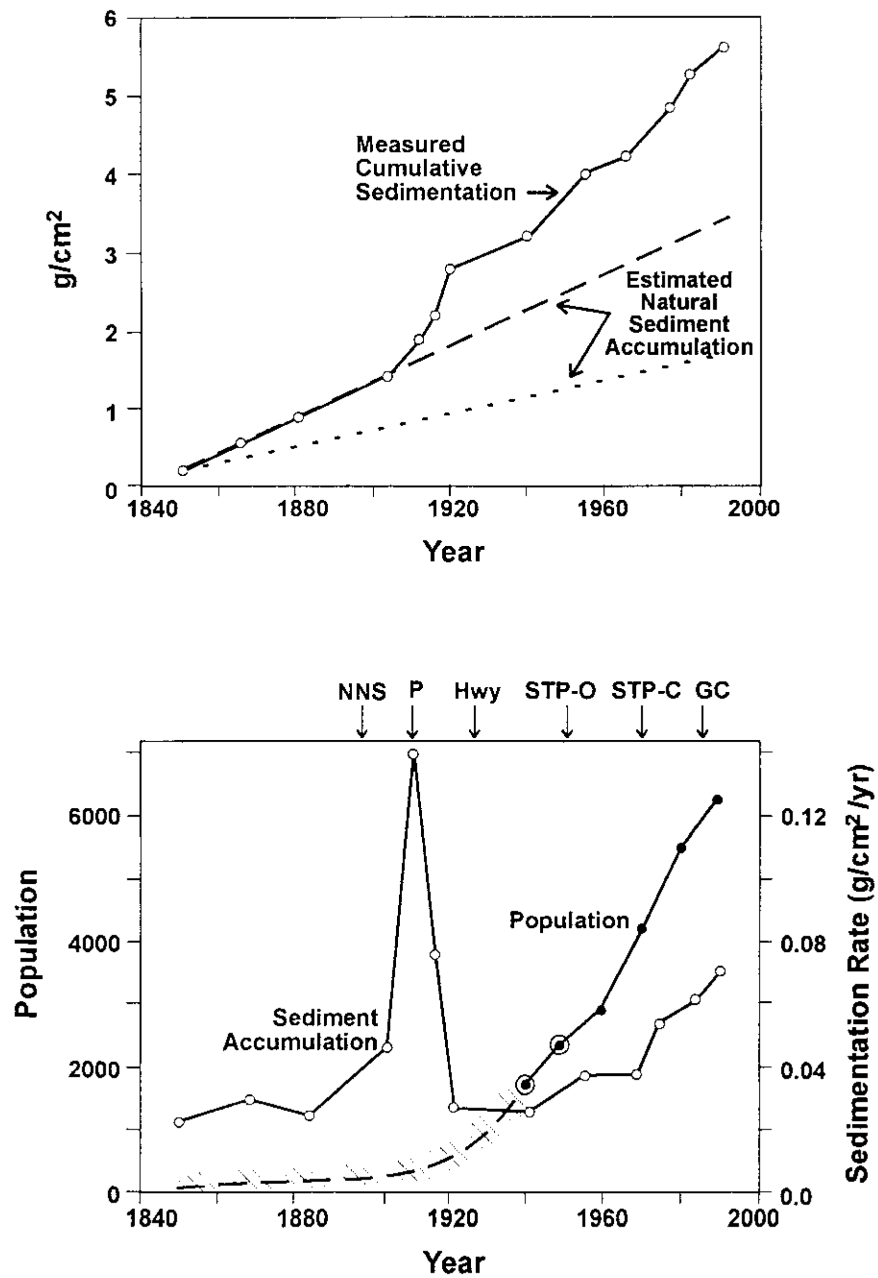

Figure 6. Major changes in the sediment history of Devils Lake as indicated by the sedimentation rate (—o—) compared to population ---•--- for the Lincoln City area. (a) The top panel shows the measured cumulative sedimentation for Devils Lake (solid line) compared to cumulative sedimentation under natural conditions assuming rates calculated from 1850 to 1900 using ^{210}Pb (middle line) and sediment accumulation calculated from ^{14}C dating techniques (bottom line). (b) Population for 1960 and later is based on census data for the city. Population for 1940 and 1950 was estimated as a percentage of Lincoln County census data. Population ranges prior to 1940 are estimates. The letters at the top refer to the following: [NNS] non-native settlement begins; [P] largest 3-day precipitation event recorded; [Hwy] highway to Devils Lake completed; [STP-O] sewage treatment plant begins discharging to lake; [STP-C] sewage treatment plant closed; [GC] first stocking of grass carp.

The sediment data suggest that the greatest changes in the biological characteristics of Devils Lake occurred in the last three decades, although the major physical changes occurred earlier in the century. However, the current trend in sedimentation rate indicates an accelerated rate of watershed erosion. If the rate of erosion continues to increase, it will cause a serious loss in lake volume over the next several decades. Unchecked sedimentation will continue to provide additional habitat for macrophytes by increasing the littoral area in the lake and resupplying macrophytes and phytoplankton with nutrients.

The increased sedimentation in Devils Lake may be typical of problems occurring in other Oregon coastal lakes. A number of these lakes have experienced changes in watershed activities similar to those reported here for Devils Lake leading to reported problems associated with eutrophication (Daggett et al. 1996). For other lakes, the pressure to log and develop the forested watersheds is more recent. The results from Devils Lake indicate that future problems in these coastal lakes could be minimized by initiating more aggressive programs to control accelerated erosion and nutrient export from the watersheds. Failure to control these activities will result in further loss of lake volume and increased likelihood of problems associated with eutrophication.

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