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Sediments of Newnans Lake: Characteristics and patterns of redistribution following a short-term drawdown [Phase II]

Johan F. Gottgens

and

Thomas L. Crisman

Department of Environmental Engineering Sciences
A.P. Black Hall, University of Florida
Gainesville, Florida 32611

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EXECUTIVE SUMMARY

The impact of lowering water level (by short-term drawdown) on deposition and redistribution of organic sediments was studied in eutrophic Newnans Lake, Florida. Sediment transfer was determined by matching marker horizons in pre-drawdown cores with those in cores taken at the same sites after water level returned to normal. These horizons were located by radio-isotope analysis or by direct field evidence of distinct stratigraphy. An average of 6.1 g $m^{-2}day^{-1}$ (N=3) of organic material eroded from the littoral zone by lowering the water depth from 62 to 30 cm for 8 weeks. Littoral sediments with low bulk density eroded fastest and bulk density of remaining substrate increased by an average of 250%. Short-term drawdowns can greatly enhance resuspension of fine littoral substrate. A record of redistribution of this material to the deeper portions of the lake was unclear. Of six profundal sites analyzed for this study, two showed evidence of sediment deposition due to drawdown. Since resuspension of fine sediments influences the ecology of a lake through habitat alteration, release of nutrients, high turbidity and enhanced oxygen demand, erosion processes must be considered when drawdowns are attempted. Finally, data from Phase I and Phase II of this work are summarized and recommendations for the management of Newnans Lake are provided.

INTRODUCTION

Water level drawdown is a well-established lake management technique. In Florida, it has been used to influence the extent and composition of the vegetated littoral zone (Holcomb and Wegener, 1971; Hestand and Carter, 1975, Tarver, 1980), to enhance sportfish populations (Wegener and Williams, 1974), and to consolidate flocculent littoral sediment (McKinney and Coleman, 1980). Increased invertebrate standing crop has been attributed to water level drawdown (Wegener et al. 1974) and positive effects of fluctuating water levels on nesting and feeding of some species of wading birds has been suggested (Ogden et al. 1980).

In the spring of 1989, a 90-day drawdown of Newnans Lake (FL) was initiated to promote oxidation and compaction of exposed littoral substrate (Krummrich, pers. comm.). The lake, located in north-central Florida has a surface area of approximately 3000 ha (Table 1) and maximum and mean depth of 3.6 and 1.5 m respectively (Nordlie, 1976). A largely undeveloped drainage area north of the lake supplies surface water inflow via Hatchet Creek, Little Hatchet Creek, and several smaller streams. Newnans Lake has a single surface water outlet, Prairie Creek, which meanders south through extensive marsh and bottomland hardwood communities. Outflow through this creek has been regulated with a spillway since 1967. This 50 m long structure consists of removable stoplogs down to the channel bed. The crest of the dam is 1.4 m above this bed. The spillway has reduced seasonal water level fluctuations in the lake and altered water quality of the discharge (Gottgens and Crisman, 1992). The drawdown was initiated by removing all stoplogs in the spillway. A description of Newnans Lake and its watershed can be found in Phase I of this report (Gottgens and Crisman, 1992) and, more detailed, in an earlier review (Gottgens and Montague, 1987).

Table 1. Morphometry of Newnans Lake, Florida.

Surface Area	3042	ha
Maximum Depth	3.6	m
Mean Depth	1.5	m
Development of Shoreline	1.09	
Drainage Basin Area	308	km^2
Lake Volume	$58x10^6$	m^3
Lake Detention Time	0.6	yrs

Management problems in this shallow, productive lake include dense growths of filamentous algae and, at times, abundant macrophytes dominated by exotics such as water hyacinth (Eichhornia crassipes) and hydrilla (Hydrilla verticillata). Sportfish populations have declined and black crappie (Pomoxis nigromaculatus) has been extirpated (Florida Game and Fresh Water Fish Commission, 1982-1989). Furthermore, the lake bottom is covered with a homogeneous layer of highly flocculent, organic sediment (Holly, 1976; Skoglund, 1990). Unconsolidated sediments such as these are easily resuspended (Sheng and Lick, 1979) resulting in increased turbidity in the water column and reduced light penetration. Deposits of flocculent sediment in the littoral zone eliminate firm substrate for plant growth and fish spawning (Bruno, 1984). Periodic resuspension of sediment can also produce increases in inorganic nutrients in the overlying water (Holdren and Armstrong, 1980; Pollman, 1983) and contribute to algal blooms. Finally, organic turbidity may exert considerable oxygen demand, which stresses heterotrophic communities in the lake and promotes rapid nutrient influx from the sediments (Mortimer, 1971; Theis and McCabe, 1978).

The intent of the partial drawdown was to correct some of these management problems. Oxidation and compaction of exposed littoral sediment might improve the establishment of desirable littoral plant communities and create better fish habitat in terms of refuge and spawning sites. Other anticipated effects of the drawdown included flushing of resuspended material through the outflow and redistribution of sediment in the lake. Phase I of this study (Gottgens and Crisman, 1992) included data analysis and discussion relative to the impact of the drawdown on the flushing of organic matter and nutrients from Newnans Lake. This report, Phase II, quantifies the removal and redistribution of material from profundal and littoral sediments. Redistribution may occur when low water levels during drawdown increase wave action on littoral substrate. This results in enhanced physical resuspension of bottom material followed by gravitational settling of the entrained particles in deeper areas (Bengtsson et al. 1990). This "sloughing" of material in the lake following drawdown has not been quantified previously. Finally, data from Phase I and II are combined here documenting both the total removal of organic matter, nitrogen, and phosphorus from the lake, as well as the redistribution of these materials in the lake following partial drawdown.

These data may be helpful to evaluate the utility of lake level drawdown for restoration programs in Florida lakes and to make comparisons with other management measures designed to reduce organic matter and nutrient levels in aquatic ecosystems.

METHODS

Removal and redistribution of lake bottom material due to drawdown was investigated using two series of nine sediment cores. Marker horizons were identified in the cores from profiles of bulk density, ^{210}Pb, ^{137}Cs, organic matter and nutrient content or from direct field evidence of distinct stratigraphy. Gain or loss of sediment at each site was then quantified by matching marker horizons between pre- and post-drawdown cores.

A. Collection of sediment cores.

Figure 1 shows the location of the cores. A Loran (Si-Tex, 797) was used to insure agreement in location of pre- and post-drawdown sampling sites. Additionally, triangular compass measurements with permanent landmarks were used for the littoral cores. Specifics of the core locations are given in Table 2. Latitude and longitude records are relative to the calibration site located near the southwestern boat ramp (Figure 1). The accuracy of this Loran to return to a sampling site is limited to a range of approximately 20 meters. This inherently results in error when comparing pre- and post-drawdown sediment stratigraphy. This error is reduced when in-lake variability between nearby sites, in terms of water depth and bottom stratigraphy, is low. This may be the case in Newnans Lake with its rather flat bottom topography (Holly, 1976) and homogeneous deposits of soft sediment (Skoglund, 1990). Additionally, by matching several marker horizons between cores, rather than one single horizon, error may be further reduced.

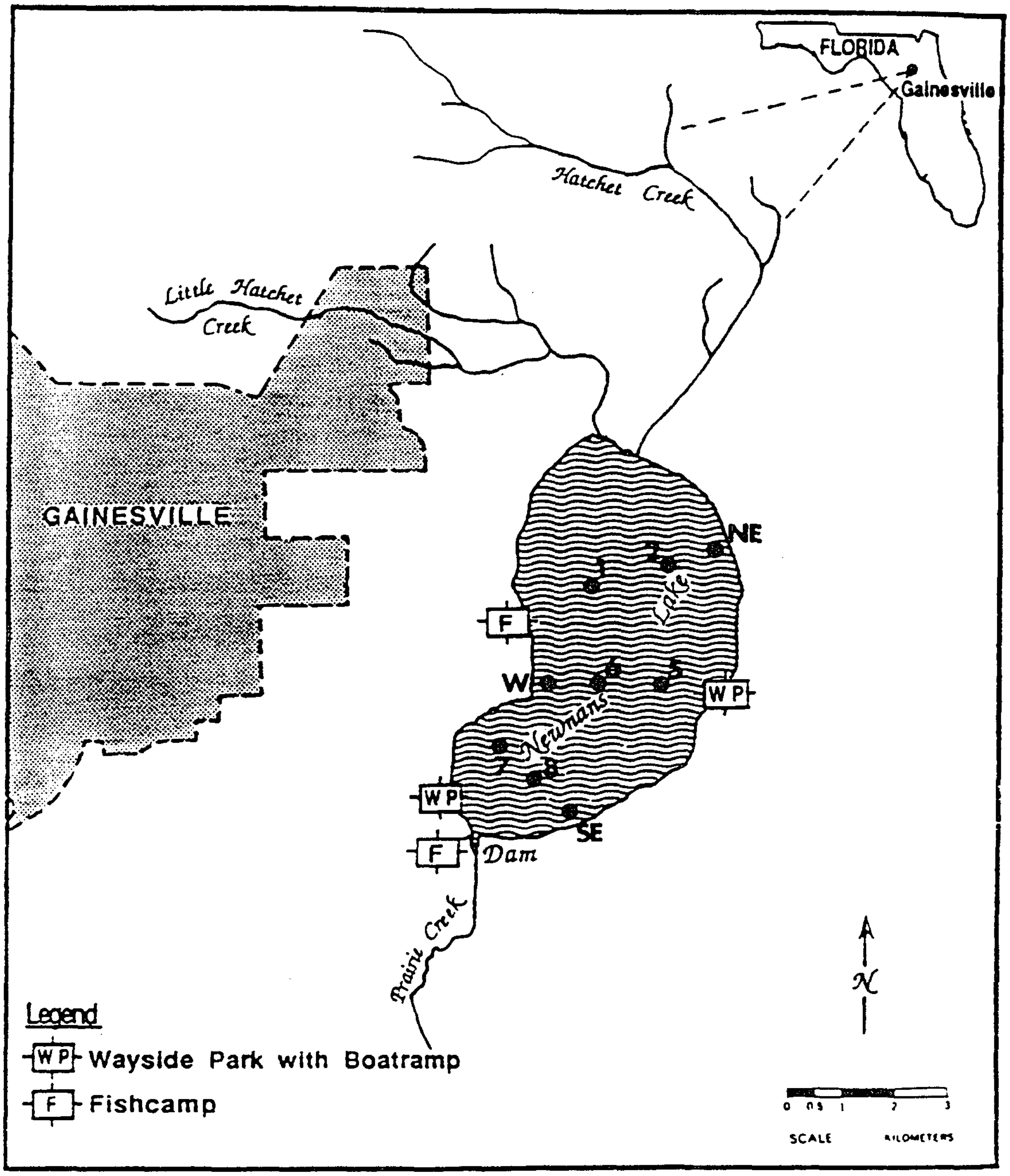

Figure 1. Map of Newnans Lake with core locations indicated.

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Cores were collected using a Livingstone piston corer (Livingstone, 1955) equipped with 4.1 cm diameter cellulose buterate tubes. The piston was positioned at the lower end of the coring tube which was then lowered to the level at which sampling was to commence. During this operation the piston cable was payed out freely, but once the sampling level was reached the cable was secured to the boat to prevent the piston from moving any farther down. The tube was driven into the sediments by pushing on the extension rod while the piston prevented the sample from being compressed or lost upon retrieval. After the apparatus was hoisted to the surface, appropriate caution was exercised to preserve the sediment-water interface. Visual observations of the cores were made in the field and again during sectioning in the laboratory to detect changes in sediment color or texture which could serve as marker horizons. Cores were kept refrigerated until sectioning.

B. Bulk density and nutrient analyses.

The cores were sectioned in 1 cm intervals to a depth of 30 cm, into 2 cm intervals from 30 to 80 cm depth, and into 4 cm intervals below that. The sections were sealed in plastic zip-lock bags and stored in a refrigerator. Bulk density, organic matter content, total Kjeldahl nitrogen (TKN), and total phosphorus (TP) were determined at intervals that were selected to give a representation of the entire core profile. Bulk density (mg/cm^3) and organic matter content (mg/mg) were determined on 1 cm^3 subsamples for as many as 45 intervals per core. Bulk density was measured by drying of subsamples at 95 ^0C for 24 hours, cooling under desiccation and weighing. Organic matter content was estimated by weight loss on ignition at 550 ^0C for 1 hour, followed by rehydration with distilled water and re-drying at 95 ^0C for 24 hours. TKN was measured using a Technicon II semi-automated manifold after digestion following Bremner and Mulvaney (1982), but modified to exclude selenium as catalyst. The digestate was also used for TP determinations. Liberated ortho-phosphate was determined with the ascorbic acid method (A.P.H.A., 1985) using a Milton Roy spectrophotometer (Model 20) with a 1-cm light path. Between 15 and 20 intervals per core were analyzed for these nutrients.

C. Radio-isotope analyses.

Marker horizons from measurement of ^{210}Pb and ^{137}Cs levels throughout the core profiles may also aid in a determination of sediment redistribution during drawdown. ^{210}Pb profiles have been reliable in documenting sediment removal due to major storm surges (Robbins et al. 1978). Pennington (1981) recorded variations in ^{137}Cs profiles in a shallow lake resulting from episodic sediment redistribution and deposition. Bengtsson et al. (1990) successfully used settling sediment traps to investigate redistribution of fine sediments in Swedish lakes. Maintaining suspended sediment traps in the water column, however, was not an option in a public use lake, such as Newnans.

Use of ^{210}Pb and ^{137}Cs in the determination of depositional markers has additional significant benefits, because such profiles permit the calculation of the age of deposited material in the cores (Eakins and Morrison, 1978; Appleby and Oldfield, 1983). ^{210}Pb in lake sediments results from two sources. First, a baseline ^{210}Pb concentration is maintained ("supported") by continued decay of ^{238}U through a series of short-lived intermediate isotopes. Second, "unsupported" ^{210}Pb is derived from ^{222}Rn emanation from the earth's crust and subsequent atmospheric fall-out. ^{222}Rn is a daughter isotope in the ^{238}U series and decays to ^{210}Pb within 10 days (Eakins and Morrison, 1978). This unsupported ^{210}Pb decays rapidly downward in the core (Goldberg, 1963) according to its half-life (22.26 years).

^{137}Cs was introduced to the atmosphere in 1954 with the advent of atomic nuclear weapon testing. Maximum fall-out levels occurred generally around 1963 (Ritchie et al. 1973). As such, measurement of levels of this isotope may produce a fixed reference point in the core. Interpretation of the previously undocumented sedimentary record in Newnans Lake will produce insight into past conditions of the lake and how it has responded to alterations. In particular, the effect of the installation of an outflow control structure on material transfer between water and sediment was analyzed with the use of ^{210}Pb and ^{137}Cs profiles (Gottgens and Crisman, in review).

Between 8 and 16 ^{210}Pb and ^{137}Cs measurements were made depending on the length of the core. ^{210}Pb and ^{137}Cs concentrations were measured by direct gamma assay. The counting system used for spectral analysis is located at the University of Florida's Department of Environmental Engineering Science's Low Background Counting Room. This room was designed to reduce the level of background radiation interference during sample counting. A diagram of the counting system is provided in Figure 2. Shield specifics (model SPG-16, Applied Physical Technology, Inc.) include an outer shield (0.95 cm steel), main shield (10.1 cm lead) and inner lining (0.05 cm cadmium + 0.15 cm copper). The N-type coaxial intrinsic-germanium detector (Princeton Gamma Tech, Inc.) has a 38% efficiency (@ 1332.5 keV) and is connected to a 32 liter liquid-nitrogen dewar to provide necessary cooling. This thin-window (beryllium), standard detector has a relatively low efficiency resulting in the need for long count times. This type of detector, however, counts over a large range of gamma energies, is suitable for many different sample configurations, and therefore more generally useful. It also detects efficiently other gammas from the ^{238}U decay series and can thus be used to determine supported and unsupported levels of ^{210}Pb simultaneously (Nagy, 1988). The electronics include a pre-amplifier (RG11B/C, Princeton Gamma Tech, Inc.), amplifier (TC 242, Tennelec), bias supply (5 kV, TC 950, Tennelec), power supply (TC 909, Tennelec), and transformer (Sola). A Zenith (Z159) computer with multi-channel analyzer ("Maestro" ADCAM 100,

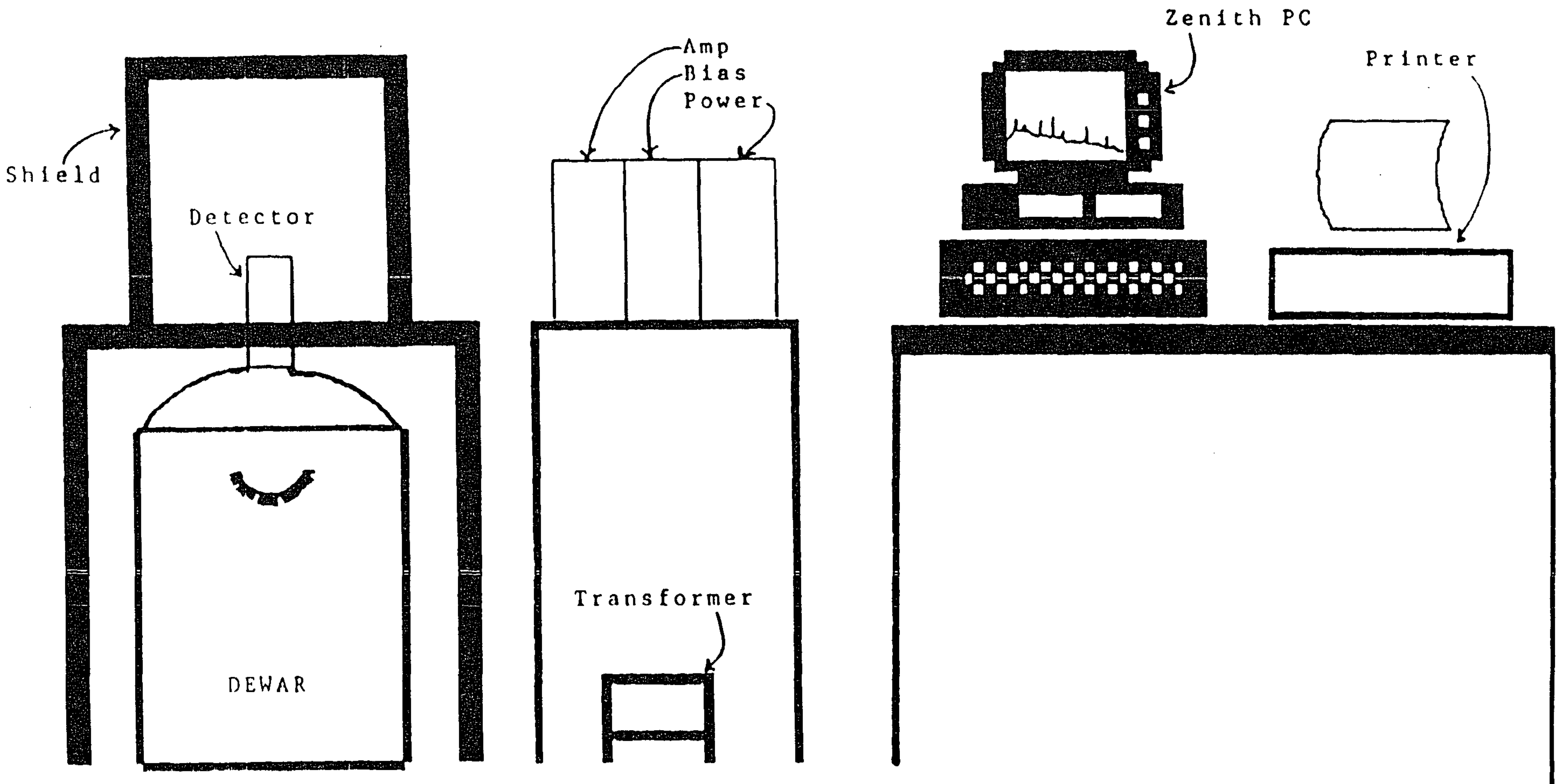

Figure 2: Diagram of the counting system at the Department of Environmental Engineering Sciences, University of Florida. (See text for specifics.) (after Nagy, 1988)

EG & G Ortec) and mathematical spreadsheet (Quattro, Borland Inc.) was used for data conversion and analysis.

Samples for isotope analyses were dried at 95 ^{0}C for 24 hours, pulverized by mortar and pestle, weighed, and placed in small plastic petri-dishes (#1006, Falcon, CA). All residual material was used and core sections were combined (up to 4 cm) to obtain an adequate sample weight (generally more than 1 gram). Petri-dishes were sealed with plastic cement and archived for 14 days to equilibrate radon with radium. Counting times varied from 14 to 45 hours depending on the weight of the sample; small samples need longer counting times to reduce uncertainty. A blank was counted for every two samples to determine background levels of radiation. Standards were run with the same frequency to track efficiency (counts/gamma) and calculate a radium conversion factor (pCi/cps). The sample spectra were analyzed for activity in the 46.5 keV (^{210}Pb) and 662 keV (^{137}Cs) peaks. Activities at 295 keV (^{214}Po), 352 keV (^{214}Pb), and 609 keV (^{214}Bi) representing uranium series peaks were used to compute supported levels of ^{210}Pb. Error prediction followed nuclear statistics (Knoll, 1979) assuming a Poisson distribution for the recorded counts.

RESULTS AND DISCUSSION

Littoral cores

Two series of three littoral cores were taken; northeast, southeast and west cores (see Figure 1). Pre-drawdown cores were taken when water depth averaged 62 cm. Following the drawdown and natural rise of the water level to pre-drawdown stage the second series of three cores were taken at the same locations. Water level at these sites was lowered from 62 to 30 cm for 8 weeks during the drawdown. Sand underlying flocculent brown substrate served as suitable marker. Sediment depth to sand decreased by an average of 42% after drawdown (Figure 3) and bulk density of the remaining substrate increased by an average of 250% at all three sites (Figure 4). Organic matter, TKN, and TP (expressed as weight/weight ratio) decreased at two of the three littoral zone sample sites following drawdown. Analogously, the amount of organic matter overlying the sandy littoral bottom was reduced (Figure 5). Calculated removal rates are given in Table 3.

Table 3. Material removal rates from littoral cores during drawdown, Newnans Lake, Florida.

Removal rates	NE	SE	W	Units
Organic matter	3.52	14.71	0.0	g $m^{-2}day^{-1}$
TKN	0.14	1.58	0.01	g $m^{-2}day^{-1}$
TP	0.01	0.11	-0.02	g $m^{-2}day^{-1}$

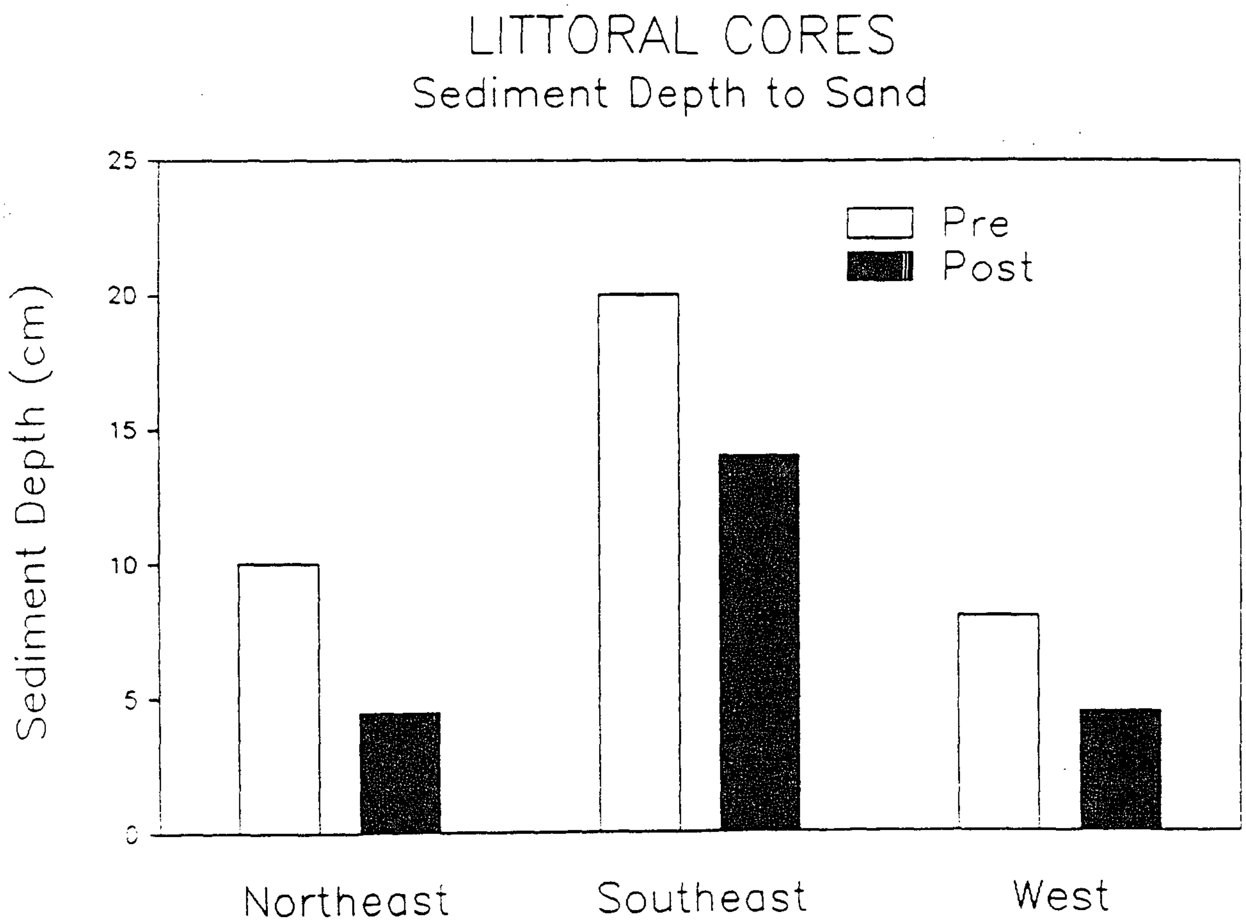

Figure 3. Sediment depth to sand in littoral cores.

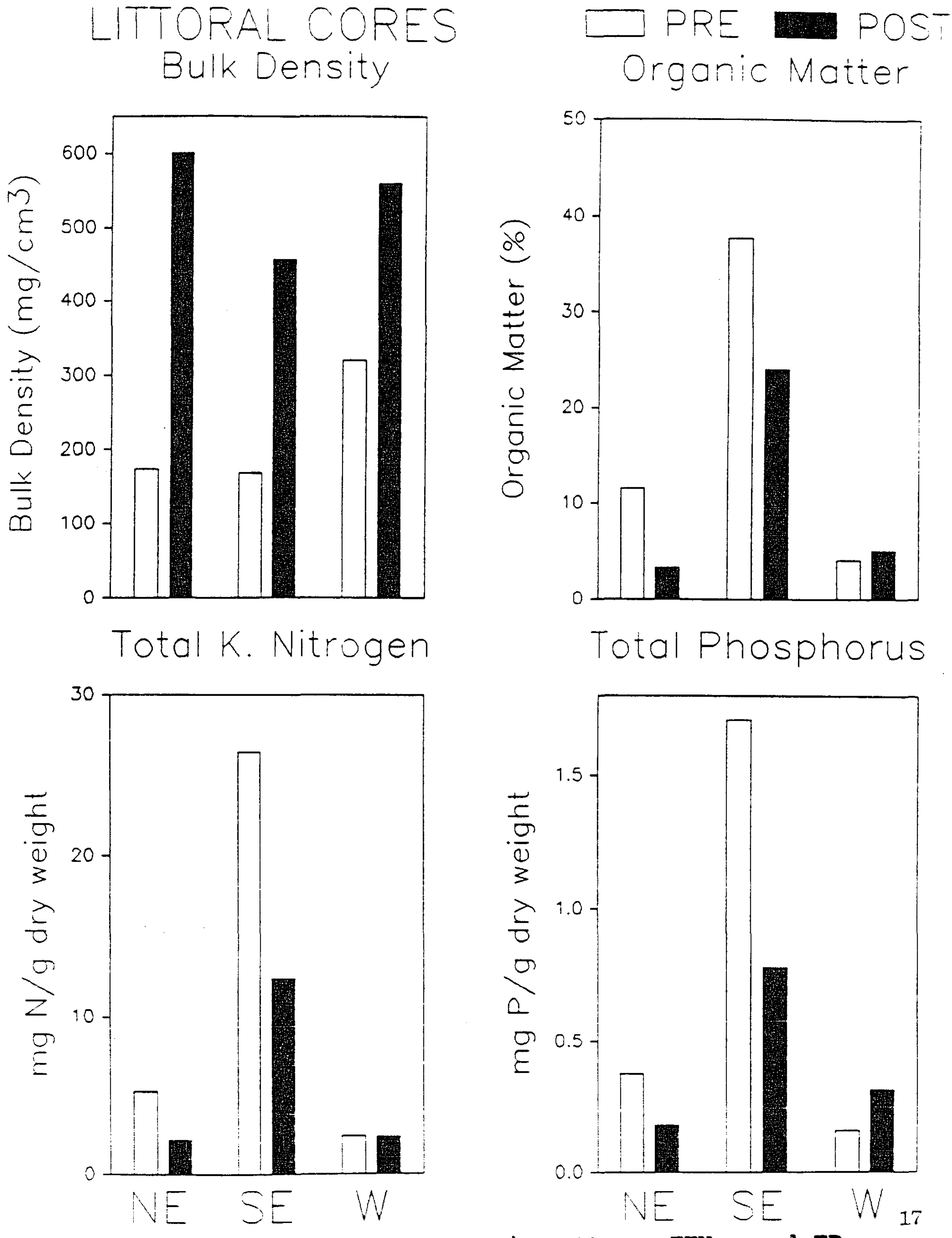

Figure 4. Bulk density and organic matter-, TKN-, and TP-content of littoral cores.

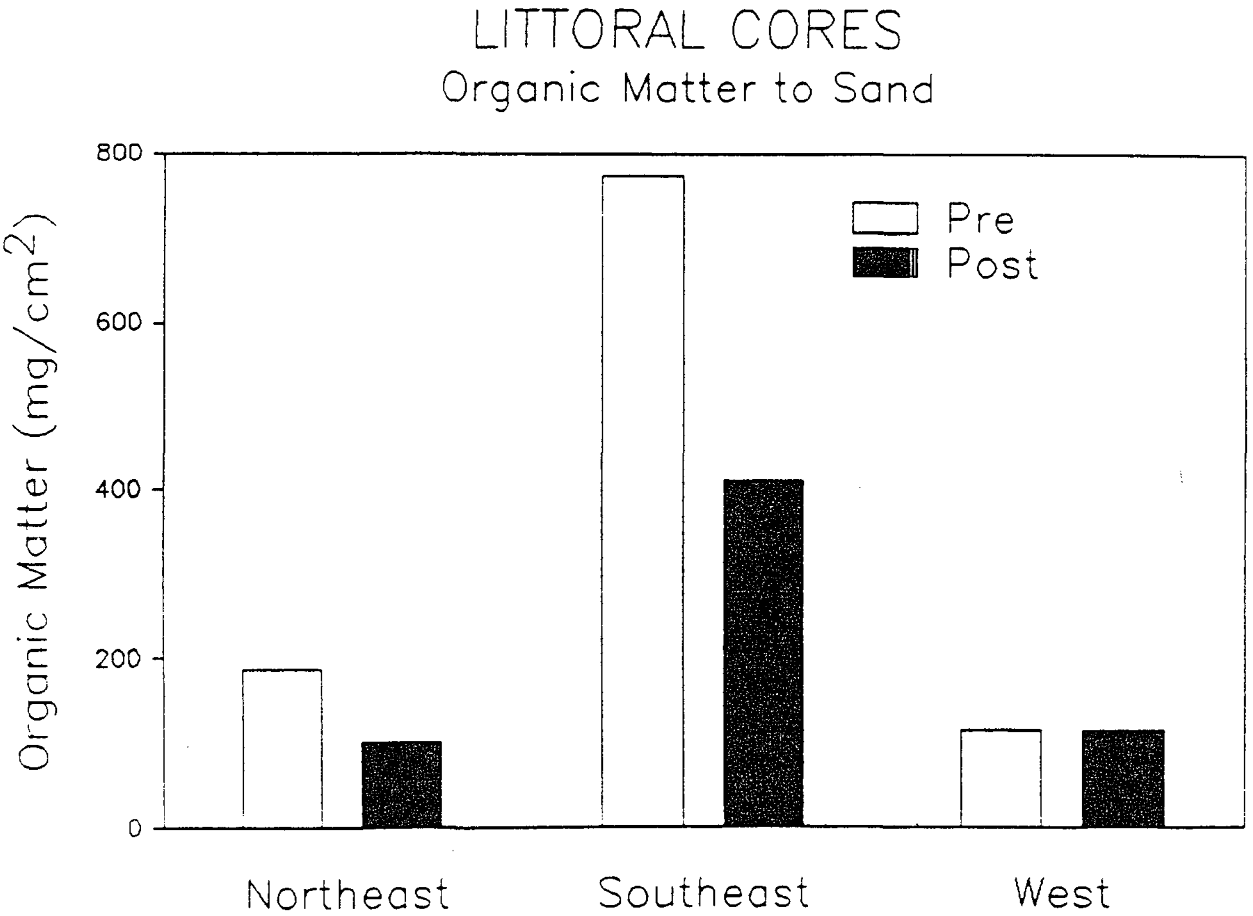

Figure 5. Amount of organic matter to sand in littoral cores.

Removal rates from the west core deviated from the observed pattern. This may have been due to the location of this station in a rather quiet littoral cove, which was less subject to wind-wave action. Sediment depth to sand (in cm) decreased at this site following drawdown, but no removal of organic matter (in mg cm^{-2}) was noted. These observations may be interpreted in two ways. First, sediment thickness may have decreased without actual removal of material due to consolidation of the substrate at this site. This appears unlikely, since this location remained inundated by at least 30 cm of water at all times. Second, erosion of material did in fact occur, resulting in the observed increased bulk density of the remaining substrate at this site. However, eroded organic material may have been replaced by net primary production during the period of drawdown. The measured increased organic matter and total phosphorus content at this site (Figure 4) support this interpretation. Enhanced primary productivity of benthic algae is likely at low water depth during the drawdown when more light may reach the littoral bottom during quiescent periods. This is particularly plausible at the relatively protected west core site.

Removal of sediment from littoral sites likely resulted from increased wind-wave action on this substrate at low water levels during drawdown. That is, such wave action produces vertical oscillations in the water column which normally attenuate with depth (Mortimer 1974; cf. Wetzel, 1983), but are able to erode flocculent littoral substrate at extreme low stages. Waves are largely wind-induced, although wake from boat traffic may also be considerable in this public-use lake. The resulting physical resuspension of bottom material may be followed by transport and settling of the entrained particles in deeper areas. As such, material can be redistributed from the littoral zone to profundal substrate.

With no removal of organic matter at the western core site, the amount of organic matter was not significantly different between the total number of pre- and post-drawdown cores although the northeast and southeast cores demonstrated a considerable reduction (Figure 5). The reduction in thickness of the sediment layer and the increase in bulk density following drawdown, observed at all three sites, were statistically significant (α=0.05, paired-t). The assumption in the study was that these three sites are representative of the littoral zone. A different approach may be to make many, simple to perform, measurements of sediment-thickness-to-sand throughout the littoral zone pre- and post-drawdown. Such sampling will statistically better represent the entire littoral zone, but with will not provide data on removal rates of bulk sediment, organic matter and nutrients.

Profundal cores

Cores 1 and 11.

Cores 1 (pre-drawdown) and 11 (post-drawdown) were taken at a central location in the northern half of the lake (see Figure 1). The flocculent nature of surface sediment at this site (and all other sites) did not permit accurate determination of water depth. It was estimated at 150 cm by carefully lowering a Secchi disk until contact between the disk and bottom substrate was noticed. The lengths of core 1 and 11 were respectively 129 and 148 cm. Material in the cores consisted of homogeneous, black muck of low bulk density (< 100 mg cm^{-3} up to a depth of 80 cm).

Figure 6 (left panel) shows the matching profiles for cores 1 and 11 for bulk density, organic matter, unsupported ^{210}Pb, ^{137}Cs, TKN, and TP. During sectioning in the laboratory, the first occurrence of clay was noted at 120 cm (core 1) and 132 (core 11). This indicates an addition of 12 cm of material to the profile at this station during drawdown. Profiles for bulk density and organic matter content revealed a second marker at a depth of 82 cm (core 1) and 94 cm (core 11). This also indicates a gain of 12 cm during drawdown.

Unsupported ^{210}Pb and ^{137}Cs profiles, however, did not indicate an addition of material. TKN and TP profiles were inconclusive as nutrient levels fluctuated widely. Average TKN concentrations in the top 120 cm of cores 1 and 11 were 33 and 27 mgN g^{-1}dry weight

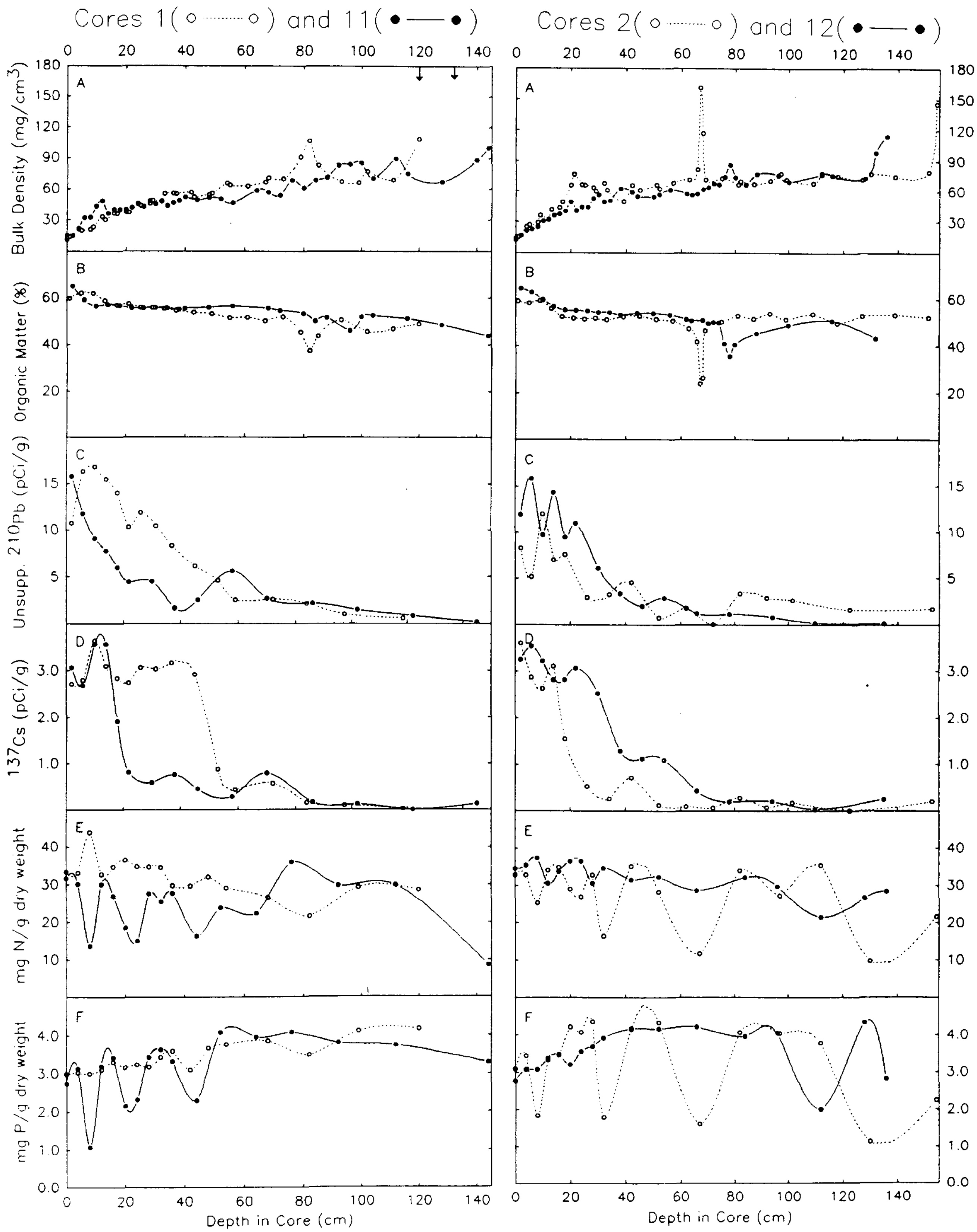

Figure 6. Depth profiles for Newnans Lake cores. Left panel; cores 1 (pre-drawdown, dashed line) and 11 (post-drawdown, solid line). Right panel; cores 2 (pre-drawdown, dashed line) and 12 (post-drawdown, solid line). Arrows indicate sand or clay horizons observed during core sectioning. A, bulk density in mg cm^{-3}; B, organic matter content in mg mg^{-1}; C, unsupported Pb-210 in pCi g^{-1}; D, Cs-137 in pCi g^{-1}; E, total Kjeldahl nitrogen in mg g^{-1} dry weight; and F, total phosphorus in mg g^{-1} dry weight.

respectively. TP levels averaged 3.4 and 3.0 mgP g^{-1}dry weight. In summary, profiles for cores 1 and 11 did not demonstrate a distinct removal or gain of bottom material due to drawdown.

Cores 2 and 12.

Cores 2 (pre-drawdown) and 12 (post-drawdown) were taken at a 200 cm deep station in the northern half of the lake (Figure 1). Total core lengths were 155 and 140 cm respectively and extracted material consisted of soft black muck. Bulk density and organic matter profiles (Figure 6, right panel) revealed clear markers at 68 cm pre-drawdown and 78 cm after the drawdown. Peaks and drops in the unsupported ^{210}Pb and ^{137}Cs profiles displayed a similar gain of approximately 10 cm of material in the post-drawdown core. Pre-drawdown (core 2) peaks in the ^{210}Pb profile at depths of 10, 18, and 44 cm occurred in the post-drawdown core (12) at 16, 24, and 54 cm. A similar gain was evident from the ^{137}Cs profiles.

The combined data indicated a gain of 8-10 cm during drawdown at this station. Based on the bulk density of the top 10 cm layer of the post-drawdown core, this gain is equivalent to 0.15-0.20 g cm^{-2}. This translates into an additional 0.8-1.3 years of sediment deposition during the 245-day drawdown period compared to normal, non-drawdown sedimentation rates (discussed later). TKN and TP profiles were inconclusive. TKN levels generally fluctuated between 25 and 35 mgN g^{-1}dry weight with a few measurements below 20 mgN g^{-1}dry weight. Averages for both cores approximated 32 mgN g^{-1}dry weight and corresponded to levels in cores 1 and 11. Fluctuations in TP were pronounced with an average concentration between 3.0 and 3.5 mgP g^{-1}dry weight.

Cores 5 and 15.

Cores 5 (pre-drawdown) and 15 (post-drawdown) were taken at a station in the east-central part of the lake (Figure 1), 50 m northwest of a fish attractor. Water depth was 170 cm. Lengths of retrieved cores 5 and 15 were 113 and 92 cm respectively. Visual analysis of the cores during sectioning demonstrated distinct sand layers at depths of 85 and 113 cm for core 5 and at 76 cm for core 15. First occurrence of clay was at 95 cm (core 5) and 86 cm (core 15). Based on these marker horizons a removal of 9 cm during drawdown is indicated.

Evidence from the core profiles was less clear (Figure 7, left panel). Bulk density and organic matter profiles appeared to display a phase difference of a minimum of 10 cm also indicating material removal during drawdown. Unsupported ^{210}Pb and ^{137}Cs profiles indicated a distinct removal of approximately 8 cm during drawdown. TKN and TP profiles both showed material removal of variable magnitude.

These lines of evidence support an interpretation that a minimum of 8 cm has been removed from the sediment profile during

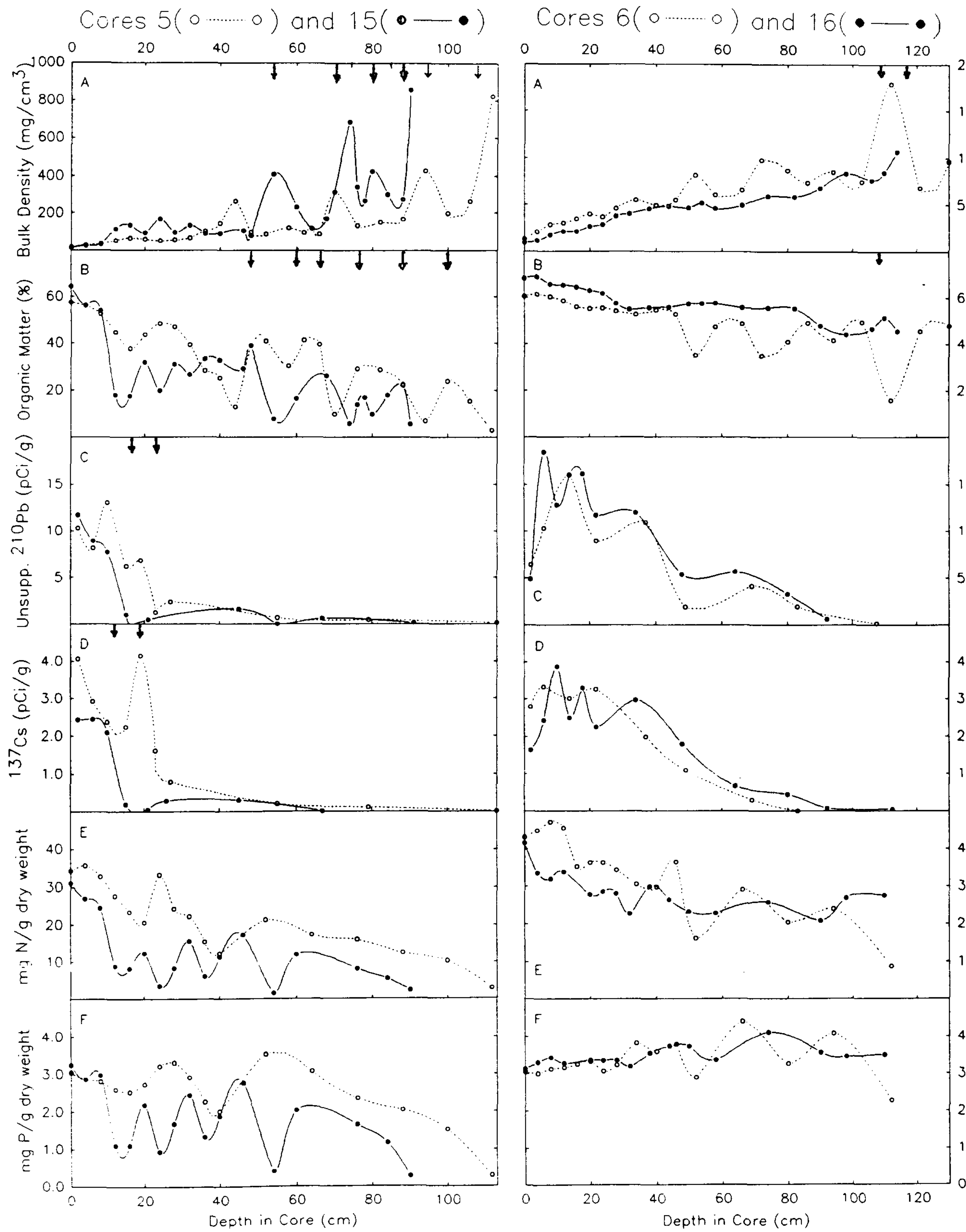

Figure 7. Depth profiles for Newnans Lake cores. Left panel; cores 5 (pre-drawdown, dashed line) and 15 (post-drawdown, solid line). Right panel; cores 6 (pre-drawdown, dashed line) and 16 (post-drawdown, solid line). Arrows indicate sand or clay horizons observed during core sectioning. A, bulk density in mg cm^{-3}; B, organic matter content in mg mg^{-1}; C, unsupported Pb-210 in pCi g^{-1}; D, Cs-137 in pCi g^{-1}; E, total Kjeldahl nitrogen in mg g^{-1}dry weight; and F, total phosphorus in mg g^{-1}dry weight.

drawdown. This equates to 0.26 g cm^{-2} or approximately 4.7 years of sediment removal at this site during drawdown (see below). The profiles also demonstrated the different character of the substrate at station 5-15 compared with other sampling sites. Bulk densities were significantly higher throughout the profiles, while organic matter and nutrient concentrations were depressed compared with deposits at similar depths in other locations. Field observations concurred with these data in that substrate appeared more firm, with a relatively high sand content.

Cores 6 and 16.

Cores 6 (pre-drawdown) and 16 (post-drawdown) were taken in the central portion of the lake (Figure 1) at a water depth of 150 cm. Core lengths were 135 and 115 cm respectively, with core contents consisting of black, soft muck. Sectioning of the core in the laboratory revealed a clay horizon in core 6 at 135 cm, well below the bottom section of core 16.

Bulk density and organic matter profiles (Figure 7, right panel) showed a rather homogeneous top 100 cm for both cores containing flocculent material (bulk density<100 mg cm^{-3}), with an organic matter content averaging 60% (weight/weight ratio). Firmer substrate started at 105 cm depth in the pre-drawdown core and at approximately 110 cm depth post-drawdown. A horizon of inorganic material is encountered first at 105 cm depth in core 6. This layer may have occurred immediately below the last sampled segment in core 16.

Isotope profiles for both cores displayed an identical shift in phase of several centimeters, while nutrient profiles appeared inconclusive. Average TKN and TP levels coincided with cores 1-11 and 2-12 (30 mgN g^{-1}dry weight and 3.0-3.5 mgP g^{-1}dry weight).

In summary, the six profiles provide weak support for the conclusion that some 5 cm of material was deposited at this site during drawdown. This equates to 0.054 g cm^{-2} or approximately 0.04 years of sedimentation in excess of "normal" sedimentation occurring during the period of drawdown (see below).

Cores 7 and 17.

Cores 7 (pre-drawdown) and 17 (post-drawdown) were taken in the southern part of the lake about 400 m south of Palm Point, a conspicuous strip of land extending into the lake (Figure 1).

Water depth at this station was 118 cm. Lengths of cores 7 and 17 were 135 and 148 cm respectively. Core sectioning in the laboratory demonstrated 1 m of black, soft, organic muck overlying a distinct firm, sandy layer in both cores. Water and organic matter content increased again below this layer. This was reflected in the bulk density and organic matter profiles at this sample site (Figure 8, left panel).

Unsupported ^{210}Pb and nutrient profiles for pre- and post-drawdown cores were also very similar. Average TKN and TP

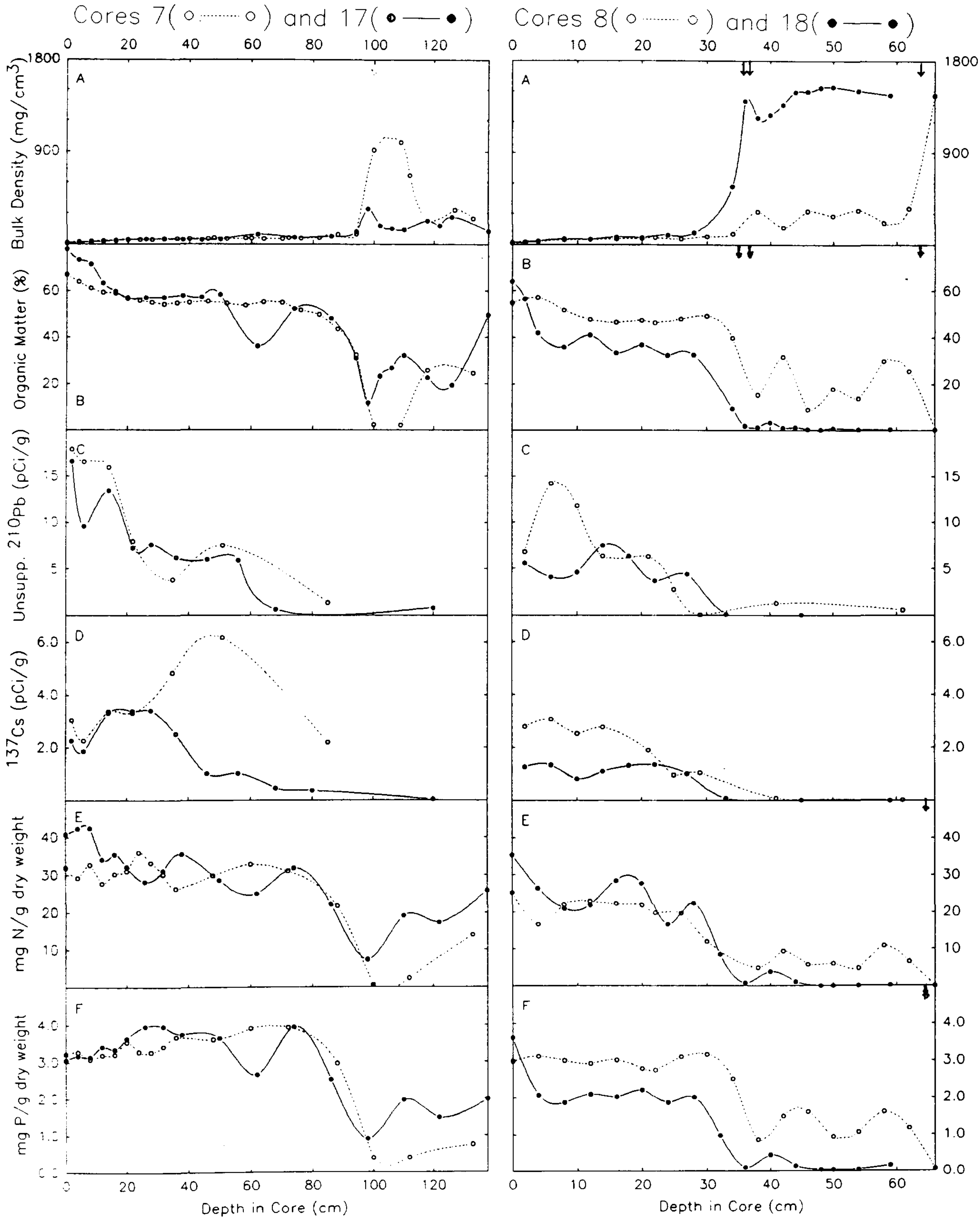

Figure 8. Depth profiles for Newnans Lake cores. Left panel; cores 7 (pre-drawdown, dashed line) and 17 (post-drawdown, solid line). Right panel; cores 8 (pre-drawdown, dashed line) and 18 (post-drawdown, solid line). Arrows indicate sand or clay horizons observed during core sectioning. A, bulk density in mg cm^{-3}; B, organic matter content in mg mg^{-1}; C, unsupported Pb-210 in pCi g^{-1}; D, Cs-137 in pCi g^{-1}; E, total Kjeldahl nitrogen in mg g^{-1} dry weight; and F, total phosphorus in mg g^{-1} dry weight.

concentrations in the top 100 cm corresponded to levels found in other cores (except site 5-15). ^{137}Cs activity was greatly elevated below 35 cm in core 7. Further testing of this material is underway in order to provide an explanation for this discrepancy.

In summary, the distinct similarity between other pre- and post-drawdown profiles for this core station points to the absence of significant redistribution of material here.

Cores 8 and 18.

Cores 8 (pre-drawdown) and 18 (post-drawdown) were taken in the central location of the lake's southern half (Figure 1) at 115 cm depth. Lengths for cores 8 and 18 were 72 and 61 cm respectively. During core sectioning, minor sand was encountered at 38 cm in core 8, with a clear, pronounced sand layer at 64 cm. Core 18 showed clear sand at 36 cm. Both the bulk density and organic matter profiles displayed these markers (Figure 8, right panel) with bulk density values in excess of 1200 mg cm^{-3} and organic matter content less than 5%. Likewise, TKN and TP concentrations approached zero at 65 (core 8) and 36 cm (core 18). Evidence from these four profiles would suggest that approximately 28 cm of material eroded from the profile at this station during drawdown.

The absence of the ^{210}Pb peak in the top 10 cm of the post-drawdown core also suggested such removal, but to a much lesser extent. Analogously, elimination of the ^{137}Cs peak in the top 20 cm of deposits in core 18 and the onset of detectable levels of this radionuclide about 10 cm deeper in the pre-drawdown profile imply removal of material during drawdown.

Such massive removal rates, however, seem implausible in light of the small flushing rates of particulate matter through the nearby outflow which were recorded during drawdown (Gottgens and Crisman, 1992). It is more likely that either the exact location of the pre- and post-drawdown cores did not match or that a significant disturbance of the sediment profile occurred at this station during drawdown. In light of these conflicting lines of evidence, no inference on gain or removal of bottom material at this site should be made.

Table 4 summarizes rates of removal or gain of material for the profundal sampling stations. The 245-day time-period covered starts immediately prior to removal of the spillway until the natural return of the water level to pre-drawdown levels following spillway re-installation. Consequently, out of six profundal cores analyzed for this study, two showed evidence of added sediment deposition during drawdown, one showed no gain or loss, one showed removal, and two were inconclusive. No conclusion can, therefore, be reached by this study's data regarding flocculent sediment accumulation in the profundal zone of Newnans Lake during the drawdown.

Table 4. Profundal cores: Gain/removal (-) rates of organic matter (g $m^{-2}day^{-1}$), TKN (g $m^{-2}day^{-1}$), and TP (mg $m^{-2}day^{-1}$).

Average gain/ removal(-) rate	Core station 1-11	2-12	5-15	6-16	7-17	8-18
Organic matter	*	4.33	-5.89	1.54	0.0	*
TKN	*	0.23	-0.29	0.09	0.0	*
TP	*	19.2	-30.5	9.5	0.0	*

*) no clear record or conflicting evidence.

Lowering the water depth from 62 cm to 30 cm for 8 weeks reduced the thickness of the flocculent sediment layer at all three littoral stations. Bulk density of the remaining substrate increased by an average of 250%. Removal rates of organic matter averaged 6.1 g $m^{-2}day^{-1}$ (0-14.7) for the three littoral cores that were analyzed. These results suggest that littoral zone sediment removal may be a lakewide phenomenon, although analysis of a larger number of cores is required to statistically show it.

Erosion of littoral sediments during drawdown likely results from increased shear stress produced by wind- and wave action. Such surface waves generate periodic oscillations in the water column, which attenuate with water depth (cf. Wetzel, 1983) but may reach the sediment-water interface in shallow water. When this stress exceeds the bulk shear strength of the surficial deposits, sediment resuspension occurs (Lick, 1982). Resuspended material may then be moved from shallow to deeper parts in the basin by water currents (Davis and Ford, 1982; Håkanson, 1982; Bengtsson et al., 1990) and, eventually, settle where water depth is sufficient to eliminate stress from wind- and wave action. Hydrodynamics in the lake, particularly during a drawdown, may alter this pattern of redistribution.

While sediment removal from the littoral zone was indicated by the results of this study, a quantitative record of this transfer to profundal sites was difficult to obtain. This is particularly true when profundal substrate consists of a thick pack of near homogeneous material without clear marker horizons. Furthermore, the small drop in lake level during this drawdown, resulting in only 13% of newly exposed lake bottom (Gottgens and Crisman, 1992), does not create large areas of erosion in the littoral zone. This reduces the magnitude of potential redistribution of sediments in the lake which reduces the signal in profundal core profiles.

Using the ^{210}Pb profiles, sedimentation rates can be computed for each profundal station. Calculations follow the Constant Rate of Supply Model (Goldberg, 1963; Appleby and Oldfield, 1983). As such, the cumulative residual unsupported ^{210}Pb, A_t, beneath sediments of age t varies according to

$$A_t = A_0 \, e^{-kt} \tag{1}$$

where A_0 = total residual unsupported ^{210}Pb (pCi cm^{-2})

k = ^{210}Pb radioactive decay constant

A_t and A_o are calculated by numerical integration of the ^{210}Pb profile. The age of sediments of depth x is then given by:

$$t = \frac{1}{k} \ln \frac{A_0}{A_t} \tag{2}$$

The sedimentation rate (r) can then be calculated directly (Appleby & Oldfield, 1978):

$$r = \frac{kA_t}{C} \tag{3}$$

where C = concentration of unsupported ^{210}Pb (pCi/g) in layer of interest.

These accumulation rates may then be compared to the gain or loss of material at those sites due to drawdown. As such, this gain or loss is equated to a time period of "normal" sedimentation. For instance, the gain of material due to drawdown at station 2-12 is equivalent to 1.1 years of sedimentation (Table 5).

Table 5. Newnans Lake profundal cores: Comparisons of recent (5 yrs. B.P.) dry-sediment accumulation rates with gain/loss (-) of material during drawdown, and with calculated dry-sediment accumulation rates

Core site	Recent dry-sed.acc.rts. ($g\ cm^{-2}yr^{-1}$)	Gain/loss during drawdown ($g\ cm^{-2}$)	Gain/loss during drawdown (yrs) 1)	Calc.recent sed.acc.rts. 2) ($g\ cm^{-2}yr^{-1}$)	Cumulative residual uns.^{210}Pb ($pCi\ cm^{-2}$)
1-11	0.06	*	*	0.05	30.2
2-12	0.10	0.17	1.10	0.10	26.4
5-15	0.07	-0.26	-4.70	0.07	17.4
6-16	0.08	0.05	0.04	0.07	28.0
7-17	0.06	0.00	-0.70	0.05	27.0
8-18	0.07	*	*	0.07	18.9

*) no clear record or conflicting evidence.
1) sedimentation normally occurring during the 245 days between pre- and post measurements is subtracted.
2) Using a model developed by Binford and Brenner (1986). Measured average cumulative residual unsupported ^{210}Pb=24.65 $pCi\ cm^{-2}$; Flux for ^{210}Pb-fallout=0.77 $pCi\ cm^{-2}yr^{-1}$.

Because inferences were made from ^{210}Pb profiles in different aspects of this work, an assessment of the level of confidence in these profiles is appropriate. This is particularly pertinent when profiles are established in soft lake sediment with the potential of disturbance in the chronology of deposits. Three independent observations aid in such an assessment.

First, recent ^{210}Pb based deposition rates are not statistically different (α=0.05; two-tailed correlated test) from calculated values using an earlier, independently developed model (Binford and Brenner, 1986) (Table 5). In this model fallout ^{210}Pb is used as a dilution tracer to compute net accumulation rates of any material in surface mud according to

$$r = F_{210Pb} \times A^{-1} \qquad (4)$$

where F_{210Pb} = the flux of fallout ^{210}Pb (pCi $cm^{-2}y^{-1}$)

A = the activity of ^{210}Pb in the sediment sample (pCi g^{-1}dry weight)

Furthermore, the different cores from Newnans Lake have comparable ^{210}Pb residuals (i.e. total residual unsupported ^{210}Pb contents) despite differences in accumulation rates (Table 5). The ^{210}Pb residuals of the cores reflect the ^{210}Pb fall-out from the atmosphere. Since this fall-out lies in the range 0.5-0.9

pCi $cm^{-2}yr^{-1}$ (Nozaki et al. 1978), depending on locality, the ^{210}Pb residuals should lie in the range 16-30 pCi cm^{-2} (the ^{210}Pb radioactive decay constant=0.03114 yr^{-1}). This corresponds closely to the measurements in Newnans Lake cores (Table 5).

Second, recent ^{210}Pb based dry-sedimentation rates correlate well with water depth (R^2=0.81; N=5), when station 5-15 is excluded. The proximity of this site to a fish attractor and, hence, higher boat traffic and boat wake may disturb the sediments and depress sedimentation rates. Consequently, direct comparisons between this sampling site and others in the lake may be misleading. The close relationship between water depth and material accumulation rates is well-established (Evans and Rigler, 1980). Including the 5-15 site, 57% of the variability in dry-sedimentation rates is explained by depth of the water column. While this relationship does not necessarily underwrite the accuracy of recent ^{210}Pb levels, it does demonstrate that these levels correlate well with each other (i.e. their precision is supported).

Finally, counting statistics and error prediction were applied to the recorded unsupported ^{210}Pb data to compute statistical precision. "Error bars" associated with the experimental data are illustrated for cores 1 and 2 in Figure 9. Other cores showed a similar magnitude of error. The length of the error bar equals one standard deviation (σ) on either side of the point

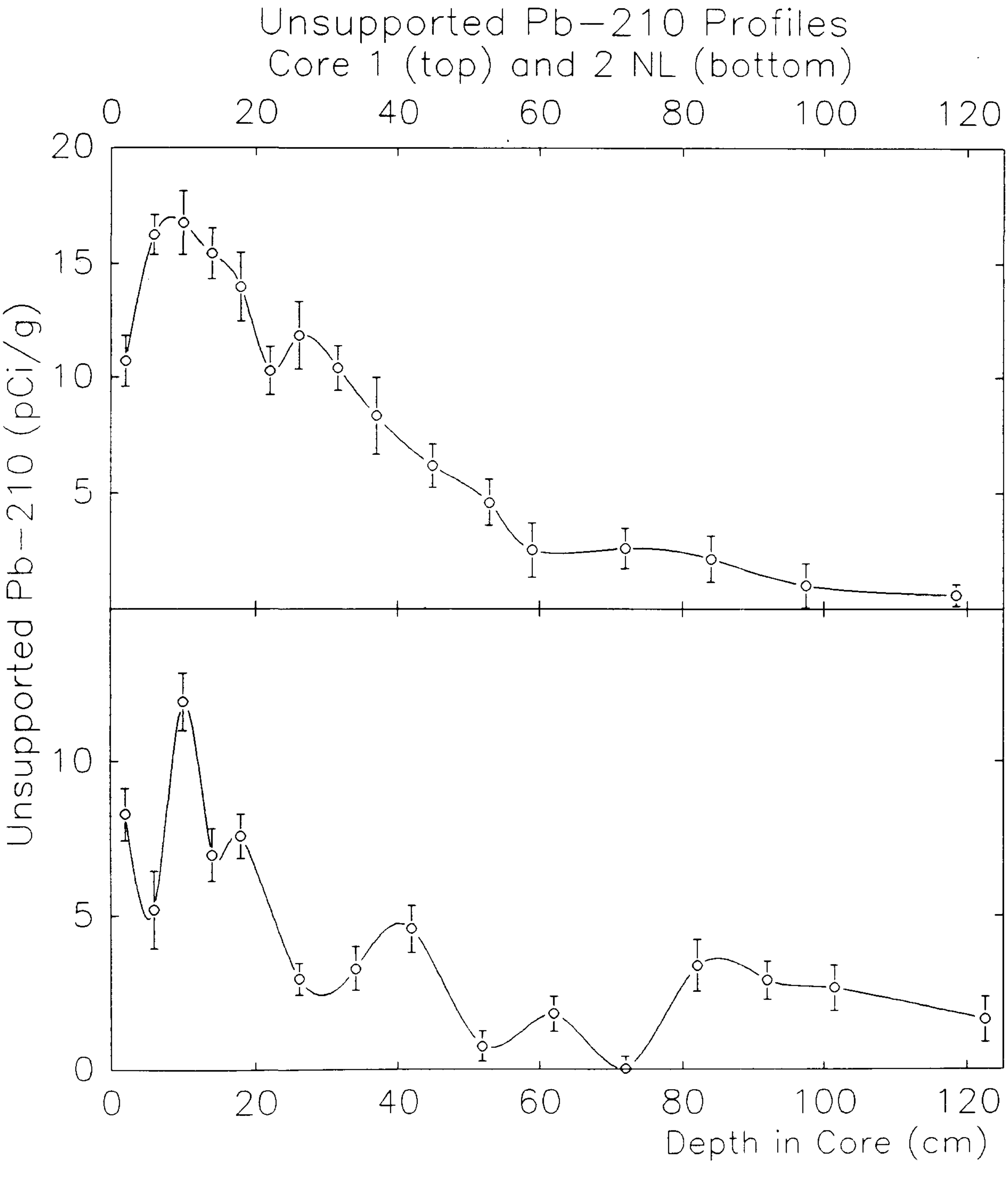

Figure 9. Unsupported Pb-210 profiles for core 1 (top) and core 2 (bottom). The length of the error bar equals 1σ on either side of the data point (see text for explanation).

(i.e. 68.3% confidence limits), which is standard practice in expressing uncertainty in nuclear measurements (Wang et al. 1975). Because the recorded counts in nuclear counting experiments follow a Poisson distribution (Knoll, 1979), the predicted standard deviation is the square root of the mean number of counts. To arrive at this mean (counts/hr), samples were counted from 14 to 45 hours depending on sample weight. Since

$$\textit{Net counts} = \textit{Total counts} - \textit{Background counts} \tag{5}$$

uncertainty in the net counts is propagated according to

$$\sigma_n = \sqrt{(\sigma_t^2 + \sigma_b^2)} \tag{6}$$

where σ_n, σ_t, and σ_b are, respectively, the standard deviations of the net count, total count, and background count.

The effect of the computed uncertainties on the interpretation of the profile in terms of marker horizons or sediment accumulation rates is small. For instance, recent sediment accumulation rates for core 1 vary between 0.049 and 0.055 g $cm^{-2}yr^{-1}$ when mean unsupported ^{210}Pb concentrations (5 years B.P.) plus and minus 1 σ respectively are substituted into equation (4). The same rates for core 2 ranges from 0.085-0.105 g $cm^{-2}yr^{-1}$. An uncertainty analysis for entire profiles will demonstrate the level of precision of assigned dates for sediment layers (Gottgens, in prep.).

SUMMARY AND RECOMMENDATIONS: PHASE I AND II

1. A short-term drawdown of shallow, algal dominated Newnans Lake (FL) was initiated in the Spring of 1989. Objectives of the drawdown included flushing of accumulated nutrient-rich deposits from the lake bottom and promoting oxidative removal of organic matter and consolidation of flocculent substrate in exposed littoral sediments. In order to lower the lake level, all stoplogs from the spillway which controls the single surface-outflow from the lake, were removed for 90 days. During the drawdown the water level in the lake remained near record-low stage for a period of 8 weeks. Approximately 20% of water volume was removed during drawdown. Small elevation gradients in the lake basin and the gradual build-up of obstructions in the lake outlet upstream and downstream from the spillway since its construction likely prevented a more dramatic drawdown of water level (personal observation). This study was concerned with (1) the flushing of particulate organic matter and nutrients in surface discharge from the lake during drawdown, (2) the effect of exposing littoral sediment to air on net oxidative removal of organic matter, and (3) the resulting removal and redistribution of organic matter and nutrients from profundal and littoral sediments.

2. During the drawdown approximately 60 metric tons (dry weight) of material were flushed from the lake in excess of base-discharge. This equals 1.61 g m^{-2} (bottom surface) of

particulate organic matter (0.31 gTKN m^{-2} and 10.0 mgTP m^{-2}) during the 90-day drawdown period (Figure 10). This removal is very low compared to the stores of flocculent sediment in the lake. It is, however, accomplished at minimal cost, since drawdowns are unquestionably among the least expensive lake management techniques (Cooke et al. 1986). Data from Phase I of this study (Gottgens and Crisman, 1992) suggest that higher lake stage at the start of the drawdown, resulting in increased hydraulic head and flow through the lake system, enhances removal. Storms stirred the water column and promoted flushing of resuspended matter. In Florida, high lake stages are common in early Spring when evapo-transpiration is low, and maximum wind velocities between October and May are approximately 30% greater than between June and September (Maceina and Soballe, 1990). Thus, short-term drawdowns during March-May have the highest probability of leading to improved lake conditions in Florida. Such drawdown are most appropriate in shallow, exposed lakes where downstream areas are able to absorb high particulate matter loadings during the period of flushing.

3. In situ and laboratory tests did not demonstrate net oxidative removal of organic matter from exposed areas of the lake bottom. Net production of organic matter was observed in field enclosures. Increased organic matter content ranged from 0.78 to 5.92 g $m^{-2}day^{-1}$ (Figure 10). Consolidated sediments remained moderately firm after reflooding in a laboratory

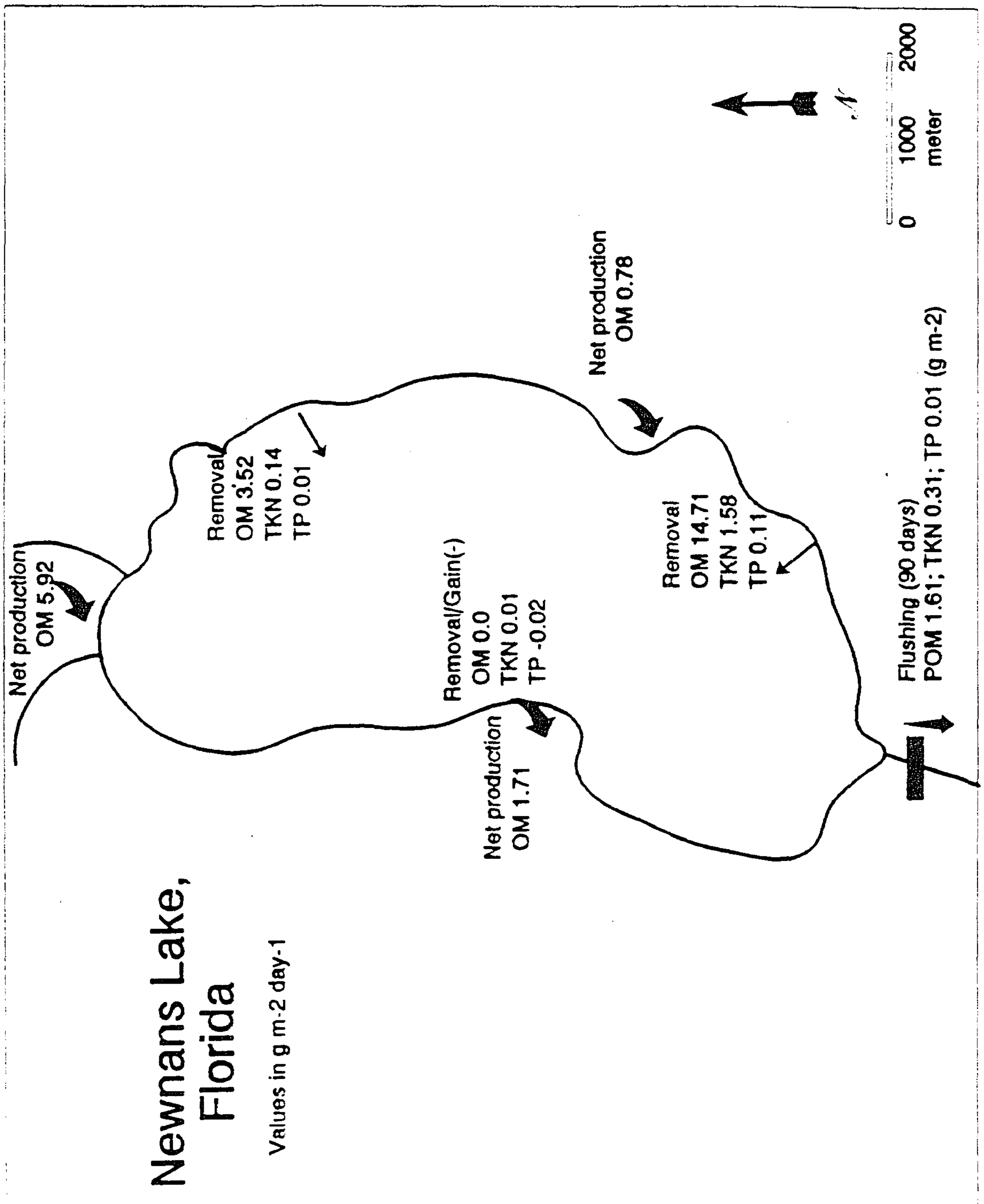

Figure 10. Diagram of Newnans Lake (FL) indicating levels of net production of organic matter on exposed littoral substrate, removal of organic matter/TKN/TP from littoral zone, and flushing of particulate organic matter/TKN/TP through outflow owing to drawdown.

experiment. This might provide improved habitat for rooted macrophytes and fish spawning in the littoral zone. Effective in situ consolidation of littoral muck, however, would require a more extreme drawdown. Observations in other Florida lakes indicate that substrate must be exposed for a minimum of five to seven months for significant consolidation to occur (Greening and Doyon, 1990). A shorter exposure time may result in the formation of a "cap" of dried organic material over unconsolidated wet sediments. This cap may then become dislodged and float to the water surface during and after refill of the lake. As was explained above, the likelihood of a natural drawdown of Newnans Lake to a stage lower than accomplished (i.e. 19.70 m MSL) is small. Dredging of the lake outlet to improve flow conditions and increase the amplitude of the drawdown may be unnecessary. Periodic removal of the dam under the above recommended conditions will likely scour the outflow to accommodate larger discharges and return this channel to its historic configuration.

4. Using marker horizons, deposition of material at profundal areas was demonstrated for two sample stations. One station showed no gain or loss, one showed removal, and two were inconclusive. Therefore, no general conclusion can be reached on whether sediment was removed or accumulated in the profundal zone during the drawdown. Redistribution of soft littoral substrate was recorded during drawdown. Although variability was high, an

average of 6.1 g $m^{-2}day^{-1}$ of organic matter (0.6 gTKN $m^{-2}day^{-1}$ and 32.3 mgTP $m^{-2}day^{-1}$) was removed from the littoral zone (Figure 10). Sediment depth to sand decreased at all three sites by an average of 42% after drawdown and bulk density of remaining substrate increased by an average of 250%. Removal of soft substrate from the littoral zone may promote rooted plant growth which may serve as nursery area and refuge for fish. In addition, such removal may improve littoral habitat for future sportfish spawning.

5. Despite the significance for lake management, redistribution of bottom material in lakes during drawdown has not been investigated previously. While removal of littoral substrate was measured relatively easily, a quantitative record of this transfer to profundal sites was difficult to obtain. This is particularly true when profundal substrate consists of a thick pack of near homogeneous material without clear marker horizons. The use of markers derived from measurements of bulk density, organic matter, radionuclides, and nutrients in this work has generated the first attempts to measure this material transfer. Two options may now be identified for further work. First, measurements limited to the littoral zone can be followed by calculations of deposition rates in the profundal if the extent of the zones of erosion, transport, and accumulation of sediment in the lake are known. Second, use of settling sediment traps to collect resuspended and transported material may provide

additional insight. In Newnans Lake, however, installation of these traps on the profundal bottom is difficult because of the soft nature of the substrate. Suspension of the traps in the water column may jeopardize public use of the lake. Instead, this technique may be used in other systems.

6. While short-term partial drawdowns during March-May can produce improved lake conditions in Newnans Lake, other options should also be considered in developing a lake management strategy. Examples of such options are a drastic drawdown using a system of water pumps, permanent removal of the spillway, modification of the spillway, and maintaining the current status. A lake management model using the data acquired in Phase I and Phase II of this project may be a cost-effective way of testing these management options. The model should express the best understanding of the effects of each of these options on criteria for multiple-objective management of the lake such as water clarity, level of primary production, availability of hard-bottom nesting areas for sportfish, extent of littoral zone, lake access, and others. When costs of management strategies are included, the model can evaluate them in terms of risks and benefits to intended uses of the lake.

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