SYSTEMS MODELS FOR UNDERSTANDING EUTROPHICATION IN LAKE OKEECHOBEE

BY

TIMOTHY LAWRENCE GAYLE

A THESIS PRESENTED TO THE GRADUATE COUNCIL OF
THE UNIVERSITY OF FLORIDA
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

1975

ACKNOWLEDGEMENTS

Appreciation is expressed to Dr. H. T. Odum, my committee chairman, for unique guidance and inspiration. Many contributions were appreciated from members of my committee: Dr. J. L. Fox and Dr. F. G. Nordlie.

Work was sponsored by contract between the Florida Department of Pollution Control and the Florida State Division of Planning and the Center for Wetlands, University of Florida as a part of a state project on Eutrophication of Lake Okeechobee. Principal investigators were H. T. Odum and F. G. Nordlie; state project coordinators were Curry Hutchinson and Dale Walker. Thomas Fontaine and Anne Meylan collaborated in project assignments. Data and advice were provided by F. E. Davis and M. E. Marshall of the Central and Southern Florida Flood Control District. Dr. W. Huber helped with the spatial model.

TABLE OF CONTENTS

TABLE OF CONTENTS - continued

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES - continued

Abstract of Thesis Presented to the Graduate Council
of the University of Florida in Partial Fulfillment of the Requirements
for the Degree of Master of Science

SYSTEMS MODELS FOR UNDERSTANDING
EUTROPHICATION IN LAKE OKEECHOBEE

By

Timothy Lawrence Gayle

June, 1975

Chairman: Howard T. Odum
Major Department: Environmental Engineering Sciences

Systems models were developed to investigate ecological changes and eutrophication trends in Lake Okeechobee, Florida. An energy flow model was used to organize data and concepts on the lake as a system. Simplified models of water budget, phosphorus budget, metabolism, and water currents were simulated to estimate the effects of changes in river flow, water levels, and nutrient loads.

Simulations of water budgets from 1951-1974 predicted lake stage within 10%. River basin channelization accelerated runoff into the lake with less water remaining on the land for use and discharge during dry season. Simulations indicated channelization causes an additional 200,000 acre-feet per year to reach the lake during summer months and be discharged to the sea as part of hurricane protection.

Present phosphorus loading rates to the lake from rain and tributaries were 0.3 to 0.4 g $P/m^2/yr$ which compared with 1 g $P/m^2/yr$ in Lake Apopka. Nearly 90% of this phosphorus load was unaccounted for in outflow and could be trapped by sediment. The turnover time of

phosphorus was about 60 days in the lake and the doubling time may be as short as 15 years under present loading conditions.

Based on several diurnal oxygen measurements primary production may be about 2.1 g C/m^2/day; this indicates the lake is moderately eutrophic. Average net organic load is estimated to be 0.07 g C/m^2/day, which is sufficient to reduce oxygen levels to 85-90% saturation. Simulations indicate that greater organic matter inflows resulting from intensive backpumping or destruction of the marsh can considerably reduce oxygen levels. Raising the lake stage regulation level two feet will drastically reduce the extent of seasonal marshes in the lake that now support wildlife, especially wading bird populations. Simulations indicated doubling phosphorus loads caused slight increases in short-term production.

Simulation of a spatial model indicated water currents circulated in a clockwise direction and rapidly distributed nutrients horizontally in the limnetic zone.

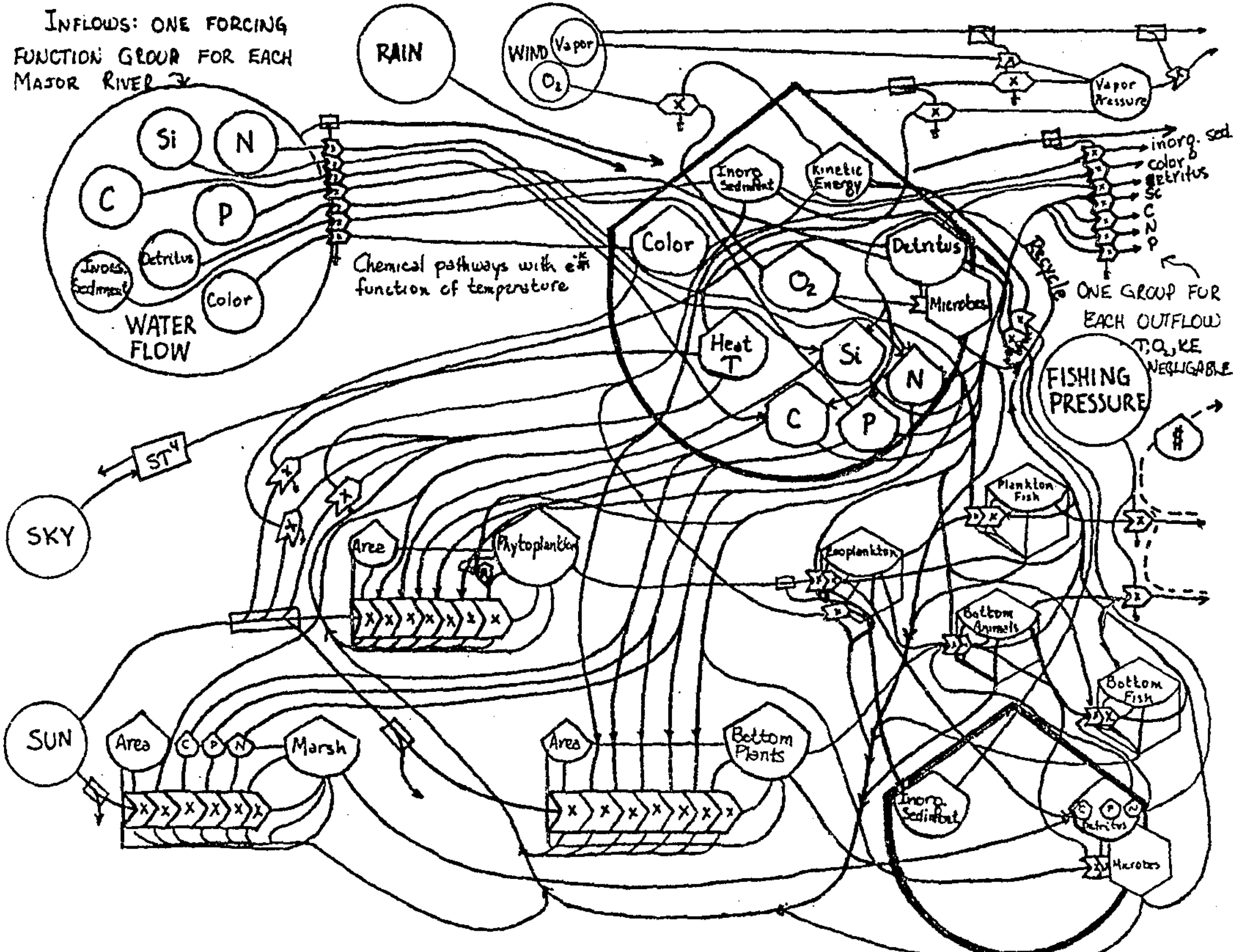
INTRODUCTION

Lake Okeechobee serves south Florida as a valuable water supply, recreational resource, and wildlife area. This important asset, however, may be changing with eutrophication. In this study systems models were used to investigate the effects of eutrophication and other ecological changes on the lake. The model in Fig. 1 represents an overview of ecological interactions within the lake. A simplified model is given in Fig. 2 from which three submodels were evaluated and simulated. Models were used to consider questions on the hydrology, nutrient budget, organic metabolism, and circulation of the lake.

The term eutrophy generally applies to waters which are productive and nutrient rich, and the degree of eutrophy depends on the quantities of energy available to the productive process. Moderate production and eutrophy are characterized by high biomass and diverse trophic levels. Extremely high production, or hyper-eutrophy, is characterized by even higher biomass, shorter food chains, less diverse trophic levels, and wide fluctuations in oxygen. Hyper-eutrophic lakes have less game fishing, and decreased water quality for contact sports and water supply.

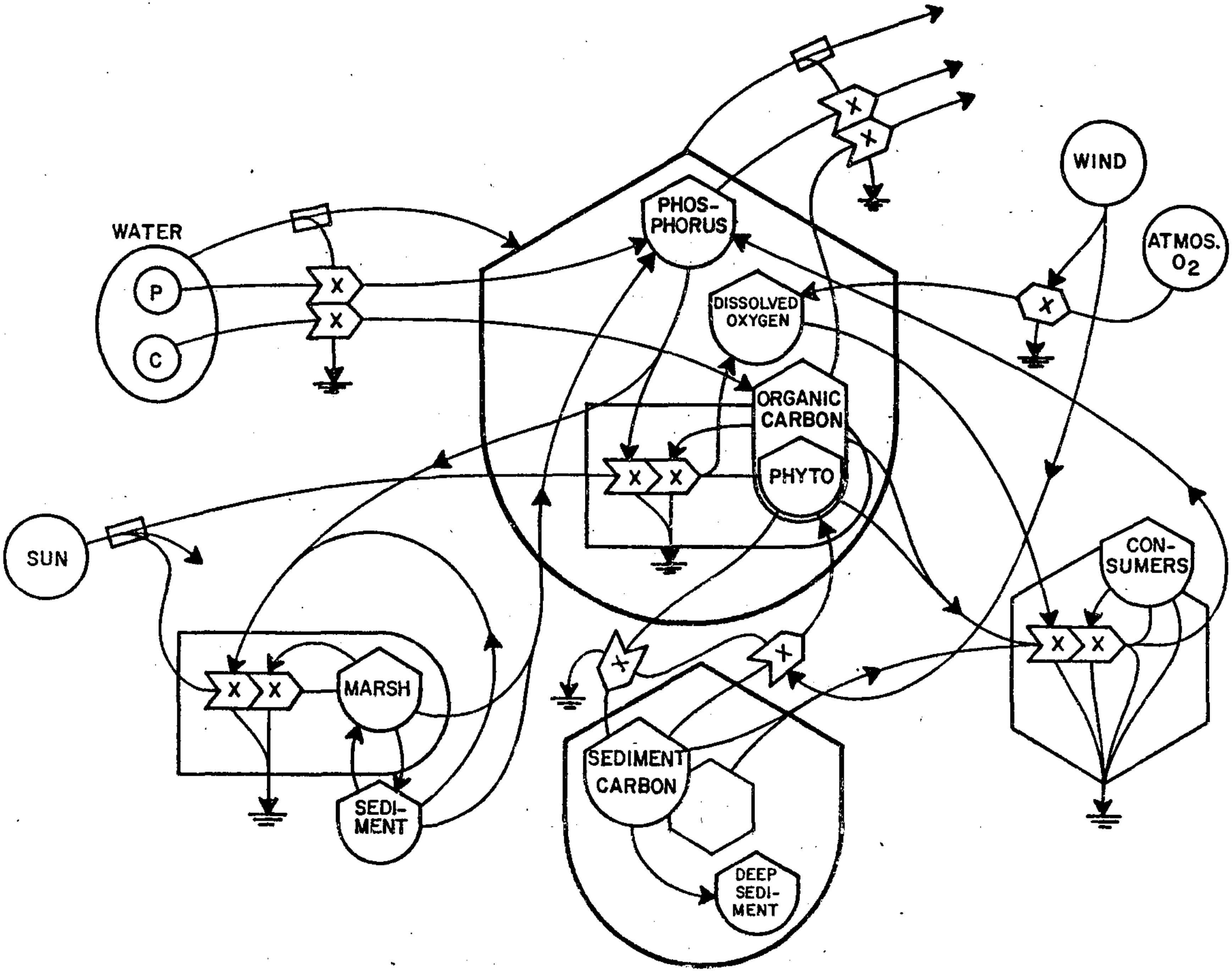
Lake Okeechobee is located in south-central Florida $26^{\circ}41'$ to $27^{\circ}13'$N and $80^{\circ}31'$ to $81^{\circ}07'$W, and has over 700 square miles of surface area making it one of the largest lakes in the United States. Geologically, the basin is part of the Pamlico Terrace, a plain formed during the recession of the sea in the late Pleistocene (Joyner, 1974). The lake bottom is variously composed of calcitic muds, marls, and gyttja

Figure 1. Model of Lake Okeechobee ecosystem showing relationships between water, sun, heat, nutrients, organisms, and man. Model drawn by H. T. Odum and F. G. Nordlie based on discussions with staff of Central and Southern Florida Flood Control District and others in 1973.



INFLOWS: ONE FORCING FUNCTION GROUP FOR EACH MAJOR RIVER
Si
N
C
P
Detritus
Inorg. Sediment
Color
WATER FLOW
RAIN
WIND
Vapor
O2
Vapor Pressure
Inorg. Sediment
Kinetic Energy
Color
Detritus
O2
Microbes
Heat T
Si
N
C
P
Chemical pathways with eff. function of temperature
inorg. sed
color
detritus
Si
C
N
P
Recycle
ONE GROUP FOR EACH OUTFLOW
T, O2, KE NEGLIGABLE
FISHING PRESSURE
$
ST4
SKY
SUN
Area
Phytoplankton
Plankton Fish
Zooplankton
Bottom Animals
Bottom Fish
Area
C
P
N
Marsh
Area
Bottom Plants
Inorg. Sediment
C
P
N
Detritus
Microbes

Figure 2. Simplified model of the ecosystem in Lake Okeechobee which relates water, phosphorus, and metabolism. Simulation models were derived from this simplified model.


WATER
P
C
X
X
SUN
X
X
MARSH
SEDI-
MENT
PHOS-
PHORUS
DISSOLVED
OXYGEN
ORGANIC
CARBON
PHYTO
X
X
X
X
WIND
ATMOS.
O_2
X
CON-
SUMERS
X
X
X
X
SEDIMENT
CARBON
DEEP
SEDI-
MENT

with bottom elevations averaging six feet above sea level and some areas below sea level (see Fig. 3). Because of the shallowness of the lake basin, small changes in water surface elevations are accompanied by large changes in the lake area (see Fig. 4).

The climate around Lake Okeechobee is semitropical, however, this water body exerts a large influence on the temperature, evaporation, and rainfall patterns on the lake (Riebsame et al., 1974). Median rainfall is 45.6 inches per year (Joyner, 1974), 60% of which falls from June through September (Casselman, 1970). Normal evaporation is 55.7 inches per year and is highest in May. Rainfall, evaporation, and runoff are quite variable seasonally and yearly and water storage in the lake reflects this.

Drainage basins around the lake have been highly modified for water control, navigation, and agricultural development. The lake is encircled by a levee 80 miles long and 25 feet high, and is located near the 15 foot contour (see Fig. 3). Most rivers flowing into the lake are channelized and their discharge is regulated by flow control structures. Excess water from agricultural lands south of the lake is backpumped into the lake. Lake stage is regulated between 14.0 and 15.5 feet above mean sea level (MSL) and excess lake water is released via two channelized rivers to tidewater. For a description of the lake basin in its pristine state see Brooks (1974).

Surveys of the lake's water chemistry were conducted by Odum (1953), Parker and others (1955), Holcomb (1968), Duchrow (1970), Joyner (1974), and Davis and Marshall (1975). Davis and Marshall found the lake well mixed vertically, with high levels of calcium, chloride, and dissolved solids. Brooks (1974) attributed the high levels of dissolved solids in

Figure 3. Location of Lake Okeechobee on peninsular Florida. Map of the lake shows basin topography and sites of major rivers and canals and the Hoover Dike. Redrawn from Brooks (1974).

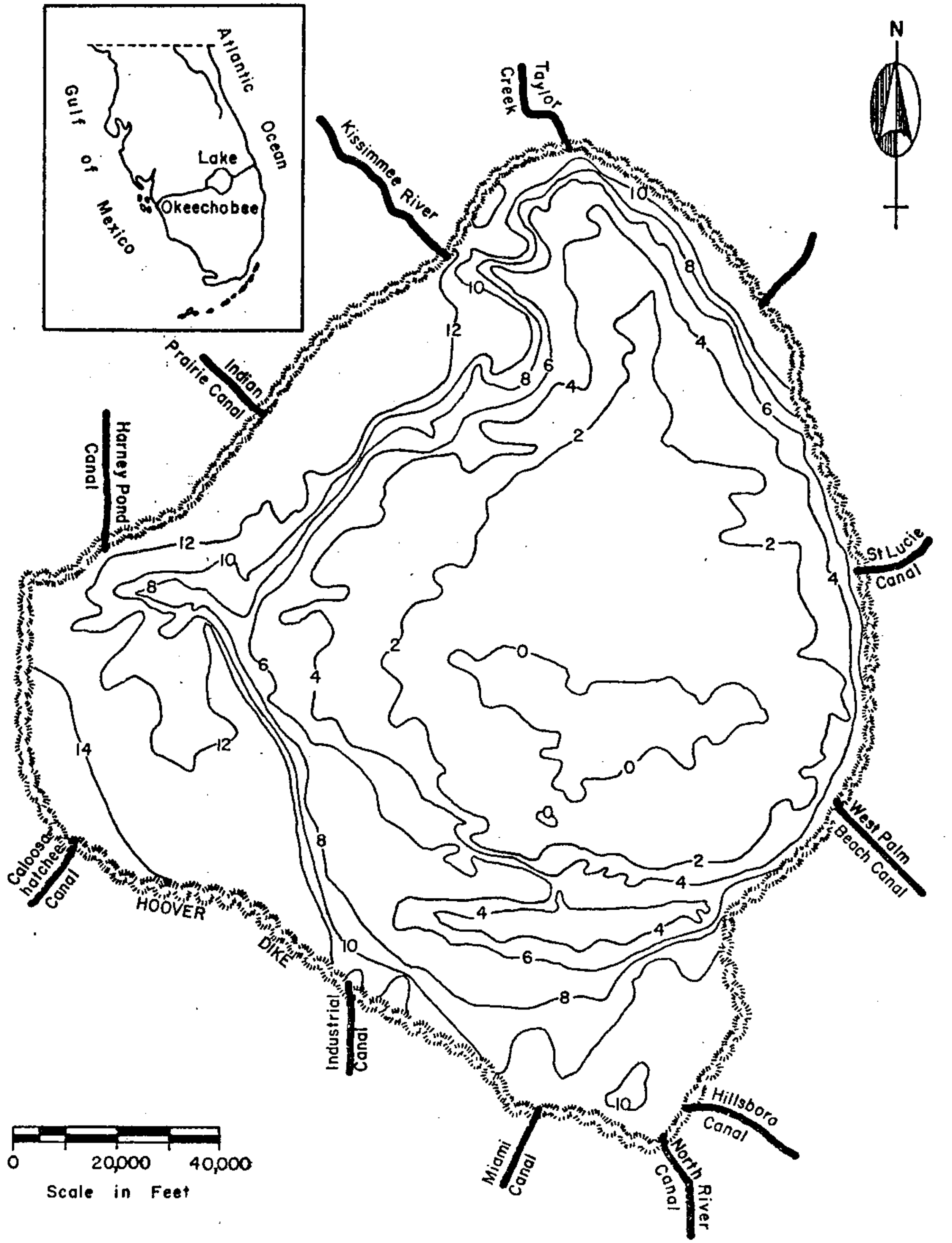
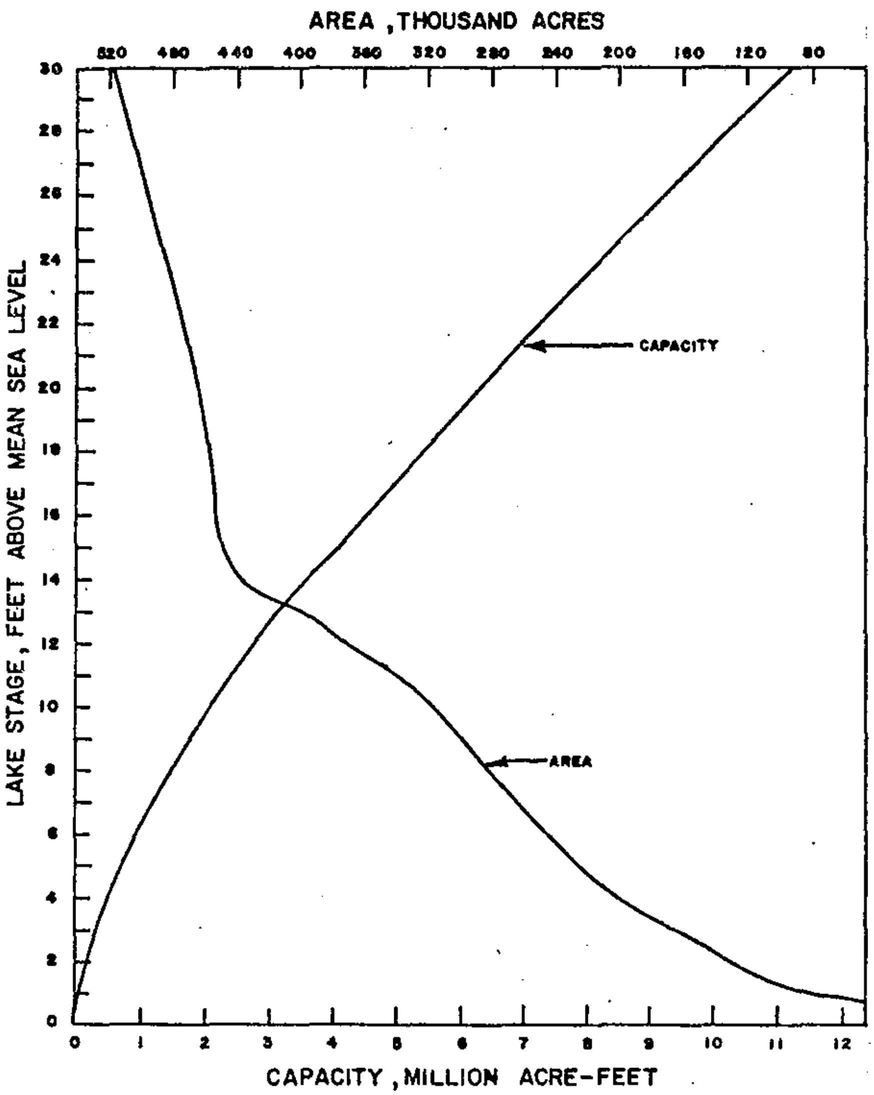

Atlantic
Ocean
Gulf of Mexico
Lake
Okeechobee
N
Taylor Creek
Kissimmee River
Indian Prairie Canal
Harney Pond Canal
St Lucie Canal
West Palm Beach Canal
Hillsboro Canal
North River Canal
Miami Canal
Industrial Canal
Caloosahatchee Canal
HOOVER DIKE
0
20,000
40,000
Scale in Feet

Figure 4. Stage-rating curve for Lake Okeechobee showing relationships between stage, storage, and area. Data is from U.S. Army Corps of Engineers, 1962.


AREA , THOUSAND ACRES
520 480 440 400 360 320 280 240 200 160 120 80
LAKE STAGE, FEET ABOVE MEAN SEA LEVEL
30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 0
CAPACITY
AREA
0 1 2 3 4 5 6 7 8 9 10 11 12
CAPACITY , MILLION ACRE-FEET

the lake to groundwater seepage, high evaporation, and construction of the Hoover Dike.

Limnetic phytoplankton and benthic fauna populations were investigated by Joyner (1974), and Davis and Marshall (1975). Ager and Kerce (1974) conducted studies on fish feeding habits and fish standing crops in the open-water zone. Sincock and others (1957), Soumela (1958), and Ager and Kerce (1974), conducted surveys of littoral zone vegetation, and fish and wildlife populations. Browder (1974) surveyed wading bird populations in the lake's seasonal marshes.

Lake ecosystem models have been developed for Lake George, New York (Park et al.,1972) and Lake Wingra, Wisconsin (Huff et al., 1973; MacCormick et al., 1972) to mention a few. More generalized lake ecosystem models have been developed by Parker (1968) and Park (1974). A good review of aquatic modeling and the eutrophication process can be found in Middlebrooks and others (1973). Although little is known about eutrophication in shallow semitropical lakes and few of these lakes have been modeled, general ecosystem principles can be applied to investigate the nature of the eutrophication process in Lake Okeechobee.

It is evident from recent studies (Joyner, 1974; Davis and Marshall, 1975; Brezonik and Federico, 1975) that Lake Okeechobee receives an abundant supply of nutrients. According to Brezonik and Federico (1975), loading of nitrogen and phosphorus are near or above "dangerous" levels and cause problems of eutrophy in the lake. In Vollenweider's (1968) study, he concluded that massive growth of blue-green algae is likely if nutrient concentrations exceed 0.01 g P/m^3 and 0.2-0.3 g N/m^3. Lake Okeechobee averages 0.05 g P/m^3 and 1.4 g N/m^3, and can be considered in most aspects a moderately eutrophic lake.

METHODS

Principal methods used were concerned with development, evaluation and simulations of models. Model output was compared with empirical data.

Models of water, phosphorus, and metabolic systems in Lake Okeechobee are presented in Figs. 6, 13, and 19, and are depicted in Energese, an energy circuit language developed by H. T. Odum. A description of each symbol and its mathematical equivalent can be found in Odum (1971b and 1972), and in Fig. 5. The algebraic equivalents of these models are presented in Figs. 6, 12, and 18, and sets of differential equations derived from these models were programmed on computers for simultaneous solutions.

Water and metabolic systems models were simulated on the Electronic Associates, Incorporated, Miniac analog computer. Analog patching diagrams, scaling factors, and pot settings are given in the Appendices.

The model for phosphorus systems was simulated on the University of Florida IBM 370/360 digital computer in Dynamo II, and the program is given in Appendix B.

The model used to simulate movement of water within Lake Okeechobee was adapted from the Receiving Water Quantity Model, a submodel of the EPA Storm Water Management Model (1971). In the model water movement is represented by a network of nodes connected by channels which are idealized hydraulic elements. These elements are characterized by parameters

Figure 5. Description of Energese, an energy circuit language used for modeling in this study (Odum, 1971, 1972).

(a) External, unlimited energy source to the system.

(b) Heat sink as required by the second law of thermodynamics in order to do work.

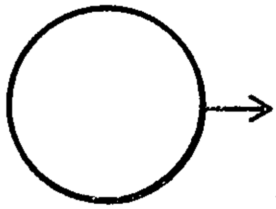
(c) Component of energy or matter storage in which quantity stored is the integral of the inflows and outflows.

(d) Interaction in which output is proportional to the product of two input forces.

(e) Interaction in which output is some unspecified function of two input forces.

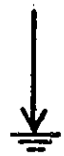
(f) Autocatalytic unit which by virtue of feedback mechanisms may enhance its ability to process energy.

(g) Force (X) acting in proportion to flow (J).



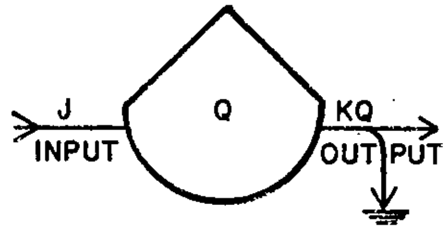
SOURCE

(a)



HEAT SINK

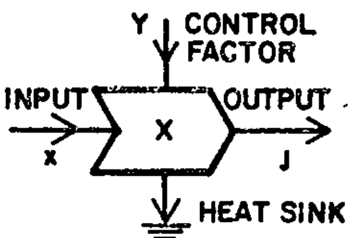
(b)



$\dot{Q} = J - KQ$

PASSIVE STORAGE

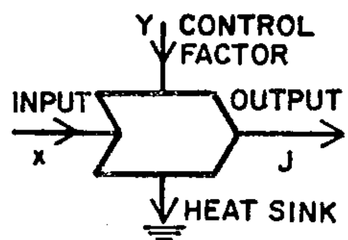
(c)



$J = KXY$

MULTIPLIER

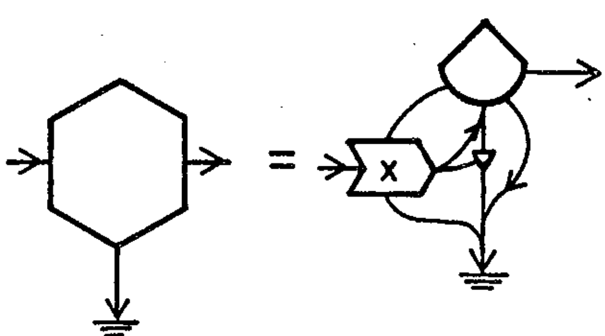
(d)



$J = f(X,Y)$

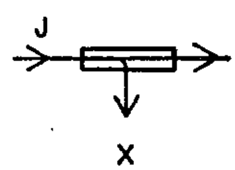
GENERALIZED WORKGATE

(e)



SELF MAINTAINING CONSUMER UNIT

(f)



FORCE FROM A FLOW

(g)

Figure 5. (continued)

(h) Cycling receptor module as in chlorophyll excitation-deactivation cycles and other anabolism.

(i) Autotrophic individual or community which has both anabolic and catabolic processes.

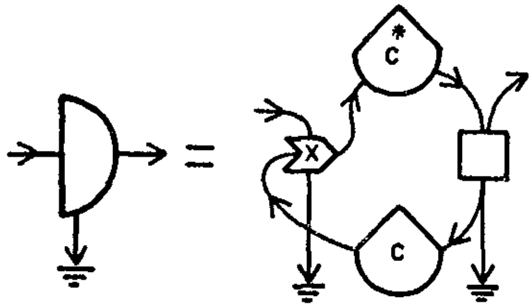
(j) Switch used when flows are regulated by on-off signals such as lake regulation or political decisions.

(k) Constant gain amplifier used when unlimited source drives low flow without affecting the source.

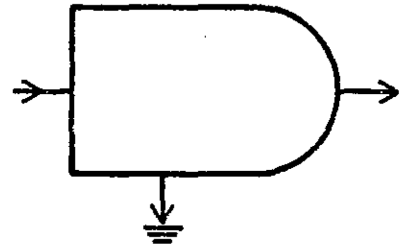
(l) Economic transactor showing opposite flow of money and energy.

(m) Two-way workgate which operates according to the gradient and driving force.

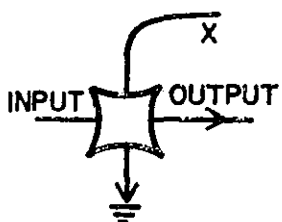
(n) Box used to lump linear processes. Nutrients can be shown being recycled from respiratory pathways.



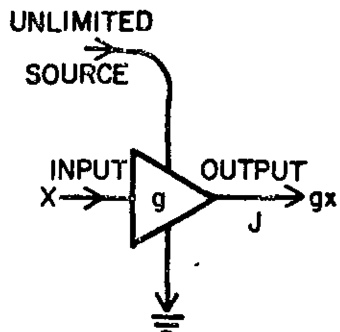
CYCLING RECEPTOR
(h)



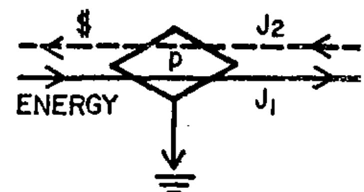
GREEN PLANT AND OTHER PRODUCERS
(i)



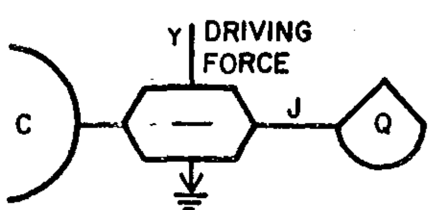
DIGITAL FUNCTIONS
(j)



CONSTANT GAIN AMPLIFIER
(k)

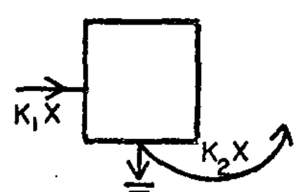


ECONOMIC TRANSACTOR
(l)



$J=K_1(1-K_2Y)(C-Q)$

DIFFUSION MODULE WITH NEGATIVE WORKGATE
(m)



GENERAL PURPOSE BOX
(n)

of length, head, floor elevation, hydraulic radius and frictional coefficients. Simultaneous solution of equations of continuity and motion for each element results in changes of stage, velocity and flow in the components of the water system.

Hand simulations of water budgets were calculated by combining monthly inflows and outflows to obtain monthly changes in lake storage.

RESULTS

Included in results are the models, data assembled for evaluation, computer simulations, and comparisons with observed data or trends. Models simulated include systems of water, phosphorus, metabolism, and water circulation.

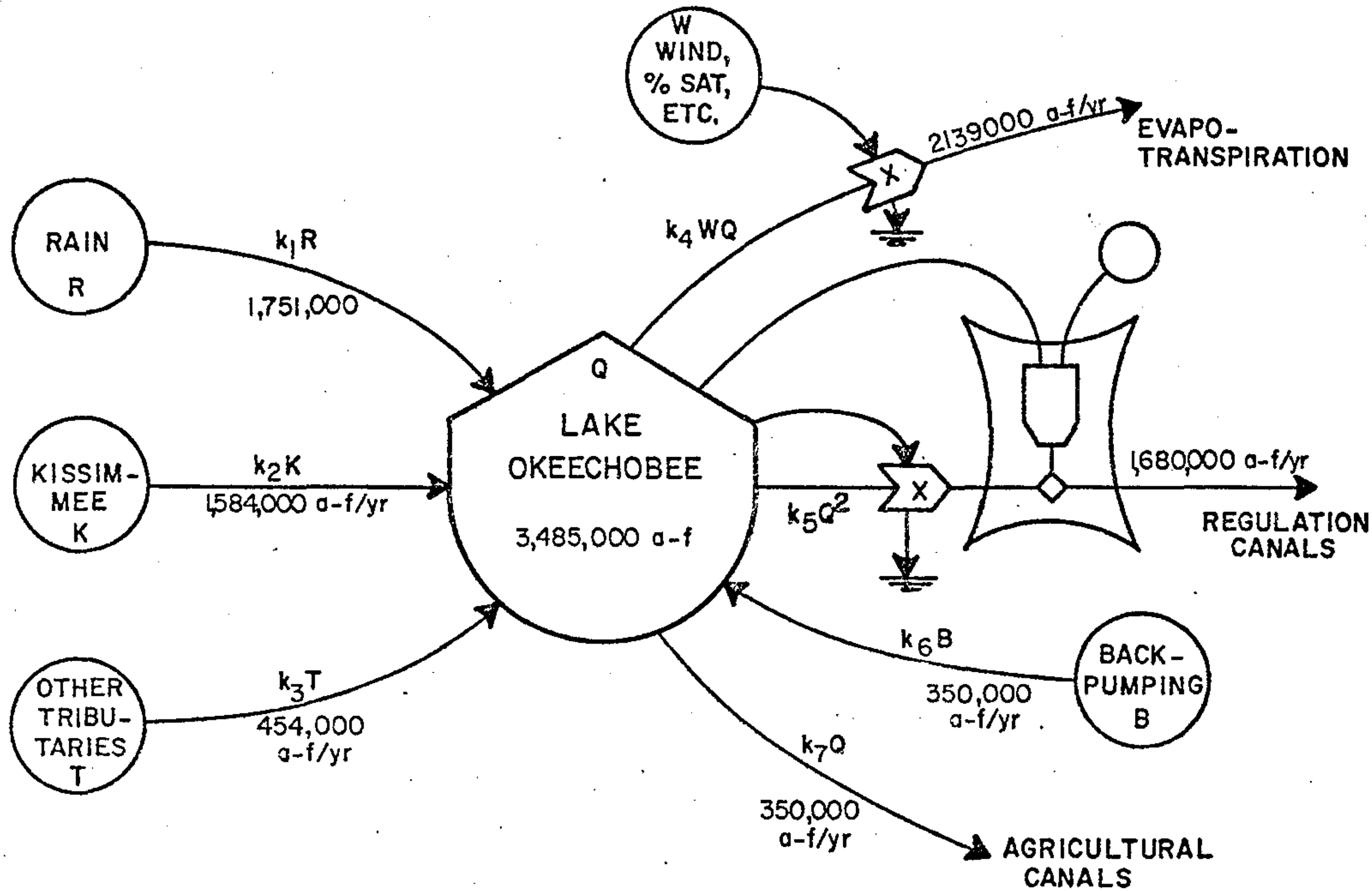
Water System of Lake Okeechobee

A water model for Lake Okeechobee is presented in Fig. 6 in which mathematical terms and values for stocks and flows are included. Long-term averages for the storages and flows were obtained from U. S. G. S. surface water records and rainfall and evaporation records of the U. S. Army Corps of Engineers. Prior to 1957 many of the surface water flows around Lake Okeechobee were unmonitored.

Inspection of the magnitudes of flows in Fig. 6 reveals that rain and river inflows to the lake are roughly equal, as are the outflows of evaporation and runoff. Inflows replace the lake volume about once a year. The short residence time of lake water is reflected in the seasonally variable stages which have ranged from 10.14 to 18.77 feet above mean sea level (MSL). Present water management practices attempt to regulate lake stages between 14.0 feet MSL in the summer and 15.5 feet MSL in the winter, however, average stages are lower than this. Because of the strong seasonality of rainfall and runoff, the lake stages are almost always high in the fall and low in the late spring.

Hand calculated simulation water budgets for monthly inflows and outflows are presented in Fig. 7 and are compared with observed data. The percentage difference between simulated and empirical values was

Figure 6. Model of water system around Lake Okeechobee with mathematical terms and average flows and storages of water. Flows are in acre-feet per year and storage is in acre-feet.


W
WIND,
% SAT,
ETC.
2139000 a-f/yr
EVAPO-
TRANSPIRATION
X
RAIN
R
k_1R
1,751,000
k_4WQ
Q
LAKE
OKEECHOBEE
3,485,000 a-f
KISSIM-
MEE
K
k_2K
1,584,000 a-f/yr
k_5Q^2
X
1,680,000 a-f/yr
REGULATION
CANALS
OTHER
TRIBU-
TARIES
T
k_3T
454,000
a-f/yr
k_6B
350,000
a-f/yr
BACK-
PUMPING
B
k_7Q
350,000
a-f/yr
AGRICULTURAL
CANALS

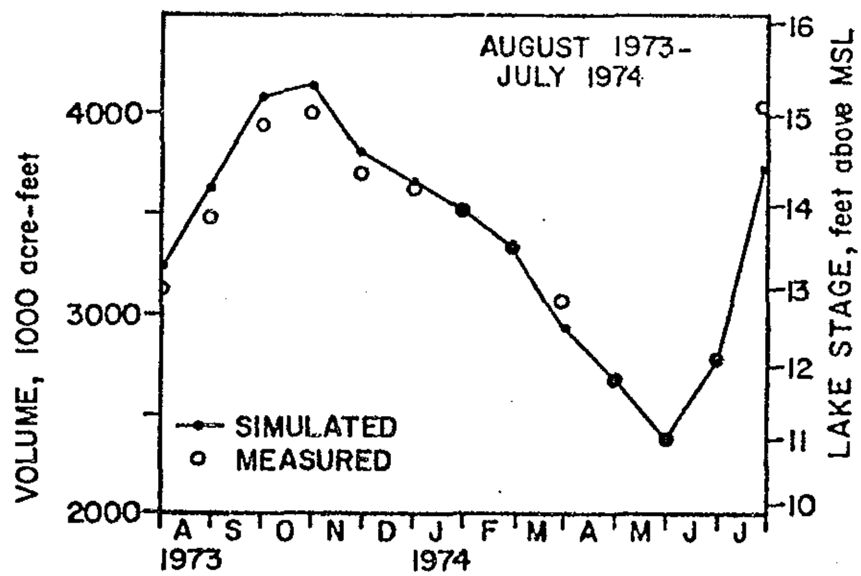
generally about 1% with a maximum of 10% in the 1951-60 period. This difference may be attributable to unmonitored backpumpage.

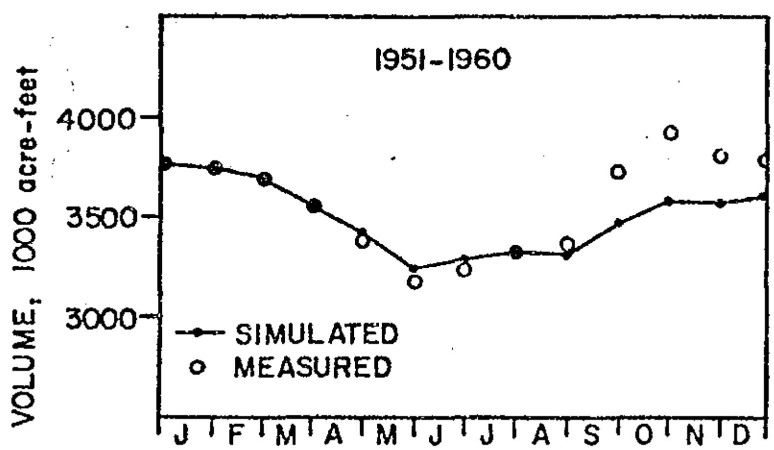
Figure 8 is a comparison of lake volumes, surface inflows and outlows and rainfall for the periods 1951-60 and 1965-74. Average monthly lake volume for the earlier period ranged from 3,160,000 acre-feet at the end of May to 3,920,000 acre-feet at the end of October, whereas the 1965-74 period had extremes in the same months but a lower minimum (2,910,000 acre-feet). River basin rainfall averaged 49.16 inches per year during 1951-60 and 47.66 inches per year during the later period. Similarly, the rain on the lake was slightly less during the decade 1965-74. In comparing rainfall-runoff relationships, peak inflow to the lake occurred earlier in the rainy season and the dry season runoff was lower during the period 1965-74. Summer inflows were 30% of the annual total during 1951-60 and 42% of the total inflow during 1965-74.

A set of cumulative rainfall-runoff graphs of the Kissimmee River in Fig. 9 shows 36,000 acre-feet of discharge per inch of rainfall occurred during 1951-60 and 22,000 acre-feet of runoff per inch of rain occurred during 1965-74.

The simulation model in Fig. 10 was used to examine the effects of differences in timing of influent runoff on lake stages. Values used in the simulation of normal conditions are presented in Table 1; storages were expressed in billion cubic meters and flows were expressed in billion cubic meters per year. Dimensions of sinusoidal parameters used in various simulations are presented in Table 2. Simulations shown in Fig. 11 are two-year hydrographs of lake volume under average, drought and flood conditions. Simulations that resulted from

Figure 7. Results of Lake Okeechobee water budget simulations for three periods: August 1973 - July 1974, 1951 - 1960, and 1965 - 1974. Simulations are compared with empirical data.


AUGUST 1973-
JULY 1974
VOLUME, 1000 acre-feet
LAKE STAGE, feet above MSL
4000
3000
2000
16
15
14
13
12
11
10
SIMULATED
MEASURED
A S O N D J F M A M J J
1973
1974


1951-1960
VOLUME, 1000 acre-feet
4000
3500
3000
SIMULATED
MEASURED
J F M A M J J A S O N D

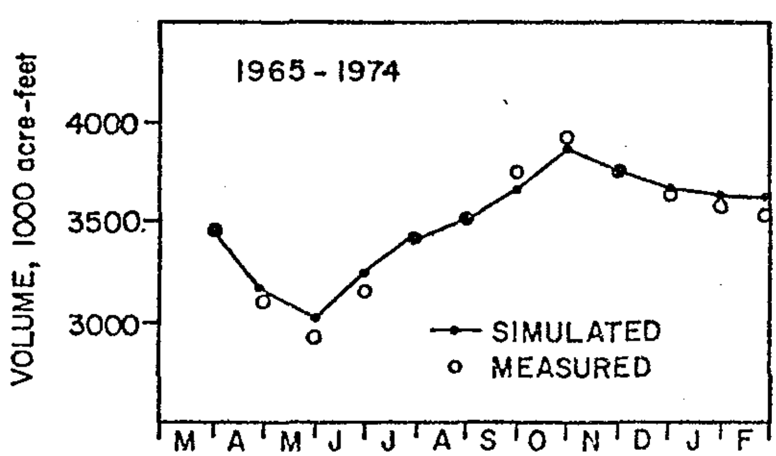
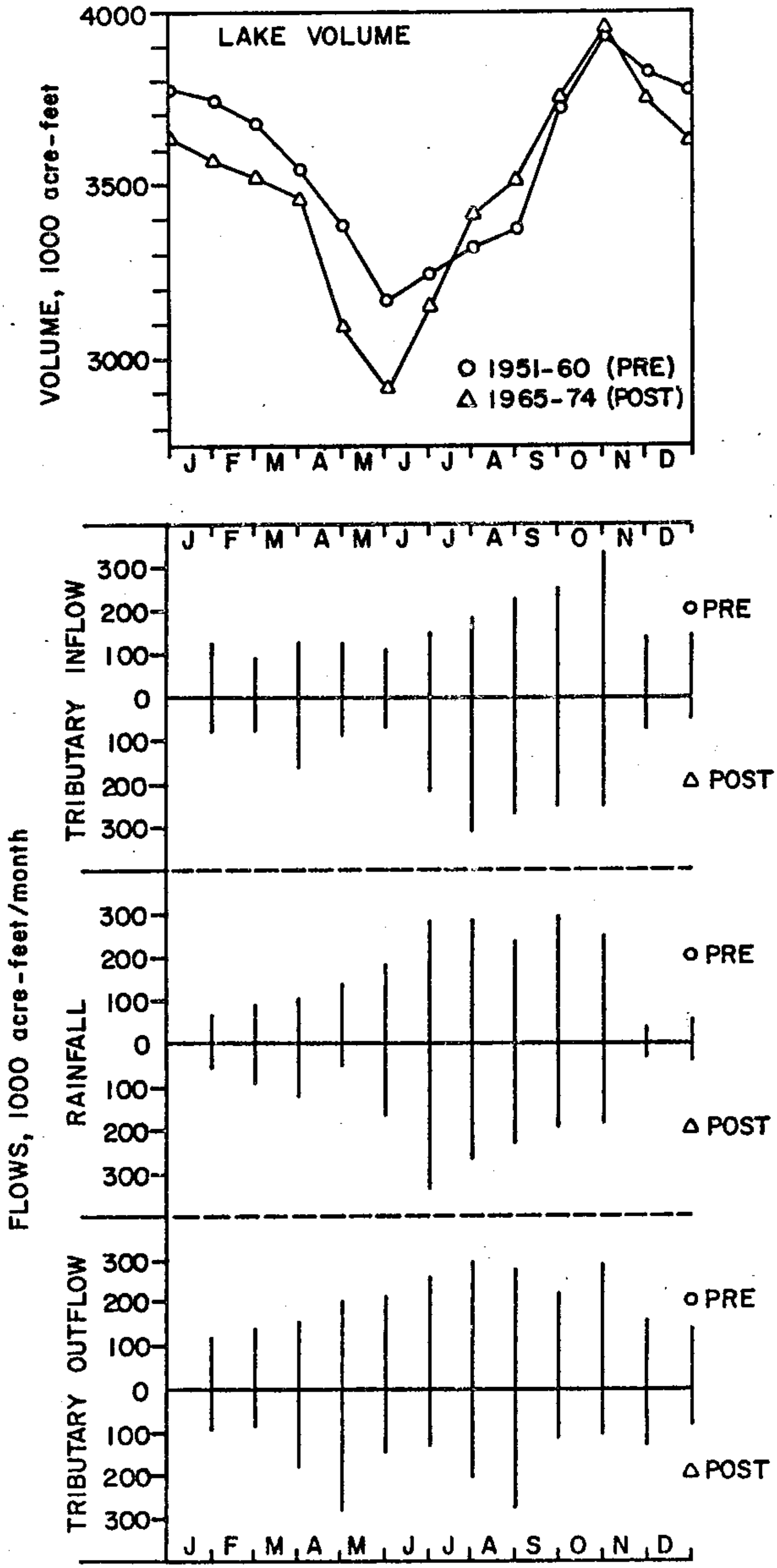
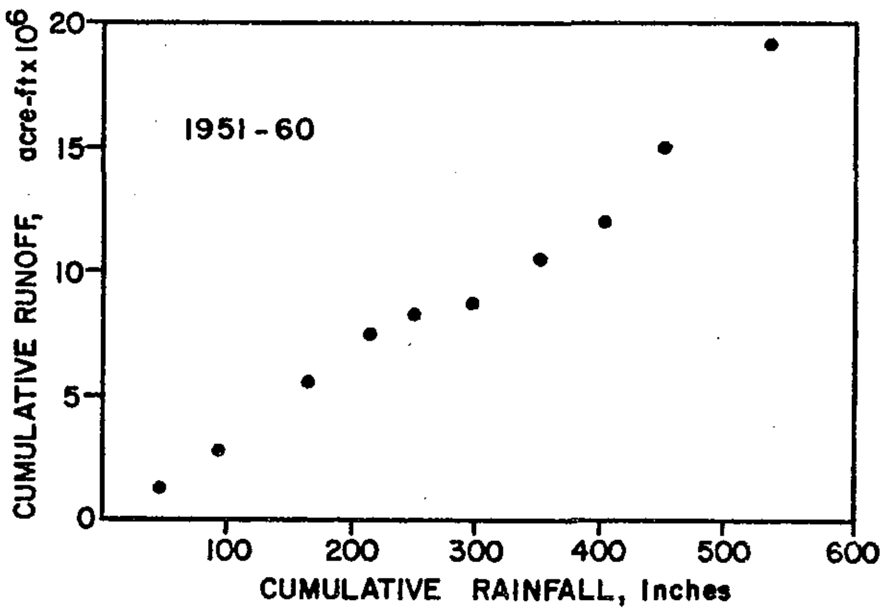

1965 - 1974
VOLUME, 1000 acre-feet
4000
3500
3000
SIMULATED
MEASURED
M A M J J A S O N D J F

Figure 8. Comparison of certain aspects of the water system of Lake Okeechobee during ten years prior to channelization (1951-60) and after channelization.


LAKE VOLUME
VOLUME, 1000 acre-feet
4000
3500
3000
○ 1951-60 (PRE)
△ 1965-74 (POST)
J F M A M J J A S O N D
FLOWS, 1000 acre-feet/month
TRIBUTARY INFLOW
RAINFALL
TRIBUTARY OUTFLOW
300
200
100
0
○ PRE
△ POST


1951-60
CUMULATIVE RUNOFF, acre-ft x 10^6
0
5
10
15
20
100
200
300
400
500
600
CUMULATIVE RAINFALL, Inches

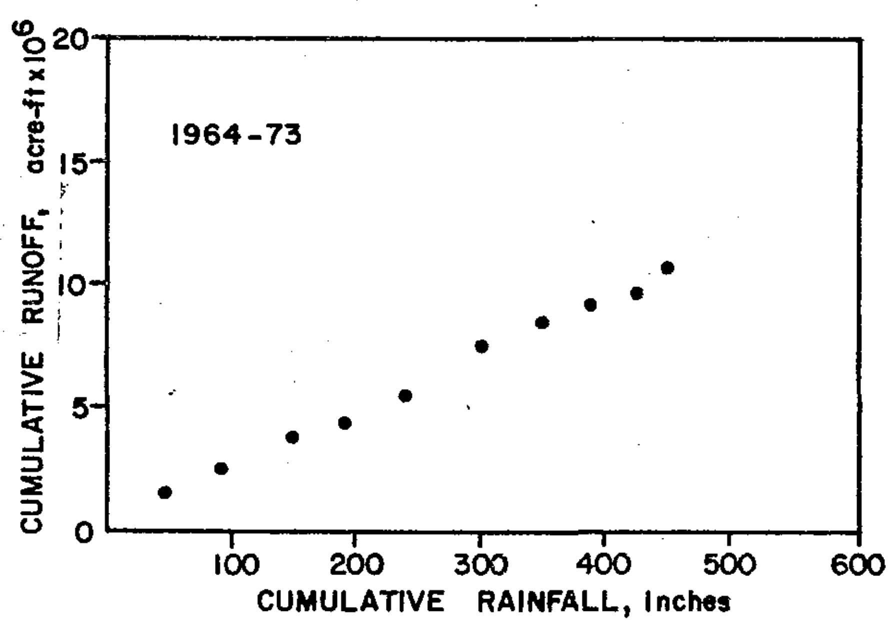

1964-73
CUMULATIVE RUNOFF, acre-ft x 10^6
0
5
10
15
20
100
200
300
400
500
600
CUMULATIVE RAINFALL, Inches

Figure 10. Water system model used to test effects of water management practices on lake stage. Flows are in billion cubic meters per year and storages are in billion cubic meters. Regulation and backpumpage flows are maximum instantaneous values which are switched by various parameters in the model.

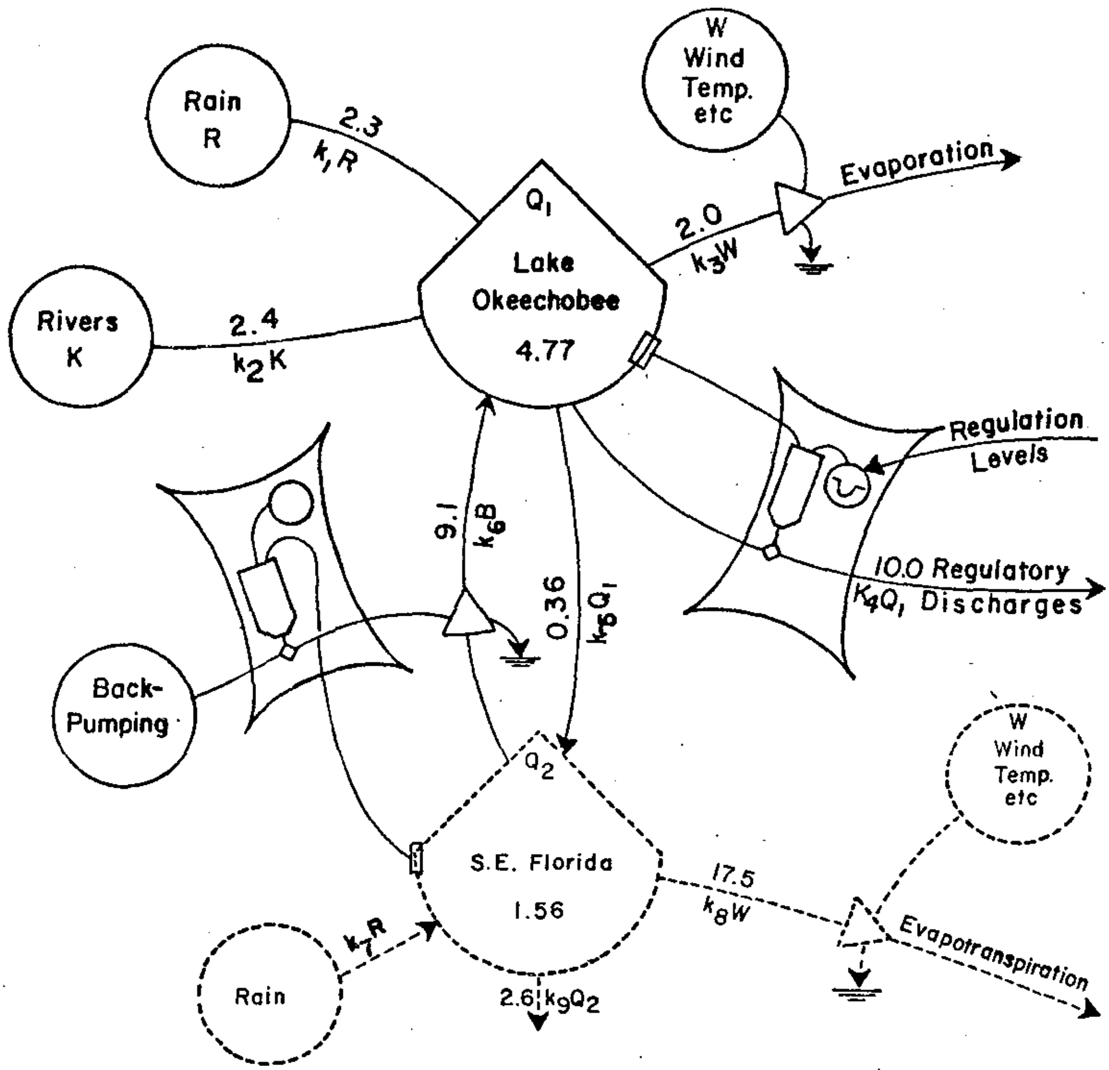

W
Wind
Temp.
etc
Rain
R
2.3
$k_1 R$
Q_1
Lake
Okeechobee
4.77
Evaporation
2.0
$k_3 W$
Rivers
K
2.4
$k_2 K$
Regulation
Levels
9.1
$k_6 B$
0.36
$k_5 Q_1$
10.0 Regulatory
$K_4 Q_1$ Discharges
Back-
Pumping
Q_2
W
Wind
Temp.
etc
S.E. Florida
1.56
17.5
$k_8 W$
Evapotranspiration
$k_7 R$
Rain
2.6
$k_9 Q_2$

TABLE 1. Table of Average Values Used in Simulation of Water System Model Shown in Fig. 10.

Parameter	Note	Description	Value, billion m^3
k_1R	1	mean rainfall on lake	2.29/yr
k_2K	2	average flow from tributaries into lake	2.39/yr
k_3W	3	normal evaporation from lake	2.00/yr
k_4Q_1	4	maximum regulation flow out St. Lucie and Caloosahatchee	10.00/yr
k_5Q_1	5	average flow out of canals at southern end of lake	0.36/yr
k_6B	6	maximum backpumping rates	9.11/yr
k_7R	7	mean rainfall on Dade, Broward, and Palm Beach Counties	20.60/yr
k_8W	8	mean evapotranspiration from counties.	17.50/yr
k_9Q_2	9	other water losses from counties	2.59/yr
Q_1	10	water in lake at 14.75' MSL	4.77
Q_2	11	water on county area	1.56

TABLE 1. (continued)

1. United States Geological Survey (USGS) by Hartwell reported average rainfall on Lake Okeechobee to be 2.29 billion cubic meters per year.

2. In USGS report by Hartwell he states tributary inflow to Lake Okeechobee amounts to 2.39 billion cubic meters per year.

3. In Hartwell's USGS report he states that average evaporation from Lake Okeechobee is 2.00 billion cubic meters per year.

4. In USGS Surface Water Records for Florida extreme flows are given for the regulation canals which total 10.0 billion cubic meters per year.

5. Hartwell reports long-term average flow of water out of the Miami, Hillsboro, North New River, and West Palm Beach Canals combined average (1940-63) 360,000 cubic meters per year.

6. USGS Surface Water Records for Florida report a maximum short term backpumping rate of 9.11 cubic meters per year.

7. According to Parker and others (1955) average rainfall on SE Florida is 53 inches per year. If this is prorated over the area of Dade, Broward, and Palm Beach counties (5907 $mile^2$) this equals 20.6 billion cubic meters per year.

8. Parker and others (1955) reported average evapotranspiration of 45 inches annually in SE Florida which converts to 17.5 billion cubic meters when prorated over the entire area of the three counties.

9. Hartwell reported other runoff from the counties to be about 2.59 billion cubic meters per year.

10. From U. S. Army Corps of Engineers stage-rating curve for the lake the volume of water at 14.75 feet above MSL is 4.77 cubic meters.

11. Prorating four inches of water over the county area this totals 1.56 billion cubic meters.

TABLE 2. Median Values and Maximum and Minimum Instantaneous Values of Sine Wave Function Used in Simulation of Water Model in Fig. 10. Values are in Billion Cubic Meters per Year.

Parameter	Description	Drought			Normal			Flood		
		Maximum	Median	Minimum	Maximum	Median	Minimum	Maximum	Median	Minimum
k_1R	rain on lake	3.4	1.7	0.0	4.4	2.3	0.2	5.6	3.5	1.2
k_2K	rivers into lake	2.6	1.8	0.1	3.6	2.4	1.2	4.8	3.6	2.4
k_3W	evaporation from lake				3.0	2.0	1.0			
k_7R	rain on counties	30.1	15.5	.9	38.6	20.6	2.6	48.9	30.9	12.9
k_8W	evapotranspiration from counties				27.0	17.5	8.0			

synchronous rainfall and runoff are shown by a solid line; lake storage that results if runoff lags three months after rainfall is shown by a broken line. Discharge from the lake is increased when water levels reach 14.0 feet MSL in the summer and 15.5 feet MSL in the winter as part of flood protection.

Under normal rainfall-runoff conditions with asynchronous timing (before channelization) a greater percentage of water entered the lake in winter months when allowable levels were higher. When rainfall and runoff enter the lake in synchrony (a highly channelized condition) allowable levels are low and some of the total inflow is discharged to the sea and is unavailable to raise lake stages in winter months. Figure 11 suggests that about 200,000 acre-feet of storage is lost yearly when runoff is synchronous with rainfall. More water is stored in the lake under drought conditions when runoff lags rain. The flood hydrograph shows higher lake stages when rain and runoff enter the lake at the same time because the total inflow reaches the regulatory discharge capacity.

Another analysis of the effects of channelization as it affects timing of inflow and lake storage is given in Tables 3, 4, and 5. Table 3 is long term (1931-65) rainfall and evaporation on the lake. Table 4 lists average monthly surface inflow during 1951-60 (A), normalized monthly surface inflow during 1965-74 (B), net atmospheric water (C), total inflow to the lake for 1951-60 (A+C), and total inflow to the lake to the lake for 1965-74 (B+C). In Table 5 monthly discharge is calculated to equal the amounts of water needed to released for closest maintenance of regulation regime.

Figure 11. Results of simulating water model shown in Fig. 10. Simulations of lake storage in which rainfall and runoff were synchronous is shown by solid line. Lake storage affected by runoff lagging three months after rainfall is shown by broken lines. These are two year hydrographs for normal (a), drought (b), and flood (c) conditions.

I

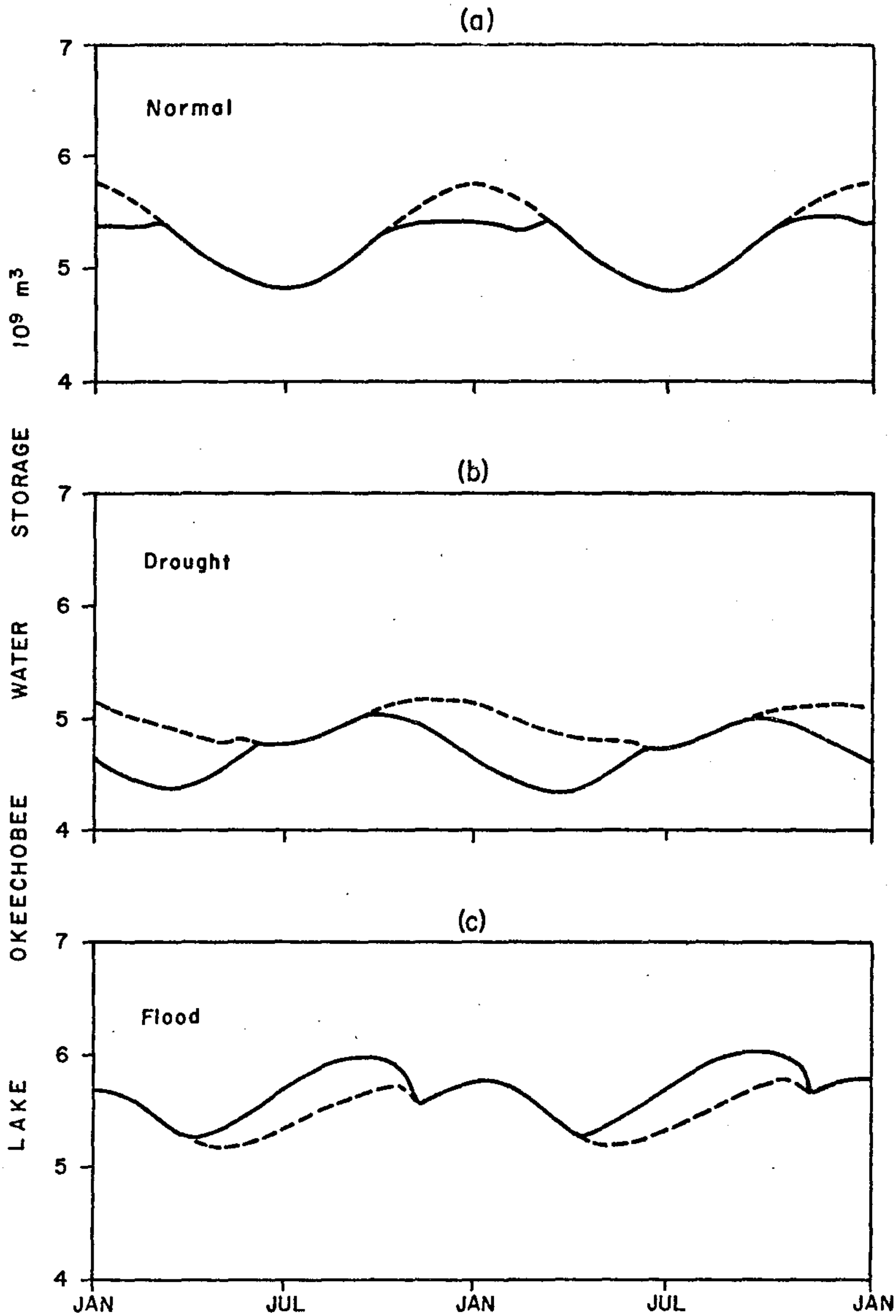

(a)
Normal
(b)
Drought
(c)
Flood
LAKE OKEECHOBEE WATER STORAGE 10^9 m^3
7
6
5
4
JAN
JUL
JAN
JUL
JAN

Table 4 shows four months of net loss of lake water because of changes in timing of runoff during 1965-74 and no months of net water loss during the earlier period. Table 5 shows more water (248,000 acre-feet) must be released in the summer months of the 1965-74 period because of higher total summer runoff. Table shows lower stages at the end of the year in the 1965-74 period. Agricultural water requirements would affect this analysis by making ending storage even lower for the 1965-74 period.

Phosphorus Systems in Lake Okeechobee

A model of the phosphorus system in the lake was developed to investigate response times and long term changes in phosphorus levels as they are affected by various nutrient input rates and sediment-water exchange rates. The model of phosphorus in Lake Okeechobee includes allochthonous sources and sinks, water-marsh exchanges and water sediment exchanges.

Figure 12 is a model of phosphorus relationships in Lake Okeechobee including mathematical terms for each source, storage, and flow. The solid lines represent relationships explicitly programmed on computer and the broken lines represent functions implicit in the program and are held constant for each simulation run. Evaluation of phosphorus interactions on a unit area basis is presented in Fig. 13; the values for inflow and outflow are from Davis and Marshall (1975). In Table 2 are values and calculation of parameters used to simulate this model. Dynamo programming equations and other information on this model also are presented in Appendix B. In Figs. 14, 15, and 16 are results of simulations of this phosphorus model. In each figure are four separate simulations in which model conditions were changed. Each simulation is 25 years of a particular

TABLE 3. Median Rainfall, Normal Evaporation, and Water Supply on Lake Okeechobee

	Median Rainfall	Normal Evaporation	Net (R-E)	Volume * (1,000 a-f)
J	1.15"	3.0"	-1.85"	-71.04
F	1.79	3.6	-1.81	-69.50
M	2.59	5.0	-2.41	-92.54
A	2.85	5.7	-2.85	-109.44
M	3.82	6.3	-2.48	-95.23
J	7.26	5.6	1.66	63.74
J	7.14	5.4	1.74	66.82
A	6.13	5.4	0.73	28.03
S	6.42	4.5	1.92	73.73
O	4.16	4.5	-.34	-13.06
N	1.12	3.7	-2.58	-99.07
D	1.17	3.0	-1.83	-70.27

* Assumed one inch equals 38,400 acre-feet (Joyner, 1974).

Data is form U.S. Army Corps of Engineers, Jacksonville, Florida.

TABLE 4. Normalized Tributary Inflow, Rainfall, and Evaporation to Lake Okeechobee

	A 1951-60 Inflow	B* 1965-74 Inflow	C** Rain-Evap.	D (A+C)	E (B+C)	Regulation
J	126.5	88.2	-71.0	55.5	17.2	4200
F	97.6	89.2	-69.5	28.1	19.7	4065
M	129.7	161.5	-92.5	37.2	69.0	3800
A	129.9	100.7	-109.4	20.5	-8.7	3527
M	116.4	79.4	-95.2	21.2	-15.8	3527
J	150.2	232.6	63.7	312.9	296.3	3527
J	182.6	337.4	66.8	249.4	404.2	3527
A	233.4	287.8	28.0	261.4	315.8	3710
S	255.6	274.4	73.7	329.3	348.1	4065
O	337.8	277.0	-13.1	324.7	263.9	4200
N	141.4	76.4	-99.1	42.3	-22.7	4200
D	149.9	50.9	-70.3	76.6	-19.4	4200
Σ	2051.2	2055.5	-387.9			

* normalized to 2,055,000 acre-feet/year by multiplying 1965-74 data by 1.09

** from Table 3

TABLE 5. Discharges and Regulation of Stages in Lake Okeechobee as it is Affected by Different Runoff Patterns

	1951-60		1965-74	
	Total Monthly Discharge	End of Month Storage	Total Monthly Discharge	End of Month Storage
J	55.5	4200.0	17.2	4200.0
F	163.1	4065.0	154.7	4065.0
M	302.2	3800.0	334.0	3800.0
A	293.5	3527.0	264.3	3527.0
M	21.2	3527.0	0	3511.2
J	213.9	3527.0	253.5	3527.0
J	249.4	3527.0	404.2	3527.0
A	78.4	3710.0	132.8	3710.0
S	0	4039.3	0	4058.1
O	164.0	4200.0	122.0	4200.0
N	42.3	4200.0	0	4177.3
D	76.6	4200.0	0	4157.9
	1660.1		1682.7	

Summer discharge is 248.8 x 10^3 acre-feet greater from 1964-74 period. Discharge equals amount of water needed to be released for closest maintenance of regulation regime. This budget does not include the 350,000 acre-feet of agricultural water needs.

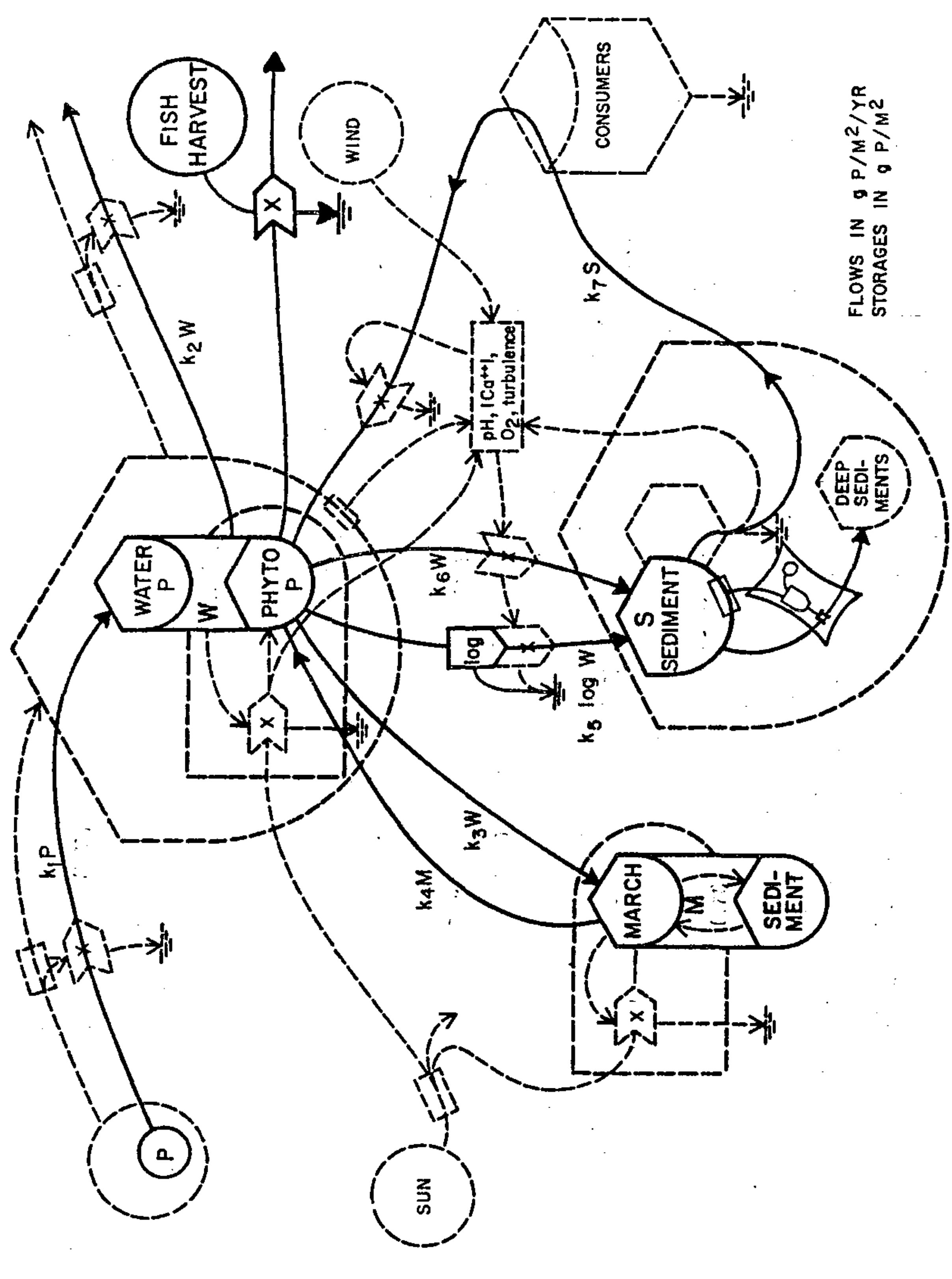
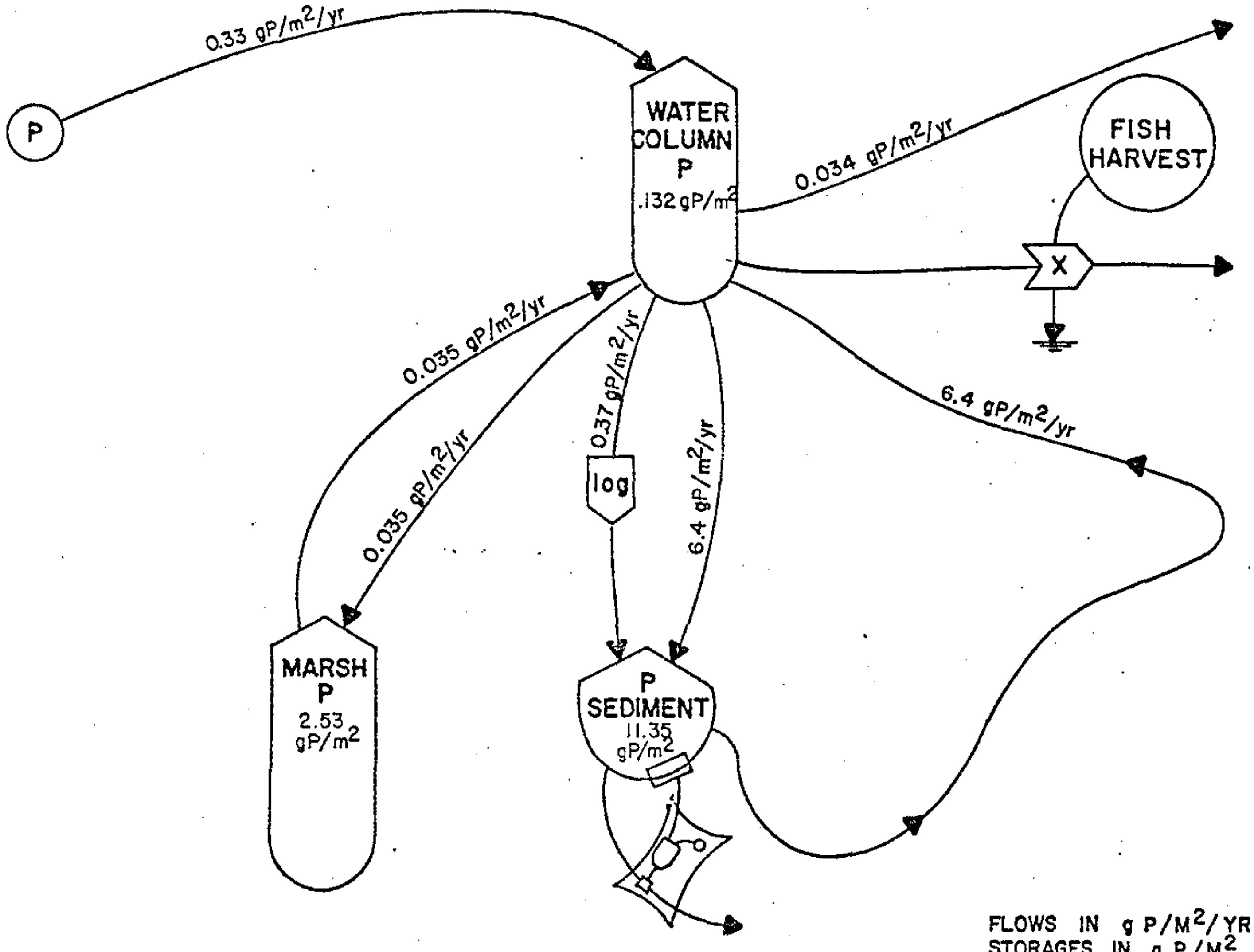

FISH HARVEST
WIND
CONSUMERS
k_2W
k_7S
pH, [Ca++], O_2, turbulence
WATER P
W
PHYTO P
k_6W
log
k_5 log W
S
SEDIMENT
DEEP SEDI-MENTS
k_1P
k_3W
k_4M
MARCH
M
SEDI-MENT
P
SUN
FLOWS IN g P/M^2/YR
STORAGES IN g P/M^2

Figure 13. A simplification of the phosphorus model shown in Fig. 12 and evaluated for present conditions. Quantities of phosphorus storage and flow are for an average square meter in the lake.



P
0.33 gP/m2/yr
WATER COLUMN P
.132 gP/m2
0.034 gP/m2/yr
FISH HARVEST
X
0.035 gP/m2/yr
0.035 gP/m2/yr
0.37 gP/m2/yr
log
6.4 gP/m2/yr
6.4 gP/m2/yr
MARSH P
2.53 gP/m2
P SEDIMENT
11.35 gP/m2
FLOWS IN g P/M2/YR
STORAGES IN g P/M2

TABLE 6. Sources, Storages, and Rates for the Phosphorus Model of Lake Okeechobee (Figs. 12 and 13).

Parameter	Note	Description	Numerical Value ($gm\ P/m^2$)
W	1	total P in 2.44 meters of water	0.132
M	2	total P in marsh peat and plants	2.53
S	3	total P in sediments	11.35
k_1P	4	total P load in 1952	0.102/yr
k_1P	5	total P load in 1969	0.389/yr
k_1P	6	total P load in 1974	0.33/yr
k_1P	7	total P load area-corrected from Lake Apopka	1.1/yr
k_2W	8	total P leaving lake in 1952	0.020/yr
k_2W	9	total P leaving lake in 1969	0.114/yr
k_2W	10	total P loss from lake in 1974	0.033/yr
k_2W	11	expected losses with Apopka-like loading	0.22/yr
k_3W	12	delivery of P to marsh	0.035/yr
k_4M	13	release of P from marsh	0.035/yr
$k_5 \log W$	14	sorption of P into sediments	0.365/yr
k_6W	15	organic sedimentation of P	6.4/yr
k_7S	16	recycle of P to water column	6.4/yr

TABLE 6. (Continued)

1. Davis and Marshall (1975) reported total phosphorus concentrations in lake average 0.054 g P/m^2. Assuming an average depth of 8 feet at a stage of 14 feet MSL, the standing crop equals 0.132 g P/m^2.

2. The author made biomass clippings of various marsh communities in Lake Okeechobee near Clewiston during August 1974. A quarter m^2 of marsh was cut, dried at 70°C for five days and weighed; the dry weights were multiplied by the factor 0.4 to convert to grams carbon. The results were: bullrush-680 g C/m^2, cattail-380 g C/m^2, spikerush-150 g C/m^2, peppergrass-90 g C/m^2, pond lilly-100 g C/m^2 (estimated). The weights were multiplied by the areas of these communities given by Ager (1974) to get a total of 65.2 X 10^9 g C in marsh plants. This equals 37.6 g C/m^2 when prorated over the lake area of 1.736 billion m^2. Assuming a C:P ratio of 100:1 in these plants, the average phosphorus standing crop is 0.376 g P/m^2.

Phosphorus in marsh soils can be estimated by assuming a bulk density of 1 g dry wt/cm^3 which equals 10^4 g dry wt/m^2/cm depth. Assuming depth of sediments in marsh is 5 cm deep and concentration is 0.27 x 10^{-3} g P/g dry wt of sediment (Joyner, 1974). The standing crop of phosphorus in marsh soils is (5 x 10^4 x 0.27 x 10^{-3} =) 13.5 g P/m^2 to 5 cm. Prorate this value overmarsh sediment area (0.276 billion m^2) and the whole lake area (1.736 billion m^2) which equals 2.15 g P/m^2.

The phosphorus in the marsh plants and soils is 2.53 g P/m^2.

3. Total phosphorus stored in sediments in the open water zone can be estimated from calculation in note 2 and prorating the standing crop to 5 cm (13.5 g P/m^2) over the area of open water zone dividing by the area of the whole lake. This equals 11.35 g P/m^2 of lake.

4. In Table 6 is the estimation of the phosphorus load delivered to the lake in 1952 (Odum, 1953). Phosphorus load was estimated to be 0.102 g P/m^2/year.

5. As estimated by Joyner (1974) and correcting for time and area of the lake this amounts to 0.389 g P/m^2/year.

6. Davis and Marshall (1975) estimated an areal loading rate of 0.33 g P/m^2/year during 1973-74.

7. Area based loading rates from Lake Apopka was estimated from Sheffield and Kuhrt (1970) by totaling the Zellwood drainage district load of 800,000 lbs o-PO_4 or 0.9 g P/m^2/year, Winter Garden area load of 245 lbs o-PO_4/day or 0.11 g P/m^2/year, and rain influx of about 0.082 g P/m^2/year. This totals 1.1 g P/m^2/year.

8. Using the model Kirchner and Dillon (1975) based on areal loading rates of water to a lake, it predicts the retention of about 80% of the phosphorus entering Lake Okeechobee. Twenty percent leaves which is (0.20 x 0.102 g P/m^2/year) 0.0204 g P/m^2/year.

9. Joyner (1974) reported the loss of 239 tons P over a thirteen month period in 1969 and 1970. Correcting for time and area, this (237 short tons/13 months/lake)(0.923 (13 months)/year)(0.907 metric tons/short ton) ÷ (1.736×10^9 m^2/lake) equals 0.114 g P/m^2/year leaving lake.

10. Davis and Marshall (1975) reported a loss of 63.9 tons P during May 1973 to May 1974. Correcting for area, this (63.9 tons) (.907 metric tons/ton) ÷ (1.736×10^9 m^2/lake) equals 0.033 g P/m^2/year.

11. Using the Kirchner and Dillon (1975) model, 20% of the inflowing phosphorus leaves lake sy surface flow. This (.20 times 1.1 g P/m^2/year) equals 0.22 g P/m^2/year leaving under corrected Lake Apopka loading rates from Lake Okeechobee.

12. Average water depth on the marsh zone (8 to 14 foot MSL contours) is about one meter. The model of water circulation (Fig. 23) predicts average current velocities of 0.01 feet per second under high flow conditions; assume velocities are 0.001 feet per second under average conditions. Water velocities of 0.001 feet per second equal about 1 meter per hour. Assume water exchanges occur over a length of marsh roughly equal to the periphery of the lake (129 km). Lake water at 0.054 g P/m^3 (Davis and Marshall, 1975) being advected at 1 m/hour over marshes 1 meter deep will deliver 0.054 g P/m^2/hour or 473.04 g P/m^2/yr. As lake water meets the marsh periphery, 473 g P/m^2/yr or (129×10^3m x 473 g P/m^2/ year) 61×10^6 g P/periphery/year is delivered. Prorating the delivery over a marsh area of 0.276×10^9 m^2 (Ager, 1974) this equals 0.22 g P/m^2/year. Prorating over entire lake area of 1.736×10^9 m^2 the average flow of phosphorus to the marsh is 0.035 g P/m^2/year.

13. Assume losses of phosphorus from marsh equals delivery of phosphorus to marsh (note 12) at steady state. Losses equal 0.035 g P/m^2/year.

14. According to Kamp-Nielson (1974) sorption of phosphorus into aerobic lake muds follows the equation $Y = -1.38x + 1.88$, where: x is the log of the concentration of μg P-PO_4/ℓ in overlying waters and Y is the rate of sorption in mg P-PO_4/m^2/day. At a pH of 8.4 the Y-intercept of the regression equation is closer to 1.13, although in the simulation a range of values was used. Total phosphate levels were corrected to o-PO_4 levels by a factor of 0.65 from Joyner (1974). Solution of this equation for Lake Okeechobee when pH is 8.4, Y-intercept is 1.13, and PO_4-P is 35 μg/ℓ yields the sorption rate of .365 gP/m^2/year.

15. Sedimentation rate is assumed to the phosphorus equivalent of the amount of carbon produced (2.1 gC/m^2/day) plus the allochthonous flows (0.07 gC/m^2/day) minus the amount of respiration in dark bottles measured by Davis and Marshall (1975) minus the amount consumed by higher animals (see calculations of carbon flows in metabolism model). This results in a sedimentation rate of

1.76 gC/m^2/day or 642 gC/m^2/year. Assuming the C:P ratio was 100:1 in this material, the amount of phosphorus sedimented equals 6.42 gP/m^2/year. The production and respiration values are from Davis and Marshall (1975). The level of higher consumption is estimated from data on fish, zooplankton, and bottom animal populations by Joyner (1974), Ager (1974), and Davis and Marshall (1975).

16. Assuming sedimentation and recycle are equal, the recycle of phosphorus was evaluated at 6.42 gP/m^2/year. If this is equivalent to 642 gC/m^2/year or 0.18 gO_2/m^2/hr, it places sediment respiration in the range normal for Florida lake bottoms (Tom Ballinger, pers. comm.).

TABLE 7. Estimated Phosphorus Loads to Lake Okeechobee During 1952*

Tributary	Concentration, mg/	Flow, acre-feet	Load, $x10^7$gP/yr
Kissimmee	0.007	1,411,000	1.219
Fisheating Creek	.031	308,300	1.179
Taylor Creek	.057	73,840	.519
Indian Prairie	.121	35,400	.529

Total phosphorus load from tributaries is 3.446 x 10^7 gP/yr or .020 gP/m^2/yr. Load from rain averages 0.082 gP/m^2/yr (Joyner, 1974). Total load to lake in 1952 is 0.102 gP/m^2/yr.

* Concentrations measured by Odum (1953) in summer of 1952. Flows from the Kissimmee and Fisheating Creek were from USGS water records, whereas flows from Taylor Creek and Indian Prairie were long-term averages from Joyner (1974).

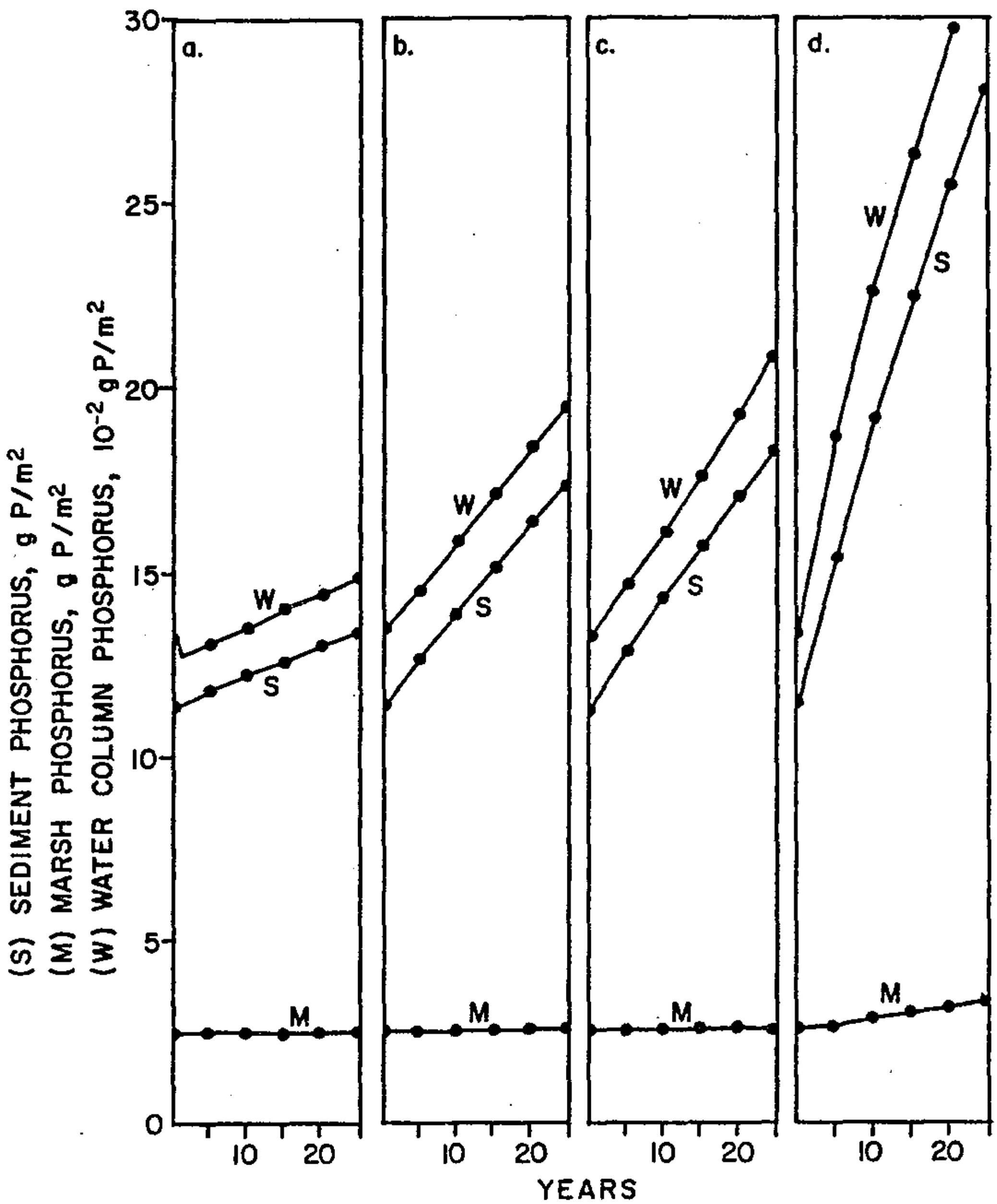
model condition during which marsh phosphorus (M), sediment phosphorus (S), and water column phosphorus (W) were monitored.

Figure 14 shows the effect of different phosphorus loading rates on the levels of phosphorus in the lake. Loading rates calculated from studies by Odum (1953), Joyner (1974), Davis and Marshall (1975), Sheffield and Kuhrt (1970) affect the results of simulations in Fig. 14a, 14b, 14c, and 14d, respectively. The phosphorus loads based on Odum's study represent more natural conditions, loads based on Joyner's study and Davis' study represent present levels, and loads based on Sheffield's work with Lake Apopka represent very high load rates.

Figure 14 shows that the rate of phosphorus build up increases with load rate. After 25 years water column phosphorus levels show increases of 12%, 49%, 58%, and 147% with each increasing net load to the lake in Figs. 14a-14d. This equals rates of increase of water column phosphorus of 0.6 parts per billion (ppb)/year, 2.6 ppb/year, 3.1 ppb/year, and 7.8 ppb/year, respectively for Figs. 14a-14d. Joyner (1974) measured an average 47 ppb total phosphorus from 1969-72 and Davis and Marshall (1975) reported an average 54 ppb total phosphorus from January 1973 to May 1974. Odum (1953) reported total phosphorus levels lower than any measured during later studies which averaged 13 ppb. The difference between earliest measurements and latest measurements is 41 ppm of water column phosphorus. The marshes in these simulations remained the same because of the small rates of exchange between water column phosphorus and marsh phosphorus.

Figure 15a shows the same simulations as 14c which is the lake under the influence of 25 years of phosphorus loads measured by Davis. All of the following simulations in Fig. 15 and Fig. 16 have Davis' loading rates but have variations of other parts of the model. Figure 15b shows the

Figure 14. Results of simulating phosphorus model shown in Figs. 12 and 13 for 25 years of four different inflow rates. In order of increasing net annual delivery to the lake were: (a) inflows of 1952 (Odum, 1953); (b) inflows of 1969 (Joyner, 1974); (c) inflows of 1974 (Davis and Marshall, 1975); and (d) inflows of area-corrected flows to a hypereutrophic lake, Lake Apopka (Sheffield and Kuhrt, 1970).


(S) SEDIMENT PHOSPHORUS, g P/m^2
(M) MARSH PHOSPHORUS, g P/m^2
(W) WATER COLUMN PHOSPHORUS, 10^{-2} g P/m^2
YEARS
a.
b.
c.
d.
W
S
M
0
5
10
15
20
25
30
10
20

effect of phosphorus losses by aerosol formation which equals rainfall loads. In this simulation water column phosphorus increases 41% in 25 years. Water column phosphorus rises similarly in Fig. 15c when marsh uptake is increased five times. Figure 15d shows the effect of marshes dying off and releasing phosphorus to the water column. This accelerates rises in water column phosphorus to 79% over 25 years; sediment phosphorus shows similar rise.

Figure 16a shows phosphorus levels from Davis' loading rates. Figure 16b shows the effect of desorption of sediment phosphorus under anaerobic or low pH conditions. The water column phosphorus levels rise suddenly in the first five years up to an 83% increase over the period simulated. Figure 16c shows the effect of constant recycle rates. The water column phosphorus holds steady at 0.054 gP/m^3. Sediment levels increase more rapidly with constant recycle. Figure 16d shows the effect of higher recycle rates (25% increase). Water column phosphorus levels increase 93% over the period simulated, whereas sediment phosphorus levels show little difference from the changes in 14a. The simulations in Fig. 16 underscore the importance of water-sediment interactions in affecting phosphorus levels. Small changes in water-sediment exchange rates have large effects on water-borne phosphorus levels.

Daily Metabolism in Lake Okeechobee

The model in Fig. 17 represents the relationships and parameters believed to be important in the daily functioning of the lake ecosystem and includes the driving forces of the sun, atmosphere and allochthonous carbon and phosphorus flows. Interactions between total dissolved phosphorus flows. Interactions between total dissolved phosphorus, dissolved

Figure 15. Results of simulating phosphorus model shown in Figs. 12 and 13. Figure 15a and 14c are identical and show response of phosphorus system to present inflow rates. Figure 15b shows phosphorus levels in lake if aerosol losses equal rain inputs. Five times higher marsh uptake rates than in Fig. 15a are shown in Fig. 15c. Figure 15d shows effects of extensive marsh die-off. Phosphorus levels are for water column (W), sediment (S), and marsh (M).

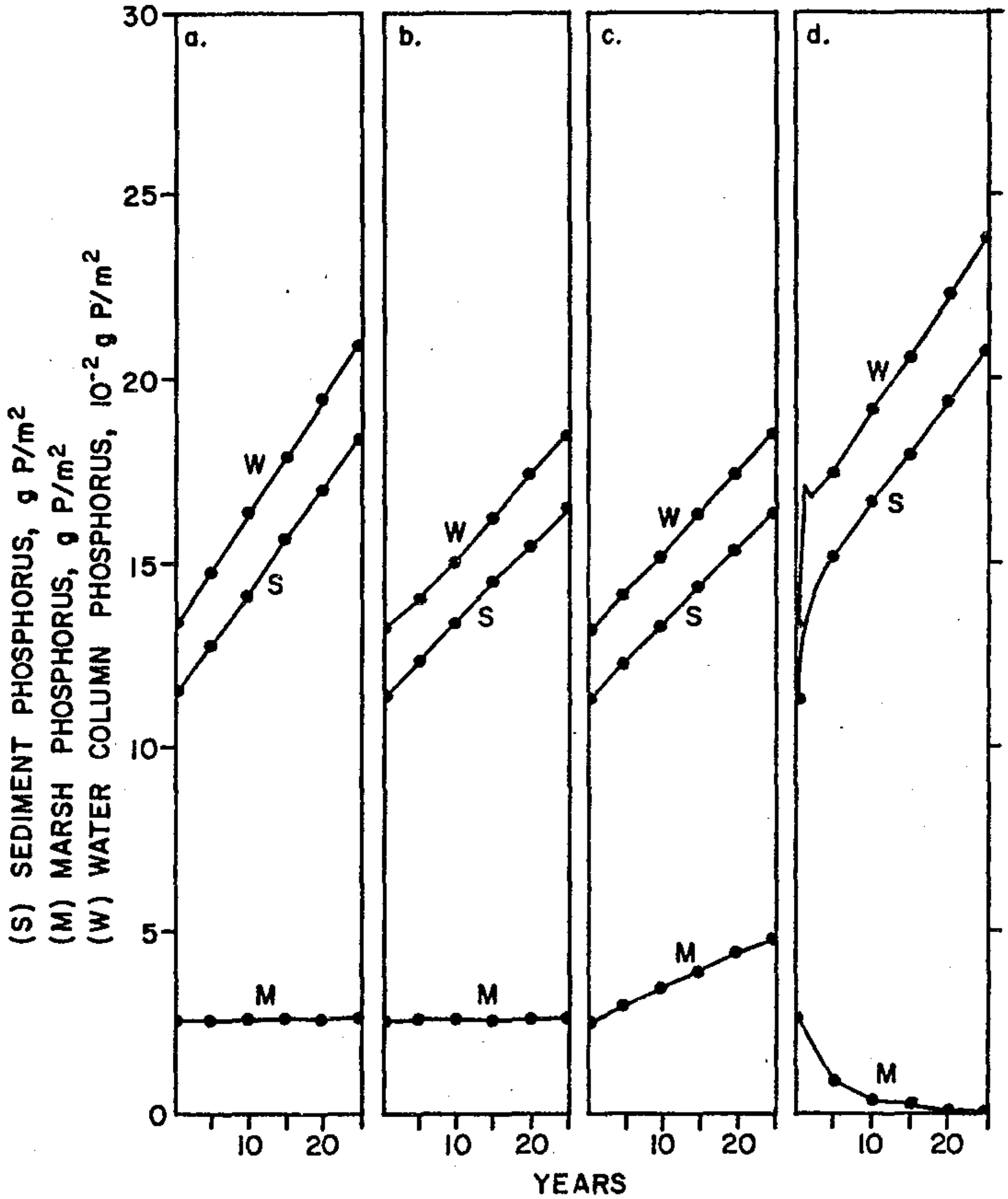
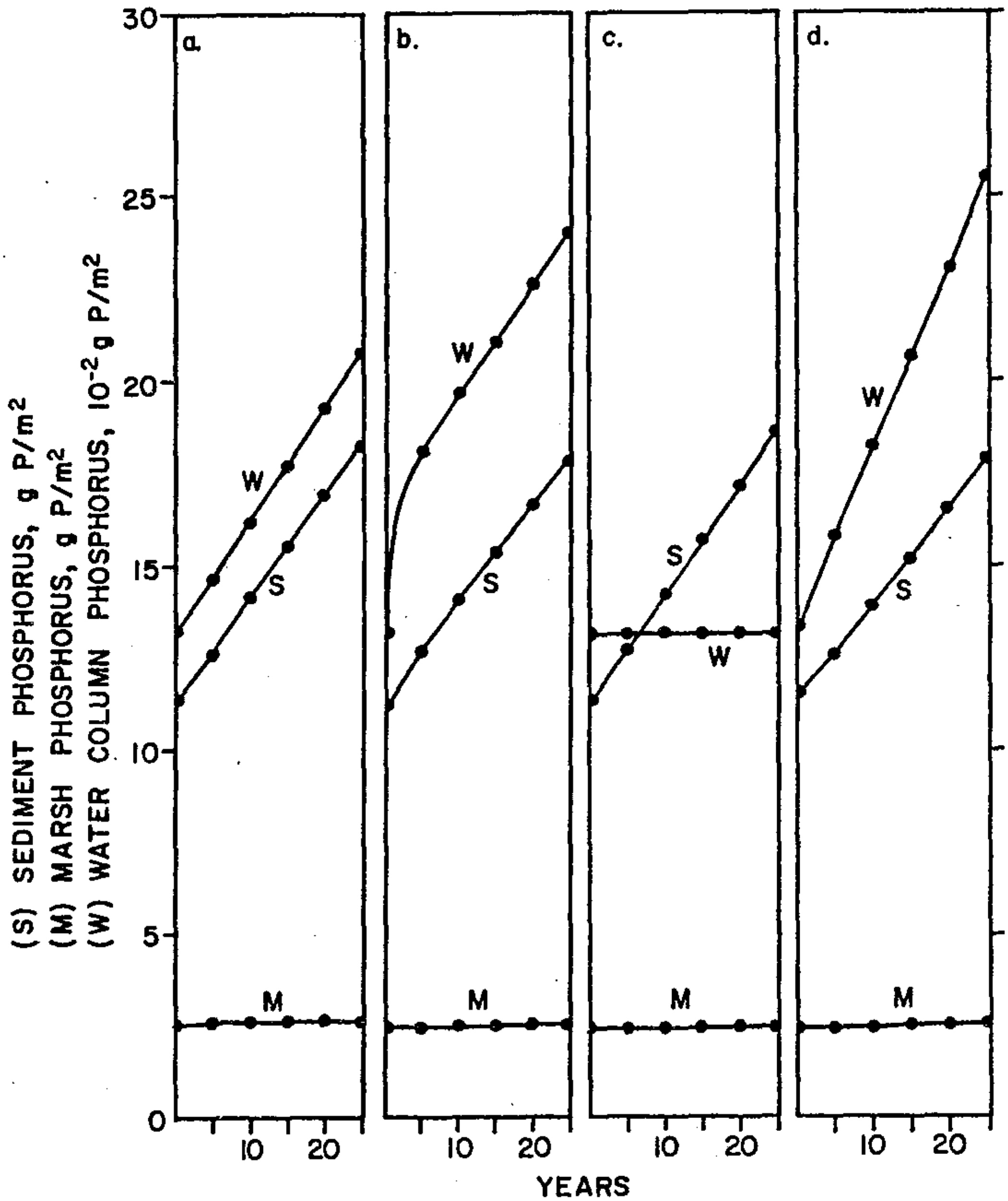

(S) SEDIMENT PHOSPHORUS, g P/m2
(M) MARSH PHOSPHORUS, g P/m2
(W) WATER COLUMN PHOSPHORUS, 10-2 g P/m2
30
25
20
15
10
5
0
a.
b.
c.
d.
W
S
M
10
20
YEARS

Figure 16. Results of simulation of phosphorus model shown in Figs. 12 and 13. Figure 16a shows effects of present loading rates. Figure 16b shows desorption of phosphorus under anaerobic conditions. Figure 16c shows constant recycle rate and Fig. 16d shows elevated recycle rates as they affect lake nutrient levels. Phosphorus levels in the water column, sediment, and marsh are represented by W, S, and M.


(S) SEDIMENT PHOSPHORUS, g P/m²
(M) MARSH PHOSPHORUS, g P/m²
(W) WATER COLUMN PHOSPHORUS, 10⁻² g P/m²
a.
b.
c.
d.
W
S
M
0
5
10
15
20
25
30
10
20
YEARS

phosphorus, dissolved oxygen, total organic carbon, sediments and consumers are represented in the various assimilation, production and recycle pathways. The mathematical relationships presented in Fig. 17 are replaced by quantified values for storages and flows in Fig. 18. In Table 8 is a list and description of these model parameters which are annotated.

Since flow of allochthonous organic carbon loads from tributaries to the lake can account for present saturation deficits of dissolved oxygen observed in the lake, the decomposition of the marsh's organic pool may be separate from that in the limnetic zone. Low current velocities and low turbidity measurements just lakeward of the marsh support this assumption.

The simulation results in Fig. 19 show diurnal changes in the lake parameters for five days of average conditions. Dissolved oxygen levels reached equilibrium with the carbon loads in five days, varying between 7.0 and 7.5 ppm. Total dissolved phosphorus varied between 32 and 38 parts per billion with highest values at sunrise after five days of average conditions. The parameters of sediment, and consumers held steady, and the water column carbon increased by about 0.1 ppm/day.

The graphs in Fig. 20 show the effects of low diffusion on the lake's oxygen levels. In five days the oxygen levels dropped to 5.3 ppm and water column carbon and sediment carbon increased 33% and 10%, respectively. The increases in standing crops of carbon was due to decreased oxidation.

The graph in Fig. 21 representing a 100-fold increase in phosphorus loading to the lake, shows phosphorus levels rising to 0.1 mg/l in five days. These high levels of phosphorus increase production of oxygen to to levels of super-saturation (120-140%). The high productivities cause greater diurnal variation of water column carbon and dissolved oxygen.

Figure 17. Model and mathematical equivalents of daily metabolism in Lake Okeechobee. The model in broken lines shows the larger system given in Fig. 2 from which this model was simplified.

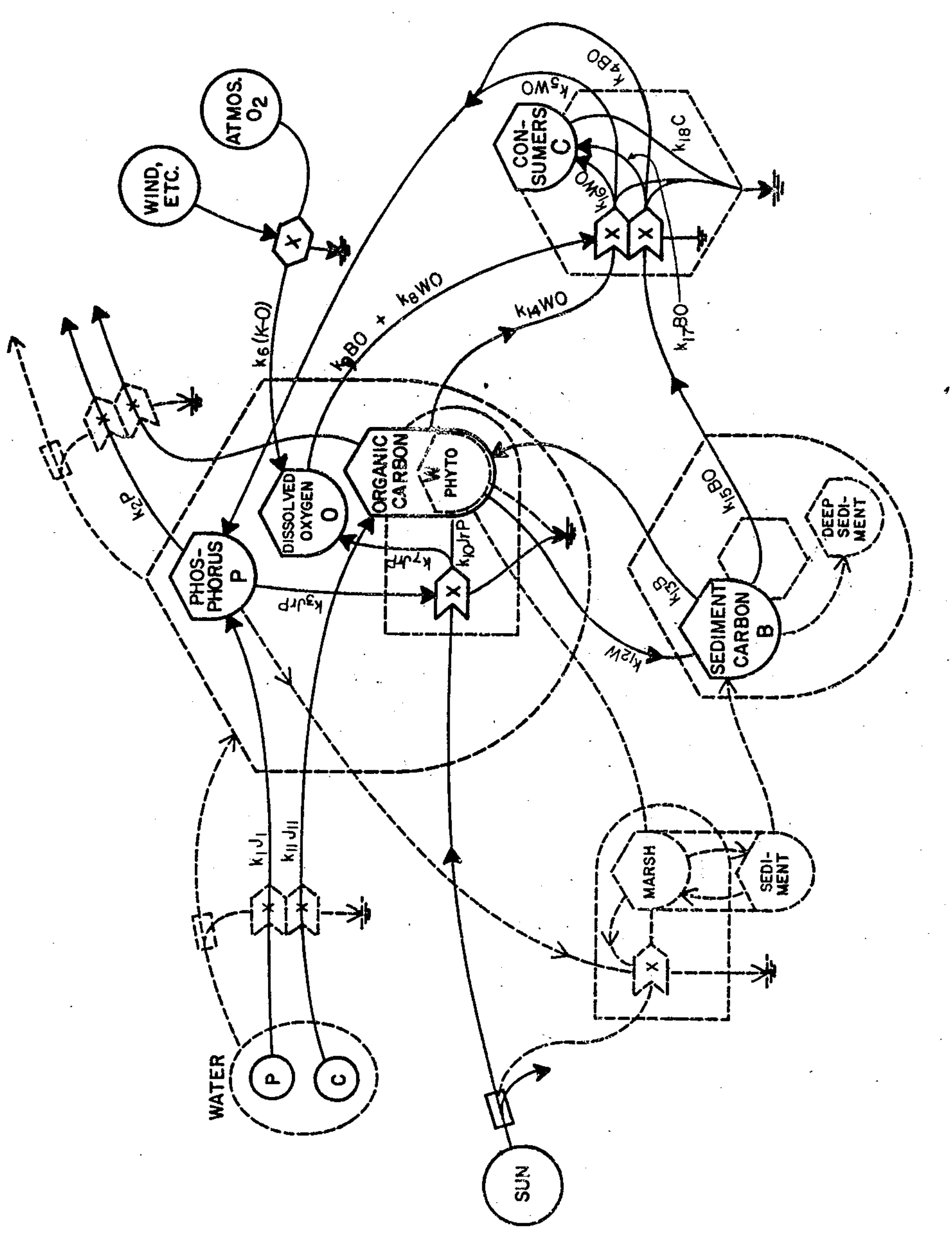

WIND, ETC.
ATMOS. O2
CON-SUMERS C
PHOS-PHORUS P
DISSOLVED OXYGEN O
ORGANIC CARBON
PHYTO
SEDIMENT CARBON B
DEEP SEDI-MENT
MARSH
SEDI-MENT
WATER
P
C
SUN
k6(K-O)
k9BO + k8WO
k14WO
k5WO
k4BO
k16WO
k18C
k17BO
k15BO
k13B
k12W
k2P
k3JrP
k7JrP
k10JrP
k1J1
k11J11

Figure 18. Model of metabolic system in limnetic zone of Lake Okeechobee. Values for flows and storages are included.

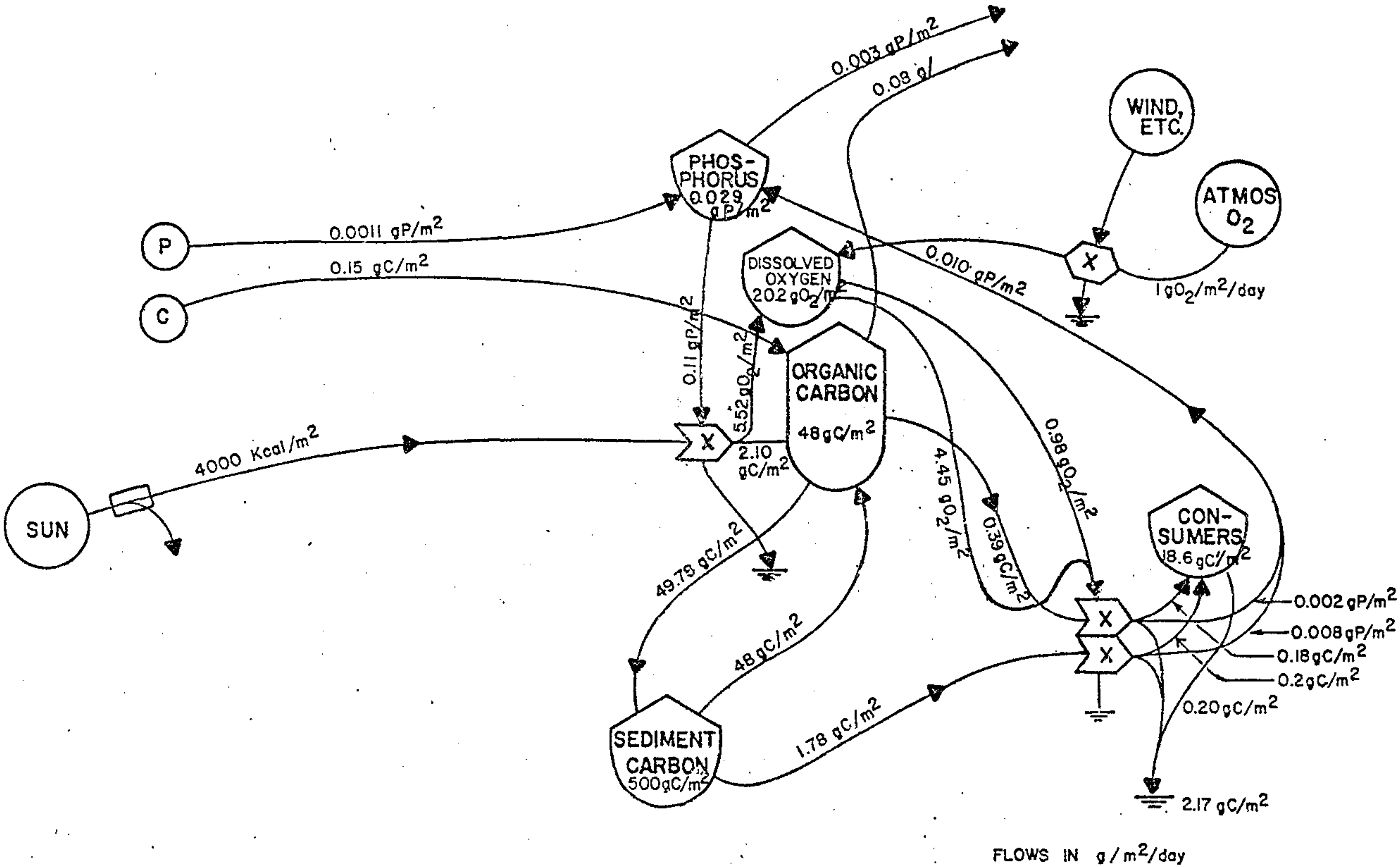

SUN
4000 Kcal/m^2
P
0.0011 gP/m^2
C
0.15 gC/m^2
PHOS-PHORUS 0.029 gP/m^2
0.003 gP/m^2
0.08 g/
WIND, ETC.
ATMOS O_2
1 gO_2/m^2/day
DISSOLVED OXYGEN 202 gO_2/m^2
0.010 gP/m^2
0.11 gP/m^2
5.52 gO_2/m^2
2.10 gC/m^2
ORGANIC CARBON 48 gC/m^2
4.45 gO_2/m^2
0.98 gO_2/m^2
0.39 gC/m^2
CON-SUMERS 18.6 gC/m^2
49.78 gC/m^2
48 gC/m^2
SEDIMENT CARBON 500 gC/m^2
1.78 gC/m^2
0.002 gP/m^2
0.008 gP/m^2
0.18 gC/m^2
0.2 gC/m^2
0.20 gC/m^2
2.17 gC/m^2
FLOWS IN g/m^2/day

TABLE 8. Values Used in Simulating the Model of Metabolic Activities in Figs. 17 and 18.

Parameter	Note	Description	Value
k_1J_1	1	inflow of phosphorus	0.0011 $gP/m^2/day$
k_2P	2	outflow of phosphorus	0.003 $gP/m^2/day$
k_3J_rP	3	phosphorus assimilation	0.011 $gP/m^2/day$
k_4BO	4	recycle from respiration and consumption of water-borne organic matter	0.008 $gP/m^2/day$
k_5WO	5	recycle from respiration and consumption of sediment organic matter	0.002 $gP/m^2/day$
$k_6(K-O)$	6	diffusion of oxygen	1.0 $gO_2/m^2/day$
k_7JrP	7	oxygen production	5.25 $gO_2/m^2/day$
k_8WO	8	respiration in water column	0.98 $gO_2/m^2/day$
k_9BO	9	respiration in sediments	4.45 $gO_2/m^2/day$
$k_{10}JrP$	10	organic carbon production from algae	2.1 $gC/m^2/day$
$k_{11}J_{11}$	11	net daily load of allochthonous organic carbon	0.7 $gC/m^2/day$
$k_{12}W$	12	gross rate of sedimentation of organic carbon	49.78 $gC/m^2/day$
$k_{13}B$	13	gross rate of suspension of organic carbon	48.00 $gC/m^2/day$
$k_{14}WO$	14	organic carbon respired in water column	0.39 $gC/m^2/day$
$k_{15}BO$	15	organic carbon respired from sediments	1.78 $gC/m^2/day$

TABLE 8. (continued)

Parameter	Note	Description	Value
$k_{16}WO$	16	net consumption of water column carbon by consumers	0.18 $gC/m^2/day$
$k_{17}BO$	17	net consumption of sediments carbon by consumers	0.02 $gC/m^2/day$
$k_{18}C$	18	respiration and mortality in consumer populations	0.20 $gC/m^2/day$
P	19	standing crop of total dissolved phosphorus	0.029 gP/m^2
O	20	standing crop of dissolved oxygen	20.2 gO_2/m^2
W	21	standing crop of total organic carbon	48 gC/m^2
B	22	carbon in sediments to 1 cm	500 gC/m^2
C	23	standing stocks of consumers	18.6 gC/m^2

TABLE 8. (Continued)

1. Joyner (1974) reported 0.389 gP/m^2/year loading to Lake Okeechobee which equals 0.0011 gP/m^2/day.

2. Joyner (1974 reported 0.114 gP/m^2/year leaving by surface outflows which equals 0.0003 gP/m^2/day.

3. Davis and Marshall (1975) reported an average daily primary production of 2.1 gC/m^2/day. Assuming for every 100 grams of carbon fixed there is 1 gram of phosphorus fixed, and half of the phosphorus fixed is supplied internally from phosphorus storages in the planktons. Daily assimilation of phosphorus equals 0.011 gP/m^2/day. This needs to be measured in lab or field experiments.

4. Davis and Marshall (1975) reported respiration was 10% of gross primary production (GPP) which they estimated to be 2.1 gC GPP/m^2/day. In percent of the GPP is 0.21 gC/m^2/day of plankton respiration. If the consumer population which has a standing crop of 18.6 gC/m^2 (see note 23), and assuming 90% of the consumer's food requirement comes from the water column, this represents a flow of 0.18 gC/m^2/day from water column carbon to consumers. The recycle of phosphorus from plankton respiration (0.21 gC/m^2/day) and consumer activities (0.18 gC/m^2/day) assuming a C:P ratio of 100:1 and a release of one-half this amount (0.18 + 0.21)(0.01)(0.5) equals 0.002 gP/m^2/day.

5. The recycle of phosphorus from sediments depends on the rate of respiration of organic carbon in the sediments. The respiration of organic carbon in sediments is assumed to equal the total fixed (2.1 gC/m^2/day) plus allochthonous sources (0.07 gC/m^2/day) minus respiration of plankton (0.21 gC/m^2/day) and minus the amount consumed by the higher trophic levels (0.20 gC/m^2/day). The calculated sediment respiration (2.1 + 0.07 - 0.21 - 0.20 gC/m^2/day) equals 1.76 gC/m^2/day. Recycle of phosphorus equals one-half of the phosphorus equivalent of carbon respiration (0.5 x 0.01 x 1.76 = 0.0088) minus that which is sorbed into the sediments. Sorption rates were calculated (from phosphorus model) to be 0.365 gP/m^2/year or 0.001 gP/m^2/day. Phosphorus recycle (0.0088 - 0.0010 gP/m^2/day) equals 0.0078 gP/m^2/day. In simulation this value was rounded off to 0.008 gP/m^2/day.

6. Diffusion of oxygen is assumed to equal moderate levels quoted by Odum (1957) for lakes: 1 gO_2/m^2/day at 100% saturation deficit.

7. Oxygen production equals the oxygen equivalent of 2.1 gC/m^2/day of GPP: (2.1 gC/m^2/day x 2.5 gO_2/gC=) 5.25 gO_2/m^2/day.

8. Respiration in the water column (see note 4) equals 0.39 gC/m^2/day; the oxygen equivalent of this is 0.98 gO_2/m^2/day.

9. Respiration in sediments is 1.76 gC/m^2/day plus consumption of sediments (10% of the food requirement of consumers) which is 0.02 gC/m^2/day. The oxygen equivalent of this (1.78 gC/m^2/day x 2.5 gO2/gC) is 4.45 gO_2/m^2/day.

10. Davis and Marshall (1975) reported 2.1 $gC/m^2/day$ for annual lake wide average.

11. Allochthonous organic carbon inflows were estimated from Brezonik's (1975) estimation of total organic carbon (TOC) in backpumpage water (100 mg/ℓ) times average backpumpage flow (350,000 acre-feet/year) and from Joyner's (1974) measurements of TOC in other tributaries which average 20 mg TOC/ℓ and flow at 2,000,000 acre-feet/year. The inflow of carbon is 0.15 g $TOC/m^2/day$. Outflows of carbon (2,000,000 acre-feet/year at 20 mg/ℓ) equals 0.08 g $TOC/m^2/day$. The net organic carbon delivered to the lake is 0.07 g $TOC/m^2/day$.

12. The rate of sedimentation equals the amount of carbon fixed (2.1 $gC/m^2/day$) minus carbon respired and consumed in the water column (0.39 $gC/m^2/day$) plus allochthonous carbon (0.07 $gC/m^2/day$). This equals 0.78 $gC/m^2/day$ of net sedimentation. An arbitrary rate of suspension of carbon was set at 48 $gC/m^2/day$, which represents the replacement of the standing crop of water carbon once a day. The gross sedimentation rate is 1.78 $gC/m^2/day$ plus 48 $gC/m^2/day$ or 49.78 $gC/m^2/day$.

13. The gross rate of suspension of organic carbon was assumed to replace water storages once a day: 48 $gC/m^2/day$.

14. Organic carbon respired and consumed from the water column (see note 4) is 0.39 $gC/m^2/day$.

15. Organic carbon respired from sediments equals 10% of the food needs of the consumer population (0.02 $gC/m^2/day$) plus 1.76 $gC/m^2/day$ of sediment respiration: 1.78 $gC/m^2/day$.

16. Consumption of water column carbon by consumers was estimated to be 90% of total food consumed (see note 23): 0.18 $gC/m^2/day$.

17. Consumption of sediment carbon by consumers was estimated to be 10% of total food consumed (see note 23): 0.02 $gC/m^2/day$.

18. Assuming consumers are in steady state their production (0.20 $gC/m^2/day$) equals their respiration and mortality (0.20 $gC/m^2/day$).

19. Standing crop of total dissolved phosphorus was estimated by averaging Joyner's (1974) phosphorus determination of filtered samples: 0.012 g dissolved and colloidal phosphorus/m^3 and 0.029 g P(dissolved)/m^2 at an average depth of 8 feet.

20. Saturation of O_2 in freshwater at 25°C and 760 mm of pressure is 8.4 ppm. At an average depth of 8 feet this (8.4 g/m^3 x 2.44m) equals 20.5 gO_2/m^2. The initial condition was set slightly below this.

21. Total organic carbon measurements by Joyner (1974) and Brezonik (1975) average 20 mg TOC/ℓ. Over a depth of 8 feet this equals 48.8 gC/m^2. The initial condition in simulation was set slightly lower.

22. At a bulk density 1 cm^3/g, one m^2 of sediment which is 10% organic matter (Burton _et al_., 1975) and one centimeter deep would contain 500 gC/m^2.

23. Consumer biomass was estimated to be 7.0 gC/m^2 of fish (Ager, 1974), 1.0 gC/m^2 of zooplankton (typical level of zooplankton for eutrophic lakes; Nordlie, personal communication), and 10.6 gC/m^2 of benthic invertebrates (numbers of invertebrates - Joyner, 1974; Davis and Marshal, 1975). The total is 18.6 gC/m^2. Benthic invertebrate net production is 73.6 x 10^9 gC/year, zooplankton net production is 30.9 x 10^9 gC/year, fish net production is 17.1 x 10^9 gC/year. The total net production was calculated to be 0.20 gC/m^2/day. The net production of zooplankton and benthic fauna was estimated from Prosser and Brown (1961), Hall (1964), and Waters (1969). The net production of fish was estimated from Gerking (1962), using standing stocks from Ager (1974). The biomass of benthic fauna was calculated by estimating individual weights per organism and multiplying them by numbers of organisms estimated by Joyner (1974) and Davis and Marshall (1975).

Figure 19. Simulation of metabolism model shown in Fig. 18 for five days of average conditions. Shown are daily changes in oxygen, phosphorus, sunlight, carbon, and consumers.

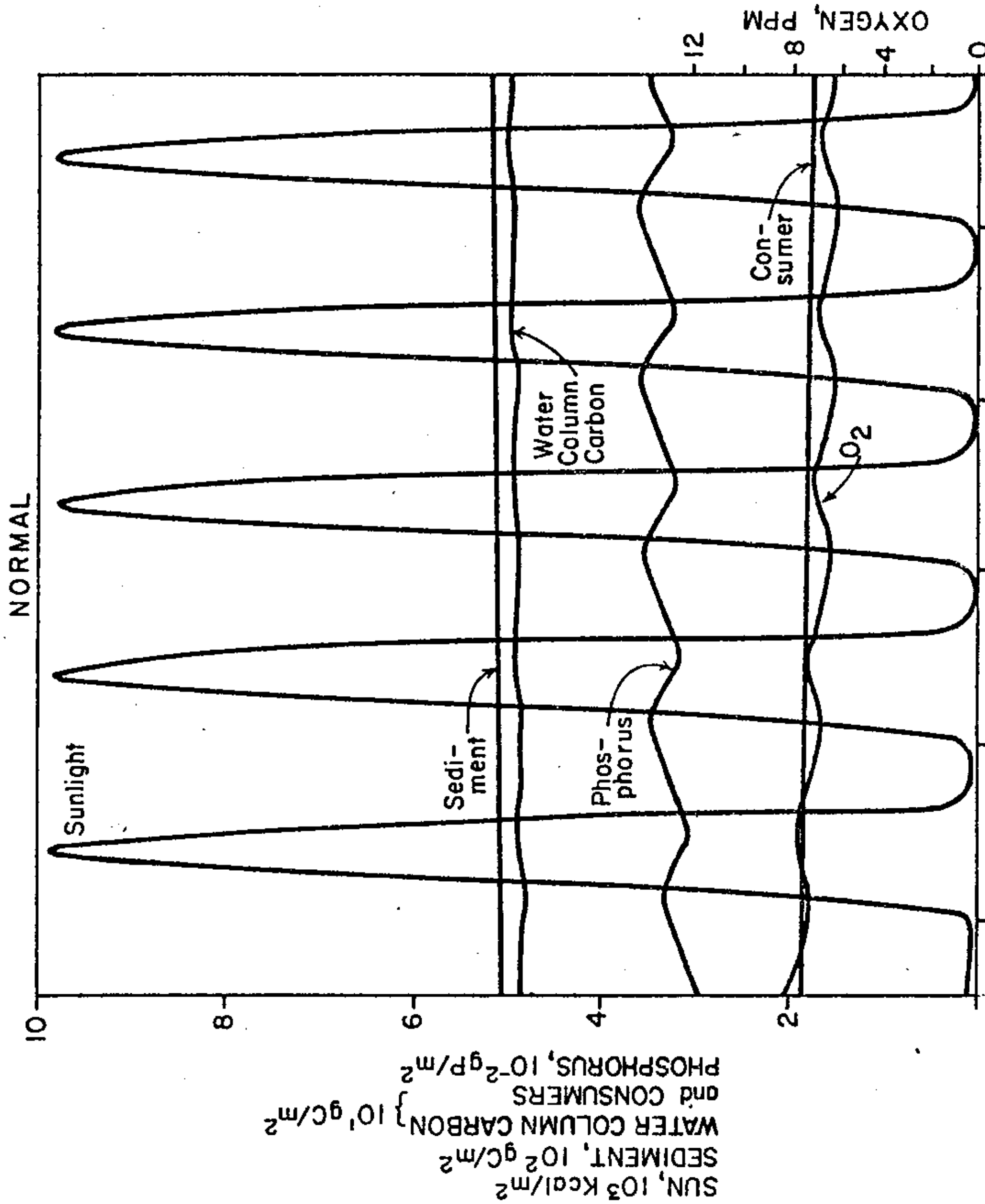

NORMAL
Sunlight
Sedi-ment
Phos-phorus
Water Column Carbon
Con-sumer
O_2
6am
6am
6am
10
8
6
4
2
12
8
4
0
SUN, 10^3 Kcal/m^2
SEDIMENT, 10^2 gC/m^2
WATER COLUMN CARBON and CONSUMERS } 10^1 gC/m^2
PHOSPHORUS, 10^{-2} gP/m^2
OXYGEN, PPM

Figure 20. Simulation of metabolism model in Fig. 18 with low diffusion.

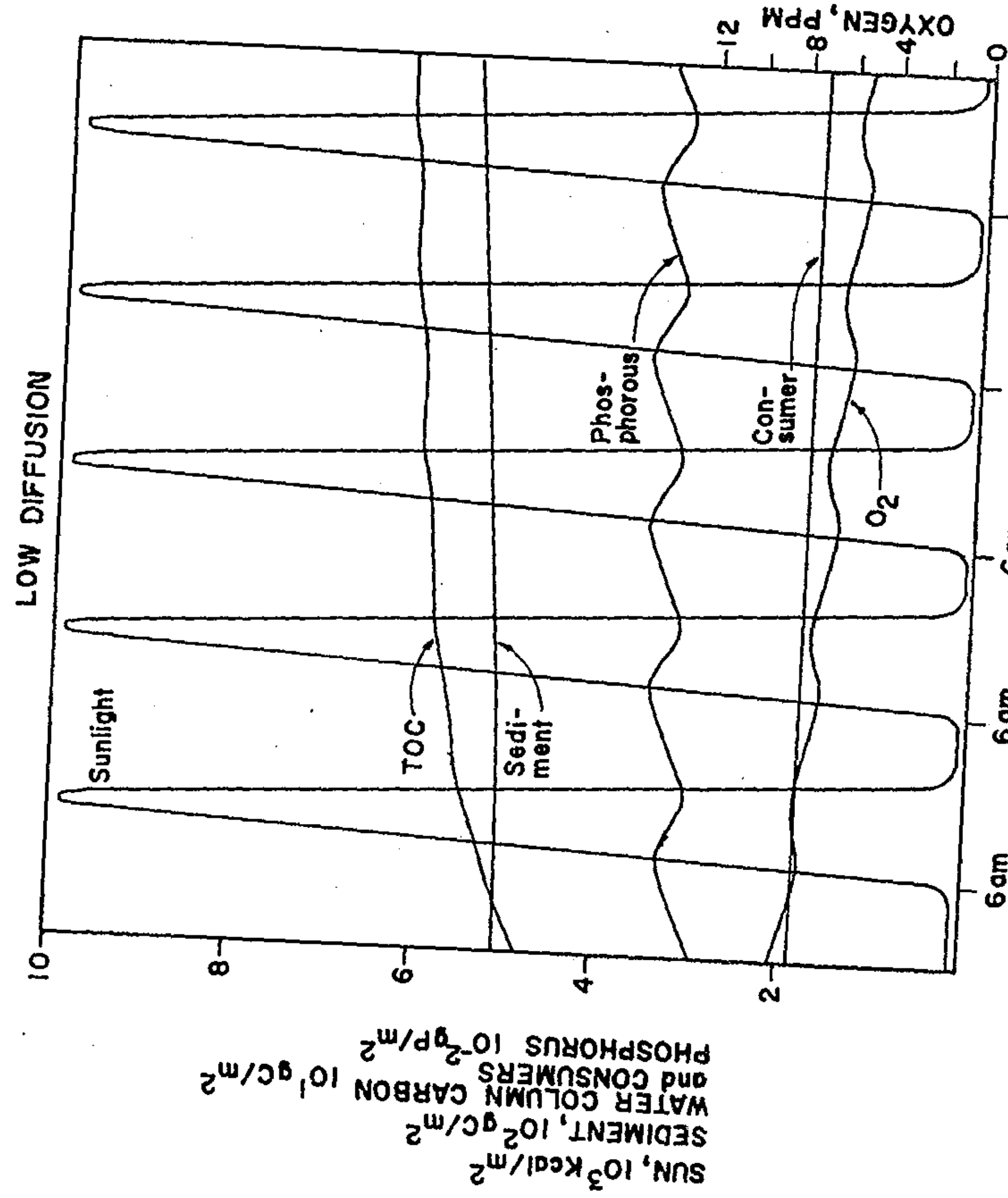
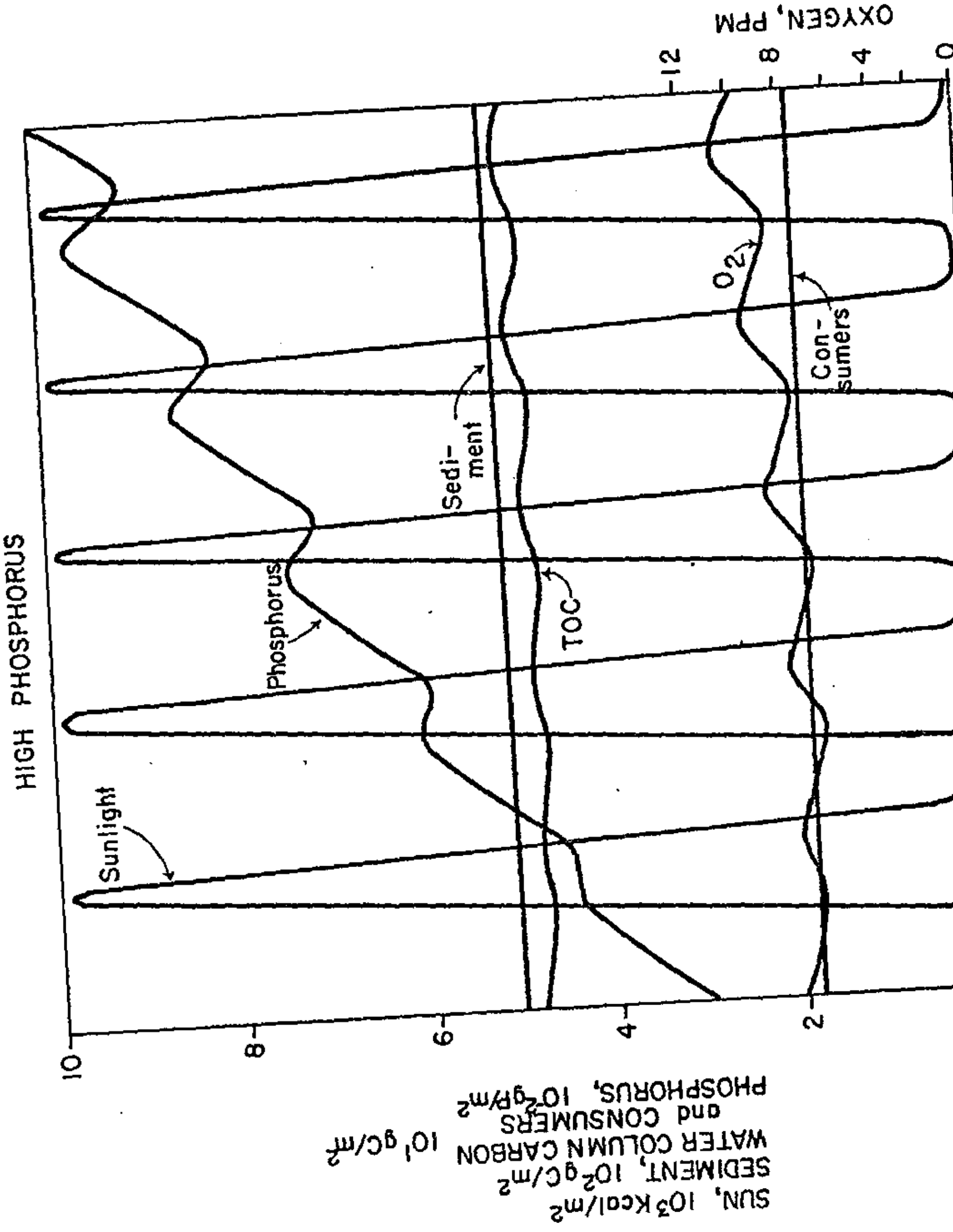

LOW DIFFUSION
Sunlight
TOC
Sedi-
ment
Phos-
phorous
Con-
sumer
O2
6am
6am
6am
OXYGEN, PPM
0
4
8
12
10
8
6
4
2
SUN, 10^3 Kcal/m^2
SEDIMENT, 10^2 gC/m^2
WATER COLUMN CARBON 10^1 gC/m^2
and CONSUMERS
PHOSPHORUS 10^-2 gP/m^2

Figure 21. Simulation of metabolism model in Fig. 18 for high phosphorus inflow.


HIGH PHOSPHORUS
Sunlight
Phosphorus
TOC
Sedi-
ment
O_2
Con-
sumers
6am
6am
6am
OXYGEN, PPM
0
4
8
12
0
2
4
6
8
10
SUN, 10^3 Kcal/m^2
SEDIMENT, 10^2 gC/m^2
WATER COLUMN CARBON 10^1 gC/m^2
and CONSUMERS
PHOSPHORUS, 10^{-2} gP/m^2

Primary production is about 5 g C/m^2/day.

The graph in Fig. 22 represents five days of average lake conditions with a ten-fold increase in organic carbon load. The standing stocks of carbon in the sediment and water column rise similarly to conditions encountered in the simulation of low diffusion. The oxygen sags to normal (80% saturation) levels in five days and reaches lower levels of about 60% saturation in steady state.

Spatial Patterns in Lake Okeechobee

The EPA Storm Water Receiving Model was modified to simulate currents and spatial patterns in Lake Okeechobee under conditions of high runoff, backpumping and strong south winds. Results of the model after five days of simulation is given in Fig. 25. The highest flow rates are in the limnetic zone of the lake between the nodes 5-11-19. The high flow rates from node 1 to node 5 suggest that Taylor Creek water can be advected into the lake from currents induced by the Kissimmee River. The low flow rates in the marsh areas (0.000 to 0.040 feet per second) suggest that transport is low in the marsh and the limnetic and marsh zone are hydraulically distinct. The simulation also indicates lower flow rates in the area of backpumpage at the south end of the lake. This would imply that the hydraulics in the South Bay area tend to restrict the spread of backpumpage water into the lake. These hydraulic characteristics of the lake are supported by observations made by FCD and NASA (Marshall, pers. comm.).

Figure 22. Simulation of metabolism model in Fig. 18 for high organic carbon inflow.

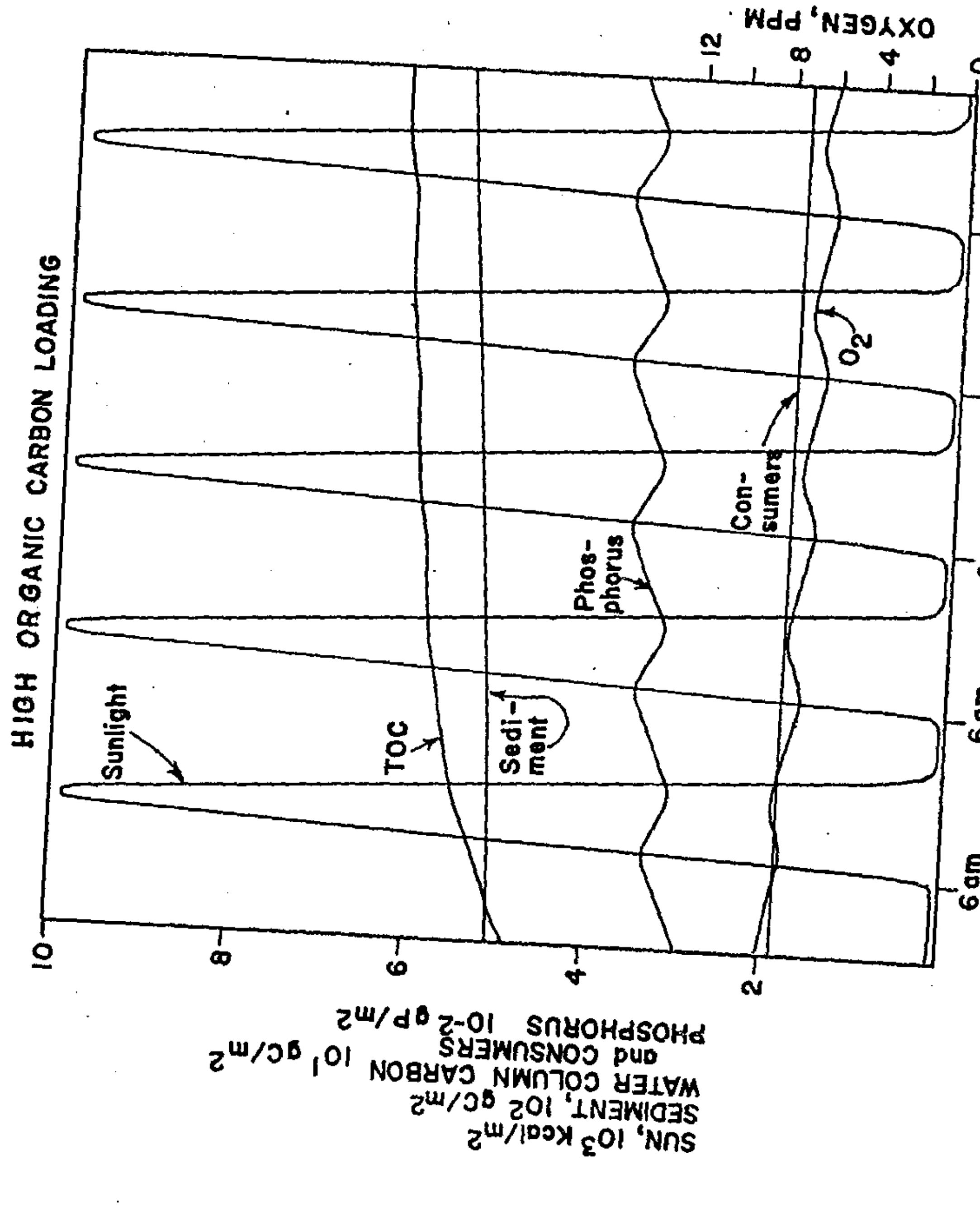
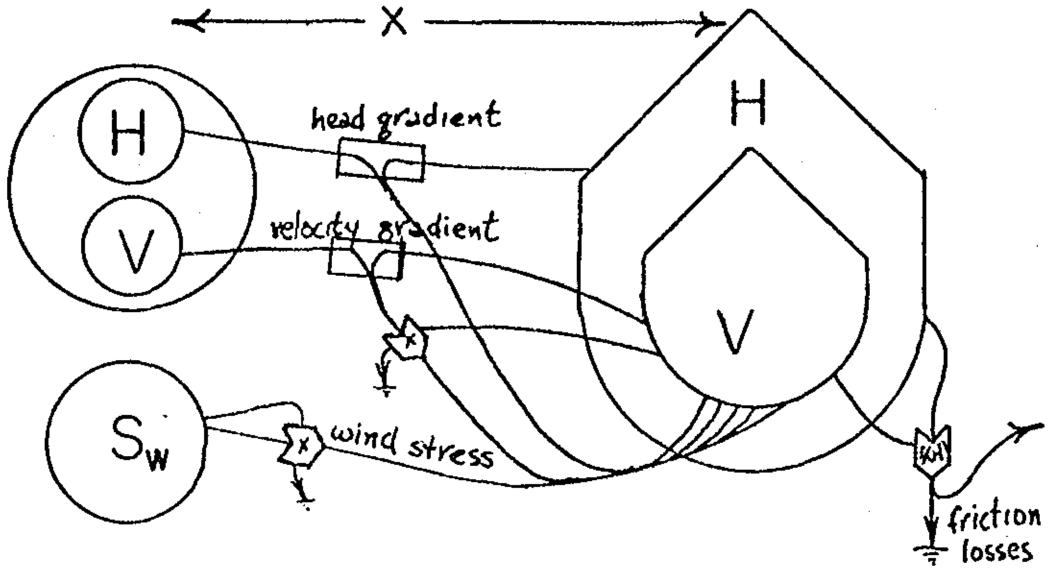

HIGH ORGANIC CARBON LOADING
Sunlight
TOC
Sedi-ment
Phos-phorus
Con-sumers
O_2
6 am
6 am
6 am
OXYGEN, PPM
0
4
8
12
10
8
6
4
2
SUN, 10^3 Kcal/m^2
SEDIMENT, 10^2 gC/m^2
WATER COLUMN CARBON and CONSUMERS 10^1 gC/m^2
PHOSPHORUS 10^{-2} gP/m^2

Figure 23. Energese model and equations of motion for a single node in the spatial model. Channel flow is exchange between the forcing function and the state variable.



Equation of motion:*

$$\frac{V}{t} = -V\frac{V}{X} - g\frac{H}{X} - gS_f + gS_w$$

where: V = velocity
t = time
X = distance
H = height of water above some datum, head
g = gravitational constant
S_f = energy gradient
S_w = wind stress

and: $$S_f = \frac{N^2 V\ [V]}{2.2\ R^{4/3}}$$

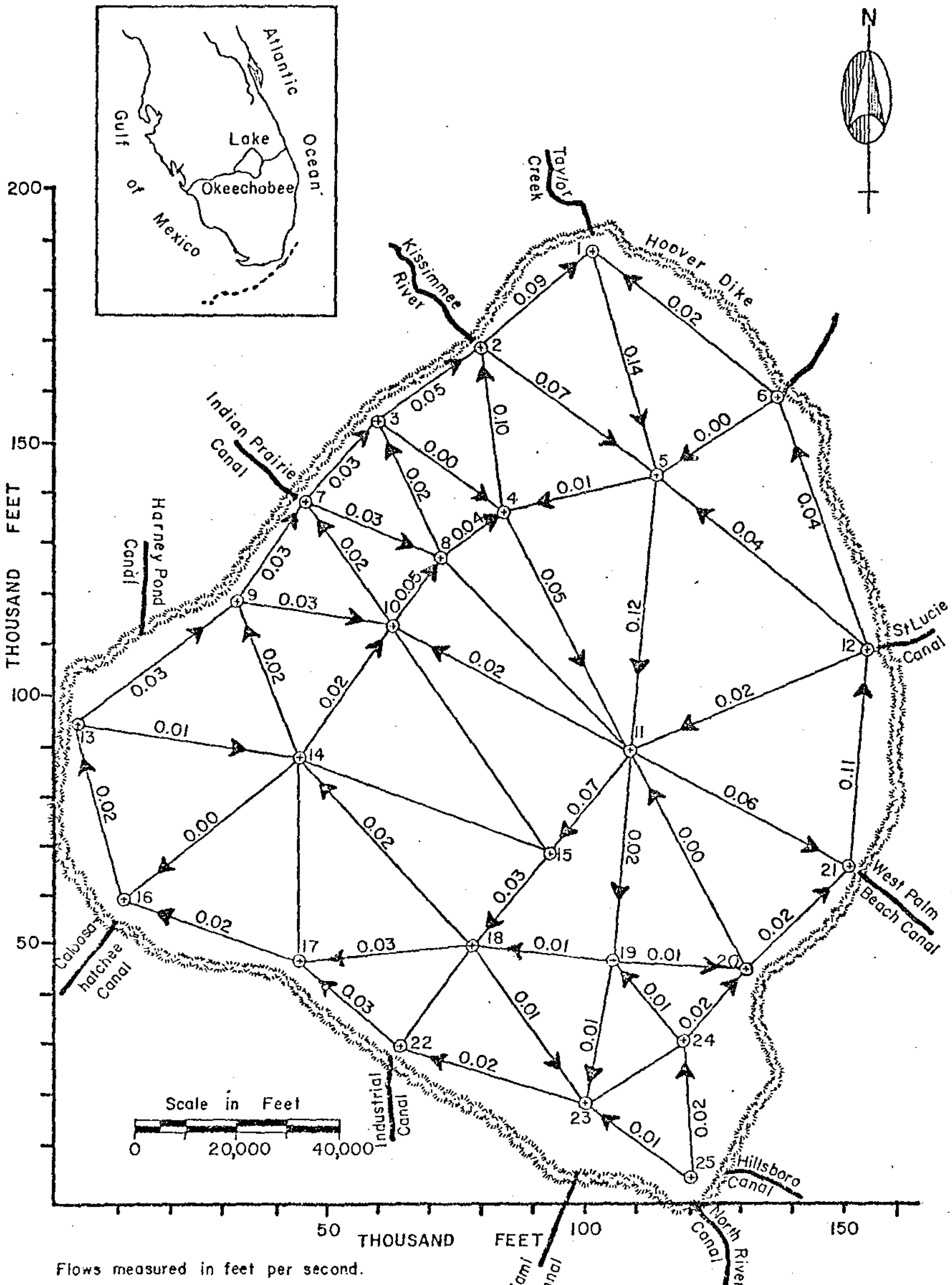
where: N = Manning's frictional coefficient
R = Hydraulic radius

and: $$S_w = \frac{K}{d} \cdot \frac{da}{gdw} \cdot U^2 \cos A$$

where: U = wind velocity
A = angle of wind stress
da = density of air
dw = density of water
d = depth of flow
K = dimensionless coefficient

*from EPA (1971).

Figure 24. Results of simulation of spatial model after five days of high flow from tributaries and pumps. Arrows on the channels (lines) show direction of flow and numbers are flow rates in feet per second.



Flows measured in feet per second.

DISCUSSION

Simulations of models suggest that Lake Okeechobee has changing water regimes and nutrient inflows due to development in watersheds around the lake. Further development in the basin could compound problems in an already eutrophic lake.

Channelization and Water Levels

Channelization of tributaries to Lake Okeechobee has accelerated runoff so that rainy season flow accounts for greater percentages of total annual inflow than under prechannelized conditions (Fig. 8). Although flooding potential is less upstream in these channelized basins, potential flooding downstream is increased. Moderately high rainfall in 1969 caused record flow rates (21,700 cfs) in the Kissimmee River channel which seriously damaged the S-65E control structure; hurricane rains will help determine the efficacy of this flood control system in the future.

Changes in timing of inflow to Lake Okeechobee causes lake stages to rise more quickly and sooner during the rainy season. In order to maintain safe storage capacities in the lake some of the inflow is discharged through the St. Lucie and Caloosahatchee canals. Generally, high rates of inflow require high rates of outflow through regulation to control lake stages. Consequently, accelerated runoff in channelized tributaries may increase runoff and flood stress in the regulation canals (Tables 3, 4, and 5). Accelerated runoff may also cause decreased average annual storage in the lake if summer discharges are increased to keep stages low and fall and winter inflows deliver insufficient water to raise and maintain higher lake stages (Fig. 8; Tables 3, 4, and 5).

Increased tributary flow variability (Heaney and Huber, 1974) may cause increased variability in lake stages (Fig. 8). Although greater ranges in storage may be desireable for managed drawdowns in Lake Okeechobee, this may be undesireable for water supply and navigation purposes. Decreased base flow (Fig. 8) and total flow (Fig. 9) from channelized basins cause lake stages to be lower in the dry season (Fig. 8) and during droughts (Fig. 11).

Channelization and drainage of river basins around Lake Okeechobee has reduced water levels in these basins to the extent that marshes and pastures become parched in dry periods and are less useful for grazing (Gatewood, 1975). Lowered water tables may also cause oxidation of organic soils (Hortenstine and Forbes, 1972) and release of nutrients which are washed to the lake during rainy periods. This decreases the natural fertility of the land and increases the eutrophy of lakes. Formerly surface waters percolated more into the ground reaching runoff streams later and apparently in greater quantity and quality.

Water Levels and the Lake Ecosystems

Water levels in Lake Okeechobee have a great effect on areas of water and marsh exposed. At a lake stage of 10.5 feet MSL there are 326,000 acres of water surface area and at 16.0 feet MSL 454,000 acres are covered by water. The lake's emergent marshes have developed between the 11.0 and 14.0 feet MSL contours (Ager, 1974) with average water levels at about 14.0 feet MSL. The area between the 11 and 14 foot contours is about 97,000 acres of which about half is emergent marsh and half is ponds and open water. If emergent marshes maintain themselves at zero to three feet below average water levels in the lake, a two-foot increase in average lake stage would put emergent marshes between the 13.0 and 16.0 feet MSL contours. The area between these contours in 57,000 acres, or 40,000 acres less potential area for emergent marsh.

However, marshes that grow in deeper water may increase in area at higher regulation levels. Bullrush and submerged communities now occupy the area between the 8.0 and 12.0 feet MSL (87,000 acres), which is two to six feet below mean lake stage. If these communities were to grow between the 10.0 and 14.0 feet MSL contours in response to a two foot rise in average lake stage, these communities could cover 120,000 acres, or an additional 33,000 acres over the same marshes at lower stages.

Since wading birds depend heavily on the shallow (seasonal) marshes in Lake Okeechobee when other feeding areas in south Florida have dried up (Browder, 1974), an increase in lake stage regulation levels and subsequent decrease in area of seasonal marshes could reduce wading bird populations. Ager (1974) reported highest levels of fish and game fish values in the outer most marsh zones and if higher stage levels increase the area of these zones, proposed regulation levels could increase fish populations in littoral areas. Furthermore, greater ranges in stages at present and proposed levels could maintain or increase the areal extent of seasonal and deep marshes by allowing colonization at lower stages. This principle was used to increase the extent of littoral zone in a lake north of Okeechobee (Holcomb, 1972). Gary Pesnell of the Central and Southern Florida Flood Control District is investigating in greater detail the relationship of water levels to marsh growth.

The limnetic ecosystem is also affected by lake stage variations. Volume changes in the lake dilutes or concentrates nutrients, and depth changes affect turbidity in the lake. Joyner (1974) noted that secchi disk readings were lowest and dissolved solids were highest when lake stages were low. Changes in lake stage affect the area of limnetic zone in production.

Lake depth also affects the degree to which the water column and bottom sediments are mixed. Price (1947) developed a regression model which predicted maximum equilibrium depth from average lake width. His model was developed for enclosed tidal basins along the Texas-Louisiana Gulf coast but was not dependent on basin origin or variety of soft sediments within the basin. Applied to Lake Okeechobee, this model predicts a maximum equilibrium depth of 16.5 feet. Deepest areas in Lake Okeechobee average 15.0 feet below long term average lake levels (14.0 feet MSL), and the model suggests the lake is near equilibrium and is tending to scour deeper. If lake stages are raised, the tendency for scouring will be less in the deeper areas of the lake. Higher lake stages and reduced sediment scouring may reduce oxygen demands on the water column, cause sediment to accumulate, lower redox potentials, and increase acidity in the sediments allowing for the release of phosphorus to the water (Figs. 16b and 16d). However, large lakes generally have thorough mixing to depths of greater than 10 m (Hutchinson, 1957).

Phosphorus Loading and Eutrophication

Total nitrogen and phosphorus ratios in Lake Okeechobee, which average about 35:1 by weight, suggest phosphorus is the limiting nutrient. Phosphorus limitation also is suggested from the higher productivities measured at the north end of the lake where phosphorus loading is greatest. Lake Apopka, which has total phosphorus levels about three times those in Lake Okeechobee, has productivities approximately three times those measured in Lake Okeechobee (Davis and Marshall, 1975).

Inflow rates of phosphorus to Lake Okeechobee are high, 0.3 to 0.4 gm P/m^2/year. Of the phosphorus entering the lake from tributaries and rain only 10% is measured leaving the lake from surface outflows. Since these large inflows of phosphorus are not accounted for in the water column, some must be lost to air, marshes or sediments.

Although most phosphorus in rainfall comes from bubble collapse and aerosol formation at sea, little is known about this phosphorus transport mechanism in fresh waters. Baylor and others (1962) showed no loss of phosphates from aeration of solutions made up of either distilled water or artificial sea water, whereas aerated seawater showed phosphorus losses. Measurements should be made on Lake Okeechobee to determine how significant this outflow may be.

If large amounts of phosphorus are assimilated and stored in marsh macrophytes, increases in standing crop or concentrations could be measured. However, the hydraulic character of the lake causes most of the inflowing phosphorus to enter directly into the limnetic zone (see Table 6, note 12). By the time a parcel of water reaches the marshes it already may be reduced in phosphorus content.

Phosphorus can be lost to sediments by coprecipitation, adsorption and organic sedimentation. Based on theoretical data by Green and Holmes (1948), solubility of phosphorus is dependent on the pH and calcium and pH in Odum (1953) and Barrett (1952). In Lake Okeechobee the pH averages about 8.4 and calcium concentrations averages 40-50 ppm, resulting in an ortho-phosphate solubility equilibria of about 0.020 ppm. Joyner (1974) found the lake to average between 0.054 and 0.029 ppm total ortho-phosphate, considerably higher than equilibria. The supersaturated tendency favors precipitation of phosphate minerals by mollusc shell formation and other processes.

Adsorption of phosphorus in sediments is a faster process than coprecipitation and could account for a large proportion of the phosphorus sink. Harter (1968) and Kamp-Nielsen (1974) reported aerobic lake muds adsorbed most of the dissolved ortho-phosphate in overlying waters within a few hours. Since Lake Okeechobee sediments are almost always aerobic and basic (Burton _et al._, 1975), rapid sorption of phosphorus is likely.

Biological uptake and sedimentation of organic matter may also account for large losses of phosphorus loads. If volume of organic sediments is any measure of this process, then the some 300 million cubic meters of organic sediment in Lake Okeechobee might suggest it is important (Gleason, pers. comm.). Assuming the loss of 0.29 g $P/m^2/yr$ (David and Marshall, 1975), a concentration of 0.27 g P/kg dry weight, then organic sedimentation could account for 1 mm of dry sediment/year and could represent up to 0.5 cm wet sediment/year. Surveys of sediments would help determine its relative importance as a phosphorus sink.

Recycle of phosphorus from the sediments is dependent on the redox potential, pH, degree of mixing, and biological activity in the substrate. Anaerobic and acid sediments tend to release phosphate. During respiration the process of oxygen consumption and carbon dioxide production lowers both pH and oxygen content of the sediments and overlying waters. If the sediments are alternately settled and reworked, phosphorus solubilized in quiescent periods is released when sediments are suspended (Burton _et al._, 1975).

The comparison of flow magnitudes in Fig. 13 suggests that rates of sedimentation, sorption and recycle are key factors determining the immediate levels of water column phosphorus. Loading rates may be many times less than rates of interchange with the sediments and serve to elevate phosphorus levels over long periods. According to this model, water-sediment phosphorus interchanges alone replace sediment stocks every 1.6 years and replace water stocks every 7 days, whereas allochthonous flows replace these stocks in about 34 years and 0.5 years, respectively. Consequently, variations in sediment-water interchanges may alter short term phosphorus levels, whereas loading rates change phosphorus levels over long periods.

Whether sediment-water phosphorus interactions are in steady state with loading rates is of utmost importance in determining eutrophication trends. If recycle increases or sorption decreases with continued loading rates, water column phosphorus will rise to higher levels. Burton and others (1975) studied sorption rates of sediments in the Kissimmee River and Lake Okeechobee and found that these aerobic sediments had maximum sorption of 0.01 g P $o\text{-}PO_4/m^2$ over a few hours after which no sorption occurred.

In the case of the simulation presented in Fig. 14, the water column phosphorus rises continually for the period simulated, recycle being a linear function of sediment phosphorus levels. For present loading rates, these simulations show 2% per year increases in water phosphorus, which correlates with percent increases between average levels in 1969 (0.050 mg/l) and average levels in 1973-74 (0.054 mg/l).

Although this is not validation of the model or future trends because of large variances in yearly averages and short time periods, it suggests further long-term increases in phosphorus levels could occur.

These simulations also show relationships between loading rates and rates of phosphorus increase. Low loading rates (Fig. 14a) showed gradual increases in water phosphorus over long periods, increases which suggest the slow, natural rates of increase in phosphorus and eutrophication. Rates of increase of water phosphorus in Fig. 14d (6% increase per year) shows the process of an eutrophic lake becoming hyper-eutrophic in a short time.

Simulations in Fig. 16 show effects of constant recycle rates, higher recycle rates, and anaerobic release of phosphorus on nutrient levels in the water column. Constant recycle rate keeps water column levels in steady state. Accelerated recycle rates increase the rate of build-up of water column phosphorus. The change of aerobic sediments to anaerobic sediments causes much more phosphorus to be released from sediments. Kap-Nielsen (1974) reported anaerobic desorption rates 10 times greater than aerobic sorption rates.

It is difficult to determine whether water phosphorus levels and production will increase if present loading rates continue. It is unlikely that phosphorus levels will increase drastically in the lake water for the next few years if loading and mixing characteristics remain as they are presently. However, marked increases in loading rates or reductions in the pH and redox character of the lake would quickly elevate water phosphorus levels. If further eutrophy is not desired, care should be taken not to overload Lake Okeechobee with nutrients; evidence from other shallow, highly eutrophic lakes suggests that recovery is slow even after diversion of much of the nutrient load (Mathieson, 1971; Andersson, et al., 1973). Furthermore, Barrett (1952) postulated lakes with greatest potential of elevated water phosphorus levels from fertilization were lakes with no stratification, high marl and organic matter content in sediments, and moderate alkalinities; a good description of Lake Okeechobee.

Chemical Loadings and the Metabolic System

Results of simulating the metabolic system indicate that oxygen levels in the lake as a whole would not fall to critical levels on the short term under anticipated conditions of carbon or phosphorus loading. The simulation, in which diffusion was low and organic loading was high, suggested depressed dissolved oxygen levels (5 ppm). However, it is unlikely that low diffusion conditions (still waters) could last very long in Lake Okeechobee. These results show that under most expected conditions, lake-wide fish-kills would be unlikely.

Although lake-wide oxygen depression is not serious, some areas are presently critical. Many fish kills have been noted in the backpumpage area and in the rim canal because of low oxygen levels (see Appendix C). Occasional high BOD loadings from other tributaries also can depress oxygen levels enough to kill fish.

Accelerated production caused by high nutrient loads (Fig. 21) in combination with high respiration from organic matter produced can increase the diurnal range of oxygen levels. Oxygen minima in the early morning during very productive periods can also cause fish-kills. Highest nutrient loading at the north end of the lake caused frequent blooms there (Appendix C).

Simulation of spatial patterns in Lake Okeechobee indicate that slow movement of water in the area of backpumpage allows time for high BOD material to reduce oxygen levels in that area. The hydraulic characteristics of the rim canal were not included in the spatial model but would exert a large effect on it.

Commercial Fishing and Eutrophication

According to Ager (1972) commercial fish harvest in Lake Okeechobee from 1968-70 amounted to 2.3 lbs/acre/year or 0.26 g wet wt/m^2/year. In terms of phosphorus removed from the lake this harvest amounts to 0.0014 g P/m^2/year if one assumes 0.278 g dry wt/g wet wt (Gerking, 1962) and 2% phosphorus in dry fish matter. Present levels of harvest do not appreciably affect the phosphorus budget of the lake. However, Ager stated that commercial fish harvest potential in Lake Okeechobee could be 76 lbs/acre/yr which would remove about 0.046 g P/m^2/year based on the same assumptions of the previous calculation. A harvest of this magnitude could affect the phosphorus budget of the lake, could reduce rates of eutrophication, and would stimulate considerably the area's economy. The ramifications of such ecosystem management should be investigated and tested.

Eutrophy in Lake Okeechobee

Development and water management practices in basins surrounding the lake increased inflows of nutrients and organic matter increasing production and eutrophication in Lake Okeechobee. Although it is not certain whether present nutrient inflows will cause continued increases in nutrient levels, it is certain that increased nutrient loads could make the lake hyper-eutrophic. Changes in the alkaline, aerobic conditions in the lake could induce more eutrophic conditions. Because of storages in sediment and marsh, about 10 years are required to increase or decrease phosphorus levels in response to changed inflow.

APPENDIX A. Supplemental Information for Water System Model as given in Fig. 10.
Summary Tables for Hand Calculated Water Budgets as Given in Fig. 7.

TABLE 9. A Water Budget of Lake Okeechobee for October 1950 to September 1960.*

Month	Inflow	Rain	Outflow	Evaporation	ΔStorage	Predicted Volume	Measured Volume
Jan	126.5	65.4	-116.1	-119.0	- 43.2	3728.8	3744
Feb	97.6	87.2	-137.3	-137.1	- 89.6	3639.2	3677
Mar	129.7	91.0	-157.0	-194.9	-131.2	3508.0	3546
April	129.9	139.1	-205.9	-225.1	-162.0	3346.0	3384
May	116.4	178.6	-209.1	-256.1	-170.2	3175.8	3172
June	150.2	284.1	-160.4	-233.5	+ 40.4	3216.2	3245
July	182.6	280.1	-194.6	-222.2	+ 45.9	3262.1	3321
Aug	233.4	236.8	-276.9	-215.7	- 22.4	3239.7	3374
Sept	255.6	296.9	-220.4	-181.5	+150.6	3390.3	3724
Oct	337.8	248.1	-288.8	-173.5	+123.6	3513.9	3927
Nov	141.4	38.0	-159.7	- 26.6	- 6.9	3507.0	3818
Dec	149.9	66.8	-142.2	- 46.7	+ 27.8	3534.8	3772

*All values are in thousand acre-feet.

TABLE 10. A Water Budget of Lake Okeechobee for July 1973 to July 1974.*

Month	Inflow	Rain**	Outflow	Evaporation	ΔStorage	Predicted Volume***	Measured Volume
July	397.5	215.6	- 15.1	-231.6	+366.4	3234.4	3112
Aug	467.2	150.8	- 14.0	-202.4	+401.6	3636.0	3489
Sept	523.4	118.0	- 16.2	-177.0	+448.2	4084.2	3930
Oct	215.6	93.2	- 57.6	-195.5	+ 55.7	4139.9	3996
Nov	23.7	7.3	-204.2	-162.4	-335.6	3804.3	3696
Dec	24.8	36.3	- 91.6	-114.0	-144.5	3659.8	3607
Jan	14.6	15.1	- 34.0	-121.0	-125.3	3534.5	3514
Feb	48.8	14.2	-106.7	-170.9	-214.6	3319.9	3304
Mar	20.9	3.8	-176.3	-239.2	-390.8	2929.1	3054
April	28.0	37.6	-270.0	-278.0	-232.4	2696.7	2647
May	63.4	82.5	-224.8	-257.7	-336.6	2360.1	2359
June	308.5	291.1	- 35.8	-197.8	+366.0	2726.1	2768
July	1097.0	254.8	-151.5	-213.5	+986.8	3712.9	4029

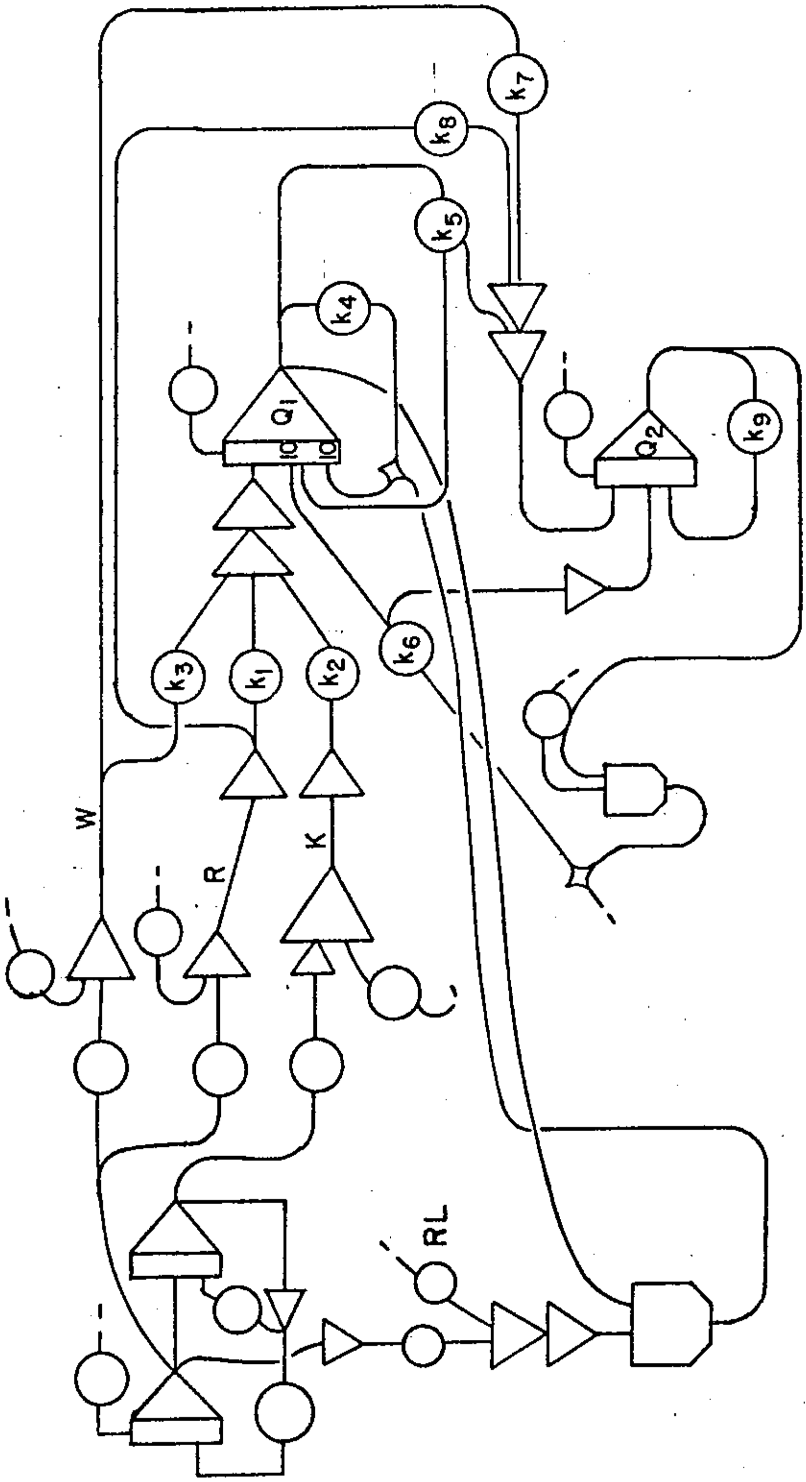
*All values are in thousand acre-feet.
**Rain volumes reduced by 30%.
***Starting volume was 2868 (1000 acre-feet).

TABLE 11. A Water Budget of Lake Okeechobee for October 1964 to September 1974.*

Month	Inflow	Rain	Outflow	Evaporation	ΔStorage	Predicted Volume	Measured Volume
Oct	254.1	185.1	- 96.9	-134.9	+207.4	3868.4	3908
Nov	70.1	34.9	-128.1	- 99.8	-122.9	3745.5	3755
Dec	46.7	45.3	- 83.1	- 86.6	- 77.7	3667.8	3629
Jan	80.9	56.8	- 91.1	- 90.0	- 33.4	3634.4	3575
Feb	81.8	84.9	- 74.1	- 99.8	- 7.2	3626.8	3527
Mar	148.2	115.6	-174.2	-147.1	- 57.5	3469.5	3468
April	92.4	42.2	-274.6	-194.8	-339.8	3129.7	3093
May	72.8	163.6	-142.6	-212.9	-119.1	3010.6	2919
June	213.4	334.1	-123.4	-186.5	+237.6	3248.2	3154
July	309.5	265.7	-196.3	-186.8	+192.1	3440.3	3414
Aug	264.0	228.5	-273.7	-181.5	+ 37.3	3477.6	3519
Sept	251.7	193.5	-112.0	-149.6	+183.4	3661.0	3755

*All values are in thousand acre-feet.

Figure 25. Analog diagram, differential equations, and scaling variables for water system model shown in Fig. 10.



k7
k8
k5
k4
Q1
Q2
k9
k3
k1
k2
k6
W
R
K
RL

Figure 25. (continued)

Differential Equations:

$$\dot{Q}_1 = k_1R + k_2K - k_3W - k_4Q_1 - k_5Q_1 + k_6B$$

$$\dot{Q}_2 = k_5Q_1 - k_6B + k_7R - k_8W - k_9Q_1$$

Initial Condition Values:

$Q_1 = 5.2$, $Q_2 = 1.6$

Calculation of Transfer Coefficients:

$k_4Q_1 = 10.0$; $Q_1 = 5.2$; $k_4 = 1.92$

$k_5Q_1 = 0.36$; $Q_1 = 5.2$; $k_5 = 0.069$

$k_9Q_2 = 2.6$; $Q_2 = 1.6$; $k_9 = 1.62$

Scaled Potentiometer Settings:

	normal	drought	flood
k_1=	.164	.121	.207
k_2=	.171	.129	.214
k_3=	.143		
k_4=	1.62		
k_5=	.069		
k_6=	.65		
k_7=	1.47	1.12	1.83
k_8=	1.25		
k_9=	1.62		

Maximum Values:

$Q_1 = 14$; $Q_2 = 14$

APPENDIX B. Supplemental Information on Phosphorus Model as Shown by Figs. 12 and 13.

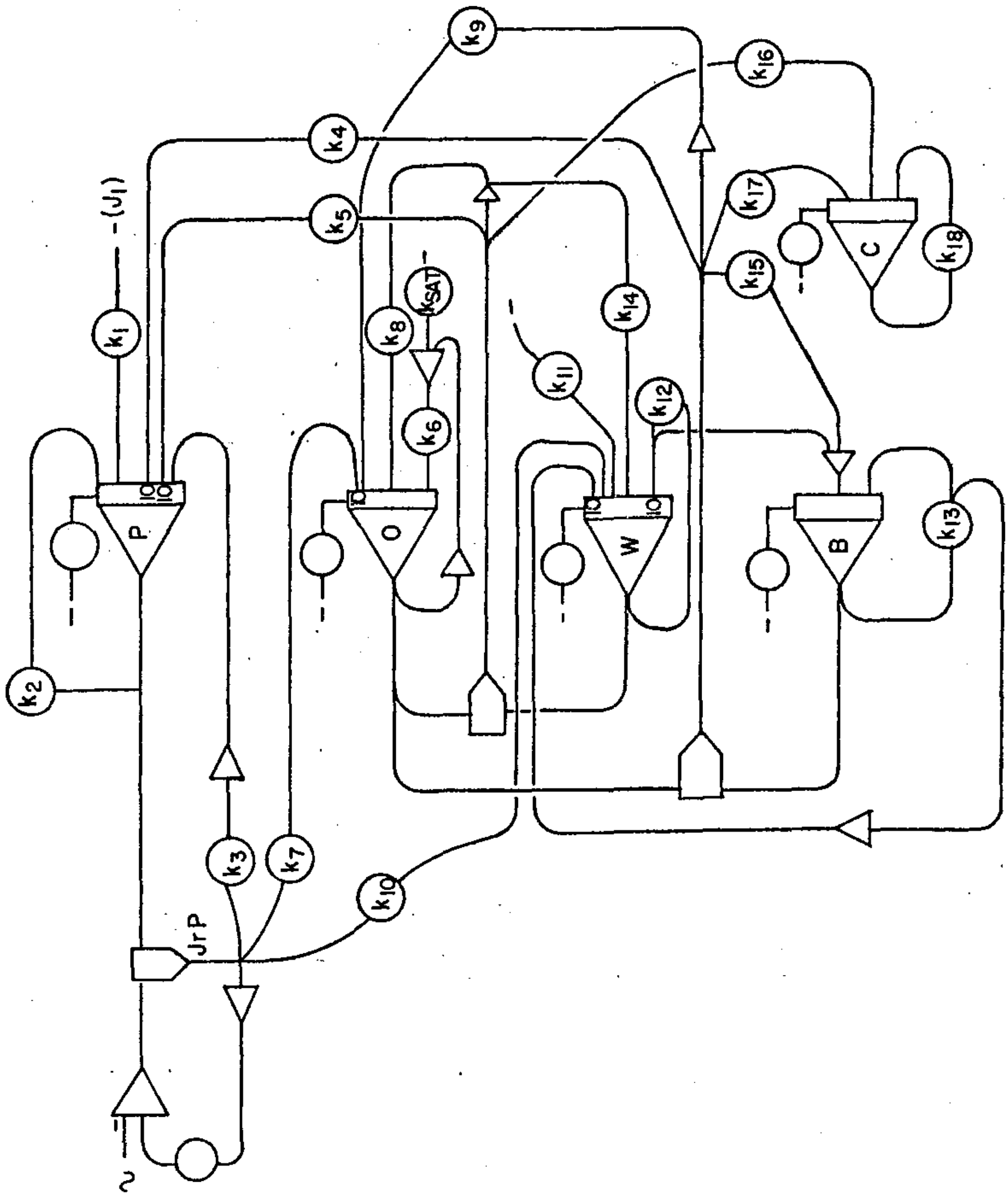
Figure 26. Dynamo II program used to simulate phosphorus system model shown in Fig. 13.

LAKE OKEECHOBEE PHOSPHORUS LOADING MODEL   5/13/75

```
*      LAKE OKEECHOBEE PHOSPHORUS LOADING MODEL
L     LV1.K=LV1.J+DT*(RT1.JK-RT2.JK-RT3.JK+RT4.JK+RT5.JK-RT6.JK+RT7.JK)
L     LV2.K=LV2.J+DT*(RT3.JK-RT4.JK)
L     LV3.K=LV3.J+DT*(-RT5.JK+RT6.JK-RT7.JK)
R     RT1.KL=C1
R     RT2.KL=LV1.K*C2
R     RT3.KL=LV1.K*C3
R     RT4.KL=LV2.K*C4
R     RT5.KL=C23*(C21*LOGN(LV1.K*C22)+C5)
R     RT6.KL=LV1.K*C6
R     RT7.KL=LV3.K*C7
N     LV1=0.132
N     LV2=2.53
N     LV3=11.35
C     C1=0.102
C     C2=0.155
C     C3=0.15
C     C4=0.0079
C     C5=1.13
C     C6=48.5
C     C7=0.564
C     C21=-0.599
C     C22=267
C     C23=0.365
PRINT          LV1,LV2,LV3,RT1,RT2,RT5,RT7
SPEC         DT=0.002/LENGTH=25/PRTPER=1
RUN            ODUM - 1952
```

APPENDIX C. Supplement to Metabolism Model as shown in Figs. 17 and 18.
List of Biological Events in Lake Okeechobee.

Figure 27. Analog diagram, differential equations, and scaling variable for metabolism model shown in Fig. 18.



k1
k2
k3
k4
k5
k6
k7
k8
k9
k10
k11
k12
k13
k14
k15
k16
k17
k18
kSAT
-(J1)
Jr P
P
O
W
B
C

Figure 27. (continued)

Differential Equations:

$\dot{P} = k_1J_1 - k_2P - k_3JrP + k_4BO + k_5WO$

$\dot{O} = k_6(K-O) + k_7JrP - k_8WO - k_9BO$

$\dot{W} = k_{10}JrP + k_{11}J_{11} - k_{12}W + k_{13}B - k_{14}WO$

$\dot{B} = k_{12}W - k_{13}B - k_{15}BO$

$\dot{C} = k_{16}WO + k_{17}BO - k_{18}C$

Initial Condition Values:

Jr = 4, P = .029, O = 20.2, W = 48, B = 500, C = 18.6

Maximum Values:

$[\frac{Jr}{6}]$, $[\frac{P}{.1}]$, $[\frac{O}{100}]$, $[\frac{W}{100}]$, $[\frac{B}{1000}]$, $[\frac{C}{100}]$, $[\frac{OB}{10}5]$, $[\frac{OW}{10}4]$, $[\frac{JrP}{.6}]$

Calculation of K's:

k_1J_1	=	.0011 gP/m^2-day	k_1 =	.0011
k_2P	=	.0003 gP/m^2-day	k_2 =	.0103
k_3JrP	=	.001 gP/m^2-day	k_3 =	.0948
k_4BO	=	.008 gP/m^2-day	k_4 =	$7 x 10^{-7}$
k_5WO	=	.002 gP/m^2-day	k_5 =	$2 x 10^{-6}$
$k_6(K-O)$	=	1.0 gO_2/m^2-day	k_6 =	$4.88 x 10^{-2}$
k_7JrP	=	5.25 gO_2/m^2-day	k_7 =	45.3
k_8WO	=	.98 gO_2/m^2-day	k_8 =	.00101
k_9BO	=	4.45 gO_2/m^2-day	k_9 =	$4.4 x 10^{-4}$
$k_{10}JrP$	=	2.1 gC/m^2-day	k_{10} =	18.1
$k_{11}J_{11}$	=	.07 gC/m^2-day	k_{11} =	0.07
$k_{12}w$	=	49.78 gC/m^2-day	k_{12} =	1.04
$k_{13}B$	=	48.0 gC/m^2-day	k_{13} =	0.096

Figure 27. (continued)

$k_{14}WO$	=	0.39 gC/m^2-day	$k_{14} = 4.02x10^{-4}$
$k_{15}BO$	=	1.78 gC/m^2-day	$k_{15} = 1.76x10^{-4}$
$k_{16}WO$	=	.18 gC/m^2-day	$k_{16} = 1.86x10^{-4}$
$k_{17}BO$	=	.02 gC/m^2-day	$k_{17} = 1.9x10^{-6}$
$k_{18}C$	=	.20 gC/m^2-day	$k_{18} = 1.08x10^{-2}$

	Unscaled K's (day^{-1})	Scaled K's
k_1	$1.1x10^{-3}$	.011
k_2	$1.03x10^{-2}$	.0103
k_3	$9.48x10^{-2}$	.569
k_4	$7x10^{-7}$	.7
k_5	$2x10^{-6}$	.2
k_6	$4.88x10^{-2}$	.049
k_7	$4.53x10^{1}$	.272
k_8	$1.01x10^{-3}$	.101
k_9	$4.4x10^{-4}$	.44
k_{10}	$1.81x10^{1}$	.109
k_{11}	$7.0x10^{-2}$	.001
k_{12}	$1.04x10^{0}$	1.04, .104
k_{13}	$9.6x10^{-2}$	.96, 1096
k_{14}	$4.02x10^{-4}$	.040
k_{15}	$1.76x10^{-4}$	.018
k_{16}	$1.86x10^{-4}$	.019
k_{17}	$1.9x10^{-6}$	.002
k_{18}	$1.08x10^{-2}$	.018

Figure 27. (continued)

Scaled Initial Condition Values:

$$P = \frac{.029}{.1} = .290$$

$$O = \frac{20.2}{100} = .202$$

$$W = \frac{48}{100} = .48$$

$$B = \frac{500}{1000} = .50$$

$$C = \frac{18.6}{100} = .186$$

TABLE 12. List of Biological Events in Lake Okeechobee

<u>Algal Blooms</u>	
August 1967	Blue-green in north end of lake
August 1968	Blue-green widespread in north end of lake
April 1970	Blue-green in C-38, S-65E, S-65D, S-65C and in lake around river mouth
May 1970	Blue-green in rim canal at Little Saratoga
June, July 1970	Blue-green in north end of lake
February 1971	Blue-green in northwest area of lake
May 1971	Blue-green in north end of lake
June 1971	Blue-green in C-38, S-65B and S-65C
<u>Fish Kills</u>	
December 1967	10,000 fish killed in rim canal at S-2 lack of dissolved oxygen
June 1968	10,000 fish killed in rim canal at S-2 lack of dissolved oxygen
July 1968	10,000 fish killed in rim canal at pump station 127, lack of dissolved oxygen
September 1971	2,000 fish killed in rim canal at S-2 lack of dissolved oxygen
July 1972	5,000 fish killed in Fisheating Creek and Tree Dike Canal at Lakeport, lack of dissolved oxygen
September and October 1972	500,000 to 1,000,000 white catfish killed due to unknown cause
June 1973	1,500 fish killed in Taylor Creek, lack of dissolved oxygen
<u>Bird Kills</u>	
June and July 1971	19 species, 398 birds, killed in Fisheating Creek Bay by <u>Clostridium perfringens</u>

APPENDIX D. Supplement to Spatial Model.

Conditions Used in Running Spatial Model in Figure

Days Simulated 5

Water Quality Cycles per day 24

Integration Cycles per Water Quality Cycle 6

Length of Integration Step is 600. seconds

Evaporation Rate, 9.7 inches per month

Wind Velocity, 10. mph Wind Direction, 180. degrees from north

No Precipitation

Input Junction Numbers for Flows from Cards Are:

1	2	7	13	25
Volume (CFS)				
500.0	4000.0	1500.0	2000.0	3000.0

TABLE 13. Data Used in Running Spatial Model

Channel Data

Channel Number	Length (ft)	Width (ft)	Area (sq ft)	Manning Coef.	Hyd Radius (ft)	Junctions at Ends	
1	28018.	44174.03	949742.	0.115	21.5	5	6
2	46228.	7828.58	137000.	0.115	17.5	1	6
3	46840.	11017.58	242387.	0.030	22.0	1	5
4	42202.	13708.24	294727.	0.030	21.5	2	5
5	29000.	18856.02	329980.	0.030	17.5	1	2
6	31780	38568.29	944923.	0.030	24.5	4	5
7	32140.	19525.24	390505.	0.030	20.0	2	4
8	29411.	12926.29	245599.	0.115	19.0	3	4
9	25807.	11085.84	177373.	0.115	16.0	2	3
10	14866.	40148.27	943484.	0.030	23.5	4	8
11	29967	8463.33	165035.	0.115	19.5	3	8
12	29155.	10709.23	208830.	0.115	19.5	7	8
13	21260.	11754.83	176322.	0.200	15.0	3	7
14	16401.	38781.19	930749.	0.030	24.0	8	10
15	29411.	11043.02	215339.	0.115	19.5	7	10
16	30265.	17294.51	345890.	0.115	20.0	9	10
17	23854.	11085.39	171824.	0.200	15.5	7	9
18	33287.	31559.56	710090.	0.115	22.5	10	14
19	34176.	22734.05	420580.	0.200	18.5	9	14
20	42579.	17120.12	308162.	0.200	18.0	13	14
21	39051.	11281.47	174863.	0.200	15.5	9	13
22	42638.	17373.25	312718.	0.200	18.0	14	16
23	35171.	15421.14	231317.	0.200	15.0	13	16
24	35114.	14364.86	215473.	0.200	15.0	16	17
25	39000.	27002.67	486048.	0.200	18.0	14	17
26	34132.	20558.73	380337.	0.200	18.5	17	18

TABLE 13. (continued)

Channel Data
(continued)

Channel Number	Length (ft)	Width (ft)	Area (sq ft)	Manning Coef.	Hyd Radius (ft)	Junctions at Ends	
27	49518.	10785.48	231888.	0.200	21.5	14	18
28	24520.	24074.58	589827.	0.115	24.5	15	18
29	51865.	14653.65	351688.	0.115	24.0	14	15
30	54644.	11995.84	305894.	0.030	25.5	10	15
31	25239.	28061.92	533176.	0.200	19.0	18	22
32	26907.	10790.93	167259.	0.200	15.5	17	22
33	38601.	7255.73	123347.	0.200	17.0	22	23
34	39408.	7336.95	146739.	0.200	20.0	18	23
35	29428.	15024.01	300480.	0.200	20.0	19	23
36	28160.	33933.64	746540.	0.200	22.0	18	19
37	22472.	19582.30	342690.	0.200	17.5	23	24
38	22023.	17550.22	342229.	0.200	19.5	19	24
39	28071.	5225.51	86221.	0.200	16.5	24	25
40	26401.	7075.02	120275.	0.200	17.0	23	25
41	20000.	8901.87	160234.	0.200	18.0	20	24
42	26019.	23278.04	477200.	0.200	20.5	19	20
43	41110.	25701.23	642531.	0.115	25.0	11	19
44	24839.	25751.36	708162.	0.030	27.5	11	15
45	47885.	7642.26	179593.	0.115	23.5	11	20
46	27586.	20722.54	445535.	0.115	21.5	20	21
47	47413.	21199.96	551199.	0.030	26.0	11	21
48	43186.	16758.93	393835.	0.030	23.5	12	21
49	50567.	28342.93	722745.	0.030	25.5	11	12
50	53907.	22753.06	557450.	0.030	24.5	5	12
51	56223.	20746.09	560145.	0.030	27.0	5	11

TABLE 13. (continued)

Channel Data
(Continued)

Channel Number	Length (ft)	Width (ft)	Area (sq ft)	Manning Coef.	Hyd Radius (ft)	Junctions at Ends	
52	54083.	7088.94	141779.	0.115	20.0	6	12
53	55471.	9509.12	242482.	0.030	25.5	4	11
54	53759.	10936.37	284346.	0.030	26.0	8	11
55	53712.	11589.63	301330.	0.030	26.0	10	11

Junction Data

TABLE 13. (continued)

Junction Number	Initial Head(ft)	Depth (ft)	Surface Area (10**6 sq ft)	Output (CFS)	Channels Entering Junction									Coordinates X	Y
1	14.00	4.0	356.20	0.	2	3	5	0	0	0	0	0	0	101.0	189.0
2	14.00	3.0	509.74	0.	4	7	9	5	0	0	0	0	0	80.0	169.0
3	14.00	1.0	292.45	0.	8	11	13	9	0	0	0	0	0	59.0	154.0
4	14.00	9.0	839.44	0.	6	10	53	7	8	0	0	0	0	83.0	137.0
5	14.00	12.0	1487.73	0.	1	50	51	3	4	6	0	0	0	114.0	144.0
6	14.00	3.0	495.74	0.	52	1	2	0	0	0	0	0	0	137.0	160.0
7	14.00	1.0	287.84	0.	12	15	17	13	0	0	0	0	0	45.0	138.0
8	14.00	10.0	596.67	0.	14	54	10	11	12	0	0	0	0	72.0	127.0
9	14.00	2.0	501.34	0.	16	19	21	17	0	0	0	0	0	32.0	118.0
10	14.00	10.0	953.20	0.	18	30	55	14	15	16	0	0	0	62.0	114.0
11	14.00	14.0	1851.14	0.	43	44	45	47	49	51	53	54	55	109.0	88.0
12	14.00	9.0	941.73	300.	48	49	50	52	0	0	0	0	0	155.0	109.0
13	14.00	1.0	427.97	0.	20	23	21	0	0	0	0	0	0	2.0	93.0
14	14.00	7.0	1411.09	0.	22	25	27	29	18	19	20	0	0	44.0	86.0
15	14.00	13.0	659.49	0.	28	29	30	44	0	0	0	0	0	93.0	69.0
16	14.00	1.0	446.89	50.	24	22	23	0	0	0	0	0	0	11.0	59.0
17	14.00	1.0	637.39	0.	26	32	24	25	0	0	0	0	0	44.0	47.0
18	14.00	8.0	942.95	0.	31	34	36	26	27	28	0	0	0	78.0	50.0
19	14.00	8.0	861.61	0.	35	38	42	36	43	0	0	0	0	106.0	47.0

TABLE 13. (continued)

Junction Data
(continued)

Junction Number	Initial Head(ft)	Depth (ft)	Surface Area (10**6 sq ft)	Output (CFS)	Channels Entering Junction									Coordinates X	Y
20	14.00	5.0	430.33	0.	41	46	42	45	0	0	0	0	0	132.0	46.0
21	14.00	10.0	575.14	0.	46	47	48	0	0	0	0	0	0	151.0	66.0
22	14.00	2.0	319.67	0.	33	31	32	0	0	0	0	0	0	64.0	29.0
23	14.00	4.0	409.54	0.	37	40	33	34	35	0	0	0	0	101.0	18.0
24	14.00	3.0	287.82	0.	39	37	38	41	0	0	0	0	0	120.0	30.0
25	14.00	2.0	83.37	0.	39	40	0	0	0	0	0	0	0	122.0	2.0

Total Area for the System 16606.43 * 10**6 sq ft or 595.67 sq miles

LITERATURE CITED

Ager, L.A. and K.E. Kerce. 1974. Aquatic plant communities - associated fauna investigation; completion report. Florida Game and Fresh Water Fish Commission.

Andersson, G., G. Cronberg and C. Gelin. 1973. Planktonic changes following restoration of Lake Trummen, Sweden. Ambio 2:44-73.

Barrett, P.H. 1952. Relationship between alkalinity and adsorption of phosphorus and regeneration of added phosphorus in fertilized trout lakes. Trans. Am. Fish Soc. 82:78-90.

Baylor, E.R., W.H. Sutcliffe, and D.S. Herschfield. 1962. Adsorption of phosphate onto bubbles. Deep Sea Res. Vol. 9 (2):120-124.

Brezonik, P.L. and A. Federico. 1975. Effects of backpumping from agricultural canals on water quality in Lake Okeechobee. Completion Report to Fla. Dept. of Poll. Control.

Brooks, H.K. 1974. "Lake Okeechobee" in Environment of South Florida: Past and Present, Memoir 2, Miami Geological Society, Patrick J. Gleason, Editor, p. 256-286.

Browder, J. 1975. Alligator holes in Carrying capacity for man and nature in south Florida, H.T. Odum and M. Brown, eds. Completion report to Dept. of Interior.

Burton, T.M., R.C. Harriss, C.F. Dreyer, and D.H. Taylor. 1975. Studies of the geochemical exchanges across the sediment-water interface in the Kissimmee River - Lake Okeechobee watershed. Completion Report to Fla. Dept. of Poll. Control.

Casselman, T.W. 1970. The climate of the Belle Glade area. Agri. Exp. Sta., Univ. of Florida, cir. S-205, 17 p.

Davis, F.E. and M.L. Marshall. 1975. Chemical and biological investigations of Lake Okeechobee, January 1973-June 1974, Interim Report. Central and Southern Florida Flood Control District Technical Publication 75-1.

Duchrow, R.M. 1970. Annual progress report for investigation project as required by Federal Aid in Fish Restoration, Dingell-Johnson Project F-21-4, 1969-70: Florida Game and Freshwater Fish Commission.

EPA. 1971. Storm Water Receiving Model

Gatewood, S. 1975. An analysis if cattle ranching in the Kissimmee River Basin. Preliminary draft submitted by EcoImpact, Inc. to Florida Division of State Planning. 171 pp.

Gerking, S.D. 1962. Production and food utilization in a population of blue-gill sunfish. Ecol. Mono. 32:31-78.

Green, J. and J.A. Holmes. 1947. Calculation of the pH saturation of tricalcium phosphate. Journal of the American Water Works Association 39:1090-1096.

Hall, K. 1964. The dynamics of a natural population of Daphnia. Verh. Int. Verein. Limnol. 15:660-664.

Harder, R.D. 1968. Adsorption of phosphorus by lake sediment. Soil Sci. Soc. Amer. Proc. 32:514-518.

Hartwell, J.H. 1970. Some aspects of the availability of water from the Everglades to the Everglades National Park, Florida. USGS Open-file report-SL-70007.

Heaney, J.P. and W.C. Huber. 1974. Environmental resources management studies in the Kissimmee River Basin, Phase I. Progress Rept. to the Central and Southern Fla. Flood Control Dist. 132 pp.

Holcomb, D.E. 1968. Annual progress report for research project as required by Federal Aid and Fish Restoration, Dingell-Johnson Project F-21-R-2: Florida Game and Fresh Water Fish Commission, 1967-68.

Holcomb, D.E. and W. Wegener. 1972. Lake Tohopekaliga drawdown. Florida Game and Fresh Water Fish Commission. Progress Report Job No. 5, Project No. F-29-1.

Hortenstine, C.C. and R.B. Forbes. 1972. Concentrations of nitrogen, phosphorus, potassium, and total soluble salts in soil solution samples from fertilized and unfertilized histosols. Journal of Environmental Quality. 1(4):446-449.

Huff, D.D., J.F. Koonce, W.R. Ivarson, P.R. Weiler, E.H. Dettman, and R.F. Harris. 1973. Simulation of urban runoff, nutrient loading, and biotic response of a shallow eutrophic lake. Pages 33-55 in E.J. Middlebrooks, D.H. Falkenborg, T.E. Maloney, eds., Modeling the eutrophication process. Utah State Univ.

Hutchinson, G.E. 1957. A treatise in limnology. Geography, Physics, and Chemistry, Vol. I. John Wiley & Sons, New York. 1015 pp.

Joyner, B.F. 1974. Chemical and biological conditions in Lake Okeechobee, Florida, 1969-72. Rept. Inv. 71. United States Geological Survey.

Kamp-Nielsen, L. 1974. Mud-water exchange of phosphate and other ions in undisturbed sediment cores and factors affecting the exchange rates. Arch. Hyd. 73(2):218-237.

Kirchner, W.B. and P.J. Dillon. 1975. An empirical method of estimating the retention of phosphorus in lakes. Water Resources Research. 11(1):182-183.

MacCormick, A.J.A., O.L. Loucks, J.F. Koonce, J.F. Kitchell, P.R. Weiler. 1972. An ecosystem model for the pelagic zone of Lake Wingra. U.S. I.B.P. E.D.F.B. memo report 72-177 103 pp.

Mathiesen, J. 1971. Summer maxima of algae and eutrophication. Mitt. Verh. Internat. Verein. Limnol. 19:161-181.

Middlebrooks, E.J., D.H. Falkenborg, and T.E. Maloney, eds. 1973. modeling the eutrophication process. Ann Arbor Science, Ann Arbor, Michigan. 228 pp.

Odum, H.T. 1953. Dissolved phosphorus in Florida waters. Report of investigations #9. Fla. Geol. Survey. 40 pp.

Odum, H.T. 1957. Primary production in flowing waters. Limnology and Oceanography. 1:102-117.

Odum, H.T. 1971. Environment, power, and society. John Wiley Interscience, New York. 317 pp.

Odum, H.T. 1972. An energy circuit language for ecological and social systems: its physical basis. Pages 139-211 in B.C. Patten, ed., Systems analysis and simulation in ecology. Vol. II.

Park, R.A., J.W. Wilkinson, J.A. Bloomfield, R.C. Kohberger, and C. Sterling. 1972. Aquatic modeling, data analysis, and data management at Lake George. U.S. I.B.P. E.D.F.B. memo report 72-70. 32 pp.

Park, R.A. 1974. A generalized model for simulating lake ecosystems. Simulation 4(2):33-50.

Parker, G.G., G.E. Gerguson and S.K. Love. 1955. Water resources of Southeastern Florida. U.S. Geol. Survey Water Supply Paper 1255. 965 pp.

Parker, R.A. 1968. Simulation of an aquatic ecosystem. Biometrics 24:803-822.

Price, W.A. 1947. Equilibrium of form and forces in tidal basins of coasts of Texas and Louisiana. Bull. Amer. Ass. Petrol. Geol. 31:1619-1663.

Prosser, C.L. and F.A. Brown. 1961. Comparative animal physiology. W.B. Saunders Co., Philadelphia. 688 pp.

Riebsame, W.E., W.L. Woodley and F.E. Davis. 1974. Radar inference of Lake Okeechobee rainfall for use in environmental studies. Weatherwise 27(5):206-211.

Sheffield, C.W. and W.H. Kuhrt. 1970. Lake Apopka - its decline and proposed restoration. Proc. Florida's Environmental Engineering Conference, Water Pollution Control Bulletin 135. Univ. of Florida Eng. Ind. Exper. Sta., Gainesville.

Sincock, J.L., J.A. Powell, R.K. Hyde, and H.E. Wallace. 1957. The relationship of wintering water fowl populations of the Kissimmee River Valley to the hydrology, topography, distribution of the vegetation and the proposed hydrological regulations. Bureau of Sport Fish and Wildlife.

Soumela, A.J. 1958. A detailed report on the fish and wildlife resources in relation to the Corps of Engineer's plan of development of the northwest shore of Lake Okeechobee, Florida. U.S. Fish and Wildlife Service.

U.S.G.S. Surface water records. 1931-74.

Vollenweider, R. A. 1968. Scientific fundamentals if eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus factors in eutrophication. OECD Technical Report. DAS/CSI/68.27, Paris, 159 pp.

Waters, T. F. 1969. The turnover ratio in production ecology of fresh-water invertebrates. Am. Nat. 103:173-185.

BIOGRAPHICAL SKETCH

Timothy Laurence Gayle was born February 23, 1952, in Gueydan, Louisiana. He attended public schools in Gueydan and Lake Arthur, Louisiana and was graduated from Goretti High School in June, 1969. He attended University of Southwestern Louisiana, Northwestern State University of Louisiana, and Louisiana State University, receiving a Bachelor of Science degree in botany from L.S.U. in December, 1972. In September, 1973, he entered the Department of Environmental Engineering Sciences at the University of Florida where he is presently a candidate for the Degree of Master of Science.