SEDIMENT CHARACTERISTICS AND SEDIMENTATION RATES IN LAKE MICHIE, DURHAM COUNTY, NORTH CAROLINA, 1990-92

By J. Curtis Weaver

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLES

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ABSTRACT

A reservoir sedimentation study was conducted at 508-acre Lake Michie, a municipal water-supply reservoir in northeastern Durham County, North Carolina, during 1990-92. The effects of sedimentation in Lake Michie were investigated, and current and historical rates of sedimentation were evaluated.

Particle-size distributions of lake-bottom sediment indicate that, overall, Lake Michie is rich in silt and clay. Nearly all sand is deposited in the upstream region of the lake, and its percentage in the sediment decreases to less than 2 percent in the lower half of the lake. The average specific weight of lake-bottom sediment in Lake Michie is 73.6 pounds per cubic foot.

The dry-weight percentage of total organic carbon in lake-bottom sediment ranges from 1.1 to 3.8 percent. Corresponding carbon-nitrogen ratios range from 8.6 to 17.6. Correlation of the total organic carbon percentages with carbon-nitrogen ratios indicates that plant and leaf debris are the primary sources of organic material in Lake Michie.

Sedimentation rates were computed using comparisons of bathymetric volumes. Comparing the current and previous bathymetric volumes, the net amount of sediment deposited (trapped) in Lake Michie during 1926-92 is estimated to be about 2,541 acre-feet or slightly more than 20 percent of the original storage volume computed in 1935.

Currently (1992), the average sedimentation rate is 38 acre-feet per year, down from 45.1 acre-feet per year in 1935. To confirm the evidence that sedimentation rates have decreased at Lake Michie since its construction in 1926, sediment accretion rates were computed using radionuclide profiles of lake-bottom sediment. Sediment accretion rates estimated from radiochemical analyses of Cesium-137 and lead-210 and radionuclides in the lake-bottom sediment indicate that rates were higher in the lake's early years prior to 1962.

Estimated suspended-sediment yields for inflow and outflow sites during 1983-91 indicate a suspended-sediment trap efficiency of 89 percent. An overall trap efficiency for the period of 1983-91 was computed using the capacity-inflow ratio. The use of this ratio indicates that the trap efficiency for Lake Michie is 85 percent. However, the suspended-sediment trap efficiency indicates that the actual overall trap efficiency for Lake Michie was probably greater than 89 percent during this period.

INTRODUCTION

A number of reservoirs in North Carolina are primary water sources for municipalities, industries, and hydroelectric utilities. Some of these reservoirs also serve other purposes, such as flood control, low-flow augmentation, and recreation. Whatever the use, the depletion of storage as a result of sedimentation has serious consequences for a reservoir's beneficiaries.

Sedimentation is of particular importance to reservoir managers, who must plan for the eventual and inevitable loss of reservoir storage. Options include increasing or restoring capacity, reducing sediment inflow rates, or allowing the ultimate failure of a reservoir to occur while seeking a new source at an alternative site.

The major source of sediment in reservoirs in North Carolina is inflowing sediment from tributary streams. The average annual transport of suspended sediment by streams in the State ranges from less than 5 to more than 500 tons/mi^2. When bedload is included, estimates of total sediment transport can be several times higher (Simmons, 1988). Rates at the higher end of the range have caused significant and, in some cases, complete sedimentation of some smaller reservoirs in the State. The amount of sediment transported depends on factors such as soil type, land use and cover, land and channel slopes, watershed size, and the frequency and severity of floods. Transport rates can change as a result of changes in land use and cover and in response to erosion-control measures. Consequently, estimates of long-term sedimentation rates periodically must be reassessed.

Lake Michie is a 508-acre municipal water-supply reservoir on the Flat River in northern Durham County, North Carolina. The Flat River Basin is located in the northeastern Piedmont physiographic province and forms part of the headwaters of the Neuse River Basin which drains to the Atlantic Ocean (fig. 1). At Lake Michie Dam, the Flat River Basin is 167.2 mi^2 in area and occupies slightly more than 3 percent of the Neuse River Basin.

Since the completion of Lake Michie in 1926, several investigators have documented the sedimentation that has occurred (Eakin and Brown, 1939; Maki and Hafley, 1972). Others assessed the potential for and evidence of soil erosion in the Flat River Basin (Martin and Bass, 1940; U.S. Soil Conservation Service, 1983). The results of these investigations indicate that sedimentation rates have been declining and that land use and cover in significant areas of the drainage basin have changed from predominantly row-crop agriculture to reforested land.

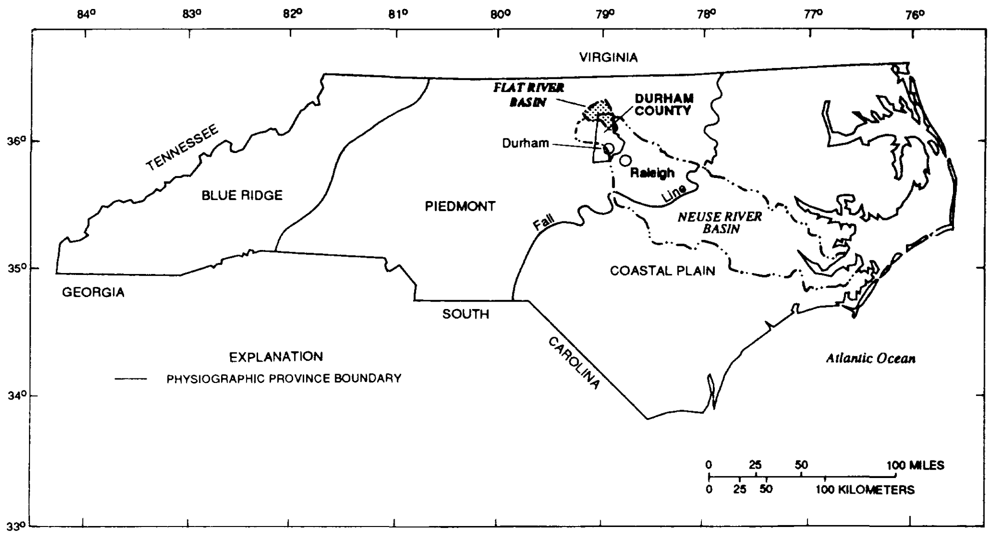
In 1990-92, the U.S. Geological Survey (USGS) conducted the most recent study of the effects of sedimentation on Lake Michie in cooperation with the City of Durham Department of Water Resources and the North Carolina Department of Environment, Health, and Natural Resources. This study focused on creating the first complete bathymetric map of the lake since its impoundment (Weaver, 1993), physically describing the sediment, and re-evaluating current and historical rates of sedimentation. The bathymetric map was published as a separate report (Weaver, 1993). The study relied on hydrologic data collected in the past for other programs, and on new data collected expressly to satisfy the immediate objectives.

Purpose and Scope

This report describes the characteristics of sediment in Lake Michie and presents estimates of current and historical sedimentation rates. The results discussed in this report were evaluated from a study of the effects of sedimentation on Lake Michie conducted during 1990-92.

To determine the characteristics of sediment in the lake, 12 cores of lake-bottom sediment were collected in June 1992 at locations ranging from the headwaters to the dam. Particle-size distributions completed for 11 of the cores were used to assess the relative composition of sand, silt, and clay in the sediment. The presence of organic matter in the sediment was analyzed by determinations of percentages by dry weight of total organic carbon (TOC) and nitrogen, and subsequently, carbon-nitrogen (C:N) ratios.

Current and historical sedimentation (deposition) rates were evaluated using three methods. Comparisons of the present reservoir storage capacity with those computed from previous surveys were used



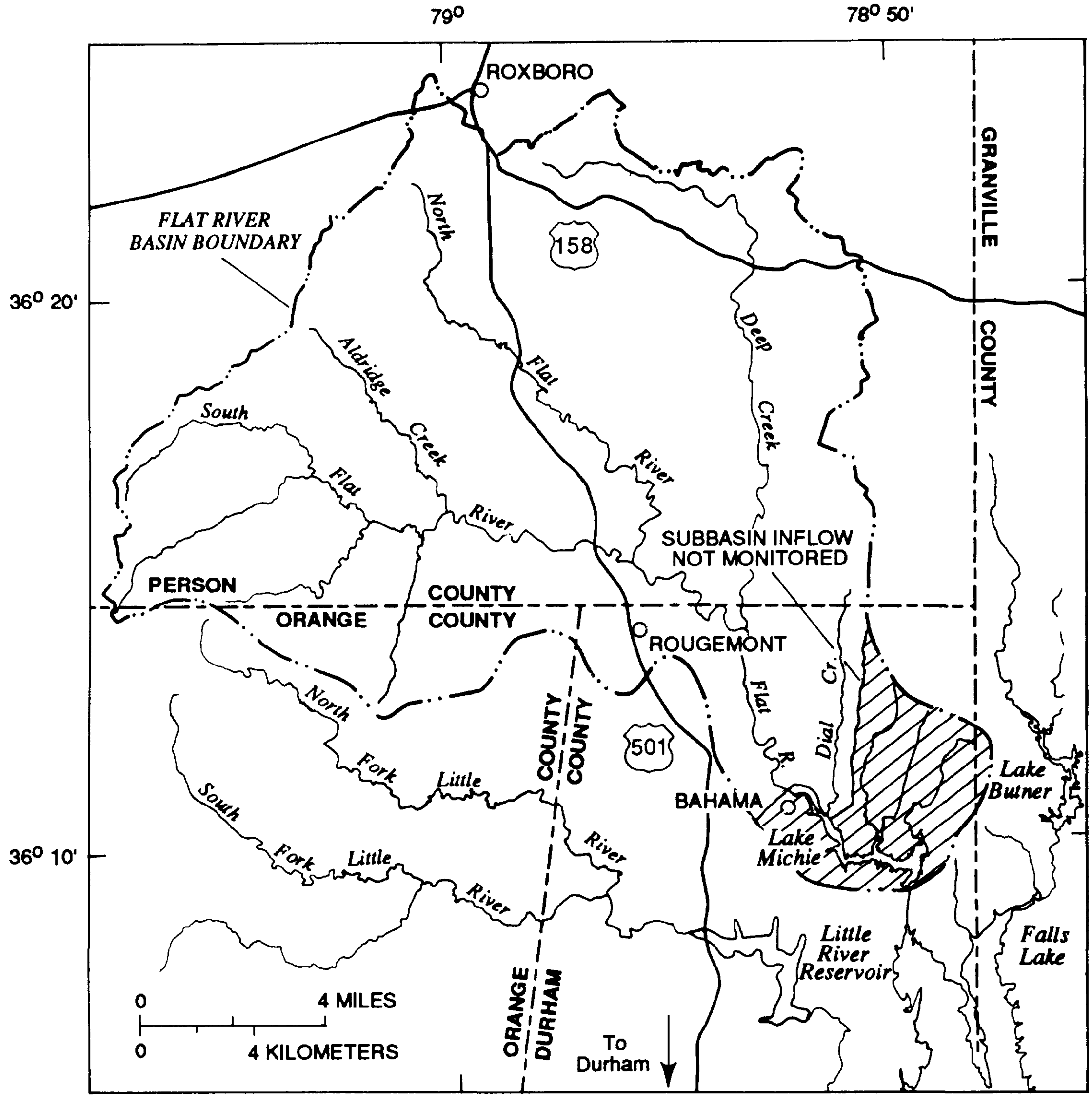


Figure 1. Location of Flat River Basin and surrounding area.

to determine the overall rates of storage depletion and the rates of sediment accretion at five cross sections in the lake. Next, analyses for cesium-137 (Cs-137) and lead-210 (Pb-210) radionuclides in the cores were made to estimate rates of sediment accretion at three different locations in the lake to indicate any changes in these rates over time.

Finally, the net transport of suspended sediment into and out of the lake during 1983-91 provided a basis for estimating the suspended-sediment trap efficiency. Historical suspended-sediment and streamflow data used for the Flat River gaging stations upstream and downstream from the lake, along with new data collected during 1990-91 at Dial Creek, provided a basis for estimating the net transport of suspended-sediment. An overall trap efficiency for Lake Michie during 1983-91 was computed using the capacity-inflow ratio.

Acknowledgments

The author thanks the City of Durham Department of Water Resources and the Department of Parks and Recreation for the use of their floating platform and storage facilities during data collection. The author is also grateful to Dr. Charles Paull and Mr. James Bisese of the Department of Geology at the University of North Carolina at Chapel Hill for providing helpful suggestions concerning the retrieval and analysis of lake-bottom sediment.

Collection and analysis of lake-bottom sediment were conducted under contract with the Department of Marine, Earth, and Atmospheric Sciences at North Carolina State University in Raleigh. The author appreciates the assistance of Mr. Stephen Snyder and Dr. David DeMaster in conducting these core retrievals and analyses.

DESCRIPTION OF STUDY AREA

Certain characteristics of reservoirs and their drainage basins are relevant to the distribution and sedimentology of lake-bottom deposits and to the rate of sediment delivery to the reservoir. This section describes the physical setting of Lake Michie and the Flat River Basin, and some of the factors that are important to an understanding of sedimentation in the lake.

Lake Michie

Lake Michie is in the northeastern Piedmont Province of North Carolina approximately 12 mi northeast of the city of Durham (fig. 1). The lake is an impoundment of the Flat River in a short, narrow valley where rock outcrops occur on some steep slopes. From its headwaters to the dam, Lake Michie is approximately 4.5 mi long and varies in width from less than 100 ft in the headwaters to about 1,200 ft one-half mile upstream from Lake Michie Dam. At the dam, the drainage area of the Flat River is 167.2 mi^2. At the USGS streamflow-gaging station on the Flat River at Bahama one-half mile upstream from Lake Michie, the drainage area is 149 mi^2 (fig. 2). The intervening 18.2 mi^2 drain into Lake Michie by way of a number of small streams that surround the lake, including Dial Creek, Dry Creek, and Rocky Creek (fig. 2).

The Lake Michie Dam is 960 ft long and consists of a concrete masonry section 660 ft long and a 300 ft long earth-fill section. The crest of the 300 ft long principal spillway within the concrete masonry section is 81 ft above the old channel bed of Flat River and is at an elevation of 341.0 ft above sea level (City of Durham, 1981). In late 1963, the elevation of the principal spillway was raised to its current level from an elevation of 340.0 ft.

Lake Michie began filling in April 1926 after completion of the dam, and initially overtopped the principal spillway in December 1926 (City of Durham, 1981). Lake Michie was the sole water-supply source for the city of Durham until 1988 when nearby Little River Reservoir, located 5 mi southwest of Lake Michie, began operating. In addition to water supply, Lake Michie has been used for hydroelectric-power generation for the city and is a popular recreational facility for many area residents.

Post-impoundment sediment deposits occur throughout the length of Lake Michie. Deposits range from 12 to 15 ft thick upstream from the Secondary Road (SR) 1616 bridge to about 5 ft thick near the dam (fig. 2). Upstream from the SR 1616 bridge, the lake-bottom is highly dynamic and can change more than a foot in elevation as a result of scour and deposition during floods. In the area adjacent to the boat house and dock (fig. 2), sediment deposited across the lake bottom has resulted in a terrain consisting of mild to gentle slopes.

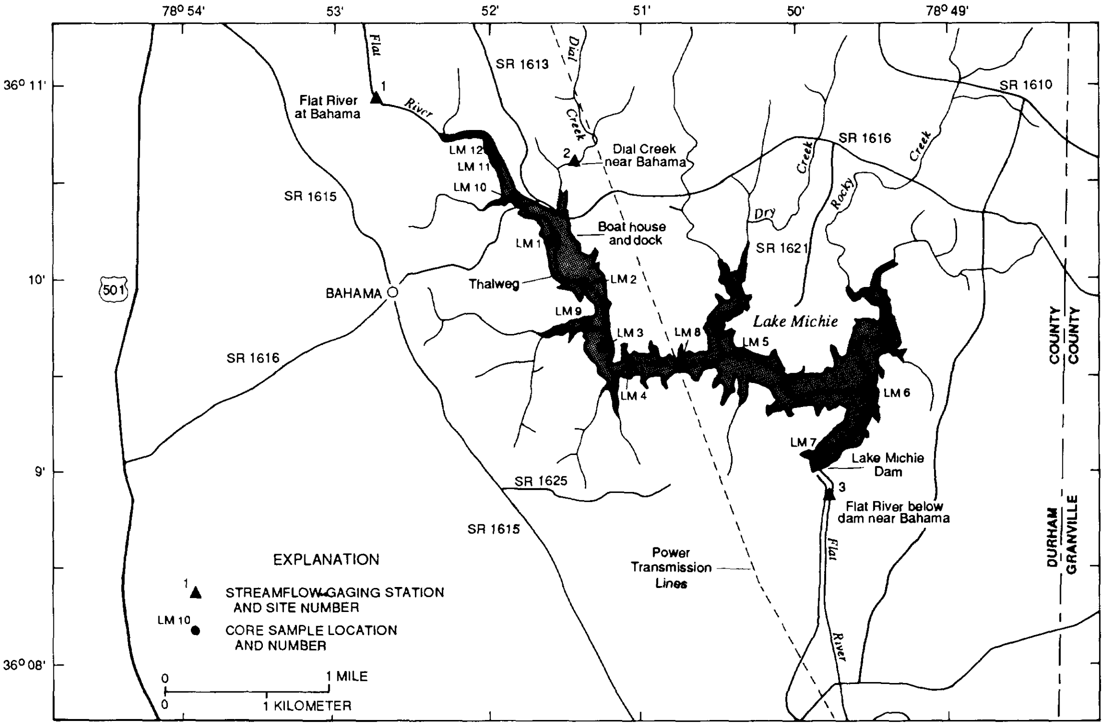


Figure 2. Lake Michie, nearby streamflow-gaging stations, and points where cores of lake-bottom sediment were collected.

Between the dam and the 90-degree bend in the lake's thalweg, approximately three-fourths mi downstream from the boat house and dock, most sediment deposits are confined to the deeper areas near the thalweg. The thalweg is defined as the deepest point in any cross section of the lake and usually marks the location of the active river channel within the lake. In the area of the lake between the 90-degree bend and the dam, sediment deposited onto the steeper valley slopes near the shoreline tend to resettle onto the deeper valley floors. However, in the areas at the mouths of Dry Creek and Rocky Creek, the lake-bottom terrain consists of mild to gentle slopes similar to those in the area adjacent to the boat house and dock.

Flat River Basin

The topography of the Flat River Basin consists of mostly gentle to moderately rolling hills with some steep, narrow valleys immediately upstream from and adjacent to Lake Michie. North of the Durham-Person County Line, Flat River is formed by the confluence of the South Flat River and North Flat River (fig. 1). Ground elevations near the headwaters of the South Flat River and North Flat River range from 650 to 750 ft and decline to 341 ft at the lake's principal spillway. The South Flat River drains rural areas in the extreme northern parts of Orange County and southwestern Person County. The North Flat River drains rural areas of central Person County and also sections of Roxboro, a municipality that lies partly within the northernmost Flat River Basin. Deep Creek, a major tributary to the Flat River, drains rural areas of southeastern Person County.

Land Use

Land use in the Flat River Basin upstream from Lake Michie is mostly rural and has been since the construction of Lake Michie. Urban growth within the basin has been limited and remains confined to Roxboro. Examinations of land-use estimates by Martin and Bass (1940) and Maki and Hafley (1972) indicate that cropland, pasture, and forest areas occupied more than 90 percent of the basin from 1926 to 1970. Results from a recent study of the Lake Michie watershed indicate that slightly more than 93 percent of the basin is cropland (15.5 percent), pasture (9.6 percent), and forest areas (68.2 percent) (Camp, Dresser & McKee, 1989). Urban and other nonagricultural uses of the land have consistently been 6 to 7 percent of the watershed area since about 1940.

At the time of Lake Michie's construction, farming was the activity that affected most of the Flat River Basin and continues to be so; however, the number and acreages of farms have decreased significantly since the mid-1950's (U.S. Department of Commerce, 1925-87). Acreages by land use in Durham, Person, and Orange Counties for agricultural census years 1925-87 provide some insight into what could be considered the most common land-use changes occurring in the basin (fig. 3). Total acreages of

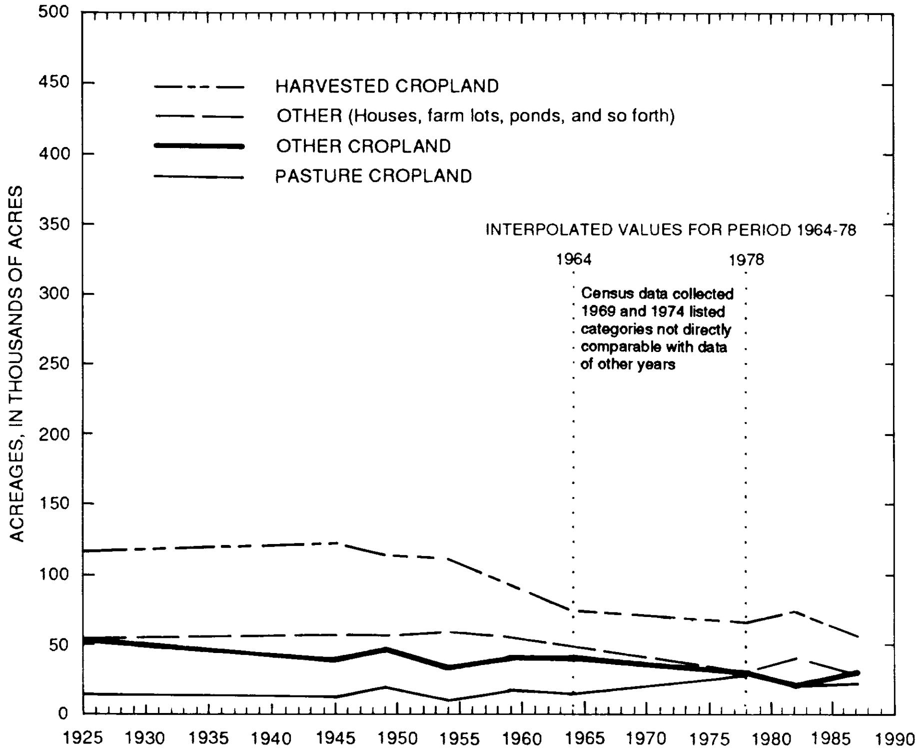


Figure 3. Acreage of active farms by land use reported by U.S. Department of Commerce for Durham, Person, and Orange Counties, 1925-87.

farms shown are for the entire areas of Durham, Person, and Orange Counties. No data were available for specific areas of each county lying within the Flat River Basin; however, changes in total acreages for farms are most likely reflective of those changes that have taken place within the basin.

Between 1954 and 1987, the total number and acreages of farms in the three counties decreased 82 and 57 percent, respectively (U.S. Department of Commerce, 1925-87). With respect to land use within farms, acreages of harvested cropland decreased by 49 percent during the same period (fig. 3). Comparisons of land-use estimates for 1970 and 1988 indicate that many large farming operations have been abandoned and, as a result, cultivated croplands are reverting to pasture, shrub land, and forest. Maki and Hafley (1972) reported that the percentage of forest areas increased from 47 to 62 percent between 1926 and 1970 and that urban and other nonagricultural areas occupied 6 percent of the drainage basin. Land-use estimates determined by Camp, Dresser, & McKee (1989) revealed that forest areas and open fields accounted for 68 percent of the drainage basin and that urban, plus other non-agricultural lands, accounted for approximately 7 percent in 1988. Comparison of these land-use estimates indicates that the percentage of open fields and forest areas has continued to increase since 1970 while urban and other nonagricultural uses have been minimal.

Soils and Soil Erosion

Soils in the Flat River Basin are derived from several types of rocks. Lake Michie and most of the Flat River Basin are underlain by metavolcanic rocks of the Carolina Slate Belt. Volcanic metaconglomerates and phyllite and schist underlie some of the upper parts of the basin in Orange and Person Counties (North Carolina Department of National Resources and Community Development, 1985).

Martin and Bass (1940) and the U.S. Soil Conservation Service (SCS) (1983) documented the soil groups (associations) and the extent and potential for erosion in the Flat River Basin. The investigation conducted in 1940 focused solely on the soils in the Flat River Basin, and the 1983 investigation focused on the soils in the Upper Neuse River Basin. The Flat River Basin is one of several headwater basins in the Upper Neuse River Basin. Identification of soil groups in the two investigations yielded some similarities in specific soil types in the larger groups whereas a number of discrepancies were noted in the identification of the remaining soils. These discrepancies are likely the result of differences in size of the two study areas and the degree of detail used to identify the soils in the investigations. In this report, the soil nomenclature of the 1983 investigation is used.

The two associations occupying a majority of the Flat River Basin account for 75 percent of the soils in the basin. The largest soil association in the Flat River Basin is the Georgeville-Tatum-Herndon association which covers nearly 64 percent of the basin (U.S. Soil Conservation Service, 1983) (fig. 4). These soils are described as being well-drained, moderately deep to deep, clayey soils that are derived from residuum weathered from slate (U.S. Soil Conservation Service, 1983). The Enon-Helena-Vance association, covers slightly more than 11 percent of the Flat River Basin in Person County (fig. 4). These soils are also identified as well-drained, moderately deep to deep soils, but are derived from residuum weathered from acidic rocks or basic rocks in the Piedmont Province (U.S. Soil Conservation Service, 1983).

The 1983 SCS study of the Upper Neuse River Basin categorized and mapped erosion in units of tons per acre per year ((tons/acre)/yr). Erosion rates greater than 5 (tons/acre)/yr are regarded as exceeding the soil-loss tolerance level. Erosion rates beyond this level hinder the soil's ability to economically sustain a high level of crop production over a long-term period (U.S. Soil Conservation Service, 1983). An average of 65 percent of the gross erosion in the Upper Neuse River Basin was reported to be from croplands. Slightly more than 36 percent of the gross erosion in the Upper Neuse River Basin originated from croplands at rates of 12 (tons/acre)/yr or less. Nearly 26 and 3 percent originated from croplands at rates of 12 to 20 (tons/acre)/yr and greater than 20 (tons/acre)/yr, respectively. The 1983 study also categorized erosion in terms of loss of soil depth. A map prepared by the SCS showing loss of soil depth for the Upper Neuse River Basin indicates that 3 to 6 in. of topsoil have been lost in most areas of the Flat River Basin where erosion was documented.

No information is available from the 1983 investigation to indicate which soil associations are most susceptible to erosion. However, land-use patterns more likely affect the potential for erosion than would be attributed to the soil's association. In the Upper Neuse River Basin, croplands comprise nearly 13 percent of the total drainage basin while accounting for 65 percent of gross erosion. Given that land-use estimates for the Upper Neuse River Basin are somewhat similar to those for the Flat River Basin, it is likely that a high percentage of the gross erosion in the Flat River Basin originated from croplands.

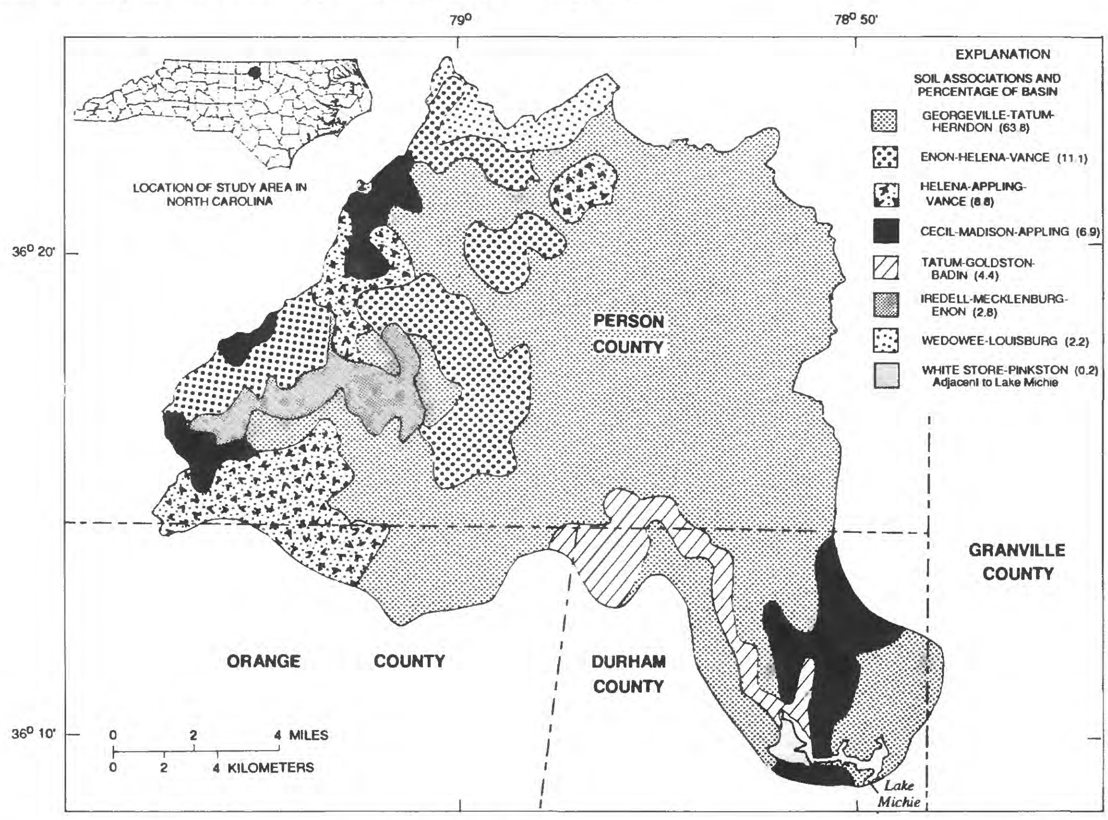


Figure 4. General soil associations in the Flat River Basin (adapted from U.S. Soil Conservation Service 1983).

Climate

The climate in the Flat River Basin, as throughout most of North Carolina, consists mainly of long, hot, and humid summers and short, mild winters with transitional seasons that provide very pleasant conditions (Kopec and Clay, 1975). Weather data collected at selected locations in and near the Flat River Basin during the period 1951-80 show that mean monthly temperatures ranged from 40 degrees Fahrenheit (°F) in January to 78 °F in July (National Oceanic and Atmospheric Administration, 1944-91). For the same period 1951-80, average annual precipitation was 42 and 45 in. in Raleigh and Rougemont, respectively.

Streams in the Flat River Basin undergo periodic floods, each of which can carry large sediment loads. Hurricanes, tropical storms, and convective storms are responsible for most of the flood-producing rain that occurs in the region. Since Lake Michie's construction in 1926, heavy rains associated with hurricanes have caused 5 of the 15 largest floods in the Flat River Basin (Carney and Hardy, 1967; National Oceanic and Atmospheric Administration, 1944-91).

DATA COLLECTION AND ANALYSIS

This section describes the collection and analysis of various types of basic hydrologic and sediment data that were required to meet the objectives of this study. Streamflow data were required to compute estimates of annual suspended-sediment yields into and out of Lake Michie. Suspended-sediment data were required to develop the relationship between discharge and suspended-sediment transport. Finally, representative samples of the lake-bottom sediment were needed to characterize the physical properties of the deposits and to perform radiochemical analyses for establishing sediment accretion rates.

Most of the streamflow and suspended-sediment concentration data were obtained from the National Water Data Storage and Retrieval System (WATSTORE) historical data base (U.S. Geological Survey, 1975). New streamflow and suspended-sediment data were obtained for this study on Dial Creek, a small stream that is a direct tributary to Lake Michie (fig. 2, site 2). In addition, because there were no available data on the sedimentology or rates of sediment accretion for lake-bottom deposits, a number of sediment cores were obtained for these analyses.

Streamflow Data

The streamflow data needed for computation of suspended-sediment transport were obtained from continuous-record gaging stations on two inflow streams and on the outflow from the lake. Streamflow data were collected according to standards and practices outlined by Buchanan and Somers (1969).

The principal inflow stream, Flat River at the gaging station 02085500, has a drainage area of 149 mi^2 at the Bahama gage (fig. 2, site 1). Slightly more than 89 percent of the Lake Michie watershed is gaged at this point. The second inflow stream, Dial Creek (fig. 2, site 2) at the gaging station 02086000, has a drainage area of 4.71 mi^2 at the gage (fig. 5).

Figure 5. Streamflow-gaging station on Dial Creek near Bahama (site 2) located 0.25 mile upstream from Lake Michie.

Not all streams draining into Lake Michie were gaged (fig. 1). The ungaged areas, approximately 13.5 mi^2, consist of small basins directly tributary to Lake Michie. Field reconnaissance and examinations of areal photogrammetry maps of the ungaged areas adjacent to Lake Michie indicate that land-use patterns in the Dial Creek basin are representative of land-use patterns in the ungaged basins. Therefore, streamflow and suspended-sediment data collected at Dial Creek were prorated by drainage area to estimate inflow and suspended-sediment yields from the ungaged areas.

The drainage area for the Flat River at the gaging station 02086500, which is 900 ft from the Lake Michie Dam, is 168.0 mi^2 (fig. 2, site 3). For the purpose of analysis in this report, flow and suspended-sediment data collected at site 3 were assumed to be equivalent to those at the dam. No tributaries drain into the Flat River between the dam and the gage at site 3.

For each of the three gages, flow-duration tables were computed for selected periods of record using daily mean discharge records (Searcy, 1959) for subsequent use in the suspended-sediment transport analysis. A flow-duration table indicates the percentage of days in a given period (in this case, a year) for which specified ranges of flow are exceeded.

The record of daily flow at site 1 was complete for the period 1926-91. The other two gages had incomplete record: Dial Creek (site 2) had record during the periods 1926-71 and 1990-91, and Flat River at the dam (site 3) had record during the periods 1928-59, 1962-66, and 1983-91. To minimize the number of water years[1] for which missing discharge record had to be estimated, the computations of suspended-sediment yields were limited to the period of 1983-91. As a result, only the missing record at site 2 had to be estimated for the 1983-89 water years. Correlation techniques outlined by Searcy (1959) were used to estimate flow-duration tables for the missing years of record at site 2.

Suspended-Sediment Sampling

The suspended-sediment concentration data required for computation of loads were obtained from the WATSTORE database for sites 1 and 3 (fig. 2), and from suspended-sediment samples taken at site 2 during the study period. For site 1, data were collected during the periods 1969-78 (Simmons, 1988) and 1988-91 as part of a statewide suspended-sediment study and an ongoing regional study of surface-water quality, respectively. Similarly, for site 3, data were obtained from samples collected during the periods 1983-87 (Garrett, 1990) and 1988-91 as a part of two separate studies of regional surface-water quality. Suspended-sediment concentration data for Dial Creek (site 2) were collected in 1990 and 1991 as part of this study. At all sites, samples collected by hand were obtained throughout a range of discharges according to standards and practices outlined by Edwards and Glysson (1988). These data were published annually in the U.S. Geological Survey's annual water-data reports for North Carolina (1969-91).

During periods of high streamflow, a number of samples collected by hand at Dial Creek were supplemented with suspended-sediment samples collected simultaneously by an Instrument Service Company (ISCO) Model 1680 automatic sampler. No bedload samples were collected at any site.

All samples were analyzed for sediment concentration using the filtration method (Guy, 1969) at the USGS sediment laboratory facilities in Raleigh, North Carolina. Sediment concentrations measured from samples collected by the ISCO at site 2 were adjusted according to a relation developed between hand-collected and ISCO-collected sample concentrations (Porterfield, 1972).

Concentration values for each of the three sites were converted into units of tons of suspended-sediment discharge per day and then plotted against instantaneous discharge at the time of sampling. A combination of linear regression and visual fit was used to define the sediment-transport relations at each site (Glysson, 1987) (figs. 6-8). At each site, curves were developed for each of the low, medium, and high ranges in instantaneous water discharge (table 1).

Collection and Analysis of Lake-Bottom Core Samples

Twelve cores of lake-bottom sediment were collected in June 1992 throughout the length of Lake Michie along or near the thalweg (fig. 2). Selected subsamples from each core were then analyzed for grain size, TOC, nitrogen content, determination of C:N ratios, and activity of Cs-137 and Pb-210 radionuclides.

[1] Water year is the period from October 1 through September 30 and is identified by the calendar year in which it ends.

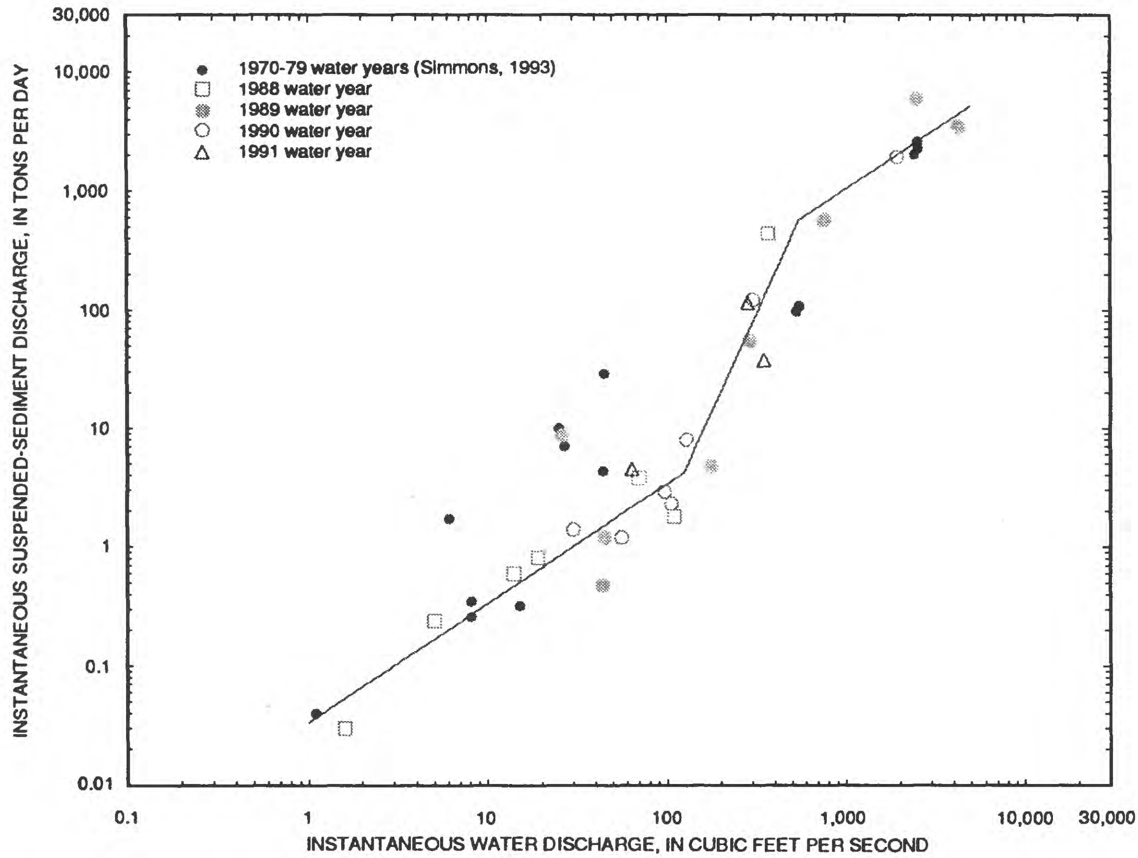


Figure 6. Suspended-sediment transport curve for Flat River at Bahama (site 1), 1970-91 water years.

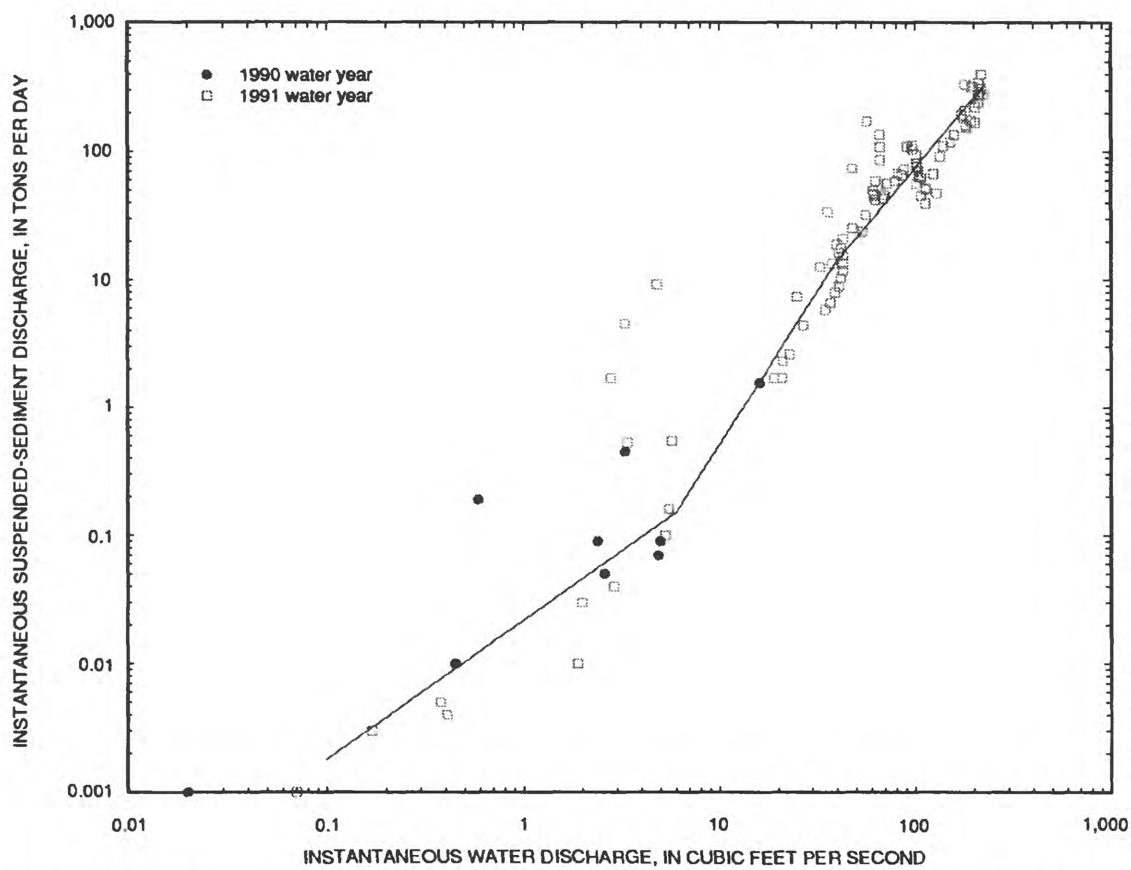


Figure 7. Suspended-sediment transport curve for Dial Creek near Bahama (site 2) 1990-91 water years.

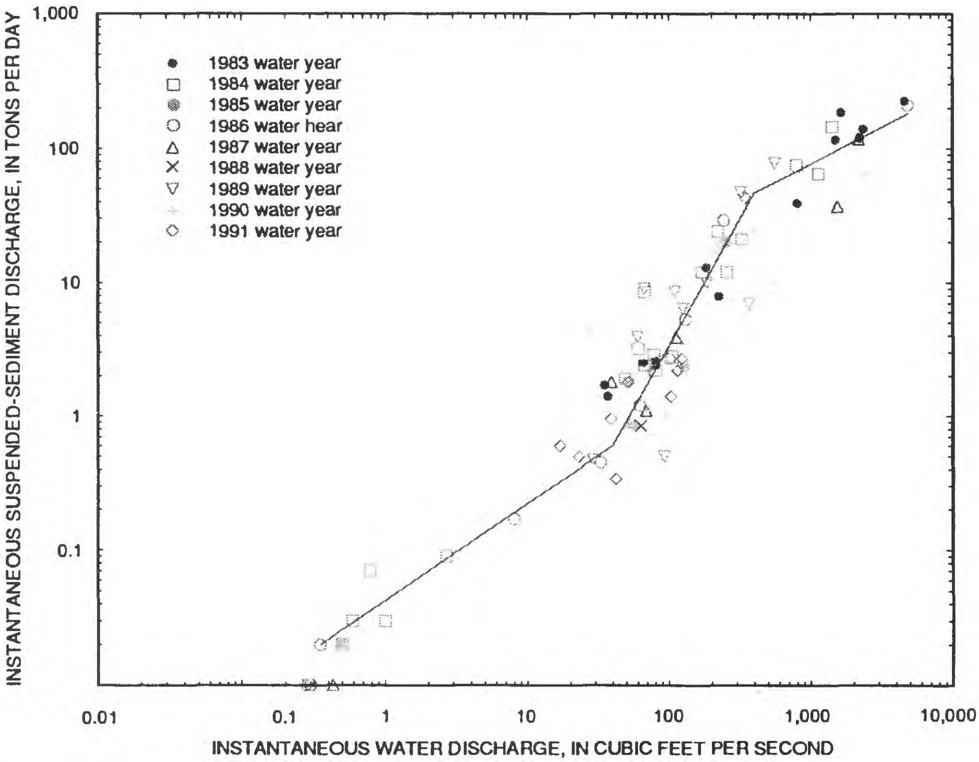


Figure 8. Suspended-sediment transport curve for Flat River at dam near Bahama (site 3) 1983-91 water years.

Table 1. Summary of data used to develop sediment-transport equations for low-, medium-, and high-flow ranges

[Q_s, instantaneous suspended-sediment discharge in tons per day; Q, instantaneous water discharge in cubic feet per second; $\leq$, less than or equal to; Med, medium; <, less than; $\geq$, greater than or equal to]

Site (fig. 2)	Period of sampling (water years[1])	Number of samples	Sediment concentration (milligrams per liter) Low	Sediment concentration (milligrams per liter) High	Water discharge (cubic feet per second) Low	Water discharge (cubic feet per second) High	Equation for indicated flow range
Site 1	1969-78, 1988-91	[2]39	4	885	1.1	4,280	Low: $Q_S=0.03354\,Q^{1.00064}$ $(Q \leq 12.5)$
							Med: $Q_S=4.7\text{x}10^{-7}\,Q^{3.31381}$ $(12.5 < Q < 550)$
							High: $Q_S=1.02679\,Q^{1.00172}$ $(Q \geq 550)$
Site 2	1990-91	[3]102	2	1,121	.02	224	Low: $Q_S=0.02149\,Q^{1.0837}$ $(Q \leq 6)$
							Med: $Q_S=0.00205\,Q^{2.39484}$ $(6 < Q < 40)$
							High: $Q_S=0.0176\,Q^{1.81325}$ $(Q \geq 40)$
Site 3	1983-87, 1988-91	102	1	59	.01	4,850	Low: $Q_S=0.04249\,Q^{0.71775}$ $(Q \leq 40)$
							Med: $Q_S=0.00057\,Q^{1.88837}$ $(40 < Q < 400)$
							High: $Q_S=1.75723\,Q^{0.54649}$ $(Q \geq 400)$

[1] Water year is the period October 1 through September 30 for the year in which it ends.
[2] Fourteen samples collected during 1969-78 were identified from archived records; 25 samples were collected during 1988-91.
[3] Thirty-seven samples were collected manually; 65 samples were collected by ISCO automatic sampler.

Ten of the cores, numbers LM 1 to LM 10, were collected using a 250-lb gravity-coring apparatus that was designed for deployment from the bow of a small boat (figs. 9 and 10). Interchangeable 4-in. diameter polyvinylchloride (PVC) barrels, averaging 5 ft in length, were used to retrieve and hold the sediment cores. A stainless steel core-catcher with flexible brass 'fingers' was attached to the bottom of each PVC barrel to prevent sediment from sliding out of the core barrel during retrieval. The average length of recovered sediment was 2.7 ft and ranged from 1.3 ft to 3.2 ft (table 2).

The other two cores, LM 11 and LM 12, were collected using a vibra-coring apparatus. A 10-ft high steel tripod frame placed on the lake bed held 3-in. diameter, aluminum core tubing vertically during coring operations. The core barrel was pushed down into the sediment using a gasoline-powered vibrator. A core-catcher similar to that described above, was used on both cores to prevent sediment from sliding out of the barrel during retrieval. Core LM 11 penetrated 11.0 ft of sediment and was within an estimated 2-3 ft of the original lake bottom; core LM 12 achieved a penetration of 12.8 ft (table 2).

Excess lengths of the core barrels above the top of each of the samples were cut off, and core barrels were capped to prevent disturbance of the samples during handling and transportation to the laboratory. In the laboratory, the samples were kept in cold storage (40 °F). Prior to any analyses, the cores were cut lengthwise and one-half of each sample was archived. The half reserved for analysis was photographed and visually described.

Eleven of the 12 cores (LM 1 - LM 11) were subsampled and analyzed for grain size. The subsamples were extracted at equal depth intervals from top to bottom of each core. The number of subsamples extracted from each core depended on the length of the core (table 2). Size classes used to identify the particles in each subsample ranged from -1 to 9 phi at intervals of one-half phi (S.W. Snyder, North Carolina State University, written commun., 1992) and are equivalent to the standard size class definitions presented by Guy (1969).

The subsamples of three cores (LM 1, LM 7, and LM 8) also were analyzed for the percentage by dry weight of TOC in the sample. From each subsample, a small volume of dried, ground, thoroughly-mixed sediment was heated to 1,100 °C to separate the gas by-products such as CO_2 and NO_2 (Verardo and others, 1990; S.W. Snyder, North Carolina State University, written commun., 1992). Data from these by-products were then compared to the pre-combustion weights to determine the percentage by dry weight of TOC and nitrogen and, subsequently, the C:N ratios.

Subsamples from the same cores used for TOC and nitrogen analyses also were used in radionuclide analyses. Concentrations of Cs-137 and Pb-210 were determined through measurements of gamma-emission activities of these radionuclides (S.W. Snyder, North Carolina State University, written commun., 1992). Profiles of these activities along the lengths of the cores were then developed to establish rates of sediment accretion and to determine changes in rates over time.

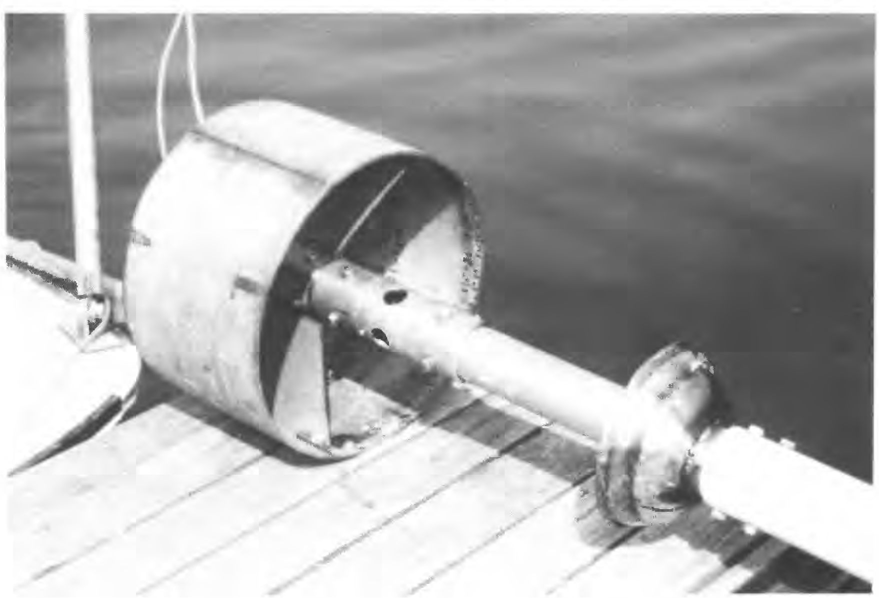


Figure 9. Gravity-coring apparatus used for collecting lake-bottom sediment cores.

Figure 10. Gravity-coring apparatus and boat-mounted frame used for collecting lake-bottom sediment cores (apparatus shown in position prior to collection of core LM 9).

Table 2. Selected characteristics of lake-bottom cores

[Average percentages are computed as the arithmetic means of percentages from subsamples selected from the core. >, greater than; <, less than; mm, millimeter; ---, no data available]

					Average percentage by weight		
Core (fig. 2)	Distance upstream from dam (feet)	Water depth (feet)	Length of core (feet)	Number of sub-samples	Sand percent >0.062 mm	Silt percent >0.004 mm and <0.062mm	Clay percent <0.004 mm
LM 12	21,250	2.0	12.8	---	---	---	---
LM 11	21,210	9.2	11.0	21	65.3	20.5	14.2
LM 10	19,720	18.0	[a] 1.3	6	48.6	33.0	18.4
LM 1	17,780	10.5	2.8	10	11.0	42.0	47.0
LM 2	15,660	23.0	2.9	12	7.2	43.7	49.1
LM 9	14,150	20.3	3.2	10	5.1	45.4	49.5
LM 3	13,480	28.2	2.8	10	4.7	45.0	50.3
LM 4	11,820	32.5	2.8	11	1.9	37.4	60.7
LM 8	10,310	36.5	2.7	9	1.4	43.0	55.6
LM 5	8,060	44.5	2.8	11	1.4	40.0	58.6
LM 6	3,370	53.0	3.0	10	1.8	31.4	66.8
LM 7	650	71.5	2.7	9	0.5	32.4	67.1

[a] Penetration of core LM 10 was cut short by a small boulder or concentration of gravel carried in by a previous flood. It is not likely that the original soil is 1-2 feet below the current lake bottom in this area. Based on visual observation, the only cores that penetrated the original lake bottom are LM 6 and LM 12. The bottom layers of sediment in each of these two cores consisted of sand mixed with numerous plant roots.

SEDIMENT CHARACTERISTICS IN LAKE MICHIE

Information about the physical characteristics of sediment that settles in Lake Michie can be useful in identifying the dominant source(s) of sediment and the processes responsible for observed sedimentation patterns. In addition, the areal distribution of sand-rich and clay-rich deposits are indicative of areas that are subject to high-velocity currents where sediment is resuspended or low-velocity currents where sediment remains relatively undisturbed. Changes in proportions of fine- and coarse-grained particles along a core can provide insight into how the sedimentation process has changed over time. Finally, determinations of carbon and nitrogen percentages along with analyses of C:N ratios in sediment can identify whether the organic matter in the sediment is from internal or external sources.

Physical Description and Grain Size of Lake-Bottom Sediment

Cores LM 1 through LM 9 were very similar in appearance and texture. Sediment in these cores consisted mostly of pale, yellowish-brown to light, olive-gray silt and clay. Occasional layers of plant debris were observed in most cores. The bottom 0.4 ft of core LM 6, the only gravity core that penetrated the original lake bottom, was composed of medium-size sand mixed with numerous plant roots (S.W. Snyder, North Carolina State University, written commun., 1992).

The sediment in cores LM 10 through LM 12 consisted of numerous layers of medium to coarse sand mixed with layers of mud and plant debris. The bottom 1.8 ft of core LM 12 (which also penetrated the original lake bottom) consisted of layers of coarse sand and small pebbles intermixed with numerous plant fragments and roots (S.W. Snyder, North Carolina State University, written commun., 1992).

Overall, sediment in the cores was rich in silt and clay (fig. 11). Average percentages by weight of sand, silt, and clay particles are given in table 2 for sample fractions from cores LM 1-11; no grain-size analysis was performed for core LM 12. The percentages of sand, silt, and clay in the samples ranged from 0.5 to 65.3, 20.5 to 45.4, and from 14.2 to 67.1 percent, respectively (table 2).

Subsamples from four cores, designated LM 1, LM 7, LM 8, and LM 10, were analyzed to determine average specific weights of lake-bottom sediment for each core. The average specific weight of lake-bottom sediment in Lake Michie was computed to be 73.6 lbs/ft^3.

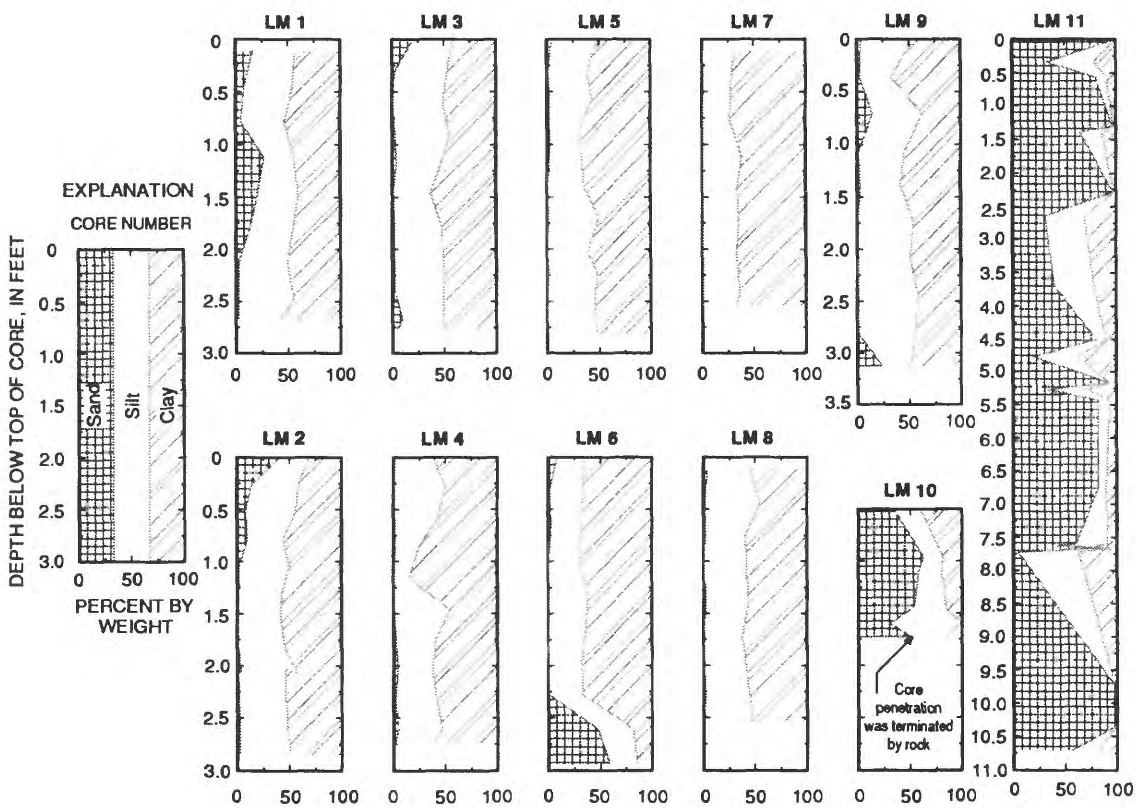


Figure 11. Grain-size splits in percentage by weight of lake-bottom sediment near thalweg in Lake Michie.

Areal Distribution of Lake-Bottom Sediment

The cross-sectional area where sediment enters the headwaters of a lake is an important factor that affects whether the sediment is deposited immediately upon entry or is carried further downstream before reaching the point of deposition. The cross-sectional area is a function of the water depth and width. For a given discharge, the velocities occurring in smaller cross-sectional areas are higher than those in larger cross-sectional areas. As a result, higher velocities cause sediment to remain in suspension longer before settling. In long, narrow reservoirs where cross-sectional areas in the headwaters may be smaller than those downstream, sand and heavier, coarser sediment can be carried farther down the lake before settling, in contrast to wide, broad reservoirs with large cross-sectional areas in the headwaters where the same sediment would settle upon entering the lake.

In Lake Michie, cross-sectional areas upstream from the SR 1616 bridge are small as a result of shallow depths and narrow widths, but increase in size not far downstream from the bridge because of larger widths and increasing depths. Also, the bridge appears to act as a restriction in the lake causing higher velocities in its immediate vicinity that carry the sediment farther downstream than if the bridge were not present.

Grading of predominant grain sizes from sand in high-velocity "upstream" areas to silt and clay in low-velocity "downstream" areas can be seen when average percentages of grain size in each core are plotted against the location of the core sample (fig. 12). Overall, deposits of silt and clay compose a significant part of the lake-bottom sediment in the middle and lower parts of Lake Michie. Sand and larger-size particles compose a significant percentage of the lake-bottom sediment upstream from the SR 1616 bridge.

As previously discussed, the smaller cross-sectional areas in Lake Michie upstream from the SR 1616 bridge permit higher velocities during flood flows. As a result, nearly all silt and clay along with smaller sizes of sand are kept in suspension or are easily resuspended and carried farther downstream. Upstream from the SR 1616 bridge, the percentage of sand ranges from 48.6 percent for core LM 10 to 65.3 percent for core LM 11 (fig. 12; table 2), while silt and clay account for nearly 50 percent or less of the lake-bottom sediment.

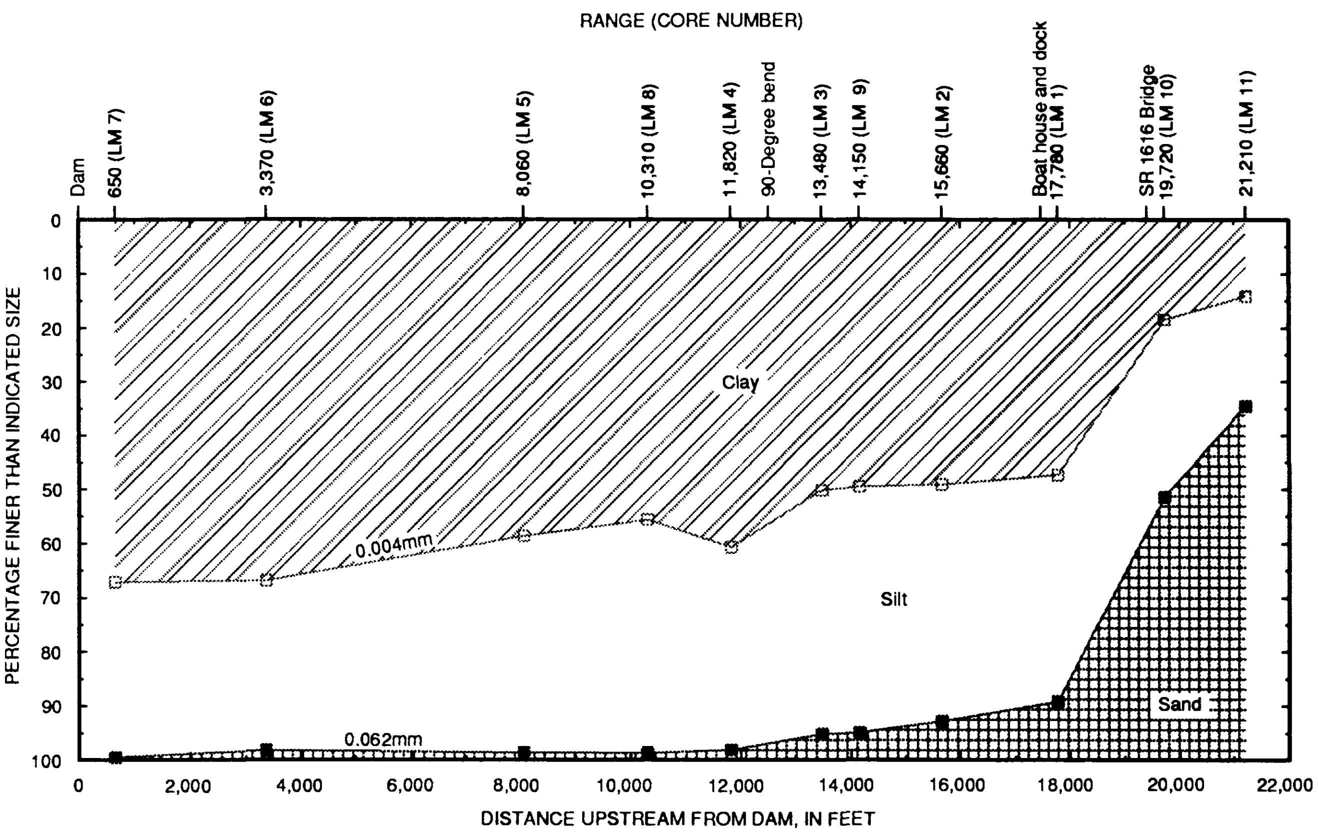


Figure 12. Distribution of lake-bottom sediment along thalweg in Lake Michie (modified from Glysson, 1977).

The percentage of sand in lake-bottom sediment downstream from the SR 1616 bridge decreases significantly from about 45 percent at the bridge to 11 percent at core LM 1 (fig. 12). Between the bridge and the area adjacent to the boat house and dock, the larger cross-sectional areas of the lake and corresponding lower velocities result in the deposition of most of the remaining sand. Downstream where the lake turns almost 90 degrees, the percentage of sand decreases to 4.7 percent for core LM 3 and to 1.9 percent for core LM 4.

Cores LM 1, 2, and 3, retrieved in the area between the bridge and the boat house, show evidence of coarsening upward in grain size; that is, the percentage of sand or larger particles at the top of the core appears to be increasing with the passage of time (fig. 11). S.W. Snyder (written commun., 1992) suggested the possibility that continued deposition of sediment upstream from the SR 1616 bridge has produced higher streamflow velocities as a result of decreasing cross-sectional areas. Sand that was deposited upstream from the bridge during the lake's early years of existence is now being carried farther downstream from the bridge before deposition.

From the 90-degree bend downstream to Lake Michie Dam, lake-bottom sediment is dominated by fine silt and clay. Silt and clay compose slightly more than 98 percent of the lake-bottom sediment in this reach with much of the silt being classified as clayey silts. The average percentage of sand within each core ranges from less than 2 percent at LM 4 to one-half percent at core LM 7 nearest to Lake Michie Dam (fig. 12). However, core LM 6 shows a large percentage of sand at the bottom of the core (fig. 11). Examination of this layer reveals plant root intermixed within sand and is indicative of the core having penetrated the original lake bottom. The location where core LM 6 was obtained is most likely on the steep valley slopes where sediment thicknesses have not accumulated as much as in the thalweg.

Total Organic Carbon and Carbon-Nitrogen Ratios in Lake-Bottom Sediment

Cores LM 1, LM 8, and LM 7 were selected for analyses of TOC. These cores were selected to permit a comparison of the TOC percentages and C:N ratios between lake-bottom sediment from the upstream region of the lake, the middle area of the lake (near the power lines), and the area in the vicinity of Lake Michie Dam (fig. 2). Analyses of subsamples in core LM 1 reveal that the percentage of TOC in the sediment ranges from 1.33 percent to 3.81 percent (table 3). Similarly, the percentage of TOC ranges from 1.05 to 2.46 percent and from 1.24 to 2.17 percent in cores LM 8 and LM 7, respectively.

Carbon-nitrogen ratios provide some insight into the source of organic material and, subsequently, the source of organic material in the deposited sediment. The C:N ratios determined from analyses of subsamples in core LM 1 range from 10.2 to 15.8 (table 3). The C:N ratios for subsamples from cores LM 8 and LM 7 range from 9.2 to 17.6 and from 8.6 to 10.3, respectively.

Table 3. Total organic carbon (TOC) content, nitrogen content, and carbon-nitrogen (C:N) ratios for cores LM 1, LM 8, and LM 7
[Subsample interval measured from top of core; ---, no data]

Core number (fig. 2)	Subsample interval (in feet)	Percent TOC	Percent nitrogen	C:N ratio
LM 1	[a]0.00 - 0.10	2.56	0.25	10.2
	[a].00 - .10	2.53	.21	12.0
(near boat	.34 - .44	1.87	.15	12.5
house and	.67 - .77	1.92	.16	12.0
dock)	1.02 - 1.12	2.45	.18	13.6
	1.35 - 1.44	2.17	.17	12.8
	1.69 - 1.79	3.81	.24	15.8
	2.02 - 2.12	---	.16	---
	2.36 - 2.46	1.33	.12	11.1
	2.72 - 2.79	1.42	.11	12.9
LM 8	.00 - .10	2.46	.14	17.6
	.33 - .43	1.45	.11	13.2
(at power	.64 - .74	1.85	.15	12.3
lines)	.97 - 1.07	1.22	.11	11.1
	1.28 - 1.38	1.37	.13	10.5
	1.61 - 1.71	1.33	.14	9.5
	1.92 - 2.02	1.20	.10	12.0
	2.25 - 2.35	1.05	---	---
	2.56 - 2.66	1.20	.13	9.2
LM 7	.00 - .10	2.17	.21	10.3
	.30. - .39	1.94	.20	9.7
(650 feet	.66 - .76	2.08	.21	9.9
upstream	1.00 - 1.10	1.44	.15	9.6
from dam)	1.30 - 1.39	1.41	.15	9.4
	1.64 - 1.74	1.37	.15	9.1
	1.95 - 2.05	1.24	.13	9.5
	2.30 - 2.40	1.27	.14	9.1
	2.59 - 2.69	1.47	.17	8.6

[a] Two subsamples from LM 1 were analyzed for TOC and nitrogen.

Comparison of TOC percentages with C:N ratios reveals a relation between them in which higher TOC percentages correlate with higher C:N ratios (fig. 13). This correlation is an indication that plant debris from the drainage basin is the primary source of organic carbon occurring in Lake Michie (Waksman, 1933; Brenner and others, 1978; S.W. Snyder, North Carolina State University, written commun., 1992). C:N ratios for terrestrial plants and peats are reported to range from 20 to 200. As plant debris decays into a more stable organic form, C:N ratios tend to decrease into the range of 10 to 13, the same general range in which most C:N ratios for sediment in Lake Michie were calculated (table 3).

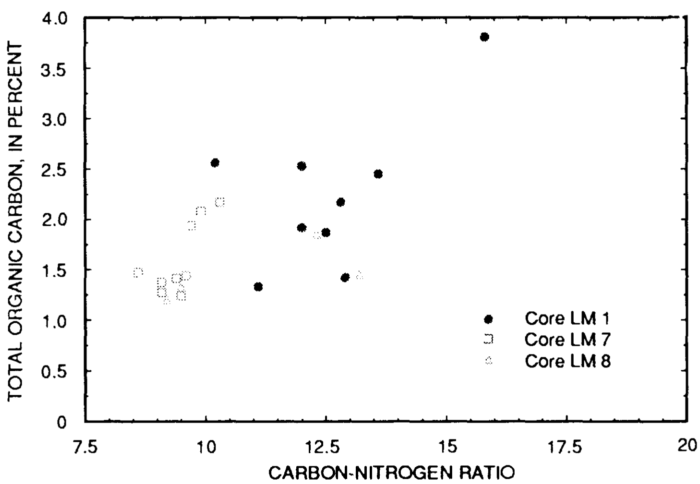


Figure 13. Percentage by weight of total organic carbon and carbon-nitrogen ratios of lake-bottom sediment in Lake Michie.

Numerous observations of plant debris were made when the cores were initially cut open in the laboratory (S.W. Snyder, North Carolina State University, written commun., 1992). These observations support the conclusion that plant debris carried into Lake Michie is the primary source of carbon.

The range of C:N ratios for lake-bottom sediment in Lake Michie is also higher than that associated with sediment produced from phytoplankton, the C:N ratios of which are in the range of 6 to 8 (Redfield and others, 1963). This indicates that organic material in the sediment is predominantly plant debris carried from the drainage basin. The production of organic material by phytoplankton does not appear to be a major part of the overall sedimentation process in Lake Michie (S.W. Snyder, North Carolina State University, written commun., 1992).

Little bioturbation was evident in any of the core samples (S.W. Snyder, North Carolina State University, written commun., 1992). It is possible that deposition of plant debris among sediment deposits and subsequent decomposition may have resulted in methane and anoxic conditions which would preclude most bottom dwelling, bioturbating organisms (C.C. Daniel, U.S. Geological Survey, oral commun., 1993). The production of methane gas in lake-bottom sediment at Lake Michie is suspected because of observations of gas bubbles breaking at the water surface during field operations of the investigation.

SEDIMENTATION RATES IN LAKE MICHIE

Several aspects of the sedimentation process are of interest to reservoir managers. One of the most important aspects is the determination of past and present storage-depletion rates, which allows for a projection of the useful life remaining in the reservoir. This information is usually presented in units of volume. Another aspect is based on the rates at which sediment covers a specific area within the lake, usually presented in units of length or depth over time. Still another aspect deals with the amount of sediment transported and trapped in terms of weight. If an average specific weight of the sediment deposited in the reservoir is known, then rates expressed in terms of volume and weight can be related.

Three separate methods were used to address these different aspects of sedimentation in Lake Michie. First, comparisons with previous surveys were made to determine the rate of storage depletion and the rates of sediment accretion in five different areas of the lake. Second, radionuclide analyses of core samples were made to provide estimates of sediment accretion rates in three different locations in the lake to provide an indication of how these rates have changed over time. Third, an analysis of the transport of suspended sediment into and out of Lake Michie provided information to compute trap efficiency.

Comparison of Volume Computations from Bathymetric Surveys

The most direct way to determine the rate of sediment accretion in a reservoir along with changes in the rates over time is to make comparisons with previous bathymetric surveys. If the surveys include recoverable cross sections, additional information can be derived with respect to how accretion rates vary throughout the lake.

At the beginning of the study, an attempt was made to recover the original range monuments established and used by Eakin and Brown (1939) in their early sedimentation surveys. A resurvey of Eakin and Brown's cross sections would have permitted a direct observation of the amount of sediment deposition at various areas in the lake. However, only a few monuments (established prior to 1926) and two complete range lines were located from the original notes.

Volume Comparisons

Comparisons of the current and previous storage volumes provided a basis for estimating sedimentation rates in Lake Michie. By 1992, there had been four determinations of the storage volume in Lake Michie. In 1935, Eakin and Brown (1939) computed a storage estimate from a survey of 32 cross sections distributed throughout the length of the lake. At several points in each cross section, Eakin and Brown also probed through sediment deposits and obtained an additional cross section of the original lake bottom in order to compute an estimate of the initial storage volume for 1926. In 1970, Maki and Hafley (1972) computed a third storage estimate from a survey of 24 cross sections different from those surveyed by Eakin and Brown. Weaver (1993) computed the latest storage from a new bathymetric map completed in 1993.

The advantages of volume comparison lie in its simplicity and in the fact that it accounts for all sediment trapped in the lake, both suspended and bed load. Some of the disadvantages lie in reconciling different surveying procedures and standards, including those that report results in terms of the weight of sediment rather than the volume of sediment. It is not always possible to evaluate the accuracy of a computed volume figure. In addition, caution must be observed to ensure that the same volume-computation procedures are followed when comparing all surveys.

Eakin and Brown (1939) and Maki and Hafley (1972) used the Range Method (Vanoni, 1975) to compute storage estimates from their surveys. In addition, the volumes presented from the 1935 and 1970 surveys are those volumes at an elevation of 340.0 ft. The spillway was raised from 340.0 to 341.0 ft in late 1963 (A.T. Rolan, City of Durham, oral commun., 1993). The Range Method is based on the summation of volume segments or prisms, bounded by successive cross sections, and on the assumption of straight-line prorations along the shoreline between the cross sections. Weaver (1993) computed the volume of Lake Michie using a Geographical Information System-based (GIS) Triangulated Irregular Network (TIN). The TIN is a series of adjacent, nonoverlapping triangles that define an accurate model of the bottom topography of a lake or other surface terrain (Environmental Systems Research Institute, 1988). Because the TIN method can depict a natural surface and the undulating land patterns common to most terrain, volume estimates computed using the TIN method are likely to be more accurate than those computed by the Range Method. Weaver (1993) reported that the TIN-generated volume for Lake Michie is 11,070 acre-ft at an elevation of 341.0 ft. However, to facilitate direct comparisons with the 1926, 1935, and 1970 determinations, volume estimates for the 1993 map at an elevation of 340.0 ft are also computed by the Range Method.

Thirty-two cross sections were located on the Weaver (1993) map in the same approximate locations as those surveyed by Eakin and Brown (1939). Computer-generated cross sections were developed from the TIN, resulting in a series of volume segments that approximated those used by Eakin and Brown. The volumes of the individual segments between the cross sections were then computed and summed to determine a new estimate of storage volume. The storage volume computed at the 340.0 ft elevation using the Range Method is 10,130 acre ft (table 4).

Table 4. Lake Michie storage volumes and estimated total net sediment deposited, 1926-92 (modified from Maki and Hafley, 1972)

[The 1926 and 1935 storage volumes were computed using the spillway elevation of 340.0 ft. The 1970 storage is reported to be at an elevation of 340.0 ft. The 1992 storage volume is adjusted to elevation 340.0 ft for direct comparison. NA, not applicable; acre-ft, acre foot; acre-ft/yr, acre-foot per year; acre-ft/mi^2/yr, acre-foot per square mile per year]

	April 1926	January 1935	October 1970	April 1992
Total time period (years)	NA	8.75	44.5	66.0
Storage volume (acre-ft)	12,671	12,276	11,299	10,130
Total net sediment deposited (acre-ft)	NA	395	1,372	2,541
Average annual deposits (acre-ft/yr)	NA	45.14	30.82	38.50
Annual deposits per square mile watershed area ((acre-ft/mi^2)/yr)	NA	.27	.18	.23
Storage volume loss (percent)	NA	3.12	10.83	20.05

By 1992, 2,541 acre-ft (slightly more than 20 percent) of the original storage volume in Lake Michie had been lost to sediment deposition (table 4). Over the entire life of the reservoir, the average annual deposition rate was 38.5 acre-ft/yr. Examination of the sedimentation rates between surveys provides estimates of how rates may have changed over time (table 5).

Table 5. Summary of net sediment deposition in Lake Michie in periods between surveys (modified from Maki and Hafley, 1972)

[Storage volumes taken from table 4. Acre-ft, acre-foot; acre-ft/yr, acre-foot per year; acre-ft/mi^2/yr, acre-foot per square mile per year; percent/yr, percent per year]

Computation with 1970 storage volume			
	April 1926 to January 1935	January 1935 to October 1970	October 1970 to April 1992
Time period (years)	8.75	35.75	21.5
Net sediment deposited, or storage volume loss (acre-ft)	395	977	1,169
Average annual deposits (acre-ft/yr)	45.14	27.32	54.37
Annual deposits per square mile watershed area ((acre-ft/mi^2)/yr)	.27	.16	.33
Storage volume loss per year (percent/yr)	.36	.22	.43

Computation without 1970 storage volume		
	April 1926 to January 1935	January 1935 to April 1992
Time period (years)	8.75	57.25
Net sediment deposited, or storage volume loss (acre-ft)	395	2,146
Average annual deposits (acre-ft/yr)	45.14	37.44
Annual deposits per square mile watershed area ((acre-ft/mi^2)/yr)	.27	.22
Storage volume loss per year (percent/yr)	.36	.30

When a calculation is made of the net amounts of sediment deposited during the periods between surveys, the average sedimentation rate computed for the most recent period (1970-92) increases significantly when compared to the rate computed for the previous period (1935-70). The average annual deposition between 1926 and 1935 was 45.14 acre-ft; between 1935 and 1970, the rate of average annual deposition decreased significantly to about 27.32 acre-ft (table 5, part 1). However, between 1970 and 1992, the rate of average annual deposition increased two-fold to 54.37 acre-ft.

In the Lake Michie watershed, the two factors that significantly control the amount of sediment delivered into streams and eventually into the reservoir, vary with time. These factors are (1) land use or cover and (2) the occurrence of large floods. Maki and Hafley (1972) attributed the decrease in Lake Michie's sedimentation rate after 1935 to three trends: (1) a decrease in the acreages of harvested cropland in the watershed (fig. 3), (2) improvements in soil conservation practices on those harvested croplands remaining in the watershed, and (3) the paving of rural dirt roads throughout the watershed. It is unlikely that the rate decreased significantly as reported between the 1926-35 and 1935-70 periods (table 5, part 1) because acreages of harvested cropland did not begin to decrease significantly until the mid-1950's. Because the Lake Michie watershed has remained mostly rural with no significant increase in urban or agricultural activity in the 1970-92 period, it is unlikely that the sedimentation rate increased by such a magnitude from the 1935-70 period.

Examination of streamflow data at site 1 (discussed in more detail in the section on Cs-137 and Pb-210 profiles in lake-bottom sediment) did not indicate a higher occurrence of large floods during the 1970-92 period as compared to the earlier period. Thus, the two-fold increase in sedimentation rate during the latter period is subject to some uncertainty as a result of uncertainty associated with the storage value reported for 1970.

If the storage volume reported for 1970 is not considered, then the average annual deposition during the 1935-92 period is 37.44 acre-ft (table 5, part 2). This rate is in better agreement with the rate computed for 1926-35. Additionally, the magnitude of the decrease between rates computed for the 1926-35 and 1935-92 periods is considered more likely in view of the land-use patterns (discussed earlier in this report) that have occurred in the Lake Michie watershed.

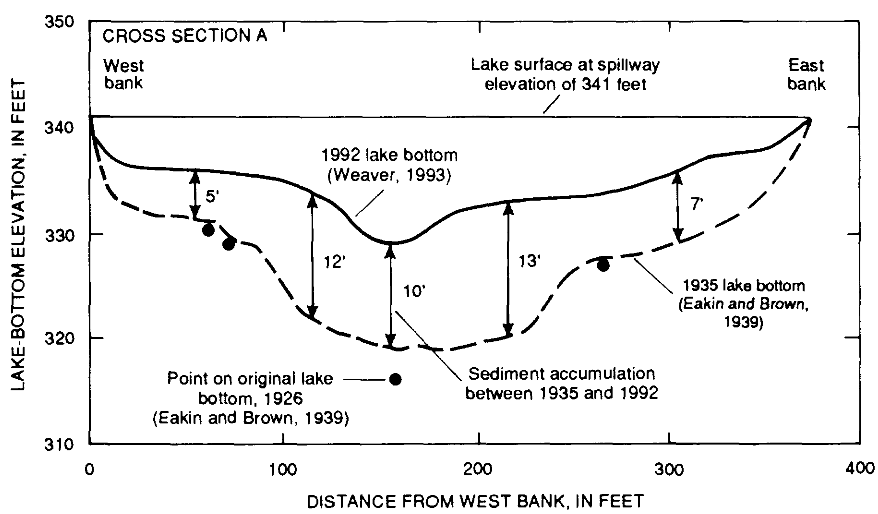
Because of the similarities in magnitudes of sedimentation rates and lengths of periods reported (tables 4 and 5), the 1992 average sedimentation rate in Lake Michie is rounded to 38 acre-ft/yr. It is possible that the 1992 rate is less than 38 acre-ft/yr. However, pending future surveys of the lake bottom, the magnitude of the difference between the 1992 average sedimentation rate and the average rates estimated for the other periods cannot be determined.

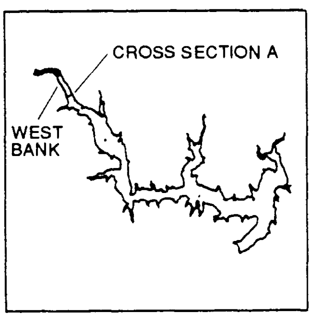
Variation in annual runoff and the magnitude and frequency of floods also offer some insight into the variability of sedimentation rates over time. The effect of variation in runoff on average sedimentation rates is addressed in more detail in the section discussing radionuclide profiles.

Sedimentation Rates from Accretion in Cross Sections

The thicknesses of the sediment are greatly variable throughout Lake Michie, and sediment rates from accretion vary. Near the shoreline, sediment thicknesses range from less than 1 ft in steeper areas to 5 or 6 ft in flatter areas in the upper third of the lake. Along the thalweg, sediment thicknesses range from 5 to 10 ft near the dam to about 15 ft in the headwaters of the lake. The maximum thicknesses consist of predominately sandy deposits upstream from the SR 1616 bridge.

At five locations, ranging from upstream from the SR 1616 bridge to a point near the dam, cross sections of the lake bottom in 1935 (Eakin and Brown, 1939) and in 1992 were compared to show the magnitude and variability of sediment deposition across the section (figs. 14-18). The points where the original lake bottom was probed in the 1935 survey also are shown for each cross section. However, the number of these points are not sufficient to draw a profile of the lake bottom in 1926. For each cross section, sediment thicknesses and corresponding sediment accretion rates are estimated at various points and an overall percentage of the loss in cross-sectional area between 1935 and 1992 is determined. The perspective of each cross section is that of looking upstream.





LOCATION OF CROSS SECTION A
IN LAKE MICHIE

Figure 14. Lake-bottom profiles for 1935 and 1992 at cross section A.

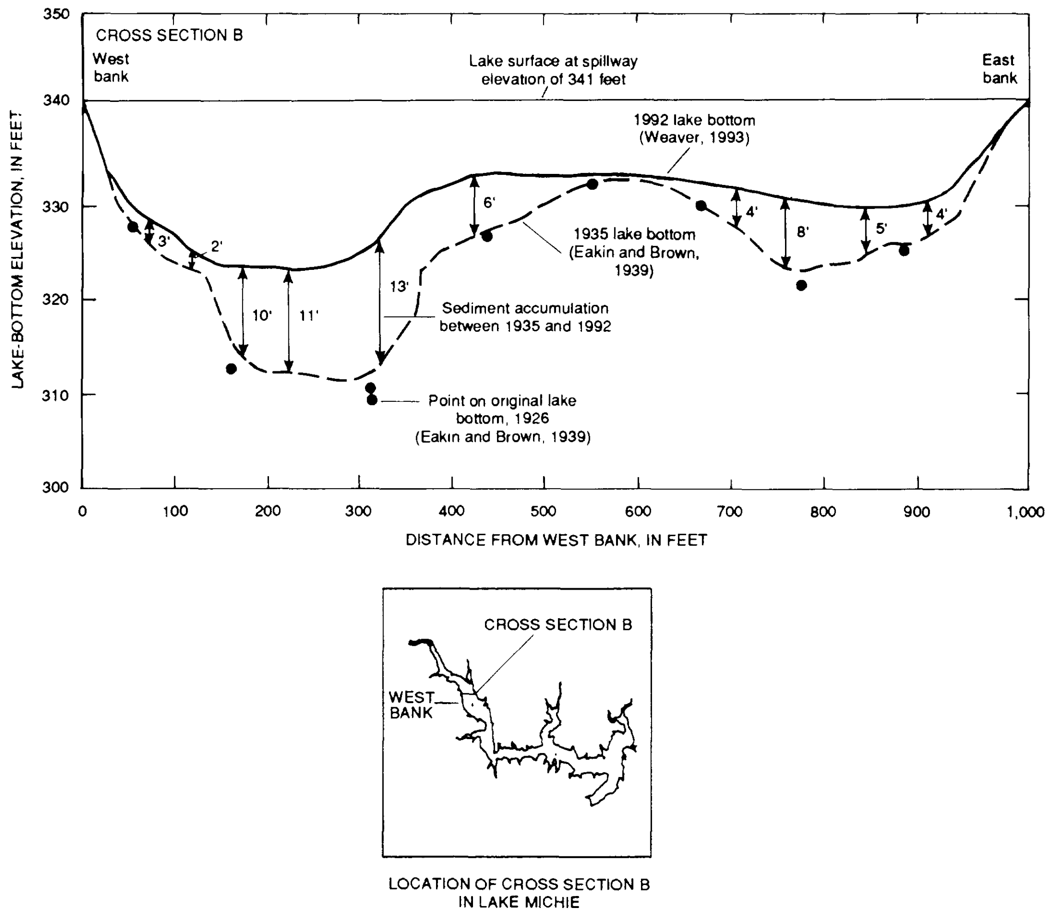


Figure 15. Lake-bottom profiles for 1935 and 1992 at cross section B.

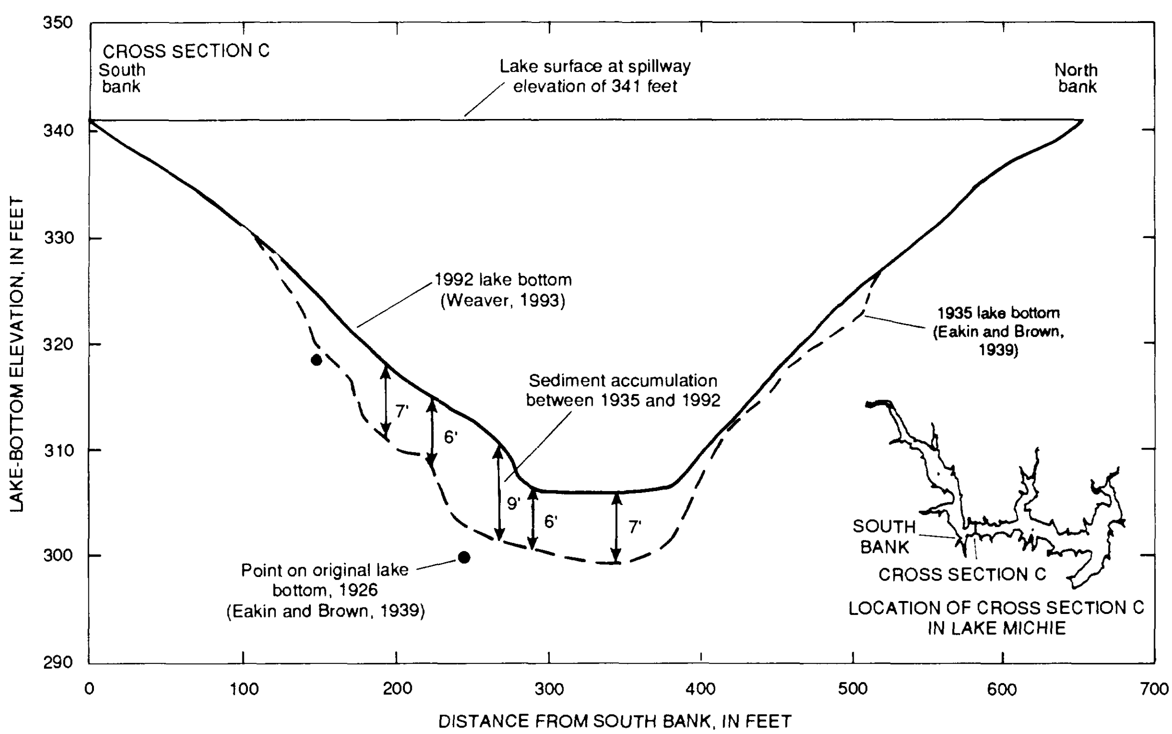


Figure 16. Lake-bottom profiles for 1935 and 1992 at cross section C.

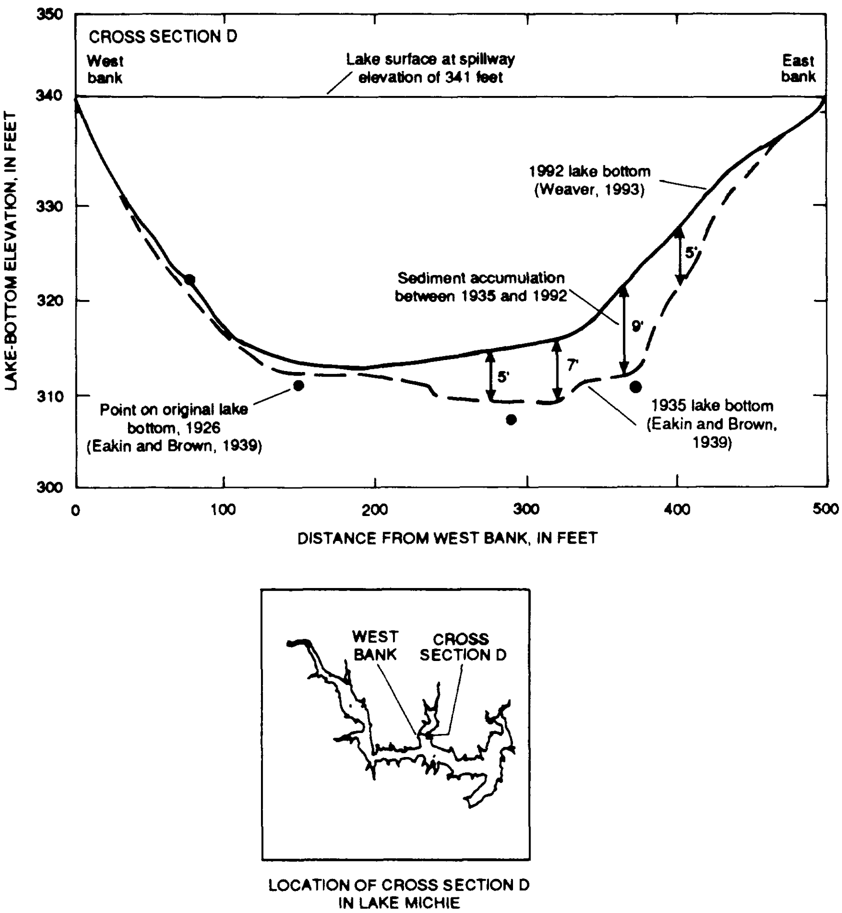


Figure 17. Lake-bottom profiles for 1935 and 1992 at cross section D.

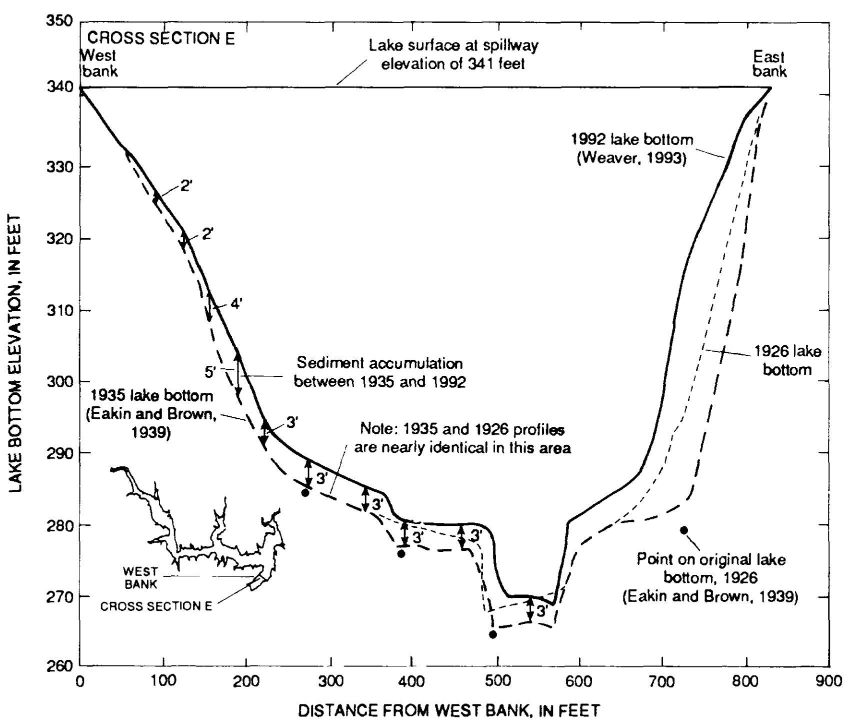


Figure 18. Lake-bottom profiles for 1926, 1935, and 1992 at cross section E.

Field notes from the 1935 survey were used to develop cross sections of the lake bottom for that year and to show the points where the original lake bottom was probed. Cross sections from the most recent bathymetric map (Weaver, 1993) were superimposed on the 1935 cross section. Cross sections A and E were obtained at the two range lines located in the field from the original notes. In three of the cross sections (B - D), field notes from the 1935 survey provided the observations needed to develop the cross section but did not provide enough information to locate precise horizontal positions of the range ends in the latest bathymetric map (Weaver, 1993). As a result, some error may exist in the estimates of the sediment thicknesses and the percentage of loss in cross-sectional area.

At cross section A upstream from the SR 1616 bridge, the most striking observation is the change of the thalweg since 1935 from a broad channel into a smaller 'V-shaped' channel that cuts into the sediment (fig. 14). Sediment ranges from about 10 ft thick at the center of the current thalweg to as much as 13 ft at points adjacent to the thalweg. Sediment thickness range from 5 to 7 ft thick on the right and left shelves near the shoreline. This corresponds to average sediment accretion rates during the period 1935 through 1992 ranging from 0.09 ft/yr on the shelves to 0.22 ft/yr in the thalweg. Between 1935 and 1992, the overall loss in cross-sectional area was nearly 56 percent. The heavier, coarser sediment carried into Lake Michie settles out in this area of the lake (fig. 14).

In the area of the lake adjacent to the boat house, sediment thicknesses in the main thalweg at cross section B range from 10 to 13 ft and from 2 to 8 ft in the old floodplain and in the secondary thalweg (fig. 15). Thus, the corresponding average sediment accretion rates range from 0.03 ft/yr to 0.22 ft/yr. The hump in the middle of the 1935 cross section is the lake bottom just upstream from a small island located in this area. The loss in cross-sectional area between 1935 and 1992 is about 34 percent.

Downstream from the 90-degree bend in the lake at cross section C, sediment thicknesses range from 6 to 7 ft in the thalweg to 9 ft in the old floodplain (fig. 16). Thus, average sediment accretion rates range from 0.10 to 0.16 ft/yr. As discussed earlier, the sediment downstream from the 90-degree bend is almost all silt and clay (> 98 percent). The overall loss in cross-sectional area between 1935 and 1992 is nearly 13 percent. The 90-degree bend not only restricts the type of sediment reaching this area, but also appears to limit the amount.

The 1935 and 1992 profiles in the Dry Creek tributary at cross section D indicate that sediment tends to settle on the side of the channel nearest the east bank (fig. 17). The sediment thicknesses range from 5 to 9 ft and correspond to average sediment accretion rates ranging from 0.09 to 0.16 ft/yr. The overall loss in cross-sectional area is about 14 percent. The existence of larger sediment thicknesses on the east side of the cross section is most likely a result of larger scour forces on the west side during periods of high streamflow. The curvature of the thalweg in this tributary indicates that much of the stream's momentum is thrust to the outside of the curve (in this case, the west side of the cross section). Thus, higher velocities occur on the west side of the cross section which carry sediment downstream rather than allow it to settle out in this section.

At cross section E located about 1,000 ft upstream from the dam, sediments range from about 3 ft thick in the thalweg to 2 to 5 ft thick on the western shelf, which corresponds to average sediment accretion rates of 0.03 to 0.09 ft/yr (fig. 18). On the eastern shelf, the 1935 and 1992 profiles indicate that more than 20 ft of sediment has been deposited in that period.

Cross section E is marked by monuments that were established prior to 1926 and was surveyed several times between 1926 and 1935 (Durham Water Works, 1923). Thus, the 1926 lake bottom was reconstructed at this cross section. The 1926 and 1935 profiles are almost identical on the western shelf; however, the 1926 profile is higher than the 1935 profile (fig. 18). The overall loss in cross-sectional area between 1926 and 1992 is nearly 11 percent.

Because the lake bottom at cross section E, as surveyed in 1935, indicates scour on the eastern shelf when compared with the 1926 lake bottom, Eaken and Brown (1939) discussed the possibility of erroneous elevations used in the 1926 survey. Whether the 1992 cross section is compared with that of 1926 or 1935, it is unlikely that sediment thicknesses of 20 ft or more lie on the eastern shelf (fig. 18). Because the slope of the eastern shelf is steeper than that of the western shelf, sediment thicknesses on the east side of the cross section are more likely in the range of those on the west side, if not less. Thus, the actual loss in cross-sectional area is possibly in the range of 7 to 10 percent.

Below is a brief table that summarizes the ranges of accretion rates from the 1935-92 profile overlays at all cross sections. Beside each range of accretion rates is the average rate for that section. The ranges are computed from the depths shown in the overlays (figs. 14-18). Thus, the value listed as the minimum end of the range is not necessarily the actual minimum in the cross section because smaller sediment thicknesses can be found near the shorelines in each cross section.

Cross section	Range in accretion rates, in ft/yr	Average accretion rate, in ft/yr
A	0.09 to 0.22	0.17
B	.03 to .22	.11
C	.10 to .16	.12
D	.09 to .16	.11
E	.03 to .09	.05
All sections	.03 to .22	.10

As seen in the above table, the range of accretion rates decreases from the upstream end of the lake to the downstream end. The overall average accretion rate for Lake Michie, not taking into account the spatial variations as indicated by the cross sections, is 0.10 ft/yr.

Cesium-137 and Lead-210 Profiles in Lake-Bottom Sediment

Analysis of radionuclide profiles, a radiochemical technique successfully used in many studies, was employed with three sediment cores collected from Lake Michie. Sediment cores LM 1, LM 8, and LM 7 (fig. 2) represent sediment deposited in the upper, middle, and lower parts of the lake, respectively. The cores were retrieved from areas where sediment was believed not to have been subject to resuspension and were analyzed for the presence of Cs-137 and excess Pb-210 radioisotopes. However, as explained below, analysis of the radionuclide profiles indicate that resuspension may have occurred at one of the cores.

The determination of sediment accretion rates is based on the property of some radioisotopes to attach themselves to suspended-sediment particles that enter the lake and eventually settle on the lake bottom. Where this sediment remains undisturbed, the radioisotopes provide a somewhat permanent record of deposition and permit the computation of historical sediment accretion rates.

As discussed in the previous section and shown in figures 14-18, sediment accretion rates vary throughout the lake and within individual cross sections. Knowledge of the accretion rate at a point in a cross section as represented by an individual core does not necessarily provide an average rate for the entire cross section, but it can provide insight as to how the rate could have changed over time.

Cs-137 is a by-product, that does not occur naturally, of the nuclear weapons testing program after World War II. It has a half-life of 30 years. Cs-137 activity reached detectable limits in the environment in the late 1950's, it peaked in 1962, and has since been declining as a result of the 1963 Nuclear Test Ban Treaty. During the time in which Cs-137 reached peak activity, it had accumulated in soils and, therefore, became a detectable part of the suspended-sediment loads of rivers and streams. In a core collected from an undisturbed sediment deposit, the point of the maximum activity of Cs-137 is interpreted as the approximate location of the lake bottom in 1962. The average sediment accretion rate since 1962 based on Cs-137 analysis of the cores retrieved in 1992 is determined by dividing the length of the core above the 1962 "marker" by 31 years.

Estimates of average sediment accretion rates based on analysis for Cs-137 were computed for two periods, 1962-92 and 1926-62. Because none of the three cores penetrated the original lake bottom, the accretion rates for the period 1926-62 are minimum estimates because of the uncertainty associated with the thickness of sediment remaining below the bottom of each core. These minimum estimates are calculated by assuming that penetration of the original lake bottom would have occurred if less than 0.01 ft of more sediment had been recovered. In all computations of accretion rates using Cs-137, no consideration was given to the possibility of a time lag between the peak of Cs-137 activity as detected in the atmosphere and the peak of Cs-137 activity in the lake-bottom sediment (David DeMaster, North Carolina State University, oral commun., 1994).

Other assumptions were made during the computation of accretion rates based on Cs-137 as well as Pb-210 radionuclides. Compaction of sediment layers in the cores (the result of core retrieval and handling, or natural settling under the weight of increasing sediment thicknesses) was assumed to be negligible. All efforts were made during coring operations to minimize compaction of sediment layers during retrieval and handling (S.W. Snyder, North Carolina State University, oral commun., 1992). Compaction of sediment layers as a result of the natural settling of deposits over time would affect the bottom layers in a core. No consideration of compaction would produce estimates of accretion rates for the 1926-62 period at Lake Michie that tend to be lower estimates of the actual rates.

No chemical migration of Cs-137 or Pb-210 radionuclides was assumed to have occurred after deposition, and physical or biological deep mixing of sediment layers was not considered during the computation of accretion rates. The effect of migration or mixing of radionuclides in the sediment layers would be to over-estimate the actual accretion rates. As stated earlier, the cores did not appear to have been subject to bioturbation (S.W. Snyder, North Carolina State University, written commun., 1992). Additionally, given the location of the cores LM 8 and LM 7 in Lake Michie, significant physical mixing is unlikely because of low-velocity conditions in the lower half of the lake.

In core LM 1, the maximum activity of Cs-137 was interpreted approximately 1.8 ft below the surface of the lake bottom (fig. 19A), yielding an average sediment accretion rate of 0.058 ft/yr for the 1962-92 period. However, particle-size distributions show a general coarsening upward in core LM 1 (fig. 11), which indicates that velocities high enough to carry sand and heavier sediment from the headwaters could also be high enough to cause some mixing and resuspension of existing sediment in this area. As a result, the 1962-92 accretion rate for LM 1 as computed from Cs-137 radionuclide analyses is not considered as reliable as those reported for cores LM 8 and LM 7 where sediment does not appear to have been subject to remixing. Furthermore, because of the possible resuspension and mixing of sediment, any estimation of sediment accretion rates for the 1926-62 period is unlikely to be accurate and therefore was not done.

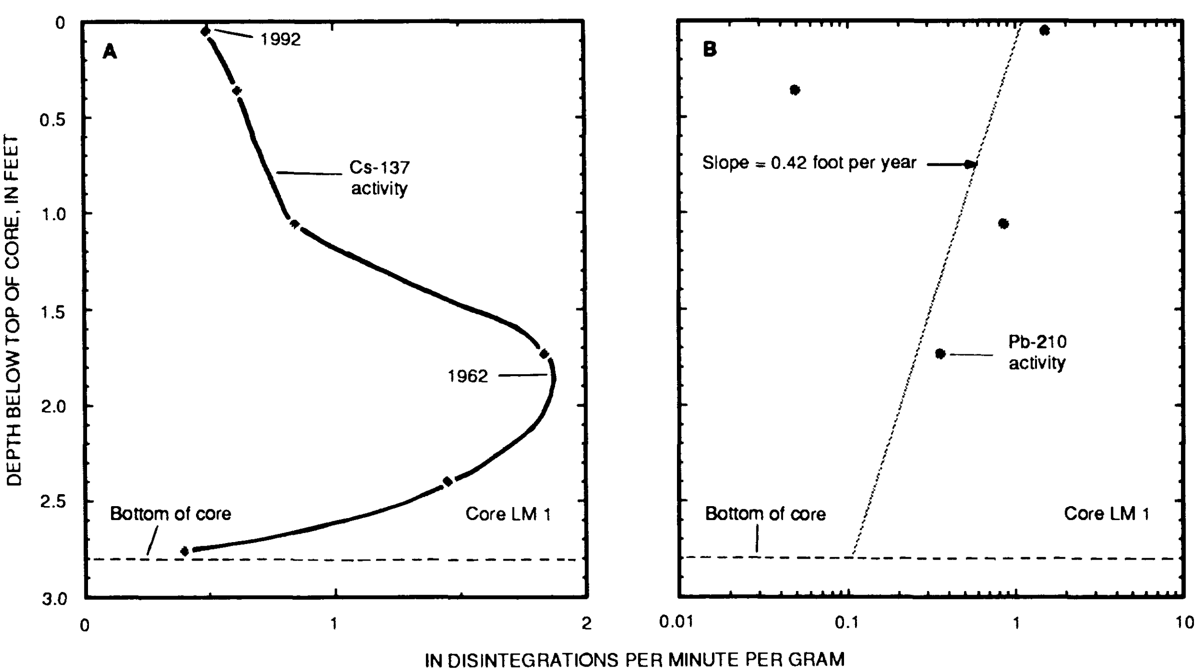


Figure 19. Relations between (A) sediment depth and Cs-137 activity and (B) sediment depth and excess Pb-210 activity in core LM 1.

In core LM 8, retrieved near the midpoint of Lake Michie, the maximum activity of Cs-137 was interpreted at a depth of approximately 1 ft below the top of the core (fig. 20A). Thus, during the period 1962-92, the average sediment accretion rate was 0.032 ft/yr. The length of core remaining between the point of maximum Cs-137 activity and the bottom of the core is 1.7 ft. Thus, the minimum estimate of accretion rate for the period 1926-62 is 0.046 ft/yr. This minimum estimate is considered reliable because sediment in this area does not appear to be subject to resuspension or bioturbation. The higher estimate for the earlier period indicates that accretion rates were higher than those of the 1962-92 period and probably reflective of a greater degree of agricultural activity in the basin during the lake's early years.

The maximum activity of Cs-137 in core LM 7 was interpreted at about 1 ft below the top of the core (fig. 21A). Thus, the average sediment accretion rate for the 1962-92 period is 0.032 ft/yr. With 1.7 ft of sediment between the point of maximum Cs-137 activity and the bottom of the core, the minimum estimate of accretion rate for the period 1926-62 is 0.046 ft/yr. Both of these rates are identical to those computed from LM 8 and further indicate that accretion rates during the 1926-62 period were higher than rates occurring during the 1962-92 period.

Further evidence to indicate that sediment accretion rates were higher prior to 1962 is provided by comparison of accretion rates in the current thalweg for cross sections C and E (figs. 16 and 18) and the rates based on analysis of Cs-137 in cores LM 8 and LM 7 for the 1962-92 period. In cross section C (fig. 16), the sediment thickness in the thalweg for the period 1935-92 is about 7 ft and corresponds to an average accretion rate of nearly 0.12 ft/yr for that period. Sediment thicknesses in the thalweg of cross section E (fig. 18) are about 3 ft, which correspond to an accretion rate of 0.05 ft/yr for the 1935-92 period. Because the locations of cores LM 8 and LM 7 are near cross sections C and E, respectively, it is likely that accretion rates during the 1962-92 period at these cross sections are similar to the rate of 0.032 ft/yr reported for LM 8 and LM 7. This comparison further indicates that accretion rates and, thus, overall sedimentation rates throughout Lake Michie, must have been higher prior to 1962 in order for the accretion rates to have attained numerical values ranging from 0.05 to 0.12 ft/yr for the 1935-92 period at cross section C and E.

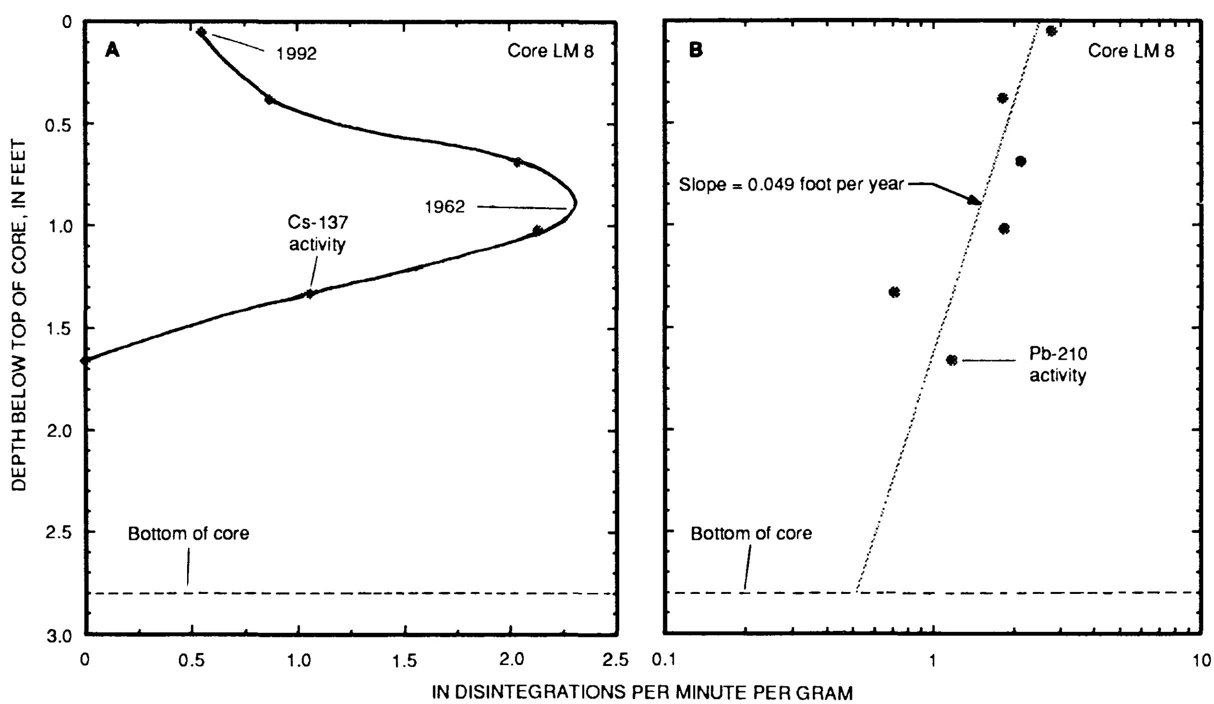


Figure 20. Relations between (A) sediment depth and Cs-137 activity and (B) sediment depth and excess Pb-210 activity in core LM 8.

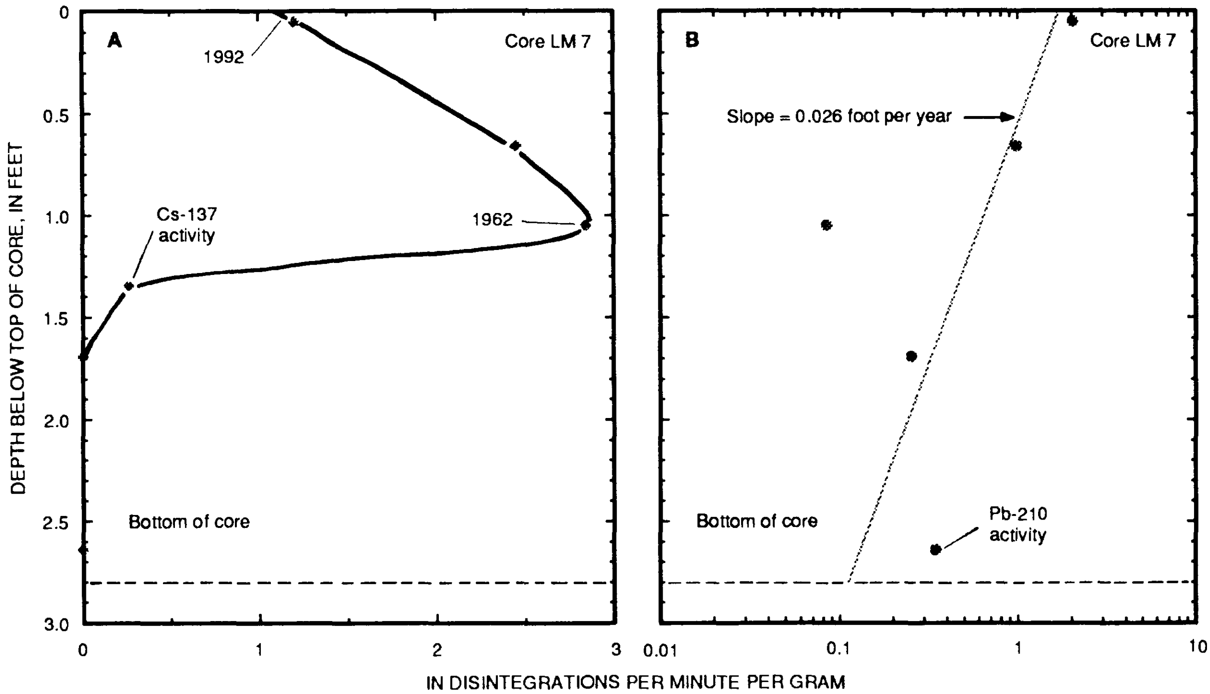


Figure 21. Relations between (A) sediment depth and Cs-137 activity and (B) sediment depth and excess Pb-210 in core LM 7.

Pb-210 is the by-product of a process that begins with the radioactive decay of radium-226, naturally occurring in soils, into radon-222, a gas which is dispersed into the atmosphere. Radon-222 decays into Pb-210 which reenters soil and waterways as fallout in precipitation and dryfall. Pb-210 has a half-life of 22 years. Pb-210 is termed "excess" when it represents the amount of Pb-210 that is added to the naturally occurring Pb-210, which is already present in sediment. The activity of excess Pb-210 is maximum at the surface of the lake bottom and decreases to background levels of naturally-occurring Pb-210 in deeper sediment. This technique can date sediment as old as 150 years. Commonly, the excess Pb-210 activity of a number of core subsamples is plotted against the depth of the subsample. The accretion rate based on Pb-210 is derived from a sediment advection-diffusion equation which is based on steady-state input of the radionuclide and contains a factor for deep mixing (Goldberg and Koide, 1962).

Estimates of average sediment accretion rates based on analysis of excess Pb-210 were computed for the entire lengths of the recovered cores. These rates ranged from 0.026 to 0.049 ft/yr (figs. 19B, 20B, and 21B). Accretion rates based on analysis of the Pb-210 radionuclide represent overall accretion rates for the entire length of core.

As discussed earlier, the 1962-92 accretion rate computed for core LM 1 using Cs-137 radionuclides is subject to uncertainty because of possible resuspension and mixing of sediment. Likewise, the rate of 0.042 ft/yr from Pb-210 analysis is not considered representative of the overall average accretion rate for core LM 1. Accretion rates for cores LM 8 and LM 7, 0.049 and 0.026 ft/yr, respectively, are considered to be in reasonable agreement with those computed for the period 1962-92 using the Cs-137 analysis (S.W. Snyder, North Carolina State University, written commun., 1992). Reasonable agreement of the results from the Pb-210 and Cs-137 analyses provide a level of quality assurance to attach to the Cs-137 rates. However, the excess Pb-210 analyses did not permit any conclusions concerning changes of the sedimentation rates within each core. Additional subsamples from each core would need to be analyzed in order to determine changes in accretion rates based on Pb-210.

Comparison of all accretion rates computed using either Cs-137 or Pb-210 with those shown in the table on page 24 indicate that the two methods (profile overlays and radionuclide analyses) used to compute the rates have produced values that fall into a narrow range. Thus, although the accretion rates based on Cs-137 and Pb-210 are subject to error if previous assumptions are incorrect, the magnitude of error is not likely to be great, and rates for the two methods compare favorably.

Flow-duration characteristics at site 1, the main inflow to Lake Michie, also provide evidence to support the conclusion that land-use changes have been the chief cause of changes in sediment accretion rates. Flow durations analyzed using the complete 1926-91 record (1926-62 and 1963-91) did not indicate that runoff rates in the 1926-62 period were higher than the 1963-91 period, and, thus, a cause of higher accretion rates. The average number of days for each water year in which daily mean discharge exceeded 200 ft^3/s was 40 and 41 days for the 1926-62 and 1963-91 periods, respectively. Furthermore, the average number of days for each water year in which daily mean discharge exceeded 1,000 ft^3/s were 9 and 7 for the same periods, respectively. Although the average number of days for the daily mean discharge exceeding 1,000 ft^3/s is higher for the earlier period, there does not appear to be any significant difference between the two averages. Therefore, with minimal differences in runoff characteristics for this site during the periods of 1926-62 and 1963-91, changes in land-use patterns become the most likely cause of the higher accretion rates during the earlier period.

Comparison of Suspended-Sediment Yields

Sediment-transport curves developed for each of the three streamflow-gaging stations (fig. 2, sites 1-3) were used to estimate annual suspended-sediment yields for each water year from 1983 to 1991 (table 6). As a result, the computations provide a basis for estimating the amount of suspended sediment trapped by the lake. In computing sediment yields into and out of Lake Michie, no adjustment was made to estimate the percentage of bed-load passing each station.

No estimates for suspended-sediment yields before 1983 were computed at any of the sites because of a lack of suspended-sediment samples for which sediment-transport curves could be developed. Additionally, suspected changes in land use in the Flat River Basin during the lake's early years precluded any attempts to use current sediment-transport curves to estimate suspended-sediment yields during periods prior to 1983. At Dial Creek (fig. 2, site 2), the sediment-transport curve developed from data collected in 1990 and 1991 was applied to the 1983-91 period to estimate yields from ungaged basins surrounding the lake. Changes in land-use patterns in these smaller basins during the last 9 years do not appear to be as significant as changes in the entire Lake Michie Basin in the lake's 66-year history.

Table 6. Estimated inflow and outflow suspended-sediment discharge and trapped suspended sediment at Lake Michie, 1983-91 water years

[Tributary inflow was computed by prorating the suspended-sediment yields for site 2 from 4.71 to 13.5 mi^2 to estimate suspended-sediment inflow for ungaged drainage areas. Values from computations of estimated inflow suspended sediment are rounded; NA, not applicable]

	Inflow					Outflow				
	Flat River at Bahama (site 1)		Dial Creek near Bahama (site 2)		Other tributaries	Flat River below dam (site 3)		Estimated inflow and trapped suspended sediment		
Water year	Stream-flow runoff (acre-feet)	Estimated suspended-sediment discharge (tons)	Stream-flow runoff (acre-feet)	Estimated suspended-sediment discharge (tons)	Estimated suspended-sediment discharge (tons)	Stream-flow runoff (acre-feet)	Estimated suspended-sediment discharge (tons)	Estimated total inflow suspended sediment (tons)	Estimated suspended sediment trapped by lake (tons)	Estimated suspended sediment trapped by lake (percent)
1983	152,300	47,600	[a]4,500	500	1,500	162,800	5,500	49,600	44,100	89
1984	162,400	57,300	[a]4,800	600	1,800	173,400	5,800	59,700	53,900	90
1985	59,600	16,700	[a]1,800	140	400	47,900	1,400	17,200	15,800	92
1986	74,800	23,000	[a]2,300	300	900	67,300	1,900	24,200	22,300	92
1987	119,300	41,100	[a]3,600	1,000	2,900	126,300	4,000	45,000	41,000	91
1988	44,100	5,300	[a]1,400	27	73	34,400	920	5,400	4,500	83
1989	151,600	54,400	4,500	700	2,100	176,900	5,500	57,200	51,700	90
1990	109,200	28,400	3,700	160	460	136,600	5,100	29,000	23,900	82
1991	83,100	23,100	2,500	240	690	93,100	2,800	24,000	21,200	88
SUM:	956,400	296,900	29,100	3,670	10,820	1,018,700	32,920	311,400	278,500	NA
AVERAGE:	106,300	33,000	3,200	410	1,200	113,200	3,700	34,600	30,900	89

[a] Estimated values for water years in which no streamflow data are available. Estimates were determined from regression of concurrent streamflow data at sites 1 and 2 for the 1926-71 and 1990-91 water years.

To compute suspended-sediment inflow from ungaged basins tributary to Lake Michie, the suspended-sediment yields for Dial Creek during 1983-91 were used. Areal photographs of the Dial Creek and ungaged basins show that land-use patterns appear to be similar. Divided by its drainage area (4.71 mi^2), the estimate of total suspended-sediment yield per square mile at Dial Creek during 1983-91 is nearly 800 tons/mi^2. Multiplying this value by 18.2 mi^2, the drainage area of Dial Creek plus the ungaged basins, the estimated suspended-sediment yield entering the lake from all tributaries during 1983-91 is 14,500 tons (table 6). Added to the suspended-sediment yield contributed by the main inflow, Flat River upstream from Lake Michie, the total suspended-sediment inflow into Lake Michie during 1983-91 is estimated to be 311,400 tons.

The estimated annual suspended sediment trapped by the lake during 1983-91 was computed by taking the difference between the inflow and outflow suspended-sediment yields. The estimated annual suspended-sediment trapped in Lake Michie ranged from a minimum of 4,500 tons in the 1988 water year to a maximum of 53,900 tons in the 1984 water year (table 6). The estimated total suspended-sediment yield at the outflow during 1983-91 is about 33,000 tons. Thus, the total suspended-sediment trapped by the lake during the same period is 278,500 tons (table 6).

Estimates of suspended sediment deposited in Lake Michie should be regarded as a minimum estimate of the total sediment load that has been carried into the lake (Harned and Meyer, 1983). The estimates do not take into account the bedload sediment or sediment that is carried in the form of sheet runoff directly into Lake Michie.

Estimates of suspended-sediment yields can be subject to errors and bias introduced into computations by the sediment-transport curves themselves. In the curves presented in this report (figs. 6-8), sediment-transport characteristics are defined for the range in discharge that occurred during the periods of sampling. However, a large percentage of the total sediment delivered by a stream during a given year is often carried by several flood flows. At sites 1 and 2, no suspended-sediment samples were collected at extremely high discharges recognized as being flood levels.

The method used to compute suspended-sediment yields also introduces a source of bias into the estimates. As stated previously, floods usually carry a large percentage of the sediment delivered by a stream. The sediment-transport method uses flow-duration characteristics of daily mean discharges. At site 1, the maximum daily mean discharge value used in the computations was nearly 9,900 ft^3/s, whereas 15 peak discharges exceeding 10,000 ft^3/s have been recorded since data collection began in 1926. Thus, estimates of suspended-sediment yields are less than the true yields.

Even though significant errors and bias can affect the estimates of suspended-sediment yields, there are advantages in using the suspended-sediment transport method. Estimates computed on a yearly basis provide some insight into the magnitude of sediment yields from year to year, especially if data are available to define sediment-transport conditions throughout the period of interest. The magnitude of yields contributed by the main inflow in relation to tributary inflow can be seen with the use of the sediment-transport method. At Lake Michie, suspended-sediment computations for 1983-91 indicate that slightly more than 95 percent of the suspended sediment was carried into the lake by the main inflow, Flat River, whereas the remainder was delivered by Dial Creek and other tributaries surrounding the lake.

Trap Efficiency for Lake Michie

The trap efficiency provides an estimate of the percentage of sediment that is trapped within a reservoir. Strand and Pemberton (1982) define trap efficiency as the ratio of the quantity of deposited (trapped) sediment to the quantity of inflow sediment. As discussed by Brune (1953), trap efficiency is based on a number of factors, which include the ratio of storage capacity to inflow, the age and shape of the reservoir, the type of outlets and methods of operation, the physical-size characteristics of sediment in the reservoir, and the behavior of finer sediment particles within the reservoir.

The trap efficiency presented in this report is an overall average trap efficiency for Lake Michie. The trap efficiency fluctuates depending on the lake level with respect to the spillway elevation. On the occasions when the lake level drops below the spillway elevation, the trap efficiency is closer to 100 percent. Conversely, when the lake level rises in response to increased streamflow, the percentage of suspended sediment passing over the spillway increases, thereby reducing the trap efficiency to levels of 70-80 percent.

Brune (1953) presents a technique for computing trap efficiency based on the capacity-inflow ratio. The capacity-inflow ratio is defined as the ratio of storage capacity of the lake to the average annual runoff. The lower the capacity-inflow ratio in a reservoir, the lower the trap efficiency will likely be. In comparing two reservoirs with identical runoff, the reservoir with the smaller capacity would have greater flow velocities throughout the length of the reservoir, thus allowing a greater percentage of suspended sediment to be carried over the spillway (Simmons, 1988). Hence, the trap efficiency would be smaller than that computed for another reservoir having a higher storage capacity. Brune (1953) reports that large reservoirs having storage capacities that equal or exceed the annual volume of water inflow tend to trap from 95 to 100 percent of sediment being carried into the lake.

During 1983-91, the average annual runoff from Flat River, upstream from Lake Michie, and other tributaries, including Dial Creek, was 118,600 acre-ft. At the crest of the principal spillway (341-ft elevation), the storage volume for Lake Michie is 11,070 acre-ft (Weaver, 1993). Thus, the capacity-inflow ratio is 0.0933. However, the storage volume used by Brune (1953) was based on data collected in the 1935 survey and was computed using the Range Method at a spillway elevation of 340.0 ft. As presented earlier, the 1992 storage volume of Lake Michie at the spillway elevation of 340.0 ft, which was computed using the Range Method, is 10,130 acre-ft. Using the adjusted storage volume, the capacity-inflow ratio is 0.0853. Using the median trap-efficiency curve for normal-ponded reservoirs developed by Brune (1953), the current trap efficiency is about 85 percent and is representative of all sediment (bedload and suspended) trapped in Lake Michie. By comparison, Brune (1953) reported a capacity-inflow ratio of 0.0998 for Lake Michie using the storage-capacity and runoff values computed by Eakin and Brown (1939) during the 1935 survey. Brune (1953) plotted the 1935 median trap-efficiency value for Lake Michie at 86 percent.

Although trap efficiency computed for 1983-91 compares favorably with that computed by Brune (1953) using 1935 data, it is an underestimate of the actual trap efficiency for Lake Michie during 1983-91. The percentage of suspended-sediment trapped by the lake ranged from 82 percent in the 1990 water year to 92 percent in the 1986-87 water years (table 6). During 1983-91, the overall average was 89 percent (table 6). Common experience has shown that almost all bedload carried from a drainage basin into a reservoir is trapped within the impoundment. Therefore, the existence of trap efficiency at 85 percent for all sediment and 89 percent for only suspended sediment cannot be possible. As a result, the overall trap efficiency for Lake Michie for 1983-91 was greater than 89 percent.

SUMMARY

This report describes the effects of sedimentation on 508-acre Lake Michie by characterizing the sediment deposited in the lake and by presenting estimates of historical and current sedimentation rates. Lake Michie, located in northeastern Durham County in the northeastern Piedmont Province of North Carolina, has a storage capacity of 11,070 acre-ft at spillway elevation of 341 ft and is one of two water-supply sources for the City of Durham.

The drainage basin has remained predominately rural since Lake Michie was completed in 1926. The only significant change in land use is a decrease in agricultural activities. Land-use data indicate that farming activities in the basin peaked in the early 1950's, and the extent of croplands decreased significantly by the mid-1970's. The land-use data further show that most croplands have reverted to pasture, shrub land, and forest; as a result, the soil cover has stabilized and the extent of erosion has been reduced. In addition, conservation measures implemented in the late 1950's continue to help control soil erosion.

Two of eight soil associations identified in the Flat River Basin by the SCS occupy 75 percent of the basin. The largest soil association, the Georgeville-Tatum-Herndon association, occupies nearly 64 percent of the basin and consists of well-drained, moderately deep to deep, clayey soils derived from residuum weathered from slate. The second largest association, the Enon-Helena-Vance association, is well-drained and consists of moderately deep to deep soils derived from residuum weathered from acid or basic rocks.

In the Upper Neuse River Basin, 65 percent of the gross erosion originated from croplands which accounts for nearly 13 percent of the total drainage basin area (U.S. Soil Conservation Service, 1983). The Flat River Basin is part of the headwaters for Upper Neuse River Basin and, therefore, erosion rates in the latter are likely applicable to the former. Erosion rates of 12 (tons/acre)/yr or less and greater than 12 (tons/acre)/yr comprised 36 and 29 percent of the gross erosion, respectively, documented in the SCS study.

Streamflow data were collected at three gaging stations adjacent to Lake Michie. Mean daily discharges from two inflow stations, Flat River near Bahama, and Dial Creek near Bahama, and one outflow station, Flat River at dam near Bahama, were used to determine flow-duration characteristics for the 1983-91 water years.

Suspended-sediment samples were collected at each of the three gaging stations and used in conjunction with duration characteristics to estimate suspended-sediment yields into and out of Lake Michie for the 1983-91 water years. A total of 243 samples from the three stations were used in the analysis. Thirty-nine samples were collected at Flat River near Bahama during 1969-78 and 1988-91, 102 samples were collected at Flat River at the dam near Bahama during 1983-91, and 102 samples were collected at Dial Creek near Bahama during 1990-91.

Twelve cores of lake-bottom sediment were obtained at locations throughout the length of Lake Michie along or near the thalweg. Eleven of the 12 cores were subsampled and analyzed for particle-size distributions to determine sediment characteristics and to obtain some indication of the spatial distribution of sediment on the lake bottom. Sand composes a significant percentage of the sediment (50 to 65 percent) upstream from the SR 1616 bridge where, during flood flows, the narrow width of the lake maintains velocities that keep small particles of sand, along with silt and clay, in suspension. Most of the remaining sand carried past the SR 1616 bridge is deposited along with silt in the area of the lake adjacent to the boat house and dock. At the 90-degree bend in the lake's thalweg (approximately 3/4 mile downstream from the boat house and dock), almost all sand carried into Lake Michie has settled and the lake-bottom sediment is dominated by silt and clay. From the 90-degree bend to the dam, the percentage of silt and clay is more than 98 percent. The average specific weight for lake-bottom sediment in Lake Michie is 73.6 lbs/ft^3.

Analyses for TOC and C:N ratios were conducted on three cores of lake-bottom sediment to provide some measure of the percentage of organic material in the sediment and to identify the primary source of this material in Lake Michie. The percentages of organic material in the sediment ranged from 1.05 to 3.81 percent among the three cores (LM 1, LM 8, and LM 7) analyzed. The C:N ratios ranged from 8.6 to 17.3. Plant debris carried into the lake from the drainage basin usually have C:N ratios in the range of 20 to 200. However, after decomposition, the C:N ratios decrease to the range of 10 to 13. Most of the C:N ratios determined in the sediment from Lake Michie occur in this range. The range of C:N ratios also indicate that phytoplankton is not a primary source of organic material in Lake Michie. C:N ratios for phytoplankton range from 6 to 8.

Comparison of the most recent bathymetric volume to previous volumes allowed for the computation of sedimentation rates in units of volume over time. As of 1992, 2,541 acre-ft of sediment had been deposited in Lake Michie which represents a nearly 20 percent loss from the original storage volume. Storage volumes computed for the years 1926, 1935, and 1970 were compared to the most recent storage volume computed in 1992. However, the 1970 storage volume was not used in estimating sedimentation rates because of some uncertainty in the reported storage volume and its effect on computations of average deposition rates. The average annual deposition rates during the cumulative periods of 1926-35 and 1926-92 were 45.1 and 38.5 acre-ft, respectively. The average deposition rates during the intervening periods of 1926-35 and 1935-92 were 45.1 and 37.4 acre-ft/yr, respectively. The average deposition rate for 1992 is rounded to 38 acre-ft/yr. The decrease in the deposition rate from 45.1 to 38 acre-ft/yr in the latter period is likely attributable to the decrease in agricultural activity in the drainage basin after the mid-1950's.

The extent of sediment accretion was examined by comparing lake-bottom profiles for 1935 and 1992 at five cross sections in Lake Michie. Sediment thicknesses in the thalweg range from 10 to 13 ft in the headwaters of the lake and from 3 to 7 ft in the lower half of the lake. These thicknesses correspond to average accretion rates ranging from 0.05 to 0.22 ft/yr for the 1935-92 period.

Changes in sedimentation rates were further examined by computing sediment accretion rates based on Cs-137 and Pb-210 radionuclide profile analyses conducted on three cores of lake-bottom sediment. Average accretion rates for the 1962-92 period and minimum estimates or rates for the 1926-62 period were computed using the results of detection for Cs-137 activity in the cores. At the upstream core (LM 1), the average accretion rate for the period of 1962-92 was computed to be 0.058 ft/yr. The location in which core LM 1 was obtained is in an area where the lake bottom has been exposed during drought condition. In addition, evidence of coarsening upward within the core suggests that sediment is subject to forces strong enough to cause mixing and some possible resuspension. As a result, some doubt is cast on the reliability of the 1962-92 accretion rate presented for this core, and no minimum estimate of the accretion rate during the 1926-62 period was computed.

In cores LM 8 and LM 7, which were collected in areas where sediment was not subject to remixing, the differences between the average accretion rate for the 1962-92 period and the minimum estimated rate for the 1926-92 period indicate that accretion rates were higher in the early period. In core LM 8, collected near the midpoint in the main thalweg, the average accretion rate for the period of 1962-92 is 0.032 ft/yr while the minimum estimate for the 1926-62 period is 0.046 ft/yr. In core LM 7, the average accretion rate for the 1962-92 period is 0.032 ft/yr, and the minimum estimate for the 1926-62 period is 0.046 ft/yr. These identically higher accretion rates for cores LM 8 and LM 7 are evidence that rates were higher prior to 1962. The higher rates are attributed to the extensive agricultural activity in the drainage basin which resulted in more sediment being delivered to the lake. Comparison of the 1962-92 accretions rates for cores LM 8 and LM 7 with the average rates of sediment accretion in the thalweg during 1935-92 at cross sections C and E provides further evidence that accretion rates and, thus, overall sedimentation rates were higher in the lake prior to 1962.

The overall sediment accretion rates computed using the Pb-210 radionuclides were in reasonable agreement with those rates computed for the 1962-92 period using Cs-137 radionuclides. However, the rates computed using Pb-210 radionuclides did not provide any insight into changes in the accretion rates during the 66-year history of the lake.

Suspended-sediment transport relations developed for sites 1-3 and applied to the water year period of 1983-91, provided a basis for estimating the suspended sediment trapped by the lake during this period. The suspended-sediment transport relations used to compute the yields presented in this report are based on data collected during 1983-91. No data were available to define sediment-transport conditions at sites 2 and 3 for years prior to 1983. From 1983 through 1991, the estimated total inflow (adjusted to include ungaged drainage area) and outflow suspended-sediment yields are 311,400 and nearly 33,000 tons, respectively. The difference of 278,500 tons represents the suspended-sediment trapped in the lake during the same period. The resulting suspended-sediment trap efficiency for the 1983-91 period is 89 percent.

An overall trap efficiency for the 1983-91 period was computed using the capacity-inflow ratio as discussed by Brune (1953), and was determined to be 85 percent. However, the actual trap efficiency must be greater because the suspended-sediment trap efficiency should be numerically smaller than the overall trap efficiency. Therefore, the overall trap efficiency for Lake Michie during the period of 1983-91 was greater than 89 percent.

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CONVERSION FACTORS, VERTICAL DATUM, AND TEMPERATURE

Multiply	by	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer hectare
acre	0.4047	
	Volume	
cubic foot (ft^3)	0.02832	cubic meter
acre-foot (acre-ft)	1,233	cubic meter
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
	Mass	
pound avoirdupois (lb)	0.4536	kilogram
ton, short	0.9072	megagram
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter
ton per square mile (ton/mi^2)	0.3503	megagram per square kilometer
ton per acre per year ((ton/acre)/yr)	224	megagram per square kilometer per year

Temperature: In this report, temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by using the following equation:

$$°F = 1.8\ (°C) + 32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.