

PRECEDINGS OF ARKANSAS LAKES SYMPOSIUM

LIMNOLOGICAL STUDIES

of

LAKE CHICOT, ARKANSAS

October 4, 5, and 6, 1983
DeGray Lodge
DeGray State Park
Arkadelphia, Arkansas

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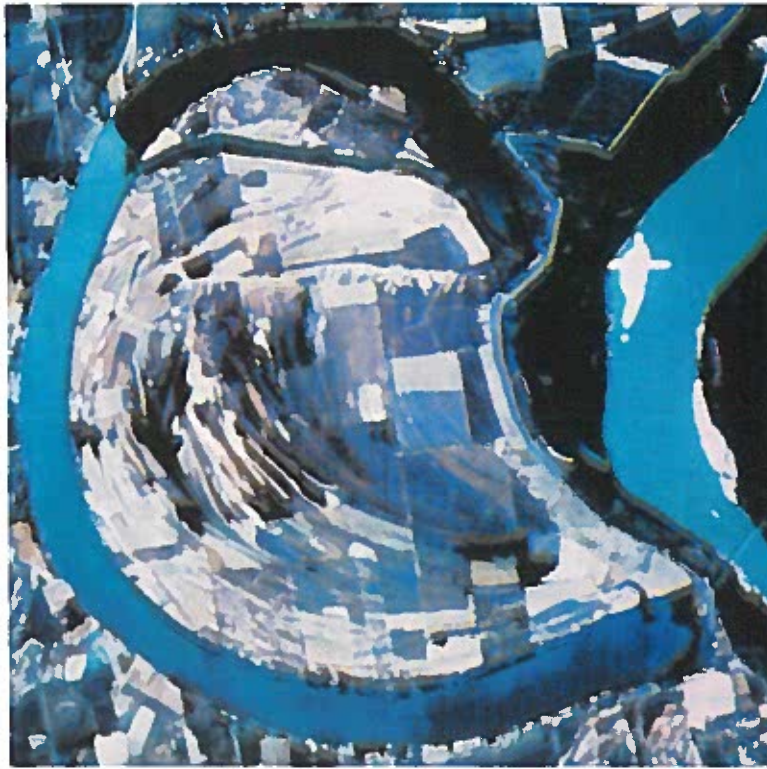
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LANDSAT 4 THEMATIC MAPPER IMAGES OF LAKE CHICOT, ARKANSAS OBTAINED SEPTEMBER 23, 1982. THE UPPER PICTURE COMBINES THE VISIBLE GREEN AND RED CHANNELS WITH A MID INFRARED CHANNEL TO FORM THE FALSE COLOR IMAGE WHILE IN THE LOWER PICTURE THE VISIBLE GREEN AND RED CHANNELS ARE COMBINED WITH THE THERMAL OR FAR INFRARED CHANNEL TO FORM THE IMAGE.



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Preface

Lake Chicot is an oxbow lake that was created more than 600 years ago by the meandering of the Mississippi River. It is located in Chicot county in southeastern Arkansas adjacent to the present Mississippi River. As the largest natural lake in Arkansas it earned an early reputation for its good fishing and recreational value. Development of a levee system forced the enlargement of the lakes watershed to its present 350 square miles.

Initially this alteration affected only the volume flow through the lake, drastically reducing the water residence time. Because the watershed was located in one of the most agriculturally productive regions in the world, the land, predominantly comprised of clay and fine silts, quickly became more intensively farmed. The use of agricultural chemicals increased, large amounts of sediments were produced and the lake began to become severely impacted by this activity.

In the early 1960's Congress enacted legislation authorizing the Corps of Engineers to begin planning a method of restoring the lake. Plans were made to construct three structures; a dam to prevent poor quality water from entering the lake, a combination gravity flow-pump facility to divert the poor quality water through the levee into the Mississippi River, and a dam on the outflow to regulate lake levels and regulate discharge. These structures are expected to be fully operational early in 1985.

In 1977 the Agricultural Research Service, USDA, entered into a cooperative agreement with the US Army Engineer District, Vicksburg to conduct a basic limnological research program to characterize the hydrological chemical, and biological regimes of the lake. The objective of this work was to develop a predictive mathematical water quality model of the lake system and to use the model to establish a strategy to operate the newly constructed structures in order to optimize water quality in the lake while allowing sufficient water for other purposes.

In addition to three ARS laboratories located at Durant, OK, Oxford, MS, and Beltsville, MD and the Army Engineer District, Vicksburg, contributions have

been made by six different universities, carefully selected for their expertise and facilities and by the National Weather Service at Stoneville, MS. The Universities involved were the University at Arkansas at Monticello, AR, Ouachita Baptist University at Arkadelphia, AR, University of Minnesota at Minneapolis, MN, University of Mississippi at Oxford, MS, the University of Oklahoma at Norman, OK, and Northeast Louisiana University at Monroe, LA.

Thanks are due all of the Scientists and personnel from all of these organizations who have contributed to this research.

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Material Budgets of Lake Chicot¹

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ABSTRACT

In anticipation of the construction of water quality control structures on Lake Chicot, an extensive investigation was conducted to determine the water, sediment, and chemical budget characteristics of the Chicot stream and lake system. The objectives were: (1) to develop rating relationships and data smoothing procedures for the hydrologic, sediment, and chemical variables, (2) to utilize these relationships to make daily and annual budget estimates of the various material fluxes into and out of the lake, and (3) to make an analysis of the material budgets to determine such lake characteristics as residence and flushing times, material trapping efficiencies, and chemical retention coefficients.

The average water residence times for the water years 1977, 1978, and 1979 were 0.37 years, 0.25 years and 0.08 years respectively. The corresponding suspended sediment trap efficiencies were 68 percent, 56 percent and 62 percent, and for the available phosphorus (dissolved ortho) the trap efficiencies were 36 percent, 36 percent and 66 percent, respectively.

¹A contribution of the USDA-ARS Water Quality and Watershed Research Laboratory, Durant, OK.

I INTRODUCTION

As part of an extensive investigation of the Lake Chicot system, detailed budgets of key materials flowing into, out of, and being trapped and recycled in the lake were determined. These materials included water, suspended sediments, dissolved solids, total phosphorus, and dissolved phosphorus.

The water years 1977, 1978, and 1979 were selected for this study. These years represent two average precipitation years and one wet year. Components of these detailed material budgets, developed for one day time intervals so as to make the results compatible with the process oriented mathematical model described elsewhere in this proceedings (Stefan et al 1983.) and elsewhere (Stefan et al. 1978).

The data used to develop the various material budgets came from these principal sources; 1) discharge and stage measurements obtained by the Army Engineer District, Vicksburg, MS., 2) suspended sediment, total solids, and nutrient measurements obtained by the USDA Sedimentation Laboratory, Oxford, MS., and 3) meteorological measurements provided by the National Weather Service, NOAA. These data were analyzed as the subject of a PhD dissertation (Swain 1980) conducted by the second author under the direction of the senior author.

In section II the analytical forms of the budgets are developed for the materials being studied. Rating relationships from observed data are determined in Section III along with certain morphometric relationships required for budget determination. The budgets are summarized and analyzed in section IV.

The primary purpose of this study was to develop a detailed data set of the various material loadings on the lake. This inflow information was required to drive the mathematical model.

II FORMULATION OF THE MATERIAL BUDGETS

The budgets will be determined in terms of the "flux" of the particular substance into, out of, being stored in, consumed by, or being lost from the lake. The flux of the substance at a river station is given by

$$F = A (\bar{C} \bar{U} + \overline{c'u'}) \quad (1)$$

in which \bar{C} is the mean concentration of a substance; \bar{U} is the mean velocity of flow; c' is the fluctuation of the concentration about the mean, u' is the fluctuation of the velocity about the mean, A is the cross-sectional area, and F is the material flux. In a relatively slow moving stream such as Connerly Bayou and Ditch Bayou, it is expected that c' is of the order of $0.02 C$ and u' of the order of $0.1 U$. On this basis, the second term of equation (1) is seen to be negligible compared to the first term and is subsequently neglected.

In a generalized form, a budget equation of any substance for a lake can be written as

$$F_{in} = F_{out} \pm F_{store} + F_{loss} - F_{gain} \quad (2)$$

which represents the inflow, outflow and storage of any particular substance in a lake as well as any losses or gains than might occur. It was required of this research that all terms be evaluated on a daily basis.

For the case of water the inflowing flux is replaced by the inflow, Q_C , from Connerly Bayou, the principle tributary and the direct precipitation on the lake, P . The outflowing flux is replaced by the discharge through Ditch Bayou, Q_D , and direct evaporation, E , from the lake's surface. The storage flux is indicated by the change of lake volume, ΔV , in a time interval, Δt , which in this case was one day. The water budget expressed analytically is

$$Q_C + P = Q_D + E \pm \Delta V / \Delta t \pm G \quad (3)$$

where the lake storage and groundwater exchange can be either positive or negative on any given day.

All of these quantities are determinable by measurement of the pertinent watershed variables. The gain and loss fluxes are represented by the single unmeasured term, G . This unknown variable represents the groundwater exchange and contains the errors have originated in

evaluating all of the other variables in the budget equation. It is likely that the errors for any one term have equal probabilities of being positive or negative. When summed over an entire year they would tend to be self cancelling and compared with the annual values of the groundwater exchange. The sediment in suspension dominates the total sediment budget of the lake and since the turbulent flux is negligible the suspended sediment budget is expressed as;

$$Q_C S_C = Q_D S_D \pm \frac{\Delta V}{\Delta t} S_D + D_{SS} - R_{SS}. \quad (4)$$

Here S_C and S_D are the concentrations of suspended sediment at the Connerly Bayou inflow and the Ditch Bayou outflow respectively. The field investigations showed that the average in lake concentration of suspended sediment did not differ significantly from the outflow value and that value was used in the lake storage term. The term, D_{SS} , represents the suspended sediment deposited on the lake bottom during the time interval and R_{SS} is the quantity of deposited sediment resuspended. Since it was impossible to determine from the available data, the resuspension term will be neglected and the net difference between deposition and resuspension will be reflected in the value of D_{SS} .

In a similar way the total dissolved solids budget is

$$Q_C^D S_C^D = Q_D^D S_D^D \pm \frac{\Delta V^D}{\Delta t} S_D^D \pm G_{DS} - R_{DS}. \quad (5)$$

The terms, G_{DS} and R_{DS} represents the total dissolved solids exchanged with the groundwater and the solution of precipitated material back into the water column. No measurements were available for this quantity and it was neglected and combined with the groundwater exchange for this analysis.

Likewise the total phosphorus, P_T , and dissolved ortho phosphorus (that component immediately available to phytoplankton) P_D , are expressed as

$$Q_C^P P_C^P = Q_D^P P_D^P \pm \frac{\Delta V^P}{\Delta t} P_D^P + D_{TP} - R_{TP} \quad (6)$$

and

$$Q_C^P P_C^D = Q_D^P P_D^D \pm \frac{\Delta V^P}{\Delta t} P_D^D \pm G_{PD} \pm B_{PD}. \quad (7)$$

The term D_{TP} represents the quantity of total phosphorus deposited on the bottom and is principally that absorbed to clay particles or associated with sedimenting organic particles. The total phosphorus being

returned to the water body, R_{TP} , again cannot be determined from available data and was combined with D_{TP} to reflect a net loss to the lake. The loss and gain terms in the dissolved phosphorus budget represent that quantity exchanged with groundwater and with the biological processes active in the water. These terms again are not directly determinable from available data and were lumped into a single gain/loss term.

III DATA CONDITIONING AND RATING RELATIONSHIPS

In order that the forgoing budgets contain sufficient temporal detail to be useful in driving the mathematical model they must be evaluated on a daily basis. Since continuous daily measurement and sampling of all of the various parameters would have consumed many times the time, personnel and funds available, methods of developing rating relationships to estimate the parameters from available information were developed.

The frequency of measurement or sampling depended on the variable being measured. Daily measurements of lake and river stages were available from continuous records at Macon Lake, at the mouth of Connerly Bayou, and at Ditch Bayou as it flowed from the lake. These are indicated by stations 3, 5, and 9 respectively on the maps of Fig. 1.

Discharge measurements from stream gaging was conducted at approximately 1 week intervals during the study period. Samples, from which suspended sediment, total dissolved solids, and phosphorus concentrations were determined, were collected at 14 day intervals.

The discharge, Q , may be related to the stage, S , by a power function of the form:

$$Q = a (S - S_0)^N \quad (8)$$

where S_0 denotes the stage where the discharge is zero, and a and N are the coefficient and exponent to be determined. Since the streams were gaged at regular intervals, most of the discharge-stage data pairs were obtained when discharges were low. A regression determination of the coefficient and exponent with the unprocessed data set results in large errors in the prediction at high discharges because disproportionate weight is given to low discharges.

The range of measured discharges varied from approximately

2.8m³/sec to over 1680 m³/sec at the Macon Lake station and 2.8 m³/sec to 840 m³/sec at the outlet through the Ditch Bayou. In order to improve the regression derived rating relationship the discharges were divided into groups. The lower bound of the first group was at the minimum flow of 2.8 m³/sec. The upper bound for the group and the lower bound of the next group was 2^{1/2} times the previous value. This grouping was continued through the entire range of measured discharges. The mean value of all the measured discharges in each group was calculated. Likewise the corresponding mean stage, the mean value of all the recorded stages in the discharge group under consideration, was calculated. This constituted a pair in the regression analysis for obtaining an improved stage discharge relationship. Based on this technique discharge relationship at Macon Lake is given by

$$Q_M = 30.79 (S_M - 32.2)^{1.72} \quad (9)$$

where Q_M is the predicted value of discharge at Macon Lake at stage S_M in SI units. The curve described by Equation 9 is also shown along with the measured data set in Figure 2.

Some difficulty was encountered when this approach was applied to Ditch Bayou. Approximately 3.2 km downstream of the mouth of Ditch Bayou there was a rubble dam. During the first 2 years of this study the data for the rating curve fit a fairly tight pattern. During the Spring of 1979, however, considerable deviation started to take place in which considerably more discharge was measured for a given lake stage. Site inspection revealed an excessive erosion around the left bank of the dam. This was apparently due to a very large event in May, 1979. This necessitated establishing two rating curves: one for use prior to May 21, 1979, and another for the remaining part of the water year. These analyses result in

$$Q_D = 8.59 (S_D - 30.92)^{2.42}$$

for 10-01-76 through 05-21-79

and
$$Q_D = 32.04 (S_D - 30.92)^{1.72}$$

for 05-22-79 through 09-30-79

for the discharge through Ditch Bayou.

Backwater effects at the mouth of Connerly Bayou prevented the determination of a similar stage-discharge relationship. A method was sought correlating the discharges at Macon Lake with the mouth of

Connerly Bayou. The data grouping technique was again used with the measured discharge pairs to establish the regression relationship

$$Q_C = 0.85 Q_M. \quad (10)$$

Ratings for total dissolved solids, suspended sediments, total phosphorus and dissolved phosphorus were obtained by assembling data sets where the pairs concentration of the material and the discharge was measured on the same day and obtaining the regression relationship between the variables. Examples are shown in Figures 3 and 4 for the suspended sediments and the total dissolved solids at Macon Lake.

Ratings for material fluxes other than water discharge could not be determined at the Ditch Bayou outlet from the lake. The concentrations of these quantities are primarily determined by processes in the lake and not the outlet channel. The concentrations used for the various budgets were obtained by plotting the data against time Fig. 6, and obtaining daily data by interpolating between points.

The budget equations all require a daily change in the lake volume, $\Delta V / \Delta t$. This quantity may be determined from the continuous record of lake stage provided that a stage-volume rating for the lake is known. These relationships may only be derived from lake surveys and for the south basin of Lake Chicot the relationship is

$$V = 493.8 (S_L - 22.2)^{2.18}. \quad (11)$$

In order to assess the volume of water contributed to the lake volume through precipitation over the lake, daily records of precipitation were obtained from four weather stations surrounding the lake. Daily variation of the precipitation over the lake was obtained by averaging the values recorded at the four weather stations.

Pan evaporation records at Stoneville, Scott and Dermott were considered adequate for estimating evaporation from the surface of the lake. The average value of the daily records at the above mentioned stations was used for the lake evaporation.

IV ANALYSIS OF THE LAKE BUDGETS

The annual water budget terms are presented in Table 1 along with the residence times (the ratio of the average lake volume to the annual inflow) and the flushing times (the ratio of the average lake volume to the annual outflow).

Table 1
WATER BUDGET
(Million cubic meters)

	WY 1977	WY 1978	WY 1979
Inflow	189.02	283.91	970.22
Outflow	183.86	282.79	982.31
Change in Volume	-2.63	3.01	-9.16
Direct Precipitation	15.68	18.07	19.27
Direct Evaporation	15.28	14.88	16.37
Loss/Gain	8.20	1.43	-.04
Residence Time (Year)	0.368	0.249	0.079
Flushing Time (Year)	0.378	0.250	0.078

The ground water exchange term, between the lake itself and the river was further examined by considering a one-dimensional flow on a horizontal impervious boundary between Lake Chicot and the Mississippi River. A sand-gravel aquifer underlies the entire area (Kolb 1968).

Using the Dupuit assumption, the flow through the aquifer is:

$$G = UB(h-h_r) \quad (12)$$

where U is the horizontal component of the velocity of flow through the aquifer at distance x from Lake Chicot, B is the effective width of the aquifer, h is the thickness of the aquifer above the MSL, and h_r is the elevation of a reference plane from the MSL.

Using Darcy's Law

$$U = -K_{sat} \frac{dh}{dx} \quad (13)$$

where K_{sat} is the saturated hydraulic conductivity and dh is the change in the hydraulic head occurring in distance dx.

Substituting the value of U and integrating

$$\int_0^L G dx = - \int_{S_L}^{S_R} K_{sat} B (h - h_r) dh \quad (14)$$

yields

$$G = K_{\text{sat}} \frac{B}{L} \left((S_L^2 - S_R^2) / 2 - h_r (S_L - S_R) \right) \quad (15)$$

From the geometrical considerations of the lake an average value of B, the North-South projection of the lake, was found to be 8.8 km. An average length, L, the distance between the lake and the river was 11.2 km. The average value of h_r is taken as 5.7 m.

The values of the lake stages, S_L , and the river stage, S_R were used in equation 15 to obtain a daily contribution to the groundwater term. this was summed over the entire water year and set equal to the loss/gain term, G, from the budget analysis for the three years studied.

K_{sat} , the saturated hydraulic conductivity, was then determined. The results are 0.65, 0.64, and 0.63 m/sec respectively for 1977, 1978 and 1979. These values are remarkably constant over the period of study giving confidence to the accuracy of the measurements and analysis.

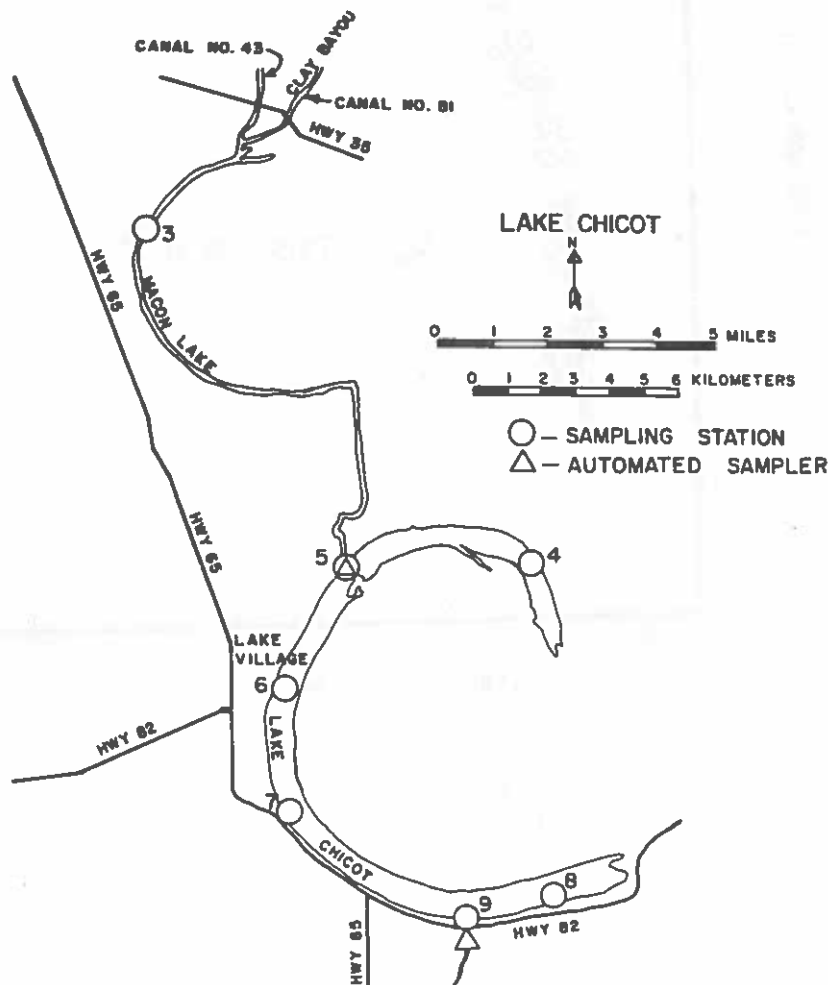


Fig. 1) Location Map of Lake Chicot and Associated Tributaries

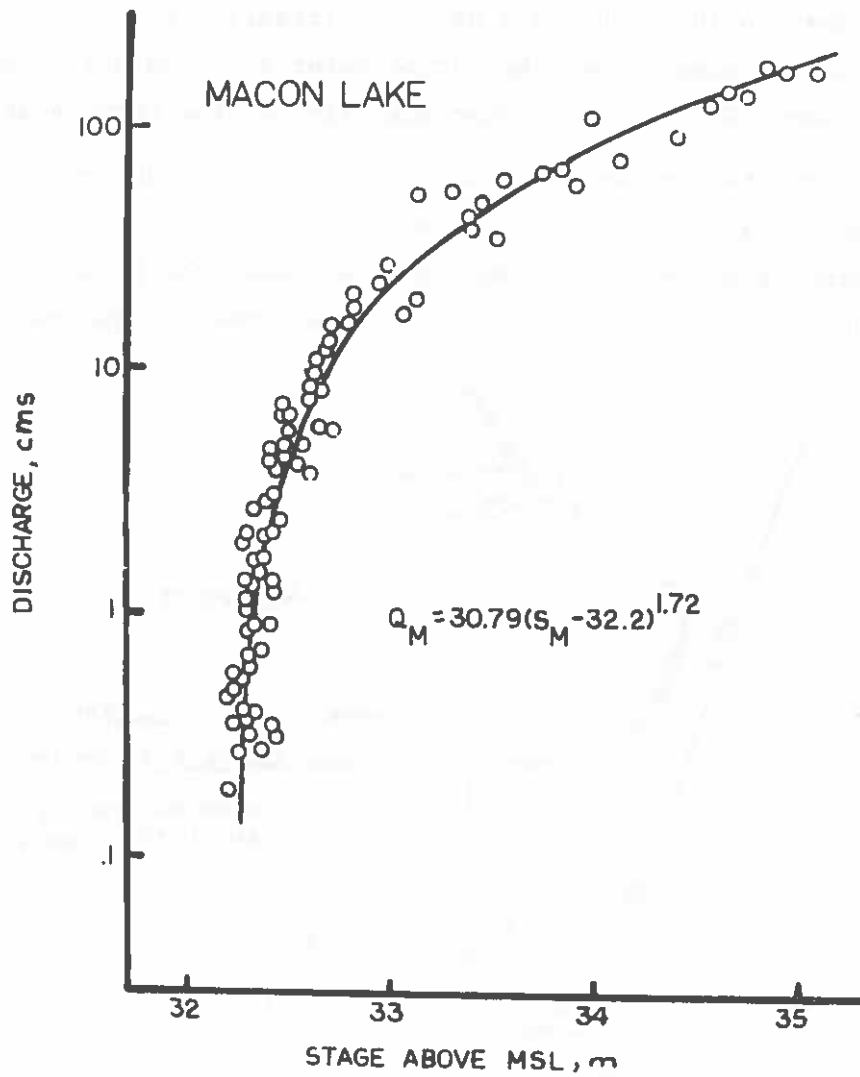


Fig. 2) Discharge Rating Curve for the Macon Lake Channel, Station 3

The remaining budgets were evaluated by using the rating equations and procedures outlined in the foregoing section on a daily basis. In each case a residual term was encountered that accounted for the quantity being trapped by the lake. As previously discussed this term contains all of the errors that originated in evaluating all other terms of the equation. When accumulated over an entire year it is likely that errors on individual terms will tend to cancel themselves.

The trap efficiency for each component and for the total sediments was computed for each year. By definition the trap efficiency is

$$E_T = 100(F_{in} - F_{out})/F_{in} \quad (16)$$

for any particular substance. These values are presented in Table 2 for the sediments and total solids and Table 3 for the phosphorus components.

Table 2

SEDIMENT BUDGET (Millions of kilograms)			
	WY 1977	WY 1978	WY 1979
Suspended Sediment Inflow	63.44	234.27	1,129.56
Suspended Sediment Outflow	44.32	102.81	426.56
Storage Change	-10.63	6.60	-34.38
Deposition	106.36	124.86	737.38
Total Dissolved Sediment Inflow	21.63	27.28	63.45
Total Dissolved Sediment Outflow	16.40	19.76	58.96
Storage Change	-9.60	.76	-16.96
Loss	14.82	6.77	21.45
Total Sediment Inflow	161.67	261.56	1,193.01
Total Sediment Outflow	60.72	122.57	485.52
Storage Change	-20.24	7.35	-51.34
Loss	112.98	121.75	729.35
Percent Trap Efficiency			
1. Suspended sediment	68.35	56.11	62.24
2. Total dissolved sediment	24.15	27.59	7.08
3. Total sediment	62.44	53.14	59.30

When compared with lakes of similar residence times (Brune 1953) the lake is not very effective in trapping sediments. The lake trapped 68 percent, 56 percent, and 62 percent for the respective three years of our study. The trap efficiencies of similar lakes would be of the order of 75 percent for WY 1979. The extremely colloidal and dispersed nature of the sub-micron suspended sediments in Lake Chicot is the obvious reason for this discrepancy.

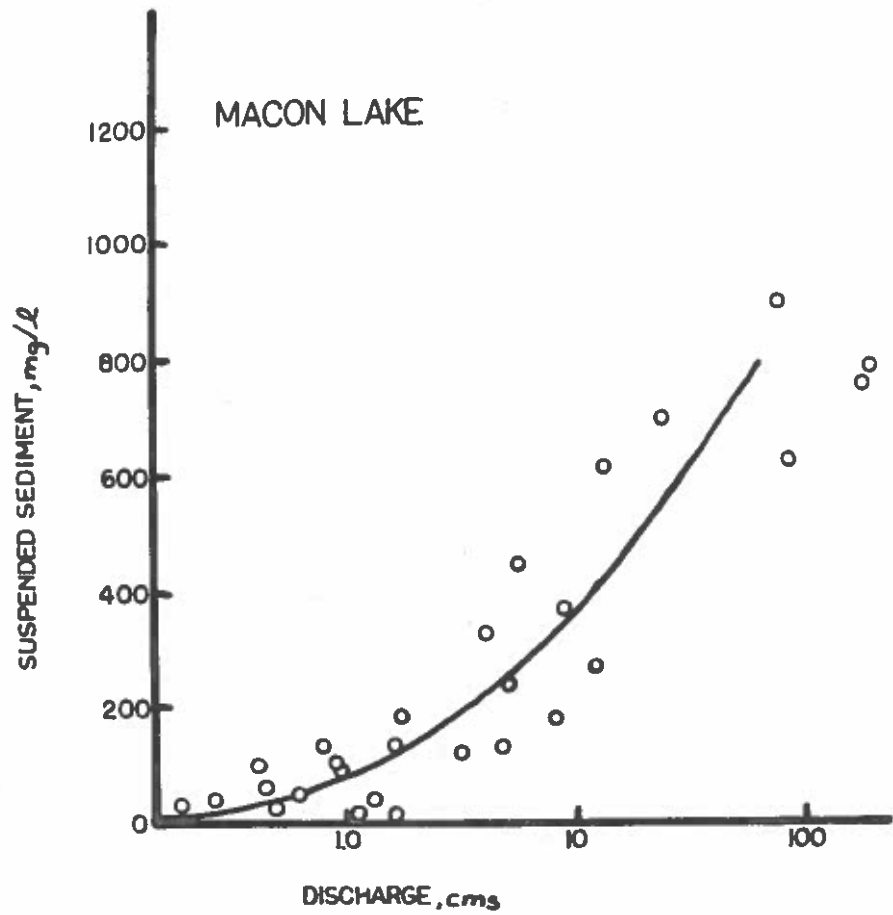


Fig. 3) Suspended Sediment Rating for the Macon Lake Channel

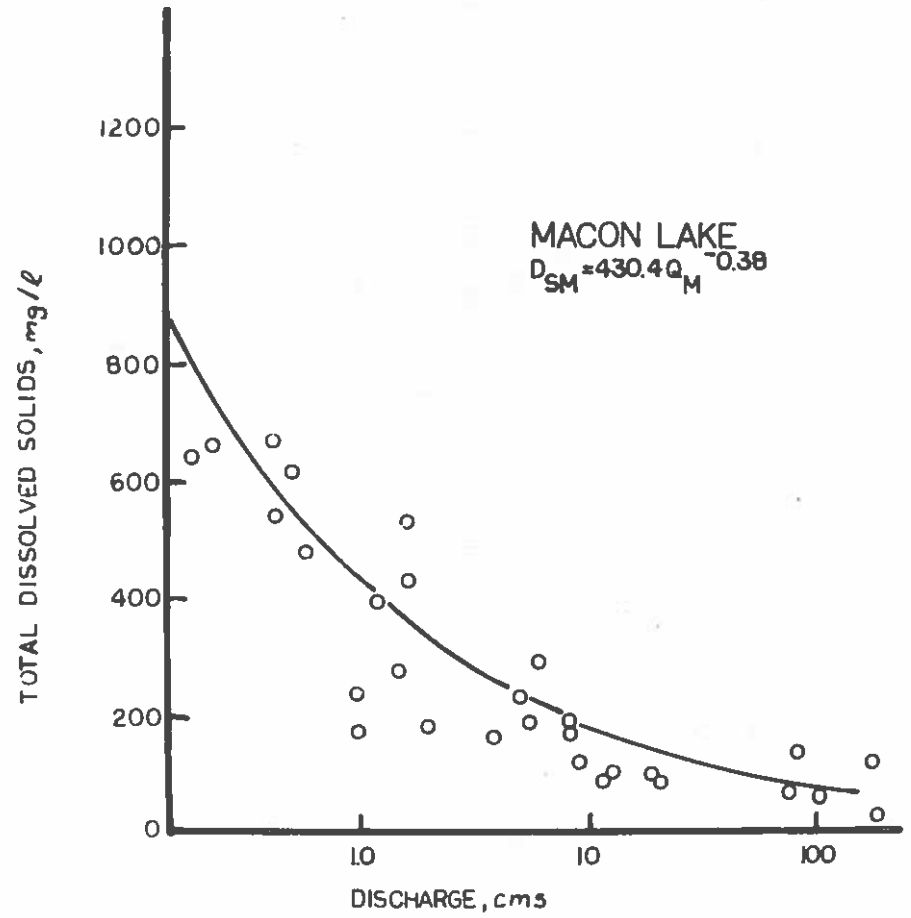


Fig. 4) Dissolved Solids Rating Curve for the Macon Lake Channel

Table 3

PHOSPHORUS BUDGET
(Kilograms)

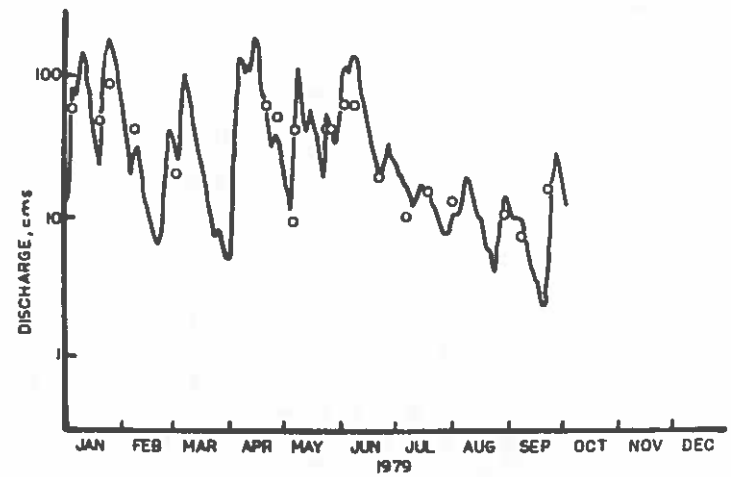
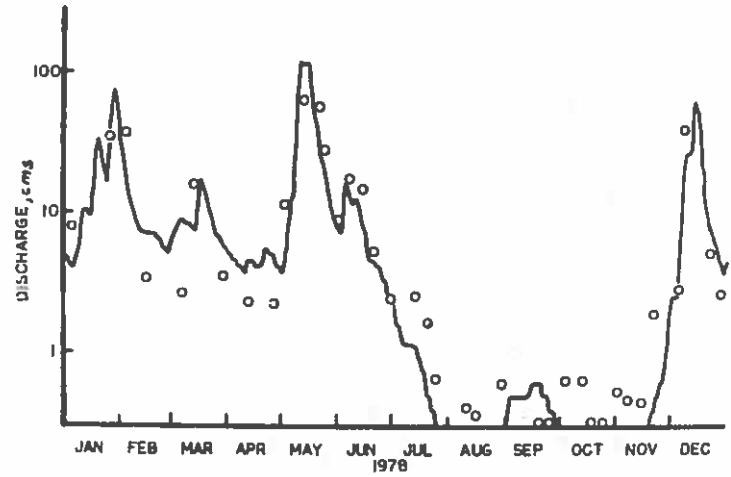
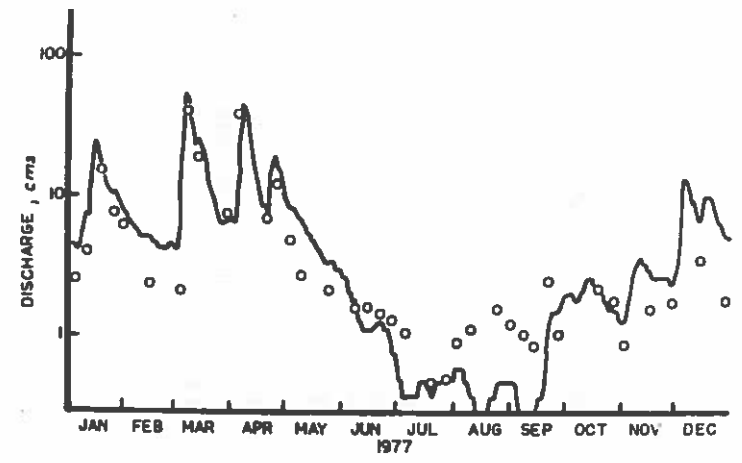
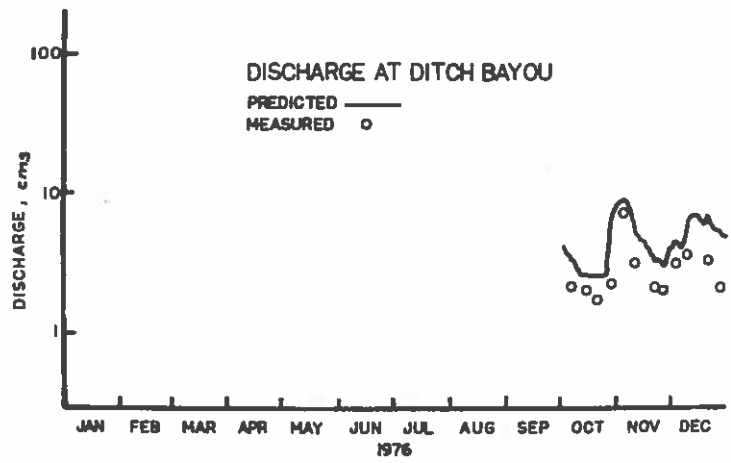
	WY 1977	WY 1978	WY 1979
Total Phosphorus Inflow	253,800	412,560	717,266
Total Phosphorus Outflow	187,518	303,254	643,343
Phosphorus Input by Atmospheric Loading	685	922	891
Storage Change	79,530	48,808	22,628
Loss/Gain	-12,564	61,420	52,186
Dissolved Ortho Phosphorus Inflow	23,103	36,751	149,839
Dissolved Ortho Phosphorus Outflow	14,683	23,594	51,291
Storage Change	4,790	2,628	1,261
Loss	4,316	11,451	98,223
Total Ortho Phosphorus Inflow	83,102	133,189	278,888
Total Ortho Phosphorus Outflow	74,313	119,792	257,341
Storage Change	27,522	15,934	7,562
Loss/Gain	-18,046	-1,614	14,876
Percent Trap Efficiency			
1. Total Phosphorus	26.11	26.49	10.30
2. Dissolved Ortho Phosphorus	36.44	35.80	65.77
3. Total Ortho Phosphorus	12.21	10.06	7.20

Water years 1977 and 1978 could be considered near long term average while water year 1979 was significantly different. While the direct precipitation in 1979 was only 23 percent greater than in 1977 the runoff into the lake was 413 percent greater. The budget equation for the lake shows a net gain from the groundwater during 1979 and significant losses during 1977 and 1978. A possible explanation is the position of the groundwater table on the watershed. The Mississippi river stages were on the order of 6 to 9 m higher in 1979 than they were in 1977. Since a sand-gravel layer underlies the entire area, the Mississippi River evidently influences the groundwater level in the entire area. In 1979 the river stages were about the same as the land surface elevations on the Lake Chicot watershed, the infiltration rate on the watershed decreased tremendously, resulting in the high inflow to Lake Chicot.

Since the concentrations of all other substances were related to the water discharge their budgets were also drastically affected in 1979.

V SUMMARY AND CONCLUSIONS

This research concerned the development of the material budgets for water, sediment and phosphorus for Lake Chicot for the 1977, 1978, and 1979 water years. The general approach was to develop rating



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Fig. 5) Discharge From Lake Chicot

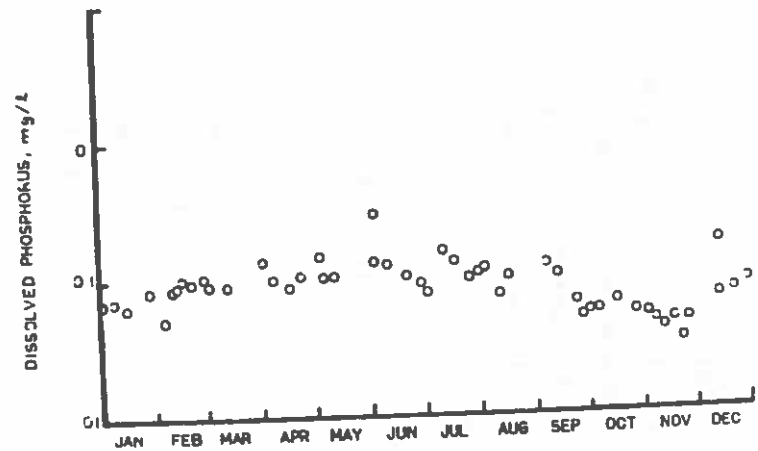
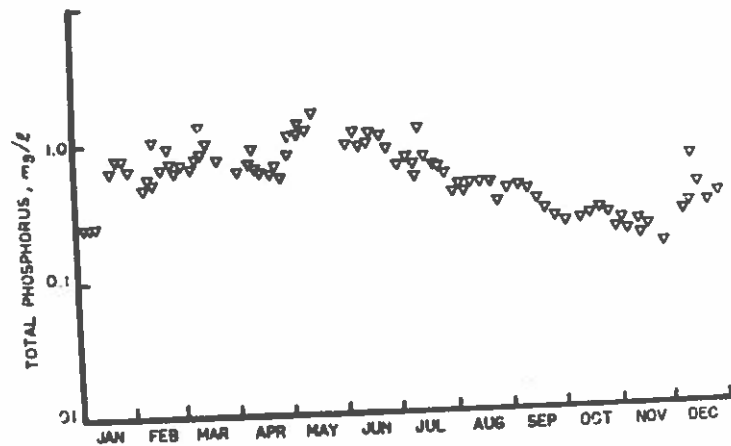
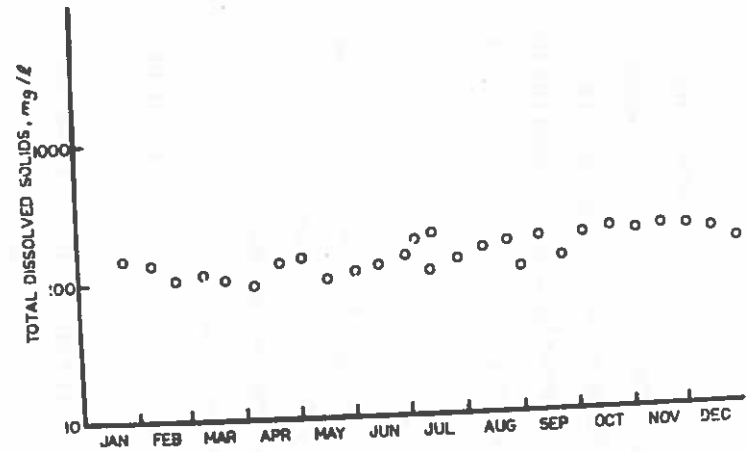
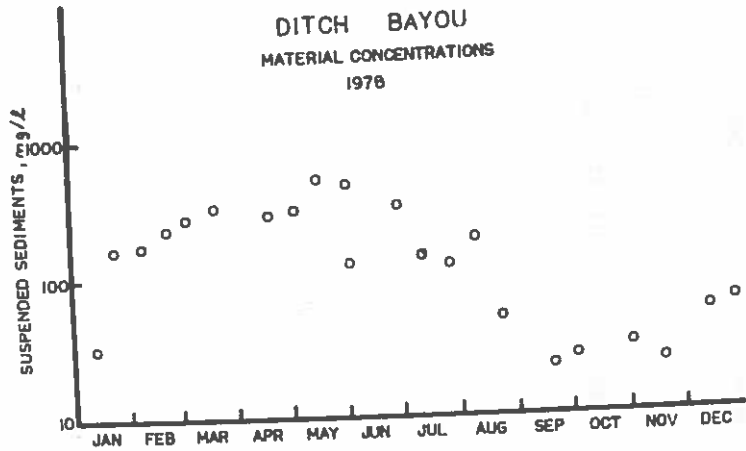


Fig. 6) Concentrations of Materials Flowing From Lake Chicot, 1978

relationships so that any particular variable could be evaluated and predicted on a daily basis. This was done and these predictions were compared with field observations of the variables made at one and two week intervals. In some cases, daily field observations were available. The daily predictions were then used in determining the annual material budgets.

Based on this analysis the following conclusions were made:

1. The saturated hydraulic conductivity, K_{sat} , computed by using Equation 15 for the soil underneath Lake Chicot is about 0.64 m/day. This is believed to be a reasonable estimate.
2. The flushing times, the ratio of lake volume to annual outflow for the three consecutive Water Years, are 0.3, 0.25 and 0.08 years respectively.
3. The magnitude of the runoff from the watershed in WY 1979 was about 5 times the runoff of WY 1977 for only 20 percent more rain. This was attributed to the much higher stages of the Mississippi River during 1979, producing a higher groundwater table on the watershed, which would significantly reduce infiltration on the watershed.
4. The annual trap efficiencies (TE) based on the suspended sediments computed for the three consecutive WYs are 68.35%, 56.11%, and 62.24%, respectively. The corresponding values of annual TE computed from total solid inputs and outputs are 62.44%, 53.14% and 59.30%.

References

- Brune, G.M. 1953. Trap efficiency of reservoirs. Trans. American Geophysical Union. vol. 34, no. 3.
- Kolb, C.R. 1968. Geological investigation of Yazoo Basin, lower Mississippi Valley. US COE-WES Technical Report No. 3-480. Vicksburg, MS.
- Stefan, H.G., S. Dhamotharan, and F.R. Schiebe. 1982. Temperature sediment model for a shallow lake. Journal of the Environmental Engineering Division, ASCE. vol. 108, no. EE4. pp. 750-765.
- Stefan, H. G., S. Dhamotharan, A. Y. Fm, and J. J. Cardoni. 1983. Mathematical Model Simulation of Lake Chicot, Arkansas. Proceedings of the Arkansas Lake Symposium, Arkadelphia, AR.
- Swain, A. 1980. Material budgets of Lake Chicot, Arkansas. PHD Thesis. University of Mississippi.

DEPOSITED SEDIMENTS OF LAKE CHICOT

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ABSTRACT

Deposited sediments in Lake Chicot, an oxbow lake in extreme southeastern Arkansas, were characterized by measurements of density, particle size, total N, total P, extractable P, and clay mineralogy. Sediment samples were collected on cross sections representative of the lake. The samples were analyzed for fallout cesium-137 content. Sedimentation rates since 1954 were calculated using the cesium-137 data. The rates averaged from 1 to 4 cm/yr, depending on location within the lake. Sedimentation rates 2 to 3 times greater in the lower lake than in the upper lake. Sediment densities increased slightly with depth where particle size remained constant; from 1.2 g/cm³ at the surface to 1.4 g/cm³ at 2 to 4 m depth. Total N and P concentrations decreased with depth in the profile and were correlated with clay content.

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INTRODUCTION

Lake Chicot, an oxbow lake created by long ago meandering of the Mississippi River, is located in Chicot County, extreme southeastern Arkansas. The lake has a surface area over 4,000 acres divided by a man-made dike into a smaller northern basin and a much larger and more turbid southern body (Table 1). As a natural cutoff lake Lake Chicot was subjected for many years to periodic flushing by floods of the Mississippi River. With the closure of the main line level system following the 1927 flood little inflow into the lake occurred from the natural drainage system. However the actions of various federal, state, and local projects during the intervening years resulted in the diversion of flood flow from some 350 square miles into Lake Chicot. As this area became more intensively farmed, and as the use of agricultural chemicals increased, the lake became a sink for sediments and associated agricultural chemicals. The result was a very turbid body of water (southern basin) with an associated higher rate of sedimentation, an increased chemical load, and a greatly reduced recreational use.

In 1977 the Agricultural Research Service proposed an assessment and evaluation of the hydrological, chemical, and microbiological regimes of Lake Chicot to the Vicksburg District, U.S. Army Corps of Engineers. This proposal was made to characterize the liminological, chemical and microbiological regimes of Lake Chicot prior to construction and operation of a project to divert flood flow, or flow of undesirable characteristics from the 350 mile drainage area directly into the Mississippi River bypassing Lake Chicot. Specific objectives of this proposal included the determination of selected parameters of the deposited sediments and the comparison of these for the two basins as well as the relationship of these characteristics to inflow, soils, plant nutrient use and land management. This paper describes the procedures used to evaluate the deposited sediments and discusses the results within the context of the management of Lake Chicot with the flood diversion works in place.

MATERIALS AND METHODS

Nineteen ranges were established on Lake Chicot (Figure 1). At selected

range lines, cross sections of the water and sediment surfaces were obtained using a recording fathometer. At selected points on these range lines in situ densities of the underlying sediment profiles were obtained using a dual gamma probe (McHenry, 1971).

Sediment samples were collected at fourteen sites (Figure 1). These samples were collected using a plastic tube (15.2 cm I.D.) (Ritchie, et al., 1970). The sediment profile cores were sectioned into 10-cm increments and like depth increments were composited, from 6 to 8 cores being taken at each site. The composited samples were placed in plastic bags, taken to the laboratory, dried at 60 °C, passed through 0.6 cm screen and dried at 100 °C.

Samples of 1000 g, or total samples, if sample was less than 1000 g, were placed in plastic Marinelli beakers for Cs-137 analyses (Ritchie, et al., 1970). The concentration of Cs-137 was determined by the method described by Ritchie and McHenry (1973), modified by using a solid state detector, germanium lithium drifted crystal, and a Canberra Model 8180 multi-channel (4096) analyzer. (Use of sampling names and trade names are provided for the benefit of the reader only and do not imply any endorsement or preferential use by the United States Department of Agriculture.)

Subsamples of the sediments were ground to pass a 60 mesh screen. Particle-size distribution was determined using a Sedigraph (Schiebe, et al., 1983). Available Phosphorus was determined as the amount of P extracted from 0.1 g of sediment by 20 ml of a 0.03 N NH_4F and 0.025 N HCl solution during 5 minutes of shaking (Bray and Kurtz, 1945). Total phosphorus was determined by perchloric acid digestion (Sommers and Nelson, 1972). In all tests the concentration of soluble P was determined on filtered samples by the method of Murphy and Riley (1962). Total N was determined by a semi-micro Kjeldahl procedure (Bremner, 1965).

RESULTS AND DISCUSSION

Morphometric Parameters:

Lake Chicot today is effectively two lakes; the result of a dike built and maintained by the Arkansas Game and Fish Commission. Morphometric parameters of the two Lake Chicots are presented in Table 1. The relationship of reference volume to reference depth as presented in Table 1 is

graphically shown in Figure 2. Additional morphological data for the lower lake is presented in Table 2. The lower lake is similar in structure throughout its length, being deeper on the outer, or south and west, side with a sloping shelf to the inside, or eastern bank. Typical cross sections obtained with the fathometer (Figure 3-7) illustrate this similarity in form. Such a form is typical of the oxbow lake, the outer perimeter being the old cutting side of the channel with the inside bank being the area of deposition. During the water years (October to September) of 1977-1979, pertinent characteristics of the lower lake were recorded and are presented in Table 3. Changes in average annual stages are not large as witnessed by these data. Fluctuations during the years may be as great as 10 to 12 feet. Note the relative large increase in surface area of the lower lake during cited years as compared to area at the reference pool level of 100 feet (Table 1).

Clay Mineralogy

Selected sediment samples from Lake Chicot were sent to NASA Langley Research Center, Hampton, Virginia, and Oklahoma State University, Stillwater, for clay mineral identification by x-ray diffraction. The samples provided NASA are the subject of a report by Bice and Clement (1981). The Lake Chicot samples were reported to contain illite, kaolinite, quartz and minor amounts of chlorite. With a decrease in particle size there was an increase in the kaolinite peak intensity as demonstrated in the following:

<u>Particle Diameter</u>	<u>Relative Ratio Percentage</u>		
	<u>Kaolinite</u>	<u>Illite</u>	<u>Quartz</u>
Whole sample (Lake Chicot sediment)	23.3	15.8	60.9
<6 ϕ (16 microns)	22.3	22.1	55.6
<8 ϕ (4 microns)	29.2	27.0	43.8
<10 ϕ (1 micron)	29.9	30.2	39.9

Coarse and fine fractions of the 10 to 20 cm depths from profiles 77-S-401, 407, 410, and 412 were analyzed by Dr. Lester Reed, Professor of Soil Chemistry, Oklahoma State University. Quartz, kaolinite, hydrous mica and smectite (montmorillonite) were reported by Professor Reed (Personal communication). The peaks associated with smectite were very strong. The intensity of the smectite peaks was increased in the fine fraction and that

of quartz decreased. The Langley Research Center did not run the x-ray diffraction down to the small angle necessary to differentiate montmorillonite. There was little difference in the clay mineral composition on percentage at the different sites sampled. Kaolinite and hydrous mica percentages did increase in the finer fraction. Because most of the sediments entering Lake Chicot have their source in alluviums, the mineralogical, as well as chemical, make up with time varies but little.

Sediment Density:

On selected ranges (Figure 1), a cross section of the water sediment interface was determined with a recording fathometer. The cross sections for ranges designated (-2), 0, +2, 7R and 11 are shown in Figures 3, 4, 5, 6, and 7, respectively. Range 7R was established for water quality studies and is equivalent to Range 6 in Figure 1. Range 0 is at Ditch Bayou, the outlet. Ranges to the east, downstream, are identified by the minus sign; those upstream are numbered from 1 through 14. Several short ranges were established upstream of Range 14, at the mouth of Connerly Bayou. Here depths were less than a meter and sediments were either sands at the surface or within 30 cm. Due to the high density of wet sands, the dual gamma probe cannot be pushed into such materials.

As indicated in the morphological description all the cross sections are similar in shape, viz., a deep trough on the outer or southwesterly bank with a gradual slope upward to the inside bank. Maximum depths of these cross sections increases from 6 meters at Range 11 to 8 meters at Range 0 and Range 7R with some shoaling to Range (-2). Actual maximum depths from Range 0 to Range 7R are nearly the same. Maximum cross sectional volume of water occurs at Range 7R with that at Range 0 being only slightly less.

On each of the five ranges listed above, sediment density profiles were determined at 4 to 6 sites per range. The in situ densities, as determined with the dual gamma probe, are summarized in Figures 8, 9, 10, 11, and 12 for Ranges (-2), 0, 2, 7R and 11. The location and depth of these logged profiles are shown in Figures 3-7. In the deeper pool areas the sediments exhibit a uniform increasing density with depth. These densities are about 1.2 g/cm^3 at the sediment surface and increase to 1.4 at 2 to 4 meters depth (of sediment). Those profiles on the slopes, or near the banks, exhibit differing characteristics. Indications of differential sediments appear as at Site 5,

(Range -2); Site 6, Range 2; and Sites 1-3 on Ranges 7R and 11. Several transitional sites indicate abrupt changes in density at a considerable depth, viz., Site 2, Range (-2); Sites 3 and 4, Range 0. The shallower sites generally indicated sands or sediments high in sand. There are smaller variations in densities within the profile, as Sites 4 and 5, Range 2; and Sites 4 and 5, Range 7R. These changes in density in an otherwise similar pattern probably indicate times, or periods, of flooding resulting in sandier sediments of higher density being deposited.

Particle-size, N, and P contents

Samples were taken at five locations (Figure 1) for characterization of particle-size, N, and P. These particular profiles were taken prior to the establishment of ranges for sediment density determination so their relationship to the aforementioned sites is approximate, not exact.

Profiles 409, 410, and 411 were sampled near Range (-2) (409 being on the inside, 411 being on the outside). These results are summarized in Figure 13. The dates 1954 to 1965 indicated on the total P profiles refer to reference dates determined from the ^{137}Cs analyses discussed below.

These profiles are truncated in comparison with those obtained for sediment density. Variations in the parameters, TKN, total P and clay contents, are small except for Profile 11 (inside bank at 5 to 6 meters depth) where about 1960-62 materials with greater N and P contents were deposited. There is no corresponding difference in clay content. In general the differences with depth of any parameter are small and usually progressive.

Similar sediment profile characteristics for profiles collected on Ranges 7R and 11 are summarized in Table 4. The distribution and content of clay ($<2\mu$) at Sites 404 and 407 (Ranges 11 and 7R) are similar in these two profiles and differ considerably from Profile 410 (Range -2). Note the rather abrupt decrease in clay content below 40 cm, viz., from 71.2 to 51.7% in Profile 407 and 71.7 to 42.3% in Profile 404. In Profile 410 the clay content to 90 cm exceeds 75.0% (from 75.0 to 79.1%) at 40 cm and deeper. Those differences indicate (1) an increasing content of fine particles in the deposited sediment as one travels downstream from the main

input (Connerly Bayou) and (2) a marked difference in the sedimentation history at Sites 404 and 407 as compared to Site 410.

Nitrogen contents generally decrease with depth although there are horizons which are exceptions. The N percentage is slightly greater in the profiles on the outside (Sites 408 and 405). There is a correlation of clay and N contents at Sites 404 and 407. Such a relationship is expected as organic matter generally is deposited with the finer inorganic particles. Total P contents also increase from inside to outside of the lake and are correlated also with clay content. It appears the decrease in depth of N and P contents is related to the decrease in clay content with depth. The percentage of P extractable, i.e., available for plant use, decreases with depth. Some fixation of P occurs with time (depth).

Sediment Deposition Rates

Rates of sediment deposition for the years 1954 through 1977 and intervening periods were calculated on the basis of ^{137}Cs data obtained for selected profiles. The data obtained are summarized in Table 5. Peak years of fallout ^{137}Cs were taken as occurring in 1958 and 1964. First significant occurrence of ^{137}Cs in an undisturbed sediment profile is assumed to be in 1954.

Rates of sedimentation deposition were greater in the lower lake than in the upper. This was expected as the turbidity problem of Lake Chicot has been largely confined to the lower lake. Sedimentation rates were somewhat higher on the outside of the lake, the area of greater water depth and that area showing the deeper sediment profiles. Sedimentation rates decreased somewhat as distance from the main sediment input, Connerly Bayou, increased. This correlates with the noted decrease in size of particles depositing with increasing distance from the source. In most profiles the data indicate sedimentation rates were greater from 1954 to 1964 than from 1965 through 1977. This is particularly true at the lower end of the lake (Range -2). At the upper end of the lake (Range 14) near Connerly Bayou sediment input during 1965-1977 appears to have been greater than during 1954-64. Here sufficient differentiation occurs in the ^{137}Cs content with depth, so we can estimate rates from 1965 to 1971, and from 1972 through 1977. The rates during the earlier period are greater than for 1972-77.

Computations of sediment input and retention to the lower lake during 1977, 1978, and 1979 have been computed (Schiebe, et al., 1983). Based on the average surface area, 0.52, 0.61, and 3.5 cm/yr of sediment were added to the average sediment profile. At Sites 400, 401 and 402 (Range 14) the computed annual rates for the years 1972-1977 using the ^{137}Cs data were 1.67, 1.67, and 3.33 cm; an average of 2.22 cm/yr. This is the average for the 6-year period. The three year, 1977-79, average was 1.54 cm. These data suggest that a considerable variation in the amount of sediment deposited on an annual basis occurs. The long time, 1954-77, average annual increment on this range was computed from ^{137}Cs data to be 3.40 cm. The computed data for 1979 indicates an accumulation of 3.50 cm. As the rates for 1977 and 1978 were computed to be much lower, it can be assumed average rates of sediment accumulation are now less than they were 10, 15, or 20 years ago. However, in some recent years the average sedimentation rate for the time period involved may be exceeded. For instance from 1965 to 1971 annual rates of sediment deposition were considerably greater than the long time average.

If the diversion of silt laden waters from Lake Chicot is achieved, the expected deposition of 2 or 3 cm per year of sediment will be diverted. Assuming an area equivalent to that at a 30.48 m stage, i.e., 1364 ha (Table 1), and taking the average bulk density to be 1.25, some 375,000 tons of sediment per year would not be deposited, i.e., would be diverted. We estimate some 450 kg of P are diverted per year also. This amount of sediment averages out to be 1.7 tons per year per watershed acre (0.63 ton/hectare) assuming a watershed of 350 square miles. These figures represent the recent past sediment trapping efficiency of Lake Chicot. We know that not all the sediment that enters the lower lake by Connerly Bayou is trapped but our interest is primarily in how much was being trapped and now may be diverted from the lake. On an area average, we know the distribution from upper to lower areas and from shallow to deep will vary, i.e., from 0 to perhaps 6 cm a year. Assuming the 2 to 3 cm of sediment diversion, a volume equivalent to a meter of depth lake wide would be saved in 30 to 40 years. This would be a notable savings.

We do not have much data on the upper lake. What we do have and that is presented here indicates the problem is less severe, perhaps realistically about a third of the lower lake. This means, however,

that in a century the upper lake can lose a meter or more in average depth due to sediment accumulation. To control or alleviate this problem on site (field) conservation measures are indicated.

REFERENCES

1. Bice, K. L., and S. C. Clement. 1981. Mineralogical, optical, and geochemical properties of John H. Kerr Reservoir and Lake Chicot sediment samples for AgRISTARS pollution research. NASA Contractor Rpt. 165761, Langley Research Center, Hampton, VA. 18 pp.
2. Bray, R. H., and L. T. Kurtz. 1945. Determination of total, organic, and available forms of phosphorus in soils. *Soil Sci.* 59:39-45.
3. Bremner, J. M. 1965. Total nitrogen. In C. A. Black (ed.) *Methods of Soil Analysis*. Part 2. *Agronomy* 9:1149-1170. Amer. Soc. Agron., Madison, WI.
4. McHenry, J. R. 1971. Sediment measurement techniques reservoir deposits, a discussion. *Jour. Hydraulics Div., Proc. Amer. Soc. Civil Eng.* 97(HY8):1253-1257.
5. Murphy, J., and J. P. Riley. 1962. A modified single solution method for determination of phosphate in natural waters. *Anal. Chim. Acta.* 27:31-36.
6. Ritchie, J. C., and J. R. McHenry. 1973. Determination of fallout ¹³⁷Cs and naturally occurring gamma-ray emitters in sediments. *Int. J. Applied Radiation and Isotopes* 24:575-578.
7. Ritchie, J. C., J. R. McHenry, A. C. Gill, and P. H. Hawks. 1970. The use of cesium-137 as a tracer of sediment movement and deposition. *Proc. Miss. Water Resources Conf., Water Resources Res. Inst., Miss. State Univ.*:149-162.
8. Schiebe, F. R., N. H. Welch, and L. R. Cooper. 1983. Measurement of fine silt and clay size distributions. *Trans. Amer. Soc. Agric. Engineers* 26:491-494, 496.
9. Schiebe, F. R., A. Swain, C. M. Cooper, and J. C. Ritchie. 1983. Material budgets of Lake Chicot. *Proc. Arkansas Lake Symposium, Arkadelphia, AR, Oct. 1983.*
10. Sommers, L. E., and D. W. Nelson. 1972. Determination of total phosphorus in soils: A rapid perchloric acid digestion procedure. *Soil Sci. Soc. Amer. Proc.* 36:902-904.

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Table 1. Selected morphological parameters for Lake Chicot.

	<u>Upper Lake</u> ft (m)	<u>Lower Lake</u> ft (m)
Depth:		
Maximum effective	15.5(4.52)	27.2(8.29)
Mean	8.9(3.01)	12.5(3.80)
Reference Pool Level	100(30.48)	100(30.48)
	<u>ac(ha)</u>	<u>ac(ha)</u>
Area: (Reference pool at 100 feet MSL)	873(353.6)	3369(1364.4)
	<u>ac.ft.(m³)</u>	<u>ac.ft.(m³)</u>
Volume: (Pool at 100 ft.)	8636(10.65x10 ⁶)	42036(51.83x10 ⁶)

$$\frac{V}{V_{ref}} = \left[\frac{h}{h_{ref}} \right]^{1.57} \quad \frac{v}{V_{ref}} = \left[\frac{h}{h_{ref}} \right]^{2.18}$$

V_{ref} = reference volume

h_{ref} = reference depth

Table 2. Morphological data of Lower Lake Chicot.

Elevation		Stage		Area		Volume	
ft	m	ft	m	Acres	hectares	ac.ft.	10^6 m^3
72.8	22.19						
75.0	22.86	2.2	0.67	192	77.8		
80.0	24.38	7.2	2.19	601	243.4	1882	2.321
85.0	25.90	12.2	3.72	1125	455.6	5981	7.375
90.0	27.43	17.2	5.24	2112	855.4	14570	17.965
95.0	28.96	22.2	6.77	2753	1115.0	26732	32.960
100.0	30.48	27.2	8.29	3369	1364.4	42036	51.830
105.0	32.00	32.2	9.81	3913	1584.8	60239	74.275

Table 3. Characteristics of Lake Chicot, 1977-1979 (lower lake).

	WY 1977	WY 1978	WY 1979
Average Stage, ft(m)	103.91(31.67)	103.88(31.66)	104.72(31.92)
Average surface area, acres (ha)	3,947(1599)	3,942(1596)	4,069(1648)
Average volume, acre feet ($10^6 m^3$)	56,333(69.46)	56,214(69.31)	56,579(69.76)
Average depth, ft (m)	14.27(4.35)	14.26(4.35)	14.64(4.46)

Table 4(a). Summary of sediment characteristics for selected profiles, Lake Chicot.

Profile	Depth	TKN	Total P	Extractable P	Particle-size			
					>20 μ	20-2 μ	<2 μ	<1 μ
Range 7 Site 406 (inside)	cm	$\mu\text{g/g}$	$\mu\text{g/Kg}$	$\mu\text{g/Kg}$	%			
	0-10	1734	1268	407				
	10-20	1326	903	305				
	20-30	1302	787	198				
	30-40	1320	839	232				
	40-50	1344	926	281				
	50-60	1422	969	297				
	60-70	1590	960	258				
	70-80	1355	887	227				
	80-90	1608	951	227				
Range 7 Site 407 (middle)	0-10	2778	1188	408	1.3 ¹	11.5	87.2	75.4
	10-20	2130	1182	495	0.7 ¹	14.2	85.1	74.5
	20-30	1872	1204	462	4.9	24.8	70.3	61.3
	30-40	1821	1341	488	2.8 ²	26.0	71.2	61.6
	40-50	1230	855	306	17.4 ²	30.9	51.7	40.0
	50-60	1260	834	277	21.1	27.2	51.7	46.2
	60-70	1272	930	257	18.8	31.5	49.7	42.7
	70-80	1554	1156	250	4.7	33.6	61.7	51.5
	80-90	1332	949	239	3.1	36.8	60.1	50.0
Range 7 Site 408 (outside)	0-10	2052	1184	391				
	10-20	2286	1178	372				
	20-30	2328	1318	353				
	30-40	2352	1347	417				
	40-50	2586	1571	464				
	50-60	2724	1760	506				
	60-70	2523	1691	443				
	70-80	1389	936	283				
	80-90	924	722	250				
	90-100	2337	1580	452				
	100-110	1287	880	304				

¹ Deposited prior to 1965

² Deposited prior to 1954

Table 4(b). Summary of sediments characteristics for selected profiles, Lake Chicot.

Range 11 Profile Site 403 (inside)	Depth cm	TKN μg/g	Total P μg/kg	Extractable P μg/kg	Particle Size			
					>20	20-2μ %	<2μ	<1μ
	0-10	1422	937	302				
	10-20	1344	698	231				
	20-30	600	491	155				
	30-40	1074	677	161				
	40-50	1116	697	183				
	50-60	1290	856	186				
	60-70	1182	838	226				
	70-80	1422	919	220				
	80-90	1233	933	218				
Range 11 Site 404 (middle)	0-10	1950	1218	279	0.1	16.9	83.0	71.8
	10-20	2034	1231	515	1.0 ¹	17.2	81.8	71.6
	20-30	2070	1268	445	1.3 ¹	20.4	78.3	68.7
	30-40	2100	1303	486	2.6	25.7	71.7	61.0
	40-50	1026	698	578	36.1 ²	21.6	42.3	38.5
	50-60	774	610	247	34.6 ²	33.4	32.0	28.3
	60-70	1017	712	199	26.7	33.4	39.9	34.8
	70-80	1014	726	209	24.9	35.3	39.8	34.0
	80-90	1572	1023	171	13.4	33.9	52.7	44.8
Range 11 Site 405 (outside)	0-10	2028	1283	421				
	10-20	2004	1359	416				
	20-30	2103	1382	409				
	30-40	2112	1542	436				
	40-50	1554	1079	349				
	50-60	618	645	195				
	60-70	948	786	223				
	70-80	1260	917	303				
	80-90	1362	985	264				

¹ Deposited prior to 1965.

² Deposited prior to 1954.

Table 5. Sediment accumulation rates in Lake Chicot, Arkansas. Based on ^{137}Cs contents of selected sediment profiles.

Range	Site	Location	Sediment deposition		
			1954-64	1965-77	1954-77
Lower Lake					
			cm / yr		
-2	411	outside	5.45 ¹	0.77	2.92
	410	middle	2.27	0.38	1.25
	409	inside	1.36	0.38	0.83
7R(6)	408	outside	4.54	2.31	3.33
	407	middle	2.73	0.77	1.67
	406	inside	4.54	0.77	2.50
11	405	outside	2.73	1.54	2.08
	404	middle	2.73	1.54	2.08
	403	inside	1.36	0.38	0.83
14	402	outside	2.73 ²	4.62 ³	3.75 ²
	401	middle	3.64	3.08 ⁴	3.33
	400	inside	3.64	3.08 ⁴	3.33
Upper Lake					
	413	outside	1.82	0.77	1.25
	412	inside	3.64	0.77	2.08

¹ 1954-58, 4.0 cm/yr; 1959-64, 6.67 cm/yr.

² Profile did not exceed depth of ^{137}Cs burial so total accumulation is not known.

³ 1965-1971, 5.71 cm/yr; 1972-77, 3.33 cm/yr.

⁴ 1965-1971, 4.29 cm/yr; 1972-77, 1.67 cm/yr.

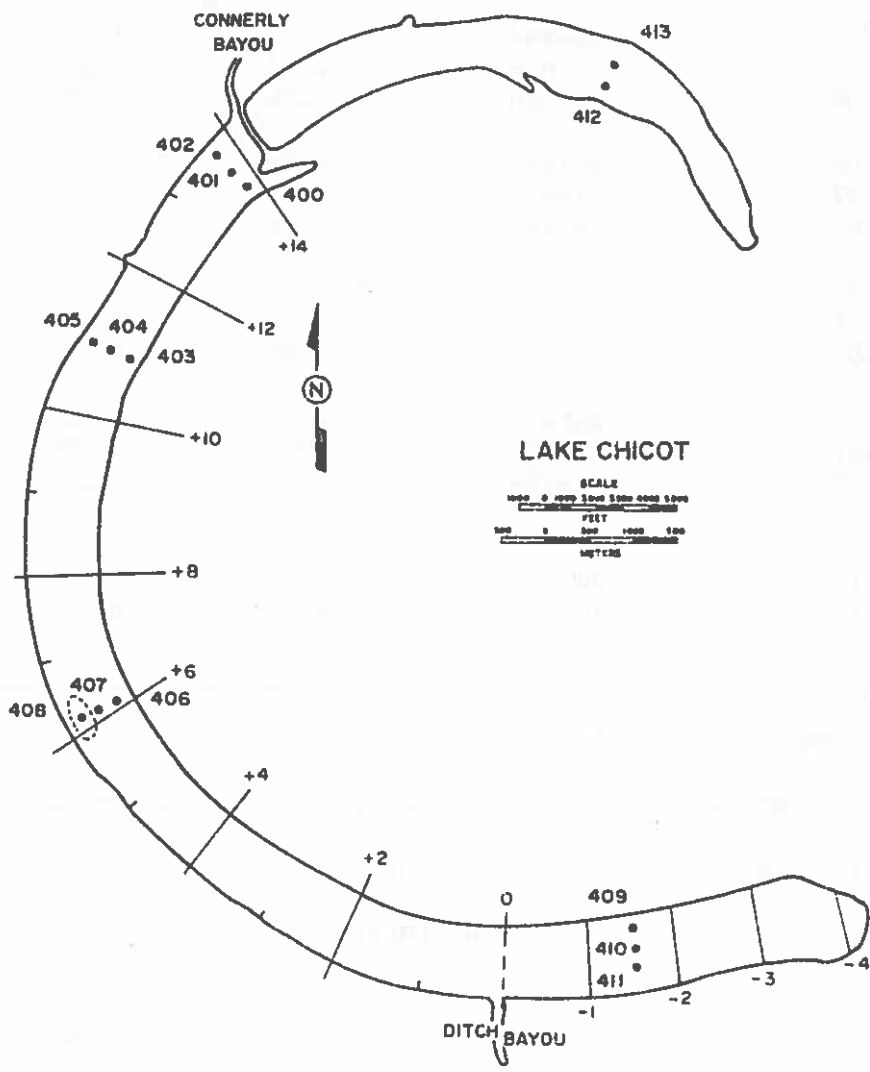


Figure 1. Sketch map of Lake Chicot showing the approximate location of the range lines established and of the profiles sampled for determination of cesium-137 content.

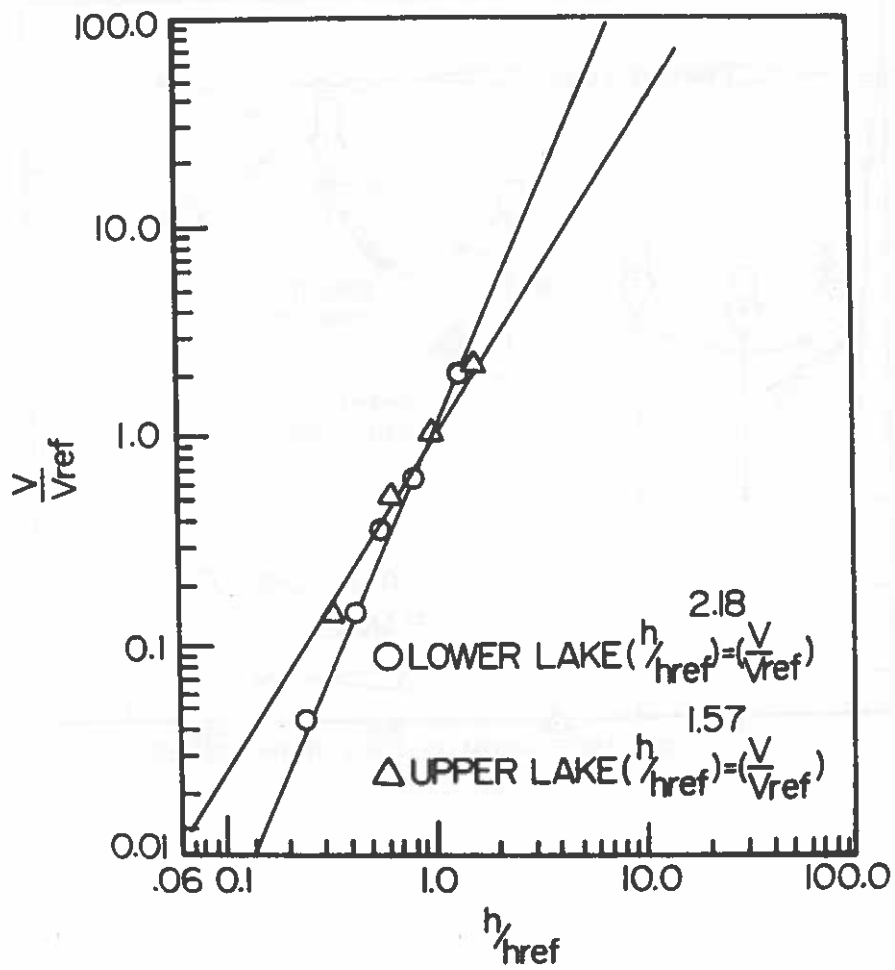


Figure 2. Morphometric relations for upper and lower basins of Lake Chicot, Arkansas.

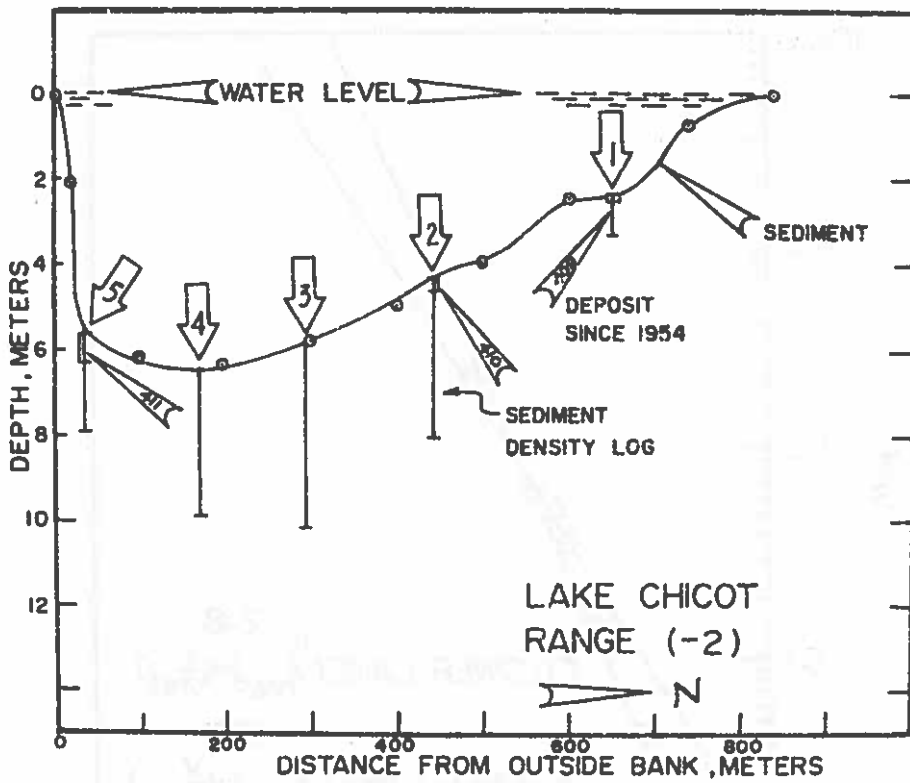


Figure 3. Cross section profile of Lake Chicot at Range (-2). Sediment profiles for ^{137}Cs , particle-size and chemical analyses are shown (Sites 409, 410, and 411).

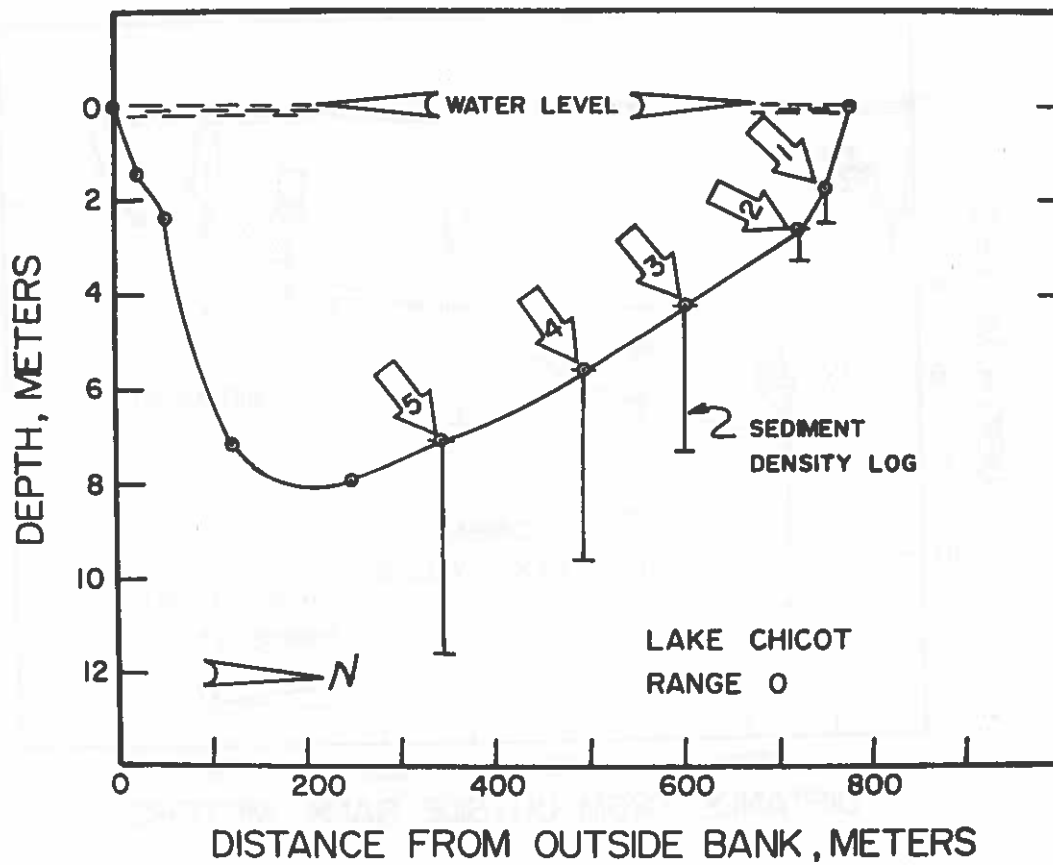


Figure 4. Cross section profile of Lake Chicot at Range 0. Location of sediment profile sites are indicated.

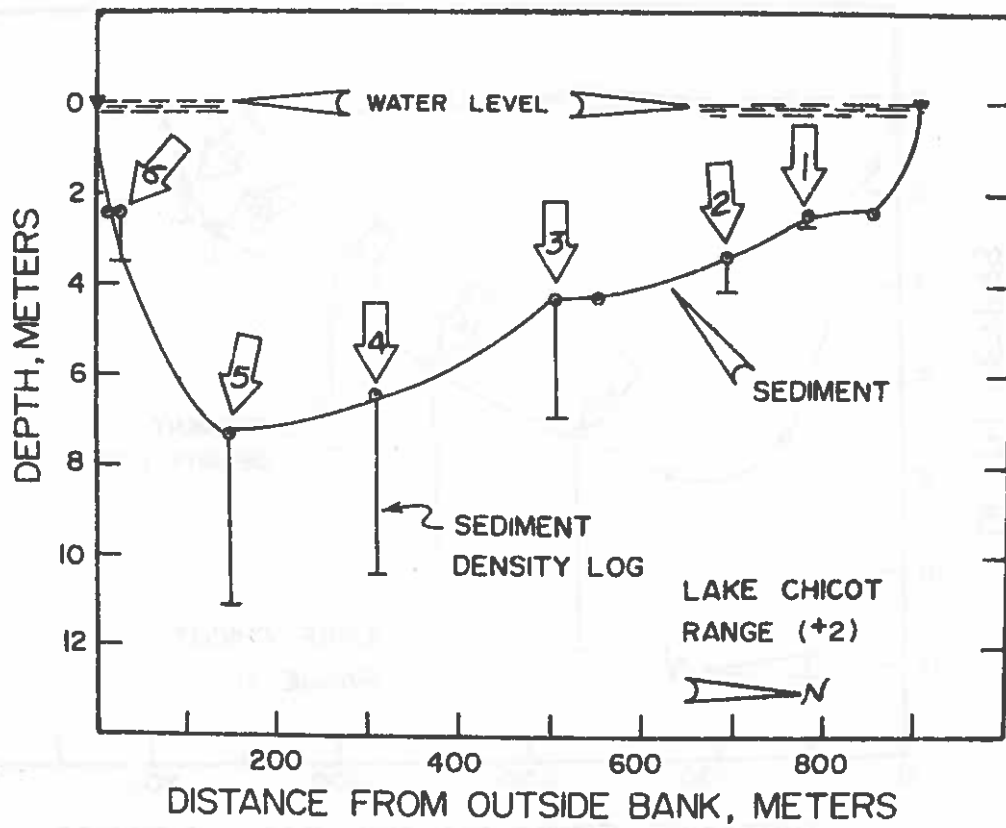


Figure 5. Cross section profile of Lake Chicot at Range 2.

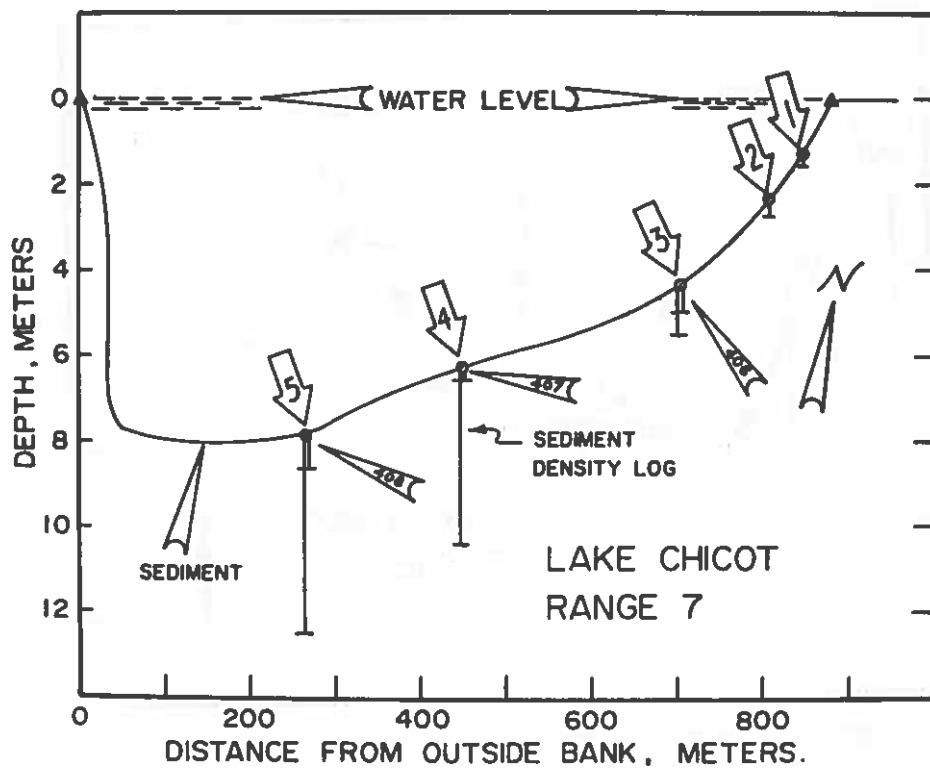


Figure 6. Cross section profile of Lake Chicot, at Range 7R (Range 6 in Figure 1). Sediment profiles are ^{137}Cs , particle-size and chemical analyses are shown (Sites 406, 407, and 408).

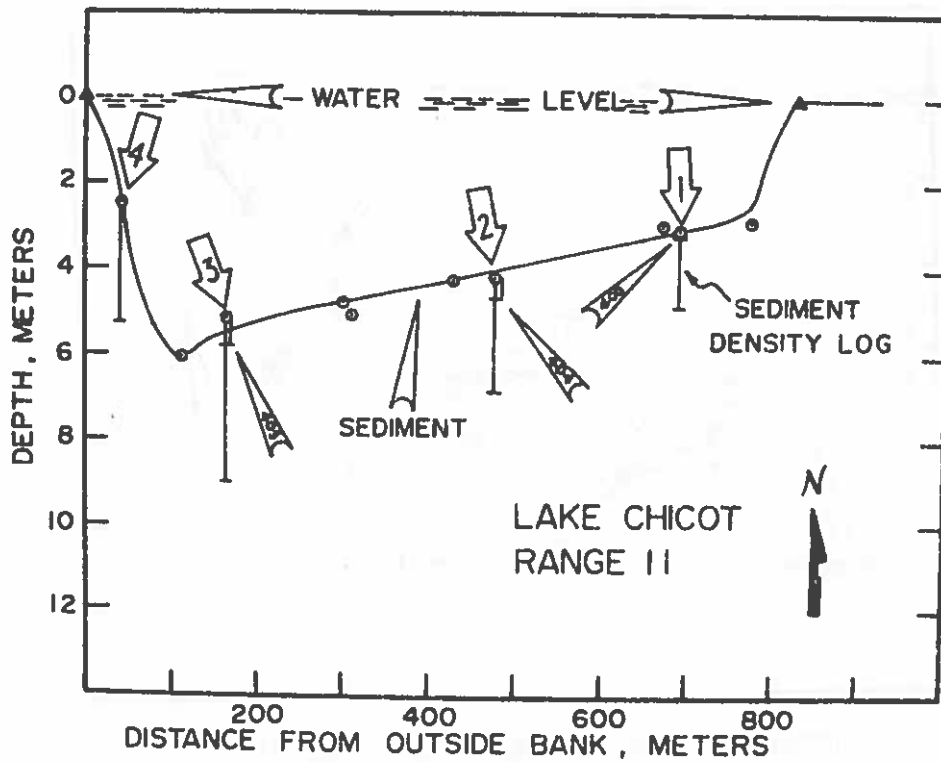


Figure 7. Cross section profile of Lake Chicot at Range 11. Sediment profiles for ^{137}Cs , particle-size and chemical analysis are shown (sites 403, 404 and 405).

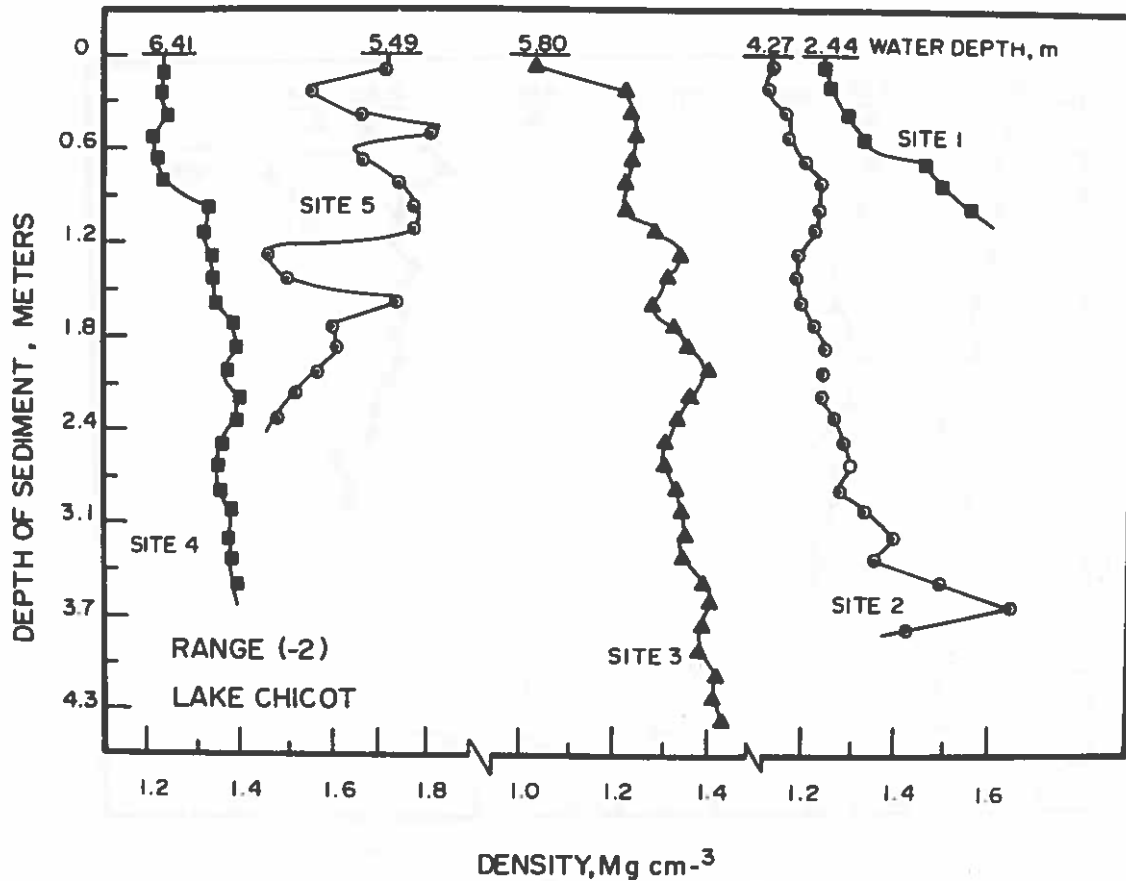


Figure 8. Sediment density profiles on Range (-2), Lake Chicot.

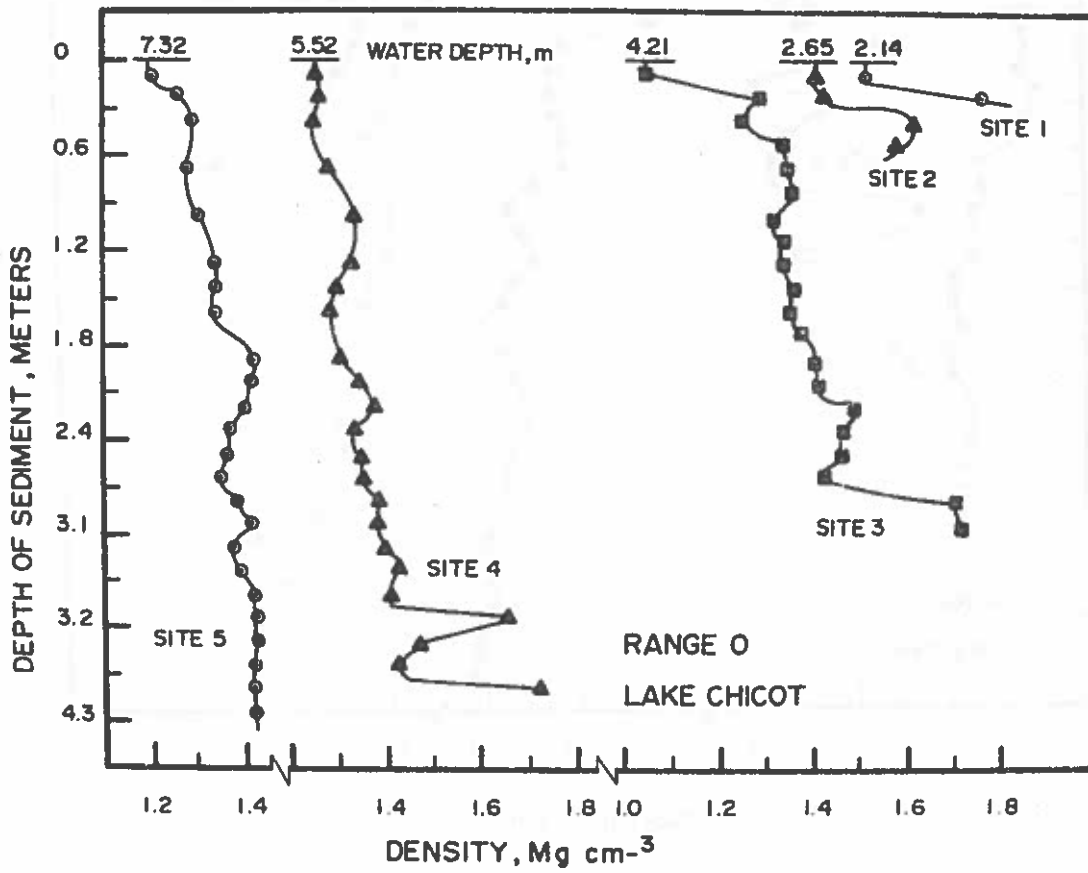


Figure 9. Sediment density profiles on Range 0, Lake Chicot.

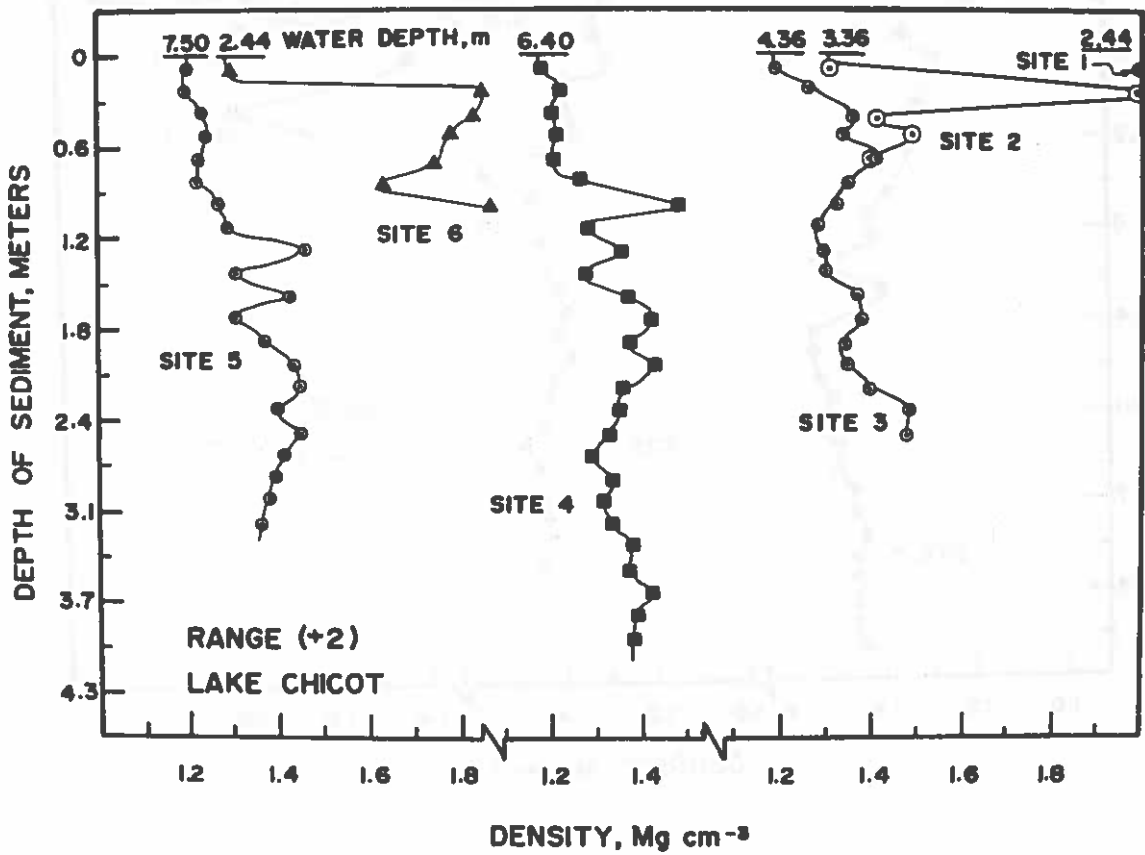


Figure 10. Sediment density profiles on Range 2, Lake Chicot.

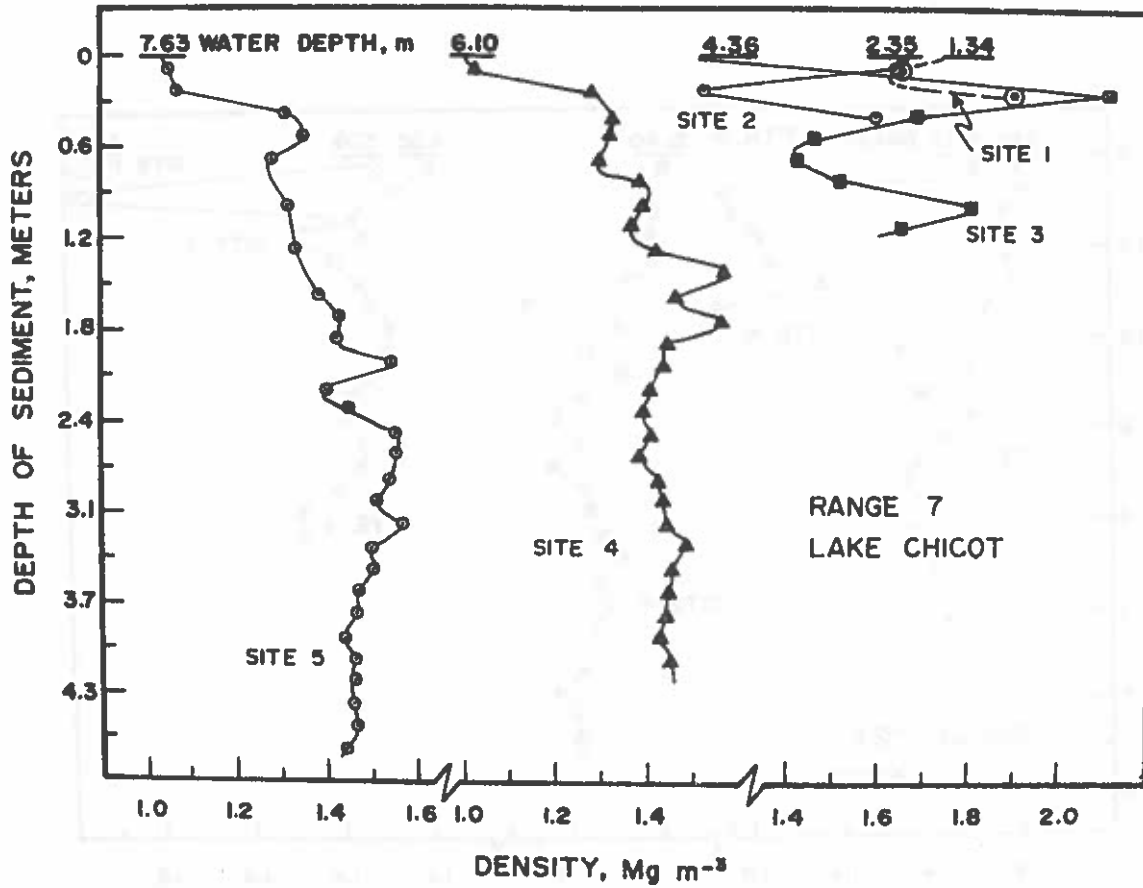


Figure 11. Sediment density profiles on Range 7R, Lake Chicot.

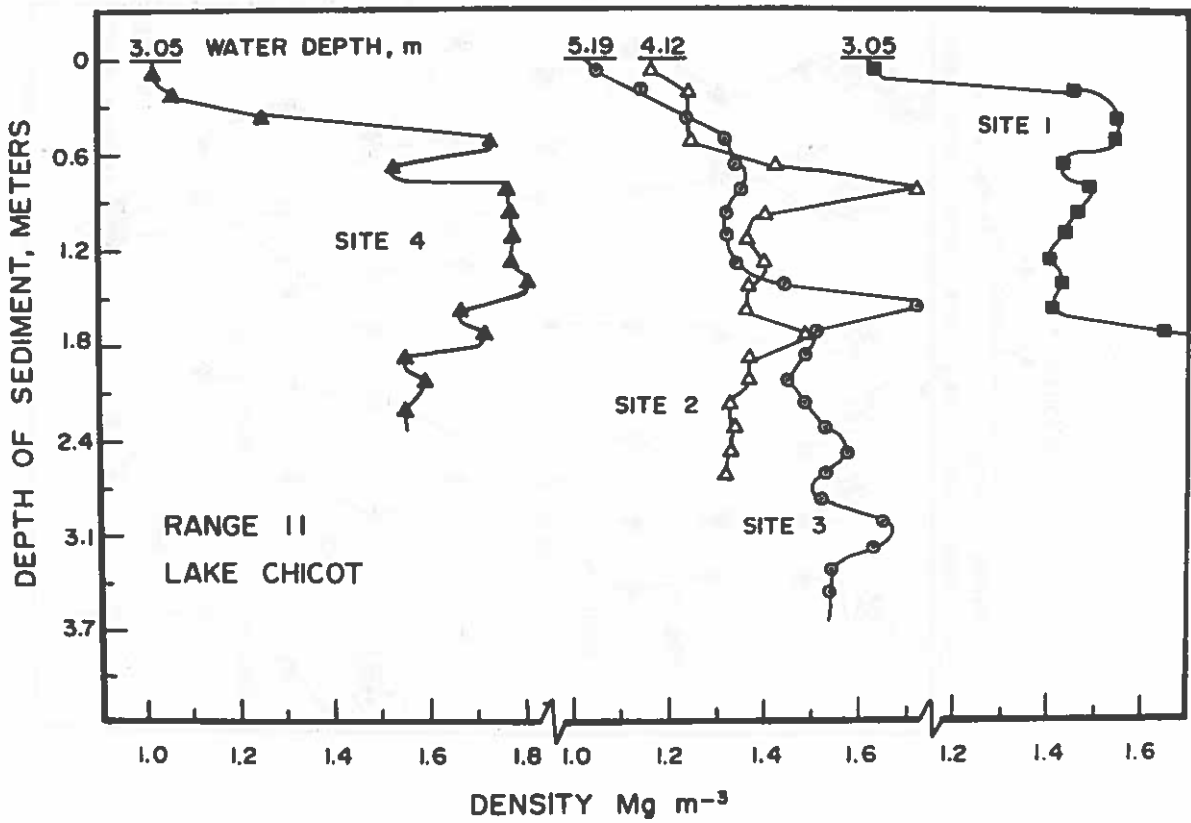


Figure 12. Sediment density profiles on Range 11, Lake Chicot.

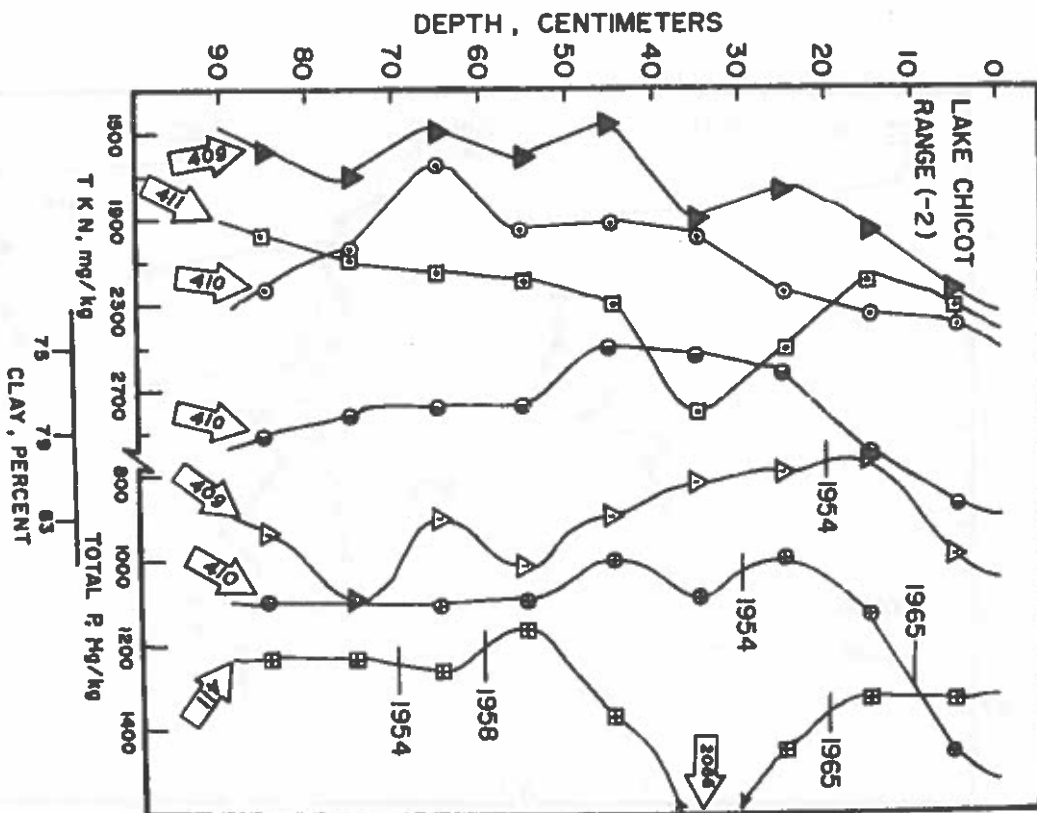


Figure 13. TKN, total P and clay contents for sediment profiles 409, 410, and 411, Range (-2), Lake Chicot.

Biological Cycles in Lake Chicot, Arkansas^{1/2/}

C. M. Cooper, E. J. Bacon, and J. C. Ritchie^{3/}

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- ^{1/} Contribution of the Sedimentation Laboratory, Agricultural Research Service, U. S. Department of Agriculture, Oxford, Mississippi, in cooperation with the University of Arkansas-Monticello and the U. S. Army Corps of Engineers, Vicksburg District.
- ^{2/} Invited paper to be presented at the Arkansas Lakes Symposium, Arkadelphia, Arkansas, October 4-6, 1983, and published in the Proceedings of the Meeting.
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Biological Cycles in Lake Chicot, Arkansas^{1/}

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Abstract

Lake Chicot, Arkansas is one of the largest oxbow lakes (19.3 km²) of the Mississippi River. Following massive flooding and watershed enlargement in 1927, a dike was constructed across the lake just above the major point of inflow, isolating the upper part of the basin. The drainage area of the larger south basin was channelized and converted from hardwoods to rowcrop agriculture (75+ percent). The watershed of the isolated north basin was cleared but was not enlarged. Patterns of primary productivity and water quality were monitored (1976-82) to determine effects of runoff from intensive agriculture. Fluctuations in the populations of coliform bacteria followed discharge patterns except for occasional independent growth of bacterial populations. Although coliform levels were not normally of public health significance, they commonly reached 10⁴/100 ml during peak discharges. Fecal coliform/fecal streptococci ratios indicated these bacteria originated almost entirely from warm-blooded animals, excluding man. Chlorophyll a values and ¹⁴C uptake showed that algal growth rates and population densities in the south basin were limited seasonally by suspended material greater than 20-30 mg/l. Productivity in the isolated north basin was significantly higher as a result of lower turbidity levels. The management plan to divert high flows should decrease coliform bacteria and suspended solids while it improves water quality and productivity.

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Contribution of the Sedimentation Laboratory, Agricultural Research Service, U. S. Department of Agriculture, Oxford, Mississippi.

Introduction

One of the predominant features of the Mississippi River delta from Memphis, Tennessee, to the Gulf of Mexico is the abundance of oxbow lakes and cutoffs along the river. While these lakes have long been noted for their aquatic productivity and recreational value, recently most of them, unfortunately, have decreased in popularity (Bingham, 1967) because of declining water quality and fisheries (Coleman, 1969). Many of the current problems being experienced by delta oxbow lakes are directly related to land use changes from forestry to agriculture that have occurred over the last 80 years (Herring and Cotton, 1970; Cooper et al., 1982).

A joint assessment of the hydrological, chemical and biological regimes of Lake Chicot, Arkansas, by the USDA Sedimentation Laboratory and the U. S. Army Corps of Engineers, Vicksburg District, began in 1976. Some portions of the assessment will continue through 1986. The objectives of the biological investigations were to (1) determine short and long term effects of inflow from an intensively cultivated agricultural watershed upon the biology of a large riverine oxbow lake and (2) utilize this information to develop management practices to improve water quality and productivity. This paper reports on fluctuations in populations of coliform bacteria and primary productivity in Lake Chicot and how both are related to inflow.

Study Area

Lake Chicot, located in extreme southeastern Arkansas, has undergone major changes during the last 60 years. Originally, a small forested watershed provided the lake with excellent water quality, fisheries, and recreational opportunities. Basin enlargement, intentional and by major flooding in 1927, increased the drainage area from approximately 100 km² to 930 km². Channelization and land use changes from forest to rowcrop agriculture have greatly altered the quality and quantity of inflowing water. The 1927 flood also formed a large sand spit on the north side of the Connerly Bayou inflow. This formation isolated the north portion of the lake basin during low water and served as a base for a permanent levee, constructed in 1948, which

separated the two basins. Currently, at normal pool elevation, the south basin is larger in all dimensions. The surface areas of the north and south basins are $3.90 \times 10^6 \text{m}^2$ and $15.4 \times 10^6 \text{m}^2$, respectively. The south basin has a maximum depth of 9.2 m and a mean depth of 4.2 m while the north basin has a maximum depth of 5.5 m and a mean depth of 3.4 m. Nine stations, including inflow, lake, and outflow, were initially chosen for sampling purposes; however, this discussion will focus mainly on the Connerly Bayou inflow site (C-5), a site in the north basin (C-4) and a site (C-7) in the south basin located midway between the inflow and outflow (Fig. 1).

A more thorough description of lake morphology is included in a paper by Schiebe et al. (1980).

Methods

Sampling was begun in June, 1976, for measurement of selected water quality parameters. Monthly estimates of primary productivity, 1977-1979, were based on the carbon-14 (^{14}C) technique described by Steemann Nielsen (1951, 1952) as modified by Saunders et al. (1962) and Goldman (1963). Water samples for chlorophyll analysis were taken approximately the same dates as samples for ^{14}C analysis. Chlorophyll analysis consisted of standard spectrophotometric methods (APHA, 1975) after filtration of 0.4 l of water through a 0.45μ filter and extraction by 90 percent acetone. Total coliforms, fecal coliforms (FC), fecal streptococci (FS), plankton counts, and 5-day biochemical oxygen demand were also analyzed monthly (APHA, 1975). Macrobenthos was collected quarterly. Nitrate nitrogen, ammonia nitrogen, and ortho and total phosphorus were measured biweekly (EPA, 1974), as were temperature, dissolved oxygen, conductivity, pH, and total and suspended solids. After completion of Phase I of the project (1976-1979), sampling for chlorophyll, plankton, nutrients, and some physical parameters were continued on a monthly basis.

Results and Discussion

Temperature cycles in Lake Chicot were typical of warm monomictic lakes. Because of mild climate, flat terrain, and the shallow basin of

the lake, periods of thermal stratification were brief, even in summer. After fall overturn in September, the lake was usually homothermous until April with only minor periods of weak stratification. Minimum water temperatures in winter usually exceeded 5°C. Maximum summer surface temperatures reached 34°C during periods of thermal stratification. Corresponding hypolimnion temperatures approached 26°C.

Other parameters that influenced water quality and productivity were controlled, at least to some degree, by inflow. Coliforms at C-5, Connerly Bayou, showed a high correlation of coliform density with inflow rate (Fig. 2) and suspended solids although not all contamination was flow related. In July, 1977, the fecal coliform levels exceeded fecal streptococci levels with a ratio of 10.9, indicating human contamination. Otherwise, the FC/FS ratio averaged 0.67. The ratio exceeded 1.0 in five out of 30 comparisons but only exceeded 4.0 in the instance previously mentioned. FC/FS ratios of less than one generally indicate warm-blooded animal pollution, while ratios of more than four indicate human origin. Flows ranged from 0.14 cms (4.9 cfs) to 131.69 cms (4650 cfs). Water temperatures in the inflow varied from 1.1 C to 36.0 C. Dissolved oxygen ranged from 4.6 mg/l (45 percent saturation) to 18.5 mg/l (super saturation). Inflow pH ranged from 5.7 to 8.7 with a mean of 7.5.

Although Station C-6 was located in the open water and coliform counts were generally lower than at C-5, counts were still influenced by inflow from Connerly Bayou. The FC/FS ratios averaged 0.14 with a high of 1.5 and a low of 0; they exceeded 1.0 only one time in 31 comparisons. Correlation between discharge into the lake and coliform counts was not significant ($P < 0.025$) at Station C-7 although the same trends were evident. Coliform levels at C-7 were generally lower than at C-6 and dampened by distance from inflow and environmental factors (Fig. 3). The FC/FS ratios at C-7 averaged 0.07 (0-0.78) and did not exceed 1.0 in 33 comparisons.

Coliform levels at Station C-4, in the isolated north basin of Lake Chicot, were affected occasionally by local rainfall and animal activity (Fig. 3). The FC/FS ratios averaged 0.22 with a high of 1.3. The ratio exceeded 1.0 only once in 32 comparisons.

Lake Chicot exhibited high coliform counts at some time in the

study at all sites, but counts were not of sanitary significance except in Ditch Bayou (C-9) where there was evidence of pollution entering the system. Not all coliform peaks were discharge-related. Coliform growth, mainly in summer, was exhibited by bacterial population growth during periods of no discharge. For inflow, the bulk of fecal material appeared to be of animal origin and was closely related to discharge and suspended solids.

Chlorophyll a levels in inflow at Connerly Bayou (C-5) ranged from 1-3 mg/m³ in winter to late summer extremes of 32-96 mg/m³. Because of its length, flow characteristics, and storage capacity, Connerly Bayou has developed an indigenous plankton and contributes to the lake plankton. Estimates of chlorophyll a at C-7 indicated a single major annual peak in the south basin during September of each year (Fig. 4). Winter minimums influenced by low temperatures fluctuated between 1.5 and 4 mg/m³. Summer peaks were delayed temporally by suspended sediments which limited light. September peaks varied greatly (23-72 mg/m³) but were indicative of moderate biomass. Chlorophyll a values in the isolated north basin showed two peaks each year (Fig. 4), the first was associated with spring turnover and the second, larger peak with summer growth (37-168 mg/m³) and increased temperatures. Winter chlorophyll levels in the north basin ranged from 4.5-22.4 mg/m³ and generally reflected the absence of suspended sediments.

As with chlorophyll a, ¹⁴C uptake rates in the isolated north basin were significantly greater ($P < 0.025$) than in the main lake body (Fig. 5). Winter rates in the northern basin are greater than summer peak rates in most lakes in North America. Summer primary productivity in 1977 at C-4 ranged from 63 to 500.0 mg C/m³/hr with a mean of 247 mg C/m³/hr. ¹⁴C rates in 1978 and 1979 averaged 230 and 143 mg C/m³/hr, respectively.

Average assimilation rates observed at C-7 in the south basin during 1978 and 1979 were much less than at C-4, i.e. 35 and 19 mg C/m³/hr. Areas of the south basin which were slightly more protected (C-6) showed some variability with annual averages of 60, 33, and 26 mg C/m³/hr for 1977, 1978, and 1979.

Algal productivity was limited by several factors during the study. Some limitations occurred on a seasonal or systematic basis while others were more sporadic. The most obvious limitation on algal

productivity was the suspended sediment concentration. Sediment inflow and resulting suspended sediment concentrations represented a major difference between the two basins. While mean suspended sediment concentrations in the north basin were 20, 31, 68, 42, and 8 mg/l for 1977 through 1981, respectively, corresponding means were 3 to 7 times greater in the south basin, i.e. 117, 199, 262, 170, and 62 mg/l. Suspended sediment concentrations in the north basin were low (Fig. 4) for most years and phytoplankton populations followed expected growth curves with evidence indicating occasional self-shading or nutrient limitation in late summer and temperature limitation in winter. Suspended sediments restricted productivity in the south basin each year until suspended sediment levels decreased to 20-30 mg/l. At this level, light penetration was evidently no longer limiting and phytoplankton levels began to increase.

Additional indications of the effects of sediments on primary productivity were measured in the normally productive north basin. Runoff in 1979 was five times that of 1977 and 3.5 times that of 1978 (Schiebe et al. 1980), thus causing increases in suspended sediments. As a result, productivity was reduced 50 percent during 1979. Increased flushing also reduced productivity levels in 1979 in the south basin.

Productivity in both basins was enhanced by large quantities of inflowing phosphorus and nitrogen. In fact, phosphorus input was so large that nitrogen may have become limiting during late summer (EPA, 1977; Bacon, 1978). Monthly mean concentrations of nitrate nitrogen in the north basin were 267, 593, 409 and 366 $\mu\text{g/l}$ for 1978 through 1981, respectively. Nitrate nitrogen concentrations in the south basin were even higher, i.e. 600, 557, 604 and 402 $\mu\text{g/l}$ for 1978 through 1981. Annual mean concentrations of total phosphorus were 307, 236, 330, 181 and 230 $\mu\text{g/l}$ in the north basin and 344, 428, 683, 180 and 369 $\mu\text{g/l}$ in the south basin for 1977 through 1981. Orthophosphorus additions were controlled by runoff, as indicated by suspended sediments (Fig. 4). Depletion was controlled by primary productivity.

Reduction of suspended sediments by diversion of high flows will be the first result of the by-pass system located north of Lake Chicot. The second result will be an increase in primary productivity which should begin in May instead of July. Late summer nutrient limitation

will depend upon diversion management policies, i.e. how much watershed runoff is allowed to discharge into the lake.

Summary

Coliform counts, especially in or near the major inflow in Lake Chicot, correlated positively with runoff events from 1976 through 1979. The diversion of high discharge events by the designed pollution abatement facilities will alleviate much of the problem of high bacterial counts.

Primary productivity estimates based on chlorophyll a and ^{14}C assimilation fluctuated seasonally in response to suspended sediments, light, temperature and nutrient levels. Significant differences in primary productivity rates and suspended sediments were observed annually when comparing the two basins. Mean annual surface values of chlorophyll a ranged from 29 to 69 mg/m^3 in the north isolated basin and from 11 to 20 mg/m^3 in the south basin. The major limiting factor during the study was suspended sediments which reduced algal productivity rates at concentrations above 20-30 mg/l . Higher suspended sediment concentrations and accelerated flushing rates in 1979 and 1980 decreased productivity levels to 50% of that during the 2 previous years in both basins. Reduction of suspended sediment levels in inflowing water by the planned diversion should increase water clarity, water quality, and improve primary productivity in the south basin of Lake Chicot.

Acknowledgements

The authors thank Kathy Roush and John May for laboratory assistance; Richard Trant, Steve Scott, Scott Knight, Steve Corbin and Terry Welch for field assistance; and Myra Shaw and Winfred Cook for assistance in manuscript preparation.

Literature Cited

American Public Health Association. 1975. Standard Methods for the examination of water and wastewater; (14th ed.), Washington, DC.

- Racon, E. J. 1978. Primary productivity, water quality, and limiting factors in Lake Chicot; Arkansas Water Resources Research Center, Fayetteville, AR. Publ. No. 56, pp. 77-78.
- Bingham, R. 1967. Bottom fauna and plankton of two oxbow lakes. Mississippi Game and Fish Comm. Completion Report F-10-R. p.1.
- Coleman, E. W. 1969. State-wide lakes and streams survey. Mississippi Game and Fish Comm. Completion Report F-8-R Appendix. 113 pp.
- Cooper, C. M., L. A. Knight, and J. Herring. 1982. Fish composition in a sediment-laden Mississippi delta stream system. J. MS. Acad. Sci. 27:163-175.
- Environmental Protection Agency, 1974. Methods for chemical analysis of water and wastewater. Methods Development and Quality Assurance Research Laboratory, Cincinnati, OH. EPA-6251 S-74-003. 298 pp.
- Environmental Protection Agency, 1977. Report on Chicot Lake, Chicot County, Arkansas, EPA Region VI. National Eutrophication Survey, Environmental Monitoring and Support Laboratory, Las Vegas, NV., and Corvallis Environmental Research Laboratory, Corvallis, OR. Working Paper No. 484, 17 pp.
- Goldman, C. R. 1963. The measurement of primary productivity and limiting factors in freshwater by Carbon-14, pp. 103-113. In M. S. Doty, Ed., Proceedings of the Conference on Primary Productivity Measurements--Marine and Fresh Water; U. S. Atomic Energy Comm. TID 7633.
- Herring, J. and D. Cotton. 1970. Pesticide residues of twenty Mississippi delta lakes. Proceedings Annual Meeting Southeastern Association of Game and Fish Commissioners 24:482-488.
- Saunders, G. W., F. B. Trama, and R. W. Bachman. 1962. Evaluation of a modified C-14 technique for shipboard estimation of photosynthesis in large lakes. Great Lakes Res. Div., Univ. Mich. Publ. 8., 61 pp.
- Schiebe, F. R., J. C. Farrell, and J. R. McHenry. 1980. Water Quality improvement of Lake Chicot, Arkansas. Proceedings of the Symposium on Surface Water Impoundments. Minneapolis, MN., June, 1980. pp. 686-693.
- Steemann Nielsen, E. 1951. Measurement of the production of organic matter in the sea by means of carbon-14. Nature 167:684-685.
- Steemann Nielsen, E. 1952. The use of radioactive carbon (C-14) for measuring organic production in the sea. J. Conserv. Perm. Int'l. Explor. Mer. 18:117-140.

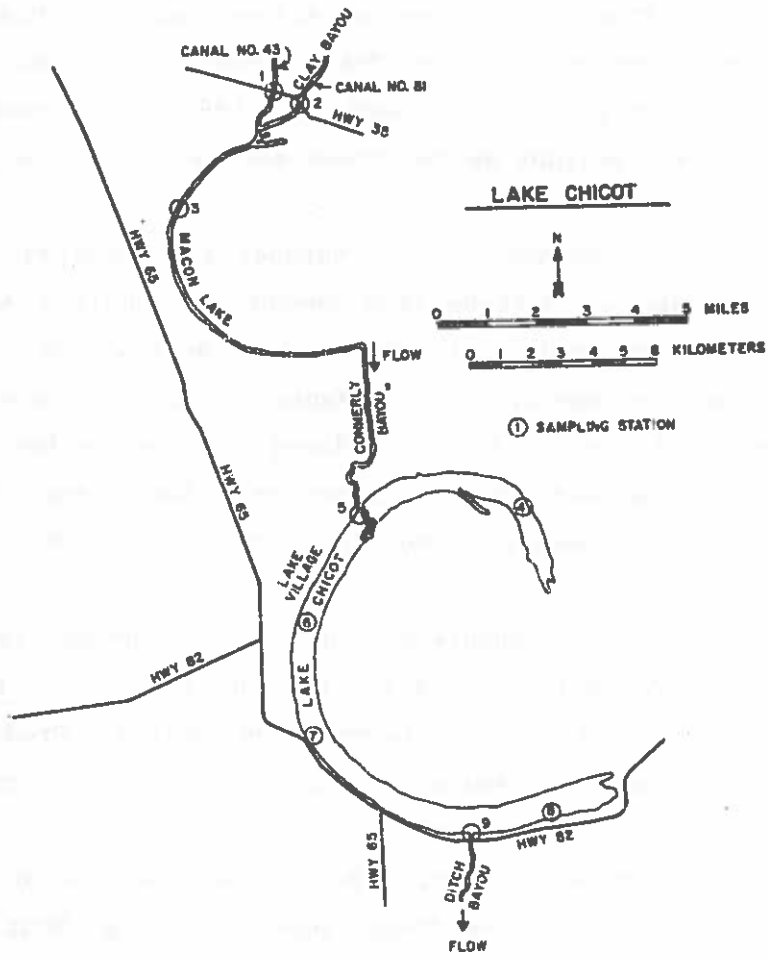


Fig. 1 - Map of Lake Chicot, Arkansas, with sampling stations indicated.

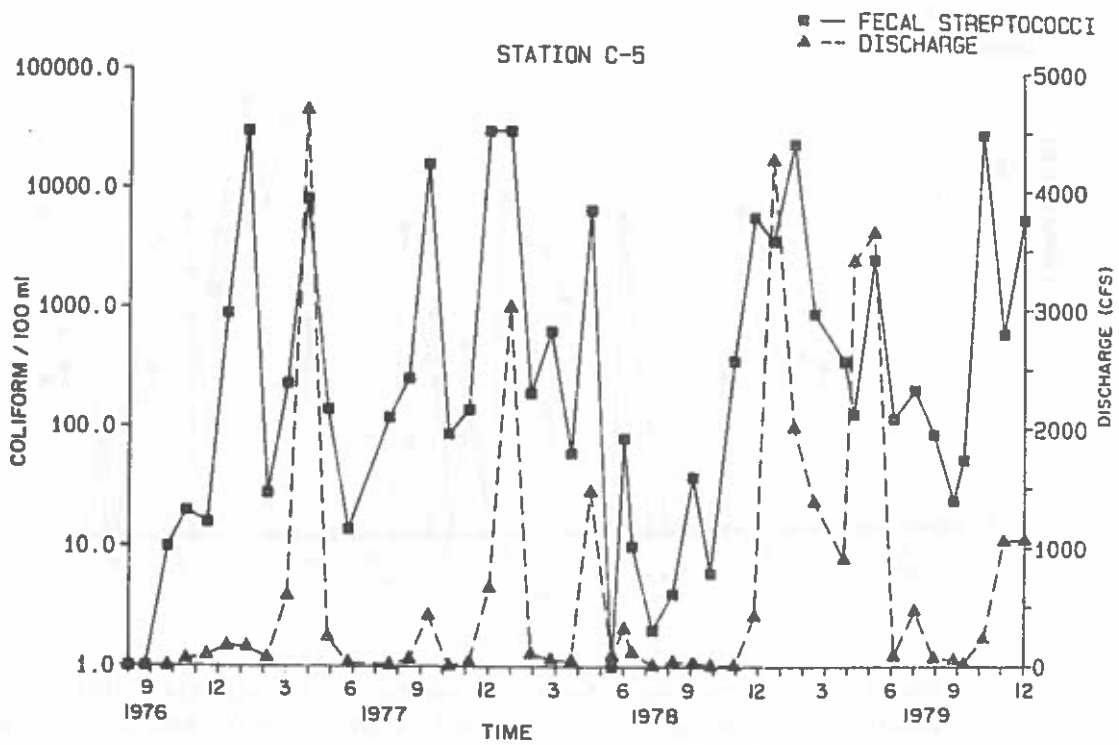
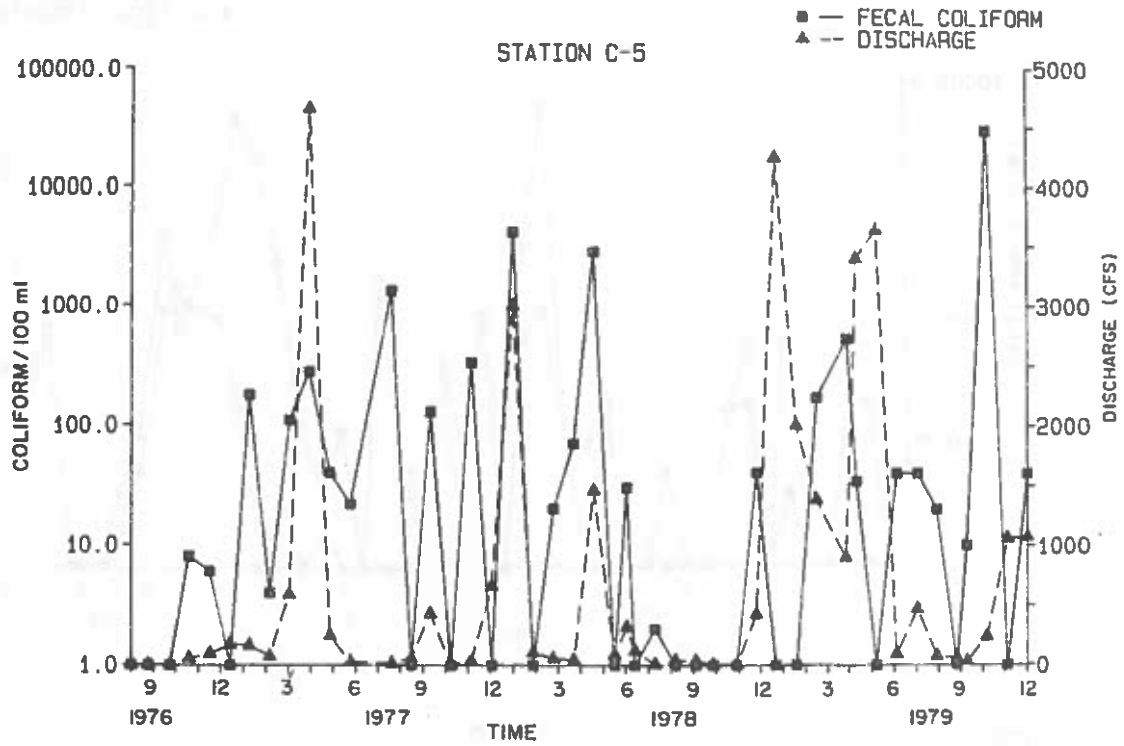


Fig. 2. - Fecal coliforms, fecal streptococci, and discharge at Connerly Bayou (C-5) where it enters Lake Chicot, 1976-1979.

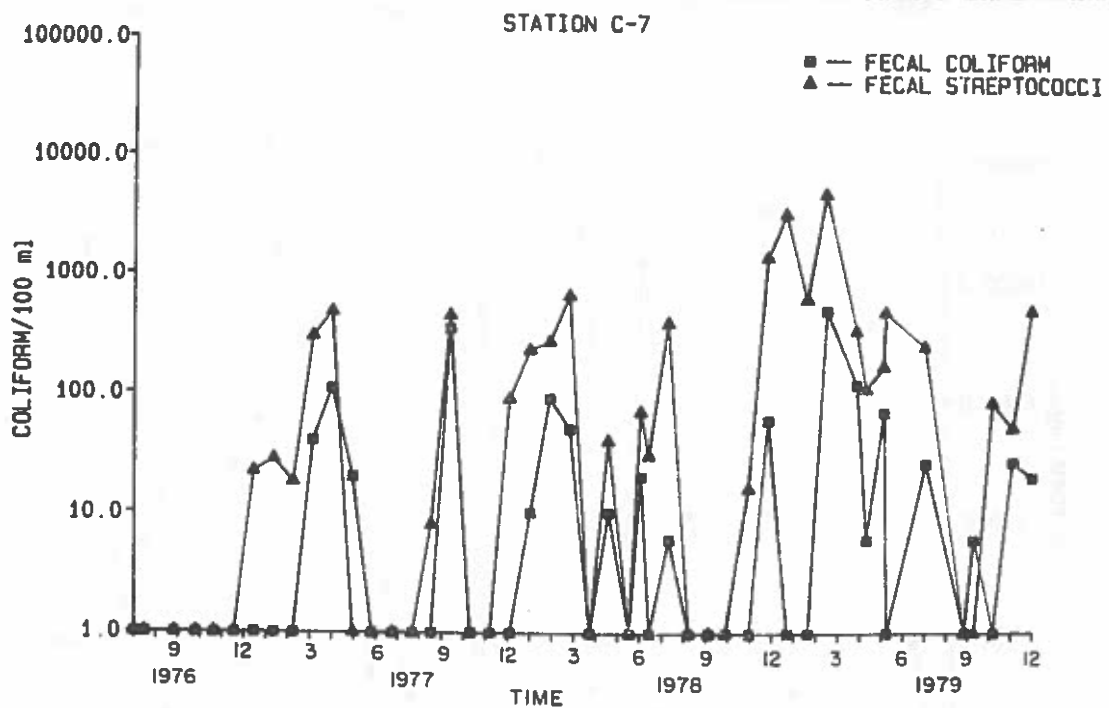
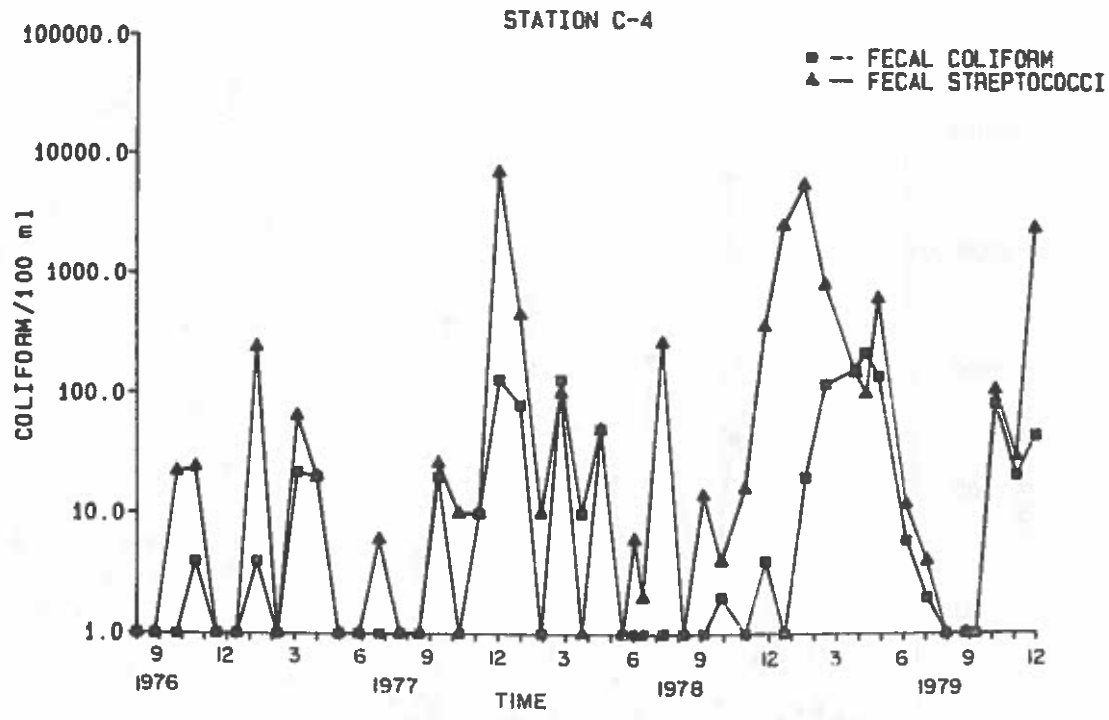


Fig. 3. - Fecal coliform and fecal streptococci colonies/100 ml of water for the north (C-4) and south (C-7) basins of Lake Chicot, 1976-1979.

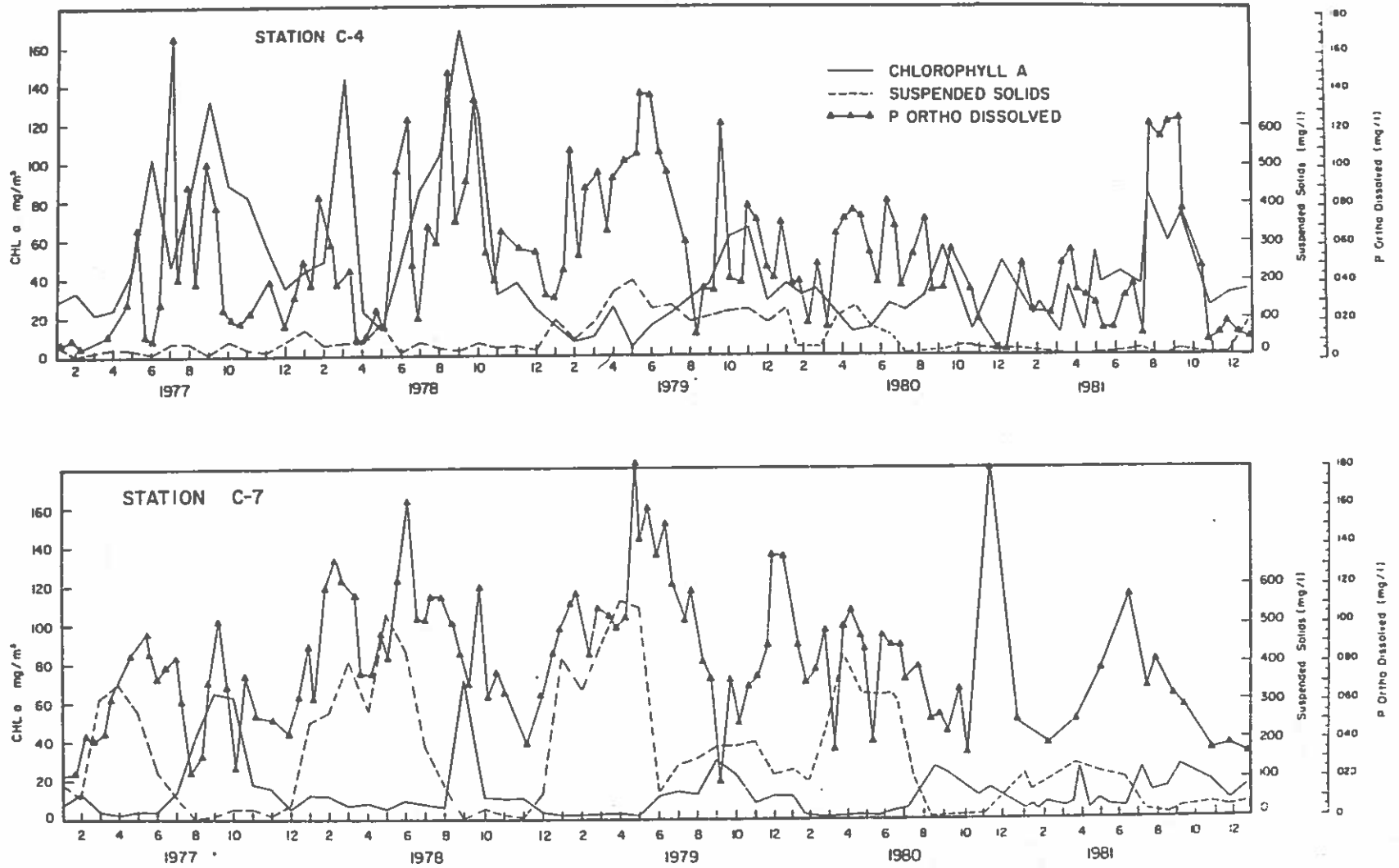


Fig. 4. - Surface chlorophyll *a* (mg/m³), suspended sediment (mg/l), and filtered orthophosphorus (mg/l) for the north (C-4) and south (C-7) basins of Lake Chicot, 1977-1982.

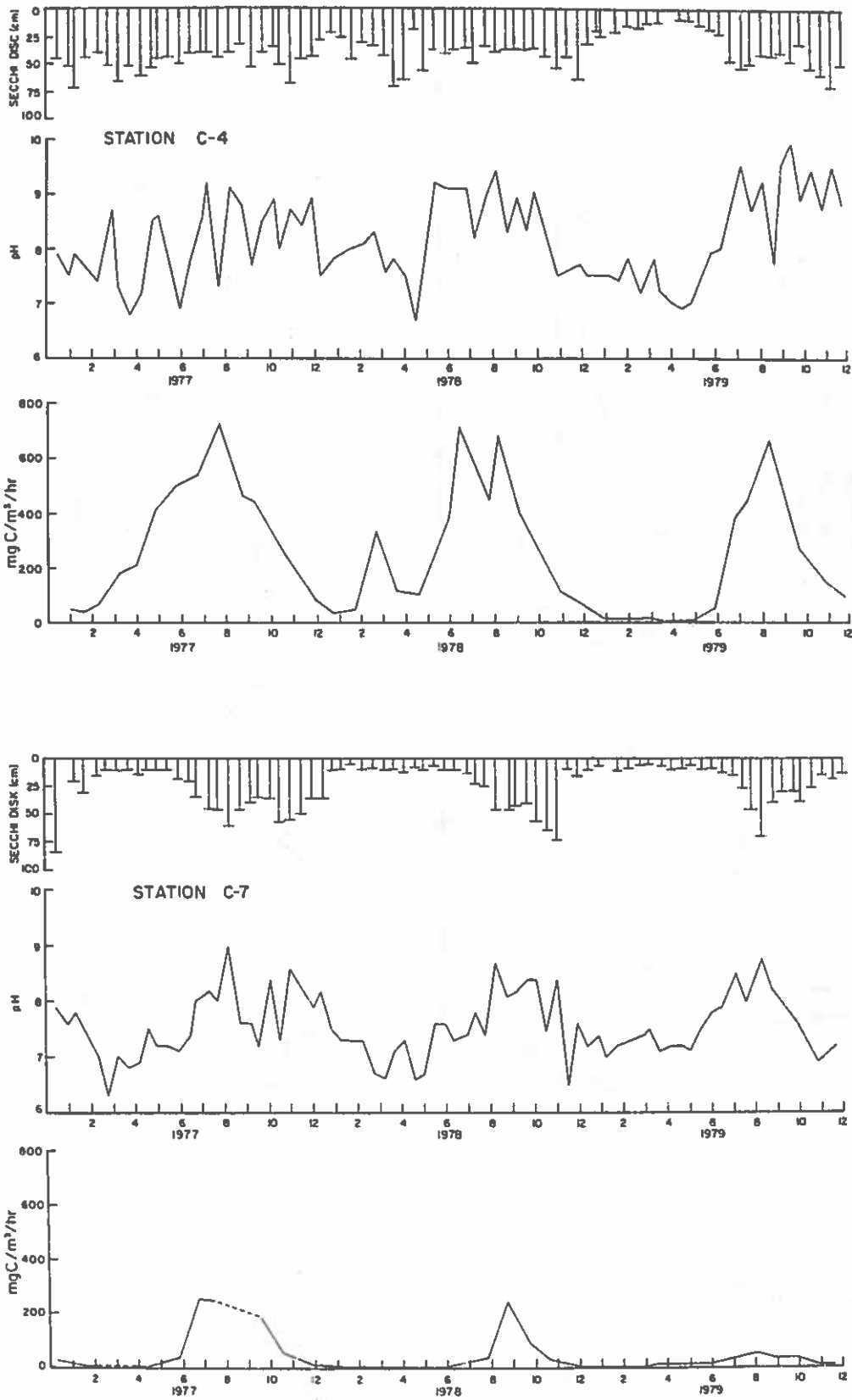


Fig. 5. - Monthly C-14 assimilation (mg C/m³/hr), secchi disc (cm), and pH for the north (C-4) and south (C-7) basins, 1977-1979.

SUMMARY OF REMOTE SENSING STUDIES ON LAKE CHICOT

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From the beginning of the joint Agricultural Research Service (ARS)-U.S. Army Corps of Engineers, Vicksburg District study on Lake Chicot it was recognized that remote sensing technology had the potential for providing valuable information on the lake condition for use in model development, model verification, and subsequent management decisions. Studies indicated that remote sensing could provide information on water area, land use, suspended sediments, chlorophyll and water temperature. Since suspended sediment is the most visible problem in Lake Chicot, our remote sensing studies concentrated on the measurement of suspended sediment in the surface water.

Studies have been conducted on three levels. Sediment samples were collected from Lake Chicot and spectral measurements were made under controlled laboratory conditions. In situ spectral measurements have been made with a portable spectroradiometer at 20-50 cm above the lake surface. Image products and computer compatible tapes (CCT's) from the Landsat satellites were analyzed. The purpose of this paper is to discuss the results of these three studies.

METHODS AND MATERIALS

Laboratory studies were conducted in a 11,600 liter water tank located at the Marine Upwelled Spectral Signature Laboratory (MUSSL) at the NASA Langley Research Center in Hampton, Virginia. The tank was illuminated by $32,280 \text{ lm m}^{-2}$ of artificial sunlight. Upwelled radiance was measured above the water surface by a rapid scanning spectroradiometer. Suspended sediment concentrations up to 700 mg l^{-1} were mixed in the tank. Water samples were tested for total suspended solids, dissolved organic carbon, total organic

carbon, particulate organic carbon, chlorophyll-a, iron, copper, sediment minerology, and particle size distribution. Upwelled spectral measurements were made between 400 and 1000 nanometers. Discussion of the MUSSL facility and research techniques is given in Whitlock (1977), Witte et al. (1979), and Freedman et al. (1980).

In situ measurements of reflected and incident solar radiation spectra were measured on Lake Chicot between July 1976 and December 1977. Measurements were made at 20-50 cm above the water surface from a small boat using a portable spectroradiometer equipped with a 2.95 m fiber optic conduit and a teflon diffusing screen. Reflected solar radiation was measured normal to the water surface and incident solar radiation was measured at 180° from the water surface. All measurements were made on cloud-free days and over water the depth of which was at least 3 times the Secchi depth. The radiometer was calibrated each time it was used. Measurements were made between 400 and 1500 nm. The data were expressed in microwatts per square centimeter per nanometer ($\mu\text{watts cm}^{-2} \text{nm}^{-1}$). Two grab samples of the surface water were collected. Total and dissolved solids were determined. Chlorophyll-a and Secchi depth were also measured. More details on the field measurements are given by Ritchie et al. (1976, 1983).

Landsat data for 33 dates between July 1976 and November 1979 were analyzed. Computer compatible tapes for nine of the images were obtained and digital data were extracted. On the other 24 dates, densitometer analysis of Landsat images was used to determine digital values from the film negatives. The data from the densitometer were obtained by procedures described in the Landsat User's Handbook (USGS, 1979). This was done by correlating the digital data extracted from the CCT's and densitometer measurements from the same nine images. Predictive equations derived from the analysis of these nine dates were used for correlating the densitometer data from the other 24 images so that the data would be consistent.

The Landsat data were converted to radiance in milliwatts per square centimeter per steradian ($\text{mWcm}^{-2}\text{Sr}^{-1}$) and reflectance (Robinove, 1982; Richardson et al. 1980). The Landsat data was corrected to be equivalent to a zenith sun angle of 45° (Richardson 1982) which is approximately the average zenith sun angle (48°) for the 33 Landsat images used.

RESULTS AND DISCUSSION

Laboratory Studies

Laboratory measurements of upwelled reflectance from Lake Chicot showed that the signals tend to have little change for total solid concentration greater than 100 mg l^{-1} for wavelengths between 400 and 600 nanometers. However, for wavelengths between 700 and 950 nanometers there was good signal discrimination for all concentrations measured (5 to 690 mg l^{-1}). The upwelled reflectance was a linear function of total solids only over limited ranges of concentrations (Whitlock 1981). The good signal discrimination between wavelength 700 and 900 nm would indicate that these wavelengths could be used to develop sediment algorithms for use with remotely sensed data. Atmospheric transmission at wavelengths greater than 900 nm would limit using these higher wavelengths due to the absorption of signal. The laboratory studies indicated that other factors influence the upwelled signal, however, the suspended solids dominated the signal response.

In Situ Studies

In situ measurements made with a portable spectroradiometer during the 18 month period between July 1976 and December 1977 showed that the intensity and distribution of reflected solar radiation varied with suspended solids (Fig. 1). As suspended solids increased, the magnitude of reflected solar radiation increased and the spectral distribution of the reflected solar radiation shifted toward the red wavelengths. Above 900 nm no significant pattern in intensity or spectral distribution was noted.

Analysis of the data by wavelength indicated that at wavelengths below 600 nm the signal tended to saturate at suspended sediment concentration greater than 100 mg l^{-1} . However, it was not as strong as was noted in the laboratory studies. Good signal separation was noted between 600 and 900 nm. The response curve was not linear over the total range of suspended sediment measured.

Even though the response curve did not appear to be linear over the entire range of suspended sediment measured, linear regression analysis gave the best fits for the relationship between suspended solids and reflected solar radiation or reflectance. Statistically significant correlation coefficients were found between 450 and 900 nm (Fig. 2) with the highest

correlation coefficients between 700 and 900 nm. Reflectance and suspended solids gave consistently 2 to 5 percent higher correlation coefficients than did reflected solar radiation and suspended solids. Correcting the data for Fresnel reflectance due to sun angle improved the correlation coefficients by 2 to 3 percent.

The linear relationship between suspended solids and reflectance or reflected solar radiation was generally better than that of total solids and reflected solar radiation. The highest correlation coefficients were calculated for wavelengths between 700 and 900 nm. An r value of 0.96 was calculated for reflectance versus suspended solids at 725, 750, and 800 nm. This means that the calculated regression equation would account for 92 percent of the variability.

While the reflected solar radiation response curve was not linear over the total range of suspended sediment measured, high concentration of suspended sediments are not found often (Fig. 3). Therefore a linear regression analysis could be used effectively to estimate suspended sediments.

Landsat Studies

Suspended sediment patterns can be observed in Landsat MSS and TM images. Such a synoptic view of a lake would be very useful information for management if the pattern could be quantified. LeCroy (1982) examined 20 Landsat MSS images of Lake Chicot covering 1972 through 1979 and concluded that Landsat imagery "provided an insight into the distribution, possible origin, and seasonal variation of turbidity in the lake". He also found that "distinct sediment patterns only appear on band 7 when the suspended loads are greater than 100 ppm, and, in addition, the upwelled signals are exponential in nature, resulting in the saturation of band 5 ..."

We analyzed 33 Landsat MSS images for the period between July 1976 and November 1979. From these 33 images 63 observations of MSS spectral response and associated ground truth (suspended sediment, Secchi, chlorophyll, etc.) were derived. Analysis of this data set showed that Landsat MSS bands 5 and 6 gave the best results (Table 1) for determining suspended sediment when using simple linear regression techniques as had been used with the in situ studies. This analysis also showed that reflectance gave better results than reflected solar radiation. The relationship between suspended solids and

MSS data was better than the relationship between total solids and MSS data. Further analysis is underway to determine other relationships which can be used to estimate surface suspended sediment from MSS digital data.

Analyses of MSS data and chlorophyll-a indicate that MSS bands 4 and 5 were better than bands 6 and 7 for determining chlorophyll-a. However, the relationship, while statistically significant, was not very strong.

Currently one Landsat Thematic Mapper scene is available for the Lake Chicot area. Analysis of this scene with available ground data has shown that the TM bands 1, 2, 3, and possibly 4, can provide useful information on the concentration of particulate matter suspended in surface water. TM band 3 showed the strongest relationship. TM bands 5 and 7 were very useful in separating water from non water areas. Responses of TM bands 1, 2, and 3 were highly interrelated for water samples (Schiebe, Ritchie, and Boatwright 1983).

CONCLUSION

Studies of the relationship between reflected light and surface suspended sediment have been made in the laboratory with samples collected from Lake Chicot, in situ with a portable spectroradiometer at 20-50 cm above the surface of Lake Chicot and by analysis of Landsat MSS and TM data. From an analysis of the results of the three studies the following conclusions are made:

1. The three studies are consistent with all leading to the same conclusions.
2. Reflected solar radiation is related to suspended surface sediment.
3. The best wavelengths for determining surface suspended sediment is between 600 and 900 nm. Atmospheric interference at wavelengths above 800 nm probably restrict the sensitivity of satellite data.
4. Signals from wavelengths less than 600 nm tend to saturate as suspended sediment concentrations approach 100 mg l^{-1} .
5. In analyses of inland agricultural lakes where suspended sediments are often higher than 100 mg l^{-1} , surface suspended sediments can be estimated using reflected solar radiation data measured at wavelengths between 600-800 nm.

LITERATURE CITED

- Friedman, E., L. Poole, A. Cherdak, and W. Houghton. 1980. Absorption coefficient instrument for turbid natural waters. *Applied Optics* 19:1688-1693.
- LeCroy, S. R. 1982. Determination of turbidity patterns in Lake Chicot from Landsat MSS imagery. NASA Contract Report 165870.
- Richardson, A. J. 1982. Relating Landsat digital count values to ground reflectance for optically thin atmospheric conditions. *Applied Optics* 21:457-464.
- Richardson, A. J., D. E. Escobar, H. W. Gausman and J. H. Everitt. 1980. Comparison of Landsat-2 and field spectrometer reflectance signatures of south Texas rangeland plant communities. Proc. Sixth Symposium Machine Processing of Remotely Sensed Data, LARS, Purdue Univ., West Lafayette, Indiana, pp. 88-97.
- Ritchie, J. C., F. R. Schiebe and C. M. Cooper. 1983. Spectral measurements of surface suspended matter in an oxbow lake in the lower Mississippi Valley. *J. Freshwater Ecology* 2:175-181.
- Ritchie, J. C., F. R. Schiebe and J. R. McHenry. 1976. Remote sensing of suspended sediments in surface waters. *Photogra. Engin. and Remote Sensing* 12:1539-1545.
- Robinove, C. J. 1982. Computation with physical values from Landsat digital data. *Photogra. Engin. and Remote Sensing* 48:781-784.
- Schiebe, F. R., J. C. Ritchie and G. O. Boatwright. 1983. A first evaluation of Landsat TM data to monitor suspended sediments in lakes. Proceedings of the Landsat-4 Early Results Symposium.
- U.S. Geological Survey. 1979. Landsat Data User's Handbook (Revised). U.S. Geological Survey, Washington, D.C.
- Whitlock, C. H. 1977. Fundamental analysis of the linear multiple regression technique for quantification of water quality parameters from remote sensing data. NASA TM X-74600, 176 pp. National Technical Information Service, Springfield, Virginia.

Whitlock, C. H., W. G. Witte, T. A. Talay, W. D. Morris, J. W. Usry and L. R. Poole. 1981. Research for reliable quantification of water sediment concentrations from multispectral scanner remote sensing data. USDA/NASA AgRISTARS Report CP-Z1-04078 (JSC-17134).

Witte, W. G., J. W. Usry, C. H. Whitlock, and E. A. Gurganus. 1979. Spectral measurements of ocean-dumped wastes tested in the Marine Upwelled Spectral Signature Laboratory. NASA TP 1480, 31 pp. National Technical Information Service, Springfield, Virginia.

Table 1. Correlation coefficients for the linear regression analysis of Landsat MSS digital data and physical properties.

	Total solids	Suspended solids	Chlorophyll-a	Secchi
MSS 4 Reflected	.48	.51	-.48	-.58
MSS 5 Reflected	.65	.68	-.55	-.75
MSS 6 Reflected	.64	.69	-.39	-.68
MSS 7 Reflected	.51	.57	-.32	-.49
MSS 4 Reflectance	.51	.52	-.56	-.59
MSS 5 Reflectance	.65	.69	-.57	-.74
MSS 6 Reflectance	.73	.78	-.44	-.75
MSS 7 Reflectance	.57	.64	-.35	-.53

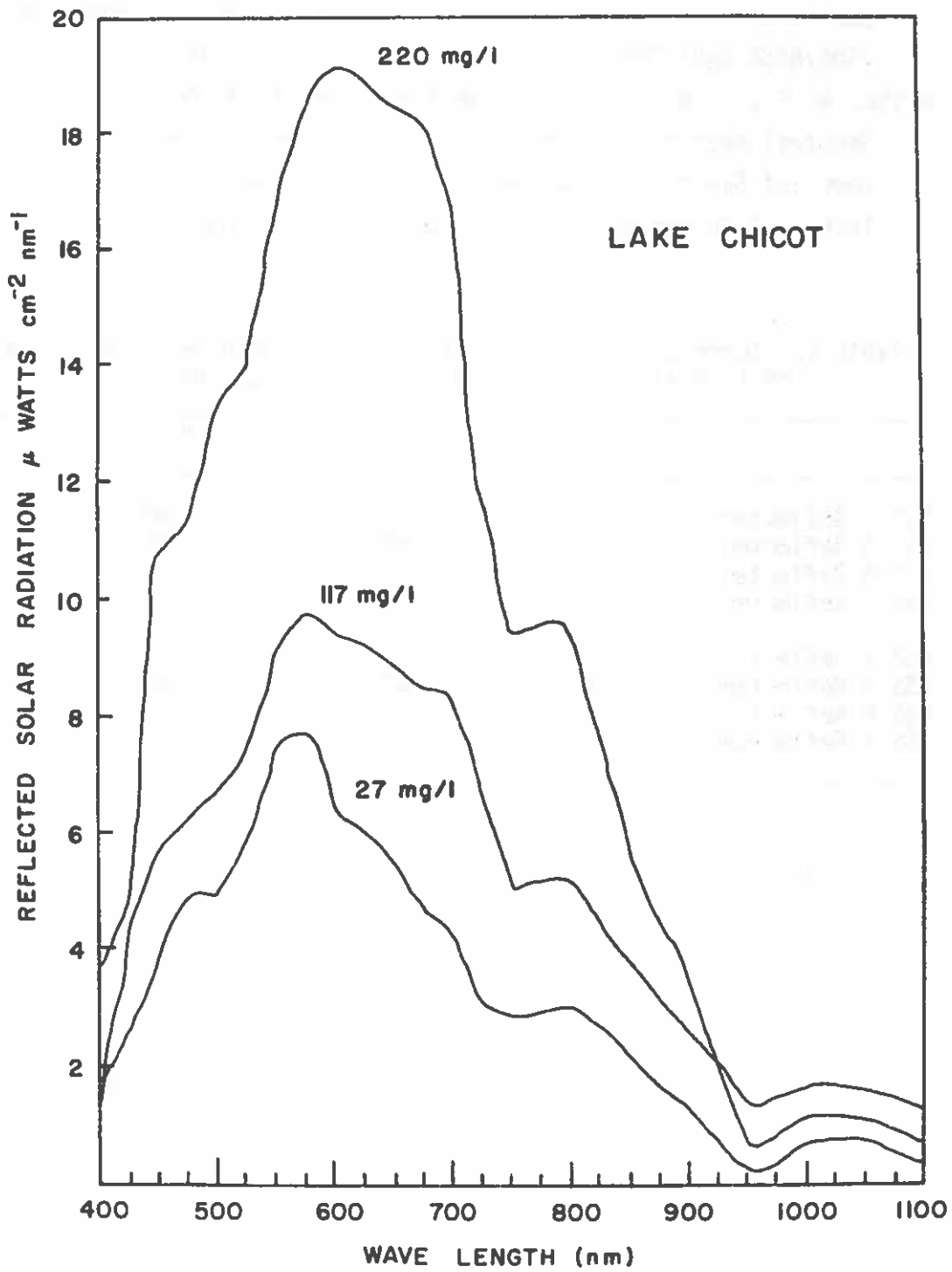


Fig. 1. The relationship between reflected solar radiation and wavelength for total suspended solids.

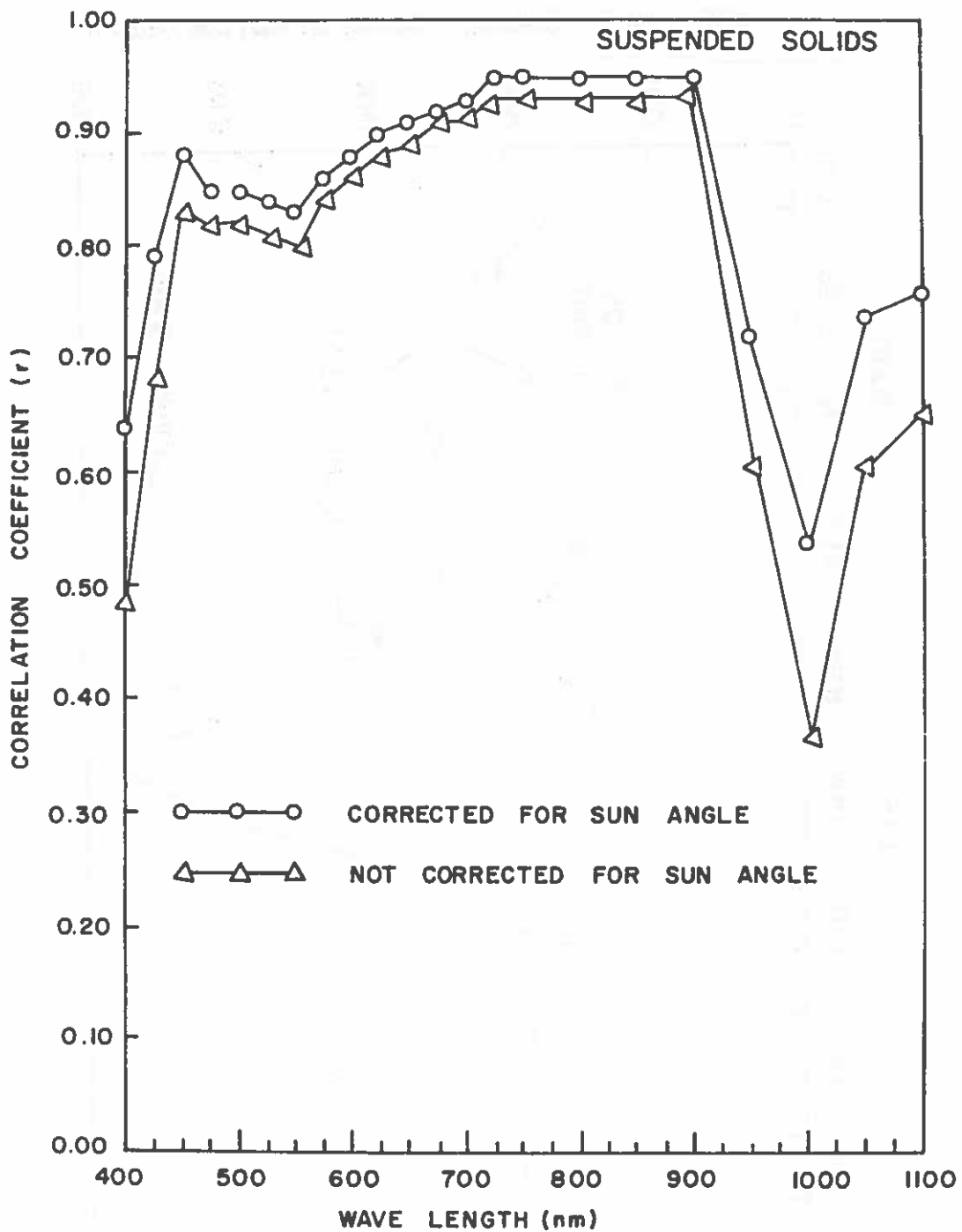


Fig. 2. The relationship between correlation coefficient and wave-length for the linear regression analysis between corrected reflected solar radiation and total solids.

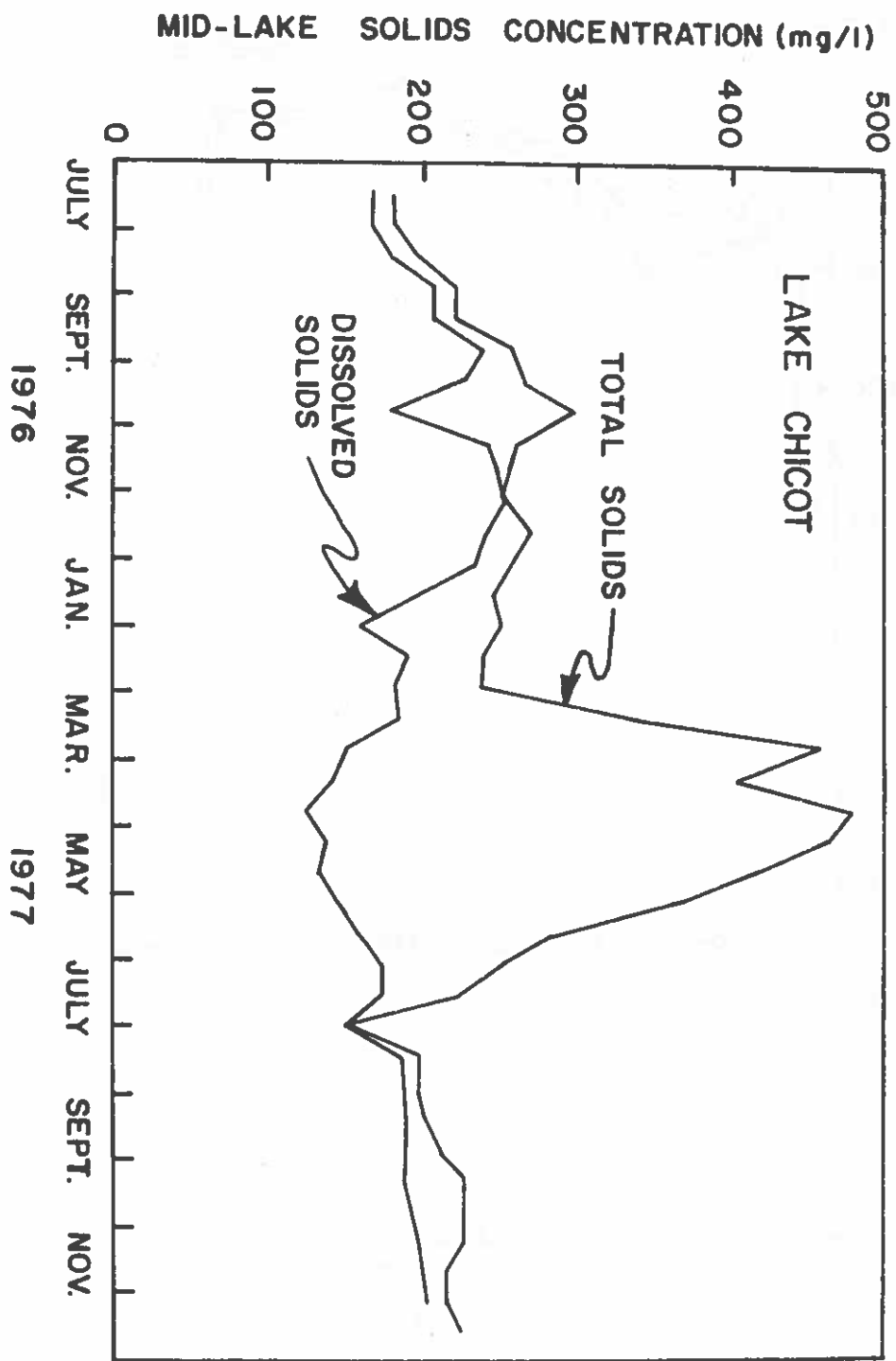


Fig. 3. Concentration of suspended solids and dissolved solids in Lake Chicot between July 1976 and December 1977.

MATHEMATICAL MODEL SIMULATION OF LAKE CHICOT, ARKANSAS

by

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I. INTRODUCTION

The inflow of fine suspended sediment from Connerly Bayou into Lake Chicot, Arkansas, has caused a profound change in the appearance, the ecology, and the recreational use of the lake. Before 1920, Lake Chicot, a large oxbow lake with limited drainage area along the Mississippi River, was attractive for recreation. A disastrous flood in 1927, construction of levees, clearing of the land for row crops, and other events have led to a significant increase of the suspended solids content and thereby the turbidity of the lake. To reduce the turbidity and to stabilize the lake level, the U. S. Army Corps of Engineers has constructed a new lake outlet structure and a 6500 cfs pumping station to divert inflow from Connerly Bayou to the Mississippi River (Rothwell and Fletcher, 1979; Schiebe et al., 1981).

The present water quality of the lake has been documented in publications by the EPA (1977), Bacon (1978, 1980), Cooper and Bacon (1981), and Cardoni and Hanson (1981). The material and nutrient budgets of the lake have been studied by Swain (1980). Swain also examined correlation between hydrologic and water quality parameters in the lake. Since July 1976, the U. S. Department of Agriculture's Sedimentation Laboratory at Oxford, Mississippi, and since January, 1980, the USDA Water Quality Laboratory in

Durant, Oklahoma, have been monitoring the lake's hydrological, chemical, and microbiological regimes. These studies have produced extensive baseline data as part of the preconstruction assessments, and they will be continued in order to document lake changes as a result of future inflow diversion and stage management. To assist in the interpretation of the data and in the selection of lake operational management alternatives, a process-oriented, dynamic model simulating several water quality parameters including transparency of the lake on a daily time scale, has been developed. Early stages of the model development were described at two symposia (Dhamotharan et al., 1978, 1981), and in a thesis (Dhamotharan, 1979). A review of the model formulation will be given in this paper. The model is described in more detail in a report by Stefan, Cardoni and Fu (1982c).

II. MODEL FORMULATION CONCEPT

The model simulates daily values of the following parameters: lake stage, surface mixed layer depth, water temperature (T), suspended solids (SS), phytoplankton ($Chla$), available dissolved orthophosphorus (P_a), non-available particulate phosphorus (P_n), light attenuation coefficient (k) and Secchi depth (z_{SD}) in a stratified or non-stratified shallow lake with inflow and outflow at the surface. The primary objective is to simulate present and future transparency of the water.

The turbidity of Lake Chicot is the result of erosion and runoff from the watershed. To simulate the response of the lake to any reduction in sediment loading all significant in-lake processes must be considered. These include stratification, advection, turbulent diffusion, sedimentation, resuspension, growth kinetics in the case of phytoplankton, etc. (Fig. 1). The mathematical model description of the processes uses the general flow chart shown in Fig. 2.

To account for the temperature and density stratification, a multi-layer model had to be formulated. To account for inflow and outflow, layers were chosen to be of variable thicknesses.

The mixing and density stratification dynamics of shallow reservoirs or lakes show a strong dependence on surface heat exchange and wind mixing at the air-water interface. A one-dimensional unsteady water temperature stratification and mixing model (MLTM) developed at the University of

Minnesota (Ford, 1976; Stefan and Ford, 1975) for a daily timescale was used as a starting point for the RESQUAL model development. Additions and changes were made in the MLTM model to account for inflow, outflow, and the effects of suspended sediment on the heat transfer processes. Subsequently, an unsteady, mass-transport sub-model for suspended sediment was formulated. Results from the temperature stratification dynamics model are used as input to the suspended sediment model. Results from the suspended sediment distribution simulation are necessary in turn to specify attenuation and reflection of radiation in the heat transfer relationships in the dynamic temperature model. Subsequently, submodels for a density current inflow, for light attenuation, for phytoplankton, for phosphorus, and for Secchi depth were added.

The RESQUAL II model gives the water quality changes as a function of depth and on a day by day basis in response to real weather, also specified on a day by day basis. It is therefore possible to use the model

- (a) to simulate existing conditions by hindcasting with measured weather conditions,
- (b) to predict conditions that would have existed had the inflow diversion been implemented, and
- (c) to forecast conditions on a realtime basis for different diversion strategies.

III. Input Data

A. Lake Morphology

Lake morphology is described by an equation developed by Dhamotharan (1979):

$$\frac{V}{V_{\text{ref}}} = \left(\frac{h}{h_{\text{ref}}} \right)^m \quad (1)$$

where V = lake volume,

h = depth,

V_{ref} = reference volume at h_{ref}

h_{ref} = reference depth = 8.29 m for the upper lake and 4.52 m for the lower lake.

m = 2.18 for lower lake

m = 1.57 for upper lake

Some bathymetric data are summarized in Fig. 3.

From the above the following equations were developed for Volume V in (m³)

$$V = 4046.8 (3.28^{m-1}) c h^m \quad (2)$$

and projected horizontal area A in (m²)

$$A = m c (3.28h)^{m-1} \quad (3)$$

where $c = V_{ref} / (h_{ref})^m$, and

h = depth in ft

B. Inflow

Inflow rates must be given. For Lake Chicot a stage/discharge relationship of the following form is used:

$$Q_C = 0.85 Q_M^{0.99}$$
$$Q_M = 140.93 (S_M - 105.63)^{1.72} \quad (4)$$

where Q_C = discharge into Lake Chicot from Connerly Bayou

Q_M = discharge from Macon Lake

S_M = stage at Macon Lake in ft above MSL

The above equations were given by Swain (1980), and provide a general trend. Backwater and other effects make the correlation between flows at Macon Lake and in Connerly Bayou rather poor, especially at low flows (Fig. 3).

Water quality in the inflow (Connerly Bayou) is also specified by correlation functions given by Swain (1980) for suspended sediment:

$$SS_C = 6.55 Q_{CAFD}^{0.58} \quad (5)$$

where Q_{CAFD} = inflow from Connerly Bayou in acre ft per day, and for chlorophyll-a (Cardoni and Stefan, 1982; Cardoni et al, 1982):

$$\text{CHLA}_C = 317(\text{SS}_C)^{-0.693} \quad (6)$$

where CHLA_C is in ppb and SS_C in ppm. For available dissolved orthophosphorus

$$P_{ac} = 100 \text{ ppb}^1 \quad (7)$$

and for nonavailable phosphorus:

$$P_{nc} = \eta \left[0.025(\text{SS})^{.573} - \frac{\text{CHLA}_C}{Y_{ca}} \right] \quad (8)$$

where Y_{ca} is the ratio of chlorophyll-a to phosphorus in the phytoplankton, and η is a fraction of nonavailable phosphorus that may become available.

The data from which the above relationships had to be derived are shown in Figs. 4 through 8.

C. Weather

The weather station nearest Lake Chicot is at Stoneville, Miss.² Air temperature (TA) and total daily solar radiation (RAD) from that station were used in the model. Wind velocity (WIND) and dew point temperature (TD) were the arithmetic means of daily measurements at Memphis, Tenn., Jackson, Miss., and Shreveport, La. The three stations showed a good correlation and Lake Chicot is located at about the center of a triangle formed by these three stations. Daily precipitation data were from measurements at Stoneville, Mississippi. Additional information on weather stations and data is given by Dhamotharan (1979).

¹As an alternative, combination of appropriate equations in Swain's thesis gives $P_{ac} = 0.015 (Q_{in})^{0.26}$ where Q_{in} is the inflow in acre-ft/day. This equation has been tested in the model and provided comparable results, as in the cases when Eq. III-7 was used, with no significant improvement on the predictions.

²Midsouth Agricultural Weather Service Center, NOAA, P. O. Box 117, Stoneville, MS. 38776.

IV. ADVECTIVE FLOW MODEL/CONSERVATION OF VOLUME

A. Advective Inflow/Outflow Mechanics in Stratified Reservoir

Lake Chicot is considered to be composed of horizontal layers of variable thickness, and density. Each layer has a mean horizontal area and volume determined by the reservoir's morphometry.

The density of each layer of water is determined by its temperature, suspended sediment content, and dissolved solids content. The inflowing water will seek a layer with a density equal to its own. It will augment the volume of that layer and consequently all the layers above it will be displaced upward. As a layer rises, its horizontal area becomes larger and its thickness consequently diminishes.

The outflow from the reservoir can be considered in a similar way. Outflow is simulated by withdrawing water from the layers in front of the weir.

Numerical computations can be kept simple by considering the reservoir as a stack of discrete volumes to which additions or subtractions are made in each timestep.

Some complicating factors need further consideration. As the inflow moves into the reservoir and towards its isopycnic layer, it entrains water from each layer it passes through. The amount of entrainment is a complex function of the flow rate, the density gradients, and other factors (Pedersen, 1980). If the inflow is into the surface mixed layer, entrainment can be ignored. Entrainment from deeper layers is specified in a density current subroutine. The characteristics of the density current, i.e. its temperature, suspended and dissolved solids content, are changed by dilution as the current passes from one layer to the next until it reaches its isopycnic layer. The temperature, suspended and dissolved solids contents of the isopycnic layer are recalculated, including the thermal energy and the mass of suspended and dissolved solids added by the density current.

B. Water Budget

The water budget for the reservoir includes precipitation, evaporation, and seepage to and from the surface layer. Evaporative losses are derived directly from the evaporative heat transfer term in the heat budget

equation. Groundwater is calculated in subroutine GWATER.

Water balance equations for each layer and between timesteps j and $j+1$, typically one day apart, are

$$V(i, j+1) = V(i, j) - [Q_e(i) + Q_w(i) + Q_s(i)]\Delta t \quad (9)$$

where V = volume of layer

Q_e = flow entrained by density current from layer i

Q_w = withdrawal rate

Q_s = seepage rate

Δt = timestep

For the surface layer ($i=1$) the relationship is expanded to include $Q_{ev}(1)$ = evaporative water loss rate and $Q_p(1)$ = volumetric rate of water added by precipitation.

$$V(1, j+1) = V(1, j) - [Q_e(1) + Q_w(1) + Q_s(1) + Q_{ev}(1) - Q_p(1)]\Delta t \quad (10)$$

For the isopycnic layer, the mass balance equations are:

$$V(ip, j+1) = V(ip, j) - [Q_w(ip) + Q_s(ip) + Q_c]\Delta t \quad (11)$$

where Q_c = density current flow rate when it meets layer ip .

$$Q_c = Q_i + \sum_{i=1}^{ip-1} Q_e(i) \quad (12)$$

For the layers below the isopycnic layer ($ip < i < N$), n being the total number of layers.

$$V(i, j+1) = V(i, j) - [Q_w(i) + Q_s(i)]\Delta t \quad (13)$$

In Lake Chicot seepage flow is assumed to affect only the surface mixed layer.

C. Layer Thickness

Layer thicknesses are determined starting with the lowermost layer. A volume-versus-elevation curve derived from the reservoir morphology is used. The thickness of each layer is

$$\Delta z(i) = V(i)/A(i) \quad (14)$$

where $A(i)$ is the horizontal area taken at the center of the layer i . $A(i)$ is a function of the elevation of the center of the layer above the reservoir bottom and therefore dependent on $\Delta z(i)$. For this reason an iteration scheme described in more detail by Dhamotharan (1979) is used to derive the best estimates of $\Delta z(i)$. To safeguard against the accumulation of round-off errors, the sum of all layer thicknesses $\Delta z(i)$ is computed at the end of each timestep and compared to the total reservoir depth derived from a hydrologic water budget equation. To equalize the two values a correction factor is applied uniformly to all $\Delta z(i)$'s in each timestep.

Initial layer thicknesses are specified by the model user. After the initial timestep, layer thicknesses will keep changing. To avoid the development of anomalies, maximum and minimum layer thicknesses are specified. Selection of a maximum layer thickness is guided by total reservoir depth and affordable computation time. A value of 75 cm, 1/10 of the total reservoir depth was chosen. Layers exceeding the specified maximum value are divided into two or more layers (Subroutine SPLIT). Minimum layer thickness chosen was 15 cm, related to maximum possible withdrawal and to total reservoir depth. Depletion of more than one layer must not occur in any one timestep. If the thickness of any one layer falls below minimum value, it is added to the layer below it (Subroutine MERGE). Layers are renumbered and the pertinent morphometric values assigned as layers are generated or eliminated.

D. Outflow from Stratified Reservoir

Outflow from Lake Chicot is through Ditch Bayou. A damaged rubble mound dam was replaced by a concrete weir in 1979. The following rating curves are used to calculate the volumetric outflow rate:

$$Q_w = 17.12 (S - 101.42)^{2.42} \quad 10/1/76 \text{ to } 7/15/79$$

$$Q_w = 146.67 (S - 101.42)^{1.72} \quad 7/15/79 \text{ to } 9/30/79$$

where Q_w = withdrawal flow rate in Ditch Bayou (cfs)
 S = lake stage (ft)

The total depth in stratified Lake Chicot from which the withdrawal flow is taking place is calculated by subroutine WDEPTH as

$$z_w = d_w + \frac{\rho_w}{\rho_{zw} - \rho_w} \frac{V_w^2}{2g} \quad (15)$$

where z_w = withdrawal depth

$d_w = S - 28.04$ = water depth in outflow channel (m)

V_w = mean flow velocity in outflow channel = Q_w/A_w

A_w = cross section of the outflow channel

g = acceleration of gravity

ρ_w = density of the outflow

ρ_{zw} = depth weighted average density over the height of the withdrawal layer thickness z_w

$\Delta\rho_w = \rho_{zw} - \rho_w$

ρ_{zw} = density of the bottommost layer of the withdrawal layer.

The withdrawal from each individual layer within the withdrawal layer is apportioned according to individual layer thickness.

$$Q_w(i) = Q_w * \frac{\Delta z(i)}{z_w} \quad (16)$$

where $\Delta z(i)$ = thickness of an individual layer.

E. Inflow Density Current

If the density of the inflowing water is higher than that of the first layer, the inflow plunges and continues as a density current. The submodel of the inflow density current follows the analysis by Akiyama and Stefan (1981).

In the analysis, it is assumed that inflow rate (q_o), inflow density (ρ_o), layer thicknesses (z), ambient density (ρ_a) and channel slope (S) are known, and that the flow is an internally supercritical flow along the lake bed.

The analysis considers first the plunging region (plunging depth), then the dilution of the density current (underflow) as it progresses from layer to layer (Fig. 9).

1. Plunging Region

Following the detailed analysis of Akiyama and Stefan (1981), the plunging depth is evaluated as a function of channel slope (S), inflow rate per unit width of inflow channel (q_{in}), total friction factor (f_t) including bed friction and interfacial friction and buoyancy (ϵ_{in}). A distinction is made between a mild slope ($S < S_c$) and a steep slope ($S > S_c$). From analysis of reservoir data the critical slope $S_c \approx 1/150$.

Water depth at the plunge point h_p and initial dilution at the plunge point γ_{in} on the steep slope are found as follows:

On a mild slope:

$$h_p = 1.6 \left(\frac{q_{in}^2}{\epsilon_{in} g} \right)^{1/3} \quad (17)$$

$$\gamma_{in} = 1.8 \quad (18)$$

The buoyancy ϵ_{in} is defined as

$$\epsilon_{in} = \frac{\rho_{in} - \rho_{\text{mixed layer}}}{\rho_{\text{mixed layer}}} \quad (19)$$

2. Underflow Region

In the underflow region beyond the plunging region the dilution of the flow by entrainment is calculated from the continuity equation (Fig. 9).

$$q_{i+1} = q_i + q_{ei} = q_i(1 + \gamma_i) \quad (20)$$

The entrainment ratio for the underflow is

$$\gamma_i = \frac{\beta}{F_i^{1/3}} \left(\frac{g \epsilon_i}{q_r^2} \right)^{1/3} \frac{\Delta z_i}{S} \quad (21)$$

with
$$\epsilon_i = \frac{\rho_{ci} - \rho_i}{\rho_i} \quad (22)$$

ρ_i = density of ambient layer i

ρ_{ci} = density of density current upon entering layer i

F_i = normal densimetric Richardson number
as given by Akiyama and Stefan (1981)

β = experimentally determined coefficient ≈ 0.0015

3. Determination of Initial Conditions (ρ_i, q_i) for Underflow

Downstream from Plunge Point

The model assumes that ambient water is uniformly entrained during plunging. The initial entrained flow from ambient water during plunging q_{ai} is

$$q_{ai} = \gamma_{in} q_{in} \quad (23)$$

where q_{in} = inflow from the inlet channel to the reservoir,

γ_{in} = total initial dilution rate as computed earlier.

Conservation of volume and mass give, respectively:

$$q_{in} = q_{ai} = q_i \quad (24)$$

$$\rho_{in} q_{in} \pm \bar{\rho}_a q_{ai} = \rho_i q_i \quad (25)$$

where ρ_i = initial density for underflow,

q_i = initial flow rate for underflow, and

$\bar{\rho}_a$ = average density of entrained ambient water.

A relationship for $\bar{\rho}_a$ was developed based on conservation of mass.

The total dilution rate at the plunge point γ_{in} is not well established. $\gamma_{in} = 1.8$ is used for Lake Chicot.

At the beginning of the subprogram DCFLOW subroutine PDEPTH is called to determine the plunging depth of the density current and the total volume of entrainment from layers lying within the plunging zone. Then the isopycnic layer is located by comparing the total density of the current with the total density of each layer as the density current flows down the

slope. The volume, water temperature, suspended sediment concentration, dissolved solids concentration and chlorophyll-a concentrations of the density current are updated according to the volume of entrainment from each layer as the density current flows past as many layers as necessary until it joins the isopycnic layer.

F. Groundwater Inflow and Outflow

The groundwater contribution to the Lake Chicot water budget is found to be dependent on the interaction between the lake and the Mississippi River stages. The groundwater flow rate is estimated by a relationship developed by Swain (1980). The groundwater is added or taken out at the surface mixed layer because studies by Winter (1978) have shown that seepage connections between a lake and an aquifer are usually most effective near the surface where contact areas and permeabilities are the largest.

The groundwater flow rate for Lake Chicot is calculated from the regression equation

$$Q_s(1) = \frac{K_s b}{\ell} \frac{S_L^2 - S_{MR}^2}{2} - h(S_L - S_{MR}) \quad (26)$$

where $Q_s(1)$ = groundwater flow rate (cfs)

K_s = bulk soil permeability = 1.3 ft/day

b = projected length of lower Lake Chicot parallel to the Mississippi River = 5.5 miles

ℓ = mean distance between Mississippi River and Lake Chicot = 7 mi

S_L = Lake stage (ft)

S_{MR} = Mississippi River stage (ft)

h = aquifer thickness = 19 ft

The above relation combines expressions for 2-D flow in an unconfined aquifer and flow in a confined aquifer. Groundwater flow out of the lake is taken from the surface mixed layer. The volume of the mixed layer is adjusted in each timestep accordingly. Groundwater flow into the lake is routed to the isopycnic layer in the lake without dilution. Groundwater temperature is set equal to the annual average air temperature. Groundwater contains no sediments or nutrients in the simulation.

G. Precipitation

Water additions by precipitation are calculated by

$$Q_p(l) = A(l) p \quad (27)$$

where $Q_p(l)$ = inflow rate from precipitation

$A(l)$ = surface area of lake

p = precipitation intensity at Stoneville

H. Dilution of Water Quality Constituents

Associated with the advective transfer of water into and out of an individual layer is the transfer of heat, and suspended and dissolved materials. Water temperatures T and concentration C of individual layers are affected only if the advective flow is into the layer. For the isopycnic layer, T and C are therefore recalculated from the conservation equations:

$$T_{(ip,j+1)} = \frac{T(ip,j) V(ip) + T_c(i) Q_c(i) \Delta t}{V(ip) + Q_c(i) \Delta t} \quad (28)$$

$$C_{(ip,j+1)} = \frac{C(ip,j) V(ip) + C_c(i) Q_c(i) \Delta t}{V(ip) + Q_c(i) \Delta t} \quad (29)$$

where V = volume of a layer

Q_c = density current flow rate

Δt = time step of computation = 1 day.

where the concentrations C are those of suspended solids SS , chlorophyll-a $Ch\&a$, available (dissolved ortho) phosphorus P_a , or non-available phosphorus P_n . Subscript c refers to the inflow density current as it arrives at layer (i) .

Inter-layer density current flow and the temperature and concentrations of suspended and dissolved solids are calculated successively for each layer by considering the dilution due to entrainment at each step down; they are also used to compute water densities both in the lake and in the density current.

$$T_i = \frac{T_{i-1} Q_{i-1} + T_{i,j} Q_{e_i}}{Q_{i-1} + Q_{e_i}} \quad (30)$$

$$C_i = \frac{C_{i-1} Q_{i-1} + C_{i,j} Q_{e_i}}{Q_{i-1} + Q_{e_i}} \quad (31)$$

where T_i = temperature of density current after passing layer i

Q_i = volume of density current before reaching layer i

Q_{e_i} = entrainment volume from layer i

C_i = concentration of suspended solids, dissolved solids,
available and nonavailable phosphorus, chlorophyll-a.

Surface layer dilution by advection requires an expanded equation

$$T(1,j+1) = \frac{T(1,j)V(1) + [Q_s T_s + Q_p T_p + Q_{in} T'_{in}]}{V(1) + (Q_s + Q_p + Q'_{in})\Delta t} \quad (32)$$

for water temperature and a similar one for concentrations. Only if the inflows are positive does a dilution effect occur. Outflow does not change a layer's temperature or concentration.

V. WATER TEMPERATURE STRATIFICATION AND SURFACE ENERGY TRANSFER MODEL

A. Concept

Because of the predominant influence of water temperature on the mid-summer density stratification and vertical mixing in Lake Chicot the dynamic, one-dimensional temperature prediction model developed by Stefan and Ford (1975) and Ford and Stefan (1980) was used as a starting point. The model uses a system of energy equations including wind energy input in addition to various forms of heat energy. It is a particularly suitable model for a shallow lake such as Lake Chicot since it can simulate vertical mixing dynamics using weather input at a timescale of a day or even shorter. Mixing is determined by a stability criterion that compares the total kinetic energy available for mixing with the incremental potential energy of the temperature profile. Thus, mixing is intermittent and occurs only when sufficient wind energy is available. The typical result of the

simulation is a daily water temperature profile. The integral energy method emphasizes the net results of wind mixing and heat exchange between the lake and the atmosphere. Meteorological and morphometric data are the only required input data.

The suspended particles causing the objectionable turbidity in Lake Chicot are tiny flat clay particles about 1 micron average size. They increase the reflectivity and re-emergence from the water body of incoming radiation at the water surface and also the attenuation of radiation penetrating the water column. For use in the temperature model, the dependence of albedo and diffuse radiation attenuation coefficient on suspended sediment concentration had to be established.

The model considers the following:

- radiation heat transfer at the water surface and absorption in the water column.
- heat losses from the water surface by backradiation, evaporation and convection;
- the surface mixed layer depth produced by wind mixing and natural convection during cooling.
- the heat transfer below the surface mixed layer by turbulent diffusion

B. Heat Transfer Equation

The one-dimensional transient diffusion equation for heat in a water column is

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left(K_z \frac{\partial T}{\partial z} \right) + \left(\frac{S}{\rho c V} \right) \quad (33)$$

where T = water temperature

t = time

K_z = vertical exchange coefficient

z = depth

S = solar radiation absorbed at depth z

ρc = specific heat per unit volume

V = volume of layer

Energy absorbed in the topmost layer is

$$S(1) = (1-r)\beta H_s + H_{an} - H_{br} - H_e - H_c \quad (34)$$

where H_s = solar radiation received
 β = near surface absorption coefficient, after Dake
 and Harleman (1969) = 0.4
 r = reflectivity
 H_{an} = net atmospheric radiation
 H_{br} = backradiation
 H_e = evaporative heat flux
 H_c = convective heat flux

The remaining radiation $(1-\beta)(1-r)H_{sn}$ is attenuated exponentially with depth. The amount S absorbed at depth z is therefore

$$S(z) = k(1-\beta)(1-r)H_s e^{-kz} \quad (35)$$

where k = attenuation coefficient (m^{-1}).

In the surface mixed layer water temperatures are first calculated layer by layer

$$T(j,i) = T(j-1,i) + \frac{S}{\rho c_p V(i)} \quad (36)$$

Then the mixed layer depth due to natural convection is determined from

$$H_L = \sum_{i=1}^{N_m} [T(j-1,i) - T(j,N_m)] V_i \rho c_p \quad (37)$$

where N_m = number of layers forming the surface mixed layer
 H_L = total surface heat loss
 $= H_{ev} + H_{br} + H_c$

The values of H_{an} , H_{ev} , H_{br} and H_c are calculated from empirical relationships discussed in detail by Stefan et al. (1982c).

Solar radiation H_s is a measured total daily quantity. Values are from the Stoneville weather station. Both the reflectivity r and the

attenuation coefficient k are functions of radiation wave length, angle of incidence of suspended sediment content, and color of the water. The dependence on suspended sediment concentration is shown in Figs. 10 and 11. Wave length was dependent only on natural radiation and assumed independent of season. Angle of incidence variations with season were expressed through radiation intensity. The following totally empirical relationship fitted Lake Chicot data somewhat and gives a shape also found in laboratory data as shown. Only measurements of incident and upwelling radiation from the water surface were available; therefore, reflectance and albedo had to be assumed as equivalent.

$$r = 0.087 - 6.76 \times 10^{-5} \text{ RAD} + 0.11[1 - \exp(-0.01 \text{ SS})] \quad (38)$$

where r = reflectance = H_r/H_{si}

H_r = reflected solar radiation

RAD = total daily incident solar radiation in $\text{cal cm}^{-2} \text{ day}^{-1}$

SS = suspended sediment concentration in mg/ℓ

The first two terms are for clear water, and the third term is from Lake Chicot data (Stefan et al., 1982a) and accounts for sediment effects. Reflectance must be adjusted for seasonal variation of the angle of incidence. This is done by the second term which was first introduced by Dingman (see Dhamotharan, 1979). Fig. 10 shows the field data from Lake Chicot, and fitted equations for two levels of radiation. The relationship (38) is not very satisfactory theoretically, but is the best available for Lake Chicot.

Attenuation of radiation is calculated using the empirical attenuation coefficient

$$k = 1.97 + 0.043 \text{ SS} + 0.025 \text{ Ch}l_a \quad (39)$$

where SS = suspended sediment concentration, (mg/ℓ)

Ch l_a = chlorophyll-a concentration ($\mu\text{g}/\ell$)

The above equation was actually derived for photosynthetically active light from Lake Chicot data by Stefan et al. (1982a), but can also be applied to the entire solar spectrum since much of the longwave components have been taken out in the surface layer.

Atmospheric radiation H_{an} , backradiation H_{br} , evaporative heat loss H_{ev} , and convective heat transfer H_c were calculated by equations given by Stefan et al. (1982c).

C. Wind Mixing

The deepening of the surface mixed layer by wind shear is considered by a stability criterion as described by Stefan and Ford (1975) and Ford and Stefan (1980).

The effect of wind on vertical diffusivities in the surfaced mixed layer and below the surface mixed layer is described by an equation of the form

$$K_z = aW^b \quad (40)$$

where K_z = vertical diffusivity (m^2/day)
 a, b = coefficients
 W = wind velocity (mph)

This empirical equation was proposed by Filatov et al. (1981). For shallow Lake Ladoga, coefficient b varied from 1.2 to 1.4. The average value $b = 1.3$ was chosen for Lake Chicot.

Coefficient a was estimated by using the seasonal mean values $K_z = 400 m^2/day$ for the mixed layer and $K_z = 1 m^2/day$ for all layers below, as previously applied by Dhamotharan (1979). For an average annual wind velocity $W = 7.73$ mph, $a = 28$ for the mixed layer and $a = 0.1$ for the hypolimnion. Thus,

$$K_z = 28 W^{1.3} \quad \text{in mixed layer} \quad (41)$$

$$K_z = 0.1 W^{1.3} \quad \text{below mixed layer} \quad (42)$$

VI. SUSPENDED SEDIMENT

In stratified lakes and reservoirs of moderate size, including Lake Chicot, advection in the horizontal direction is rapid, relative to vertical mixing. This had been verified in Lake Chicot by measurements of longitudinal temperature gradients (Dhamotharan, 1979), and hence only vertical gradients in suspended sediment concentration C were simulated.

Biweekly suspended sediment measurements in the lake also showed that one-dimensionality was an acceptable assumption for Lake Chicot. A relationship among suspended sediment concentration profiles, vertical mixing intensity, rate of deposition, and time is

$$A \frac{\partial(C)}{\partial t} + \frac{\partial(WAC)}{\partial z} - WC \frac{\partial A}{\partial z} - \frac{\partial C}{\partial z} (AK_z \frac{\partial C}{\partial z}) = 0 \quad (43)$$

where C = suspended sediment concentration
 W = fall velocity of suspended sediment in quiescent water
 A = surface area of x-section
 K_z = vertical turbulent diffusivity

The first term in this equation represents the change in sediment content with time, the second term is the rate of transfer by settling from one layer to another, the third term is the rate of deposition on the lake bed, and the fourth term is the vertical turbulent mixing rate. The particle fall velocity was determined after Gibbs et al. (1971). For Lake Chicot a mean particle size was determined as $r_s \approx 1 \mu$ by Schiebe (1980) and confirmed by model calibration.

The sediment transport equation accounts for deposition on the shelf. The equation is solved over the entire depth. Solution of the equation requires two boundary conditions which are:

(i) no suspended sediment transfer at the water surface, i.e.

$$K_z \frac{\partial C}{\partial z} - WC = 0 \quad \text{at } z = 0 \quad (44)$$

(ii) no resuspension at the bottom, i.e.

$$K_z \frac{\partial C}{\partial z} = 0 \quad \text{at } z = h \quad (45)$$

condition (i) is usually well satisfied while condition (ii) requires field verification. In Lake Chicot no resuspension was observed even after storms. A uniform concentration distribution $C = C_0$ is specified as the initial condition at $t = 0$ (Oct. 1, 1976, after the fall overturn).

Equation 43 describes a balance between advective transport by settling and diffusive transport by vertical mixing. In a stratified

reservoir, vertical exchange coefficients are strongly dependent on depth and wind on the surface. For the Lake Chicot simulation annual average values of $K_z = 400 \text{ m}^2/\text{day}$ for the surface mixed layer, and $K_z = 1 \text{ m}^2/\text{day}$ were used for all layers below (see Section V-D). The depth of the surface mixed layer was variable and simulated by the temperature stratification model. The two values of K_z which were also used in the temperature model were established by calibrating the model against field measurements of water temperature profiles. Daily variations in K_z were computed from Eqs. 41 and 42.

The model also computes a suspended sediment budget and determines the amount of sediment deposited in the reservoir. The apparent trap efficiency is defined as

$$\text{ATE} = \frac{\Sigma \text{ Sediment Inflow} - \Sigma \text{ Sediment Outflow}}{\Sigma \text{ Sediment Inflow}} \quad (46)$$

The trap efficiency ATE is meaningful only when computed over long time periods. It does not take into account the change in storage of suspended sediment in the lake.

The real trap efficiency RTE is the apparent trap efficiency ATE minus the change in storage in the lake. It is calculated from

$$\text{RTE} = \text{ATE} - \frac{\text{Change in Storage}}{\Sigma \text{ Sediment Inflow}} \quad (\text{VI-6})$$

Change in storage is the amount of suspended sediment in the lake at the beginning of the time interval minus the amount at the end.

VII. PHYTOPLANKTON MODEL

A. Concepts

The upper and lower basins of Lake Chicot represent distinctly different systems in terms of suspended solids concentration and primary productivity. The lower basin is highly turbid due to inorganic suspended solids, and biological productivity in this basin is substantially lower than in the upper basin (Cooper and Bacon, 1981). Observed seasonal variations in chlorophyll-a and suspended solids (Cooper and Bacon, 1981)

indicate that primary productivity in the lower basin is limited by the amount of available light.

Surges in phytoplankton populations occur whenever inorganic sediment concentrations and turbidity have diminished. If flow diversion effectively reduces inorganic sediment concentrations and turbidity in the future, phytoplankton will grow more substantially. It is for this reason that phytoplankton was modelled.

Phytoplankton concentrations can be described by a suspended sediment equation except that fall velocities are smaller than for clay, and terms for biological growth and loss kinetics must be added. At present growth of nuisance algae in Lake Chicot is predominantly controlled by the light available for photosynthesis. Losses of phytoplankton are due to settling and respiration. Grazing by zooplankton was not included separately because the observed species (Bacon, 1978; Cooper and Bacon 1981; and EPA, 1977) are not desirable food sources.

A relationship between productivity rate, light intensity, and temperature was developed from available field measurements by Cardoni and Stefan (1982). Nutrient limitation was not considered at first because at present a light limited situation occurs frequently in lower Lake Chicot (EPA, 1977). An extension of this analysis, including a nutrient limitation (phosphorus), was later made by Cardoni et al. (1982).

B. Basic Equation

The parameter used to indicate algal abundance is chlorophyll-a concentration [Chla]. The basic dynamic equation is

$$\frac{\partial[\text{Ch}l_a]}{\partial t} + \frac{1}{A} \frac{\partial(AW_c[\text{Ch}l_a])}{\partial z} - \frac{W_c[\text{Ch}l_a]}{A} \frac{\partial A}{\partial z} - \frac{1}{A} \frac{\partial}{\partial z} \left(A K_z \frac{\partial[\text{Ch}l_a]}{\partial z} \right) + K_2 T[\text{Ch}l_a] - P'[\text{Ch}l_a] = 0 \quad (48)$$

where [Chla] = chlorophyll-a concentration, mg/m³
 A = area at center of layer, m²
 W_c = Chla fall velocity in quiescent water, m/day
 K_z = vertical turbulent diffusivity, m²/day

K_2 = respiration/mortality loss coefficient, $\text{day}^{-1} \text{ } ^\circ\text{C}$

T = water temperature, $^\circ\text{C}$

P' = productivity rate, day^{-1}

Equation 48 is of the same form as Eq. 43 for the concentration of suspended solids but includes the additional source and sink terms, P' and K_2 . Also, the fall velocity W_c is different for algal particulates than for the suspended sediment particulates (mostly clay).

C. Primary Productivity

Productivity of Lake Chicot was measured by Bacon (1978), using the carbon-14 uptake method, and reported in part by the USDA (1977-1980). Bacon's data was converted to a specific growth rate by dividing measured rates of carbon-14 uptake by the concentration of chlorophyll-a present in the lake (Schiebe, 1980) thus obtaining productivity in units of mg carbon/mg Chl a/hr. Unfortunately carbon uptake and chlorophyll-a were never measured in the same water samples and interpolations had to be made.

A relationship between productivity rate, light intensity, and temperature in Lake Chicot was developed by Cardoni and Stefan (1982) from all available field measurements.

All light intensity data were from the National Weather Service Station in Stoneville, Mississippi, and attenuated with depth in the lake using an empirical equation given earlier (Eq. 39).

The productivity versus light intensity data displayed the expected characteristic relationship between productivity and light: (1) An approximately linear increase in growth rate with light intensity at low values of light, and (2) a plateau of maximum growth rate at the higher light intensity. Photoinhibition, i.e. the decrease of growth rate at excessive light exposure was not observed. This is not unexpected, since light intensity in Lake Chicot is usually quite low due to rapid attenuation with depth.

The shape of the P(I) curve can be described by a variety of mathematical and mostly empirical formulations. Some include the effect of photoinhibition. Comparisons of some of the equations to sets of measured data have given inconclusive results (Field and Effler, 1982; Jassby and

Platt, 1976). All empirical equations for the P(I) curve require the use of coefficients, usually P_{\max} and the initial slope of the curve. The selection of a mathematical equation for the P(I) curve may not be as critical as the determination of the coefficients used in the equation.

A Michaelis-Menten type equation was selected. After an extensive field data analysis by Cardoni and Stefan (1982), the following relationships were retained for simulation of light and temperature controlled primary productivity rates in Lake Chicot:

$$P = (1.2 + 0.187T) \frac{I}{100+I} \quad \text{for } 0 < T < 32^{\circ}\text{C} \quad (49)$$

$$P = (52.9 - 1.43T) \frac{I}{100+I} \quad \text{for } 32 < T < 37^{\circ}\text{C} \quad (50)$$

$$P' = 24P/\phi \quad (51)$$

where P = primary productivity rate ($\text{mg C mg Chl}a^{-1} \text{ hr}^{-1}$),
 P' = primary productivity rate (day^{-1}),
 I = light intensity ($\mu\text{E m}^{-2} \text{ s}^{-1}$), and
 T = water temperature ($^{\circ}\text{C}$).
 ϕ = 30 mg C/mg Chl a (from model calibration)

Sample plots of the relationship (49) between productivity, light intensity, and temperature are shown in Fig. 12.

Underwater Light Penetration Model

To apply the P(I) relationships to the prediction of daily photosynthesis in a stratified lake it is necessary to describe the variation of underwater irradiance as a function of depth and time over the course of a day. A model for underwater irradiance in Lake Chicot was developed by Stefan et al. (1982a). The input to the model is terrestrial (above water) total daily solar radiation measurements as available, e.g. from the Stoneville, Mississippi, weather station. Using empirical equations for albedo (Fig. 10) and attenuation (39), and a conversion from energy units to quantum units, a composite relationship is derived for photosynthetically

active radiation (PAR) under water.

Radiation available with depth is calculated as

$$I(t) = I_s(1 - \text{albedo})e^{-k(z)z} \quad (52)$$

Total daily solar radiation measurements are converted to average PAR values by

$$I_s = \frac{27.25}{t_d} H_s \quad (53)$$

where I_s = average photosynthetically active radiation over daylight period, above surface ($\mu\text{E m}^{-2} \text{sec}^{-1}$)

H_s = measured total daily radiation above water surface ($\text{cal cm}^{-2} \text{day}^{-1}$)

$$t_d = 12.16 + 2.36 \cos \left[\frac{2\pi}{365} (172-D) \right] \quad (54)$$

t_d = length of daylight (hrs), at latitude 35°N (U. S. Naval Obs., 1977)

D = number of days of year (Jan. 1: $D=1$)

The variation of irradiance over the length of the daylight is described by a cosine function:

$$I(t) = I_{\max} \cos \left(\frac{\pi t}{t_d} \right) \quad (55)$$

$I(t)$ = PAR intensity at time t ($\mu\text{E/m}^2\text{-sec}$)

I_{\max} = maximum PAR intensity ($\mu\text{E/m}^2\text{-sec}$)

t = time of day starting with $t=0$ at solar noon (hours)

which is transformed to

$$I(t) = I_s \frac{\pi}{2} \cos \left(\frac{\pi t}{t_d} \right) \quad (56)$$

For the numerical computation, the daylight period is divided into eight subperiods. Productivity is calculated for each period and averaged over a

day. This procedure is repeated for each layer (depth z). The details of the computation are given by Cardoni and Stefan (1982).

D. Loss Rate And Settling Rate

Loss rate represents the decrease in phytoplankton mass by endogenous respiration and other factors causing phytoplankton mortality (e.g. zooplankton grazing, toxic pesticides, etc.). Loss rate is taken to be a combination of all processes that cause a decrease in phytoplankton mass, except settling. Zooplankton grazing has not been considered independently since there is not sufficient data to make this distinction. Values from the literature for loss rate in phytoplankton mass modeling typically range from 0.05 to 0.25 day^{-1} (Di Giano, 1978; Schnoor, 1980; Imboden, 1978; O'Connor et al., 1973).

The relationship proposed by O'Connor et al. (1973) is for endogenous respiration rate. Since endogenous respiration represents a significant portion of the total loss rate, a temperature dependence of the form used by O'Connor is used in the model:

$$\text{loss rate} = K_2 T(^{\circ}\text{C}) \quad (57)$$

The coefficient K_2 was determined by calibration with Lake Chicot Chl a measurements to be on the order of $.005 \text{ }^{\circ}\text{C}^{-1} \text{ day}^{-1}$.

The settling rate of phytoplankton is a highly variable parameter dependent on species, season, nutrient concentration, age of the population, time of day, and relative brightness of the day (Burns and Rosa, 1980). Jorgensen et al. (1981) quote the settling velocity of *Scenedesmus* as ranging from 0.1 to 0.6 meters per day. Burns and Rosa (1980) measured settling velocities of ten species of phytoplankton, and found values ranging from $0.07 \pm .21 \text{ m/day}$ to $0.32 \pm 0.32 \text{ m/day}$.

No direct measurements of phytoplankton settling velocities from Lake Chicot are available. Due to the highly variable nature of this parameter and the difficulty associated with measuring it accurately, the model was calibrated by varying the settling rate within the range of values reported in the literature. By comparison of measured in-lake chlorophyll- a concentrations with those predicted by the simulation model, a settling rate on the order of $.04 \text{ m day}^{-1}$ was determined.

E. Chlorophyll Model Formulation

To predict the concentration of phytoplankton, Eq. 48 must be solved with appropriate boundary and initial conditions. The parameter to indicate algal abundance is chlorophyll-a concentration [Chla]. The model is set up for use on a daily time basis. The input parameters to the chlorophyll-a model are incident (above surface) light intensity, suspended solids concentration, and water temperature, each on a daily basis. The boundary conditions are the same as for the suspended sediment model (Eq. 44 and 45). Based upon these input parameters and an initial value of [Chla], the model predicts [Chla] for each layer in the lake. The dynamic Eq. 48 in numerical form is applied to each layer derived in the temperature model and the suspended sediment model. Inflow of chlorophyll from Connerly Bayou is accounted for by the concentration Eq. 6. The transport of incoming chlorophyll to the appropriate isopycnic layer is handled by a density current submodel as described in Section IV. Outflow through Ditch Bayou uses the analogy to suspended sediment transport.

Equation 48 is of the same form as Eq. 43 for the concentration of suspended solids in the lake except for additional source and sink terms. The chlorophyll equation can be solved in the same manner as the suspended solids equation (Dhamotharan et al., 1981).

A flow chart outlining the procedure for predicting chlorophyll-a concentration is shown in Fig. 13.

The scheme of calculations is repeated for each day of the simulation. Details on the procedure are provided by Cardoni and Stefan (1982).

VIII. NUTRIENT MODEL

At present phytoplankton growth in Lake Chicot is most often controlled by available light. Nutrient concentrations in the lake are generally high and primary productivity is not significantly inhibited by lack of nutrients. The Lake Chicot restoration project is designed to reduce the amount of water and suspended sediment entering the lake. The input of nutrients will therefore also be significantly reduced. A nutrient limitation in the growth model is desirable for future conditions when lower nutrient levels may restrict phytoplankton growth.

Phosphorus and nitrogen are the most likely limiting nutrients. Both

have been considered, but only phosphorus is at present represented in the model. EPA (1977) suggested that phosphorus may be more significant in controlling growth in Lake Chicot. Baker (1982) reviewed more recent Lake Chicot nutrient data and came to the conclusion that nitrogen may also be an important nutrient controlling phytoplankton growth.

The framework and general approach to the modeling of phosphorus and nitrogen cycles and interactions with phytoplankton growth in Lake Chicot have been given by Cardoni, Hanson and Stefan (1982) and Baker (1982), respectively. The cycles of both elements are quite complex and their dynamic modeling requires substantial numbers of rate coefficients and field and laboratory data presently not available. It is for this reason that only a phosphorus submodel of a relatively simple form has been incorporated into the Lake Chicot model.

A. Phosphorus Model Formulation

In-lake measurements of phosphorus were made from 1976 through 1980. Available data include total (P_t), total dissolved (P_{td}), ortho- (P_o), and ortho-dissolved (P_{od}) phosphorus. Measurements were made at the water surface; the time interval between measurements varied from one day to one month. While there are several different forms of phosphorus in lake water, only forms of immediate influence on the phytoplankton growth were selected for the model: phosphorus tied up in the phytoplankton cell-mass, available dissolved phosphorus (dissolved orthophosphorus), and a pool of "non-available" phosphorus that may become available phosphorus. Figure 14 shows schematically these three phosphorus compartments and the associated inputs and outputs.

Available phosphorus corresponds to dissolved orthophosphorus, which is immediately available for uptake by planktonic algae. Non-available phosphorus represents phosphorus that is not immediately available but can be converted to the available form. Much of this quantity is associated with the inorganic suspended solids in the lake. Phytoplankton represents both a sink and a source of available phosphorus. Available phosphorus is taken up during algal growth. Planktonic mortality, decomposition, and respiration release organic phosphorus to the available form.

The actual phosphorus cycle in a lake is much more complex than that shown in Fig. 14. In particular, organic detritus and zooplankton have

not been modelled as specific compartments. The available data do not at present allow accurate calculation of the required coefficients for a complex phosphorus cycling system. The simplified cycle shown in Fig. 14 includes the most important components of the system. The exchange coefficients are calibrated to suite lower Lake Chicot.

The equations governing the phosphorus cycle depicted in Fig. 14 are:

Available phosphorus:

$$\frac{\partial P_a}{\partial t} - \frac{1}{A} \frac{\partial}{\partial z} \left(AK_z \frac{\partial P_a}{\partial z} \right) - K_2 Tr \frac{Chla}{Y_{ca}} + \mu_m \left(\frac{I}{K_I + I} \right) \left(\frac{P_a}{K_p + P_a} \right) \frac{Chla}{Y_{ca}} - \left[\frac{K_r A}{V} \right]_{\text{bottom layer}} = 0 \quad (58)$$

Non-available phosphorus:

$$\frac{\partial P_n}{\partial t} + \frac{1}{A} \frac{\partial}{\partial z} \left(A W_n P_n \right) - \frac{W_n P_n}{A} \frac{\partial A}{\partial z} - \frac{1}{A} \frac{\partial}{\partial z} \left(A K_z \frac{\partial P_n}{\partial z} \right) - \left[\frac{K_{rr} A}{V} \right]_{\text{bottom layer}} = 0 \quad (59)$$

Phytoplankton:

$$\frac{\partial Chla}{\partial t} + \frac{1}{A} \frac{\partial [AW_c (Chla)]}{\partial z} - \frac{W_c (Chla)}{A} \frac{\partial A}{\partial z} - \frac{1}{A} \frac{\partial}{\partial z} \left[AK_z \frac{\partial (Chla)}{\partial z} \right] + K_2 T (Chla) - \mu_m \left(\frac{I}{K_I + I} \right) \left(\frac{P_a}{K_p + P_a} \right) (Chla) = 0 \quad (60)$$

These equations are solved for each layer of the lake on a daily time scale. The variables and coefficients are:

P_a = available phosphorus, ppb

P_n = non-available phosphorus, ppb

- A = projected (horizontal) lake area, m^2
 K_z = vertical turbulent diffusivity ($m^2 day^{-1}$)
 K_2 = respiration/mortality loss coefficient ($day^{-1} \cdot ^\circ C^{-1}$)
 T = water temperature ($^\circ C$)
 r = fraction of cellular phosphorus converted immediately
to available phosphorus
 Chl_a = chlorophyll-a concentration (ppb)
 Y_{ca} = yield coefficient, chlorophyll-a to phosphorus
 I = light intensity ($\mu E m^{-2} sec^{-1}$)
 K_I = half saturation coefficient for light ($\mu E m^{-2} sec^{-1}$)
 μ_m = maximum phytoplankton growth rate (day^{-1})
 K_P = half saturation growth coefficient for phosphorus (ppb)
 K_R = bottom release rate of available phosphorus from
sediments ($mg P_a m^{-2} day^{-1}$)
 W_n = fall velocity of non-available phosphorus ($m day^{-1}$)
 K_{RR} = resuspension rate of non-available phosphorus from the
lake bottom ($mg suspended solids m^{-2} day^{-1}$)
 W_c = fall velocity of chlorophyll-a ($m day^{-1}$)

B. Determination of Model Coefficients

1. Plankton - Available Phosphorus Link

Models which use the limiting nutrient concept assume that the yield of phytoplankton will in part be determined by the concentration of the limiting nutrient when the nutrient concentration is low. The classical Monod growth rate for phosphorus limitation is used.

The most straightforward approach to formulating a growth rate expression involving both nutrient and light limitation is to multiply the maximum growth rate by the reduction factors for both the limiting nutrient and available light. This approach has been suggested by Chen (1970) and O'Connor et al (1973). The resulting growth expression, using the light limited term and maximum growth rate μ_m developed earlier is

$$\mu = \mu_m \left(\frac{I}{K_I + I} \right) \left(\frac{P_a}{K_p + P_a} \right) \quad (61)$$

where μ = specific growth rate for phytoplankton (day^{-1}). An alternative is to calculate the fractions $I/(K_I + I)$ and $P_a/(K_p + P_a)$ separately, and to retain only the smaller of the two.

Phytoplankton growth usually requires available phosphorus uptake. Equation 61 can be used to represent this uptake:

$$u = \mu \frac{\text{Ch} \lambda a}{Y_{ca}} \quad (62)$$

where u = specific rate of available phosphorus uptake ($\text{mg } P_a \text{ m}^{-3} \text{ day}^{-1}$), μ in day^{-1} , $\text{Ch} \lambda a$ in mg m^{-3} , and Y_{ca} = the $\text{Ch} \lambda a$ to P_a ratio. Equation 61 and 62 are incorporated in Eq. 58. Measurements in the upper basin of Lake Chicot during July, 1981, (Cardoni and Hanson, 1981) indicate a value of Y_{ca} equal to from about 0.2 to 0.75.

Many values have been given in the literature for the half-saturation growth coefficient for phosphorus, K_p , ranging from 0.003 to 0.1 mg/l (DiToro, 1980; Lewis and Ni, 1978; O'Connor et al., 1973).

The release of available phosphorus from the phytoplankton can be formulated as

$$R = K_2 T r \frac{\text{Ch} \lambda a}{Y_{ca}} \quad (63)$$

where R = specific rate of available phosphorus release ($\text{mg } P_a \text{ m}^{-3} \text{ day}^{-1}$) and the other terms are as previously defined. Nyholm (1978) used a value $r = 0.6$. Equation 62 is included in Eq. 58. Two values of r are employed, r_m for the mixed layer and r_h for the hypolimnion, where $r_h > r_m$.

2. Available/Nonavailable Phosphorus Link

Non-available phosphorus is the phosphorus pool that is not in a form immediately available to plant growth but can be converted in time to available phosphorus. Lee et al. (1978) estimated that roughly 20 percent of the difference between the total phosphorus and the soluble ortho-phosphorus will be available in addition to the soluble orthophosphorus.

McDowell et al. (1980) indicate that this percentage could range from 5 to 40 percent.

It is proposed that much of the non-available phosphorus is associated with suspended solids. The sediments entering the lake are partially from erosion in the upstream drainage basin and partially from growth processes in Macon Lake and Connerly Bayou. About 10 percent by weight of the incoming sediments has been determined to be organic material at times.

The literature indicates that the bulk of phosphate adsorption-desorption is complete within a 24-hour time span. The Lake Chicot model is on a daily time scale; therefore, an equilibrium rather than a kinetic approach was used.

Phosphorus transfer is included by "partitioning" in the following way. Equations for non-available and available phosphorus are solved numerically. Then the concentration of available phosphorus (P_a) in each layer is compared with an equilibrium concentration of available phosphorus ($P_{a,eq}$). The value of ($P_{a,eq}$) can be determined by a laboratory experiment (see Cardoni et al., 1982b). If available phosphorus concentration is greater or equal to ($P_{a,eq}$), no transfer takes place. If $P_a < (P_{a,eq})$, phosphorus is transferred from the non-available form to the available one until equilibrium is reached. The process continues until $P_{n_{new}} = 0$.

This "partitioning" is done after the solution of the two governing equations and before advancing to the next time step.

3. Inflow, Settling, and Resuspension Rates

The concentration of available phosphorus in the inflow is fairly constant, with an average value of 100 ppm over the period of data collection (Section III-B). The inflow of convertible non-available phosphorus is estimated from Eq. 8.

Non-available phosphorus is assumed to be mostly associated with the suspended solids in the lake. Thus, non-available phosphorus will have a settling velocity W_n equivalent to that of the suspended solids.

Resuspension of non-available phosphorus from the lake bottom would be in the form of suspended solids resuspension. In Lake Chicot, solids resuspension does not seem to be significant at present.

Release of available phosphorus from the bottom sediments requires anoxic conditions at the sediment-water interface. This condition may be

attained during a stratified period with much organic decay at the lake bottom. Under the present conditions anoxic conditions occur rarely and this term is neglected.

Table 1 summarizes the coefficients required for the phytoplankton/phosphorus submodel, and their respective values.

4. Total Phosphorus Concentration

Total phosphorus concentration in Lake Chicot is modeled as a function of the suspended solids concentration in the lake. The data in Fig. 8 relates suspended solids concentration to the difference between total phosphorus and dissolved orthophosphorus, both in the lake and at the inlet to the lake. Equation 8, without subtraction of the phosphorus associated with the plankton and without the η reduction is used to predict the total phosphorus concentration in the lake.

$$P_t = 0.025(SS)^{.573} + P_a \quad (64)$$

IX. SECCHI DEPTH MODEL

Secchi depth is a comprehensive measurement of water transparency. Lay people can easily relate to the meaning of Secchi depth.

Secchi depths in upper and lower Lake Chicot were analyzed and related to attenuation coefficients by Stefan et al. (1982). Secchi depths in the lower lake were related to total suspended solids (Fig. 15) and Secchi depths in the upper lake were related to Ch λ a (Fig. 16). Equations 65 and 66 describe the data in Figs. 15 and 16, respectively.

$$1/z_{SD} = 2.16 + 0.0265(SS) \quad (65)$$

$$1/z_{SD} = 1.66 + 0.0083 (Ch\lambda a) \quad (66)$$

z_{SD} is the Secchi depth in meters, (SS) is the suspended solids concentration in ppm and (Ch λ a) is the chlorophyll-a concentration in ppb.

The effects of suspended solids and Ch λ a have been isolated by considering the lower and upper basins of Lake Chicot during periods when inorganic suspended solids and phytoplankton, respectively, dominated

turbidity (Figures 15 and 16). The data from the upper lake were obtained when suspended solids concentrations were less than approximately 45 mg/l. The coefficient for the effect of Ch_la, 0.0083, is lower than that presented by Brezonik (1978) ($\approx .03$) and by Shapiro (1982)(.0146). Brezonik's data is from 55 Florida lakes, and Shapiro's data is from Minnesota lakes. To combine Eqs. 65 and 66, the effects of SS and Ch_la are considered additive. The intercept value is not the same in both basins, indicating that factors other than SS and Ch_la in each of the respective basins were not the same. Using an average of the intercept values, the composite relationship for Secchi depth is

$$1/z_{SD} = 1.9 + 0.00265(SS) + 0.0083(Ch_{l}a) \quad (67)$$

A second approach to formulating a Secchi depth model involves logarithmic relationships for Secchi depth. The logarithmic equations provided a slightly better fit than Eq. 66 to the data in Fig. 16. The effect of suspended solids on the Secchi depth is adequately described by Eq. 65. The following composite relationship is therefore proposed:

$$\frac{1}{z_{SD}} = \frac{(Ch_{l}a)^{.258}}{1.37} + 0.0265(SS) \quad (68)$$

The SS term in Eq. 68 isolates the effect of SS, and does not include other factors influencing transparency. The Ch_la term does not have an intercept that isolates other factors affecting z_{SD} , and thus they are included in this term. To prevent the Secchi depth from going to infinity at zero Ch_la and SS concentrations, a minimum Ch_la concentration of 3 ppb will be imposed. This sets the maximum possible Secchi depth at 1.03 meters, which is slightly deeper than the maximum Secchi depth measurement from the available Lake Chicot data. Equation 68 is graphically presented in Fig. 17. Equation 68 is used to predict Secchi depth in the model.

The shading of phytoplankton by inorganic suspended sediment produces an inverse correlation between Ch_la and SS. Therefore, only the range of the Ch_la values to the left of the dotted line in Fig. 17 is of practical interest.

X. COMPUTER PROGRAM RESQUAL II

A. Organization

The submodels identified in Fig. 2 are incorporated in computer program RESQUAL II. There are a total of 53 subroutines in RESQUAL II. A complete alphabetical listing and brief description of all subroutines were assembled by Fu (1982).

The main program calls the submodels in sequence. By not solving all equations simultaneously, the program is simplified and the computing time is considerably reduced. The uncoupling of the submodels requires that input data into one submodel be taken from the output of the other submodels in the previous timestep. This is appropriate for three reasons.

First, the model is operated with a timestep (1 day) over which changes in the computed parameters are small. The error introduced in using e.g. suspended sediment concentration from the previous day instead of the current day affects results to a lesser degree (as was verified by adding additional iteration steps to the program) than the uncertainties in estimating model input parameters, e.g. settling velocity of particles and entrainment coefficient of density inflow, surface heat exchange coefficients, albedo, etc.

Second, the coupling between the main submodels in RESQUAL is actually very weak. Most of the inflow into Lake Chicot occurs during the two months just prior to the summer stratification period. Outflow is always from the surface mixed layer. Suspended sediment concentration affects mainly the radiation balance of the mixed layer and suspended sediment concentration in the mixed layer changes only slowly. Dissolved solids concentrations do not control density stratification to any appreciable degree.

Third, the input variables which drive the model most strongly are runoff and weather related. The latter are highly variable in time and have to be obtained from measuring stations remote from the lake. Because of that variability, lake temperatures and mixing "tend" towards constantly changing equilibrium or ultimate temperatures. Therefore, prediction errors are not cumulative.

B. Numerical Solutions

The partial differential equations (advection/diffusion equations) for T, SS, Chla, P_a and P_n are solved by implicit methods.

1. Water Temperature (Eq. 33)

In the formation of a finite difference scheme, stability and accuracy are of main concern. For the water temperature Eq. 33, a fully implicit central difference scheme was selected. The scheme was formulated for variable layer thickness $\Delta z(i)$. The resulting finite difference equation is of the form

$$T(i, j+1) - T(i, j) = - D^*(i-1/2) [T(i, j+1) - T(i-1, j+1)] \\ + D^*(i+1/2) [T(i+1, j+1) - T(i, j+1)] + S^* \Delta t \quad (69)$$

where i = number of layer counted from the surface
 j = timestep (day)

$$D^*(i-1/2) = \frac{2\Delta t D(i-1/2)}{\Delta z(i) [\Delta z(i) + \Delta z(i-1)]}$$

$$D^*(i+1/2) = \frac{2\Delta t D(i+1/2)}{\Delta z(i) [\Delta z(i) + \Delta z(i+1)]}$$

and $S^* = \frac{S}{\rho c V(i)}$

The above equation may be rewritten as

$$aT(i-1, j+1) - bT(i, j+1) + cT(i+1, j+1) + d = 0 \quad (70)$$

where $a = D^*(i-1/2)$
 $c = D^*(i+1/2)$
 $b = 1 + a + c$
 $d = T(i, j) + S^* \Delta t$

To compute $D(i-1/2)$ and $D(i+1/2)$, a harmonic mean is used

$$D(i+1/2) = \frac{2D(i) D(i+1)}{D(i) + D(i+1)} \quad (71)$$

$$D(i-1/2) = \frac{2D(i) D(i-1)}{D(i) + D(i-1)} \quad (72)$$

Equation 70 was solved by a tri-diagonal matrix algorithm. The boundary conditions applied are:

- (i) no heat flux to and from the sediment or $T(j+1,N) = T(j+1,N+1)$, where $N+1$ refers to a dummy layer below the bottom layer of the reservoir.
- (ii) No diffusive heat flux between the surface mixed layer and the hypolimnion

$$\left[D \frac{\partial T}{\partial z} \right]_{m+1/2} = 0$$

where m = number of last layer in surface mixed layer.

The numerical solution of the diffusion equation for heat necessary to predict water temperature stratification is accomplished as part of subroutine HEBUG.

2. Suspended Sediment Eq. 43

The subroutine which solves the suspended sediment Eq. 43 is RESSETL. An implicit, hybrid finite difference scheme was developed to solve the suspended sediment equation. That scheme has been described in detail by Dhamotharan et al. (1981). It is stable for various combinations of vertical turbulent diffusivities and particle fall velocities.

3. Chlorophyll-a Eq. 48

CHLORO is a modified version of the subroutine RESSETL. The modification of RESSETL is required to account for the additional source and sink terms that are contained in the chlorophyll-a model. This subroutine solves Eq. 48 for all layers of the lake by using an implicit finite difference scheme.

C. Computational Options

Subroutine START controls input and computing options. One need not use all available submodels each time. Three options are available to select submodels by setting the elements of the integer array MODEL(I) to either 1 or 0. If all elements of MODEL(I) are set to zero, only the water temperature, suspended solids, and dissolved solids submodels will be selected. If MODEL(1) is set to one and all others zero, the light-limited chlorophyll-a submodel will be selected in addition to the water temperature, suspended solids and dissolved solids submodels. If MODEL(2) is set to one and all others zero, all the submodels will be selected.

D. Model Input

Model RESQUAL II requires four types of input data:

- initial conditions
- morphometric lake and channel data
- inflow data
- weather data

The initial conditions which need to be specified include:

- (a) the initial number N of layers in the lake typically 20
- (b) $T(i,1)$
- (c) $SS(i,1)$
- (d) $Chla(i,1)$
- (e) $P_a(i,1)$; $P_n(i,1)$

where the number of layers varies, $1 < i < N$. An initial lake stage is also required.

Lake morphology and inflow have been described in Section III. The

parameters m and c in Eq. 3 need to be specified.

Inflow rate is given by specifying an upstream stage elevation S_M and then computing flow rate by Eq. 4. Inflow water temperature must be specified. Inflow suspended sediment concentration, chlorophyll-a, and phosphorus of the inflow are estimated by Eq. 5 to 8.

Required weather data comprise daily total solar radiation, daily mean air temperature, dew point temperature, mean wind velocity, daily precipitation, and daily cloud cover.

E. Model Output

Model output is either in the form of tables or graphs as described by Fu (1982).

XI. CALIBRATION

RESQUAL II contains submodels which simulate several water quality parameters. Coefficients in each of these submodels have to be assigned numerical values. Some of these are physical constants, others are known from previous investigations or can be derived from Lake Chicot data. For some coefficients, only order of magnitude estimates or ranges of numerical values are known. More precise values of these coefficients applicable only to Lake Chicot are established by model calibration, i.e. comparison of simulated and observed results.

The calibration was made with data collected during water year 1977 (Oct. 1, 1976 - Sept. 30, 1977). The data were collected by the USDA/ARS mostly at biweekly intervals. Calibrations were made in the major submodels successively and in the order in which they are listed in Table 2.

In the mass flow and temperature stratification models, the two parameters which were the least well established and had to be calibrated were vertical turbulent exchange coefficient K_z and initial dilution at the plunge point γ_{in} .

The temperature model was at first calibrated for mean annual values of $K_z = 400 \text{ m}^2/\text{day}$ in the surface mixed layer and $K_z = 1 \text{ m}^2/\text{day}$ in the hypolimnion, respectively. (See Dhamotharan, 1979). Then, coefficients $a_m = 28$ for the mixed layer, $a_h = 0.1$ for the hypolimnion, and $b = 1.3$ in Eq. 40 were determined by using a mean annual wind in these equations.

In the suspended sediment model a particle size on the order of 1 μ as determined by sediment analysis had to be used. The complete size distribution of particles was never obtained. Calibration confirmed that 1 μ gave loss rates by settling in agreement with measurements.

The chlorophyll submodel required several coefficients. Literature and Lake Chicot field values of these coefficients are given in Table 1. The range of values tested in the model and the calibrated value are given in Table 2.

The phosphorus model had several coefficients to be calibrated. Ranges and values are shown in Tables 1 and 2.

Simulated results and calibration data are shown in Fig. 18 through 26. The root mean square calibration error (ϵ) for each water quality parameter was computed. The root mean square calibration error ϵ is defined as

$$\epsilon = \sqrt{\frac{\sum_{i=1}^n (C_{ic} - C_{im})^2}{n}} \quad (73)$$

where C_{ic} = computed water quality parameter on the i th day
 C_{im} = measured water quality parameter on the same day
 n = number of measurements

Calibration coefficients were changed until the value of ϵ could not be further reduced.

More systematic schemes to calibrate RESQUAL II such as the least-squares optimization adopted by Norton (1974) in calibrating the RMA-12 model were not used because of the large computing cost which would have been involved.

XII. MODEL VERIFICATION

Water quality data sets measured during the water years 1977/78 and 1978/79 were used for model verification. A comparison between predictions and data was again made. The root mean square error between predictions and measurements is shown in Table 3. Total suspended sediment trap effi-

ciencies, both calculated and measured, are shown in Table 4. Agreement between predictions and measurements was approximately the same for the calibration and verification. Weather and lake conditions were different in the three years. The conclusion was drawn that the model is sufficiently verified for application to the exploration of some management alternatives for Lake Chicot. Major limitations in the available data are with reference to the inaccuracies in inflow rates (Fig. 5) and the weak correlation between inflow water quality and inflow rate which had to be used in the simulation. The greatest limitation in the model formulation itself is believed to be in the phosphorus model with its many coefficients and exchange processes between different forms of phosphorus.

XIII. MODEL APPLICATION

Simulations with reduced inflow rates into Lake Chicot have been made. In anticipation of the operation of the pumping station at Macon Lake, inflow rates have been truncated at 5 cfs, 50 cfs, 100 cfs, 250 cfs, and 500 cfs. Flows above these values are diverted to the Mississippi River. The predicted water quality under the weather conditions encountered in 1976/77, 1977/78, and 1978/79 have been simulated (see Stefan et al., 1982c). The suspended sediment concentration, and hence turbidity of the lake, is found to be very much a factor of inflow; the recovery of the lake from a suspended sediment problem over a three-year period and for six rates of diversion was established. As lessened turbidity of the lake permits an increase in light penetration, phytoplankton growth increases, as expected.

An estimate of the clarity of the lake under the various diversions was calculated in terms of predicted Secchi depths. Values more than 0.5 m were rarely exceeded, even after diversion.

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REFERENCES

1. Akiyama, J. and Stefan, H. G., "Theory of Plunging Flow into a Reservoir," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Internal Memorandum No. IM-97, 83 pp., Dec., 1981.
2. Bacon, E. J., "Primary Productivity, Water Quality, and Limiting Factors in Lake Chicot," Arkansas Water Resources Research Center, Fayetteville, AR. Publ. No. 56, 1978.
3. Bacon E. J., "Primary Productivity in Lake Chicot, Chicot County, Arkansas, Quarterly Progress Reports, University of Arkansas, Monticello, AR, Oct. 1977-Sept. 1980.
4. Baker, L. "Concepts of a Nitrogen Cycling Model of Lake Chicot, Arkansas," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Internal Memorandum No. 99, July, 1982.
5. Burns, N.M. and Rosa, F., "In Situ Measurement of the Settling Velocity of Organic Carbon Particles and 10 Species of Phytoplankton," Limnol. Oceanogr., 25(5), 1980.
6. Brezonik, P. L., "Effect of organic color and turbidity on Secchi disk transparency," Jour. Fish Res. Board, Canada, 35:1410-1416, 1978.
7. Canale, R. P. and Vogel, A. H., "Effects of Temperature on Phytoplankton Growth," ASCE, Jour. Env. Engr. Div., Vol. 100, EE1, pp. 231-241, 1974.
8. Cardoni, J. J. and Hanson, M. J., "Lake Chicot Intensive Field Investigations, June 30 to July 10, 1981," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, External Memorandum No. 176, 92 pp., Dec., 1981.
9. Cardoni, J. J. and Stefan, H. G., "A Model for Light and Temperature Limited Primary Productivity in Lake Chicot," University of Minnesota, St. Anthony Falls Hydraulic Laboratory External Memorandum M-177, 46 pp., May, 1982.
10. Cardoni, J. J., Hanson, Mark J., and Stefan, H. G., "A Model of Phosphorus Available for Phytoplankton Growth in Lake Chicot, University of Minnesota, St. Anthony Falls Hydraulic Laboratory External Memorandum M-178, July, 1982.
11. Chen, C. W., "Concepts and Utilities of Ecological Model," ASCE, Jour. Sanitary Engr. Div., Vol. 96, pp. 1085-97, Oct., 1970.
12. Cooper, C. M. and Bacon, E. J., "Effects of Suspended Sediments on Primary Productivity in Lake Chicot, Arkansas," Proc., Sym. on Surface Water Impoundments, June, 1980, Minneapolis, Minnesota, publ. by American Society of Civil Engineers, Oct., 1981.

13. Dake, J.M.K. and Harleman, D.R.F., "Thermal Stratification in Lakes: Analytical and Laboratory Studies," Water Resources Research, Vol. 5, No. 2, pp. 404-495, 1969.
14. Dhamotharan, S., "A Mathematical Model for Temperature and Turbidity Stratification Dynamics in Shallow Reservoirs," Ph. D. Thesis, University of Minnesota, 319 pp., March, 1979.
15. Dhamotharan, S., Gulliver, J., and Stefan, H., "Unsteady One-Dimensional Settling of Suspended Sediment," Water Resources Research, Vol. 17, No. 4, pp. 1125-1132, Aug., 1981.
16. Dhamotharan, S., Stefan, H. G., and Schiebe, F. R., "Turbid Reservoir Stratification Modelling," Proceedings, 26th Annual Hydraulic Div. Specialty Conf., ASCE, Univ. of Maryland, College Park, Maryland, Aug., 1978.
17. DiGiano, F. A., Lijklema, L., and Van Stratan, G., "Wind Induced Dispersion and Algal Growth in Shallow Lakes," Ecological Modelling, Vol. 4, pp. 237-252, 1978.
18. DiToro, D. D., "Applicability of Cellular Equilibrium and Monod Theory to Phytoplankton Growth Kinetics," Ecol. Modelling, Vol. 8, 1980, pp. 201-218.
19. Environmental Protection Agency, Report on "Chicot Lake, Chicot County, Arkansas, EPA Region VI." National Eutrophication Survey, Environmental Monitoring and Support Laboratory, Las Vegas, NV and Corvallis Environmental Research Laboratory, Corvallis, OR. Working Paper No. 484, 17 pp., 1977.
20. Field, S. D. and Effler, S. W. Photosynthesis-Light Mathematical Formulations, Jour. Env. Engr. Div., ASCE, Vol. 108, EEl, pp. 199-203, 1982.
21. Filatov, N. N., Rjanzhin, S.V., and Zaycev, L. V., "Investigation of Turbulence and Langmuir Circulation in Lake Ladoga," Jour. of Great Lakes Research, Vol. 17, No. 1, pp. 1-6, 1981.
22. Ford, D. E., "Water Temperature Dynamics of Dimictic Lakes: Analysis and Prediction Using Integral Energy Concepts," Ph. D. thesis, University of Minnesota, June, 1976.
23. Ford, D. E. and Stefan, H., "Thermal Prediction Using Integral Energy Model," ASCE, Jour. of the Hydraulics Division, Vol. 106, HY1, pp. 39-55, Jan., 1980.
24. Fu, Alec, "User Instructions for RESQUAL II, A Dynamic Water Quality Simulation Model for a Shallow Stratified Lake or Reservoir," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, External Memorandum No. 179, July, 1982.
25. Garges, E., "A Manual for Phytoplankton. Primary Production Studies in the Baltic," Baltic Marine Biologists in Cooperation with the Danish Agency of Environmental Protection, Copenhagen, 88 pp., 1975.

26. Gibbs, R. J., Mathews, M. D., and Link, D. A., "The Relationship Between Sphere Size and Settling Velocity," Jour. of Sedimentary Petrology, Vol. 41, No. 1, March, 1971.
27. Imboden, D. M. and Gachter, R., "A Dynamic Lake Model for Trophic State Prediction," Ecological Modelling, 4:77-98, 1978.
28. Jassby, A. D. and Platt, T., "Mathematical Formulation of the Relationship Between Photosynthesis and Light for PHYtoplankton, Limnol. Oceanogr. 21(4), pp. 540-547, 1976.
29. Jorgensen, S. E., Mejer, H., and Friis, M., "Examination of a Lake Model," Ecological Modelling, 4:253-278, 1978.
30. Jorgensen, S. E., Jorgensen, L. A., Kamp-Nielson, L., and Mejer, H.F., "Parameter Estimation in Eutrophication Modelling," 13:111-129, 1981.
31. Lee, G. F., Rast, W., Jones, R. A., "Eutrophication of Water Bodies: Insights for an Age-Old Problem," Environmental Science and Technology, 12:900-908, Aug., 1978.
32. Lewis, S. and Nir, A., "A Study of Parameter Estimation Procedures of a Model for Lake Phosphorus Dynamics," Ecol. Modelling, Vol. 4, pp. 99-117, 1978.
33. McDowell, L. L., Schreiber, J. D., and Pionke, H. B., "Estimating Soluble (PO_4 -P) and Labile Phosphorus in Runoff from Croplands," CREAMS: A field-Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems, W. G. Knisel, ed., USDA Conservation Research Report No. 26, pp. 509-533, 1980.
34. Metropolitan Waste Control Commission, St. Paul, Minnesota. Upper Mississippi River Water Quality Modeling Study, 208 Grant, preliminary copy, 131 pp., Nov., 1978.
35. Norton, W. R., Final Report for the Upper Mississippi River Basin Model Project, Water Resources Engineers, Walnut Creek, Calif. 94596, 1974.
36. Nyholm, N., "A Simulation Model for Phytoplankton Growth and Nutrient Cycling in Eutrophic, Shallow Lakes," Ecological Modelling, 4:279-310, 1978.
37. O'Connor, D. J., Thomann, R. V., and DiToro, D., "Dynamic Water Quality Forecasting and Management," Manhattan College, Bronx, New York, EPA-600/3-73-009, 1973.
38. Pedersen, F. B., "A Monograph on Turbulent Entrainment and Friction in Two-Layer Stratified Flow," Institute of Hydrodynamics and Hydraulic Engineering, Techn. University of Denmark, Lyngby, 1980.
39. Rothwell, Edward D. and Fletcher, Bobby P., "Lake Chicot Pumping Plant Outlet Structure, Arkansas," Tech. Report HL-79-10, U. S. Army Waterways Experiment Station, Vicksburg, Miss., June, 1979.

40. Schiebe, F. R., Personal communication, USDA, Durant, OK, 1980.
41. Schiebe, F. R., Farrell, J. O., McHenry, J. R., "Water Quality Improvement of Lake Chicot, Arkansas," Proceedings, Symposium on Surface Water Impoundments, Minneapolis, Minnesota, June, 1980, publ. by ASCE, 1981.
42. Swain, A., "Material Budget of Lake Chicot, Ph. D. disseration, University of Mississippi, Oxford, Miss., 190 pp., 1980.
43. Schnoor, J. L. and DiToro, D.M., "Differential Phytoplankton Sinking and Growth Rates: An Eigenvalue Analysis. Ecological Modelling, 9:233-245, 1980.
44. Shapiro, J., personal communication, 1982.
45. Smith, R.A., 1980. The Theoretical Basis for Estimating Phytoplankton Production and Specific Growth Rate from Chlorophyll, Light and Temperature Data, Ecological Modelling, 10:243-264, 1980.
46. Stefan, H. G., Cardoni, J.J., Schiebe, F. R., and Cooper, C. M., "A Model of Light Penetration in Lake Chicot," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, External Memorandum 174, Feb., 1982a.
47. Stefan, H.G., Dhamotharan, S., Schiebe, F. R., "Temperature/Sediment Model for a Shallow Lake," ASCE, Jour. of the Env. Engr. Div., Vol. 108, No. EE4, Aug, 1982b
48. Stefan, H. G., Cardoni, J. J., and Fu, A. Y., "Resqual II: A Dynamic Water Quality Simulation Program for a Stratified Shallow Lake or Rervoir: Application to Lake Chicot, Ark.," Project Report No. 209, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, 1982c.
49. Stefan, H. and Ford, D., "Temperature Dynamics in Dimictic Lakes," ASCE, Jour. of the Hydraulics Div., Vol. 101, HY1, Jan., 1975.
50. Swain, A., "Material Budgets of Lake Chicot," Ph. D. dissertation, University of Mississippi, Oxford, 190 pp., 1980.
51. Winter, J. C., "Numerical Simulation of Steady State Three-Dimensional Groundwater Flow Near Lakes," Water Resources Research, Vol. 14, No. 2, pp. 245-254, April, 1978.

TABLE 1. PHYTOPLANKTON MODEL COEFFICIENTS

Symbol	Meaning of Symbol	Value	Reference Source	Calib. Value	Comments
K_2	Phytoplankton Mortality/ Respiration Rate	0.096 day ⁻¹	DiGiano (1978)	.005T(°C)	Mineralization coefficient
		.05-.25 day ⁻¹	Schnoor (1980)		
		.005*T(°C)day ⁻¹	O'Connor et al (1973)	day ⁻¹	Endogenous Respiration
		0.1 day ⁻¹	Imboden (1978)		Mineralization rate
K_I	Half saturation coefficient for light	100 $\mu\text{E}/\text{m}^2\text{-sec}$ 400 k cal/m ² -day	Lake Data Jorgensen (1978); Gargas (1975)	100 μE m ⁻¹ sec ⁻¹	400 K cal/m ² -day = 45 $\mu\text{C}/\text{m}^2\text{-sec}$ (Combs conversion)
K_P	Half saturation growth coefficient for phosphorus	.0003-.0015 mg/l	DiToro (1980)	.015	Variable cell nutrient quota constant cell nutrient quota
		= .01 mg/l	O'Connor et al. (1973)	mg/l	
		= .01-.1 mg/l	Lewis & Nir (1978)		
K_r	Bottom release rate from sediments	.704 mg P/m ² -day	Golterman (1975)	0	Great Lakes, Oxygenated, winter
K_{rr}	Resuspension rate of non- available phosphorus (at bottom layer, gm SS/m ² -day)			0	
P_{equil}	Equilibrium concentration of available phosphorus			0.08 mg/l	
r_h	Phosphorus release fraction (hypolimnion)	> 0.6		1.0	
r_m	Phosphorus release fraction (mixed layer)	0.6	Nyholm (1978)	0.8	
W_c	Settling velocity of chlorophyll-a	0.1-0.6 md ⁻¹	Jorgensen et al. (1981)	0.4	Literature range, SCENEDESMUS
		.08-1.87 md ⁻¹	Schnoor (1980)		From Titman & Kilham (1976)
		< .1 md ⁻¹	Schnoor (1980)		Bluegreens & phytoflagellates
		1-3 md ⁻¹	Schnoor (1980)		Green algae
		.1-1.0 md ⁻¹	Schnoor (1980)		Diatoms
		.1-5 md ⁻¹	Lewis & Nir (1978)		
Y_{ca}	Yield coefficient (in cell) (chlorophyll-a to phosphorus)	0.3	Lake Data (1981)	0.6	
		1.19 to 16.3	Nyholm (1978)		
		1.0	Metro Waste Control Comm. (1977)		
η	Fraction of difference between P_{total} and $P_{\text{ortho-dissolved}}$ that may become available phosphorus	.20 .05-.40	Lee et al. (1978) McDowell et al. (1980)	.20	
ϕ	Yield coefficient (carbon to chlorophyll-a)	65	Canale & Vogel (1974)	30	Assumed average for optimal light and nutrients
		25.2	Nyholm (1978)		
		50	Jorgensen (1981)		
		13-135	Smith (1980)		

TABLE 2. COEFFICIENTS OF SUBMODELS

Submodel	Symbol	Coefficient	Range of Value Tested	Value Used
1. Temperature	a_a	Wind dependent vertical diffusion coeff.	28.0	28.0
	b	exponent in the wind dependent vertical diffusion coeff.	1.3	1.3
	a_h	wind dependent vertical diffusion coeff.	0.1	0.1
	γ_{in}	Plunging entrainment coefficient	1.8 - 5.0	1.8
2. Suspended Sediment		FRAC = fraction of inflow suspended sediment deposited instantly at Lake inlet	0.3 - 0.65 (Before Mar. 10) 0.8 - 1.0 (after Mar. 10)	0.35 before March 10 and 0.8 after Mar 10
		Particle diameter (DS)	0.8 μ - 4.0 μ	1.0 μ
3. Chlorophyll-a	w_c	Fall velocity (FVCHLA)	0.03 m/day - 1.0 m/day	0.04 m/day
	ϕ	Carbon chlorophyll ratio (YCCHLA)	25 - 60	30
	K_I	Half saturation coeff. for light (HSC)	75 $\mu E/m^2$ -sec to 100 $\mu E/m^2$ -sec	100 $\mu E/m^2$ -sec
	--	Threshold concentration value of chlorophyll-a	1 ppb - 5 ppb	3 ppb
	K_2	Respiration/loss coeff.	0.003 - 0.006/ $^{\circ}C$ -day	0.005 $^{\circ}C$ day
4. Dissolved ortho-phosphorus (Avail. Phosph.)	K_P	Half saturation coeff. for available phosphorus (HSCPA)	0.01 ppm - 0.02 ppm	0.015 ppm
	r_m	Release fraction of phosphorus (RFM) in the mixed layer	0.6 - 0.8	0.8
	r_h	Phosphorus release fraction of phosphorus in the hypolimnion (RFH)	1.0	1.0
	K_r	Bottom release rate (RR)	0	0
	Y_{ca}	Chlorophyll to phosphorus ratio (YCA)	300 - 700	600 (ppb/ppm)
	$P_{a, equill}$	Equilibrium conc. of available phosphorus (PAEQ)	0.08 ppm - 0.10 ppm	0.08 ppm
	5. Convertible Phosphorus (Non-avail. phosph.)	n	Fraction of convertible phosphorus in particulate (PNFRAC)	0.2 - .25
K_{rr}		Resuspension rate of non-available (mostly particulate) phosphorus	0	0 g SS/ m^2 day

TABLE 3. RMS Errors in RESQUAL II Model Applied to Lake Chicot

Parameter	Water Year		
	1977	1978	1979
Stage (ft)	0.43	0.49	0.76
Temperature (°C)	2.88	1.42	1.58
Suspended Sediment (ppm)	42.	94.	123.
Chlorophyll-a (ppb)	11.8	13.9	15.5
Available Phosphorus (ppb)	24.	27.	31.
Total Phosphorus (ppb)	146.	104.	199.
Secchi Depth (m)	0.17	0.10	0.13

TABLE 4. SUSPENDED SEDIMENT TRAP EFFICIENCIES

Water Year	Maximum Inflow (cfs)	Computed Apparent Trap Efficiency (%)	Observed (Estimated) Trap Eff.
1976-77	Actual	70.2	68
1977-78	Actual	59.9	56
1978-79	Actual	53.6	62

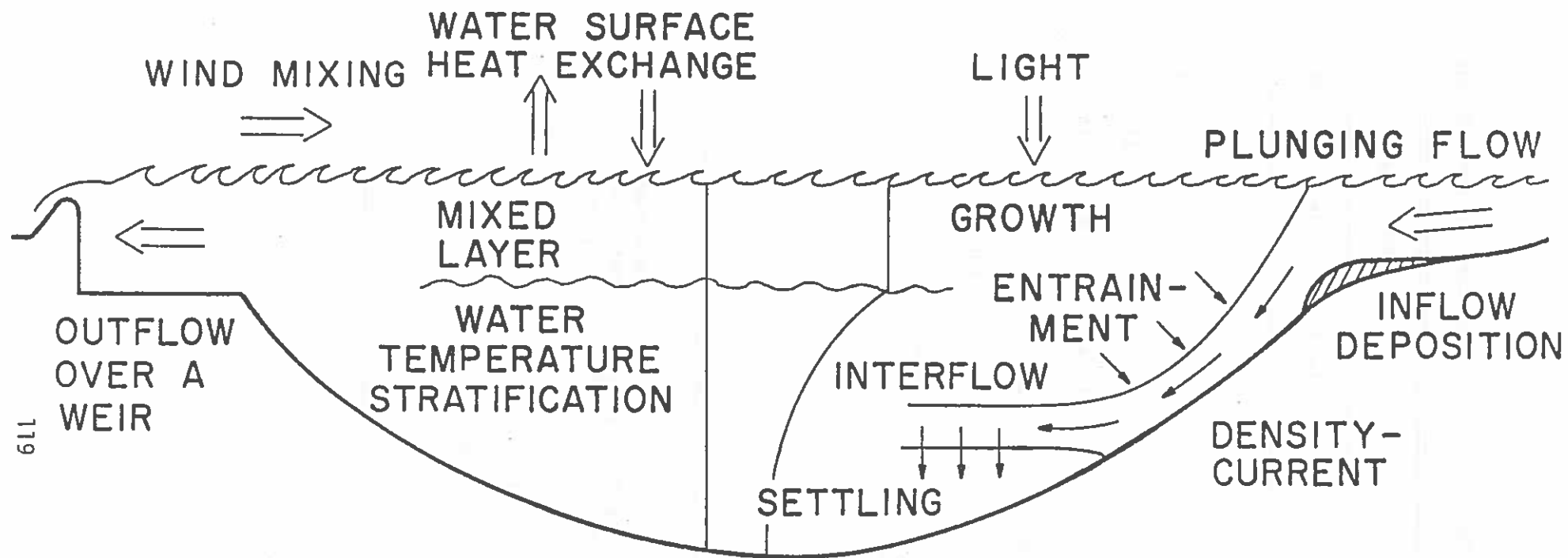


Fig. 1. Schematic of physical processes represented by model RESQUAL.

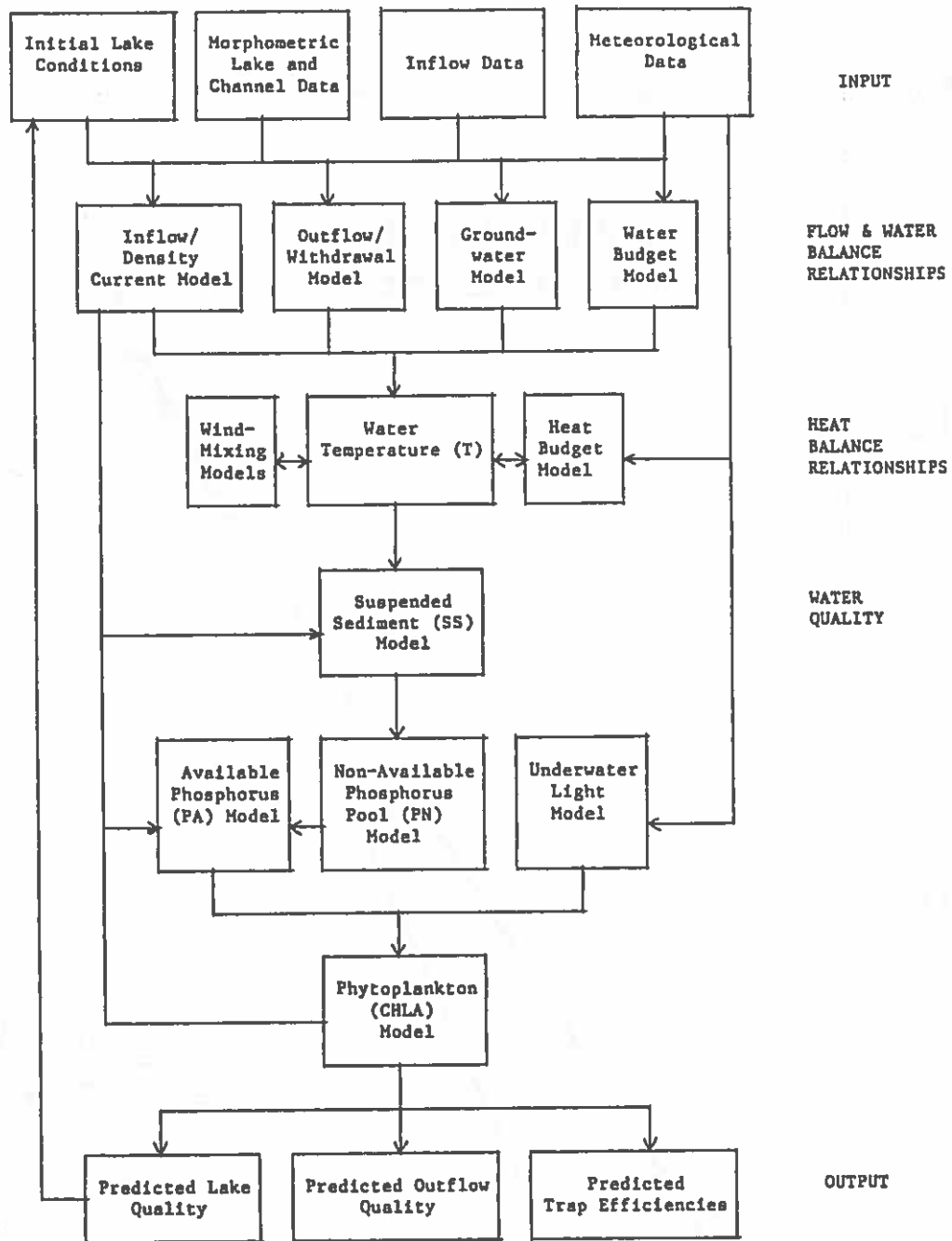


Fig. 2. Information flow in RESQUAL II.

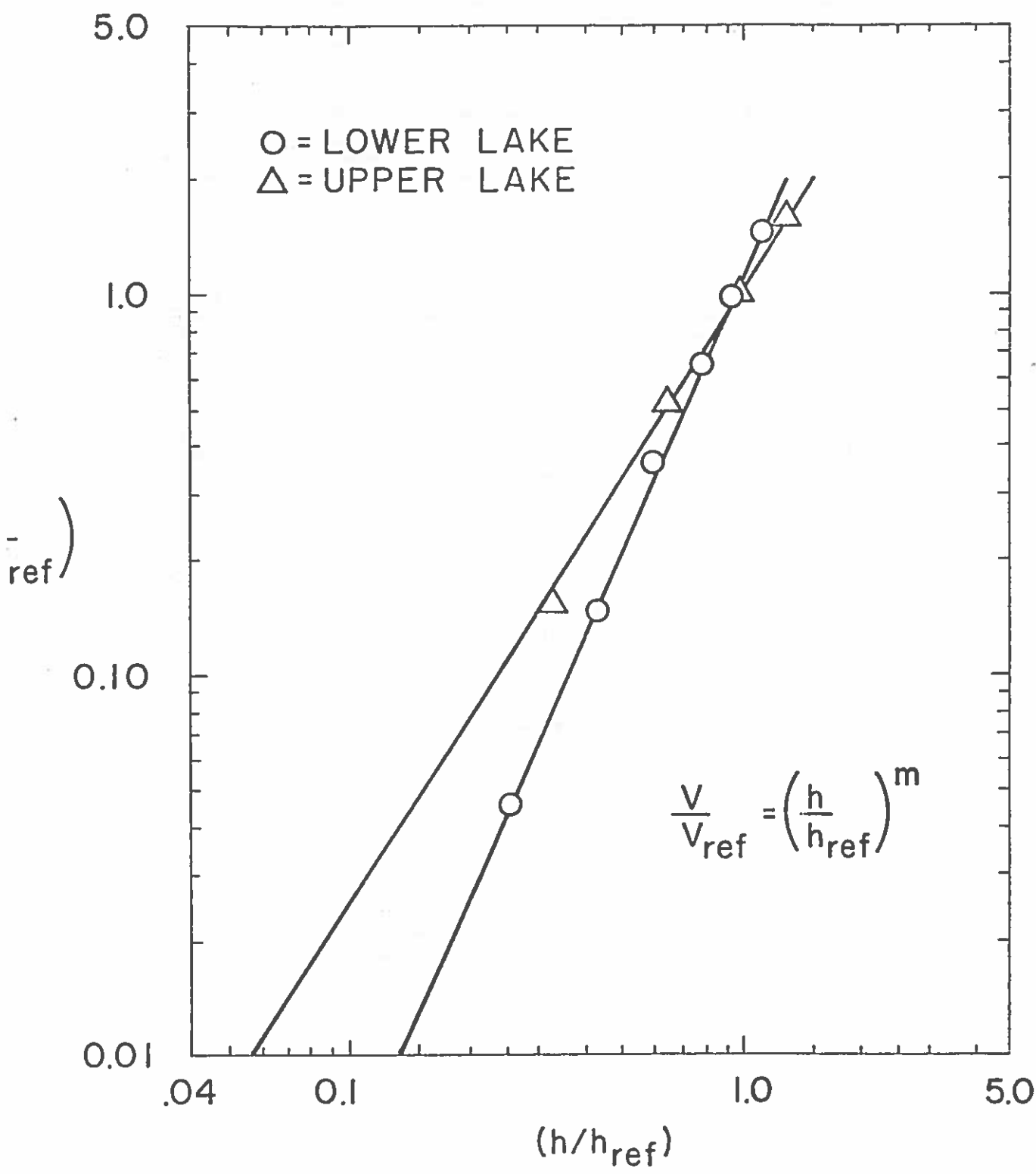


Fig. 3. Plot of morphometric equation for upper and lower Lake Chicot.

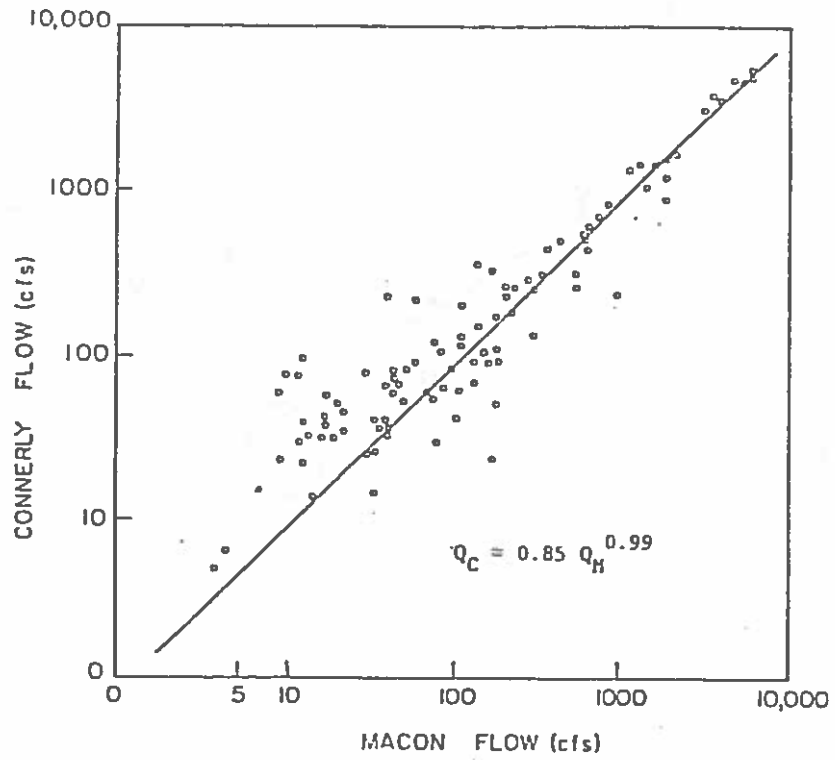


Fig. 4. Macon Lake and Connerly Bayou Discharge Relationship. (Swain, 1980).

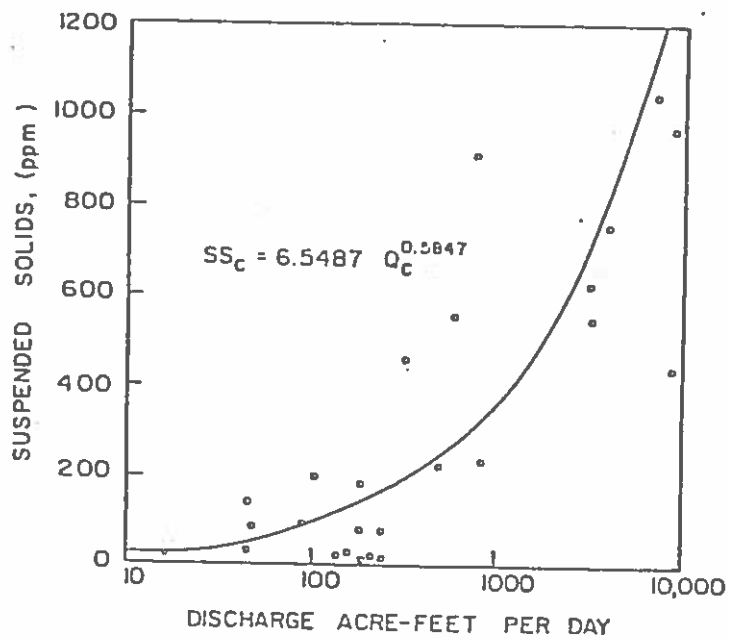


Fig. 5. Relationship between suspended solids (sediments) and discharge at Connerly Bayou. (Swain, 1980).

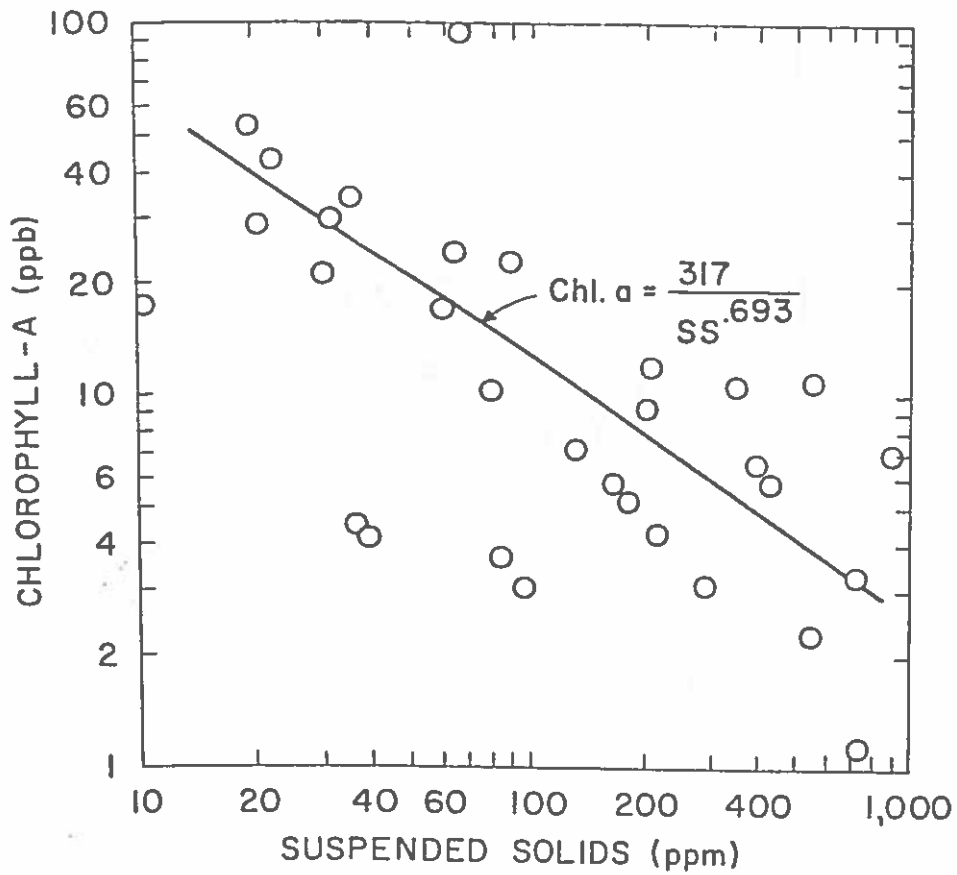


Fig. 6. Chlorophyll-a versus suspended solids in inflow to Lower Lake Chicot, USDA Station C-5.

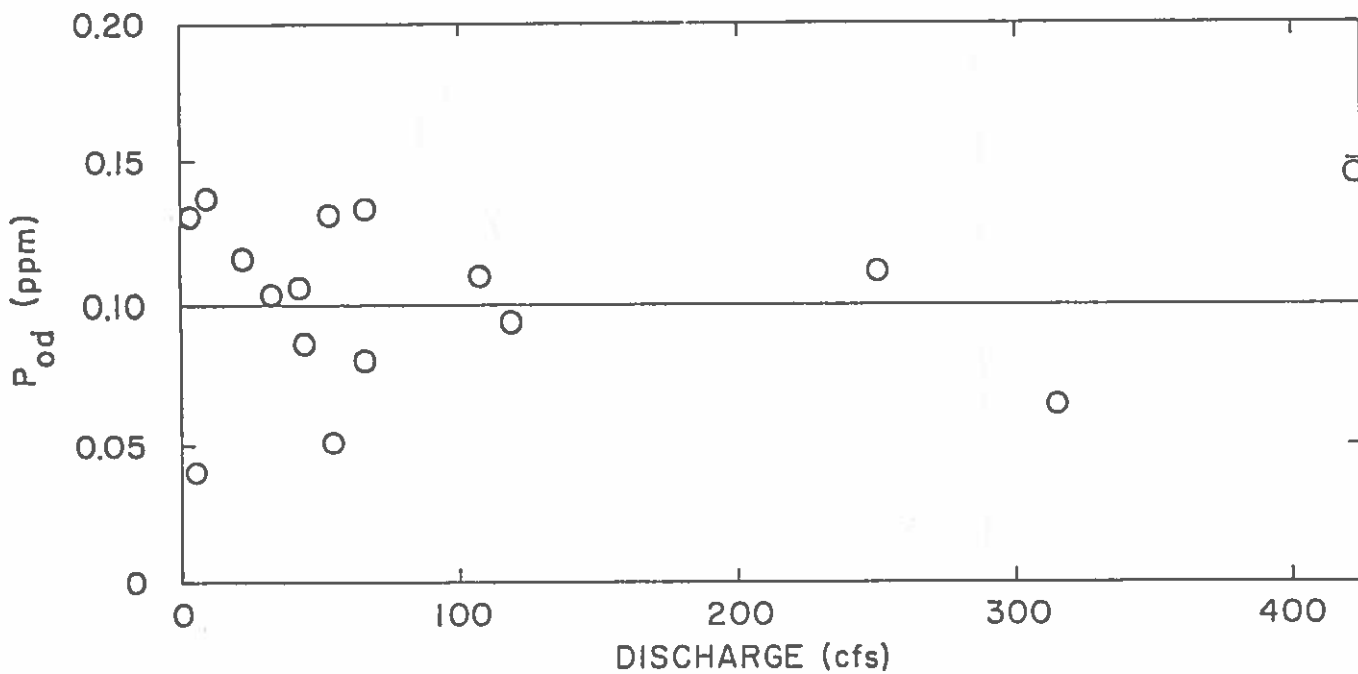


Fig. 7. Dissolved orthophosphorus concentration versus discharge into Lower Lake Chicot, USDA Station C-5.

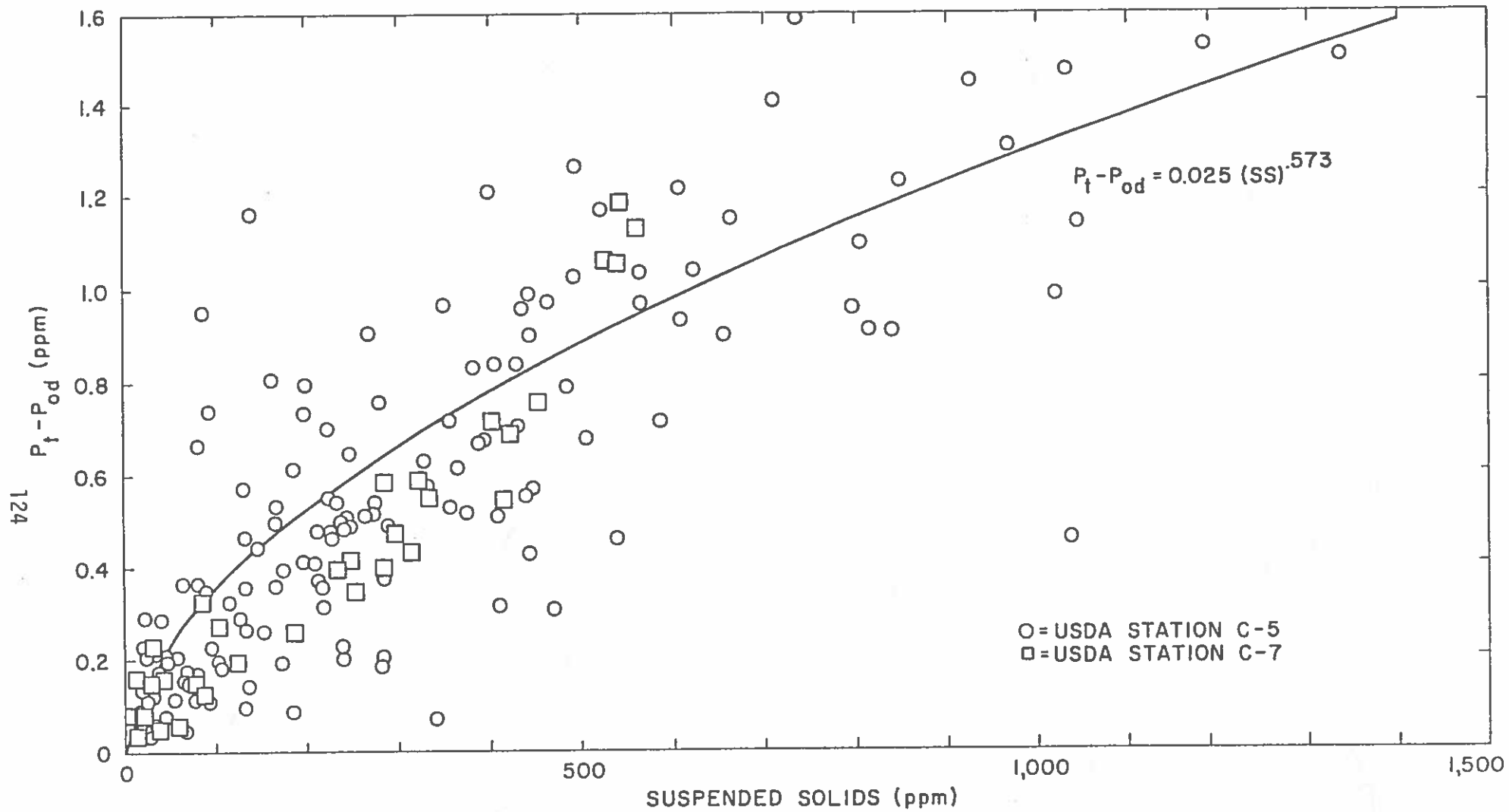


Fig. 8. Total phosphorus (P_t) minus dissolved orthophosphorus (P_{od}) versus suspended solids, lower Lake Chicout.

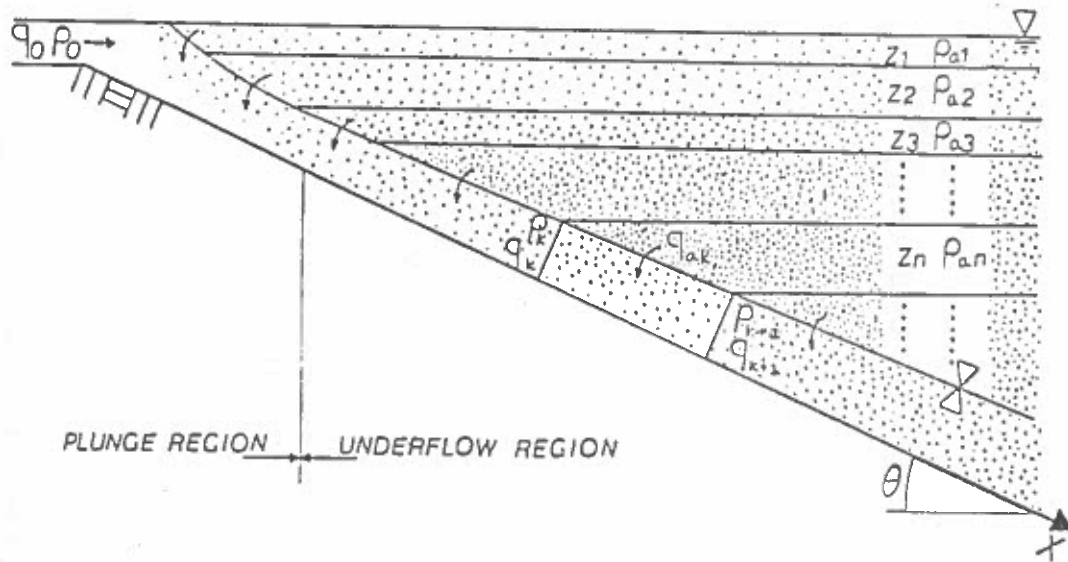


Fig. 9. Schematic of underflow in multi-layered lake.

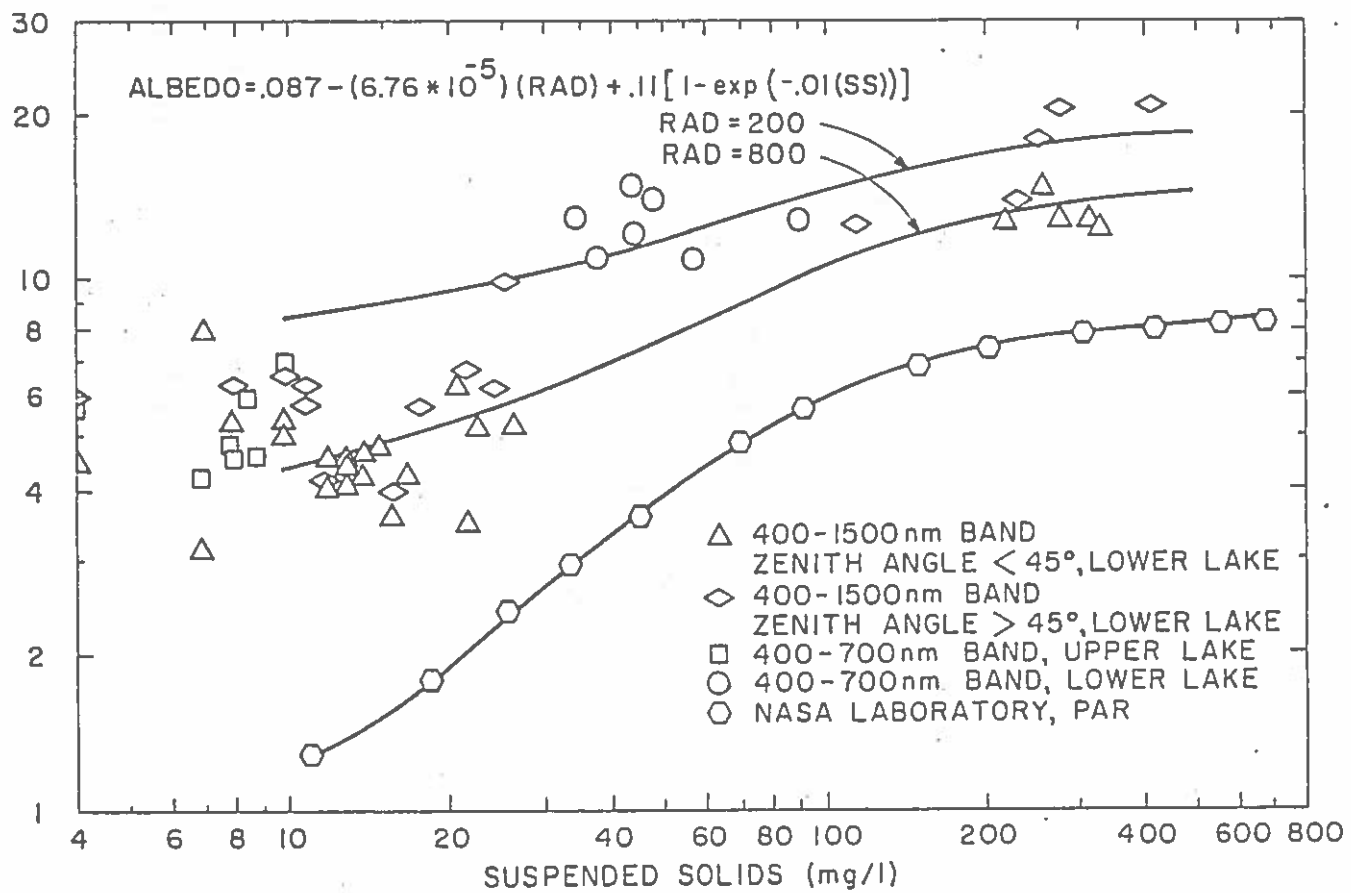


Fig. 10. Albedo in Lake Chicot (400 - 1500 nm band).

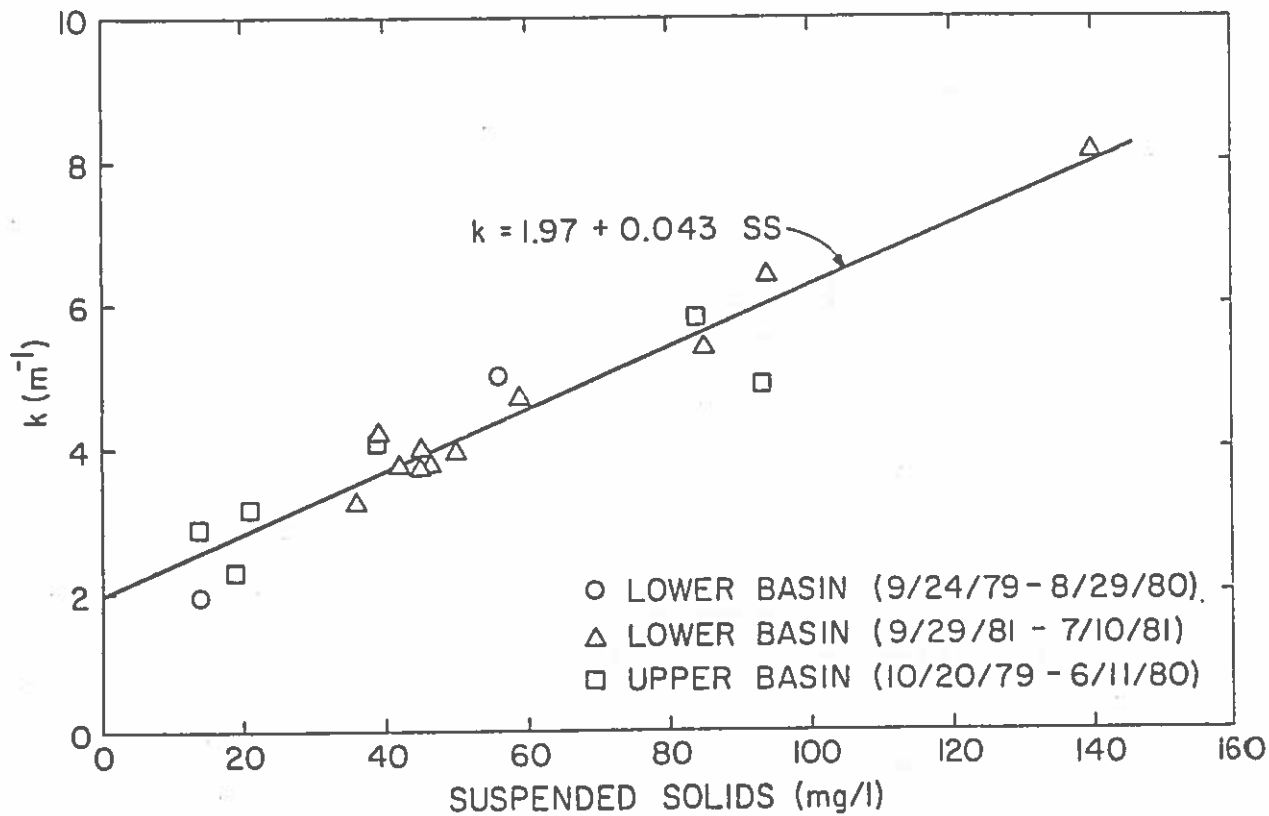


Fig. 11. Suspended solids versus attenuation coefficient ($k = k_{\text{parsph}}$).

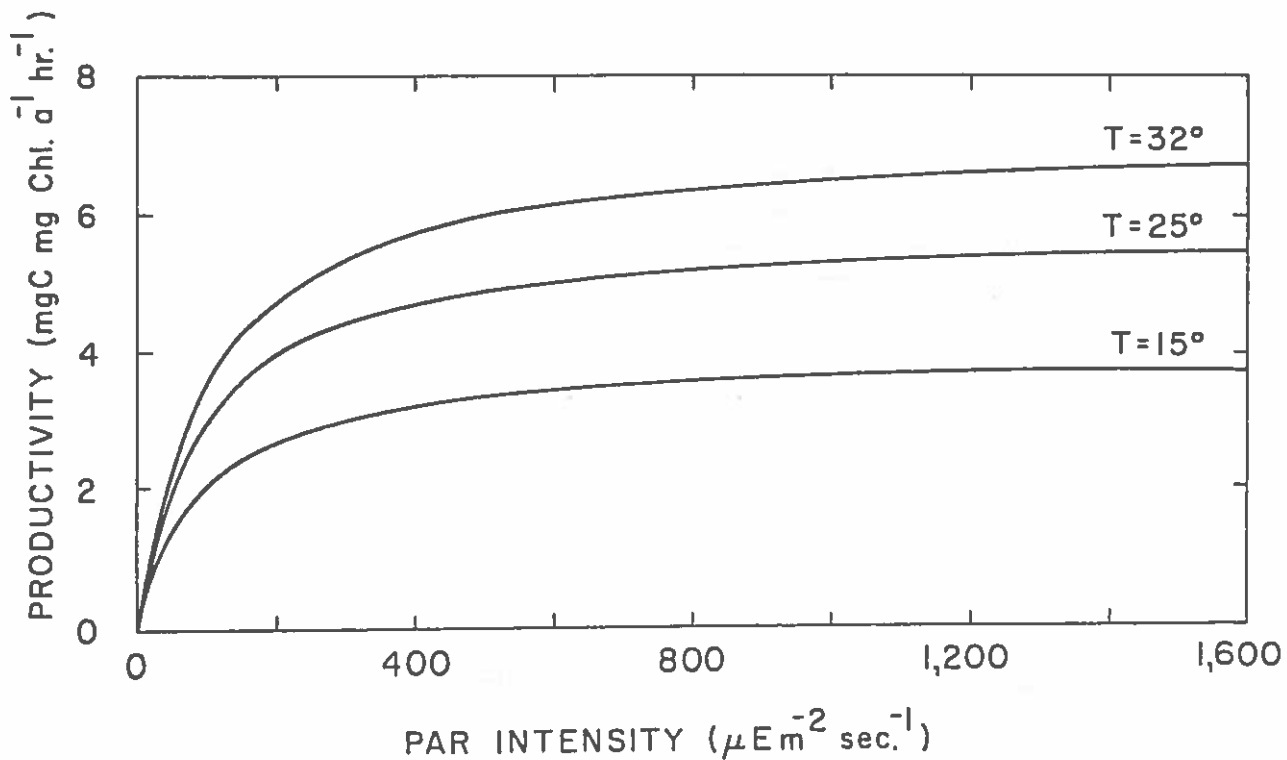


Fig. 12. Productivity rate versus PAR intensity and temperature relationship used in model.

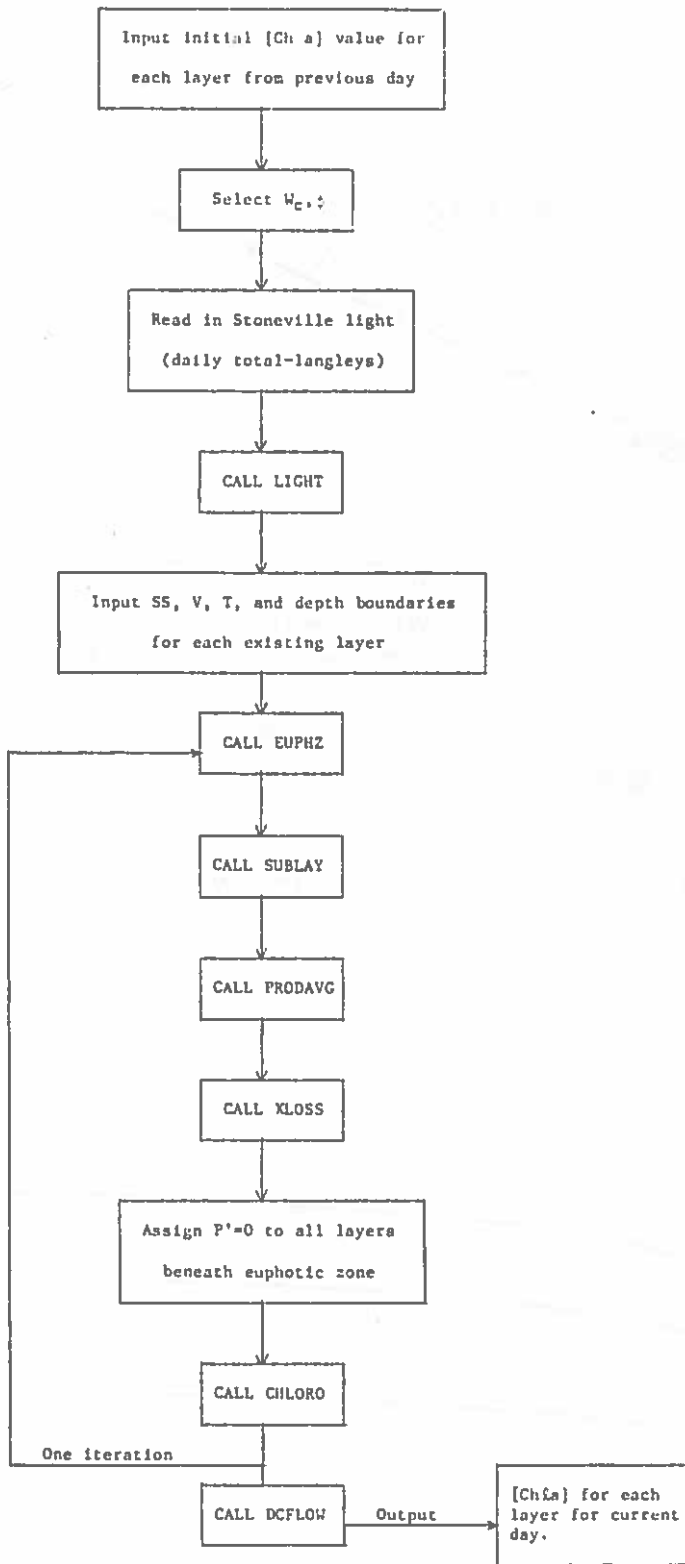


Fig. 13. Flow chart of chlorophyll-a model.

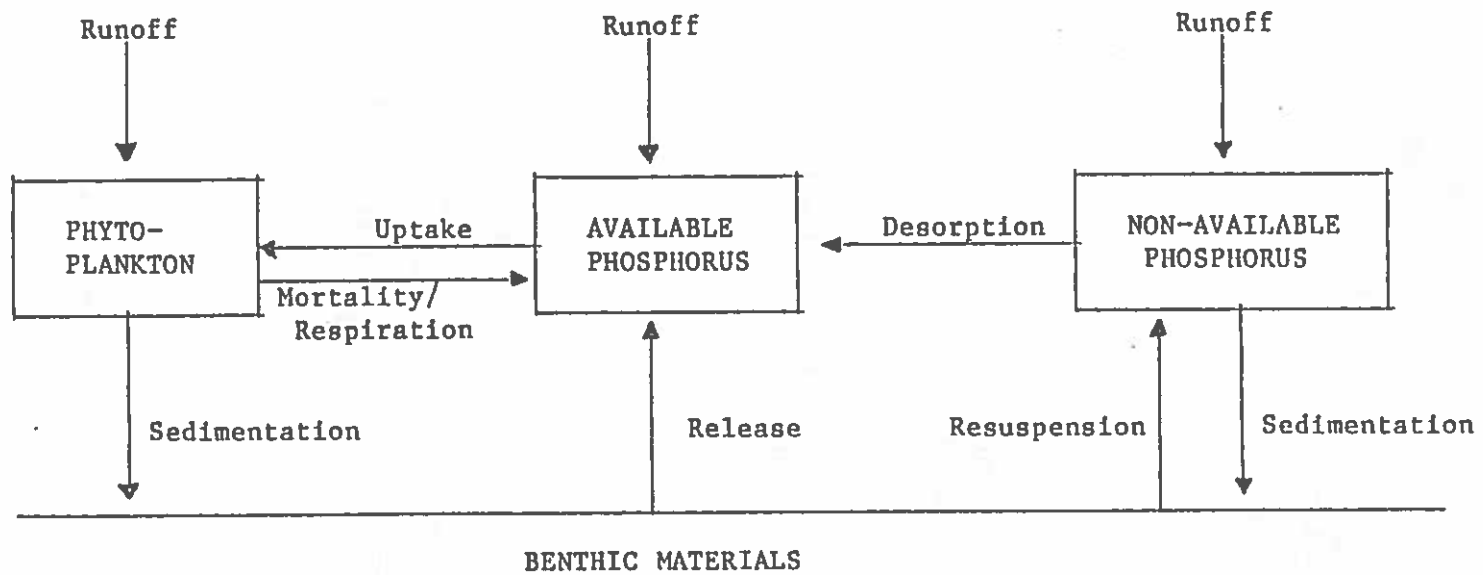


Fig. 14. Phosphorus Submodel.

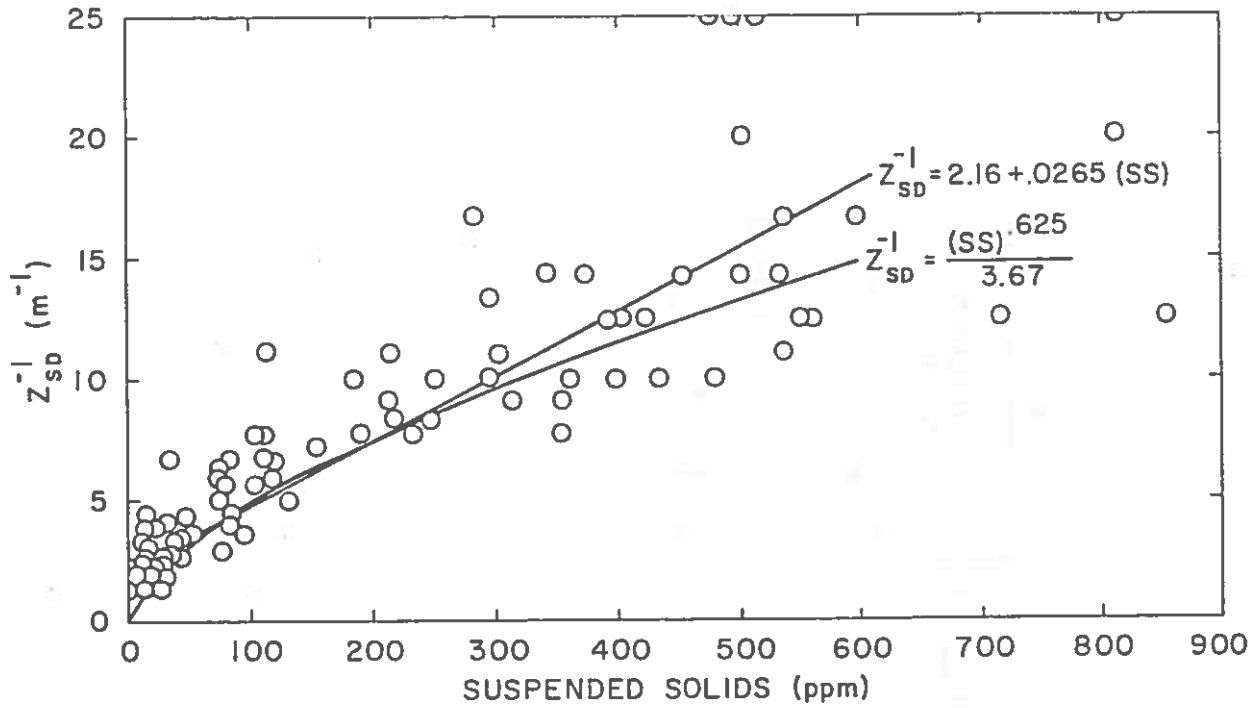


Fig. 15. Inverse of Secchi depth versus suspended solids concentration, Lower Lake Chicot.

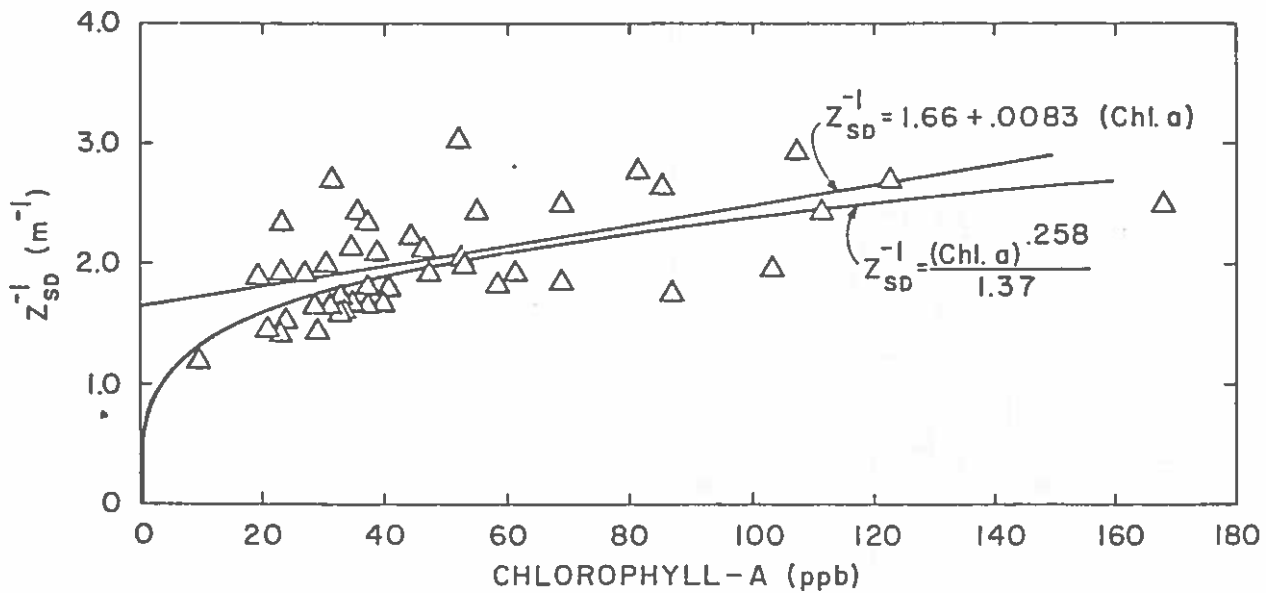


Fig. 16. Inverse of Secchi depth versus chlorophyll-a concentration, Upper Lake Chicot (SS concentration < \approx 45 ppm).

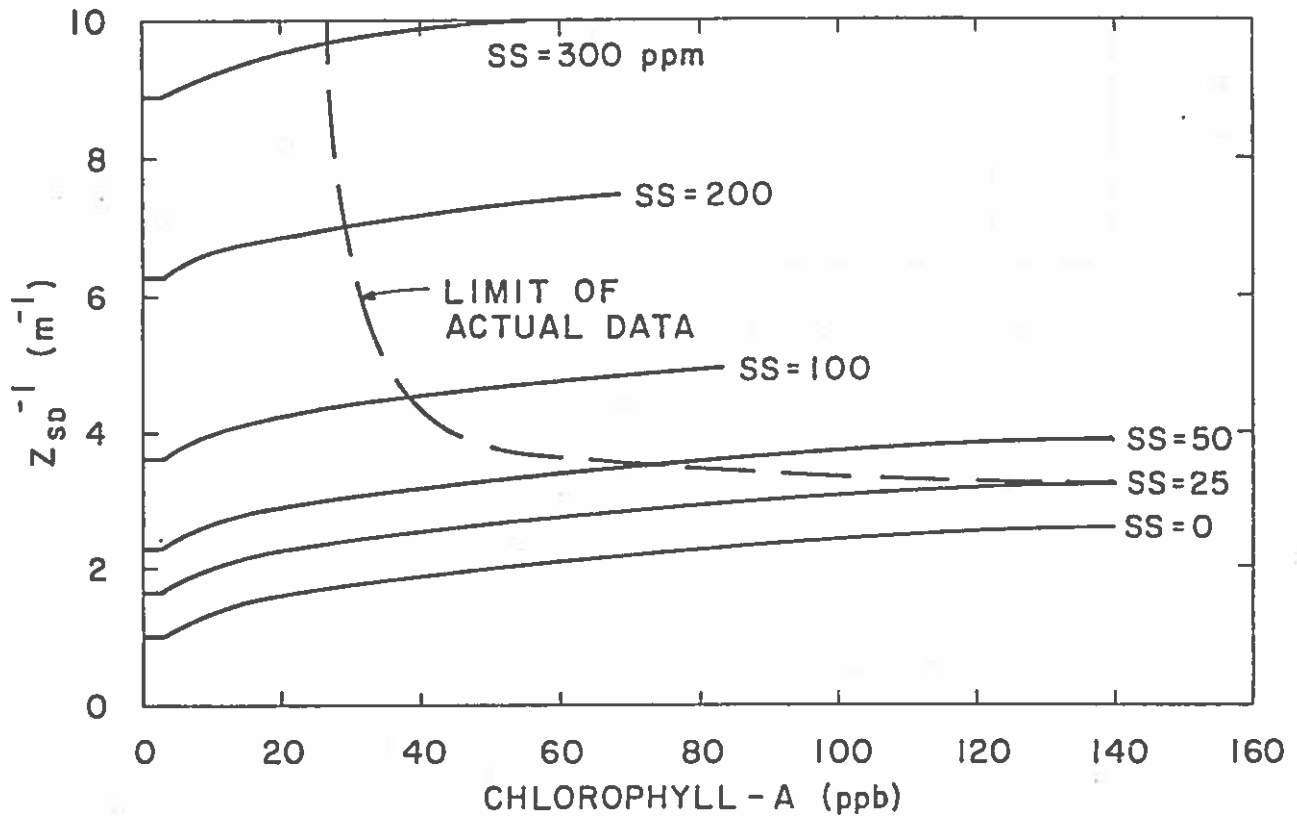


Fig. 17. Inverse of Secchi depth versus chlorophyll-a and suspended sediment concentration, proposed composite relationship for Lake Chicot.

LAKE CHICOT 1976/1977

COMPUTED AND MEASURED LAKE STAGES

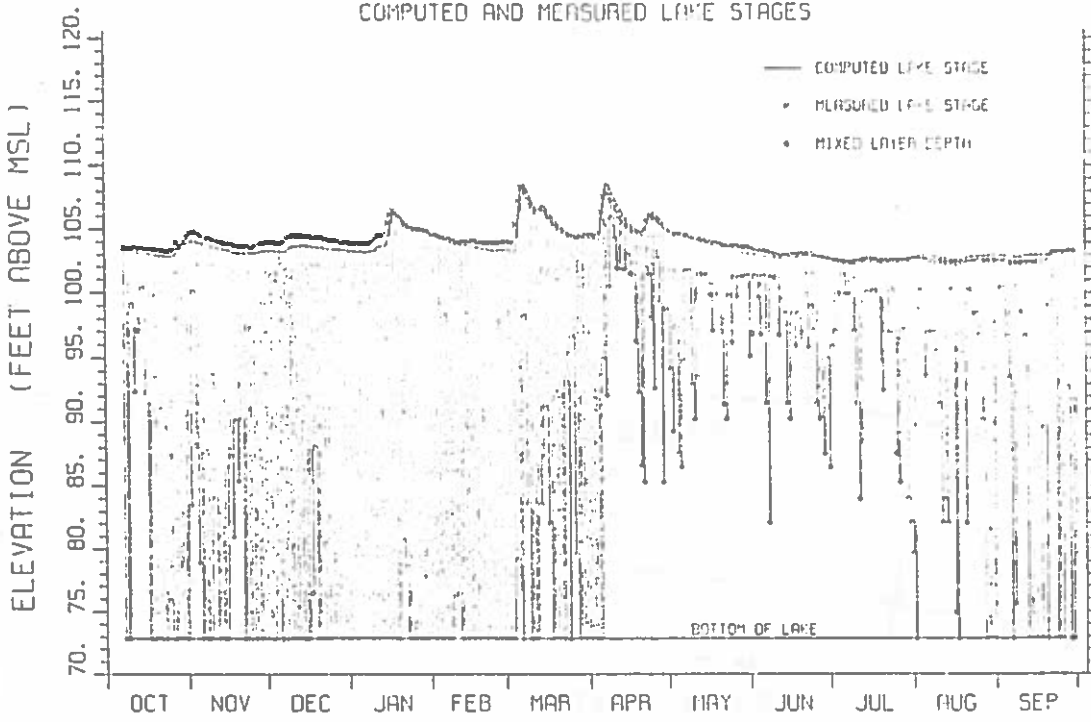


FIGURE 18

LAKE CHICOT 1976/1977

SURFACE TO 7-METER TEMPERATURE RANGE

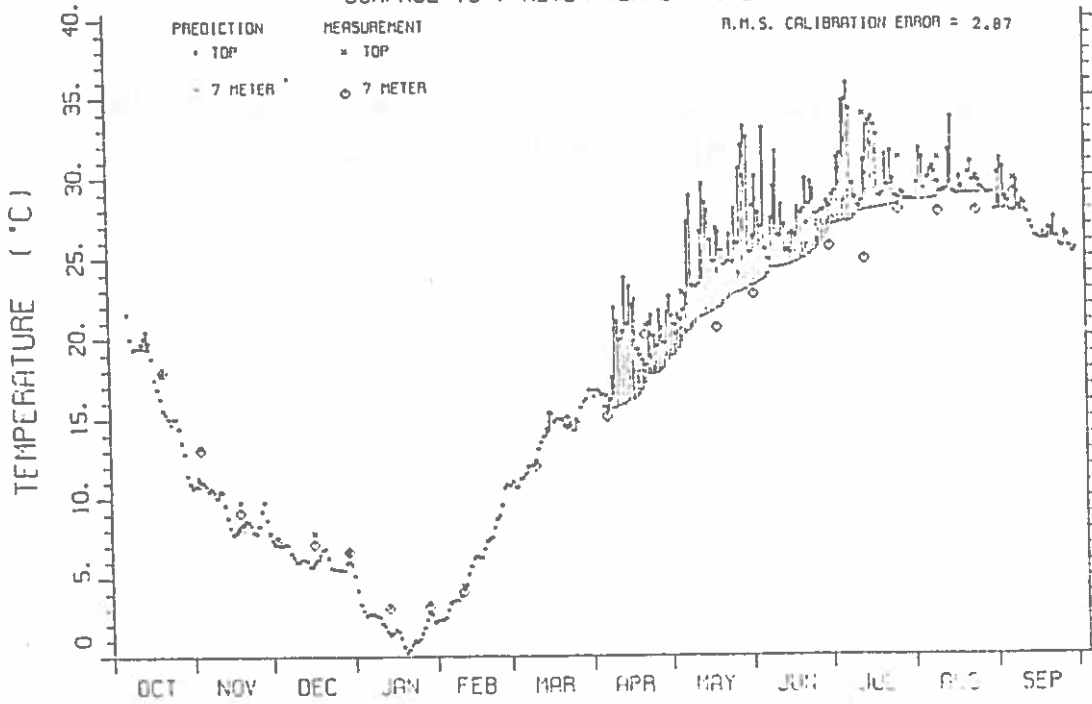


FIGURE 19

LAKE CHICOT 1976 / 1977

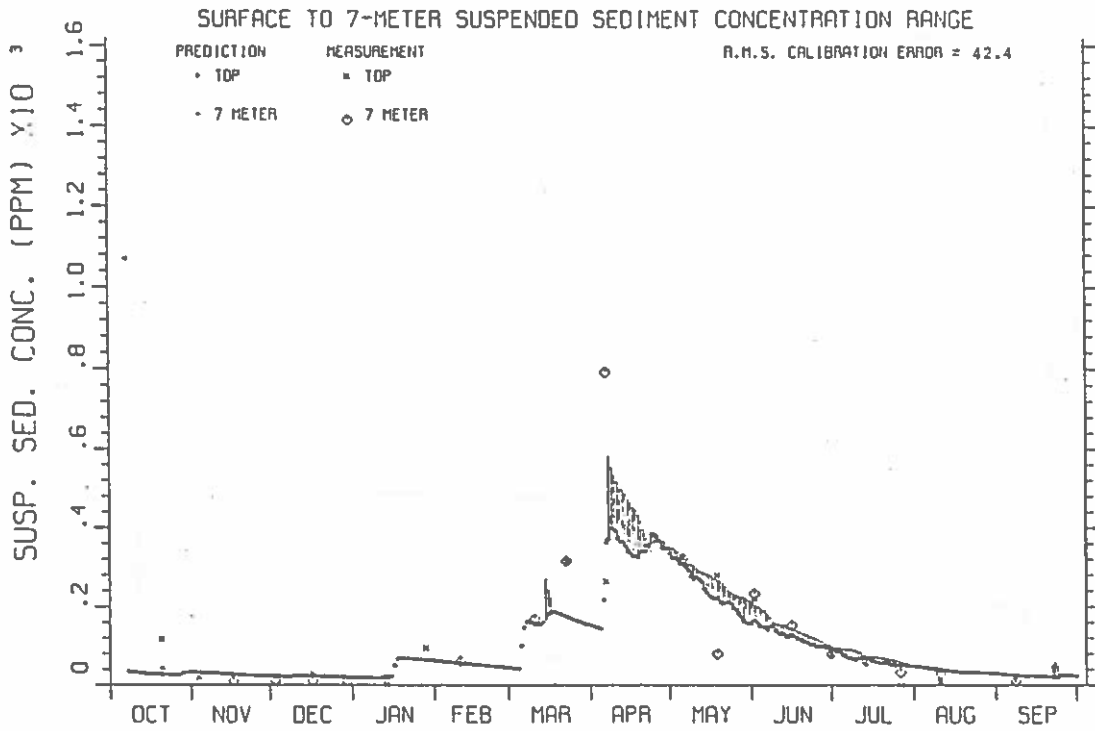


FIGURE 20

LAKE CHICOT 1976 / 1977

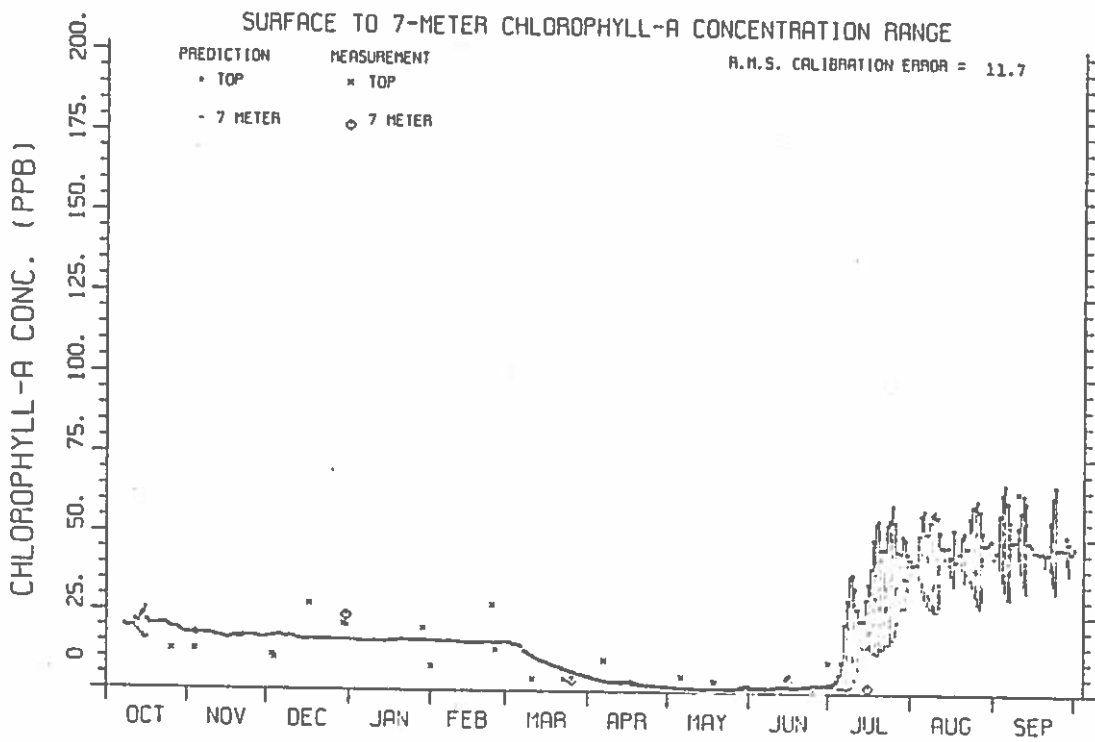


FIGURE 21

LAKE CHICOT 1976/1977

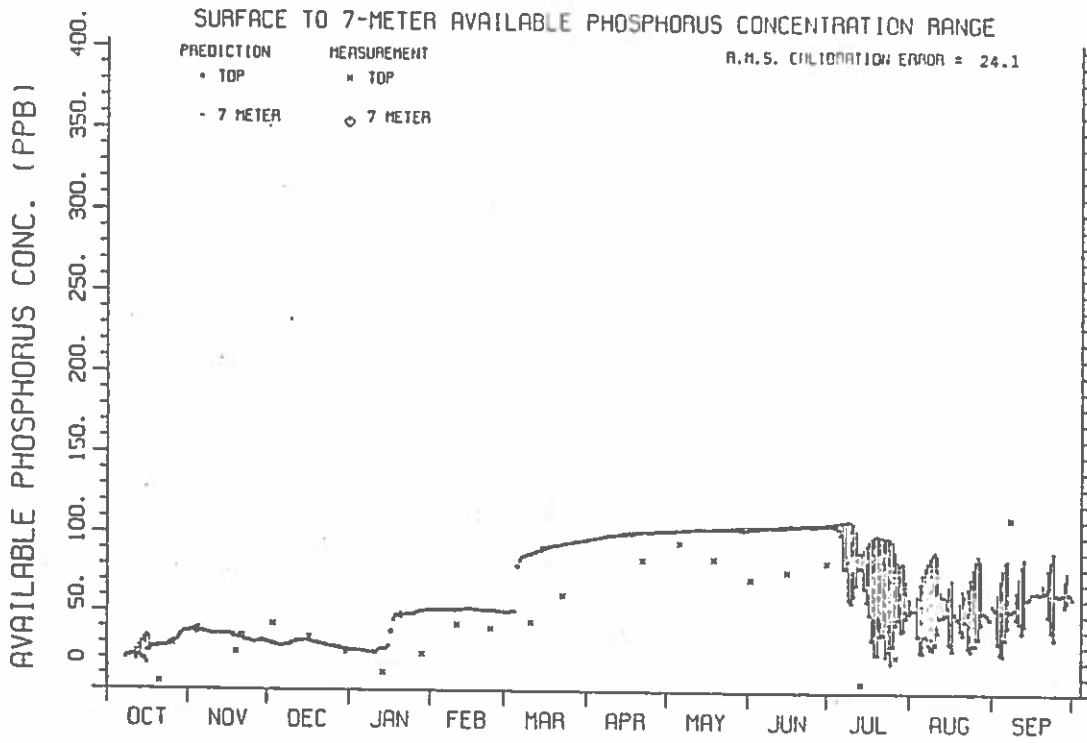


FIGURE 22

LAKE CHICOT 1976/1977

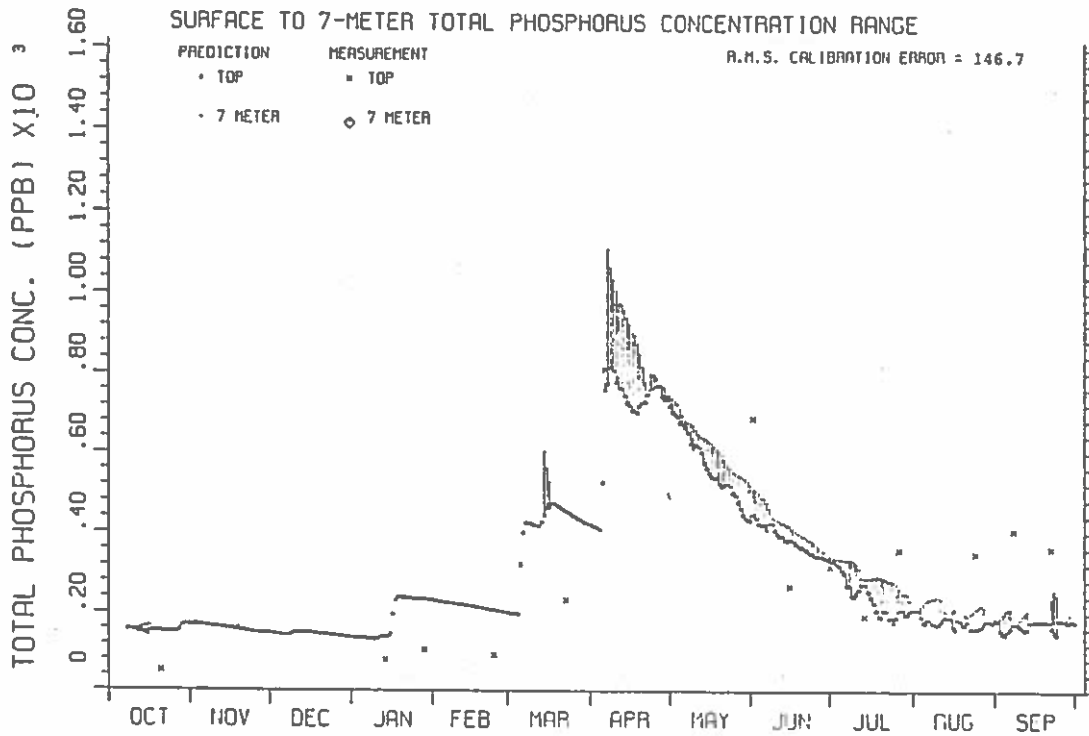


FIGURE 23

LAKE CHICOT 1976/1977

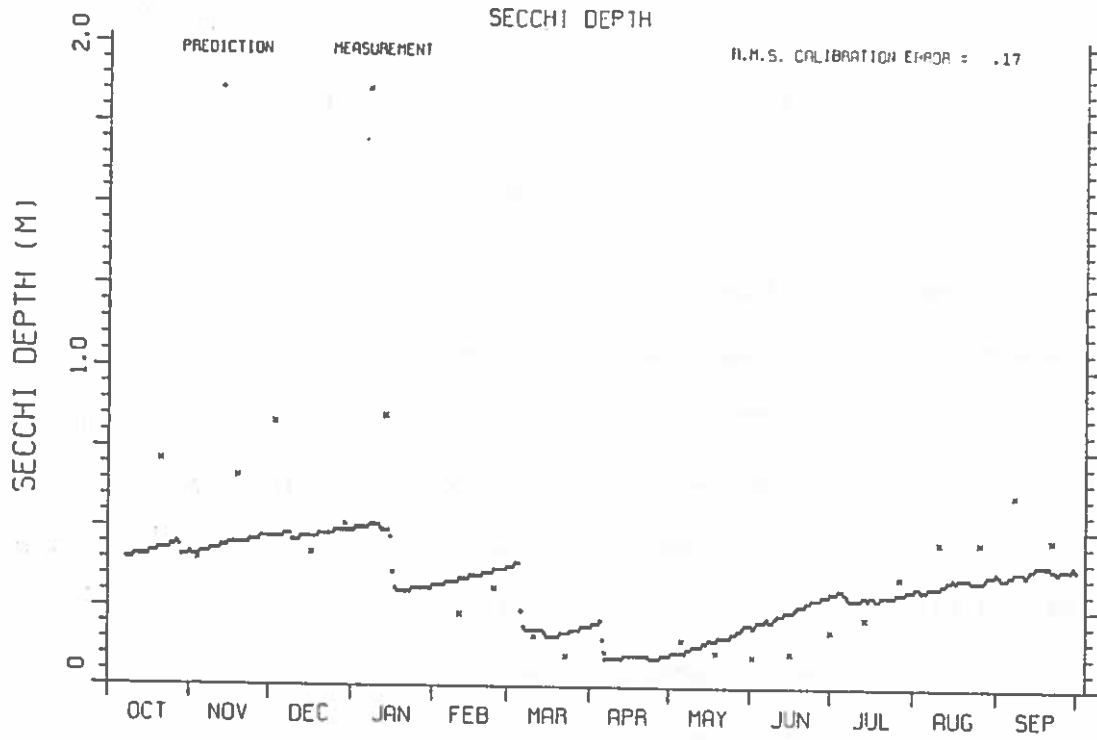


FIGURE 24

MANAGEMENT STRATEGY FOR LAKE CHICOT

R. Price, F. Schiebe, H. Stefan, and A. Fu¹

ABSTRACT

The Lake Chicot Pump Project was authorized and designed to improve the water quality at Lake Chicot by diverting turbid inflows from Connerly Bayou to the Mississippi River. The Connerly Bayou structure controls inflows to the lake while the lake inflow is controlled by the Ditch Bayou Structure. A math model was developed to predict the lake stage and water quality from Connerly Bayou inflows and outflows from Ditch Bayou. Several operational plans involving various inflows-outflows and lake stage were examined using the model. The effects of the operational strategies on the water quality ranged from a stable lake stage with good quality water to a fluctuating lake stage with poor water quality.

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INTRODUCTION

Lake Chicot, an oxbow lake formed by a cutoff of the Mississippi River approximately 400 years ago, is located in Southeastern Arkansas. Fishery investigations conducted in the 1950's determined that fish and wildlife of the lake had suffered a decline due to turbid inflow and excessive stage fluctuation of the lake. These were brought about by extensive enlargement of the Connerly Bayou watershed, the major tributary to the lake. The lake was divided by a causeway in the 1930's creating a northern and a southern basin. Currently, the northern portion is high in productivity and low in inorganic suspended solids while the south lake is low in productivity and high in inorganic suspended solids (Cooper and Bacon, 1981).

In 1963, Congress authorized the U.S. Army Corps of Engineers to investigate the water quality problems at Lake Chicot and provide mitigation for the degraded water quality (USAE, 1966). This resulted in the construction of 3 hydraulic structures (pump plant and two gated structures) to divert turbid inflows away from the lake and stabilize the lake stage. The operation of the project is to begin in 1985.

In order to operate the 3 structures according to the authorized project purposes, an operational plan must be developed. A water quality model of Lake Chicot was formulated and used to examine the effects of various operational plans on the lake water quality and stage fluctuation.

PROJECT DESCRIPTION

Lake Chicot, located in Southeastern Arkansas, is a Mississippi River oxbow lake. The major tributary to the lake is the Connerly Bayou watershed with an approximate area of 350 square miles (900 km). The lake itself is divided by a dam (with sluice gates) into a northern and a southern basin. Currently, the northern basin exhibits no problem with suspended sediments. The southern basin which exhibits a problem with excessive turbidity has an average width of 0.5 mile (0.8 km) and is approximately 11.25 miles (18 km) long. Volume of this lake is 52,802

acre-feet ($65.1 \times 10^6 \text{m}^3$) at an average stage of 103.0 feet NGVD.

The U. S. Department of Interior, Fish and Wildlife Service was asked to provide criteria to mitigate damage to the fish and wildlife of Lake Chicot. In their investigations in 1965 (USDI, FWS, 1965) water quality conditions were defined by levels of turbidity. A turbidity level of 22 ppm or less was essentially a "clear" lake while in excess of 100 ppm was a "muddy" lake. Between 25 and 100 ppm was defined as intermediate. This classification scheme relates also to the volume of inflow (Figure 1) in that inflow equaling or exceeding 50% of the volume of the lake will create a "muddy" condition. Inflows less than 15% of the lake would maintain a clear lake and inflows between 15% and 50% would create an "intermediate" lake. In the report it was determined that to maintain an effective fishery management program the lake had to remain clear 5 out of 6 years. To achieve this goal, it was recommended that a diversion capacity of 6,800 cfs ($192 \text{ m}^3/\text{sec}$) be adopted for the Lake Chicot Pumping Plant. Further refinement of the hydrologic data base and additional data indicated 6,500 cfs ($182 \text{ m}^3/\text{sec}$) to be an acceptable design criteria.

There are three hydraulic structures involved in the operation of this project. Inflows to the lake from Connerly Bayou are controlled by two 5 X 4 feet (1.5 by 1.2 m) sluice gates in the Connerly Bayou structure. A 300 foot (90 m) weir at elevation 116 feet NGVD provides relief for discharge in excess of the diversion capability of $6,500 \text{ ft}^3/\text{sec}$ ($182 \text{ m}^3/\text{sec}$). The turbid inflows will be diverted away from Lake Chicot by closing the Connerly Bayou gates and directing the water to the Lake Chicot Pumping Plant and then the Mississippi River. When stages on the Mississippi River are higher than the diverted flows, a combination of ten-600 ft^3/sec ($17 \text{ m}^3/\text{sec}$) and two-250 ft^3/sec ($7 \text{ m}^3/\text{sec}$) pumps can be used to achieve the total plant capacity of $6,500 \text{ ft}^3/\text{sec}$ ($182 \text{ m}^3/\text{sec}$). A gated section will also allow gravity flows up to $12,500 \text{ ft}^3/\text{sec}$ ($350 \text{ m}^3/\text{sec}$) through the structure when stages permit.

Lake Chicot stage is controlled by the Ditch Bayou structure. Two 8 X 5 foot (2.4 by 1.5 m) sluice gates allow for discharge out of Ditch Bayou. The 200 foot (61 m) weir has a crest at 106 feet NGVD to allow flood flows out of the lake.

LIMNOLOGICAL INVESTIGATIONS

Initial monitoring of the water quality was begun in 1976 under an interagency agreement between the Corps of Engineers and the USDA Sedimentation Laboratory in Oxford, Mississippi. Because of the extensive agricultural watershed and its relation to the turbidity problem the USDA had a prime interest in this project. Monitoring was designed to describe baseline biological processes occurring in Lake Chicot.

Investigation of the effects of the turbidity on the biological productivity by Cooper and Bacon (1981) indicated the southern basin at Lake Chicot to be light limited by excessive suspended solids. This verification that turbidity was affecting the biological production was essential to formulation of alternatives utilizing the hydraulic structure. Work accomplished by earlier hydraulic models resulted in a water quality model utilizing version of RESQUAL II. The individual accomplishments leading up to the current version are published elsewhere (Dhamotharan et al, 1978; Dhamotharan, 1979; Stephan et al, 1980; Swain, 1980).

MODEL DESCRIPTION

The mathematical model RESQUAL II is a physically-based process-oriented model calibrated and verified for Lake Chicot. Three years of observed data (1976 to 1979) were used in the verification process. Input to the model consists of daily climatological data (precipitation, relative humidity, temperature and solar radiation) morphometric data (stage, lake volume and area) and inflow-outflow data (daily discharge, suspended sediments, outflow channel geometry, etc.).

The output of the model can be either tabular or graphic. Tabular results are required for computing model statistics such as minimums and maximums. However, to evaluate the effects of an operational scheme for a five-year period, the graphic output is more beneficial. Currently, the model predicts temperature structure, suspended sediment concentration, phosphorus (available and total), secchi disc depth, chlorophyll a and inflow and outflow discharges.

MANAGEMENT STRATEGY

The water quality, particularly the turbidity, of Lake Chicot to a large extent is dominated by inflows from Connerly Bayou. The stage of Lake Chicot is controlled by the Ditch Bayou structure. Since some outflow from the lake is desired to maintain water supply downstream (Ditch Bayou), some inflow to Lake Chicot is required. The operational plan, therefore, must include instructions for both Connerly Bayou and Ditch Bayou structures and criteria for selecting acceptable water for inflow and releases from the lake. This water management plan, therefore, must contain provision for quality as well as quantity of inflow to control the water quality of Lake Chicot.

The model developed to investigate various plans incorporated the water quality of the lake as driven by meteorological conditions and inflows. It has been used to examine several schemes, with the major difference being alteration of inflow and outflow criteria and meteorological conditions. The objective was to optimize outflows from Ditch Bayou while maintaining a relatively stable lake stage and an essentially clear lake.

Several specific operational plans have been examined (Table 1). When observed meteorological conditions were used in the model with inflows at Connerly Bayou limited by the stage of the lake, i.e. (when lake stage = 106 feet NGVD, divert all inflows to the river) and outflows at Ditch Bayou ranged from 75 cfs (0.2 m³/sec) to 150 cfs (4.2 m³/sec) lake stage for the 5 water year period from 1976 to 1981 varied between 97 and 107 feet NGVD while the suspended solids varied from 6 to 85 mg/l.

In this case, both stage and water quality suffer. If the inflows to the lake is limited by the suspended solids of the inflow or the lake then the water quality improves, however, excessive stages occur on the lake (109 feet NGVD). By adding a criteria for maintaining the lake stage at 106 feet NGVD, the stage fluctuates between 106 and 103 feet NGVD and the suspended solids range from a maximum of 67 to 21 mg/l; however, there is no outflow from Ditch Bayou. If the outflow at Ditch Bayou is increased to 50 cfs from 1 April to 30 September of each year the stage

fluctuation is unaffected but the water quality suffers (maximum suspended solids increase to 35 mg/l). If the discharge is increased to 75 cfs stage fluctuates from 101 to 107 feet NGVD while the suspended solids increase to 82 mg/l. From this series of simulations it appears that a water quality criteria along for operation of the structure is not beneficial. A combination of stage and water quality criteria yields a more acceptable plan.

Another series of simulations utilizing diversion of inflows with a lake stage at or above 106 feet NGVD and also diverting all inflows in excess of 175 cfs produced 2 schemes revealing the impacts of increased discharge from Ditch Bayou while maintaining acceptable water quality. With a discharge of 75 cfs from 1 April to 30 September, the lake stage varied from 102 to 106 feet NGVD with a maximum suspended solids concentration of 35 mg/l. If the discharge is increased to 150 cfs, stage fluctuates from 93 to 106 feet NGVD with no impact on the suspended solids.

These model simulations have been based on 5 years of water quality data, however, over a longer period of time more extreme events do occur. With this in mind, modification to the meteorological data base was made. The first case involved simulation of a drought in which there was zero precipitate on the lake and only base flow (7.4 cfs) enters the lake from April 1 to September 30. With discharge of 150 cfs from Ditch Bayou year round as the only constraint, the lake stage fluctuates from 109 to 93 feet NGVD and suspended solids vary from 182 to 2 mg/l. When the 106 feet NGVD lake stage criteria is added and the Ditch Bayou discharge is reduced to 75 cfs, the stage fluctuation decreases from 16 feet to 10 feet (107 to 97) and the maximum suspended solids improves to 117 mg/l. If the Ditch Bayou discharge is further reduced to 25 cfs even more improvement occurs (stage ranges 108-102 suspended sediment 109 to 8). However, the best management scheme involved adding the suspended solids criteria that if the lake or inflow exceeded 25 mg/l, inflows were diverted. Stage fluctuation was 108 to 102 feet NGVD with a maximum suspended solids concentrate of 65 mg/l.

The last case examined utilized a simulated storm which moved across the watershed from 1 September to 3 September creating 2"/day of runoff with a maximum discharge of 17,049 cfs on 3 September. All flows extend the lake. The outflow from Ditch Bayou was 150 cfs. The maximum stage reached 114 feet NGVD with a maximum suspended solids of 1,502 mg/l. If the discharge from Ditch Bayou was reduced to 75 cfs and the 106 feet NGVD lake stage criteria was in force, the maximum stage would have been 115 feet NGVD with a suspended solids concepts of 1885 mg/l. The effects of such a storm in September would last for nine months or better.

The results of these simulations indicate the relationship among the inflows, outflows, stage of the lake and the water quality of the lake. With some operational schemes some considerations are scarificed at the expense of others. Because of the complex relationships among the constituents, a definite operational plan has not been agreed upon.

The model will also serve as a management tool for operation of the structure in a "near" real time mode. A typical example would be a case where the diversion capacity of the pump plant is reached and more rain is predicted over the watershed. By imparting existing conditions and predicted runoff, it may be possible to suspend releases at Ditch Bayou to achieve more dilution of turbulent inflow to Lake Chicot, thereby, minimizing the impact. This mode of operation will require near real time data as supplied by the satellite data collection system.

CONCLUSION

The use of the Lake Chicot Water Quality Model to predict the water quality of Lake Chicot under various operational schemes has revealed several important management aspects of Lake Chicot:

a. The water quality criteria can not be used alone in defining operation conditions for the project. A combination of stage criteria and/or outflow criteria is required to both improve the water quality and reduce extreme fluctuation of stage.

b. Discharge out of Ditch Bayou must be limited to certain degree since the simulation with higher discharge lowered the lake stage excessively.

c. Limiting the inflow to 175 cfs and outflows to 75 cfs during the 1 April to 30 September period does not lower the lake stage excessively but in some years may go below 102. Higher inflows (above 175 cfs) appears to be detrimental to the water quality.

d. During extreme hydrological conditions (i.e., drought, flood) modifications of operational plan may be necessary to lesser the impact on the water quality.

REFERENCES

- COOPER, C. M. AND E. J. BACON. 1981. Effects of suspended sediments on primary productivity in Lake Chicot, Arkansas in Proceedings, Symposium on Surface Water Impoundments, June 1980. Minneapolis, Minnesota. American Society of Civil Engineer. New York.
- DHAMOTHARAN, S., STEFAN, H. G. AND F. R. SCHIEBE. 1978. Prediction of post-construction turbidity of Lake Chicot, Arkansas. Proceeding, Intermediate Symposium on Environmental Effects of Hydraulic Engineering Worker, Knoxville, Tennessee.
- DHAMOTHARAN, S. 1979. Mathematical model for temperature and turbidity stratification dynamics in shallow reservoir. Ph.D. thesis. University of Minnesota, Minneapolis, MN.
- STEPHAN, H. G., S. D. DHAMOTHARAN AND F. R. SCHIEBE. 1980. Temperature/sediment model for a shallow lake. J. Environ. Eng. Div. Am. Soc. Civ. Eng. 108 (EE4) 750-765.
- SWAIN, A. 1980. Material budgets of Lake Chicot, Arkansas. Ph.D. thesis. University of Mississippi, Oxford, Mississippi.
- U. S. ARMY ENGINEER DISTRICT, Vicksburg. 1966. Review Report Lake Chicot, Arkansas, Vicksburg District.
- U. S. DEPARTMENT OF INTERIOR. 1965. Fish and Wildlife Service, Letter Report, Lake Chicot Project.

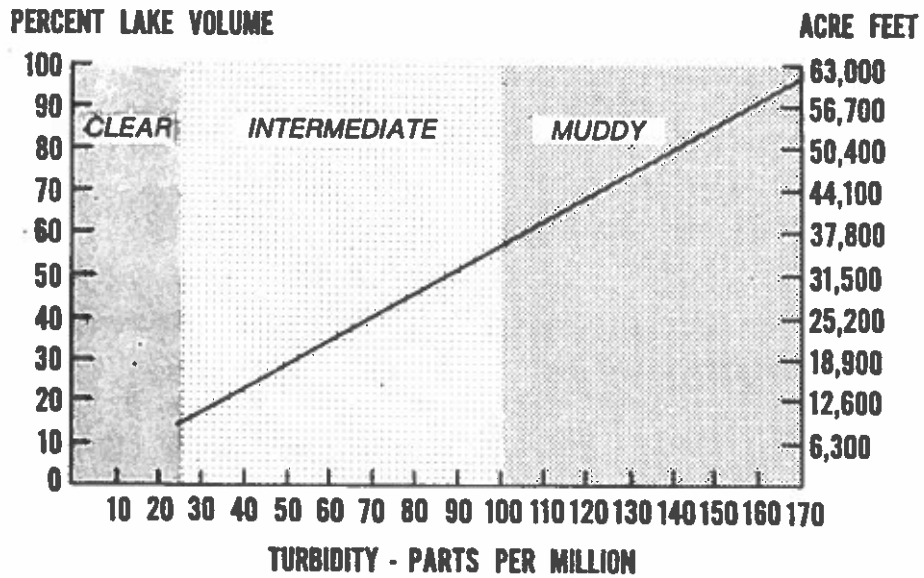
Table 1. Lake Chicot operational plan.

Case	Hydrologic Conditions	Operating Rules	Outflow Conditions (Min. Water Release)	Lake Stage (ft above MSL)		Surface Suspended Sed. (mg/l)	
				Max.	Min.	Max.	Min.
Ia	Natural	1	April 1-Sep 30 $Q_{gate} = 150$ cfs	107	97	85	6
Ib	Natural	1	April 1-Sep 30 $Q_{gate} = 75$ cfs	107	103	54	6
Ic	Natural	1	April 1-Sep 30 $Q_{gate} = 100$ cfs	107	101	84	6
IIa	Natural	3	Outflow is over weir only	109	103	67	10
IIb	Natural	1+3	Outflow is over weir only	106	103	21	2
IIc	Natural	1+3	April 1-Sep 30 $Q_{gate} = 75$ cfs	107	101	82	5
IId	Natural	1+3	April 1-Sep 30 $Q_{gate} = 50$ cfs	106	101	35	5
IIIa	Natural	1+2	April 1-Sep 30 $Q_{gate} = 150$ cfs	106	93	35	5
IIIb	Natural	1+2	April 1-Sep 30 $Q_{gate} = 75$ cfs	106	102	35	5

Table 1. continued

Case	Hydrologic Conditions	Operating Rules	Outflow Conditions (Min. Water Release	Lake Stage (ft. above MSL)		Surface Suspended Sed. (mg/l)	
				Max.	Min.	Max.	Min.
IVa	Dry Summer	None	All year $Q_{gate} = 150$ cfs	109	93	182	2
IVb	Dry Summer	1	All year $Q_{gate} = 75$ cfs	107	97	117	11
IVc	Dry Summer	1	All year $Q_{gate} = 25$ cfs	108	102	109	8
IVd	Dry Summer	1+3	All year $Q_{gate} = 25$ cfs	108	102	65	3
VIa	Storm	None	June 1 - Sept 30 $Q_{gate} = 150$ cfs If Chicot Lake stage is less than 103', outflow = 0	114	103	1502	1
VIb	Storm	1	June 1 - Sept 30 $Q_{gate} = 75$ cfs If Chicot Lake stage is less than 103', outflow = 0	115	103	1885	1

**TURBIDITY (PPM) IN RELATION TO LAKE CHICOT
VOLUME DISPLACEMENT
BASED ON 3,500 SURFACE ACRES AT 106 FEET M. S. L.**



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REPORT, SEPTEMBER 22, 1965

Fig 1. Water quality of Lake Chicot as related to inflow volume.