FACTORS GOVERNING INORGANIC TURBIDITY
IN A GREAT PLAINS RESERVOIR

By

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FACTORS GOVERNING INORGANIC TURBIDITY
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PREFACE

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CHAPTER I

THE RESEARCH PROBLEM

Introduction

High levels of suspended sediment contribute to the degradation of water quality in many aquatic systems. Reservoirs of the southern Great Plains region of the United States are particularly susceptible to inorganic turbidity problems which generally result from a combination of factors associated with geology, meteorology, and basin morphology. High turbidity levels not only lead to decreased aesthetic and recreational value of these impoundments, but also have definite effects on physical, chemical, and biological reservoir components (Wallen 1951, Schiebe et al. 1975, Grobbellaar and Stegman 1976). The United States Select Committee on National Water Resources (1960) identified sediment as the major water pollutant by volume and weight and emphasized the ability of suspended sediments to carry nutrients, pesticides, and pathogenic microorganisms.

Suspended sediments exert considerable influence on a number of water quality parameters. The ability of sediment to adsorb and transport nutrients (Green et al. 1978, Gloss et al. 1980) and heavy metals (de Groot 1976, Forstner 1976, Litherathy and Laszlo 1976) has been well-documented. Thorton et al. (1980b) described increased fecal coliform concentrations associated with storm waters of high turbidity. High levels of sediment loading in reservoirs often result in losses of storage capacity and increased cost of water treatment in impoundments used for municipal water supplies (Brown 1941, Paulet et al. 1972).

Biologists are particularly interested in the effects of turibidity on the biota of aquatic ecosystems. High concentrations of suspended material radically alter the degree of light penetration and may produce marked effects on primary productivity (Jewson and Wood 1975, Schwartzkopf and Hergenrader 1978, Gloss et al. 1980). These turbidity-induced reductions in primary productivity may be reflected throughout entire food chains in many aquatic systems. Turbidity also affects the survival, reproduction, and behavior of sport fishes (Wallen 1951, Hemistra et al. 1969) and influences aquatic predator-prey interactions (Vinyard and O'Brien 1976, Confer et al. 1978).

While the effects of high turbidity levels on various aspects of reservoir ecology are generating an increasing amount of research interest, few studies have attempted to assess quantitatively the actual causes of turbidity in these systems. An increased knowledge of the factors governing inorganic turbidity in impoundments would undoubtedly be of value in the construction of new reservoirs and in the management and possible restoration of reservoirs with existing turbidity problems.

Lake Carl Blackwell

Lake Carl Blackwell (LCB), located approximately 14 km west of Stillwater in Payne County, Oklahoma, was constructed in 1938 as part of a Federal Government Land Utilization Project. The reservoir has high turbidity which may be responsible for its reduced recreational usage (Howick et al. 1982). Fluctuating water levels, unprotected shorelines, runoff from the watershed, and direct exposure to wind all contribute to the turbidity problem of this impoundment.

Because of this turbidity problem, the Environmental Protection Agency funded a one-year diagnostic study of LCB under the Clean Lakes Program established by Section 314 of the Clean Waters Act. A major emphasis of the study concerned the collection of baseline limnological data to define the current physical, chemical, and biological conditions of the impoundment.

Turbidity values obtained during the study exceeded the state water quality limit for turbidity (25 NTU) except from October 1980 to March 1981. Turbidity levels were lowest at LCB during fall and winter, but increased drastically during spring and summer (Howick et al. 1982). High turbidity levels during spring and summer are particularly undesirable because recreational usage is highest during these seasons.

A multiple regression model was developed during the Clean Lakes Study to predict turbidity of LCB surface waters at various stations and times (Howick et al. 1982). Data for the model were processed by the Statistical Analysis System using a stepwise regression program. The model uses water depth, wind speed, precipitation, exposure, sediment particle size, and exposure:depth ratio as possible independent variables, and turbidity as the dependent variable. At best the model is able to explain 42% of the variance in turbidity. However, the model is based on limited data and requires further development.

Purpose of the Study

Because inorganic turbidity is a major problem at Lake Carl Blackwell and other reservoirs, the factors governing turbidity in this reservoir definitely merit further investigation. The present study was conducted with the following objectives:

1. To document temporal and spatial variations in turbidity in Lake Carl Blackwell.
2. To define the relative effects of water depth, wind velocity, fetch, precipitation, and sediment particle size on turbidity in Lake Carl Blackwell.
3. To expand and refine the existing LCB turbidity model.
4. To form a basis for predicting the usefulness and effectiveness of various lake restoration techniques in reducing turbidity in reservoirs.

CHAPTER II

LITERATURE REVIEW

Introduction

Information regarding sources of turbidity in reservoirs is essential for establishing effective reservoir construction, management, and restoration techniques. Equally important is an understanding of the effects of turbidity on physical, chemical, and biological parameters of reservoir limnology. While many researchers have described the effects of suspended sediment on various components of aquatic systems, relatively few studies have investigated the factors governing turbidity in specific impoundments.

Sources of Turbidity

Sediment Inputs

Turbidity problems in many reservoirs result from the transport of large amounts of sediment from the watershed. Sediment may be transported by sheet erosion of unprotected areas of the watershed or by erosion of stream banks during high flow periods (Brown 1941). Kennedy et al. (1980) described a ten-fold increase in suspended solids concentration of water entering Lake Red Rock, Iowa, following a period of heavy rainfall. Suspended silt carried by floodwaters into Lindleyspoor Dam, South Africa, increased surface water turbidity from

28 to 220 JTU (Jackson Turbidity Units) (Walmsley 1978).

The movement and distribution of water of varying densities due to solids concentrations play significant roles in reservoir hydrodynamics (Thornton et al. 1980a). Depending upon density differences between reservoir and inflowing waters, a water mass may enter a reservoir as an overflow, interflow, or an underflow. These flow patterns may produce a variety of vertical turbidity profiles exemplified by those reported for Lindleyspoor Dam, South Africa (Walmsley 1978). In December, 1975, floodwaters entered Lindleyspoor Dam as an underflow, resulting in an increase in bottom waters turbidity from 60 to 310 JTU. No apparent change in the turbidity of surface waters was observed. Drastic increases in surface water turbidity from 28 to 220 JTU following a later flood in January, 1976 indicated the movement of an overflow across the reservoir. An interflow was recorded during October, 1976 when a significant turbidity peak was observed between 10 and 14 m. Serruya (1977) reported the flow of turbidity currents along the top of the thermocline during summer stratification in Lake Kinneret, Israel.

A number of density current experiments designed to model underflows of turbid waters in reservoirs were conducted by Lambert and Luthi (1977). Results of these experiments indicate that the displacement of overlying water moved by turbidity currents may be responsible for the circulation and oxygenation of some lakes. Deposition from turbidity currents initiated by littoral sediment slumping accounts for approximately 50% of the total sediment accumulation in the central basin of Fayetteville Green Lake, New York (Lundlam 1974).

Because reservoirs typically have high drainage to surface area ratios, watershed land use and management practices have a great impact on sediment loading of impoundments. Brown (1941) cited increasing rates of deforestation, overgrazing, cultivation of oversteep slopes, and improper tillage as important factors contributing to the loss of storage capacity due to silting in many reservoirs. The degree of plant cover and grazing activity by livestock were found to be significant in determining turbidity levels in small Oklahoma farm ponds (Epperson 1972).

Sedimentation rates and the composition of sediments are also dependent upon the geology and soil types of the watershed (Paulet et al. 1972). Thus, the relative erodability of soil materials is an important consideration. Rhoton et al. (1979) demonstrated the differential erosion of clay particles from the watersheds of the Maumee River Basin by observing that sediments transported by runoff contained 18.4% more clay than watershed surface soils. A survey of Indiana and Illinois watersheds indicated that montmorillonite clays are more easily eroded than other clay materials (Lund et al. 1972). This is of particular importance since colloidal suspensions of montmorillonite clays have been cited as the major cause of turbidity in central Oklahoma reservoirs (Irwin and Stevenson 1951).

Sediment Resuspension

Another significant source of turbidity in many reservoirs is the resuspension of sediments by wind-induced water currents and wave action. Resuspension is of particular importance in shallow, exposed impoundments and may be influenced by a number of morphological, climatological, and hydrological factors. Hakanson (1977) cited such variables as wind velocity, duration and direction, fluctuating water levels, fetch, water circulation patterns, water depth, rate of sedimentation, sediment compaction, and lake bottom roughness as significant in determining the extent of sediment resuspension in a given system.

Several investigators have noted the effects of wind on turbidity in lakes and reservoirs. Chandler (1942) and Andrews (1948) reported increases in turbidity levels of western Lake Erie following periods of high winds. Changes in turbidity gradients from vertical to horizontal during mixing periods in Lake Hemlock, New York are partially the result of resuspension of sediments in shallow areas (Stewart and Martin 1982). Water depth and exposure to wind were cited by Epperson (1972) as important factors controlling turbidity in Oklahoma farm ponds.

The resuspension of loose sediments by wave activity was cited as the major cause of inorganic turbidity in Lake Chautauqua, Illinois (Jackson and Starrett 1959). In years when vegetation was sparse and ice cover was absent, turbidity varied directly with wind velocity. In years of heavy vegetation or ice cover, wind velocity was found to have little or no effect on turbidity levels. Resuspension was reported as high in areas of water depth less than 1.5 m but insignificant in areas where depth exceeded 1.8 m. These authors also recorded highest turbidities during low water level stages when large expanses of shoreline were susceptible to erosion. Similarly, Carter (1977) estimated that over 62% of the annual load of sediment to Lake Erie resulted from shoreline erosion.

Serruya (1976) identified resuspension as a significant process in Lake Kinneret, Israel, especially during turnover periods. Average amounts of trypton collected in sediment traps were greater by an order of magnitude than trypton inputs from the Jordan River, the major tributary to the lake. These differences were attributed to the resuspension and redeposition of in situ sediments. Drastic increases in sedimentation rates of deeper stations were observed during turnover periods, but sedimentation rates in shallow stations remained fairly constant throughout the year. Differences in the N:P ratios of Jordan River materials and in situ sediments were also used to determine the source of fluctuating suspended solids concentrations. The average rate of resuspension for Lake Kinneret of 897 g m^{-2} yr^{-1} was determined to be equivalent to the resuspension of the upper 2.9 mm of sediment.

Measurements of the redeposition of pollen grains were used by Davis (1968, 1973) to estimate rates of resuspension in a dimictic Michigan lake. Data obtained from core samples were used to calculate an average annual pollen deposition rate, and significantly higher pollen collection rates in sediment traps were attributed to the resuspension of pollen-containing sediment. The ratio of pollen deposition:input was estimated at approximately 4:1. Periods of the highest deposition in this lake were closely correlated with seasons of water mixing, and thermal stratification was identified as a major barrier to resuspension. Deposition values of 5 to 6 grains cm^{-2} day^{-1} during summer stratification increased to as high as 1,000 grains cm^{-2} day^{-1} during turnover. Extensive redeposition was observed in littoral areas, even during stratification periods.

Sediment resuspension and resulting increases in turbidity may also be caused by the rooting activity of fish or other organisms. Cahoon (1953) reported that the removal of carp (Cyprinus carpio) and various catfish species over a 5-year period from Lake Mattamuskeet, North Carolina, resulted in a gradual increase in transparency from 15 cm to 92 cm. Thompson and Bennett (1939) found that several Illinois lakes cleared after the removal of carp and other bottom-feeding species. Roiling by livestock and feeding waterfowl was reported as a significant cause of turbidity in several Oklahoma farm ponds (Epperson 1972).

Turbidity Effects

Water Temperature

The effects of turbidity on the temperatures of surface waters of reservoirs was investigated by Schiebe et al. (1975). Surface water temperatures were monitored in two adjacent impoundments with widely contrasting turbidity levels. On all sampling dates, water temperatures were lowest in the reservoir with the greatest turbidity. The loss of heat caused by the backscattering of solar radiation by suspended particles in the turbid reservior was believed to be responsible for these differences.

Loss of Storage Capacity

The loss of storage capacity caused by the transport and deposition of sediments is also a problem in reservoirs. Erosion and sediment delivery rates, trap efficiencies of the reservoir, and sediment bulk densities all determine the rate of storage capacity loss in reservoirs (Paulet et al. 1972). According to the United States Department of Agriculture (1973), of reservoirs built in the Great Plains states prior to 1935, 33% have lost 25 to 50% of their original capacity, 14% have lost 50 to 75%, and approximately 10% have lost all usable storage capacity as a result of sediment deposition. Annual sedimentation rates reported for many of these reservoirs were extremely high. Kennedy et al. (1980) reported sedimentation rates as high as 27.1 cm yr^{-1} for Lake Red Rock, Iowa.

Sedimentation rates in reservoirs are largely influenced by the efficiency of the reservoir in retaining sediment inputs. Rausch and Schreiber (1979) cite the ratio of reservoir volume to annual inflow (volume/year) as the most important factor in determining reservoir trap efficiency. Sediment trap efficiencies of 87% and 93% were reported for Callahan Reservoir (Rausch and Schreiber 1979) and Lake Red Rock (Kennedy et al. 1980), respectively.

Nutrients

In addition to creating unaesthetic conditions, suspended sediments exert considerable influence on many chemical water quality parameters. The ability of sediments to adsorb and transport nutrients, especially phosphorus, may lead to undesirably high levels of productivity. While soluble P is considered more available to aquatic producers, P associated with suspended sediments may influence the soluble phase through adsorption-desorption dynamics (Li et al. 1972).

A number of studies have illustrated suspended sediment-phosphorus relationships. Rausch and Schreiber (1979) reported that of the P entering or leaving Callahan Reservoir in central Missouri, 96% and 90% respectively, was associated with suspended sediments. The accumulation of P in the bottom sediments of this impoundment was reported as nearly proportional to the sediment accumulation rate (Schreiber and Rausch 1979). Increases in both orthophosphorus and total phosphorus were closely correlated with turbidity increases associated with mixing by motorboats in shallow lakes of central Florida (Yousef 1979).

The highest P adsorption potentials are generally associated with clay-sized particles (Reddy 1976, Green 1978) and are dependent upon the chemical constituents of these particles. In a study of Wisconsin lake sediments, Shukula (1971) reported that noncalcareous sediments adsorbed more added P than calcareous sediments. Oxalate-extractable iron was identified as the most important factor contributing to P adsorption of both sediment types. Green et al. (1978) reported a positive correlation between P adsorption capacity and calcite content of sediments, but indicated that P adsorbed by calcite is easily desorbed.

Heavy Metals

Suspended sediments may also influence heavy metal dynamics in aquatic systems. In many systems, the transportation and distribution of metals is largely dependent upon the hydrodynamic activity of the associated suspended matter (de Groot 1976). Highest metal concentrations are generally associated with fine-grain materials such as clay particles (Forstner 1976). de Groot (1976) found that elements such as chromium, lead, and copper are easily bound by sediments, while metals such as zinc and nickel occur most frequently in the dissolved phase. The amount of a trace metal carried by suspended materials is largely dependent upon the chemical form of the specific element (Reddy 1976).

Primary Productivity

Biologists are particularly concerned with the effects of turbidity on the biota of aquatic ecosystems. Suspended sediments alter the degree of light penetration in aquatic systems and frequently produce significant effects on primary productivity. The growth of phytoplankton populations may be regulated by light-limiting effects of turbidity on primary productivity, even in systems with high nutrient concentrations (Murphy 1962, Hergenrader and Hammer 1973). Schwartzkopf and Hergenrader (1978) reported significant decreases in phytoplankton growth in a Nebraska reservoir during periods of sediment resuspension and also described significant increases in chlorophyll _a_ levels following the settling of suspended materials.

Several studies have focused on the effects of turbidity on plankton production in farm ponds. Buck (1956) reported that the average volume of net plankton in surface waters of clear ponds (less than 25 ppm turbidity) during the 1954 growing season was eight times greater than in highly turbid ponds (greater than 100 ppm). Claffey (1955) reported decreased levels of plankton productivity in turbid ponds and Butler (1964) cited turbidity as the cause of decreased primary production in farm ponds and laboratory microecosystems.

Rates of photosynthesis in phytoplankton may also be affected by the circulation of algal cells through turbidity-influenced gradients of light intensity and spectral range (Jewson and Wood 1975). Jewson and Taylor (1978) reported that the circulation of algae through light-dark gradients may result in decreased rates of net photosynthesis and the establishment of depth gradients of dark respiration. These authors identified the ratio of light to dark regions in the water column as an important consideration in estimating net photosynthesis in turbid systems.

The lower limit of the euphotic zone in aquatic systems is generally defined as the depth at which 1% of the surface irradiance occurs (Talling 1971). Grobbelaar and Stegman (1976), however, found this measurement to be of little value in turbid impoundments. These authors reported algal ^{14}C assimilation at depths as great as 530% deeper than the 1% light intensity depth in Hendrik Verwoerd Dam, South Africa. Unusual patterns of wavelength transmission were also observed in this reservoir. While blue light is generally transmitted deepest in relatively clear-water lakes (Wetzel 1975), blue light was rapidly attenuated and red light transmitted most in the turbid waters of Hendrik Verwoerd Dam. Similar results were reported by Walmsley et al. (1980) for another turbid South African reservoir. These observations are of particular importance due to the selective absorption of red light by chlorophyll molecules.

Invertebrates

Inorganic turbidity may also have detrimental effects on zooplankton populations. McCabe and O'Brien (1982) reported that even low levels of turbidity resulted in significant decreases in both filtering and assimilation rates of *Daphnia pulex* at low to medium algal concentrations. These effects were reportedly the result of dense packing of silt particles in the guts of test animals. This study also indicated that zooplankton population growth may be severely diminished by suspended silts and clays. Rainwater (1969) reported a similar decrease in the number of species, number of individuals, and total biomass content of benthic macroinvertebrate assemblages in turbid farm ponds as compared to clear ones.

Predator-Prey Dynamics

Alterations in aquatic predator-prey interactions may also be the result of high levels of inorganic turbidity. Moore and Moore (1976) reported that turbidity reduced the ability of European flounders (Platichthys fleses) to see prey and increased the time spent in capturing pursued prey. Increased turbidity may also reduce the reaction distances of several fish species to zooplankton prey (Vinyard and O'Brien 1976, Confer et al. 1977). Wright (1981) reported a 60% reduction in reaction distance of white crappie (Pomoxis annularis) to Daphnia magna at turbidity levels of 33 NTU.

Gardner (1981) cited turbidity as the cause of reduced feeding rates of bluegills (Lepomis macrochirus) preying on two size classes of Daphnia pulex. Feeding rate declined from approximately 14 prey per minute in clear water to 7 per minute in turbid water (190 NTU). The role of turbidity in influencing the ability of planktivorous fish to locate prey was reported as the reason for differing sizes of zooplankton found in two Kansas reservoirs (McCabe and O'Brien 1982). Turbidity may also alter taxon selectivity by planktivorous fish making slowly-moving and reacting prey types more susceptible to predation (Gardner 1981).

Fish Productivity

While naturally-occurring turbidity levels seldom result in direct lethal effects on fishes (Wallen 1951), other detrimental effects on fish populations have been reported. Hemistra et al. (1969) described altered behavior patterns and reduced activity levels of green sunfish (*Lepomis cyanellus*) in moderately turbid waters. Summerfelt and Shirley (1978) reported significant positive correlations between turbidity levels and year class strength of largemouth bass (*Micropterus salmoides*) in Lake Carl Blackwell, but attributed these observations to associated rises in water level rather than to turbidity.

The effects of turbidity in farm ponds on several species of popular sportfish were studied by Buck (1956). Ponds were classified as clear (< 25 ppm turbidity), intermediate (25 to 100 ppm), and muddy (> 100 ppm). At the end of two growing seasons, average total weight of fish in clear ponds was approximately 1.7 times greater than in intermediate ponds and approximately 5.5 times greater than in muddy ponds. These differences were attributed to faster growth and greater reproduction in clear ponds. At the end of the first growing season, largemouth bass had increased their average individual weights 6.4 times in clear ponds, 4.0 times in intermediate ponds, and 1.3 times in muddy ponds. Reproductive success was also reduced by turbidity. Young-of-the-year bass were found in seven of 12 intermediate ponds, four of 12 intermediate ponds, and none of nine muddy ponds. The same study indicated that high turbidity may drastically reduce angler fishing success rates in Oklahoma reservoirs.

Turbidity Models

Several investigators have reported on attempts to develop mathematical models aimed at predicting the dynamic processes of sediment resuspension, transportation, and deposition in aquatic systems under a given set of meteorological, morphological, and hydrological conditions. Many of these studies were reviewed by Norman (1964). Eagleson and Dean (1959) provided theoretical expressions for motion and velocity of spherical sediment particles under oscillatory waves, and Hakanson (1977) used water content of sediments as a physical parameter to construct diagrams aimed at identifying areas of sediment erosion, transportation, and accumulation in Lake Vanern, Sweden.

While many of these theoretical models have proven empirically sound for coarse-grained beach materials, sediments composed primarily of fine silts and clays have a different resistance to resuspension than larger grain sizes (Norrman 1964). Therefore, models developed for the erosion and transportation of large grain sizes are not applicable to the fine silt and clay sediments characteristic of reservoirs of the Great Plains. The only study found relating the resuspension and dispersion of fine-grained sediments is that of Sheng and Lick (1979) conducted in western Lake Erie.

Turbidity as a Water Quality Parameter

The use of turbidity as a water quality parameter has been criticized by Austin (1974) because of the failure of this measurement to account for the absorption of light in a water medium. Walmsley et al. (1980), however, claim that turbidity measurements are of particular value in waters where the attenuation of light is largely a function of scattering by inorganic suspended materials rather than absorption by other components.

CHAPTER III

THE STUDY AREA

Lake Carl Blackwell is located in northcentral Oklahoma, 14 km west of Stillwater in Township 19N, Range 1E to 1W in Payne County. The reservoir, formed by the impounding of Stillwater Creek, was completed in 1938. The original spillway elevation for LCB was 288.37 m msl, but was lowered to 287.78 m msl in 1948 because of structural problems with the dam. The reservoir is owned and operated by Oklahoma State University and serves as a site for recreational activities such as boating, waterskiing, fishing, camping, and picknicking; provides for flood control; and serves as a source of drinking water for Stillwater and several surrounding municipalities (Howick et al. 1982). LCB is located in a highly-populated region of the state with 850,000 people, 29% of Oklahoma's present population, living within an 80 km radius of the reservior (Howick et al. 1982). Morphometric characteristics of LCB are shown in Table 1.

LCB's watershed is located in northwestern Payne and southcentral Noble Counties of Oklahoma. The fine-grained sandstones and mudstone conglomerates of the Wellinston formation dominate the geology of the watershed. These materials impart a reddish-brown color to the soils of the region and are ultimately responsible for the red color of LCB water (Howick et al. 1982). The watershed of LCB is completely rural and generally covered by grasslands and upland forests. As of 30 July 1980,

Table 1. Morphometric characteristics of Lake Carl Blackwell at spillway elevation (287.78 m msl).[a]

Surface area	1250 ha
Volume	6.16×10^3 ha m
Average depth	4.93 m
Maximum depth	15 m
Shoreline length[b]	88.5 km
Shoreline development[b]	6.8
Maximum length	8.28 km
Drainage area	193 km^2

[a] From Howick et al. (1982).

[b] From Gomez and Grinstead (1973).

the watershed consisted of 62.2% grasslands, 10.0% upland forests, 11.1% transitional zone between grasslands and forests, 9.1% bottomland forests, 4.7% cropland (dominated by wheat, milo, alfalfa, and soybeans), and 2.4% wet soil (Howick et al. 1982).

CHAPTER IV

MATERIALS AND METHODS

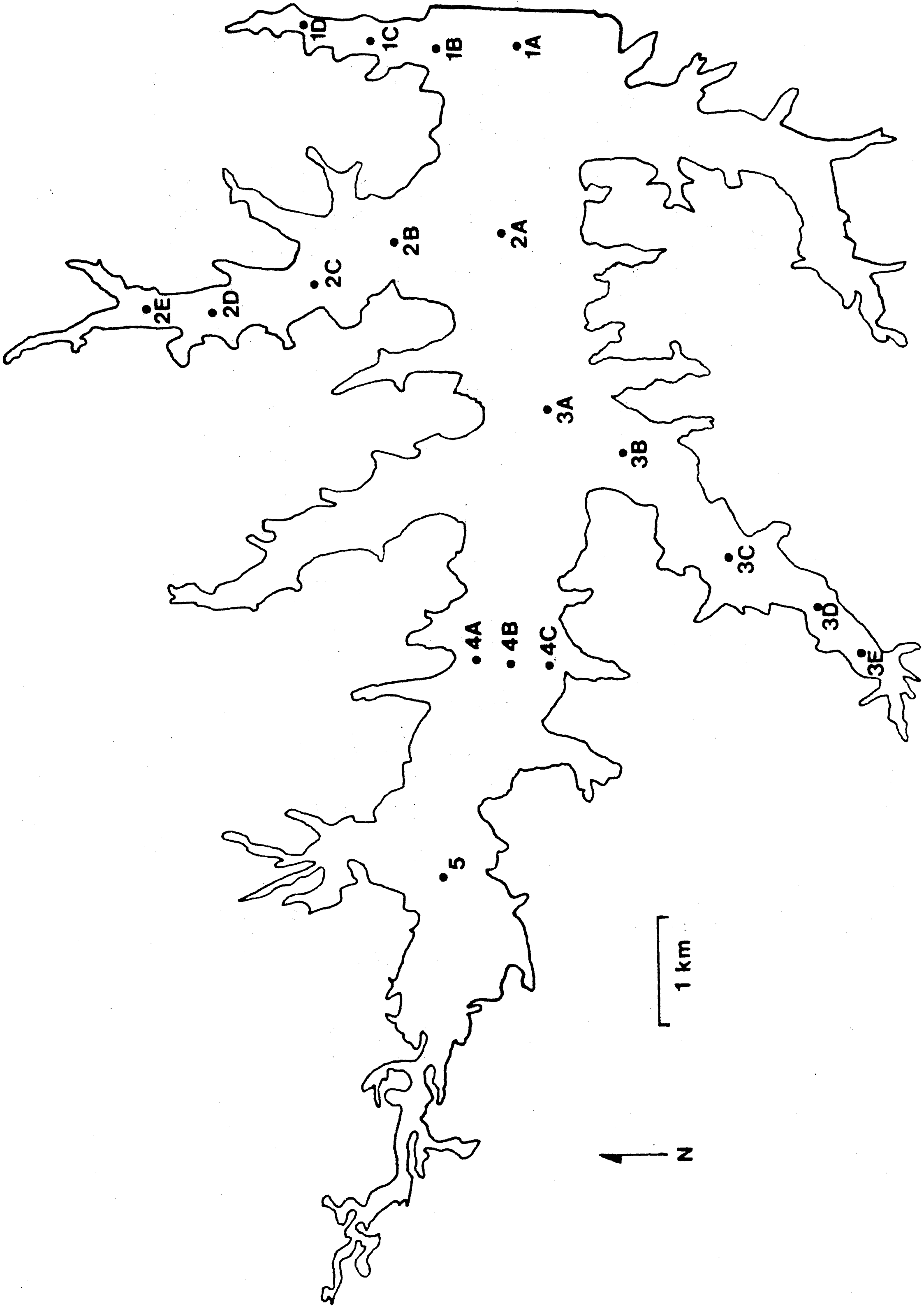
Introduction

A longitudinal and transverse series of sampling stations were established in Lake Carl Blackwell to facilitate sampling a variety of depths and locations within the reservoir (Figure 1). Stations 2E and 3E were added on 23 July 1982 as additional shallow water stations following lake level rises in summer. Sampling began on 12 February 1982 when samples were collected under ice cover at Station 1A and continued through 24 January 1983. On several occasions, sampling trips were discontinued before completion due to dangers associated with high winds and waves. Overall, the study incorporated 54 sampling dates, many of which were concentrated around periods of significant rainfall or high wind velocities.

Turbidity

Water samples for turbidity analysis were collected from 5-10 cm below the surface at each station and analyzed in the field on a Hach Model 16800 nephelometer. Turbidity readings were recorded in nephelometric turbidity units (NTU). Initially, replicate samples were collected at each station, but consistently identical values of replicates proved this practice unnecessary. When turbidity values exceeded the nephelometer scale (100 NTU), samples were diluted with

Figure 1. Lake Carl Blackwell sampling stations.


1A
1B
1C
1D
2A
2B
2C
2D
2E
3A
3B
3C
3D
3E
4A
4B
4C
5
1 km
N

distilled water, read, and the results multiplied by the appropriate dilution factor. The nephelometer was standardized with a commercial turbidity standard (Amco Standards International, Inc.) prior to each sampling trip.

Secchi Disc

Secchi disc transparencies were measured at each station as described by Lind (1979). In accordance with this procedure, measurements were generally made between 0900 and 1400 h CST. Due to the somewhat subjective nature of Secchi disc measurements, these values were obtained by the same observer throughout the study. High winds and waves frequently made accurate Secchi disc measurements difficult to obtain.

Depth

Because water depth was an important parameter to this study, an estimate of the average depth in the vicinity of each station was more desirable than a single depth measurement at the immediate station. Both transverse (shore-to-shore) and longtitudinal (perpendicular to transverse) SONAR transects were recorded through each station with a Lowrance Model LRG-1501B chart-recording depth finder. Longitudinal transects were run to shore or for a maximum distance of 100 m either side of the station. Average depth for each transect was calculated by dividing the cross-sectional area of the transect (as determined by polar planimetry) by the transect length. These values for each of the two transects were then averaged to obtain a final measure of average depth (m) for each station. Average depth values were corrected for significant changes in lake level during the study period.

Wind Data

Wind velocity measurements were obtained for each day during the study period from the Agricultural Experiment Station, Oklahoma State University. These measurements were recorded as miles of wind (the number of miles of wind which pass a given point in a 24 h period), which, when converted to km and divided by 24, yielded an average wind velocity for the day (km hr^{-1}). Wind direction data for Payne County, Oklahoma were obtained from records of the National Climatic Center, Asheville, North Carolina. When wind directions varied during a day, the dominant wind direction for that day was used.

Effective Fetch

Fetch is the distance along open water over which wind blows and, along with wind velocity and duration, is an important factor controlling wave height. Although fetch is generally measured as the straight line distance in the direction of the wind from shore or island to a specific point on a body of water, the Beach Erosion Board (1962) developed a measure of "effective fetch" which has proven more accurate than straight line distances in estimating wave height. The method accounts for small deviations in wind direction from a main direction and is based on the concept that the width of a fetch places a restriction on the length of the effective fetch. Thus, the less the width:length ratio, the smaller the effective fetch.

Effective fetch is calculated by constructing 15 radials on a map of the reservoir from the sampling station at intervals of 6° out to an angle of 45° on either side of the wind direction. These radials are extended until they intersect the shore. The length (km) of each radial is multiplied by the cosine of the angle between the respective radial and the wind direction. The resulting values for each radial are then summed and divided by the sum of the cosine of all individual angles (Beach Erosion Board 1962, Hakanson 1981).

Effective fetch distances (km) corresponding to eight different wind directions were calculated for each LCB sampling station.

Rainfall and Lake Level

Rainfall measurements (cm) and lake level readings were obtained from the U.S. Department of Agriculture Hydraulics Laboratory located adjacent to the north end of the LCB dam.

Sediment Particle Size

Sediment samples were collected with an Eckman dredge on 21 September 1982 for particle size analysis. Samples were returned to the lab and analyzed by means of the hydrometer method described by ASTM (1955).

Statistical Methods

Data were analyzed using Statistical Analysis Systems, Inc. (SAS) computer programs (SAS Institute, Inc. 1976). Individual analyses of variance (ANOVA) were performed for most parameters under the General Linear Models procedure. Sources of variation included date and station. When the ANOVA indicated a significant difference at the 95% confidence level, Duncan's multiple range test was used to examine variation within a source. The maximum R^2 improvement technique of the Stepwise Regression procedure was used to construct all multiple regression models. A minimum significance level of 0.05 was used for all statistical tests throughout this study.

CHAPTER V

RESULTS OF THE STUDY

Turbidity and Secchi Disc

Turbidity varied spatially in Lake Carl Blackwell during the study. Turbidity values ranged from 16 NTU at Station 1A during mid-February to 1140 NTU at Station 5 on 13 May 1982 (Table 2). Over the entire sampling period, variation within stations generally increased with decreasing water depth. The greatest range in turbidity was observed at Station 5 and levels for this station were significantly higher than those of all other stations.

Seasonal variation in turbidity was also observed (Figure 2). Values increased through spring, increased drastically following heavy mid-May rains, and decreased through late summer, fall, and winter. Variation among stations was high in spring and early summer, extremely high during May, and low during fall and winter.

Dramatic increases occurred in turbidity following heavy rains in May (Figure 3). An increase of 1010 NTU was observed between 11 and 13 May at Station 5, and turbidity decreased along the central pool from west to east within the reservoir. Turbidity levels at Station 1A increased only 12 NTU during the same 2 day period. Similar patterns of decreasing change in turbidity from the ends of the arms to the central pool were observed.

Table 2. Means and ranges of depth, turbidity, and Secchi disc measured at Lake Carl Blackwell from 12 February 1982 to 24 January 1983.

Station	Number of Samples	Depth (m)		Turbidity (NTU)			Secchi Disc (cm)		
		Mean	Range	Mean	Range	SD	Mean	Range	SD
1A	54	11.0	9.9-11.7	46.0	16-138	29.2	47.1	12-85	17.3
1B	51	6.8	5.6- 7.5	46.7	19-138	28.4	46.7	15-85	17.6
1C	53	5.0	4.0- 5.6	47.4	20-138	29.1	44.7	14-84	16.6
1D	51	3.9	3.1- 4.5	50.4	19-136	30.1	42.3	16-87	17.0
2A	51	7.5	5.9- 8.4	49.3	19-138	30.6	45.0	15-83	16.4
2B	51	5.3	4.1- 6.1	49.6	19-138	30.0	44.7	15-85	16.6
2C	50	4.3	3.3- 4.9	52.8	20-150	34.5	41.5	14-80	16.5
2D	50	1.6	0.3- 2.2	62.8	22-390	60.3	38.1	5-73	16.7
2E[a]	21	0.9	0.0- 1.4	34.4	24-45	5.7	44.6	21-110	10.0
3A	50	6.7	5.3- 7.6	60.2	20-284	47.5	37.9	11-69	12.7
3B	49	5.4	3.9- 6.2	64.7	21-312	52.8	35.7	7-72	12.9
3C	49	3.5	2.5- 4.1	73.3	28-432	67.1	31.8	6-53	11.9
3D	49	2.2	1.1- 2.9	84.7	28-564	89.6	28.2	6-49	10.6
3E[a]	21	0.9	0.0- 1.4	51.1	30-78	13.7	32.8	19-51	7.6

Table 2. Continued.

Station	Number of Samples	Depth (m)		Turbidity (NTU)			Secchi Disc (cm)		
		Mean	Range	Mean	Range	SD	Mean	Range	SD
4A	50	3.4	2.2-4.1	77.7	30-450	66.2	27.7	4-48	11.4
4B	49	3.8	2.5-4.7	79.3	30-510	75.6	29.4	9-80	13.9
4C	49	3.2	1.8-3.9	97.7	30-720	139.5	27.9	4-49	11.4
5	49	1.8	0.5-2.2	128.7	30-1140	226.0	23.8	2-50	11.1

[a] Added to sampling scheme on 23 July 1982.

Figure 2. Temporal variation in mean surface turbidity ($\pm$ 1s) and Secchi disc in Lake Carl Blackwell from 12 February 1982 to 24 January 1983.

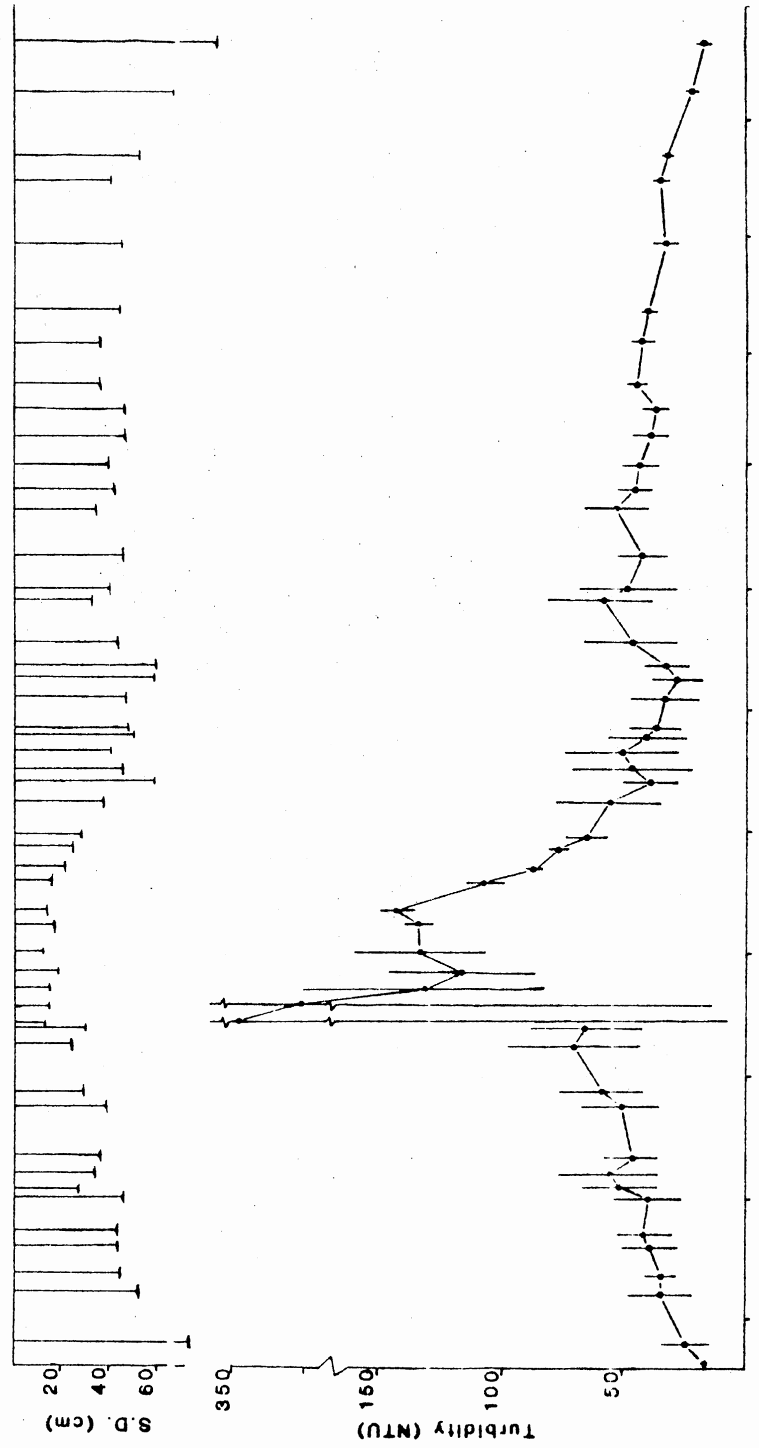
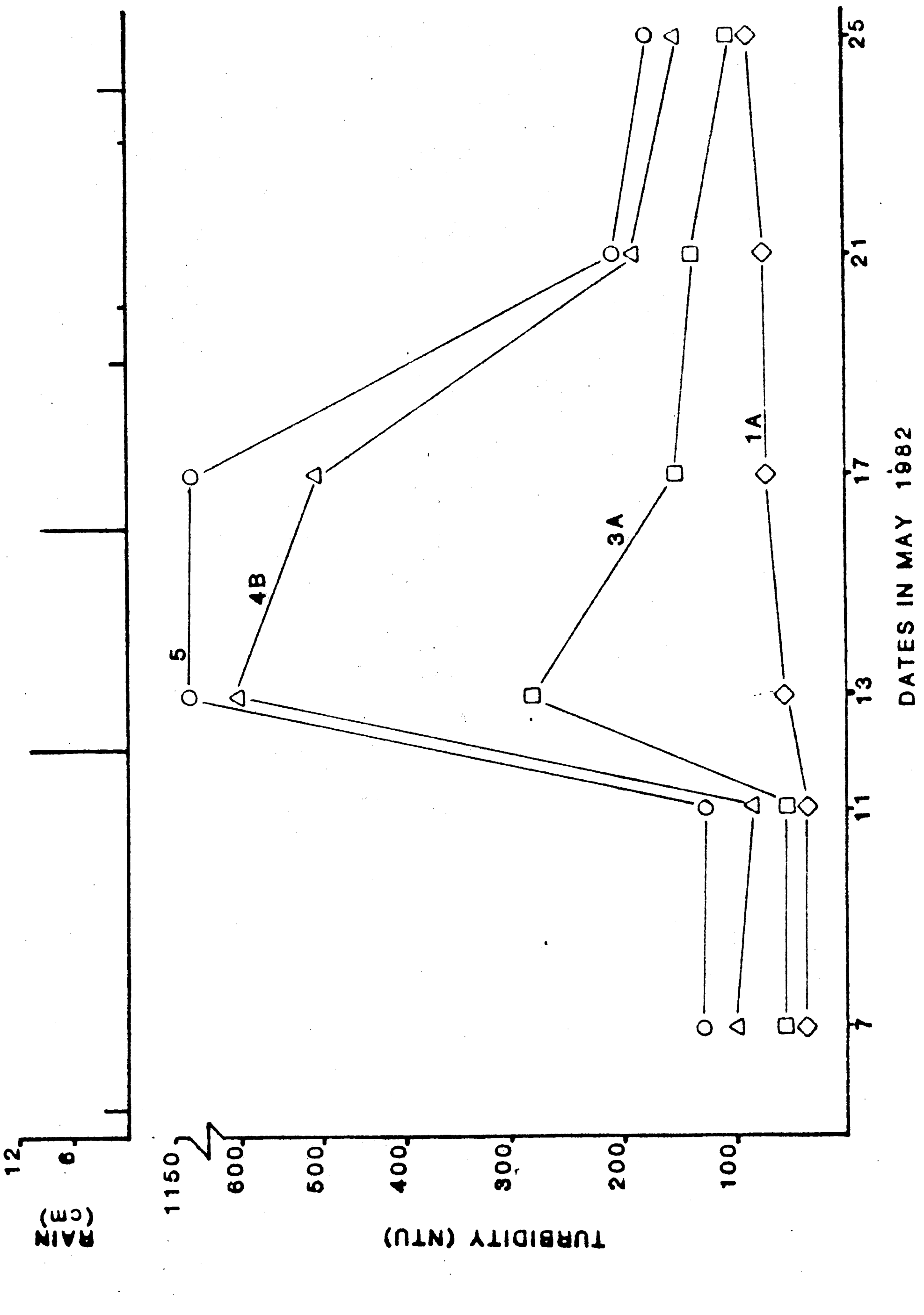

S.D. (cm)
20
40
60
Turbidity (NTU)
350
150
100
50
F
M
A
M
J
J
A
S
O
N
D
J

Figure 3. Rainfall and horizontal variation in turbidity in Lake Carl Blackwell from 6 to 25 May 1982.


RAIN (cm)
12
6
TURBIDITY (NTU)
1150
600
500
400
300
200
100
5
4B
3A
1A
7
11
13
17
21
25
DATES IN MAY 1982

Secchi disc transparency measurements were inversely related to turbidity (Figure 2) and varied significantly with both date and station. Secchi disc measurements ranged from 2 cm at Station 5 on 5 May 1982 to 110 cm at Station 2E on 24 January 1983 (Table 2).

Morphological Parameters

Average depths at each station during the study are given in Table 2. The deepest sampling station was Station 1A (11.7 m at spillway elevation) and the shallowest station was 3E (1.4 m at spillway elevation). Prior to the rise in summer lake level, Stations 2E and 3E were dry land and Station 5 was the shallowest station. Lake Carl Blackwell decreases in depth from east to west and from the central pool into the arms of the reservoir. The bottom is highly irregular in the arms and western end of LCB due to the presence of deep and winding channels.

Effective fetch distances varied significantly among stations during the study. The largest effective fetch (2.39 km) occurs at Station 1B when winds are from the southwest (Table 3). The shortest effective fetch is 0.12 km at Station 1D when winds are from the east. A southwest wind results in the largest mean effective fetch for all stations (0.98 km) with the smallest mean (0.71 km) resulting from a north wind. Effective fetch distances for Station 1B were significantly higher than those of all other stations. Due to the narrow nature of the central pool and arms of LCB, effective fetch distances are considerably shorter than straight-line fetch determinations.

Table 3. Effective fetches (km) for Lake Carl Blackwell.

	Wind Direction							
Station	N	NE	E	SE	S	SW	W	NW
1A	0.77	0.42	0.18	0.31	0.85	1.72	2.22	1.69
1B	0.53	0.40	0.35	0.56	1.37	2.39	1.51	0.37
1C	0.35	0.29	0.18	0.36	1.31	1.12	0.20	0.29
1D	0.16	0.18	0.12	0.12	1.03	0.73	0.17	0.13
2A	1.24	1.07	1.45	1.33	0.82	1.73	1.88	1.21
2B	1.01	0.56	0.61	1.92	1.87	1.33	0.60	0.90
2C	0.68	0.27	0.40	1.61	1.35	0.31	0.26	0.59
2D	0.42	0.29	0.12	0.57	1.01	0.40	0.23	0.23
2E	0.24	0.19	0.18	0.47	0.83	0.36	0.17	0.24
3A	0.91	1.28	1.94	1.11	1.13	1.07	1.70	1.71
3B	1.62	1.62	1.22	0.38	0.77	0.96	0.84	1.35
3C	0.96	1.62	0.78	0.26	0.52	0.87	0.58	0.31
3D	0.89	1.41	0.59	0.25	0.56	0.60	0.41	0.36
3E	0.96	1.14	0.23	0.18	0.31	0.49	0.33	0.22
4A	0.22	0.22	1.22	1.67	0.86	1.32	1.08	0.79
4B	0.59	0.91	1.95	1.32	0.53	0.81	1.49	1.29
4C	0.84	1.39	2.03	1.00	0.17	0.45	1.10	1.43
5	0.52	0.79	2.00	1.47	0.56	0.98	0.94	0.52
$\bar{x}$	0.71	0.78	0.84	0.82	0.88	0.98	0.87	0.75

Climatological Measurements

Wind velocities and directions were highly variable during the study (Table 4). Winds were generally strongest during spring and decreased in intensity during mid and late summer. Highest daily wind speeds were observed on 3 April 1982 when gusts up to 96 km hr^{-1} (60 mph) were recorded. The calmest day of the study was on 7 October 1982 when wind velocity averaged only 0.2 km hr^{-1}. Winds were primarily from the north during the first 3 months of the study, but southerly winds prevailed during late summer and fall.

Rainfall was unusually high in the LCB watershed during May of 1982 (Table 4) and these rains caused significant runoff into the reservoir. Rainfall totaled 31.97 cm (12.6 in) during May and the highest daily rainfall was 11.56 cm (4.6 in) on 12 May 1982. Lake level increased 1.4 m in only 6 days (11 to 17 May) and the reservoir exceeded spillway elevation on 27 May 1982. This was a particularly rare event as Lake Carl Blackwell has reached spillway elevation only six times since impoundment in 1938 (Howick et al. 1982).

Sediment Particle Size

The average size of sediment particles increases in Lake Carl Blackwell from east to west and from the central pool into the arms (Table 5). Sediments near the dam are dominated by clay-sized particles but silt comprises the highest percentage of sediments at most sampling stations. These patterns of sediment size distribution are similar to those reported by Norton (1968) and Howick et al. (1982).

Table 4. Monthly wind velocity, dominant wind direction, and rainfall at Lake Carl Blackwell from February 1982 to January 1983.

Month	Wind Velocity (km wind day^{-1}) Mean	Minimum	Maximum	Dominant Wind Direction	Rainfall (cm)
February	175.2	50.4	360.0	N	3.97
March	189.6	45.6	343.2	N	3.88
April	194.4	52.8	408.0	N	7.14
May	158.4	40.8	362.4	SW	31.97
June	134.4	55.2	292.8	SE	3.84
July	136.8	52.8	252.0	S	0.33
August	122.4	36.0	204.0	S	0.53
September	168.0	81.6	384.0	S	4.24
October	139.2	4.8	402.8	S	0.74
November	187.2	31.2	393.6	S	4.57
December	151.2	19.2	352.8	NW	2.67
January	117.6	21.6	247.2	N	1.23

Table 5. Lake Carl Blackwell sediment particle size analysis for samples collected on 21 September 1982.

Station	Percent Clay[a]	Percent Silt[b]	Percent Sand[c]	Mean Size (μm)
1A	66	34	0	1
1B	28	38	34	26
1C	15	19	66	95
1D	8	8	84	330
2A	39	45	16	7
2B	14	74	12	12
2C	18	49	33	35
2D	10	34	56	57
2E	8	45	47	48
3A	22	30	48	46
3B	18	29	53	56
3C	22	74	4	14
3D	10	48	42	42
3E	13	53	34	37
4A	25	41	34	25
4B	46	46	8	3
4C	27	47	26	17
5	23	59	18	18

[a] Clay particle diameter = less than 2 μm.

[b] Silt particle diameter = 2 to 50 μm.

[c] Sand particle diameter = 50 to 500 μm (USDA system, Hausenbuiller 1972).

CHAPTER VI

DISCUSSION

Introduction

Results of this study clearly reveal the importance of two major processes in the regulation of inorganic turbidity levels in Lake Carl Blackwell. While tremendous fluctuations in turbidity during the study were associated with heavy rains and sediment input, the important effects of wind-induced sediment resuspension were also noted. The relative importance of these two factors varied during the study.

Runoff and Sediment Inputs

Tremendous fluctuations in nephelometric turbidity during early summer in the present study resulted from sediment inputs from runoff following heavy May rains. Turbidity increases in reservoirs following periods of heavy rainfall have been well-documented (Brown 1941, Walmsley 1978, Kennedy et al. 1980).

Horizontal gradients of turbidity change during runoff in LCB can be attributed to the settling of coarse-grain suspended materials prior to transport to deep-water stations. High percentages of coarse-grained materials in sediments of the western end and upper arms of Lake Carl Blackwell support this explanation. Sedimentation surveys conducted at LCB further reveal that the highest sedimentation rates have occurred in the arms and the western end of the impoundment (Howick et al. 1982).

While sediment inputs from runoff resulted in tremendous turbidity increases during this study, inflow is probably less important in the regulation of LCB turbidity on a long-term basis. Early summer rains during this study were nearly three times higher than normal for the season (Myers 1976) and historically declining water levels characteristic of LCB (Howick et al. 1982) indicate the rarity of such inflow events.

Sediment Resuspension

Sediment resuspension results from the vertical translation of energy from waves to sediments in areas of shallow water (Sheng and Lick 1979). While a number of factors relating to geology, meteorology, and basin morphology determine the extent of sediment erosion in aquatic systems (Hakanson 1977), two important considerations relating to resuspension are wave height and water depth. Impoundments possessing extensive shallow littoral regions exposed to high winds are most susceptible to sediment resuspension (Jackson and Starrett 1959).

Resuspension was cited as the primary cause of turbidity in Lake Carl Blackwell during the Clean Lakes Study of 1980 and 1981 (Howick et al. 1982). Observations of increases in turbidity associated with spring winds during the present study reinforce the significance of this process. Following the melting of ice cover in mid-February 1982, mean surface turbidities increased from 24.2 NTU to 57.4 NTU by the end of April. While some rainfall occurred during this period, no significant lake level increases were recorded. Thus, turbidity increases observed during this time can be attributed largely to resuspension. High variation in turbidity levels among stations during spring was the result of rapid turbidity increases in shallow stations in comparison to those of deeper areas. Variations within stations during this period increased with decreasing depth indicating that shallower stations were the most dynamic in terms of turbidity fluctuations.

Long-term water level fluctuations characteristic of LCB (Howick et al. 1982) further aggravate problems associated with resuspension. Decreasing water levels not only expose large areas of shallow water to wave effects, but also leave barren shorelines highly susceptible to wave-induced sediment erosion. On many sampling days, bands of highly turbid water were observed along barren, wind-swept shorelines.

Increased turbidity levels associated with resuspension during spring and fall turnover have been reported (Serruya 1976). Since thermal stratification is a weak and transitory process in Lake Carl Blackwell (Howick et al. 1982), turbidity increases associated with specific turnover events were not observed.

Turbidity-Secchi Disc Relationship

As expected, turbidity varied inversely with Secchi disc transparency. A regression of turbidity (Turb) on Secchi disc (SD) yielded the equation:

$$\text{Turb} = 166.28 - 2.70\ \text{SD} \qquad (n=790,\ r=-0.53).$$

The correlation coefficient for this equation is lower than expected due to the nonlinear relationship between turbidity and Secchi disc at extremely high turbidity levels. Under extremely turbid conditions, drastic increases in nephelometric turbidity result in only minimal changes in Secchi disc transparency. Log-transformation of the turbidity data resulted in the regression formula:

$$\ln \text{Turb} = 5.13 - 0.03\ \text{SD} \qquad (n=790,\ r=-0.88).$$

Further data transformation (log-log) yielded:

$$\text{Turb} = 2368 \times \text{SD}^{-1.09} \qquad (n=790,\ r=-0.96).$$

Turbidity Models

Multiple regression models relating nephelometric turbidity to measured climatological and morphometric parameters at Lake Carl Blackwell were constructed. These models not only represent an attempt to simplify and quantify factors controlling turbidity in LCB during the study, but also propose a possible basis for predicting future turbidity dynamics in LCB and similar impoundments.

It seems reasonable to assume that meteorological conditions immediately preceeding sampling dates would be of greater importance in determining turbidity levels than those conditions farther removed from time of sampling. Values of wind velocity and effective fetch were therefore weighted according to a simple equation similar to one proposed by Ayers et al. (1958) to estimate wind-displacement of chlorophyll. The equation is:

$$P_t = P_1 + 1/2\ P_2 + 1/4\ P_3 + 1/8\ P_4 + 1/16\ P_5$$

where: P_t = weighted parameter of interest for sampling day;

P_1 = parameter value on day prior to sampling day;

P_2 = parameter value 2 days prior to sampling day;

•

•

P_5 = parameter value 5 days prior to sampling day.

This equation does not suggest that an accumulated wind velocity or fetch exists, but only that there is an accumulated effect of these parameters (Small 1963). Values for wind velocity and effective fetch weighted according to this equation yielded better correlations with turbidity than any other unweighted cummulative values tested.

It was also desirable to develop a single variable that integrated all parameters influencing sediment resuspension. Resuspension is primarily a function of wave height and water depth. Since wave height is determined primarily by wind velocity and fetch length (Beach Erosion Board 1962), the following parameter, referred to as wind effect, was used as a measure of total wind effect prior to sampling dates:

$$\text{Wind Effect} = \frac{f \times v}{z_{\bar{x}}}$$

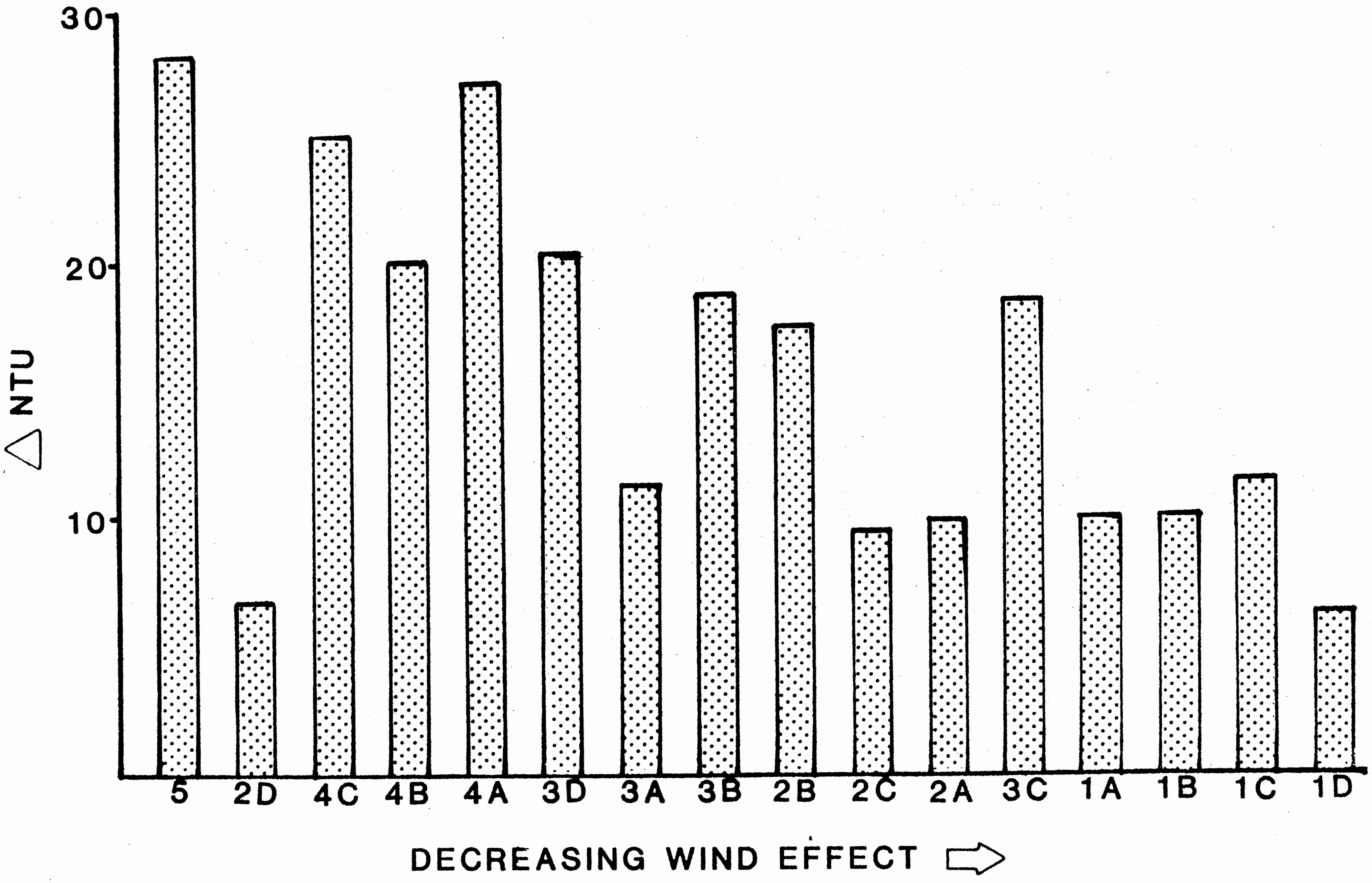
where: f = weighted effective fetch (km)
v = mean wind velocity (km h^{-1})
$z_{\bar{x}}$ = mean depth (m)

High wind velocities and large fetches impinging upon shallow areas result in high values of wind effect. Low values occur at deep locations or when values for wind velocity and fetch are small.

The predictive capabilities and usefulness of the wind effect variable are illustrated in Figure 4. High wind velocities (up to 96 km hr^{-1}) were recorded from 1 to 6 April 1982. Stations with the highest values of wind effect during this period generally exhibited the greatest increase in nephelometric turbidity. Lessening turbidity increases were observed at stations with decreasing values for wind effect.

Various parameters associated with rainfall were also examined for inclusion in the turbidity models. Cummulative values of rainfall for 1 to 5 days preceeding sampling were correlated with turbidity. A measure of rainfall weighted according to the previously-mentioned equation was also examined. Rainfall accumulations for 2 days prior to sampling were most closely correlated with turbidity levels and were therefore used as

Figure 4. The influence of wind effect (see text) on changes in turbidity levels of Lake Carl Blackwell sampling stations from 1 to 6 April 1982.


30
20
10
△ NTU
5
2D
4C
4B
4A
3D
3A
3B
2B
2C
2A
3C
1A
1B
1C
1D
DECREASING WIND EFFECT ⇨

the rainfll parameter in the models.

The maximum R^2 improvement technique of the SAS Stepwise procedure (SAS Institute Inc. 1976) was used to construct the turbidity models. Turbidity served as the dependent variable in these models and independent variables included average depth, weighted wind velocity, weighted effective fetch, weighted wind:depth ratio, weighted fetch:depth ratio, wind effect, and cummulative rainfall 2 days prior to sampling. Sediment particle size could not be used in the models due to autocorrelations with depth (Table 5).

Two separate multiple regression turbidity models were developed for this study. The first is based upon all data collected during the entire sampling period. The best obtainable model for this period is a two variable model:

$$\text{Turb} = 40.6 + 23.43\ \text{CR2} + 1.30\ \text{WE} \quad (n=716,\ R=0.61)$$

where: Turb = nephelometric turbidity (NTU);

CR2 = cummulative rain (cm) 2 days prior to sampling;

WE = wind effect.

Cummulative rain alone explains 35% of the variance in turbidity in this model. The addition of wind effect increases the amount of variance explained to 37%. The tremendous variation in turbidity resulting from excessively heavy rains during a significant portion of the study period is reflected in the importance this model places on rainfall. This equation does emphasize the significance of runoff and sediment input during the sampling period, but is probably limited in its predictive capabilities to infrequent periods of heavy rains and significant lake level rises.

A much more useful and practical turbidity model was constructed using data collected prior to heavy rains during the study. This model uses data collected through April 1982 and emphasizes the effects of wind without the confounding influence of excessive runoff. The best obtainable model for this period is the three variable model:

$$\text{Turb} = 46.93 + 0.63\ \text{WE} + 7.21\ \text{CR2} - 2.21\ z_{\bar{x}} \quad (n=158,\ R=0.69)$$

where: Turb = nephelometric turbidity (NTU);
WE = wind effect;
CR2 = cummulative rain (cm) 2 days prior to sampling;
$z_{\bar{x}}$ = average depth (m).

Average depth accounts for 33% of the variance in turbidity in this model while CR2 and WE increase the amount of variance explained to 41% and 48% respectively. This equation predicts turbidity under the more common conditions of average winds and moderate rainfall and is therefore the more useful of the two.

Factors Not Addressed by the Study

In addition to those parameters investigated by this study, several other factors are of obvious importance in regulating turbidity levels in LCB and other reservoirs. While quantification of these parameters proved too complex for the present study, these processes are of considerable importance and do merit mention.

The transport of suspended sediments by wind-induced water currents is a significant process in reservoirs. While sediment transport associated with inflow events has been measured (Lambert and Luthi 1977, Serruya 1977, Walmsley 1978), sediment transport by wind-influenced water movements has received little study. The complex nature of water movements in reservoirs makes sediment transport by these processes extremely difficult to measure. Turbidity increases at deep water stations observed during the present study were undoubtedly the result of sediment transport from shallow stations, rather than the resuspension of underlying sediments.

Settling velocities associated with varying sediment particle sizes and degrees of turbulence are also important, yet difficult to measure. Ever-changing patterns of turbulence in natural systems make laboratory-derived settling equations questionable for field application. The importance of settling velocities of suspended material varies with existing turbidity levels and watershed geology. While drastic decreases in turbidity due to settling were observed at high NTU levels during the study, settling velocities associated with colloidal clay suspensions characteristic of Great Plains impoundments (Leonard 1950, Irwin and Stevenson 1951) may be of lesser importance. Further research in the areas of sediment transport and deposition would greatly increase our currently-sparse knowledge of reservoir limnology.

CHAPTER VII

SUMMARY

1. Turbidity (NTU) and Secchi disc measurements were collected at Lake Carl Blackwell, Oklahoma on 54 sampling dates from 12 February 1982 to 24 January 1983. Meteorological conditions were also recorded for this period.

2. Turbidity values ranged from 16 to 1140 NTU and Secchi disc transparency measurements ranged from 2 to 110 cm. Both measurements varied significantly with date and station.

3. Turbidity values were generally highest at shallow water sampling stations in the western end and upper arms of LCB and decreased with increasing depth within the reservoir.

4. Increases in turbidity levels during the spring of 1982 were attributed to sediment resuspension and drastic turbidity increases were observed following heavy early summer rains.

5. Two multiple regression turbidity models were developed to predict nephelometric turbidity levels for a given set of climatological and morphometric parameters. One model was based on data for the entire sampling period and is useful in predicting turbidity under high inflow conditions. A second model used data collected prior to periods of heavy rains and is useful in predicting turbidity under more common conditions of moderate winds and rain.

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