ENERGY BASIS OF A COASTAL REGION:
FRANKLIN COUNTY AND APALACHICOLA BAY, FLORIDA

By

WALTER RAYMOND BOYNTON

A DISSERTATION PRESENTED TO THE GRADUATE COUNCIL OF
THE UNIVERSITY OF FLORIDA
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1975

ACKNOWLEDGEMENTS

I wish to acknowledge the guidance and insights provided by H. T. Odum, the chairman of my committee. I was fortunate to work with a man who so clearly sees the unity of urban and natural systems. My supervisory committee included E. E. Pyatt, P. L. Brezonik, C. Feiss, and R. L. Iverson.

The research was supported by the Office of Sea Grant, U. S. Department of Commerce, Grant 04-3-158-43 entitled "Simulation and Evaluation of Macromodels to Air Coastal Planning," H. T. Odum, principal investigator. Initial work on the Franklin County project was done by C. Gray and D. Hawkins.

Mr. C. Wojick assisted in producing the land-use maps. Mr. James Estes, Franklin County Agricultural Extension Agent, provided much information on urban and fishery matters in Franklin County. R. L. Iverson and his students provided data critical to this study and arranged with R. C. Harriss for the use of the facilities of the Florida State Marine Laboratory at Turkey Point on Apalachicola Bay. Data were also provided by R. J. Livingston, and R. W. Menzel of Florida State University.

Field data from Apalachicola Bay were collected with the assistance of M. Kemp, T. Ahlstrom, J. Schumacher, H. McKellar, R. Livingston, G. Lewis, and H. Bittaker. The Mobile District, U. S. Army Corps of Engineers provided information on Jim Woodruff Dam, and the Apalachicola River. A. Clewell of the Botany Dept., Florida State University, was helpful in classifying local terrestrial ecosystems.

I gratefully acknowledge my fellow graduate students and especially my wife, Mary Ellen, for their support, assistance and good humor which added much to both this work and my graduate school experience.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Dissertation Presented to the Graduate Council of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

ENERGY BASIS OF A COASTAL REGION:
FRANKLIN COUNTY AND APALACHICOLA BAY, FLORIDA

By

Walter Raymond Boynton

July, 1975

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

The energy basis for a coastal region at Franklin County and Apalachicola Bay, Florida was evaluated with models, field measurements, energy calculations, land-use maps from aerial photographs, and computer simulations. Energetic relationships between urban and coastal ecosystems were studied to help understand ecosystem relationships on a regional scale and predict consequences of adding urban development and changing water quality to an economy based on a marine fishery. Simulations of a regional model suggested a near steady state pattern of urban activities in the county which was consistent with previous studies. A slow decline in urban activities was recorded when further inflation was introduced. Trends were level temporarily when investments and government spending were added. Temporary growth was observed when the investment rate was increased to twice the present rate. Growth could not be

stimulated by increasing oyster harvest effort without developing special feedback to stimulate the oyster reefs. Growth trends initiated by investment in urban development were reversed and a decline observed if the oyster industry was closed because of a decrease of water quality. Reducing the seasonal pulse and increasing and decreasing river flow also reduced oyster biomass and the urban economy. The model indicated that natural predation rather than harvest was the major cause of mortality of oysters.

An aggregated submodel of diurnal dissolved oxygen dynamics in Apalachicola Bay was programmed to investigate the possibility of low oxygen occurring under a variety of conditions. Community metabolism and organic carbon stocks in the bay and river were measured in the summer of 1973 to evaluate models. Metabolism ranged from 3.1 to 21.6 g O_2/m^2/day and was generally comparable to other estuarine areas. Low predawn oxygen levels were not observed. Total organic carbon averaged 6.4 and 5.3 g C/m^3 in the bay and river, respectively.

Simulation of the model with reduced diffusion and increased detritus input depressed oxygen levels to 3.2 ppm. Nutrient loading produced larger diurnal changes but not lower oxygen levels. Evaluation of this model suggested that phytoplankton photosynthesis was the major source of organic matter in the summer (75%). Eighty percent of the nitrogen used in photosynthesis was from the recycle of nitrogen from imported organic matter.

Energy calculations indicated that natural energy inputs accounted for 84% of the total energy input in the country. The ratio of purchased to natural, free energy inputs (investment ratio) for the county was low compared to Florida and the nation. On a county basis, full development of the barrier island for tourism changed the ratio from 0.19 to 3.1, exceeding the 2.5 national average. On a local basis calculations indicated that the planned development may be too dense for best fit of natural and purchased resources.

The oyster industry accounted for 60% of the total county income in 1970. Within the county, natural energies predominated and accounted for 84% of the total energy used in oystering as measured at dockside. When traced to final consumption the natural energies involved in producing oysters were matched elsewhere in the national economy with the work of fossil fuels in ratio of 1:2.2. Preliminary calculations suggested that the bay could support twice the current oyster population without adding extensive fossil fuel subsidies.

INTRODUCTION

This is a study of principles organizing man and nature in the coastal zone. The study considers purchased and natural energy flows that together support a coastal fishing economy. Questions are considered for fitting man's increasing interaction with coastal waters into patterns which maximize regional value. Included here are land-use maps developed from aerial photographs, an aggregated model of urban-coastal relationships, energy analyses of development alternatives, simulation models of subsystems, and examination of ways that changes in international energy regimes control county activity. This study was made to develop, apply, and extend ecological principles of organization and function to a regional scale.

Over the world, during the period of accelerating urban growth based on fossil fuels, there was an increasing harvest drawn from both recreational and commercial marine fisheries at the same time that coastal developments were removing habitat and interfering with the necessary food chain base of coastal fisheries. In many areas there was a burst of economic activity as boats utilized a virgin fishery followed by periods of overfishing, coastal disturbance, loss of the fishery, and replacement with urban development that may have unnecessarily decimated the fishery resource. We need to test, clarify, and recommend ways to retain the value of marine resources, while adding fossil fuel-based developments.

However, in 1974 with changing patterns of fuel availability and prices, the relative values of the natural work and fossil fuel-based work began changing, and we need an understanding of the trends ahead. As trends reverse, strong marine resources may be needed as an economic cushion.

This study considered the general problem of coexistence of economic development and marine resources using Franklin County, Florida which includes the mouth of the Apalachicola River and a very valuable resource of oyster and shrimp landings. Major external developments affecting Franklin County include changing prices of purchased goods and fuels, river flow and coastal modifications, development of coastal islands for tourism, and changing populations pressures for tourist and retirement developments. To gain understanding of the energetic base of this area, system models were constructed as follows: (1) an oxygen balance model of production, respiration, exchange and diffusion in Apalachicola Bay, with special emphasis on the role of the river as a source of nutrients and organic matter; and (2) a regional model showing trends caused by external driving functions on human activity on land interacting with estuarine and fishery activities that together constitute the economy of Franklin County, Florida. Using numerically evaluated models, energy analyses were made of the primitive and present patterns of land-use in the county, the oyster industry, and a proposed tourist development on the barrier island. Land-use maps were constructed from aerial photographs to show spatial relationships of the primitive condition and current use by systems of nature and man. The energy quality of the potential energy of river head was also calculated and used in the energy analyses. Lastly, calculations were made using an energetic basis to estimate the appeal of the coastal zone as a place for fossil fuel-based development.

Theoretical Coastal Zone Issues

In evaluating the energy basis of coastal Franklin County, three theoretical issues were studied as follows:

(1) A seasonally pulsing energy flow may accelerate the net yield of a system. The pulsing discharge of the Apalachicola River may be an example affecting net yields of the bay. What is the energy value of a pulsing regime with net yield? How does it compare to other river programs which have regular flow and less net yield? Does the system receiving the pulse benefit from it? What are the feedbacks or characteristics exported to insure continued pulsing programs?

Is there a direct or indirect rate of the yield related back to the pulsing inflow?

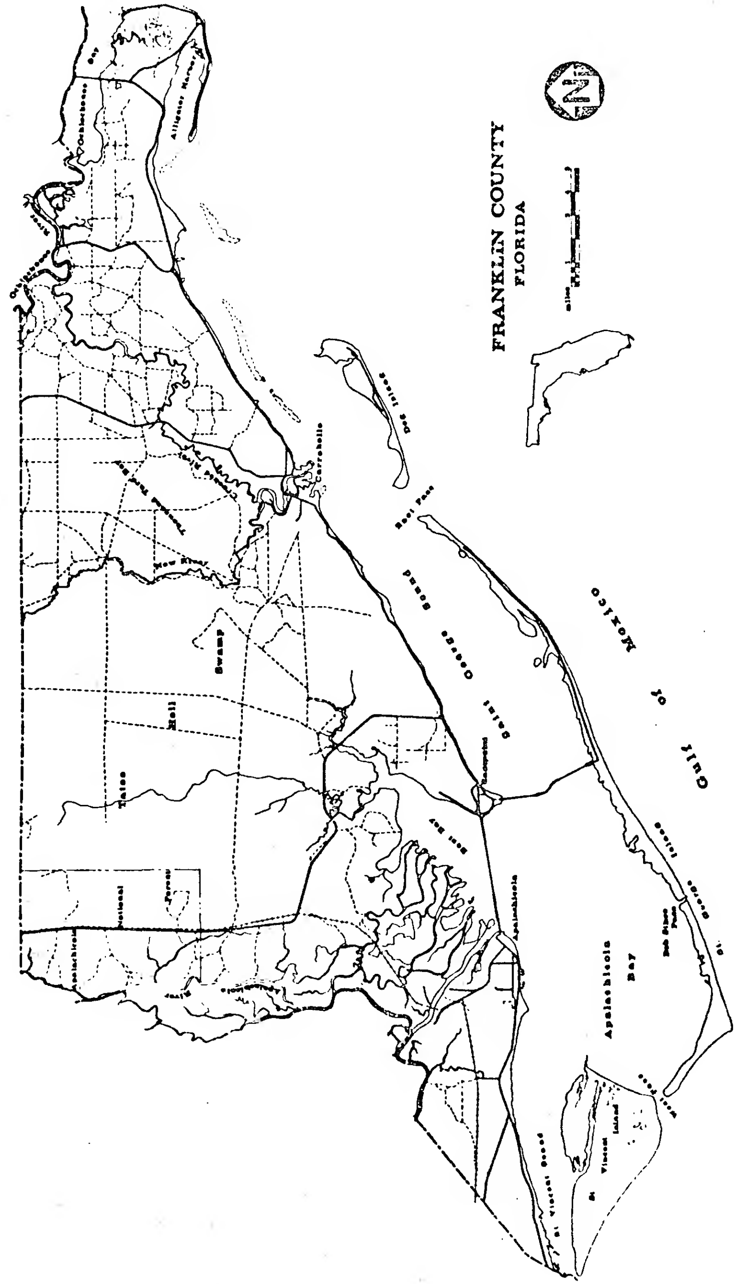
(2) A second question is the relationship of the image of the coastal zone to energy flow. Is it possible that this attractiveness or image is based on the richness both in types and magnitudes of natural coastal zone energy flows which find viable couplings with urban development?

(3) The third question concerns the forward and feedback exchange of value between estuarine productivity and its coupled fishery harvest. In agriculture there is a well-known give and take between farmer and field with yields related to feedback studies of soil preparation, fertilization, breeding, weed control and the like. What are the feedbacks from urban areas required to maintain yielding estuarine processes? Can additional feedbacks be established to promote net yields and prevent deterioration of fisheries?

Description of Study Area

Franklin County is located on the northwest Gulf Coast of Florida (Fig. 1). It is bounded on the north by Liberty and Wakulla Counties, on the west by Gulf County and on the east and south by the Gulf of Mexico. The county is rural with most of the 7,000 residents living along the

Fig. 1. Map showing major features of Franklin County and Apalachicola Bay, Florida.


FRANKLIN COUNTY
FLORIDA
Gulf of Mexico
Apalachicola Bay
Saint George Sound
Dog Island
St. Vincent Island
St. Vincent Sound
Apalachicola
Carrabelle
East Bay
East Pass
New River
Tates Hell Swamp
Ochlockonee Bay
Alligator Harbor

coast. The gross area of the county consists of 361,000 acres, of which 18,400 acres are freshwater rivers and lakes. The county consists mostly of flatlands, with swampy forests covering over 90% of the land area. Apalachicola Bay, a medium salinity estuary separated from the Gulf of Mexico by several offshore islands, extends nearly the entire length of the county.

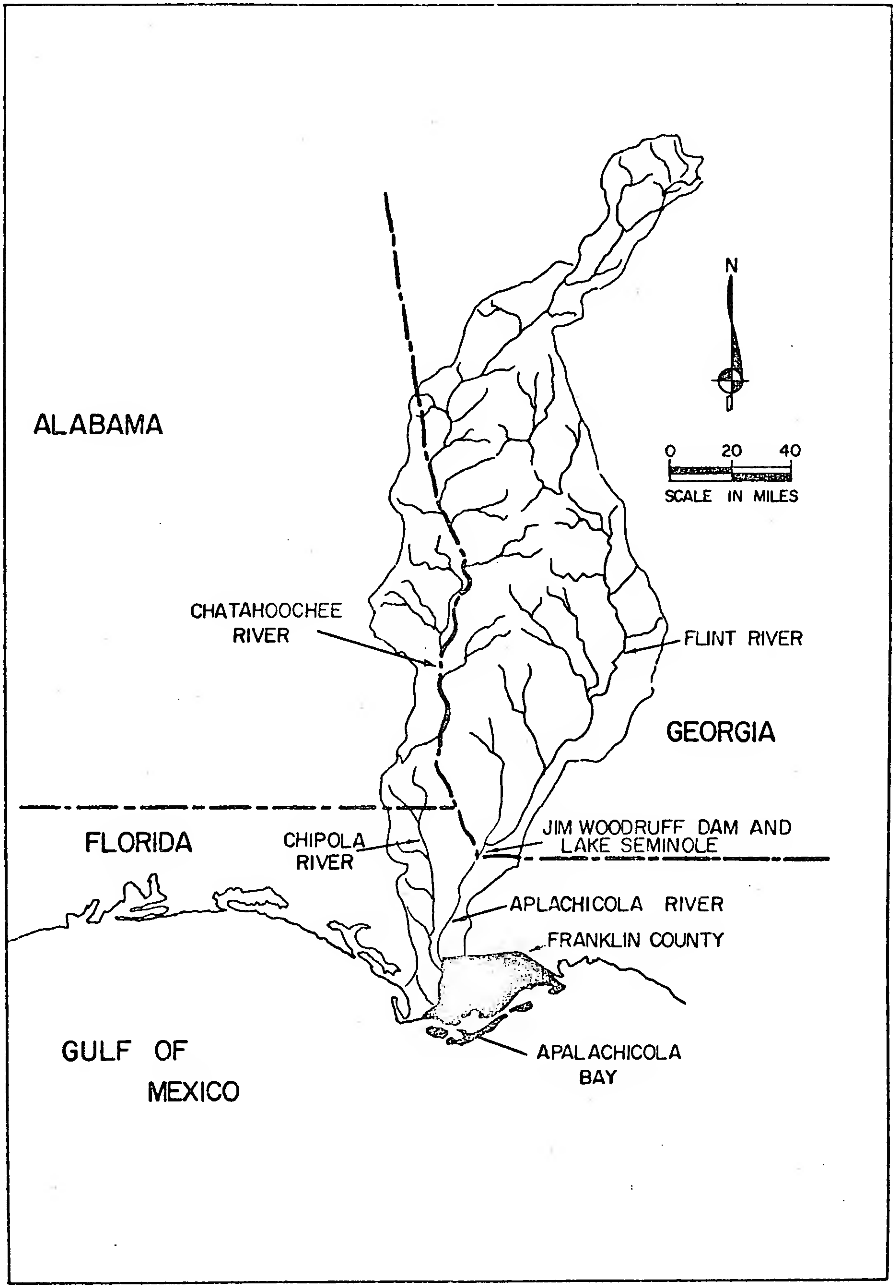
The bay is approximately 36 miles long, 1 to 14 miles wide and covers an area of 104,320 acres (163 square miles) including all of St. Vincent Sound on the west, East Bay on the north, Apalachicola Bay proper, and St. George Sound as far east as the western tip of Dog Island. Of the 104,320 acres, 9,400 acres contain submerged vegetation most of which occurs in St. George Sound. Species include *Thalassia testidinum*, *Syringodium filiforme*, *Diplanthera wrightii*, and *Halophila engelmannii*. Major emergent species cover approximately 21,000 acres of marsh and include *Spartina alterniflora*, *S. patens*, *Juncus roemarinus*, *Distichlis spicata*, and *Salicornia perennias* (McNulty *et al*., 1972).

Gorsline (1963) estimated that river water remains in the bay system for a few days in the winter and up to a month in the summer. However, the oyster producing area of Apalachicola Bay is smaller than the bay area defined by Gorsline and the retention time for this area may be less. The mean depth of the bay system at low water is

2.3 meters (7.5 feet). During the winter season the bay appears to be well mixed but has salinity induced stratification around the inlets. During the warmer seasons, stratification is generally observed with salt wedge penetration extending into East Bay at times (Estabrook, 1973). This condition may be a recent feature as both previous hydrologic studies (Dawson, 1955a; Gorsline, 1963) reported no stratification except in dredged channels. High turbidity was associated with river discharge, being highest in the winter (Estabrook, 1973). Surface circulation in the bay is partly wind-driven and partly driven by the river discharge flowing to the westward most often. Water flows east when west winds are strong. Bottom salinities had a different distribution from the surface except when the bay was well mixed (Estabrook, 1973).

The Apalachicola River has an average yearly discharge of 26,713 cfs (cubic feet per second)(6.53×10^7 m^3/day) draining a watershed of 18,000 square miles including parts of Georgia and Alabama (Hawkins, 1973)(Fig. 2). River flow had a well-defined seasonal cycle with highest and lowest flows occurring in March and September, respectively. High and low flow monthly averages, over a 43-year recording period, were 52,000 cfs and 17,000 cfs, respectively. The river is the major source of both coarse quartz sands and clays. Most of the finer sediments are located in the basin of Apalachicola Bay proper (Kofoed and Gorsline, 1963).

Fig. 2. Map showing location of Franklin County and Apalachicola Bay on the northwest Florida coast and the extent of the Apalachicola River drainage basin.


ALABAMA
N
0 20 40
SCALE IN MILES
CHATAHOOCHEE RIVER
FLINT RIVER
GEORGIA
FLORIDA
CHIPOLA RIVER
JIM WOODRUFF DAM AND LAKE SEMINOLE
APLACHICOLA RIVER
FRANKLIN COUNTY
GULF OF MEXICO
APALACHICOLA BAY

About 8% of the land area is owned by commercial pulp and paper companies or is part of the Apalachicola National Forest. Most of the land is unavailable for industrial or residential development in the foreseeable future. Paper company activities account for a small part of the economic base of the county (Colberg and Windham, 1965; Rockwood, 1973). The local economy is predominantly dependent on water resource-based activities centered on Apalachicola Bay. The Bay produces 90% of the commercial oyster harvest in the state and supports shrimp, crab, and finfish industries with an annual dockside value of several million dollars (Rockwood, 1973). The largely undeveloped forest lands, inland and coastal waters, and barrier islands in Franklin County support a tourist business and provide recreational opportunities for the residents (Florida Tourist Study, 1970). Agriculture and manufacturing activities are small at present. A large tourist-retirement community is planned for one of the offshore islands. Most basic goods, fuels, and services are purchased from outside the county with money derived from oyster sales, tourism, and land development income. Per capita income is low compared to other areas of Florida and the nation. Population levels have changed little due, in part, to emigration of residents searching for more productive, stable jobs (Colberg and Windham, 1965). In the 1930's Apalachicola was a boom town of the Gulf Coast, second only to Mobile and New Orleans in size. A major part of this growth was supported by cotton trade with the interior which reached a peak during the years 1835-1860. Some 75,000 bales of cotton were shipped from Apalachicola in 1839, and 125,000 bales in 1843. The population of Apalachicola was 2,060 in 1837. Timber, rice and sugar cane production also played a role in the economy during the territorial period. No mention was made of commercial fisheries during this period (Martin, 1944). Following the Civil War, lumbering (primarily cypress) was a major local activity with oystering, fin fishing, and boat building also mentioned (Sawyer, 1974). Severe hurricanes hit the county in 1873 and 1898, causing considerable damage. A fire burned most of the business district in 1900. The population of the county at that time was 3,077 (Sawyer, 1974).

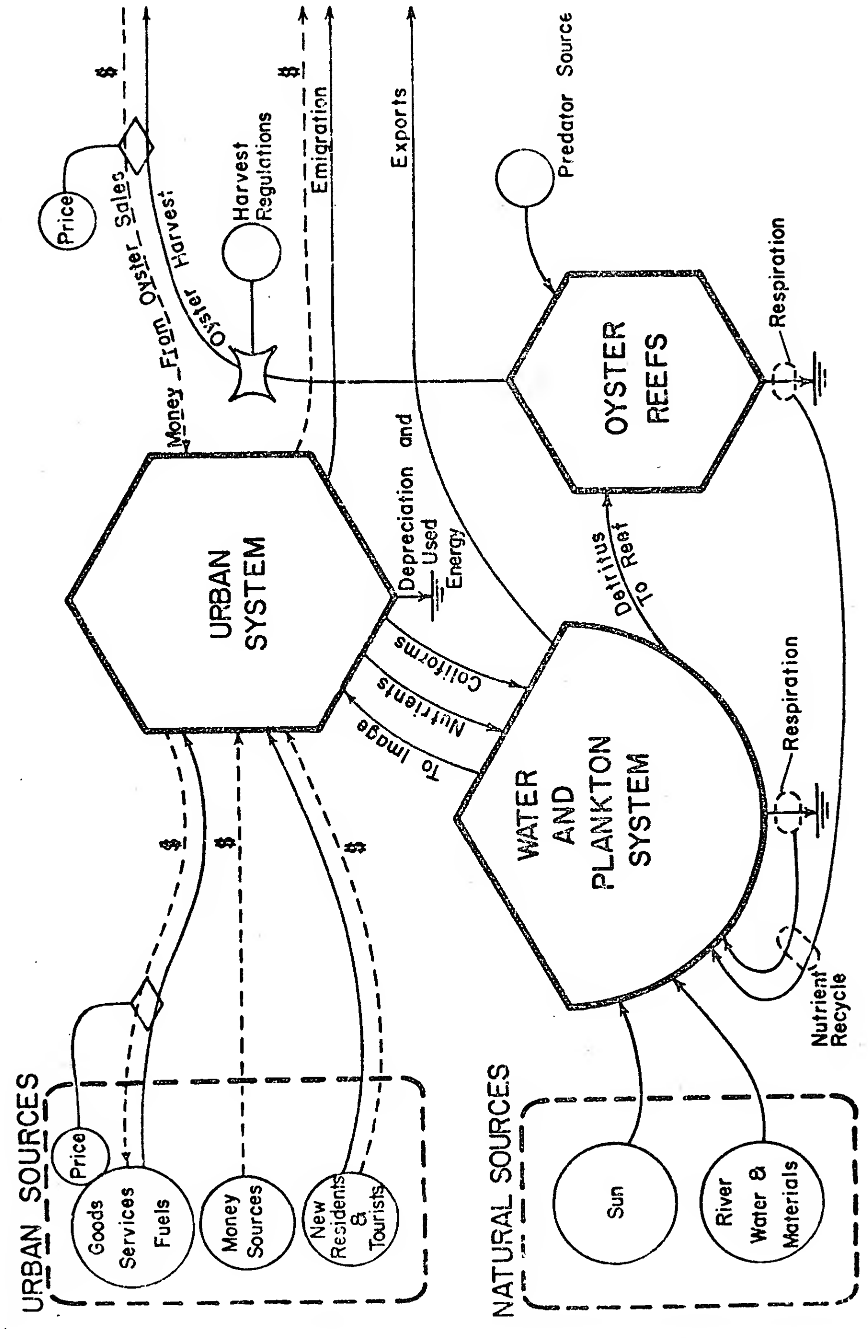
Following the turn of the century, slow growth, unemployment and underemployment were characteristic of the county. Shipping declined on the Apalachicola River due to a shallow channel to Columbus, Georgia and development of more dependable rail transportation. Oysters and fish were mentioned after 1900 as important products of the area (Franklin County Overall Economic Development Program, 1965). The current economy retains its dependence on fishery products (oysters, shrimp, and fin fish) with additional income generated from tourism, government expenditures, and some outside investment in retirement and tourist facilities.

A summary of county trends including fuel usage, fishery yields and value, population, tourism, and income are given in Figs. 30 through 34 in the Results section. A simplified model suggesting relationships within the county is given in Fig. 3. This diagram shows major inputs, aggregated storages of urban, plankton and oyster reef systems and depreciation. Figure 28a shows the model with the complexity used in simulations.

Previous Studies in Franklin County

Early studies conducted in Franklin County were primarily concerned with the biology of the local oyster fishery. Several economic and planning studies have been recently completed. Early studies by Ingersoll (1881), Swift (1897), and Danglade (1917) discussed oyster reef position, density of oysters and associated oyster reef fauna. Ingle and Dawson (1953) conducted a survey of oyster reefs including information on spawning, setting, growth, and condition of oysters (Ingle, 1951; Ingle and Dawson, 1950, 1952). Menzel *et al*. (1957, 1966) published data on oyster abundance in relation to oyster predation as influenced by salinity. Menzel and Cake (1969) reported data on temperature, salinity, diversity, and biomass of invertebrates and fish, and commercial catch for important species. Livingston and Thompson (1974) reported pesticide concentrations and other characteristics

Fig. 3. Simplified model of Franklin County and Apalachicola Bay, Florida. Model shows major inputs (urban and natural), components (urban, plankton, and oyster reef systems) and pathways connecting components and external markets. Details of this model are shown in Fig. 28a.


URBAN SOURCES
Price
Goods
Services
Fuels
Money
Sources
New
Residents
&
Tourists
$
$
$
Price
URBAN
SYSTEM
Depreciation and
Used
Energy
Coliforms
Nutrients
To Image
Money From Oyster Sales
Oyster Harvest
$
Harvest
Regulations
$
Emigration
Exports
Predator Source
OYSTER
REEFS
Detritus
To Reef
Respiration
WATER
AND
PLANKTON
SYSTEM
Respiration
Nutrient
Recycle
NATURAL SOURCES
Sun
River
Water &
Materials

of the bay (Livingston et al., 1974). Information on nutrient stocks, phytoplankton biomass and productivity was recently developed by Estabrook (1973). Cox (1970) and Cox and Auth (1971) compiled information on water quality and fish populations in the Apalachicola River. Barkuloo (1961) has reported on the striped bass population in the river.

Hydrographic studies were conducted by Dawson (1955a) and Gorsline (1963). A single layer spatial simulation model of salinity and other conservative materials was produced by Swallows (1973). Estabrook (1973) also discussed hydrographic features in the bay.

Jordan (1951) described the geology of the continental slope off the Apalachicola River and reef formation in the adjacent Gulf of Mexico (Jordan, 1952). Kofoed and Gorsline (1963) published maps of the sedimentary geology of Apalachicola Bay. Summaries of water quantity information, fishery yields, river flow, climatological data, and coastal land uses were given in McNulty et al. (1972) and Jones et al. (1973). A statistical summary and maps of Florida coastal counties were produced by the Florida Coastal Coordinating Council (1970).

Economic studies emphasized the importance of the oyster industry to the local economy and included those by Colberg and Windham (1965), Colberg, Dietrich, and Windham (1968), and Rockwood (1973). The Rockwood report also included suggestions for oyster industry management. Whitfield (1973) described the success of construction and rehabilitation of oyster reefs in the county and elsewhere. He also presented estimates of the value of submerged lands based on present and projected dollar sales of marine products.

Regional studies include those which considered economic and industrial development in Franklin County (Franklin County Planning and Development Committee, 1965), commercial tourism and land absorption (Northwest Florida Development Council, 1972), and an economic development profile of Apalachicola, Florida (Florida Dept. of Commerce, 1973). Recently, the RMBR Planning/Design Group (1974), under a federal grant, produced a county development plan including information on social, economic, and environmental conditions. Included in the report was a proposed set of land development regulations. Hawkins (1973) and Boynton *et al*. (1975) developed mathematical simulation models showing relationships between the estuarine oyster industry and coastal development. The Florida Statistical Abstract (1973) contains detailed social, climatological and economic data by both state and county areas. The Florida Division of State Planning has developed a bibliography for Apalachicola Bay and the Apalachicola River basin.

Issues for Decision in Franklin County

From discussions with local leaders in Franklin County, synthesis of data collected in previous and ongoing studies in the county, and from general principles of systems ecology (Odum, 1971a, 1973) the following list of questions needing understanding and decision was developed.

(1) What is the energy value of a generally higher more stable salinity regime on an oyster producing estuary adapted to seasonal pulses in river flow, sunlight, and temperature?

(2) What is the value of proposed coastal island development as a part of a coastal fishing economy?

(3) What are the prospects for future growth in Franklin County and its impact on the oyster industry?

(4) What are estuarine responses to nutrient and detritus loading from river and local sources?

(5) What are the major energy sources characterizing Apalachicola Bay estuarine ecosystems and oyster fishery?

METHODS

The evaluation of the energy basis of Franklin County included system models, direct field measurements, energy calculations, and aerial maps. Energy flows and storages were identified and their interactions characterized with energy circuit diagrams. The model diagrams indicated critical data to be collected in the field and were the basis for simulations and energy value calculations. Field measurements were made of total metabolism, seasonal salinity patterns, and organic matter inputs and stocks. Nutrient flows and stocks, fishery stocks and yields, and county-wide money flows were available from other studies. Maps were used to quantify areas of urban and natural land-uses and to show changing land-use patterns. Computer simulations of simplified energy models were used to test our concepts of interactions of processes as compared to field data. After sensitivity checks and validation, simulation results suggested future county trends. Energy calculations were made to determine which of several development alternatives now facing the county has the greatest survival contribution.

Modeling Techniques

From literature reviews, assembled field data, and discussions with individuals familiar with local processes in the study area, an initial list of model components was prepared. The components included all storages of materials in the system, external forcing functions and pathways of interaction identified as important to the study area. In translating the component list to diagram form, storages or state variables were shown by the tank symbol, and forcing functions or external energy sources which affect amounts in storage by the circle symbol. Transfer relationships between storages and between storages and forcing functions were shown with solid lines. Money flows were shown as dashed lines and flowed counter-current to material and energy flows. Interactions were shown with the workgate symbol and were some function of the interacting pathways. Intersection functions may be additive, multiplicative, logarithmic, exponential, or switching. An explanation of energy circuit language symbols is given in Appendix A. After further discussions and literature reviews an improved diagram was made summarizing knowledge about form and function within the study area.

In modeling efforts selection of system boundaries determines which components are state variables, and which are forcing functions and independent of model behavior. If modeling boundaries are chosen one scale larger than the size scale containing the specific component of interest, there are fewer external driving functions. For example, if understanding oyster production is a modeling goal, modeling would be done at the scale of the estuary. In this way, more components subject to change or interaction are contained within the model. The procedure avoids the mistake of showing a storage, subject to change, as a constant source independent of changes within the model.

When the full model was diagramed, numerical data were obtained on observed chronological records. The model was evaluated and simulated with initial values for an initial time period. In cases where local information was not available for evaluating a portion of the model, data were taken from the same process in a similar area. In some portions of the model where no data were available, some rates and storage values were calculated by difference as if the system was in a temporary steady state.

When all components of the system have been evaluated numerically, the relative sizes of storage and flows become evident. Indications of the importance of flows and the stability of state variables can be obtained by calculating the residence time of materials in each storage (calculated by dividing the amount in storage by the total inflow). Flows that are of a similar nature are compared. Those that are several orders of magnitude larger than others are carefully considered because they may have controlling actions in the model. Flows with effects several orders of magnitude smaller than identical flows can be omitted.

Simplification of Simulation Models

Fully evaluated models were simplified prior to simulation for several reasons. First, in the evaluated model many pathways were small and thus not considered to be essential. Rather than model these flows by themselves, they were either lumped with similar, larger flows or neglected. The same procedure was applied to state variables. Thus some complexity was eliminated. Second, some factors included in the evaluated model may not change or limit any process. These factors can be eliminated from the models while their effect remains implicit in the calculation of transfer coefficients. Comparison of simulation results from condensed models with field and literature data provide indications of model realism.

Writing and Scaling Equations

The set of differential equations associated with each model is taken directly from the energy language diagrams. Scaled terms for each equation are given in Appendix Tables C-3 and D-3. Odum (1972a) gives theoretical derivations of mathematical equivalents of the energy symbols.

In analog simulations real world values contained in equations must be magnitude-scaled so as not to exceed the voltages available in the analog computer. To do this, transfer coefficients must have scaled values between 0.001 and 0.999, and state variables and forcing functions must have scaled values as a percent of full scale of the computer. Each state variable and forcing function is assigned a maximum value. This number is at least as large as the maximum value expected for that variable but preferably two to ten times larger so as to avoid overloads in the early modeling stages. The calculated transfer coefficient associated with each term in each equation is multiplied by the maximum value (or product of the maximum values if the term is multiplicative) associated with that term. This product is then divided by the maximum value of the state variable which the full equation describes. In this fashion, proportionality of all terms is maintained while each term is adjusted to stay within the capacity of the machine. If after this procedure is completed, scaled transfer coefficients are less than 0.001 or exceed 0.999, time scaling may be required. This procedure increases or decreases the time period used to calculate flows. For instance, if a scaled model had flows calculated in units of per year, division of transfer coefficients by a factor of 10 would reduce the transfer coefficient value by a factor of 10 and flows to units of per 0.1 years. This discussion was intended to provide an overview of the scaling process required in analog computation. Details of magnitude and time scaling are given in Peterson (1967).

Simulation Techniques

The regional model was simulated on two slaved Electronic Associates, Incorporated Model 580 computers. The oxygen balance model was simulated on two slaved Electronic Associates, Incorporated MiniAc analog computers. For each model an analog patching diagram was developed directly from scaled differential equations and patched onto appropriate analog boards. Analog patching diagrams are given in Appendix Figs. C-1, D-1, and D-2.

Following checks to be sure all translational procedures to this point were correct, each model was tested for responses to expected changes in the study areas. Each computer run was similar to a controlled experiment in which one or more factors were changed. Expected changes were first calculated and then translated into new computer settings and run. Model output was either photographed directly from the oscilloscope attached to the computer or obtained from a plotter.

Validation and Basis for Model Configurations

The following procedures were used in validating models. For some variables and some rates, graphs of historical data were assembled and compared to model output with the model being started in the past. Good agreement between model output and graphs indicates an absence of contradictions. This procedure was especially useful when systems had undergone appreciable changes in the past. Simulations of natural system models were validated with time graphs obtained from field studies in Apalachicola Bay, microcosm studies and field studies in similar areas. In a second validation technique, model sensitivities were compared with single and multiple flow rate test changes.

This section also provides a rationale for the use of the energy symbols in the models presented in this dissertation. Given here are the criteria concerning the selection of state variables, forcing functions, pathways, and interactions. Storages (state variables) were used to define functional groupings within the system which were expected to vary with time and which had interaction with other components or pathways in the model. Everything included in a tank had characteristics which were similar for the purposes of the simulation and could be considered as a whole. For instance, the natural land tank in the regional model (Fig. 28a) contained a variety of ecosystem types (see Appendix B). When used for purposes other than simulation this storage was broken down into 8 specific ecosystems (see Figs. 6 and 7). Each of those could be further subdivided if a finer level of detail was required. However, each of the 8 ecosystems contained in the natural land storage had the properties of occupying space in the county and self-maintenance without urban inputs.

Obviously, not all storages of energy within the boundaries of each model have been included. The same is true for forcing functions and pathways. Those which were expected to change were identified and retained in the model. Those which were very large or not expected to change and those which were small or had few or no major interactions in the county were deleted. A similar process was followed in arranging pathways and forcing functions.

Three types of interactions were used in the models and included multiplicative and drag action workgates and workgates operated by a force from a sensor. Multipliers were used extensively because they had the property of requiring all inputs to be present for a flow to occur. Often it was possible to identify factors required for a flow to occur and thus multipliers were used to show this requirement. Secondly, the flow produced from this type of interaction is proportional to the levels in the input storages. If one or both increased, then the flow increased until one became limiting. This property was useful because it was often possible to identify such relationships. In some cases, as in primary production, the response of a multiplier is of the limiting factor type which is a well-established photosynthetic response (Odum, 1971a; Odum, 1972a; Rabinowitch and Govindjee, 1969).

Drag action workgates were used in cases where one flow was inhibited by increases in one state variable, but increased with increases in another. These were useful in approximating situations having both stimulating and inhibiting factors interacting and producing a flow. For instance, in the regional model shown in Fig. 28a, juvenile oysters feed in proportion to the food available but are inhibited when salinity is very low. If salinity reached zero, there would be no food intake by the juvenile oysters. While the exact nature of the feeding-salinity relationship was not known, this interaction captured the basic features.

Lastly, workgates operated by a force from a sensor were used in all cases where energy with or without materials flowed in proportion to some other flow. All river inputs were done this way as well as inflows of capital associated with incoming tourists and new residents as shown in the regional model (Fig. 28a).

Field Study Techniques

Field study techniques used here included measurements of community metabolism in the bay, particulate carbon concentrations in the bay and river, and two synoptic salinity surveys in the bay.

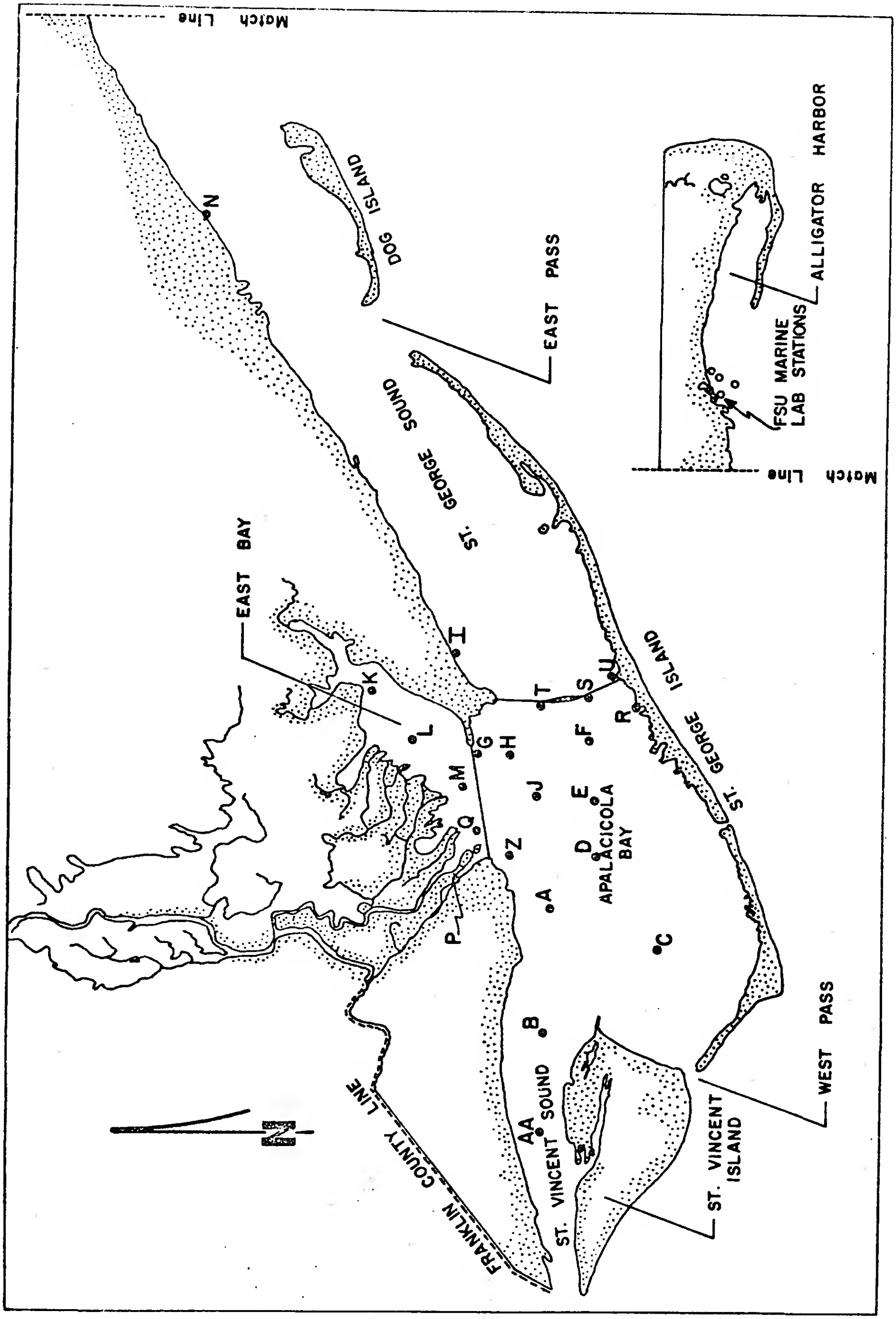
Metabolic Measurements

Community metabolism was measured using the diurnal oxygen sampling method of Odum and Hoskins (1958) and an abbreviated dawn-dusk-dawn method used by McConnell (1962). Oxygen was measured using the azide modification of the Winkler technique (Strickland and Parsons, 1972) with a further modification of thiosulfate normality which allowed convenient use of small sampling bottles. Details of the procedure used here are given by McKellar (1975).

Between June 22 and September 30, 1974, 36 diurnal stations were occupied with stations AA, A, C, D, F, H, L each occupied twice (Fig. 4). The sampling scheme was aimed at generally characterizing the magnitude of metabolism and the photosynthesis-respiration (P-R) balance in the dominant bay environments. Stations were chosen to represent the three dominant ecosystem types existing in the bay. Stations J, K, L, M, Q, Z, Y and the boat basin station at the Florida State University Lab were established in areas where respiration predominated. In the medium salinity portion of the bay system stations AA, A, B, C, D, E, F, H were established where phytoplankton activity predominated and most oyster bars were located. Along the shorelines and clearer areas where benthic grasses predominated stations were established at the Florida State Lab and station N. Two stations were also taken where wastes were suspected of entering the bay (P and I).

Over the course of any one diurnal, stations were sampled from 3 to 7 times depending on travel time between stations and weather conditions. The minimum number of

Fig. 4. Map of Apalachicola Bay showing location of stations used for diurnal metabolism and organic carbon measurements. Stations G, I, N, R, S, T and U were near-shore stations sampled from the shore, bridges or docks.


Match Line
DOG ISLAND
EAST PASS
ST. GEORGE SOUND
EAST BAY
ST. GEORGE ISLAND
APALACHICOLA BAY
ST. VINCENT SOUND
ST. VINCENT ISLAND
WEST PASS
FRANKLIN COUNTY LINE
ALLIGATOR HARBOR
FSU MARINE LAB STATIONS
Match Line
N
N
I
K
L
G
H
T
S
U
R
F
M
J
E
Q
Z
D
A
P
C
B
AA

samples required for a complete diurnal was a dawn-dusk-dawn sample sequence. Each sampling included measurements of oxygen, salinity, temperature, and depth.

Diurnal oxygen data were plotted and calculated as shown by Odum and Hoskins (1958), except for the diffusion adjustment to the final rate of change curve. One measurement of diffusion between the water and the air was measured using a small nitrogen-filled plastic dome which floated on the surface (Hall, 1972, based on original work by Copeland and Duffer, 1964). The diffusion rate as g $O_2/m^2/hr$ at 100% deficit was calculated from the area and volume of the dome, ambient oxygen concentration in the water, and the rate of oxygen increase in the dome. Oxygen changes were measured using a membrane oxygen probe. The calculation of a diffusion coefficient followed the method used by McKellar (1975). In calculating rate of change curves, diffusion coefficients were estimated from a graph that included the one measurement made in Apalachicola Bay and measurements reported by McKellar (1975) for Crystal River, Florida.

Salinity Measurements

In September of 1973 and April of 1974 synoptic salinity surveys were made in Apalachicola Bay. Stations are shown as dots in Figs. 8 and 9. Each survey was started about two hours before high tide and was completed about 2 hours after high tide. In each survey top and bottom salinity and temperature measurements were taken at each station using a Beckman electrodeless induction salinometer.

Dissolved and Particulate Carbon Analyses

In the summer of 1973 one effort was made to estimate the standing stock of particulate and dissolved organic carbon in the water column and in the river for use in the simulation models. Sixteen stations were sampled including two stations in the Apalachicola River located approximately 1 and 2 miles upstream from the mouth. Water samples were taken approximately 1 meter from the surface for all bay stations and approximately 1 meter from the top and bottom of the river. Samples were stored in acid-washed polyethelene bottles and preserved immediately with 2-3 drops of saturated mercuric chloride solution per 100 ml of sample. Analyses for total organic carbon were made from unfiltered water. Particulate carbon measurements were made with material retained on precombusted 0.45 μm glass fiber filters. Dissolved organic carbon values were obtained by difference. Subsequent techniques in the analysis followed those specified for use with the Oceanography International Total Carbon System (1972).

Energy Value Calculations

Energy value calculations were made to quantify total work contributions from various components of man and nature. Value was calculated as the work done for the total economy of man and nature when all work processes were expressed as work equivalents of one kind of energy. The procedure takes as its theoretical base Lotka's maximum power principle (Lotka, 1922) as developed by Odum (1971a). This principle states that the system that tends to prevail over alternative systems is the one that maximizes the use of all energy flows available to it and is then one which develops useful feedback roles for all participants for the purpose of assuring continued energy flows and for capturing any additional flows that come available. In a system containing both man and nature (towns, estuaries, fisheries, river, industry, and forests), the principle requires using the variety of components in partnerships rather than in competition to obtain maximum work per time (power) through the full system. Two additional concepts were used in energy calculations and are presented next, followed by the general procedure.

Energy Quality Concept

The value of a system process was defined as the contribution of the process to the useful work of the system. In evaluating energy models, all pathways were first shown in units of kilocalories/area/time. Raw energy flows, as measured in kilocalories of heat, do not represent the ability to do work but rather show only the heat content of that particular flow. Whereas any energy flow can be degraded to heat with 100% efficiency the ability of an energy flow to do useful work depends on the packaging or concentration of the energy flow. For instance, the kilocalories associated with wood production in photosynthesis represent the concentration to wood kilocalories of the dilute kilocalories of unprocessed sunlight and energy of collecting wood to one location. Approximately 99% of the sunlight kilocalories are degraded to heat to make one kilocalorie of wood quality. While it is difficult for human systems to use the dilute energy contained in sunlight directly, the energy contained in wood has been concentrated or upgraded at the expense of sunlight energy and thus represents a higher quality energy. In the same way electrical energy is at higher concentration than the energy contained in coal; its generation requiris approximately four kilocalories of coal type energy to obtain one unit of electrical type energy. Three kilocalories of coal energy are contributed from the coal to operate steam engines and one kilocalorie is expended to perform the work of constructing and maintaining the power plant structure. Several other examples of conversion calculations are given by Odum _et al_. (1974b) for relating kilocalories of wind, wood, and electricity. Energy quality relationships relating producers and many consumers in a shallow marine ecosystem were given by McKellar (1975). One calculation of the energy quality of the potential energy of river head being converted to electricity was given by Young et al. (1974). An additional calculation of river head-electrical relations is contained in this dissertation for the dam on the Apalachicola River. Thus, the above considerations suggest ways to compare varying types of energy flows in macroscopic systems of man and nature. Before comparisons are made, each flow must be converted to a common baseline energy quality. In this dissertation, all energy flows have been converted to the fossil fuel quality level (expressed as $Kcal_{FFE}$). A complete list of conversion factors used in this dissertation is given in Table 1.

In this study, the following method is used to determine the energy quality of a work flow relative to other types of flows. The method involves calculating the energy required to generate the high-quality work flow. As shown in Fig. 5, the quality factor is obtained by comparing the output of the conversion process with the input energy after all required feedbacks and subsidies have been converted to equivalents of the same quality and subtracted. All output feedback and subsidy energies must be of the same quality before being manipulated. A complete calculation of this type is given in Table 13, where potential energy of river head is converted to fossil fuel and electrical work equivalents. This method assumes that maximum energy conversions done through one pathway equal those done

Table 1

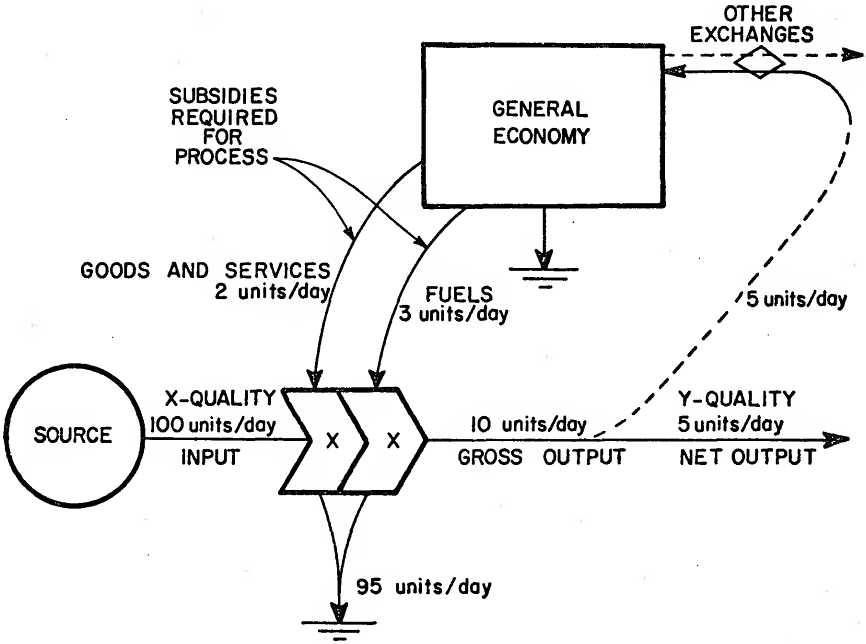
Energy quality factors relating different work processes.

Energy Conversion Process	Energy Quality Factor[a]
	(divide by)
Sunlight to gross photosynthetic production	100
Gross photosynthetic production to wood	10
Wood to fossil fuel	2
Wood to electricity	8
Fossil fuels to electricity	3.6
Gross photosynthetic production to fossil fuel	20
Sunlight to fossil fuel	2000
Wind to fossil fuel	7.7
Tidal energy to fossil fuel	2.5
Hydrostatic head to fossil fuel	0.63[b]
Fresh/salt water concentration	0.3
Heat gradient to fossil fuels	10,000
Waves to fossil fuels	5
Fossil fuel flow to dollar flow in U.S.	25,000 Kcal/dollar

[a]Energy quality factor is the ratio of energy input of one type required to generate another type of higher quality. (See Methods section) Energy quality factors used here are preliminary and may be subject to revisions. For calculations leading to ratios given above see Odum *et al*. (1974b), and Young *et al*. (1974).

[b]Calculations for conversion of hydrostatic head to electricity and fossil fuel are given in the Results section of this dissertation.

Fig. 5. Diagram showing example of the upgrade method of calculating energy quality ratios. Note that a portion of the gross output is fed back to the process, via the general economy, to cover full cost of operating the process. This is required to get a true net relationship between X and Y forms. The energy quality ratio relating X to Y is 20 in this example (100/5).


OTHER
EXCHANGES
SUBSIDIES
REQUIRED
FOR
PROCESS
GENERAL
ECONOMY
GOODS AND SERVICES
2 units/day
FUELS
3 units/day
5 units/day
SOURCE
X-QUALITY
100 units/day
INPUT
X
X
10 units/day
GROSS OUTPUT
Y-QUALITY
5 units/day
NET OUTPUT
95 units/day

through another if the systems are under competition for survival and selected to operate at maximum power.

Thus, the application of energy quality ratios to all energy flows allows for equal evaluation of all types of work whether they be associated with man and money flows or supplied without money exchanges.

Energy Investment Ratio Theory

In some energy evaluations, total energy flow following a proposed alteration is greater than before the alteration. By criteria of maximum power, the new pattern would seem better than the old and should be adopted. However, outside goods, services, and fuels have to be purchased, and the income and investments for these purchases can only be assured if the resident natural energies are enough to attract the required capital. The energy investment ratio is the ratio of high quality external energies that are attracted from outside the system and paid for by some kind of exchange to the natural energies operating in the study area. In 1973 this ratio was estimated to be 2.5 to 1 for the United States (Odum *et al.*, 1974c). Systems that have lower investment ratios can match high quality external energies with more lower quality natural energies and thus compete well with those things offered for exchange. The theory suggests that as the local investment ratio exceeds the ratio of surrounding systems, the local system generates less value per unit of high-quality energy used. This decline in value per unit could be reflected in higher prices required for exports and thus a disadvantage in competing with other, less developed systems for high-quality energies. The ultimate contribution of energy flows depends both on high-quality purchased flows of fossil fuels and resident natural energies with which the high-quality flows interact.

Energy Evaluation of a Process or Alternative

The first step in the energy evaluation of a process or an alternative is to construct a diagram using the energy symbol language including all major work processes occurring in the study area. These diagrams include the work done by nature in maintaining soils, water flows, forests, estuarine and river systems, beaches, etc., as well as the work associated with man's activities. By putting the work processes of both man and nature on the same diagram, we summarize all of the work processes that contribute to the welfare of a region. The summary diagram avoids the common mistake of counting as valuable only those processes associated with money (Odum 1972b, 1973).

The next step is to evaluate all pathways in the diagram in units of work (Kcal/area/yr). In this dissertation, natural system work was evaluated by using gross community metabolism as an estimate of total work. Work done by physical systems such as tides, waves, wind, etc., was calculated by standard formulas. Work done by human activity was often available as dollar expenditures and converted to work units in the following way. In the U. S. economy as a whole, there is an average exchange ratio between work done and money flow (Kcal/dollar). After several previous calculations (Odum _et al_., 1972), this ratio in the United States was estimated to be approximately 25,000 $Kcal_{FFE}$/dollar in 1973 (Odum and Brown, 1975). This figure was obtained by summing total fuel usage in the U.S. per year and total work of the natural systems expressed as $Kcal_{FFE}$ required to do the same work. This figure was then divided by the gross national product for that year giving an average ratio of work that accompanies a dollar expenditure expressed in kilocalories/dollar. Thus, when data on human activity are given in dollars, the dollar figure can be converted to kilocalories using the ratio of 25,000 Kcal/dollars if the nature of that work has energy uses similar to the national average.

When the energy diagram is fully evaluated a table is constructed with each pathway in the diagram becoming an entry in the table. Next, each work flow is expressed in units of equivalent work by one type of energy. Thus, all energy flows are converted to a common work quality level. Once all entries are converted, they may be summed to a total showing total value generated in the region per year under the present pattern of man and nature. The investment ratio can also be calculated. Following this, separate tables can be constructed for the totally natural condition as it was thought to once exist and for anticipated outcomes or patterns of man and nature under each alternative. Investment ratios for each alternative can be calculated and compared to national and local averages.

Land-Use Maps from Aerial Photographs

Two sets of maps were constructed to show spatial features, one of the primitive condition and one of the present pattern of man and nature in the Franklin County region.

The primitive map was constructed using a soils map of the region. The assumption was made that soil types reflect original vegetation types. The scale on the map was 1 inch equals 4 miles.

The map showing present land-use was developed from aerial photographs taken in 1973 on a scale of 1 inch equals 2000 feet. The map was verified with checks on the ground and with the Franklin County Agricultural Extension Agent. Each system type shown on the maps is defined in Appendix B.

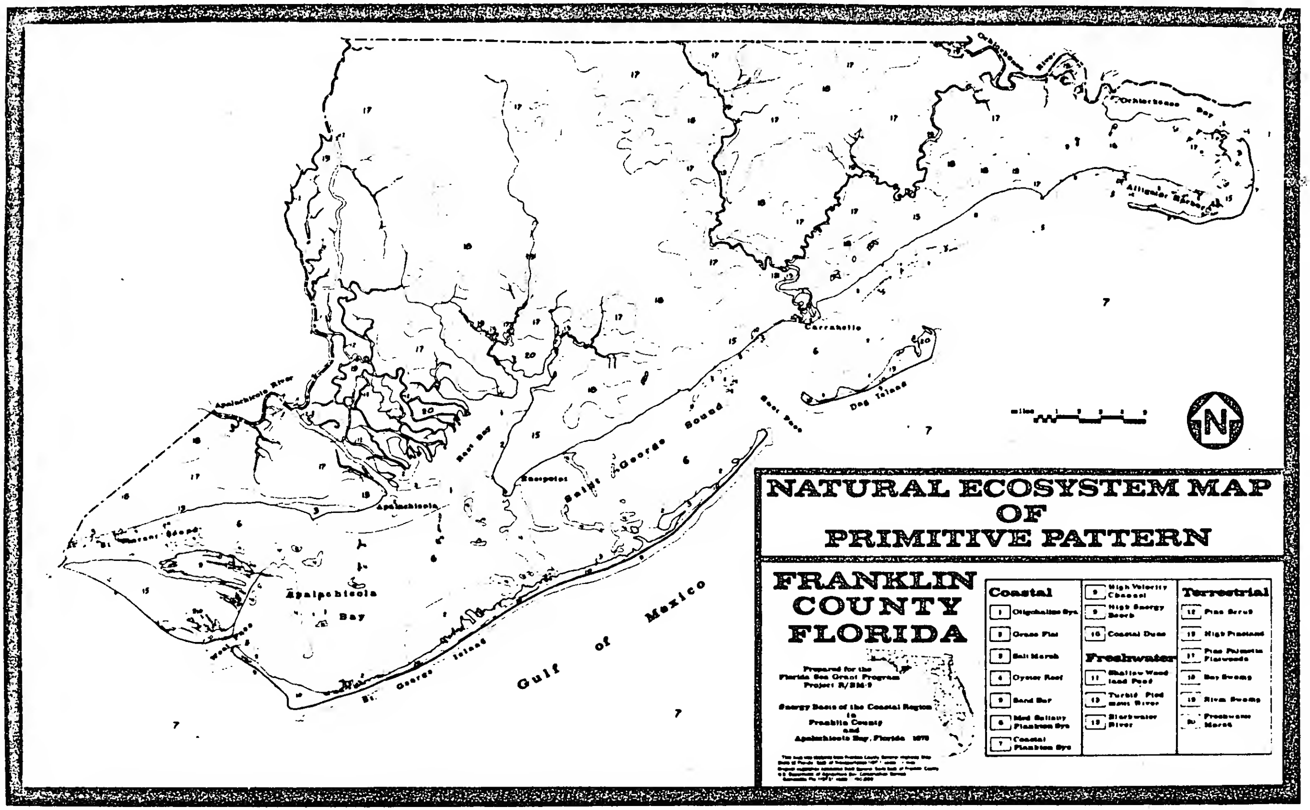
RESULTS

Maps of Principal Ecosystems in Franklin County

Shown in Figs. 6 and 7 are maps of the ecosystems in Franklin County. A description of each type of system is given in Appendix B. Figure 6 is the map showing the primitive pattern prior to the first commercial cutting of the forest (circa 1838). Areas of each ecosystem in the primitive pattern are given in Table 2.

The present pattern is shown in Fig. 7. Areas of present land-use are given in Table 3. In the present pattern urban land accounts for only 0.5% of the total regional area (about 1.2% of the land area). Approximately 15% of the original bay swamp and most of the original pine palmetto flatwoods, high pinelands, and pine scrub have been converted to pine forests. Cleared/planted lands account for approximately 26% of the land area, most of which was originally bay swamps and pine palmetto flatwoods. The river swamp area is approximately 15% smaller than in the primitive pattern. In the estuary, new systems account for only 1.4% of the bay area and include boat basins and harbors (200 acres), navigation channels (560

Fig. 6. Reduced map of primitive pattern of ecosystems in Franklin County, Florida. Full-sized map is given in Appendix E.



NATURAL ECOSYSTEM MAP
OF
PRIMITIVE PATTERN
FRANKLIN
COUNTY
FLORIDA
Prepared for the
Florida Sea Grant Program
Coastal
Grass Flat
Salt Marsh
Oyster Reef
Sand Bar
Coastal
High Velocity
Channel
High Energy
Beach
Coastal Dune
Freshwater
Terrestrial
Pine Scrub
High Pineland
Bay Swamp
Gulf of Mexico
Apalachicola Bay
Apalachicola
St. George Island
Dog Island
Carrabelle
Ochlockonee Bay
Alligator Harbor
East Bay
St. George Sound
East Pass
Eastpoint
Apalachicola River

Table 2

Area and percentage of total area of each ecosystem type in primitive pattern in Franklin County.

Ecosystem Type	Area, Acres	Percentage of Total Area[a]
Marine		
Oligohaline system	14,842	1.65
Grass flats	19,415	2.16
Salt marsh	7,701	0.86
Oyster reef	7,539	0.84
Sand bar	1,534	0.17
Medium salinity plankton system	82,971	9.25
Coastal plankton system	406,400	45.30
High velocity channels	718	0.08
High energy beach	(11,596)	(1.30)
Coastal dunes	4,426	0.49
Freshwater		
Shallow woodland ponds	1,388	0.15
Turbid piedmont river	3,644	0.41
Blackwater river	2,396	0.27
Terrestrial		
Pine scrub	43,118	4.81
High pineland	11,586	1.29
Pine-palmetto flatwoods	111,209	12.40
Bay swamp	118,044	13.16
River swamp	35,575	4.00
Freshwater marsh	13,052	1.45
TOTAL	897,154	100.00

[a]Total county area includes all land and water ecosystems in the county and adjacent Gulf of Mexico to the 10-fathom line.

Fig. 7. Reduced map of present pattern of ecoysystems (1973) in Franklin County, Florida. Full sized map is given in Appendix E.

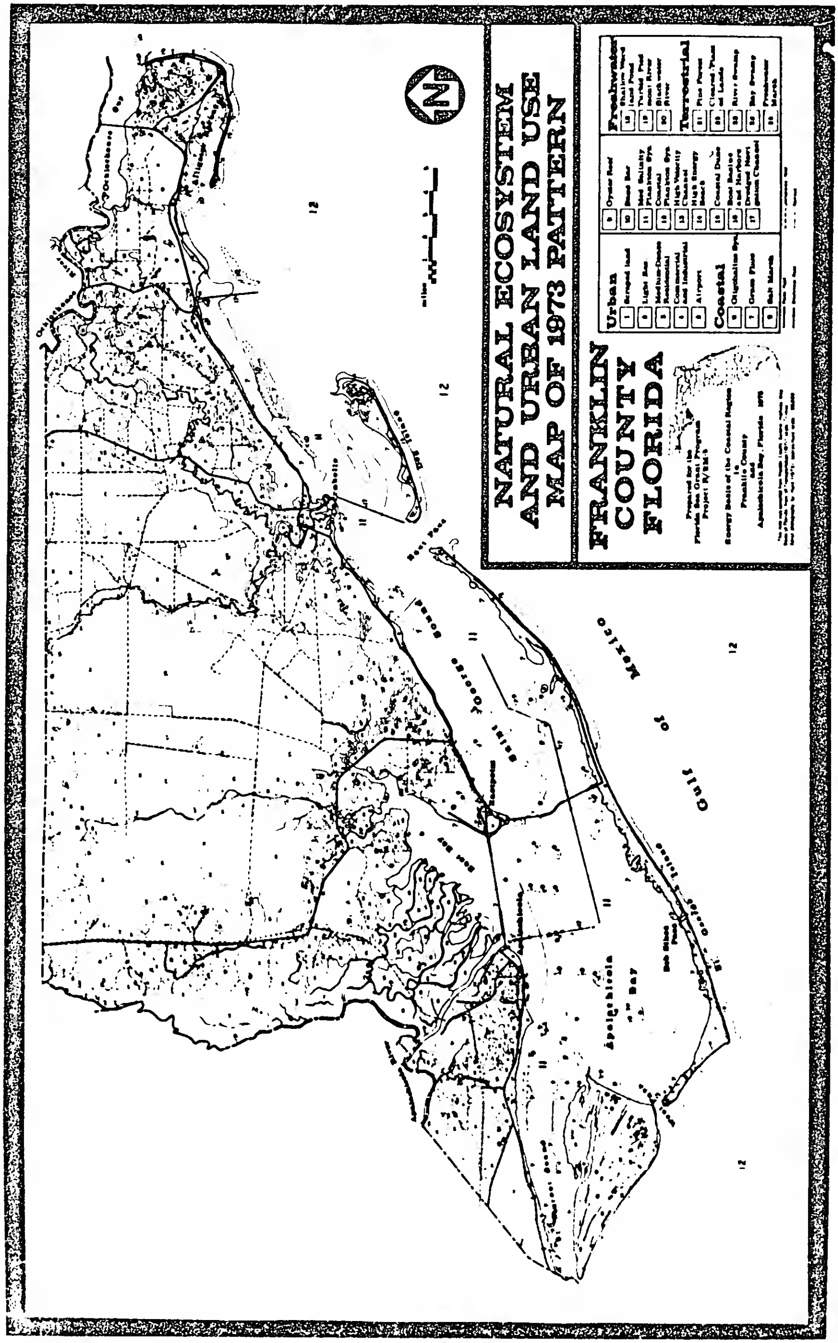

NATURAL ECOSYSTEM
AND URBAN LAND USE
MAP OF 1973 PATTERN
FRANKLIN
COUNTY
FLORIDA
Urban
Coastal
Freshwater
Terrestrial
Gulf of Mexico

Table 3

Area and percentage of total area of each ecosystem type in present pattern in Franklin County.

Ecosystem Type	Area, Acres	Percentage of Total Area[a]
Urban		
Scraped land	1,134	0.13
Residential—light	1,789	0.20
Residential—med. dense	478	0.05
Commercial—industrial	412	0.05
Airports	459	0.05
Marine		
Oligohaline system	14,841	1.64
Grass flats	19,415	2.14
Salt marsh	7,072	0.78
Oyster reefs	8,870	1.00
Sand bars	1,534	0.17
Medium salinity plankton system	80,217	8.85
Coastal plankton system	406,400	44.84
High velocity channels	767	0.08
High energy beaches	11,595	1.28

[a]Total county area includes all land and water ecosystems in the county and adjacent Gulf of Mexico to the 10 fathom line.

Table 3 - continued

Ecosystem Type	Area, Acres	Percentage of Total Area[a]
Marine (cont.)		
Coastal dunes	4,782	0.53
Boat basins and harbors	200	0.02
Dredged navigation channels	560	0.06
Freshwater		
Shallow woodland ponds	1,388	0.15
Turbid piedmont River	3,644	0.40
Blackwater river	2,396	0.26
Terrestrial		
Pine forests	103,303	11.40
Cleared/planted lands	93,015	10.26
River swamp	30,539	3.37
Bay swamp	99,494	10.98
Freshwater marsh	12,100	1.33
TOTAL	906,401	100.00

acres), Bob Sikes Pass (49 acres) and planted oyster bars (1331 acres).

Characteristics of Apalachicola Bay

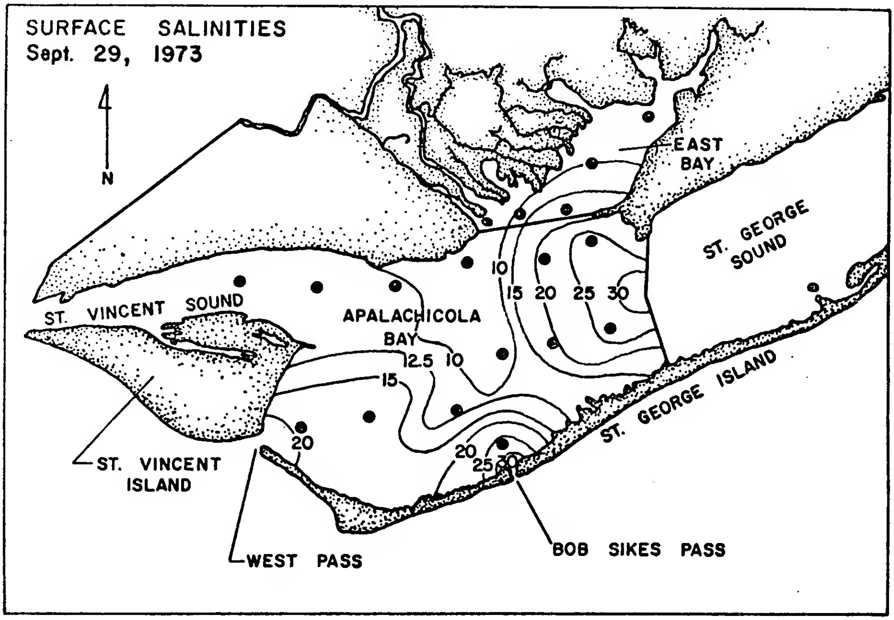
This section brings together data on Apalachicola Bay collected in this project and assembled from other investigators. Using these data, an aggregated model of the diurnal properties of the bay ecosystem was evaluated, simulated, and compared with field data.

Salinity Measurements

Figures 8 and 9 are maps showing the surface and bottom salinity distribution on September 29, 1973 and April 20, 1974. Both sets of measurements were taken on a rising tide. The September measurements were taken when river flow was low (15,060 cfs) while the April measurements were taken during high flow (49,390 cfs). Salinity stratification was evident over most portions of the bay in the fall (Fig. 8). This observation is supported by data collected by Estabrook (1973). Area weighted average surface and bottom total salt content for the bay was 3.58×10^9 kg and 6.0×10^9 kg, respectively. These correspond to average surface and bottom salinities of 15 and 26 ppt, respectively.

In the spring sample, both surface and bottom salinities were lower, averaging 4.9 and 11.5, respectively

Fig. 8. Salinity pattern in Apalachicola Bay on September 29, 1973, (a) surface; and (b) bottom. River flow was 15,060 cfs and wind was from the southeast. Salinity stations are indicated by dots.


SURFACE SALINITIES
Sept. 29, 1973
N
EAST BAY
ST. GEORGE SOUND
ST. VINCENT SOUND
APALACHICOLA BAY
10
15
20
25
30
12.5
ST. GEORGE ISLAND
ST. VINCENT ISLAND
WEST PASS
BOB SIKES PASS

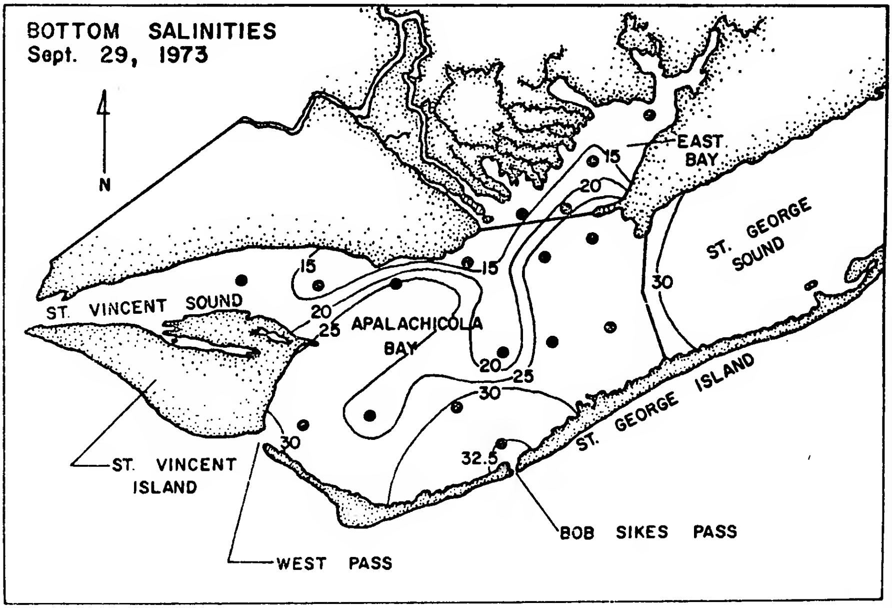
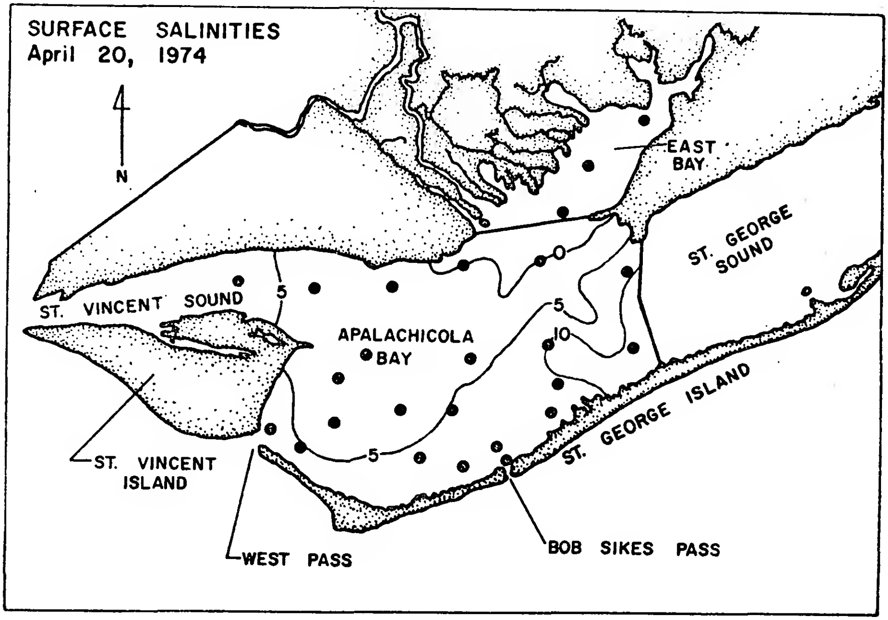
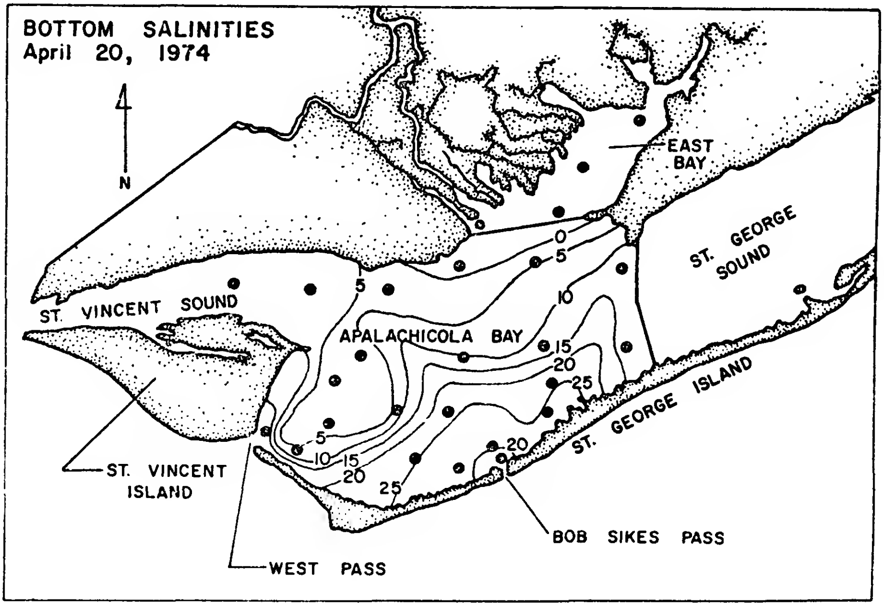

BOTTOM SALINITIES
Sept. 29, 1973
N
EAST BAY
ST. GEORGE SOUND
ST. VINCENT SOUND
APALACHICOLA BAY
15
20
25
30
32.5
ST. GEORGE ISLAND
ST. VINCENT ISLAND
WEST PASS
BOB SIKES PASS

Fig. 9. Salinity pattern in Apalachicola Bay on April 20, 1974, (a) surface; and (b) bottom. River flow was 49,390 cfs and the wind was from the east at 10-15 knots. Salinity stations are indicated by dots.


SURFACE SALINITIES
April 20, 1974
N
EAST BAY
ST. GEORGE SOUND
ST. VINCENT SOUND
APALACHICOLA BAY
0
5
10
ST. GEORGE ISLAND
ST. VINCENT ISLAND
WEST PASS
BOB SIKES PASS

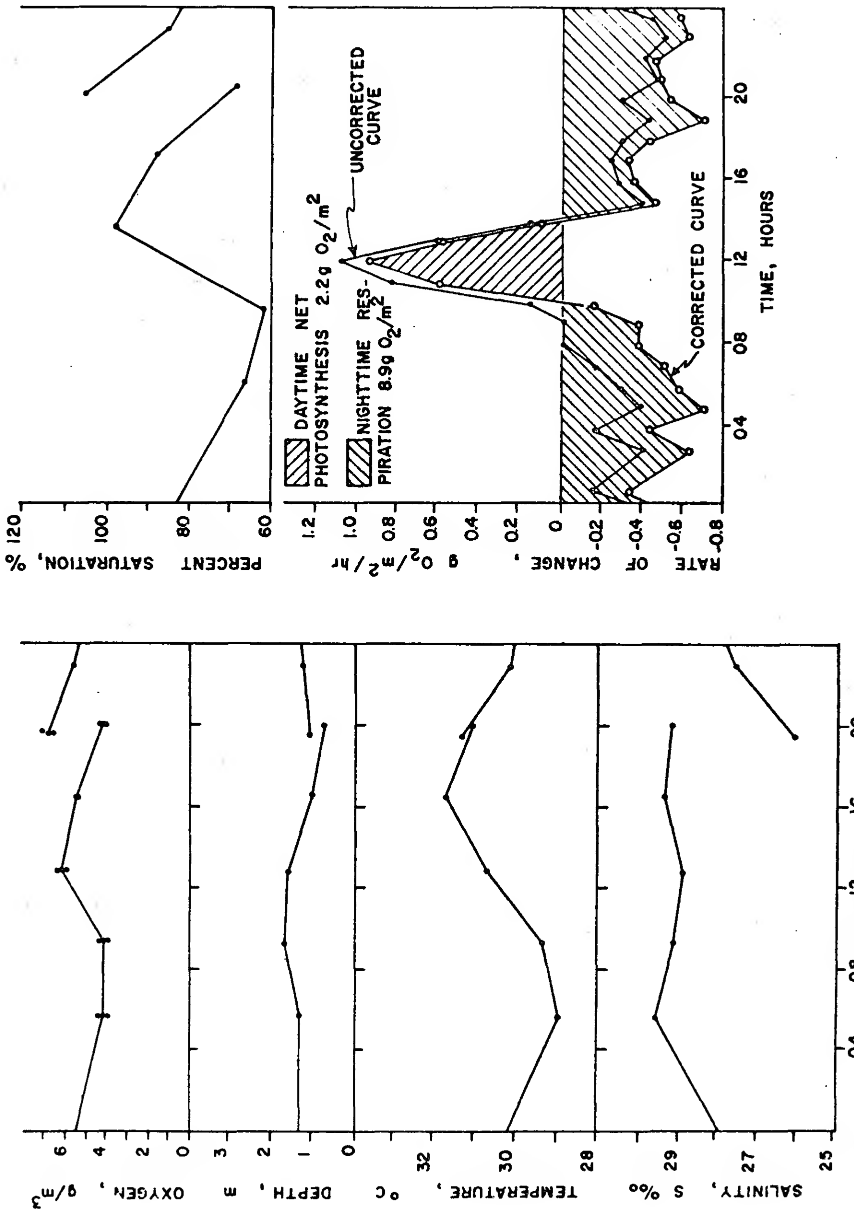

BOTTOM SALINITIES
April 20, 1974
N
EAST BAY
ST. GEORGE SOUND
ST. VINCENT SOUND
APALACHICOLA BAY
0
5
10
15
20
25
ST. GEORGE ISLAND
ST. VINCENT ISLAND
WEST PASS
BOB SIKES PASS

(Fig. 9). However, the average relative difference between surface and bottom salinity was greater in the spring sample than in the fall sample. High salinity bottom water (20-30 ppt) was evident in a large portion of the bay along the barrier island on both sides of Bob Sikes Pass. Very little stratification was evident nearer the river mouth and in East Bay in the spring sample. There was no evidence of thermal stratification. Surface and bottom temperatures seldom differed by more than several degrees.

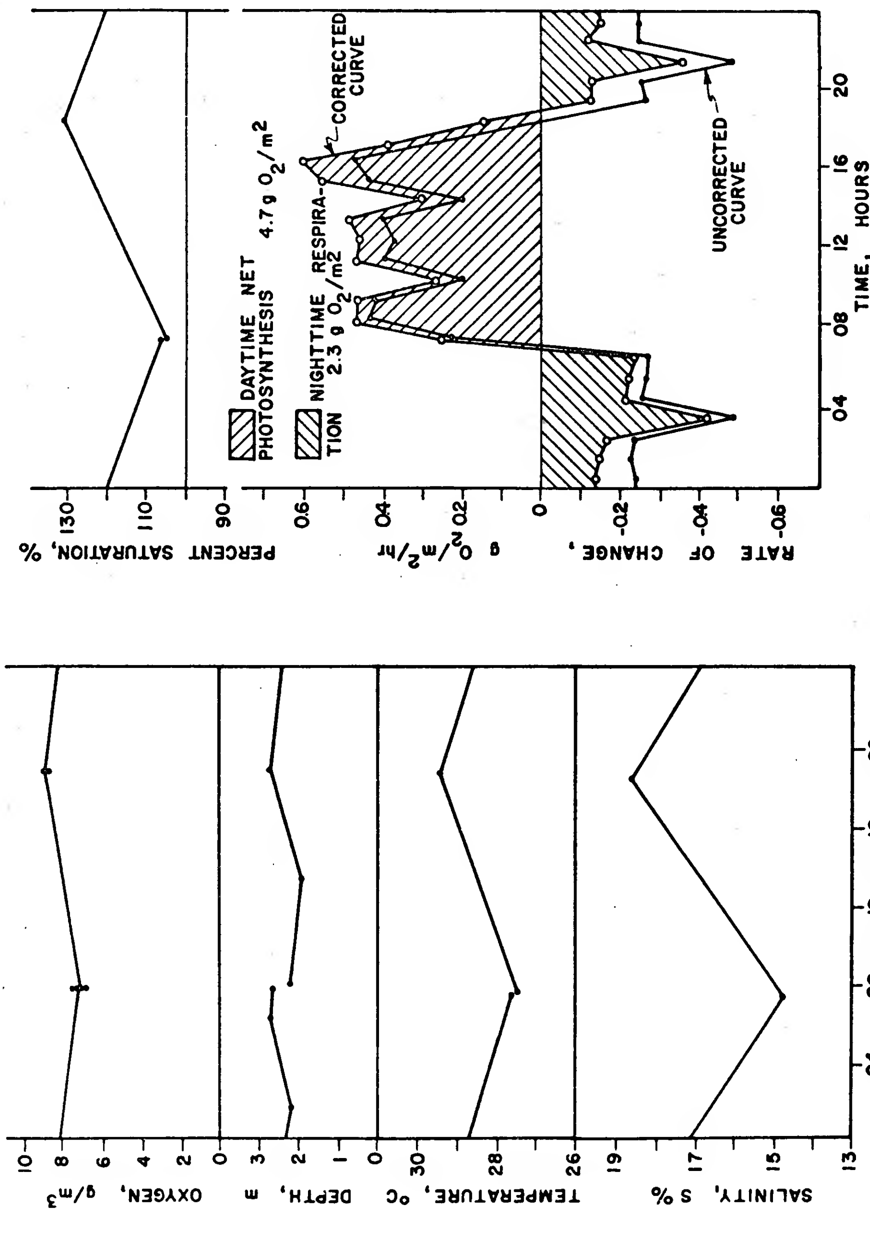
Diurnal Metabolism Measurements

Thirty-six diurnal metabolism measurements were taken in the bay between June 22 and September 30, 1973. Station locations were given in Fig. 4. Data from two 24-hour diurnal metabolism surveys (Station I, July 24-25, 1973, and Station C, September 29, 30, 1973) are shown in Figs. 10a and 10b. In Fig. 10a respiration exceeded day-time net production (see rate of change curve) by a factor of four indicating that a large portion of the respiratory activity was supported by organic matter supplied from other areas. Photosynthesis was at a maximum at 1100 hours (1.05 g $O_2/m^2/hr$) and declined rapidly in the early after-noon. Respiration averaged about 0.5 g $O_2/m^2/hr$ during the night. At this station the water was generally under-saturated with oxygen. Hence, when the rate of change curve was corrected for diffusion, hourly rates of

Fig. 10. Examples of diurnal records used to calculate community metabolism. (a) Station I, July 24-25, 1973; and (b) Station C, September 29-30, 1973. The rate of change curve was plotted by calculating the hourly rate of change from the oxygen curve and then multiplying that by depth. The rate of change curve was then corrected for diffusion. The area under the curve above the zero line represents daytime net photosynthesis. The area below the zero line represents night respiration. Details of the open water diurnal method of measuring community metabolism are given by McKellar (1975). The mean oxygen value from replicate samples is connected by a solid line. Actual data points are also shown. Circled points indicate that replicates were too similar to plot separately.


PERCENT SATURATION, %
RATE OF CHANGE, g O2/m2/hr
DAYTIME NET PHOTOSYNTHESIS 2.2g O2/m2
NIGHTTIME RESPIRATION 8.9g O2/m2
UNCORRECTED CURVE
CORRECTED CURVE
TIME, HOURS
OXYGEN, g/m3
DEPTH, m
TEMPERATURE, °C
SALINITY, S ‰
TIME, HOURS

(a)


OXYGEN, g/m3
DEPTH, m
TEMPERATURE, °C
SALINITY, S %
TIME, HOURS
PERCENT SATURATION, %
RATE OF CHANGE, g O2/m2/hr
DAYTIME NET PHOTOSYNTHESIS 4.7 g O2/m2
NIGHTTIME RESPIRATION 2.3 g O2/m2
CORRECTED CURVE
UNCORRECTED CURVE
(b)

respiration became larger as shown on the corrected rate of change curve. Most stations followed a pattern similar to the one at Station I, except that the relative proportion of photosynthetic and respiratory activity (P/R ratio) varied from station to station. Figure 10b shows results from a station (C) where photosynthesis was predominant and the P/R ratio was greater than 1.0.

A summary of diurnal metabolism measurements taken in the bay in the summer of 1973 is given in Table 4. Results are grouped in the table according to major features characterizing the portion of the bay from which the samples were taken (Odum _et al_., 1974a). During the sampling period, metabolism (daytime net photosynthesis plus night respiration) ranged from 3.1 g $O_2/m^2/24$ hrs at Station L to 21.6 g $O_2/m^2/24$ hrs at the FSUML boat basin. The latter station was the deepest station where a measurement was taken and this in part accounts for the large metabolism, most of which was respiration. There was some variability at stations where metabolism was measured twice.

Figure 11 shows total metabolism plotted against time. No clear seasonal trend was evident over the four-month sampling period. Average metabolism was 8.5 g $O_2/m^2/24$ hrs. Figure 12 shows daytime net photosynthesis plotted against nighttime respiration for each station. The diagonal line represents a P/R ratio of 1.0. When plotted in this fashion those stations in East Bay (K, L, M,), near

Table 4

Summary of diurnal metabolism measurements taken in Apalachicola Bay during the summer of 1973. Station locations are given in Fig. 4. Area definitions are from Odum *et al*. (1974a).

Area	Date	Station	P Photosynthesis g O_2/m^2/day	R Respiration g O_2/m^2/night	P/R
Medium Salinity					
Plankton System	July 28-29	T	2.0	4.0	0.5
		U	0.3	2.8	0.1
		S	2.2	2.6	0.9
		R	1.6	1.7	0.9
	Aug. 2-3	E	3.5	2.9	1.2
		H	3.1	3.5	0.9
		F	5.2	5.4	0.9
		D	5.1	4.9	1.0
		A	2.3	3.4	0.8
	Aug. 14-15	C	6.9	5.3	1.3
		AA	2.2	2.5	0.9
		B	4.6	3.8	1.2
		A	5.7	2.4	2.4
	Sept. 29-30	C	4.7	2.3	2.1
		H	2.3	2.0	1.1

Table 4 - continued

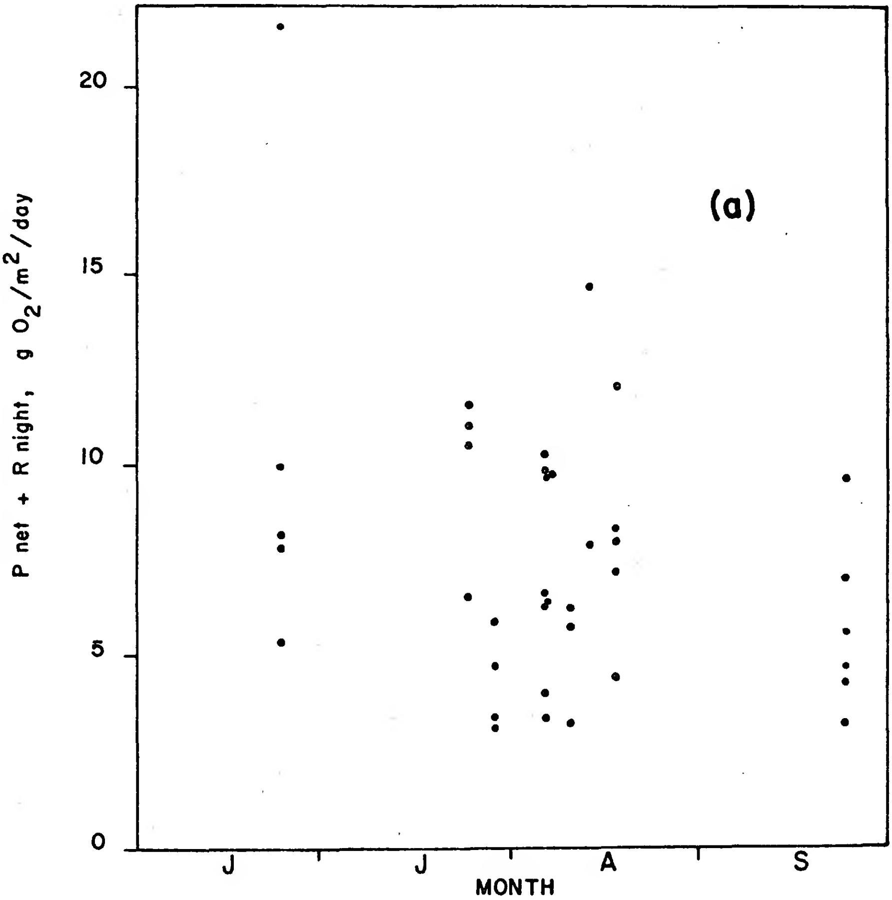
Area	Date	Station	P Photosynthesis g O_2/m^2/day	R Respiration g O_2/m^2/night	P/R
Medium Salinity Plankton System (cont.)	Sept. 29-30 (cont.)	AA	4.0	0.7	5.8
		D	5.4	4.2	1.3
		F	3.3	2.4	1.4
Oligohaline System					
	Aug. 2-3	Z	0.5	2.9	0.2
		J	1.2	2.9	0.4
	Aug. 4-5	K	0.2	3.1	0.1
		M	0.9	4.8	0.2
		L	1.7	4.6	0.4
	Aug. 11-12	Q	4.2	3.8	1.1
		Z	3.1	4.1	0.8
	Sept. 29-30	L	1.4	1.7	0.8
Low Salinity Areas Receiving Man-Related Wastes	July 24-25	I	2.2	8.9	0.2
	Aug. 11-12	P	5.4	9.4	0.6

Table 4 - continued

Area	Date	Station	P Photosynthesis g O_2/m^2/day	R Respiration g O_2/m^2/night	P/R
High Salinity Areas Receiving Natural Organic Inputs	June 22-23	FSUML[a] (boat basin)	5.2	16.4	0.3
	June 24-25	G	2.5	4.1	0.6
High Salinity Grass Flats	June 22-23	FSUML	4.9	2.9	1.7
		FSUML	4.6	3.8	1.2
	June 24-25	FSUML	6.9	4.8	1.4
		N	5.9	4.7	1.3
High Salinity Areas Without Grass Flats	June 22-23	FSUML	3.0	2.6	1.2
		FSUML	5.1	4.9	1.0

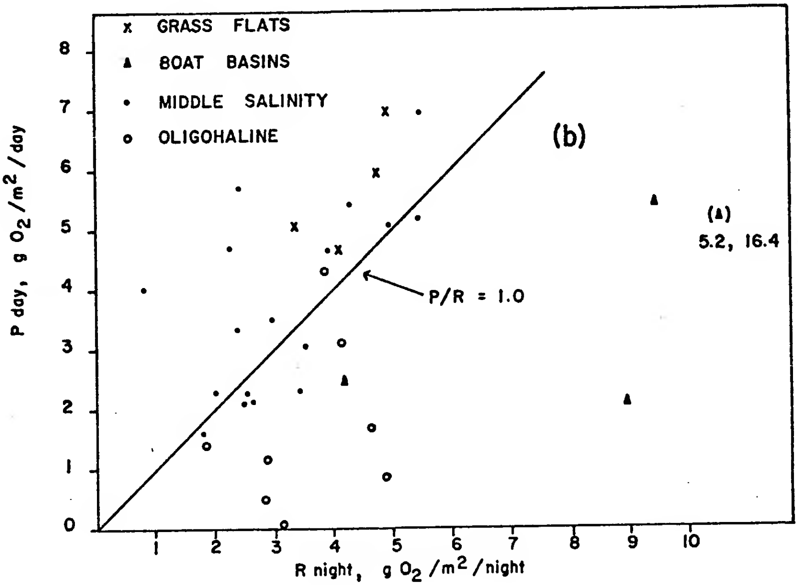
[a]Florida State University Marine Lab at Turkey Point.

Fig. 11. Graph of bay productivity for June-September, 1973. Each point represents sum of daytime net photosynthesis and nighttime respiration from a 24-hour record of oxygen.



(a)
P net + R night, g $O_2/m^2/day$
0
5
10
15
20
J
J
A
S
MONTH

Fig. 12. Graph of daytime net photosynthesis as a function of nighttime respiration for systems in Apalachicola Bay (grass flats × ; boat basins ▲ ; medium salinity plankton system • and oligohaline system o). The diagonal line represents a P/R ratio of one.



GRASS FLATS
BOAT BASINS
MIDDLE SALINITY
OLIGOHALINE
(b)
P/R = 1.0
5.2, 16.4
P day, g O_2/m^2/day
R night, g O_2/m^2/night

the river mouth (Z, J) and stations suspected of receiving man-related wastes (I, P, FSUML boat basin) all had P/R ratios less than 1.0. The medium salinity plankton system stations (A, AA, B, C, D, E, F, H, R, S, T, and U) had P/R ratios of about 1.0 or somewhat greater. Average metabolism in this area was 6.8 g $O_2/m^2/24$ hrs. The grass flat stations (N, and FSUML stations) all had P/R ratios greater than 1.0. Average metabolism at the grass flat station was 9.6 g $O_2/m^2/24$ hrs.

Organic Carbon Measurements

Fourteen stations were sampled for particulate and dissolved organic carbon between September 20 and September 30, 1973. Organic carbon data are summarized in Table 5. The average concentration of total and particulate organic carbon in the bay area was 5.9 and 0.8 g C/m^3, respectively. Surface and bottom concentrations of total and particulate organic carbon in the river were 4.5 and 0.6 g C/m^3 and 3.3 and 0.62 g C/m^3, respectively. The dissolved to particulate organic carbon ratio for an average of all bay stations was 6.4 This ratio was 5.3 for the river. In general, organic matter concentrations in the bay were higher than those in the river.

Data Assembled from Other Sources

Given in Fig. 13 is a plot of monthly average river flow from October 1928 through October, 1972 (Mann, 1975).

Table 5

Summary of organic carbon measurements taken in Apalachicola Bay in September, 1973. Station locations are given in Fig. 4. Numbers in parentheses indicate the number of replicates averaged.

Station	Date 1973	Total organic carbon, mg C/l	Particulate organic carbon, mg C/l
FSUML[a] (boat basin)	Sept. 20	8.5 (4)	1.3 (2)
FSUML (1/4 mi. offshore)	Sept. 20	8.6 (3)	——
Station I	Sept. 20	7.8 (1)	1.2 (2)
John Gorrie Bridge[b] (eastern end)	Sept. 20	4.8 (4)	0.7 (3)
John Gorrie Bridge (western end)	Sept. 20	5.2 (4)	0.6 (3)
River Mouth	Sept. 20	6.1 (2)	0.4 (2)
Station C	Sept. 30	4.7 (3)	0.7 (2)
Station AA	Sept. 30	5.4 (3)	0.9 (1)
Station D	Sept. 30	5.4 (2)	0.6 (1)

[a]Florida State University Marine Lab at Turkey Point, Franklin County, Florida.

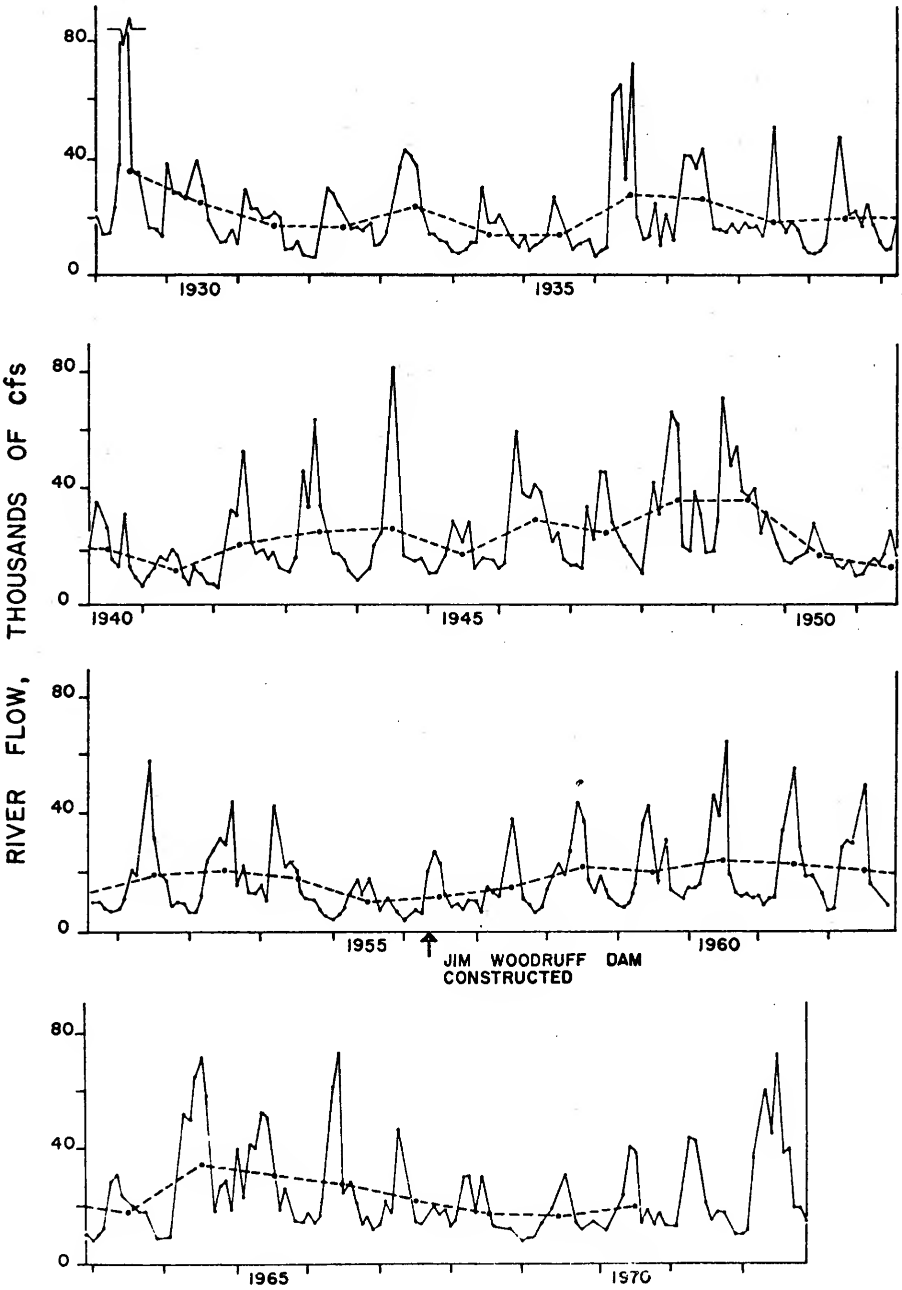
[b]The John Gorrie Bridge crosses Apalachicola Bay connecting the towns of East Point and Apalachicola.

Table 5 - continued

Station	Date 1973	Total organic carbon, mg C/l	Particulate organic carbon, mg C/l
Station F	Sept. 30	4.2 (1)	0.6 (1)
Station H	Sept. 30	5.0 (1)	0.7 (1)
Station L	Sept. 30	5.5 (3)	0.7 (1)
River (bottom)[c]	Sept. 30	4.5 (4)	0.6 (1)
River (surface)	Sept. 30	3.3 (3)	0.6 (1)

[c]The river station was taken about a half mile downstream of the railroad bridge crossing the Apalachicola River.

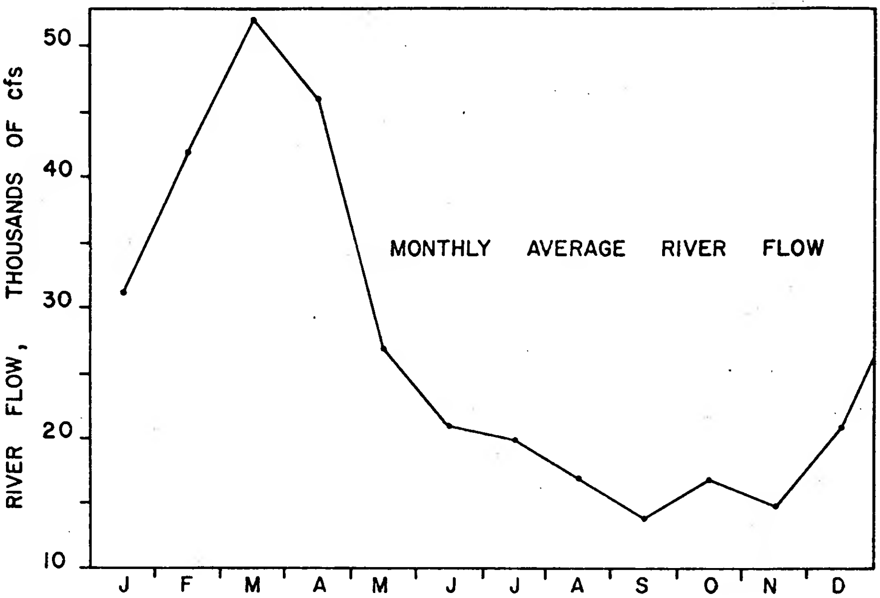
Fig. 13. Monthly average flow (cfs) of the Apalachicola River at Chattahoochee, Florida from October, 1928 to October, 1972.


RIVER FLOW, THOUSANDS OF cfs
80
40
0
1930
1935
1940
1945
1950
1955
1960
JIM WOODRUFF DAM
CONSTRUCTED
1965
1970

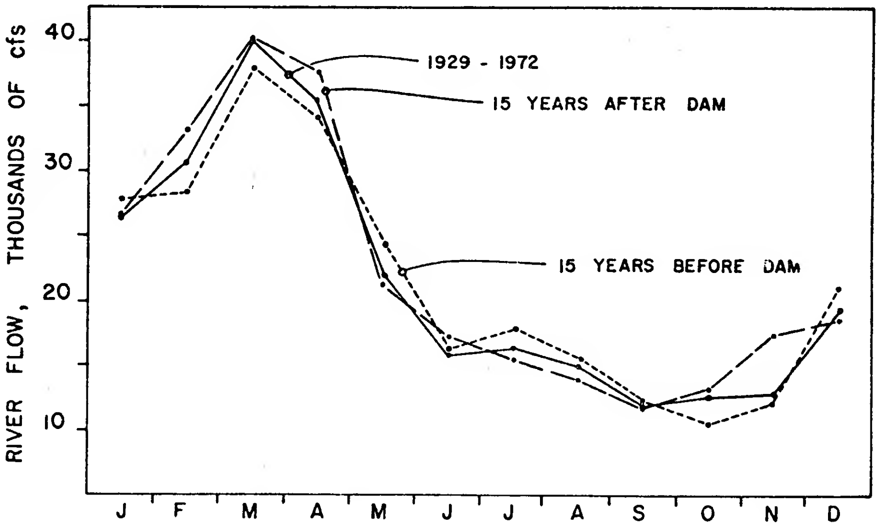
Yearly average flow for this period is shown along the dotted line. During this period, average flow was 21,690 cubic feet per second (cfs). The maximum and minimum flows were of 293,000 and 4,950 cfs recorded in March, 1929 and October, 1954, respectively. The flow rates presented in Fig. 13 were recorded at Chattahoochee, Florida. An estimate of river flow into Apalachicola Bay was made by adding the flow of the Chipola River to that recorded at Chattahoochee and increasing the total by 10 percent (Dawson, 1955a). With this adjustment, the 44-year average flow becomes 25,179 cfs.

Figure 14a shows average monthly river flow over the period 1929 through 1972. Flow was adjusted to approximate the volume which enters the bay as described above. Peak flow occurred in March (52,107 cfs) and minimum flow in September (12,801 cfs). Peak flow occurred as a pulse from January through April with the remaining monthly average flows near or below the yearly average. Figure 14b shows monthly average river flow for 15-year periods before and after construction of Jim Woodruff Dam at Chattahoochee, Florida. The combined average flow for the full 43-year recording period is also shown. All three curves are similar. Apparently, the relatively small storage capacity of Lake Seminole behind Jim Woodruff Dam did not affect the timing of discharge.

Fig. 14. Monthly river flow, (a) averaged for the period 1929 through 1972; and (b) averaged for the 15-year period before and after construction of Jim Woodruff Dam at Chattahoochee, Florida.


MONTHLY AVERAGE RIVER FLOW
RIVER FLOW, THOUSANDS OF cfs
50
40
30
20
10
J F M A M J J A S O N D

(a)


1929 - 1972
15 YEARS AFTER DAM
15 YEARS BEFORE DAM
RIVER FLOW, THOUSANDS OF cfs
40
30
20
10
J F M A M J J A S O N D

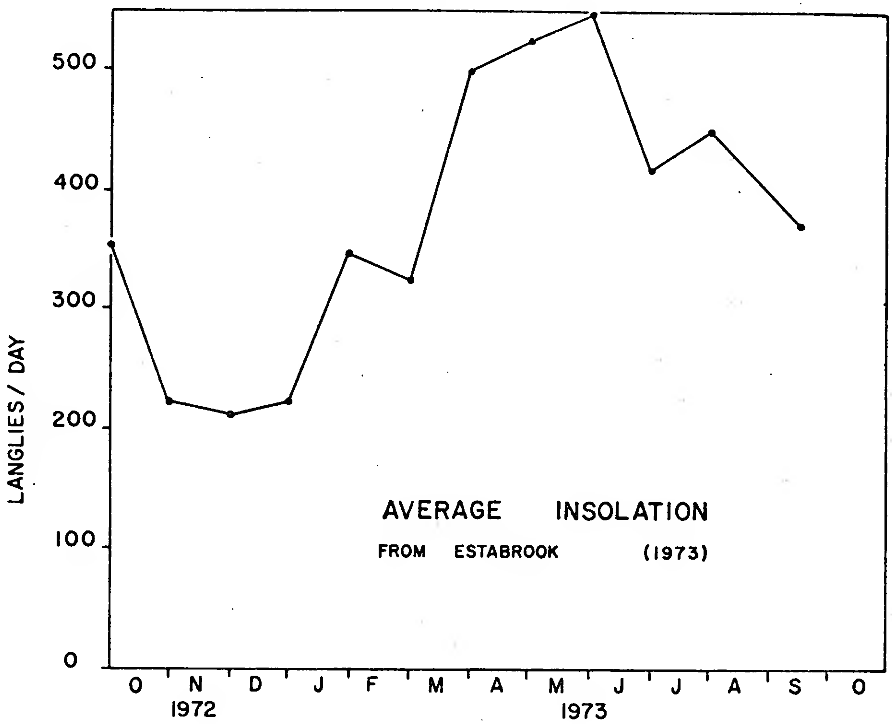
(b)

Given in Figs. 15-17 are estuarine data developed by Estabrook (1973) in a study of phytoplankton ecology and hydrography of Apalachicola Bay. They were redrafted and presented here for use in both the diurnal activity and the regional models.

Figure 15a shows monthly average insolation for 1972-1973. The monthly averages show a seasonal cycle typical of Florida with maximum insolation in May and lower values later in the summer due to rainy season cloud cover. Minimum insolation occurred in December. Figure 15b shows average surface and bottom salinities for the bay. The average salinity of the bay was lowest in February during high river flow and highest in September during low river flow. The average difference between surface and bottom salinities was 8.5 ppt with a seasonal range of 1 to 18 ppt. Detailed salinity maps are given in Figs. 8 and 9 and in Estabrook (1973).

Average water temperature is shown in Fig. 16a. The maximum average temperature was about 60°C in September with a minimum of about 10°C in February. Figure 16b shows average values for phytoplankton production as measured by Estabrook (1973) using the C-14 technique. The dashed lines are 95% confidence limits. Mean daily phytoplankton production ranged between 1.69 g C/m^2/day in April to 0.06 g C/m^2/day in February. However, there was a wide range in productivity in the bay at any one sampling time as indicated by the large confidence intervals.

Fig. 15. Monthly average insolation (a) and average surface and bottom salinity for Apalachicola Bay (b). Data are from Estabrook (1973).


AVERAGE INSOLATION
FROM ESTABROOK (1973)
LANGLIES / DAY
0
100
200
300
400
500
O N D J F M A M J J A S O
1972
1973

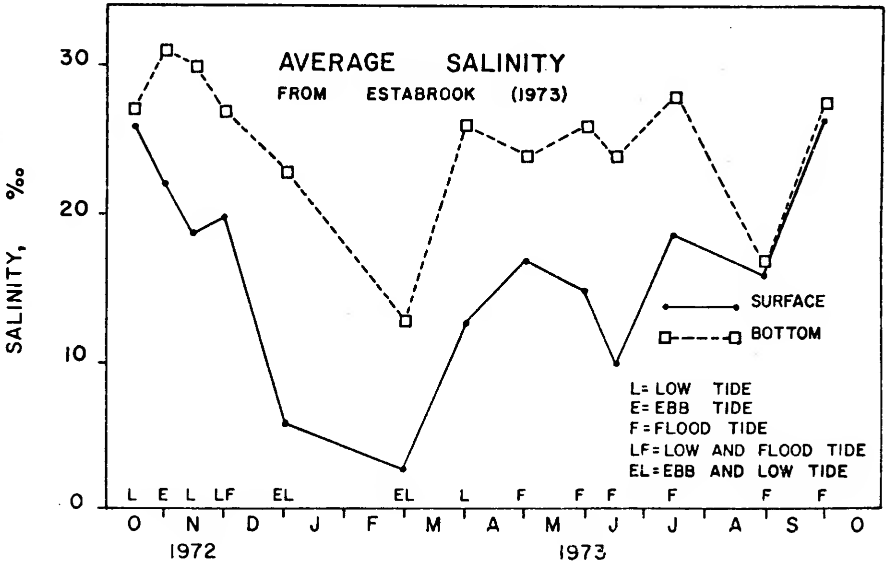
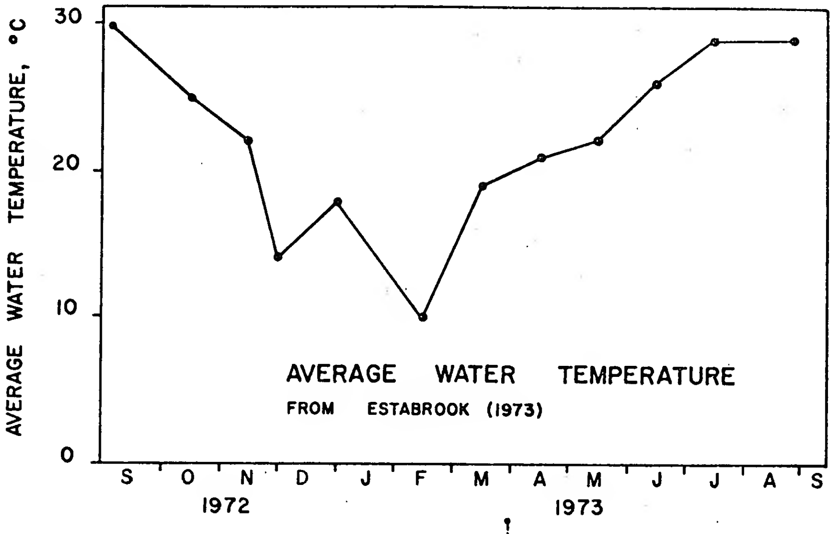
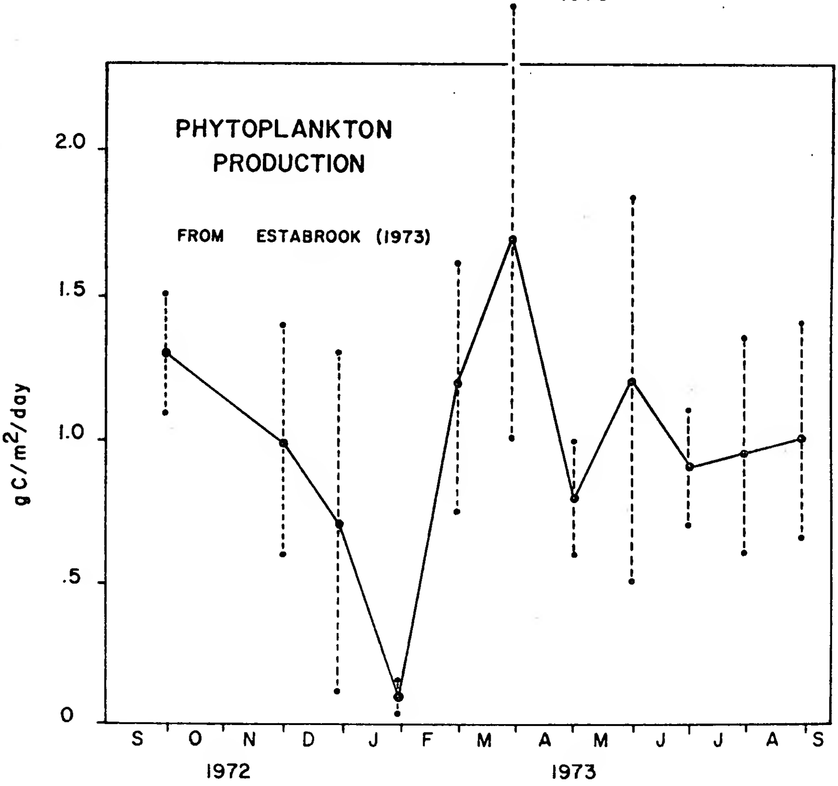

AVERAGE SALINITY
FROM ESTABROOK (1973)
SALINITY, ‰
0
10
20
30
SURFACE
BOTTOM
L= LOW TIDE
E= EBB TIDE
F= FLOOD TIDE
LF= LOW AND FLOOD TIDE
EL= EBB AND LOW TIDE
L E L LF EL EL L F F F F F F
O N D J F M A M J J A S O
1972
1973

Fig. 16. Average seasonal water temperature (a) and average daily phytoplankton production in Apalachicola Bay (b). Dashed lines in (b) are 95% confidence limits. Data are from Estabrook (1973).



AVERAGE WATER TEMPERATURE, °C
30
20
10
0
AVERAGE WATER TEMPERATURE
FROM ESTABROOK (1973)
S O N D J F M A M J J A S
1972
1973



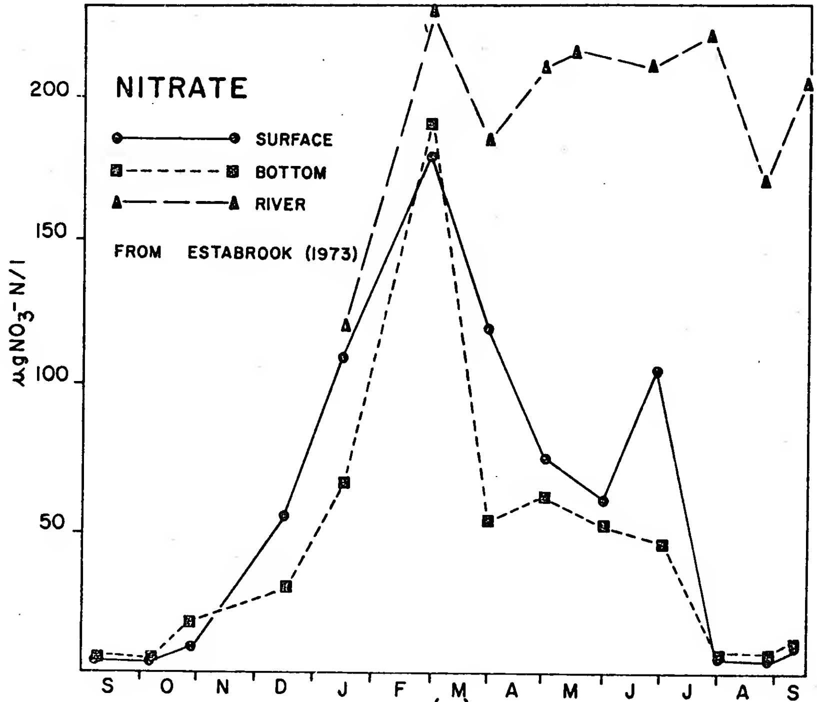
PHYTOPLANKTON PRODUCTION
FROM ESTABROOK (1973)
gC/m2/day
2.0
1.5
1.0
.5
0
S O N D J F M A M J J A S
1972
1973

Shown in Figs. 17a and 17b are seasonal concentrations of nitrate and ammonia in the surface and bottom waters of the bay and from the surface of the river (Estabrook, 1973). Nitrate concentrations in the river were rather constant ranging from 0.18-0.20 mg N/l. Average nitrate concentrations in the bay showed a seasonal cycle with high concentrations in February of about 0.18 mg N/l when river flow was high. Low concentrations of about 0.05 mg N/l occurred in the fall when river flow was low. Bottom nitrate concentrations were generally less than surface concentrations except when river flow was low, at which time there was little difference between surface and bottom.

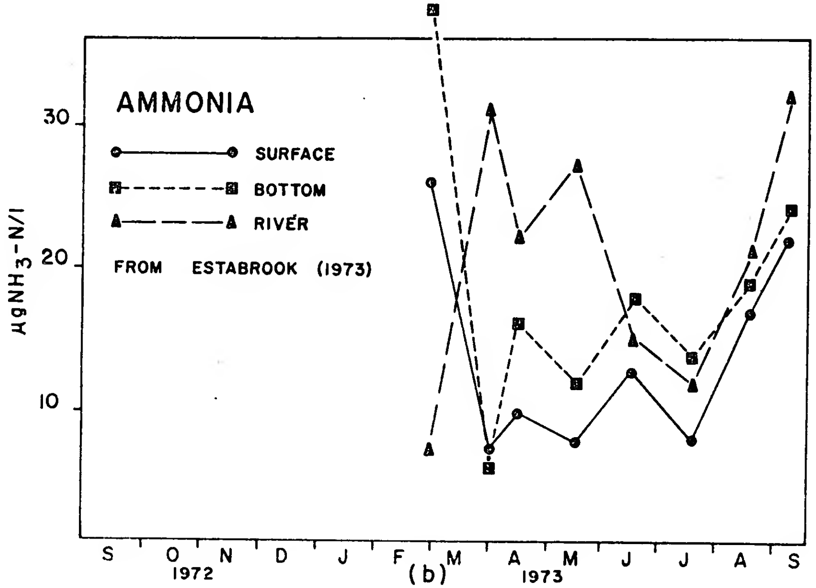
Ammonia concentrations are shown in Fig. 17b. Concentrations in the bay ranged from 7-40 μg N/l. No clear seasonal trend was evident. Bottom water concentrations of ammonia were generally higher than surface water levels. Ammonia concentrations in the river varied considerably ranging from about 7-35 μg N/l over the year. At times ammonia concentrations in the bay were higher than those in the river.

Shown in Fig. 18 are monthly estimates of fish and benthic invertebrate biomass from 15 stations in Apalachicola Bay (Menzel and Cake, 1969). Oyster reef biomass was not included in these estimates. Biomass was in g/m^2 wet weight. While there was considerable variation in biomass between samples from any one sampling data,

Fig. 17. Seasonal record of nitrogen concentrations in the Apalachicola River and in surface and bottom waters of Apalachicola Bay. Data are from Estabrook (1973). (a) Nitrate, (b) Ammonia.

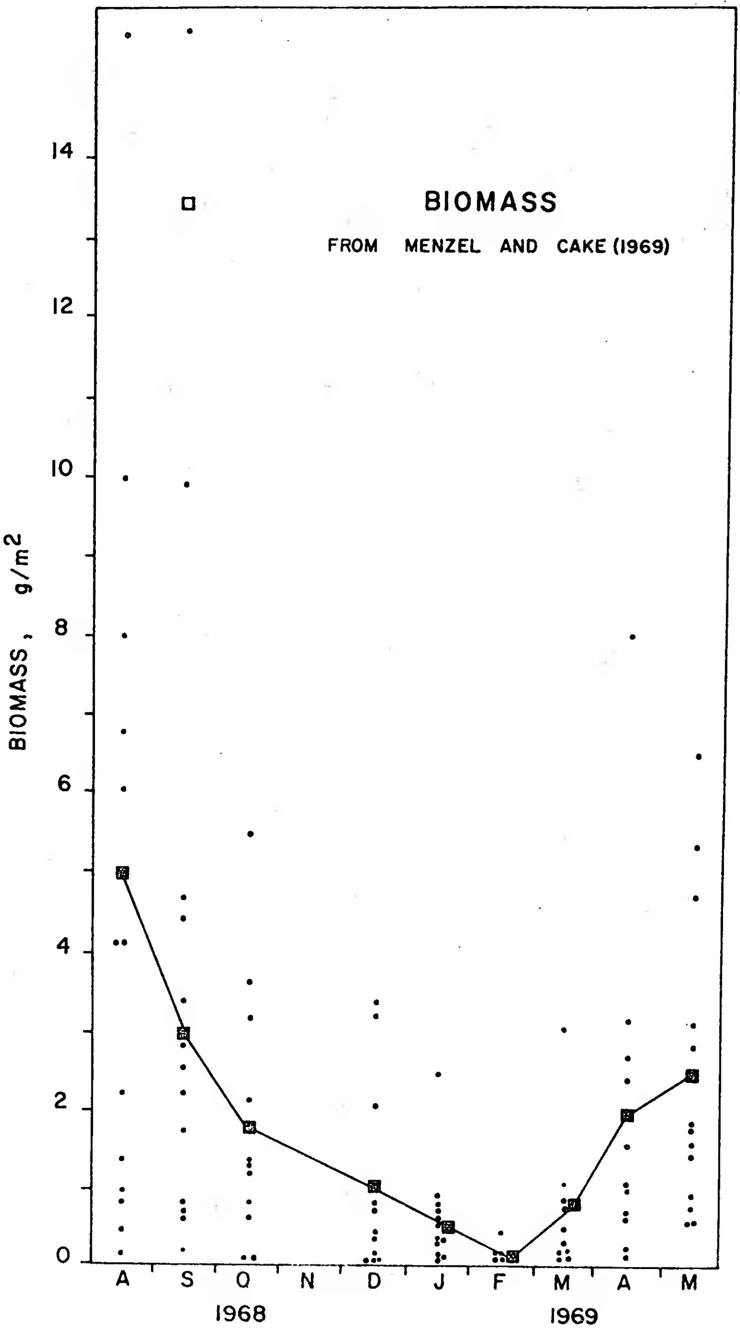

NITRATE
SURFACE
BOTTOM
RIVER
FROM ESTABROOK (1973)
200
150
100
50
$\mu g NO_3^- - N/l$
S
O
N
D
J
F
M
A
M
J
J
A
S

(a)


AMMONIA
SURFACE
BOTTOM
RIVER
FROM ESTABROOK (1973)
30
20
10
$\mu g NH_3 - N/l$
S
O
N
D
J
F
M
A
M
J
J
A
S
1972
1973

(b)

Fig. 18. Seasonal estimates of combined fish and benthic invertebrate biomass in Apalachicola Bay. Data were adapted from Menzel and Cake (1969).


BIOMASS
FROM MENZEL AND CAKE (1969)
BIOMASS, g/m^2
0
2
4
6
8
10
12
14
A
S
O
N
D
J
F
M
A
M
1968
1969

biomass was larger in the warmer periods of the year. Average biomass ranged from 0.12 g/m^2 in February to 5 g/m^2 in August.

Since no direct estimates of oyster biomass for Apalachicola Bay were available, several indirect methods of calculating biomass were used. These are given in Table 6. In the first calculation biomass was estimated from 1970 oyster harvest data with corrections for predation mortality and harvest losses. Total weight in pounds was then converted to grams dry weight. Corrections for predation and harvest losses were estimated by Menzel (1973).

In the second method harvest per acre was multiplied by total area of oyster reef and then corrected for predation and harvest losses. This calculation was repeated for both marginal and very productive oyster reefs. In the third method, areas of three grades of oyster bars were planimetered from an oyster reef survey map (U.S. Army Corps of Engineers, 1968). From data developed by Menzel et al. (1966) concerning oyster size and numbers occurring on reefs, total weights of both adult (defined as being of harvestable size) and juvenile (all oysters less than harvestable size) oysters were calculated. Total weights varied from 3.1×10^8 g in the first calculation to 29.0×10^8 g in (b) of calculation II. Calculation III yielded an intermediate estimate of 14.2×10^8 g. The estimate from calculation III was used in simulation models both

Notes to Table 6

[a]Total estimated annual harvest in 1970 (Division of Marine Resources, 1970).

[b]Estimated that 40% of adult oyster biomass is annually consumed by predators (Menzel, 1973).

[c]Estimated that 75% of adult oyster biomass is taken as harvest after predation is subtracted from available biomass (Menzel, 1973).

[d]Estimated conversion from oyster meat wet weight to dry weight using data from Lehman (1974).

[e]Yield estimates are for a marginal and very productive commercial oyster bar in Apalachicola Bay (Menzel *et al*., 1966).

[f]Estimated acreage of productive oyster bars in Apalachicola Bay (Menzel and Cake, 1969).

[g]Average conversion factor relating pounds of oyster meat to bushels: 1 bu oysters = 1 gal oyster meat (Estes, 1975).

[h]All acres planimetered from detailed project report on breakwater at Eastpoint, Apalachicola Bay, Florida. Map of oyster bottoms (U.S. Army Corps of Engineers, 1968).

[i]Biomass of adult and juvenile oysters was estimated from data of Menzel *et al*. (1966) and length-weight relationships given by Lehman (1974).

Table 6

Calculation of oyster biomass.

I. Yearly harvest (lbs)[a] x 1.66[b] (ratio to adjust for predation) x 1.33[c] (ratio to adjust for harvest) x 454 g/lbs x 0.1 g[d]/g wet wgt.

3.04×10^6/lbs x 1.66 x 1.33 x 454 g/lbs x 0.1 g/g wet wgt = 3.1×10^8 g dry wgt.

II. Yearly harvest (bu/acre[e]) x 5000 acres[f] x 1.66[b] x 1.33[c] x 8 lbs[g]/bu x 454 g/lb x 0.1[d] g/g wet wgt

(a) (225 bu/acre[e])(5000 acres)(1.66)(1.33)(8 lbs/bu)(454 g/lb)(0.1) = 9.0×10^8g dry wgt

(b) (715)(bu/acre[e])(5000 acres)(1.66)(1.33)(8 lbs/bu)(454 g/lb)(o.1) = 29.0×10^8 dry wgt

III. Adult biomass

Area of dense oysters[h] (biomass of adults[i]) + Area of scattering oyster (biomass of adults) + area of depleted bars (biomass of adults) = adult oyster biomass.

$[(1.96 \times 10^7 m^2)(411\ g/m^2)(411\ g/m^2) + (0.51 \times 10^7 m^2)(121\ g/m^2) + (0.72 \times 10^7 m^2)(0.0\ g/m^2)]$
0.1 g/g wet wgt = 8.7×10^8g

Juvenile biomass (less than harvestable length)

Area of dense oysters[h] (biomass of juveniles[i]) + area of scattering oysters (biomass of juveniles) + area of depleted bars (biomass of juveniles = juvenile oyster biomass

$[(1.96 \times 10^7 m^2)(160\ g/m^2) + (0.51 \times 10^7 m^2)(400\ g/m^2) + (0.72 \times 10^7 m^2)(48.6\ g/m^2)]$
0.1 g/g wet wgt = 5.5×10^8g

because the result was intermediate in the range of values obtained and because it gave an estimate of both adult and juvenile biomass. The estimate obtained in II(b) (715 bu/acres) is a very high yield and probably not representative of average conditions. Calculations I and IIa and IIb include only adult biomass and thus may underestimate total oyster biomass. Adult biomass estimates IIa and III are similar (9.0×10^8 gms and 8.7×10^8 gms).

Model of Diurnal Activities

The diurnal activity model shown in Fig. 19 has component storages of phytoplankton biomass (Q_1), consumers (Q_2), dissolved oxygen (Q_3), detritus (Q_4), and nitrogen (Q_5). Tracing flows from left to right across the diagram inputs from external sources of sunlight (J_o), nitrogen (N), detritus (D), and advected oxygen (A) enter storage modules. At the top of the diagram, oxygen in the atmosphere (As) exchanges with oxygen dissolved in the water depending on the saturation gradient ($As-Q_3$) and the amount of turbulence (T). On the left, sunlight and nutrients interact multiplicatively to produce oxygen (J_2) and phytoplankton biomass (J_1). Losses from the phytoplankton storage (Q_1) include respiration (J_4), death (J_{17}), and exports (J_{18}). Inputs to the nitrogen storage (Q_5) come from an external source (N), and from recycle along pathways J_{12}, J_{15}, and J_{16}. Losses include flushing (J_{20})

Fig. 19. Model of diurnal activity of Apalachicola Bay. Symbols used in the diagram are explained in Appendix A. Pathway values are given in Appendix C-1, scaled equations in Appendix C-2. Unscaled equations are given below. (a) Model with terms used in differential equations given below. (b) Estimates of mean values used to evaluate coefficients.

Phytoplankton biomass

$$Q_1 = k_1 J_r Q_5 - k_4 Q_1 Q_3 - k_{17} Q_1 - k_{18} Q_1$$

Consumer biomass

$$Q_2 = k_{10} Q_3 Q_4 - k_{11} Q_2$$

Dissolved oxygen

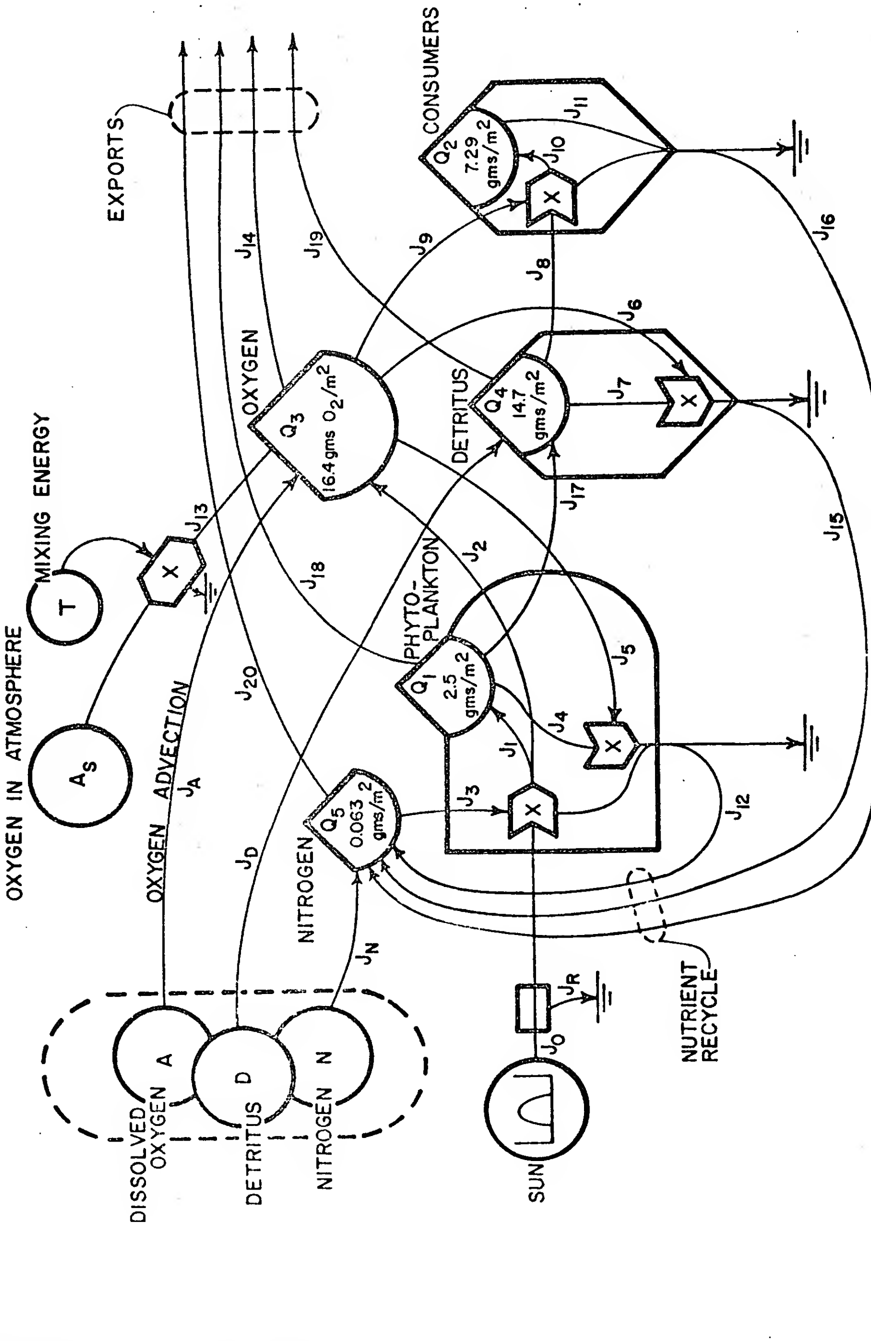
$$Q_3 = k_4 A + k_{13} T(A_s - Q_3) + k_2 J_r Q_5 - k_{14} Q_3 - k_9 Q_5 Q_4 - k_6 Q_3 Q_4 - k_5 Q_3 Q_1$$

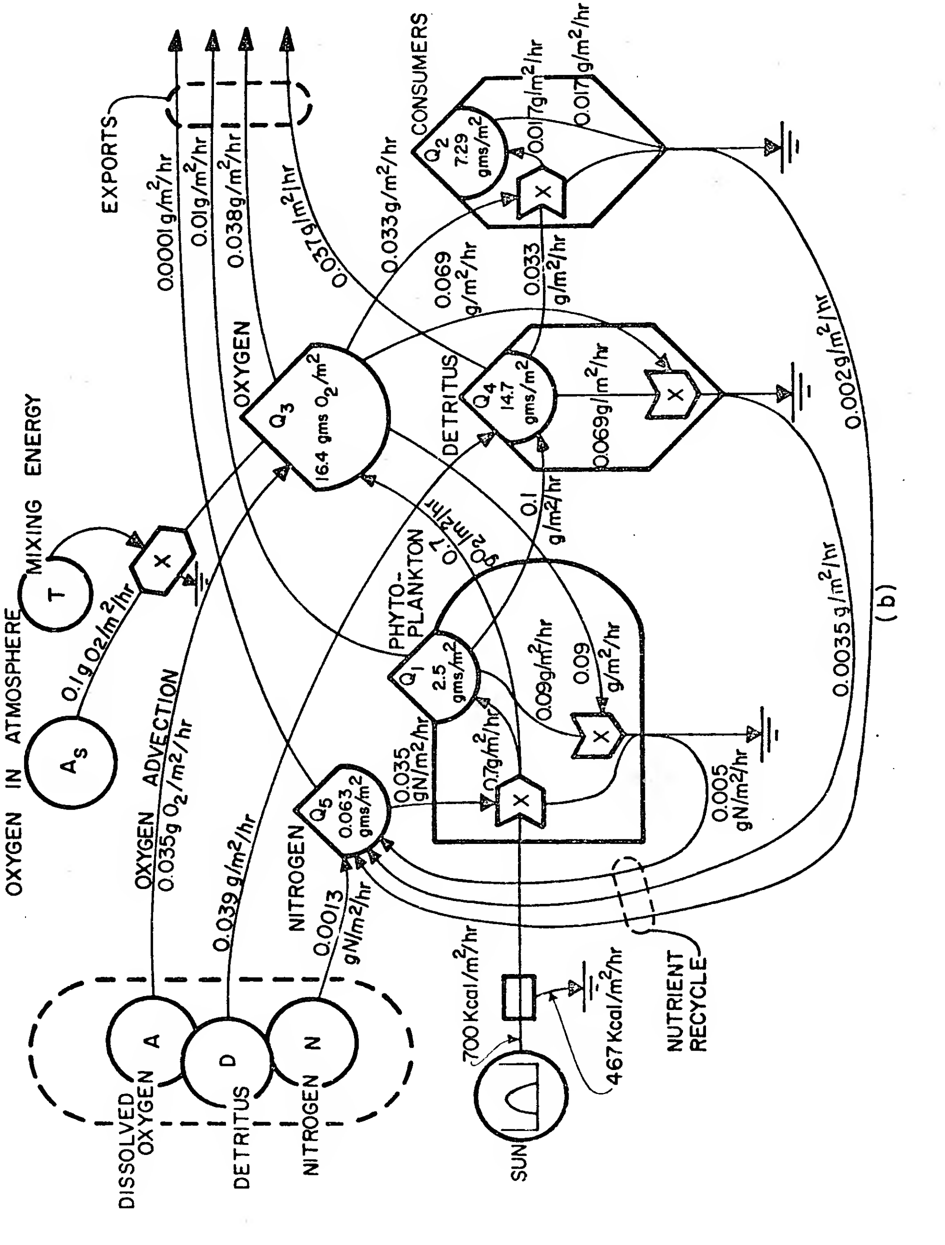
Detritus

$$Q_4 = k_d D + k_{17} Q_1 - k_7 Q_3 Q_4 - k_8 Q_3 Q_4$$

Nitrogen

$$Q_5 = k_n N + k_{12} Q_1 Q_3 + k_{16} Q_2 + k_{15} Q_3 Q_4 - k_{20} Q_5 - k_3 J_r Q_5$$


OXYGEN IN ATMOSPHERE
A_S
T
MIXING ENERGY
X
J_13
OXYGEN ADVECTION
J_A
J_D
J_20
NITROGEN
Q_5 0.063 gms/m^2
J_N
DISSOLVED OXYGEN
A
D
N
DETRITUS
NITROGEN
SUN
J_O
J_R
NUTRIENT RECYCLE
J_3
J_1
PHYTO-PLANKTON
Q_1 2.5 gms/m^2
J_4
J_5
J_12
J_18
J_2
OXYGEN
Q_3 16.4 gms O_2/m^2
J_14
J_19
EXPORTS
DETRITUS
Q_4 14.7 gms/m^2
J_17
J_7
J_6
J_8
J_9
CONSUMERS
Q_2 7.29 gms/m^2
J_10
J_11
J_16
J_15
(a)



OXYGEN IN ATMOSPHERE
A_S
T
MIXING ENERGY
0.1g O2/m2/hr
X
OXYGEN ADVECTION
0.035g O2/m2/hr
0.039 g/m2/hr
NITROGEN
0.0013 gN/m2/hr
DISSOLVED OXYGEN
A
D
DETRITUS
N
NITROGEN
SUN
700 Kcal/m2/hr
467 Kcal/m2/hr
NUTRIENT RECYCLE
Q5 0.063 gms/m2
0.035 gN/m2/hr
0.7g/m2/hr
PHYTO-PLANKTON
Q1 2.5 gms/m2
0.09g/m2/hr
0.09 g/m2/hr
0.005 gN/m2/hr
0.1 g/m2/hr
0.1 g/m2/hr
OXYGEN
Q3 16.4 gms O2/m2
DETRITUS
Q4 14.7 gms/m2
0.069g/m2/hr
0.069 g/m2/hr
0.033 g/m2/hr
0.033g/m2/hr
CONSUMERS
Q2 7.29 gms/m2
0.017g/m2/hr
0.017g/m2/hr
0.0035 g/m2/hr
0.002g/m2/hr
EXPORTS
0.0001 g/m2/hr
0.01g/m2/hr
0.038g/m2/hr
0.037 g/m2/hr

(b)

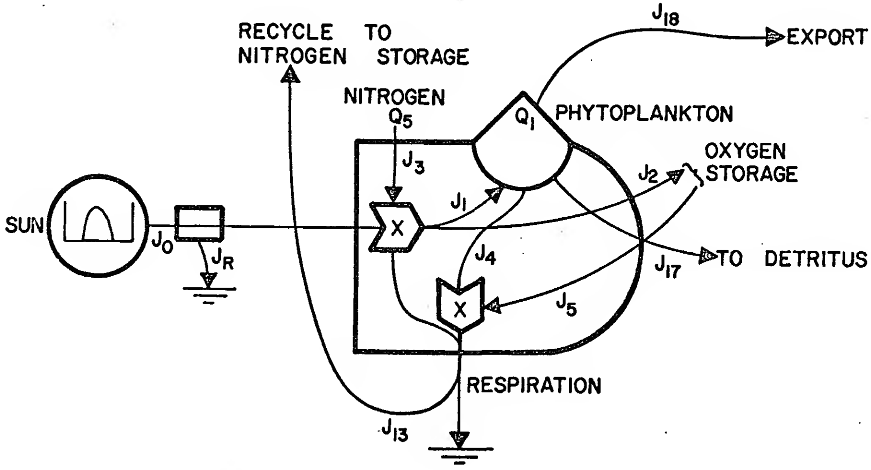
and utilization in photosynthesis (J_3). Inputs to the detritus storage (Q_4) come from phytoplankton death (J_{17}) and an external source (D). Losses from this storage include microbial and consumer utilization (J_7 and J_8) and flushing (J_{19}). Microbe biomass is part of the detritus. The oxygen content in the water (Q_3) is determined by the net balance of respiratory utilization (J_5, J_6, J_9), phytoplankton production of oxygen (J_2), advection of oxygen into (Ja) and out of the system (J_{14}), and by reaeration (J_{13}). All inputs to the model are constant flow sources except sunlight which enters as a chopped sine wave or square wave to simulate daily sunlight conditions. Temperature and salinity are held constant over 24 hours because only small changes were observed in the field. Justifications for the model configuration are given in Fig. 20. Calculations and assumptions used in evaluating the model are given in Table C-1. Scaled equations are given in Table C-2. The analog patching diagram is given in Fig. C-1.

Simulation Results and Comparisons with Field Data

Simulation results obtained from the diurnal activity model are given in Figs. 21 and 23-27. Comparisons of "control condition" model output with field data are given in Fig. 22. Table 7 is a tabular summary of model output for all runs.

Fig. 20. Justification of the configuration used in the diurnal activity model shown in Fig. 19a. (a) phytoplankton; (b) consumers; (c) oxygen; (d) detritus; (e) nitrogen.

Fig. 20a. Phytoplankton were chosen as a state variable because they were the major biological producers of oxygen and organic matter in the bay, and because the stock of phytoplankton were subject to frequent changes (Estabrook, 1973). Photosynthesis was modeled with a multiplicative workgate because the response is of the limiting factor type observed for photosynthesis. In this model either nitrogen or sunlight could be the limiting factor. The special equation for J_R is given in Appendix C-2. Phytoplankton respiration was assumed to be a multiplicative function of biomass and oxygen. Nutrient recycle was assumed to be a constant proportion of the respired material. Phytoplankton death and excretions were accounted for by linear drain J_{17}.



RECYCLE TO NITROGEN STORAGE
NITROGEN
Q_5
J_3
J_{18}
EXPORT
Q_1
PHYTOPLANKTON
OXYGEN STORAGE
J_2
SUN
J_0
J_R
X
J_1
J_4
J_{17}
TO DETRITUS
X
J_5
RESPIRATION
J_{13}

Fig. 20b. Consumers were chosen as a state variable because the stock is subject to change (Menzel and Cake, 1968) and because of the role in oxygen and detritus utilization and nutrient recycle played by consumers. Consumer use of detritus (J_8), oxygen (J_9) and consumer assimilation (J_{10}) was assumed to be a multiplicative function of detritus and oxygen stocks since respiration is related to oxygen and has a limiting factor response. Since the stock was a mixture of all consumers except microbes, utilization rates for each specie were probably somewhat different. In this case the multiplicative workgate has two advantages. First, it requires that both oxygen and detritus be present for a flow to occur. This requirement is obvious. Secondly, utilization rates can vary depending on available stocks of detritus and oxygen and are not constrained by the requirements of any one specie. The multiplier arrangement implies that as the rates change, different species become dominant in the consumer storage. Consumer death and excretion were accounted for by linear drain J_{11}. Nutrient recycle (J_{16}) was assumed to be a constant proportion of J_{11}.

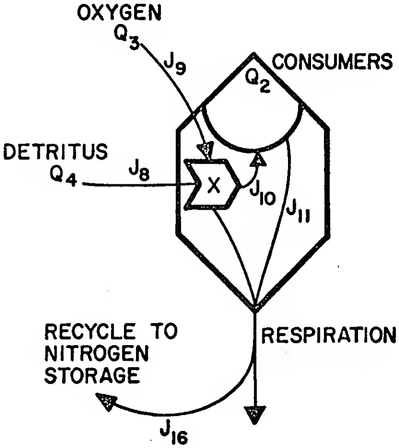

OXYGEN
Q_3
J_9
CONSUMERS
Q_2
DETRITUS
Q_4
J_8
X
J_{10}
J_{11}
RECYCLE TO NITROGEN STORAGE
RESPIRATION
J_{16}

Fig. 20c. Oxygen was chosen as a state variable because its diurnal behavior was a main interest in this model. Photosynthetic production of oxygen (J_2) and multiplicative losses (J_5, J_6, and J_9) have already been explained. The reaeration pathway (J_{13}) is the same as the standard turbulent diffusion equation. Oxygen advection (J_A) was assumed to be constant over a diurnal cycle. Linear pathway J_{14} accounts for a diurnal cycle. Linear pathway J_{14} accounts for oxygen exports via flushing. Pathways J_2, J_5, J_6, and J_9 are nonlinear. See Fig. 19 for details.

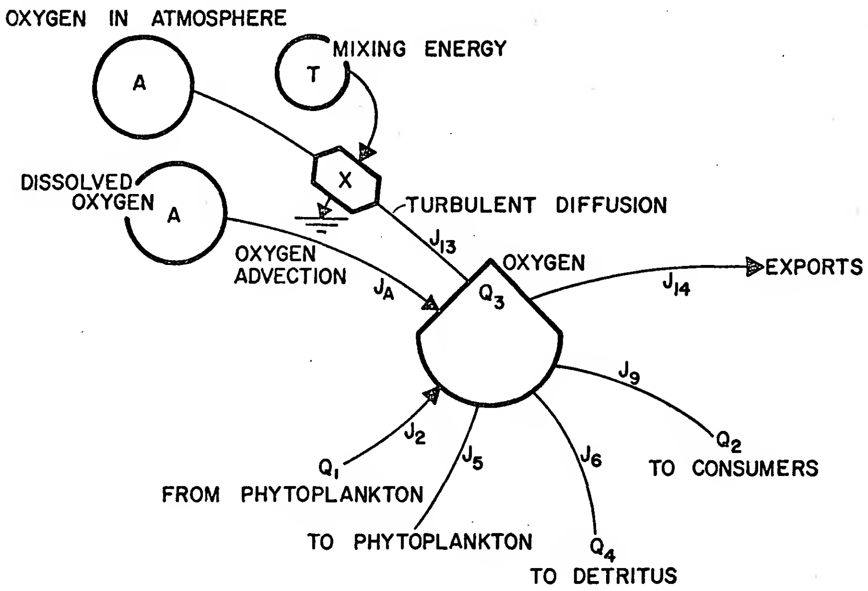

OXYGEN IN ATMOSPHERE
A
T
MIXING ENERGY
X
DISSOLVED OXYGEN
A
TURBULENT DIFFUSION
J_{13}
OXYGEN ADVECTION
J_A
OXYGEN
Q_3
J_{14}
EXPORTS
J_9
Q_2
TO CONSUMERS
J_2
Q_1
FROM PHYTOPLANKTON
J_5
TO PHYTOPLANKTON
J_6
Q_4
TO DETRITUS

Fig. 20d. Detritus was chosen as a state variable because it was the major storage of organic matter in the water column, a major source of bound nitrogen, and had several interactions with oxygen. The hexagon group symbol was used to recognize that detritus in this model included some living components (microbes). The group symbol does not imply additional pathways beyond those shown. Detritus input (J_D) from an external source (D) was assumed to be constant. Input due to phytoplankton death and excretion was assumed to be in proportion only to the phytoplankton stock. Detritus export was assumed to be in proportion to the detritus stock. The respiration pathway was dependent on both oxygen and detritus which are necessary for any aerobic respiratory process.

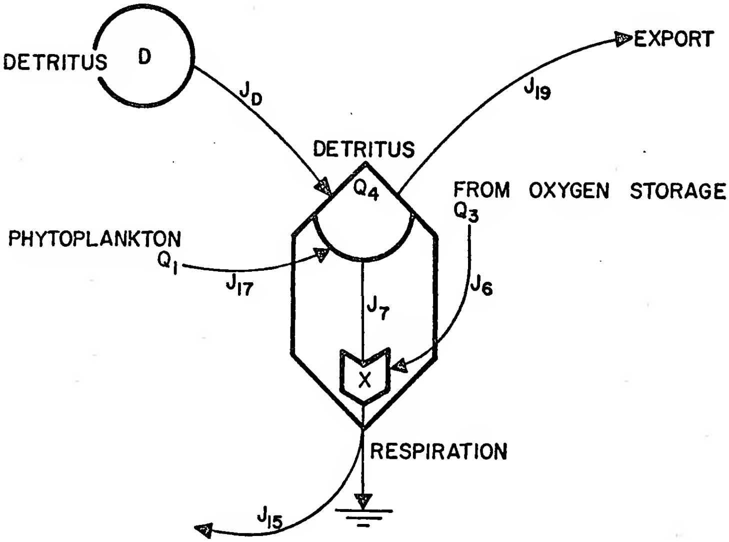
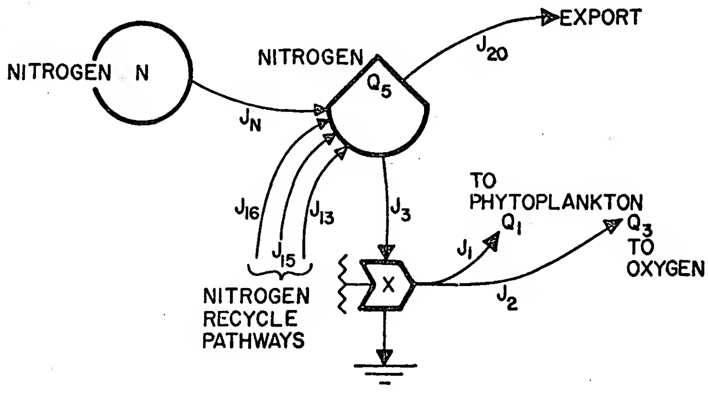
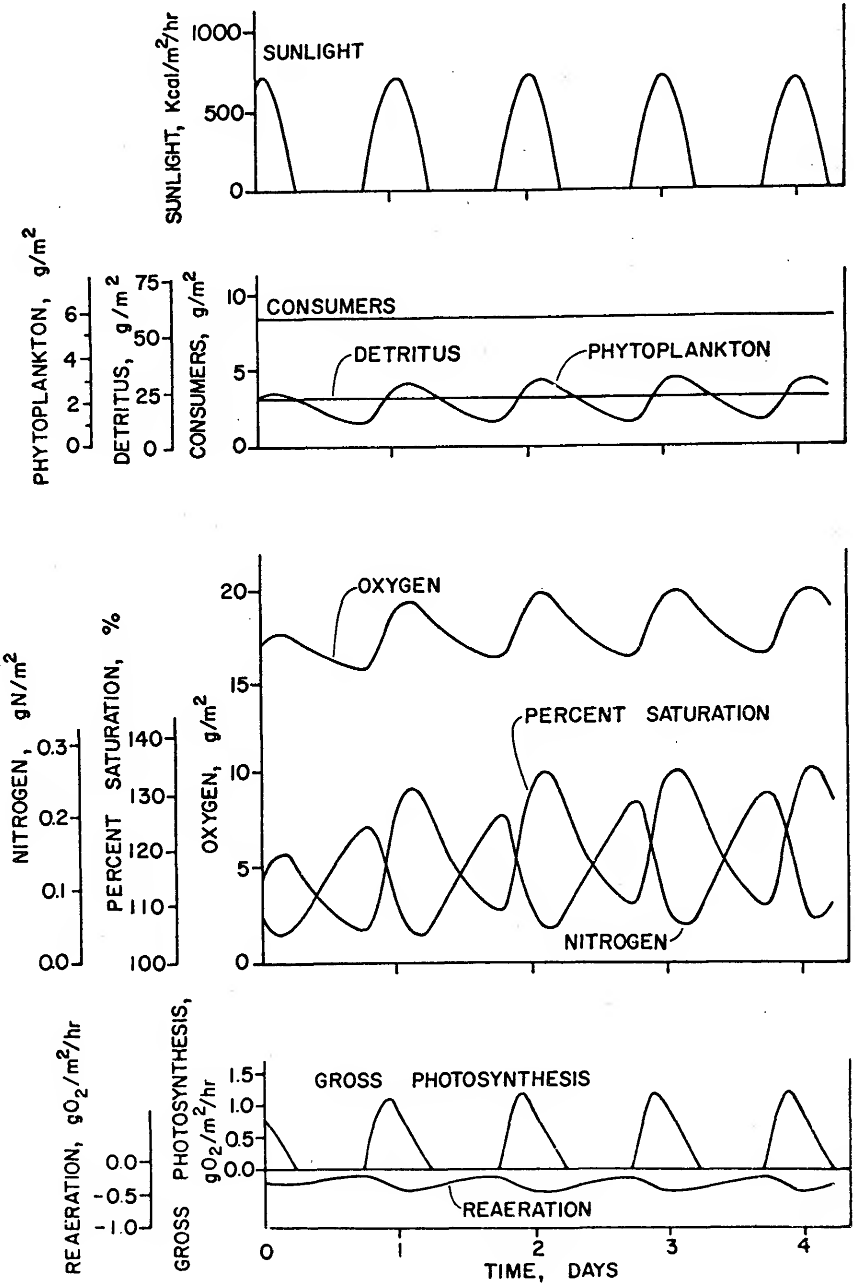

DETRITUS
D
J_D
EXPORT
J_{19}
DETRITUS
Q_4
FROM OXYGEN STORAGE
Q_3
PHYTOPLANKTON
Q_1
J_{17}
J_6
J_7
X
RESPIRATION
J_{15}

Fig. 20e. Nitrogen was chosen as a state variable for several reasons. First, nitrogen is required in photosynthesis and in turbid coastal plain estuaries of the United States may be the primary limiting nutrient (Pomeroy _et al_., 1972). Secondly, the nitrogen stock could be expected to change due to changes in recycle rates or due to changes in the input rate. Nitrogen input from an external source was assumed to be constant during each simulation run. Estabrook (1973) found fairly constant concentrations of total inorganic nitrogen in the river (Fig. 17).


NITROGEN N
NITROGEN
Q_5
EXPORT
J_{20}
J_N
J_{16}
J_{15}
J_{13}
J_3
NITROGEN RECYCLE PATHWAYS
X
TO PHYTOPLANKTON Q_1
J_1
Q_3 TO OXYGEN
J_2

Computer simulations for the control condition are shown in Fig. 21. Sunlight is shown on the top of Fig. 21. Maximum daily insolation was estimated to be 700 Kcal/m^2/hr at 1200 hrs (Estabrook, 1973). Day and night were divided into equal 12-hour segments which closely approximated the day length for late September. Consumer and detritus stocks remained at initial condition levels through the 4.5 days which the model was run. However, phytoplankton biomass showed a diurnal change ranging from 0.8 g/m^2 at dawn to 2.9 g/m^2 in the late afternoon. Indications of diurnal changes in phytoplankton stocks have been reported (Platt and Conover, 1971). Dissolved oxygen ranged between 15.4 and 19.9 g/m^2 (water column of 2.1 meters) with low and high values at 0700 and 1600 hours, respectively. Phytoplankton production was the major source producing the daily pulse. Advection in this run was small. The sharp increase in oxygen in the morning was due to high phytoplankton activity under conditions when nitrogen was high and sunlight increasing while respiratory activity was low due to depressed phytoplankton stocks. Diffusion was also small during the morning. The afternoon and evening decline in oxygen was not as sharp as the morning increase. Nitrogen also exhibited a diurnal change ranging between a high of 0.20 at dawn to 0.04 g N/m^2 at sunset. The daytime decline in nitrogen was sharper than the nighttime recovery. Gross photosynthesis reached a maximum rate of 0.95 g

Fig. 21. Graphs of diurnal activity simulated with the model Fig. 19a, using transfer coefficients calculated from data in Fig. 19b.



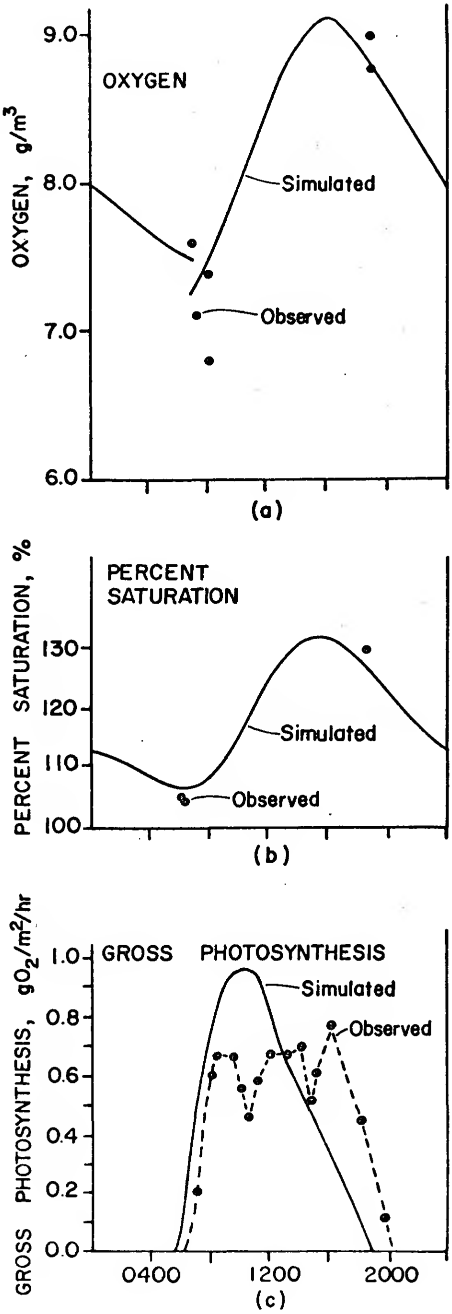
SUNLIGHT, Kcal/m²/hr
1000
500
0
SUNLIGHT
PHYTOPLANKTON, g/m²
6
4
2
0
DETRITUS, g/m²
75
50
25
0
CONSUMERS, g/m²
10
5
0
CONSUMERS
DETRITUS
PHYTOPLANKTON
NITROGEN, gN/m²
0.3
0.2
0.1
0.0
PERCENT SATURATION, %
140
130
120
110
100
OXYGEN, g/m²
20
15
10
5
0
OXYGEN
PERCENT SATURATION
NITROGEN
REAERATION, gO2/m²/hr
0.0
-0.5
-1.0
GROSS PHOTOSYNTHESIS, gO2/m²/hr
1.5
1.0
0.5
0.0
GROSS PHOTOSYNTHESIS
REAERATION
0
1
2
3
4
TIME, DAYS

O_2/m^2/hr at 1100 hours. The afternoon decline in gross photosynthesis was more gradual than the early morning increase. This was due both to declining sunlight and a sharply declining nitrogen stock.

Figure 22 compares control condition model output to field data for which diurnal measurements were available. Neither detritus nor consumers changed appreciably over the four-day simulation run retaining values close to those measured or estimated (see Tables 5 and 6 and Fig. 18). In general, seasonal changes were larger than diurnal changes for these storages. Nitrogen stocks (NH_3 + NO_2) changed by a factor of 5 over a 24-hr period ranging from 0.04 to 0.20 g N/m^2. No field data are available to estimate the actual diurnal change of available, labile nitrogen. In a model developed prior to the one reported here, the nitrogen storage included labile and less labile fractions as total nitrogen (NO_3 + NH_3 + particulate and dissolved organic nitrogen) and diurnal changes were much smaller. In that model, conversion of organic nitrogen compounds to NH_3 was made a function of both sunlight and the total nitrogen stock.

Figures 23-27 show simulation output of model variables under a range of conditions which may occur in the study area. These included reduction in sunlight due to increased turbidity (Fig. 23), increased nitrogen (Fig. 24), and detritus (Fig. 25) input rates, changes in microbe

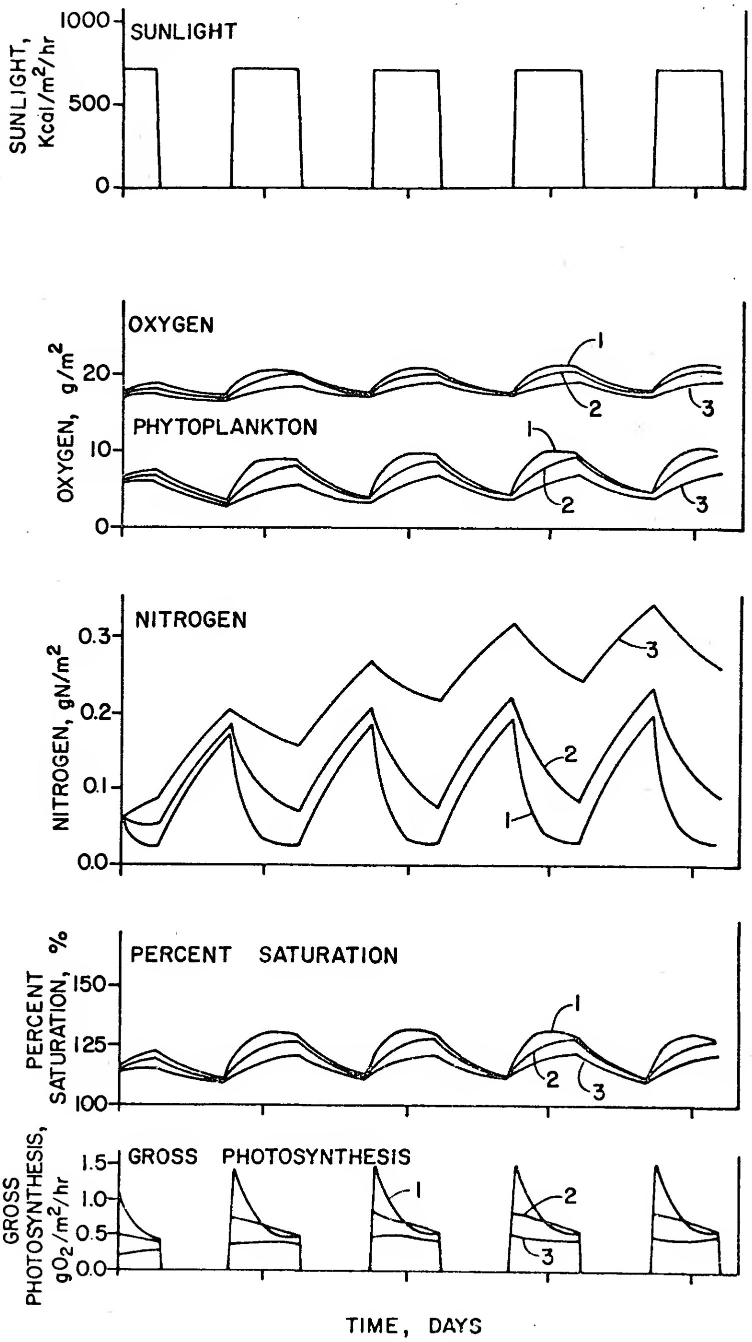
Fig. 22. Comparisons of field data with computer output from the model given in Fig. 19a. Computer output was obtained using transfer coefficents calculated from data used to evaluate the model. (a) oxygen, (b) percent saturation, (c) gross photosynthesis.


OXYGEN
OXYGEN, g/m3
9.0
8.0
7.0
6.0
Simulated
Observed
(a)
PERCENT SATURATION
PERCENT SATURATION, %
130
120
110
100
Simulated
Observed
(b)
GROSS PHOTOSYNTHESIS
GROSS PHOTOSYNTHESIS, gO2/m2/hr
1.0
0.8
0.6
0.4
0.2
0.0
Simulated
Observed
0400
1200
2000
(c)

respiration under nutrient and detritus loading (Fig. 26), and finally a mixture of these changes under reduced rates of oxygen exchange between the atmosphere and water (Fig. 27). The results are summarized in Table 7.

In Fig. 23 sunlight was changed to a square wave with an average input of 700 Kcal/m^2/hr. The change caused only small changes in variable responses most notably in gross photosynthesis where a sharp morning peak (1.33 g O_2/m^2/hr) developed. This peak was followed by a sharp decline to lower values (0.46 g O_2/m^2/hr) for the afternoon. The decline was caused by the decreasing nitrogen stock. Other variables were comparable to control condition levels. The slight increase in most variables was a result of more sunlight entering the system due to the difference in area beneath a square wave and sine wave of the same amplitude. When sunlight was decreased to 0.5 of the initial value, gross primary production did not show a sharp morning peak and the nitrogen limitation was not as sharp. Nitrogen stocks increased slightly but other variables remained about the same. At 0.25 of the initial sunlight input rate the diurnal range in phytoplankton and oxygen values both decreased but minimum values were similar to the control situation. Gross primary production was constant at 0.33 g O_2/m^2/hr and did not show effects of nitrogen limitation. The diurnal peak in the nitrogen stock was 80% greater than in the control condition. Major changes in model output

Fig. 23. Simulation results from the model given in Fig. 19a with input of sunlight as a square wave. Families of curves are shown for each variable with designations of 1, 2, and 3 corresponding to sunlight inputs of normal, 1/2 normal, and 1/4 normal.


SUNLIGHT
SUNLIGHT, Kcal/m²/hr
1000
500
0
OXYGEN
PHYTOPLANKTON
OXYGEN, g/m²
20
10
0
1
2
3
NITROGEN
NITROGEN, gN/m²
0.3
0.2
0.1
0.0
1
2
3
PERCENT SATURATION
PERCENT SATURATION, %
150
125
100
1
2
3
GROSS PHOTOSYNTHESIS
GROSS PHOTOSYNTHESIS, gO₂/m²/hr
1.5
1.0
0.5
0.0
1
2
3
TIME, DAYS

under conditions of decreasing available sunlight were mainly decreased gross photosynthesis, and increased stocks of nitrogen.

Diurnal responses to increased nitrogen input rates are given in Fig. 24. Under these conditions consumers and detritus increased only slightly above control values. Gross primary production increased by a factor of 1.6 beyond the control value for both treatment cases. The nitrogen stock also increased but the magnitude of the diurnal change decreased from a factor of 5 in the control run to a factor of 3 in the run with a 5x input rate. Oxygen increased both in amount and in the amount of change over a daily cycle. In the cases with decreased sunlight (Fig. 23) and increased nitrogen input (Fig. 24), the amount of oxygen in the water did not fall below control values at any time.

Fig. 25 shows model responses when the detritus input rate was increased by factors of 2, 5, and 10 times the normal input rate. The detritus stock increased by factors of about 1.6, 3, and 6 over the control condition. All three input rates had the effect of lowering oxygen levels below control condition levels and increasing the range of diurnal oxygen changes. In the control condition, oxygen ranged from 16.4-14.2 (ΔO_2 = 2.8 ppm) whereas in the 10x input rate case oxygen ranged from 11.9-16.5 (ΔO_2 = 4.6 ppm). Gross photosynthesis increased by factors of 1.1, 1.5, and 1.6 above the peak control rate of 0.90 g

Fig. 24. Simulation results from the model given in Fig. 19a with varying rates of nitrogen input. Families of curves are shown for each variable with designations of 1, 2, and 3 corresponding to inputs of normal, twice normal, and five times the normal rate.

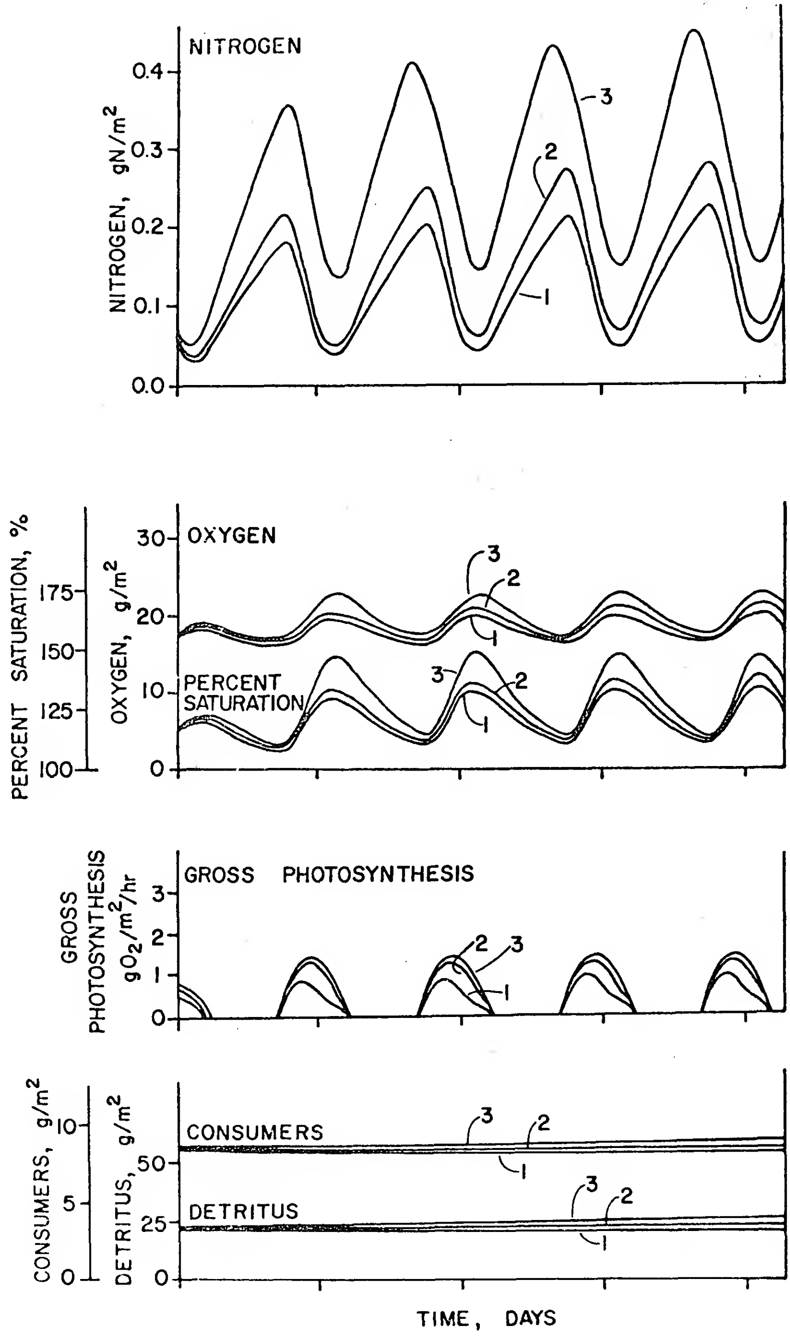
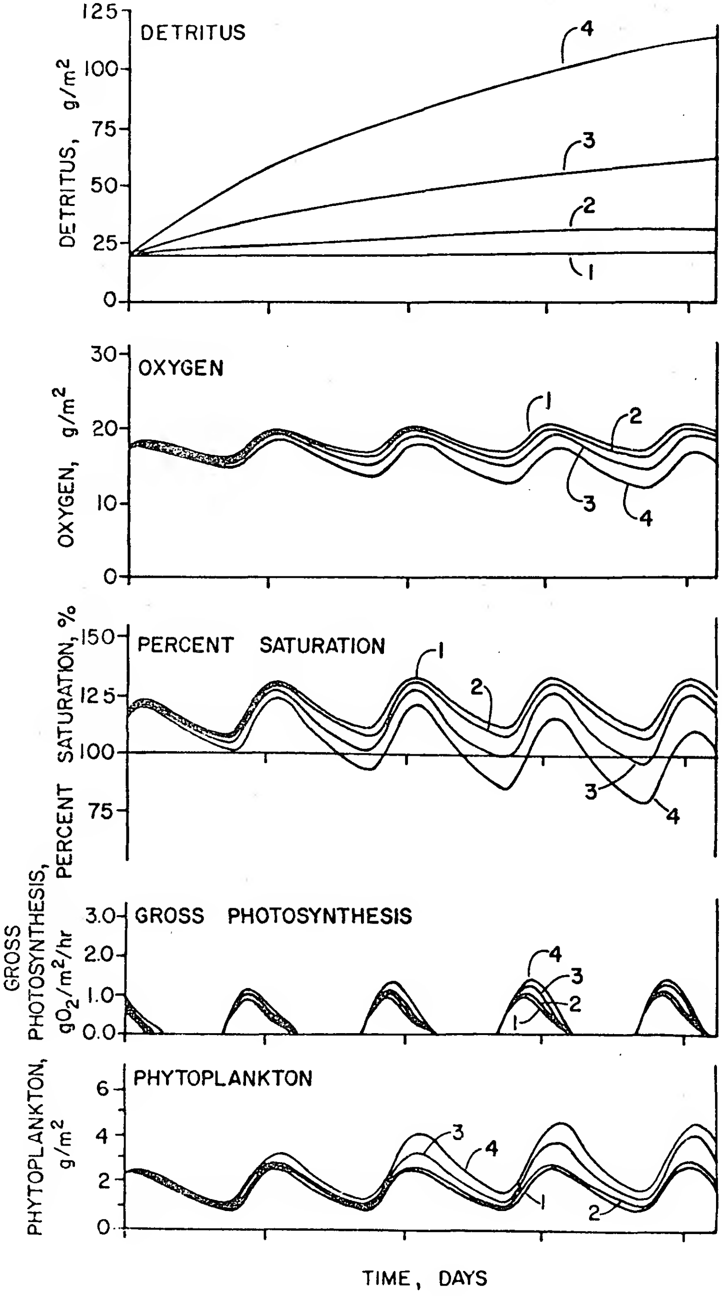
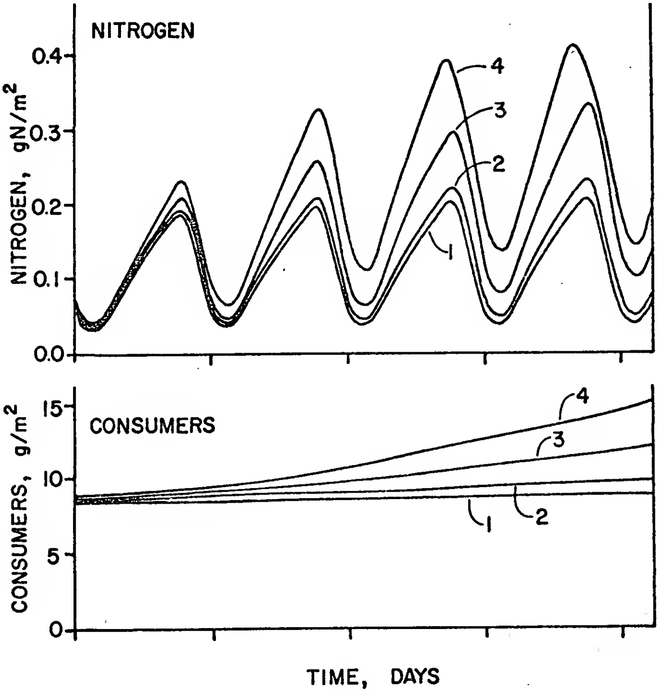

NITROGEN
NITROGEN, gN/m2
0.0
0.1
0.2
0.3
0.4
1
2
3
OXYGEN
PERCENT SATURATION, %
100
125
150
175
OXYGEN, g/m2
0
10
20
30
PERCENT SATURATION
1
2
3
GROSS PHOTOSYNTHESIS
GROSS PHOTOSYNTHESIS gO2/m2/hr
0
1
2
3
1
2
3
CONSUMERS
DETRITUS
CONSUMERS, g/m2
0
5
10
DETRITUS, g/m2
0
25
50
1
2
3
TIME, DAYS

Fig. 25. Simulation results from the model given in Fig. 19a with varying rates of detritus input. (1) control condtions; (2) 2x normal input rate; (3) 5x normal input rate; (4) 10x normal input rate. (a) detritus, oxygen, percent saturation, photosynthesis and phytoplankton; (b) nitrogen and consumer stock.


DETRITUS
DETRITUS, g/m²
125
100
75
50
25
0
1
2
3
4
OXYGEN
OXYGEN, g/m²
30
20
10
0
PERCENT SATURATION
PERCENT SATURATION, %
150
125
100
75
GROSS PHOTOSYNTHESIS
GROSS PHOTOSYNTHESIS, gO₂/m²/hr
3.0
2.0
1.0
0.0
PHYTOPLANKTON
PHYTOPLANKTON, g/m²
6
4
2
0
TIME, DAYS

(a)


NITROGEN
NITROGEN, gN/m^2
0.4
0.3
0.2
0.1
0.0
1
2
3
4
CONSUMERS
CONSUMERS, g/m^2
15
10
5
0
1
2
3
4
TIME, DAYS

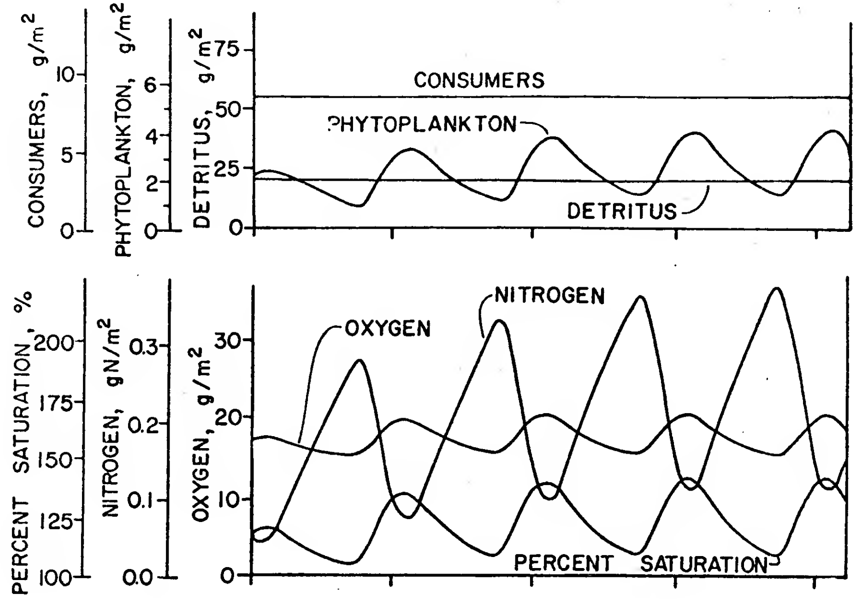
(b)

$O_2/m^2/hr$. The increase in photosynthesis observed under increased detritus input rates was not so large as the increase observed for similar increases in nitrogen input rates. Consumer biomass in the model increased by factors of 1.1, 1.4, and 1.7 beyond the control case.

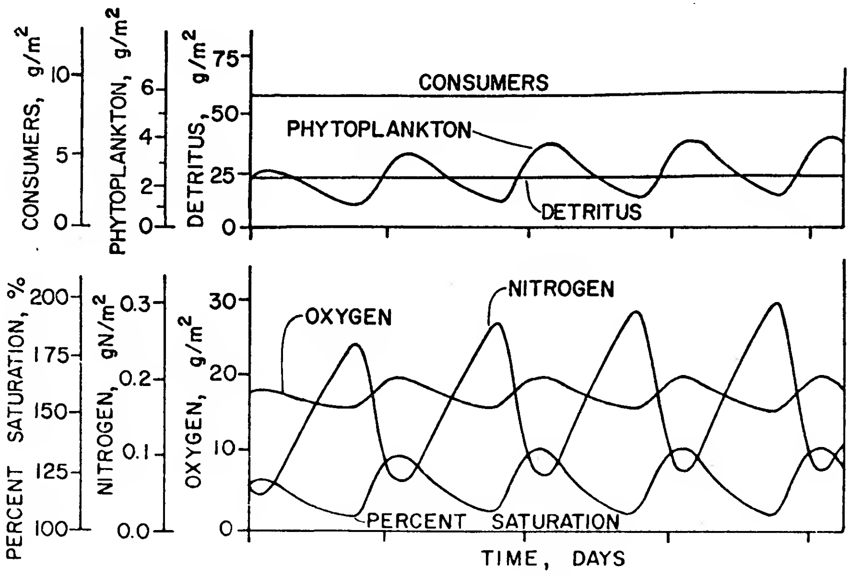
Figure 26 shows model output under conditions where microbial respiration of detritus (J_7) was increased by a factor of 2.0. Microbial respiration was not known and was increased to check the sensitivity of the model to this type of change. Microbial use of oxygen (J_6) and nitrogen recycle (J_{15}) were also increased by factors of 2.0. In Fig. 26a nitrogen input was at 2x the control rate and in Fig. 26b detritus input was at 2x the control rate. In general, only small changes were observed when these curves were compared to curves in Fig. 24 and 25 corresponding to 2x input rate increases in nitrogen and detritus, respectively. In both cases, minimum oxygen levels were lower than observed under the same increased input conditions with no increased microbial activity. Little change was observed in maximum values.

Figure 27 shows simulation graphs for oxygen. In all three graphs the rate of oxygen exchange between the atmosphere and water was decreased to 0.1 of the control condition value. In all cases oxygen levels dropped below control conditions. In case (3) maximum and minimum levels decreased by 10.8 ppm and 9.6 ppm respectively, below

Fig. 26. Results of simulating the model given in Fig. 19a with microbe respiration increased by a factor of two above control values. In (a) nitrogen input was twice the control rate. In (b) detritus input was twice the control rate.


CONSUMERS, g/m2
PHYTOPLANKTON, g/m2
DETRITUS, g/m2
CONSUMERS
PHYTOPLANKTON
DETRITUS
PERCENT SATURATION, %
NITROGEN, gN/m2
OXYGEN, g/m2
NITROGEN
OXYGEN
PERCENT SATURATION

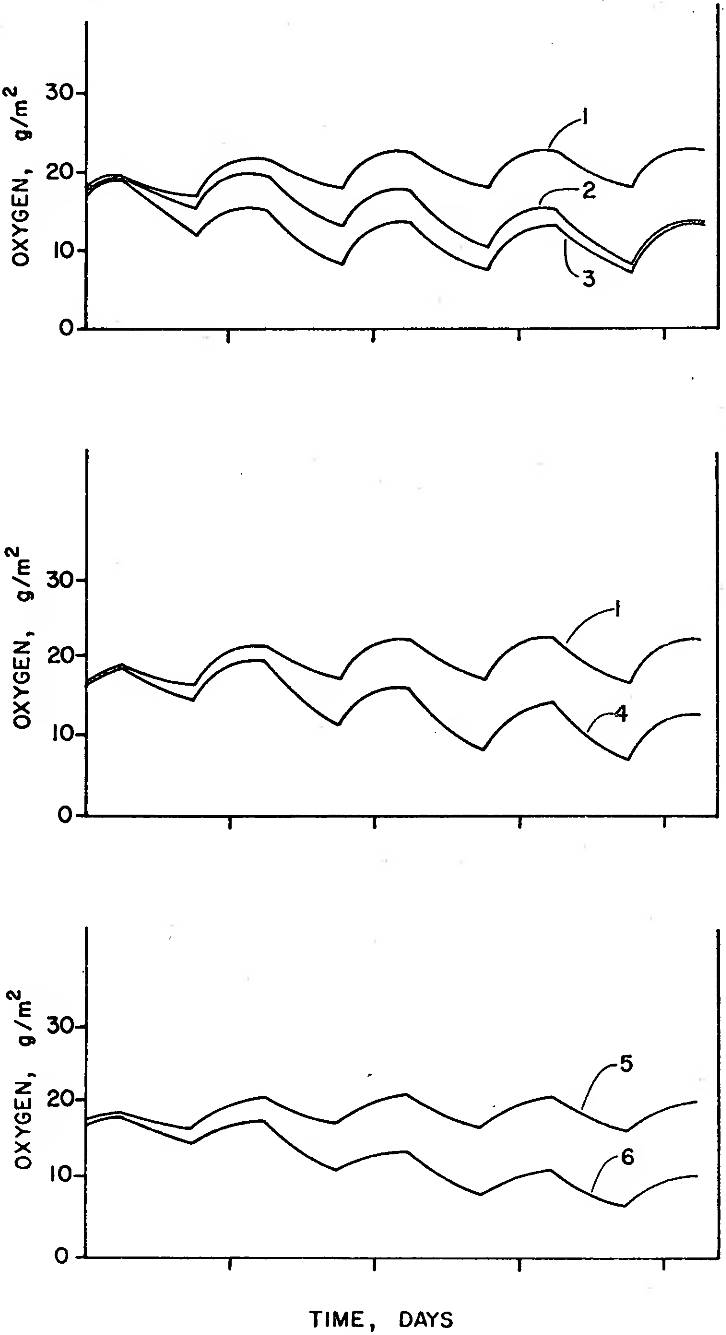
(a)


CONSUMERS, g/m2
PHYTOPLANKTON, g/m2
DETRITUS, g/m2
CONSUMERS
PHYTOPLANKTON
DETRITUS
PERCENT SATURATION, %
NITROGEN, gN/m2
OXYGEN, g/m2
NITROGEN
OXYGEN
PERCENT SATURATION
TIME, DAYS

(b)

Fig. 27. Graphs of oxygen resulting from simulating the model in Fig. 19a with the reaeration rate reduced to 10 percent of control conditions, varying inputs of detritus, nitrogen, and sunlight, and with sunlight as a square wave.

1. control conditions
2. detritus input 4x normal rate
3. detritus input 10x normal rate
4. detritus and nitrogen inputs 4x normal rate
5. control conditions but with sunlight at 1/2 normal input rate
6. sunlight input 1/2 normal rate; detritus and nitrogen input rates at 4x normal rate.



OXYGEN, g/m^2
30
20
10
0
1
2
3
OXYGEN, g/m^2
30
20
10
0
1
4
OXYGEN, g/m^2
30
20
10
0
5
6
TIME, DAYS

Table 7

Summary of simulated values from diurnal activity model.

Conditions	Parameters						
	Phytoplankton biomass g/m^2	Consumer biomass g/m^2	Oxygen g/m^2	Detritus g/m^2	Nitrogen g/m^2	Gross Photosynthesis $g\ O_2/m^2/hr$	Percent saturation %
Control conditions (Fig. 21)	1.0-2.9	7.3	15.4-19.4	19.8	0.04-0.20	0.90	105-132
Sunlight changes (Fig. 23)							
control	1.1-2.9	8.5	16.0-20.0	20.0	0.04-0.20	0.46-1.33[a]	114-131
0.5 control	1.1-2.2	NC[b]	16.1-19.6	NC	0.09-0.27	0.47-0.70	114-128
0.25 control	1.1-1.8	NC	16.1-18.0	NC	0.24-0.35	0.33	114-121
Nitrogen input (Fig. 24)							
control	NR[c]	8.5	15.4-19.4	21.3	0.04-0.20	0.90	105-132
2x control	NR	8.7	17.0-20.4	22.5	0.05-0.26	1.31	110-136
5x control	NR	8.8	17.3-27.3	23.8	0.15-0.42	1.40	115-149

[a]Double entries for gross photosynthesis indicates there were multiple peaks in production during the day.

[b]NC indicates no change or a change, either positive or negative, too small to record on the plotter.

[c]NR indicates parameter was not recorded during that simulation run.

Table 7 - continued

Conditions	Parameters						
	Phytoplankton biomass g/m^2	Consumer biomass g/m^2	Oxygen g/m^2	Detritus g/m^2	Nitrogen g/m^2	Gross Photosynthesis $g\ O_2/m^2/hr$	Percent saturation %
Detritus input (Fig. 25)							
control	1.0-2.5	7.3-8.9	16.4-19.2	20.0	0.04-0.21	0.85	113-133
2x control	1.0-2.8	7.3-9.8	16.1-19.2	32.5	0.50-0.23	0.93	109-132
5x control	1.4-3.8	7.3-12.1	14.2-18.8	60.0	0.08-0.33	1.20	98-127
10x control	1.6-4.5	7.3-15.0	11.9-16.5	115.0	0.14-0.42	1.36	80-111
Nitrogen input at 2x with microbe respiration at 2x (Fig. 26a)	1.3-3.4	8.7	16.2-20.4	20.0	0.08-0.33	1.36	109-136
Detritus input at 2x with microbe respiration at 2x (Fig. 26b)	1.35-3.5	8.7-8.9	15.8-20.0	20.0-22.5	0.07-0.29	NR	108-134
Combined factors (See Fig. 27 for details of each case).	1.25-3.5	8.7-8.9	15.8-20.0	20.0-22.5	0.07-0.29	NR	108-134
1			17.7-22.7				
2			8.5-15.4				
3			6.9-13.1				
4			17.7-22.7				
5			7.3-15.0				
6			16.5-20.8				
7			6.5-11.5				

control levels. The oxygen range also increased in cases (2) and (3) over the control case (1). Oxygen in case (4) had a diurnal range of 7.7 ppm. In (c) both plots show oxygen levels below control values. In case (5) the diurnal range of oxygen was reduced to 4.3 ppm. In case (6), both maximum and minimum oxygen values were lower than in any other case. The diurnal range of oxygen values increased over case (5) and was similar to the control condition range.

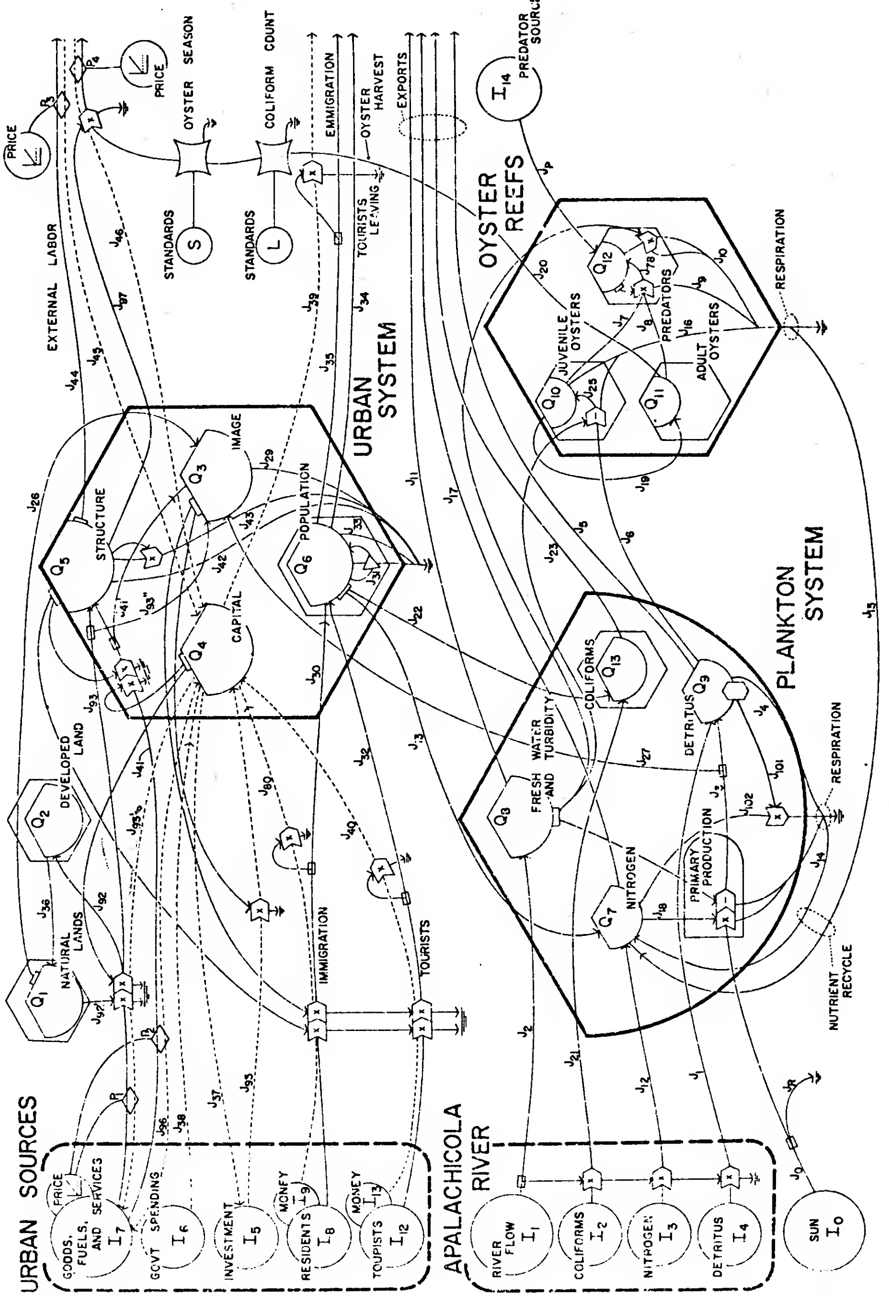
Characteristics of Franklin County Region

Results of characterizing the regional system of Franklin County were organized with the regional model in Fig. 28. Data were assembled for evaluating the main features of the model in Table 8 and Figs. 30 to 34. Included are graphs for fuel use, tourism, population, income, sales, and oyster and other fishery yields. Included with the model is a description, justification of the model configuration (Fig. 29), simulation graphs (Figs. 35 to 49), and comparisons of simulation output with field data.

Regional Model

Shown in Fig. 28 is the detailed model of Franklin County and Apalachicola Bay, Florida. This is an elaboration of the energy circuit language diagram given in Fig.

Fig. 28. Regional model of Franklin County and Apalachicola Bay, Florida. (a) energy circuit diagram, (b) equations. Data sources and calculations used in evaluating the model are given in Appendix Table D-1. The scaled differential equations describing the model are given in Appendix Table D-2. Scaled transfer coefficients and scaled variables and forcing functions are given in Appendix Table D-3. The analog patching diagrams are given in Appendis Fig. D-1 and D-2. All flows (J's) have been calculated as averages over a 20 day interval in June. Nutrients are expressed as grams of nitrogen (gN); coliforms as number of organisms (MPN); freshwater and turbidity as m^3 of water; structure and image as $Kcal_{FFE}$; capital in dollars; natural and developed land as m^2 of area; population as number of people; and detritus, juvenile and adult oysters, and predators as grams of dry organic matter.


URBAN SOURCES
GOODS, FUELS, AND SERVICES
PRICE
GOVT SPENDING
INVESTMENT
MONEY
RESIDENTS
TOURISTS
APALACHICOLA RIVER
RIVER FLOW
COLIFORMS
NITROGEN
DETRITUS
SUN
NATURAL LANDS
DEVELOPED LAND
IMMIGRATION
TOURISTS
URBAN SYSTEM
STRUCTURE
IMAGE
CAPITAL
POPULATION
EXTERNAL LABOR
PRICE
OYSTER SEASON
COLIFORM COUNT
STANDARDS
EMMIGRATION
OYSTER HARVEST
TOURISTS LEAVING
EXPORTS
OYSTER REEFS
JUVENILE OYSTERS
ADULT OYSTERS
PREDATORS
PREDATOR SOURCE
RESPIRATION
PLANKTON SYSTEM
FRESH AND WATER TURBIDITY
COLIFORMS
DETRITUS
NITROGEN
PRIMARY PRODUCTION
RESPIRATION
NUTRIENT RECYCLE

(b)

$$\dot{Q}_1 = k_{36}Q_2 - k_{92'}I_7'Q_1Q_4$$

$$\dot{Q}_2 = k_{92}I_7'Q_1Q_4 - k_{36}Q_2$$

$$\dot{Q}_3 = k_{26}Q_1 + k_{27}k_3YI_o + k_{41}'I_7Q_4Q_5 + k_{93}''I_7'Q_1Q_4 - k_{29}Q_3$$

$$\dot{Q}_4 = k_{38}I_6 + k_{95}I_5Q_3 + k_{80}I_8I_9Q_3Q_5 + k_{40}I_{12}I_{13}Q_3Q_5 +$$
$$k_{46}Q_5Q_{11}P_4 + k_{44}Q_5P_3 - k_{37}Q_4 - k_{39}Q_6 - k_{96}I_7Q_4Q_5P_2$$
$$- k_{93'}I_7'Q_1Q_4P_1$$

$$\dot{Q}_5 = k_{41}I_7Q_4Q_5 + k_{93}I_{7'}Q_1Q_4 - k_{42}Q_5 - k_{43}Q_5^{\,2} - k_{97}Q_{11}Q_5$$

$$\dot{Q}_6 = k_{30}I_8Q_3Q_5 + k_{31}Q_6 + k_{37}I_{12}Q_3Q_5 - k_{33}Q_6 - k_{34}Q_6 - k_{35}Q_6$$

$$\dot{Q}_7 = k_{12}I_1I_3 + k_{13}Q_6 + k_{14}Q_9 + k_{15}Q_{10} - k_{17}Q_7 - k_{18}YI_o -$$
$$k_{102}Q_7Q_9$$

$$\dot{Q}_8 = k_2I_1 - k_{11}Q_8$$

$$\dot{Q}_9 = k_1I_4I_1 + k_3YI_o - k_4Q_9 - k_{101}Q_9Q_7 - k_6Q_9\ (1-Q_8)$$

$$\dot{Q}_{10} = k_{25}Q_9(1-Q_8) - k_{19}Q_{10} - k_{16}Q_{10} - k_7Q_{10}Q_{12}$$

$$\dot{Q}_{11} = k_{19}Q_{10} - k_8Q_{11}Q_{12} - k_{20}Q_{11}Q_5$$

$$\dot{Q}_{12} = k_7Q_{10}Q_{12} + k_8Q_{11}Q_{12} - k_9Q_{12} - k_{10}Q_{12}Q_8 + k_pI_{20}$$

$$\dot{Q}_{13} = k_{21}I_1I_2 - k_{22}Q_6 - k_{23}Q_{13}$$

3 to summarize structure, function, inputs, exchange, and interactions in the county. The model is given in equation form in Fig. 28b. Each transfer coefficient (k) has a subscript that corresponds directly to the subscripted flows (J's) given on the energy circuit diagram. The pathways in Fig. 28 can thus be traced to the differential equations. Values used in evaluating the model are given in Table 8 with all calculations, assumptions, and references given in Appendix Table D-1. The scaled differential equations which describe model behavior are given in Appendix D-2. The analog patching diagram is given in Appendix Figs. D-1 and D-2. Parts of the model are isolated in Fig. 29 with more comments on the reasons for the configuration used.

The regional model is composed of three major groupings: the urban system, water and plankton system, and the oyster reef system. Land-use distribution is shown by two storages located to the upper left of the urban sector of the model (Q_1 and Q_2). Urban sources include tourists (I_{12}) and tourist money (I_{13}), new residents (I_8) and new resident money (I_9), investment (I_5) and government money (I_6) and goods, fuels and services (I_7). Urban storages include image (Q_3), capital (Q_4), structure (Q_5) and population (Q_6).

In the urban sector, image had inputs from all major productive processes of the region including one from the input to structure (J_{41}'), development of new

Table 8

Numbers used to evaluate regional model of Franklin County and Apalachicola Bay given in Fig. 28a.

Designation on model (Fig. 28a) and in Appendix Table D-1	Name	Numerical value
Storages		
Q_1	Natural lands	$9.26 \times 10^7 m^2$
Q_2	Developed lands	$5.84 \times 10^7 m^2$
Q_3	Image	2.03×10^{12} Kcal
Q_4	Capital	7.77×10^6 dollars
Q_5	Structure	1.41×10^{12} Kcal
Q_6	Population	7423 people
Q_7	Nitrogen	7.5×10^7 g N
Q_8	Freshwater and turbidity	$5.2 \times 10^8 m^3$
Q_9	Detritus	$1.06 \times 10^{10} g$
Q_{10}	Juvenile oysters	$5.53 \times 10^8 g$
Q_{11}	Adult oysters	$8.68 \times 10^8 g$
Q_{12}	Predators	$3.11 \times 10^7 g$
Q_{13}	Coliforms	5.51×10^{14} coliforms
Forcing Functions		
I_0	Sunlight	4.5×10^{13} Kcal/20 days
I_1	River flow	$1.04 \times 10^9 m^3$/20 days
I_2	Coliform concentration	2.5×10^6 coliforms/m^3

Table 8 - continued

Designation on model (Fig. 28a) and in Appendix Table D-1	Name	Numerical value
Forcing Functions (cont.)		
I_3	Nutrient concentration	0.25 g N/m^3
I_4	Detritus concentration	8.0 g/m^3
I_5	Capital investment	$\$3.29 \times 10^4$/20 days
I_6	Government spending	8.2×10^4/20 days
I_7	Goods, fuels and services	1.96×10^{10}Kcal/20 days
I_8	Immigration	20.6 people/20 days
I_9	Money associated with new residents	$\$6.12 \times 10^3$/person
I_{12}	Tourist inflow	576 people/20 days
I_{13}	Tourist money inflow	$\$7 \times 10^4$/20 days
I_{14}	Predator inflow	1.64×10^6 g/20 days
Flows		
J_0	Sunlight	4.5×10^{13}Kcal/20 days
J_1	Detritus inflow	8.32×10^9 g/20 days
J_2	River flow	$1.04 \times 10^9 m^3$/20 days
J_3	Phytoplankton production	2.72×10^{10}g/20 days

Table 8 - continued

Designation on model (Fig. 28a) and in Appendix Table D-1	Name	Numerical value
Flows (cont.)		
J_4	Community respiration	2.30×10^{10} g/20 days
J_5	Detritus export	8.50×10^{9} g/20 days
J_6	Food uptake by juvenile oysters	1.46×10^{9} g/20 days
J_7	Predation of juvenile oysters	1.21×10^{7} g/20 days
J_8	Predation of adult oysters	1.90×10^{7} g/20 days
J_9	Predator respiration	2.34×10^{7} g/20 days
J_{10}	Predator stress respiration	7.7×10^{6} g/20 days
J_{11}	Bay flushing	$1.04 \times 10^{9} m^{3}$/20 days
J_{12}	River nitrogen input	2.6×10^{8} g N/20 days
J_{13}	Nitrogen from towns	2.77×10^{6} g N/20 days
J_{14}	Nutrient regeneration	1.28×10^{9} g N/20 days
J_{15}	Oyster nutrient regeneration	7.2×10^{7} g N/20 days
J_{16}	Oyster respiration	1.3×10^{9} g/20 days
J_{17}	Nutrient export	1.34×10^{9} g N/20 days
J_{18}	Nutrient uptake in photosynthesis	1.36×10^{9} g N/20 days

Table 8 - continued

Designation on model (Fig. 28a) and in Appendix Table D-1	Name	Numerical value
Flows (cont.)		
J_{19}	Adult oyster recruitment	2.91×10^7 g/20 days
J_{20}	Oyster harvest	1.06×10^7 g/20 days
J_{21}	Coliform input from river	2.6×10^{15} coliforms/20 days
J_{22}	Coliform input from towns	1.89×10^{14} coliforms/20 days
J_{23}	Coliform losses	2.79×10^{15} coliforms/20 days
J_{25}	Oyster uptake of detritus	1.46×10^9 g/20 days
J_{101}	Microbe respiration	2.56×10^9 g/20 days
J_{102}	Microbe nutrient utilization	1.28×10^8 g N/20 days
J_{27}	Estuarine input to image	6.2×10^9 Kcal/20 days
J_{29}	Image depreciation	2.95×10^{10} Kcal/20 days
J_{30}	Immigration	20.6 people/20 days
J_{31}	Birth rate	6.6 people/20 days
J_{32}	Tourist inflow	576 people/20 days
J_{33}	Death rate	4.6 people/20 days
J_{34}	Tourist outflow	576 people/20 days
J_{35}	Emigration	18.2 people/20 days

Table 8 - continued

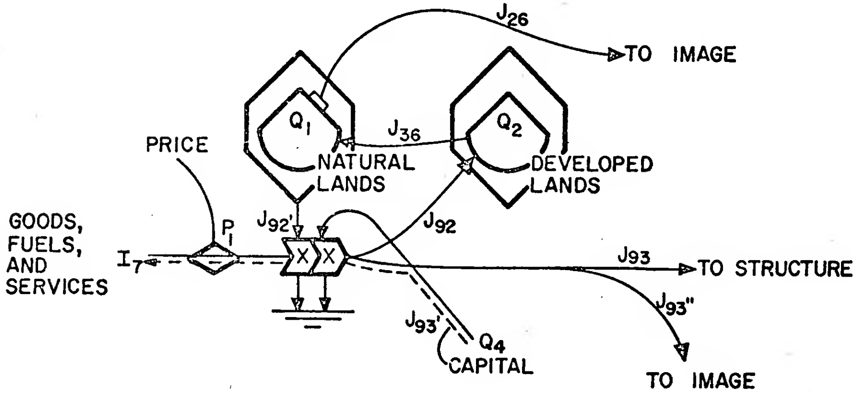
Designation on model (Fig. 28a) and in Appendix Table D-1	Name	Numerical value
Flows (cont.)		
J_{36}	Return to natural land	$5.6 \times 10^3 m^2$/20 days
J_{37}	Investment return	\$1.64 x 10^3/20 days
J_{38}	Government spending	\$8.2 x 10^4/20 days
J_{39}	Money outflow with emigration	\$1.13 x 10^5/20 days
J_{40}	Tourist money inflow	\$7.0 x 10^4/20 days
J_{80}	Money inflow with immigration	\$1.38 x 10^5/20 days
J_{41}	Maintenance of structure	1.89×10^{11} Kcal/20 days
J_{41}'	Urban input to image	1.89×10^{11} Kcal/20 days
J_{42}	Linear depreciation of structure	1.5×10^{10} Kcal/20 days
J_{43}	Square drain depreciation of structure	2.86×10^9 Kcal/20 days
J_{45}	Income earned outside the county	\$1.02 x 10^5/20 days
J_{46}	Income due to oyster sales	\$4.76 x 10^5/20 days
J_{92}	Land development	$5.6 \times 10^3 m^2$/20 days
J_{92}'	Loss of natural lands	$5.6 \times 10^3 m^2$/20 days

Table 8 - continued

Designation on model (Fig. 28a) and in Appendix Table D-1	Name	Numerical value
Flows (cont.)		
J_{93}	Goods, fuels, and services used to develop land	7.4×10^8 Kcal/20 days
J_{93}'	Capital outflow for development of new lands	\$2.96 $\times 10^4$/20 days
J_{93}''	New land development input to image	7.4×10^8 Kcal/20 days
J_{95}	Investment rate	\$3.29 $\times 10^4$/20 days
J_{96}	Capital outflow for goods, fuels, and services	\$7.6 $\times 10^5$/20 days
J_{97}	Oyster harvest effort	1.74×10^9 Kcal/20 days
J_P	Predator inflow	1.64×10^6 g/20 days

Fig. 29. Justification of the configuration used in the regional model of Franklin County and Apalachicola Bay shown in Fig. 28a.

Fig. 29a. Natural land (Q_1) was chosen as a state variable because Franklin County leaders felt land available for development played a role in attracting investment and people to the county and could in the future be a factor limiting areal urban growth. A developed land storage (Q_2) was included to account for all land in the county. The double workgate was chosen because three factors were suggested as being the minimum number required for urban growth (J_{92}, J_{93}) to occur. These were capital to pay for fuels, space, and a source of fuels (I_7). Other factors which are required (labor, information, etc.) were assumed to be nonlimiting. Pathway J_{36} was included to show the continual effect of depreciation and was made linear because no important interactive affects seemed to be present. The price (P_1) paid for goods, fuels, and services was controlled by outside factors because Franklin County does little, even in the oyster industry, to affect average prices (Colberg and Windham, 1965). Both natural and developed land storages are enclosed by the hexagon group symbol in recognition of the self-maintaining nature of natural ecosystems. The use of the group symbol here does not add additional pathways or interactions to the model.



J_{26}
TO IMAGE
Q_1
J_{36}
Q_2
PRICE
NATURAL LANDS
DEVELOPED LANDS
GOODS, FUELS, AND SERVICES
P_1
J_{92}'
J_{92}
I_7
X
X
J_{93}
TO STRUCTURE
J_{93}''
J_{93}'
Q_4
CAPITAL
TO IMAGE

Fig. 29b. Image (Q_3) is the long-term ability of the area to attract outside goods, fuels, and services, investment, tourists, and new residents. Image was chosen to be a state variable to integrate the diverse factors that may attract people and capital to the county. As a state variable image had a decay time and could influence other pathways for a period of time after inputs stopped. It was assumed that image had inputs from all major work activities in the area (J_{41}, J_{26}, J_{93}"). The linear drain (J_{29}) was included to show depreciation effects. It was assumed that losses from image were negligible in attracting outside materials to the county because promotion and advertising were not large county activities. No special feedback interactions were used between image and image inputs for this same reason.

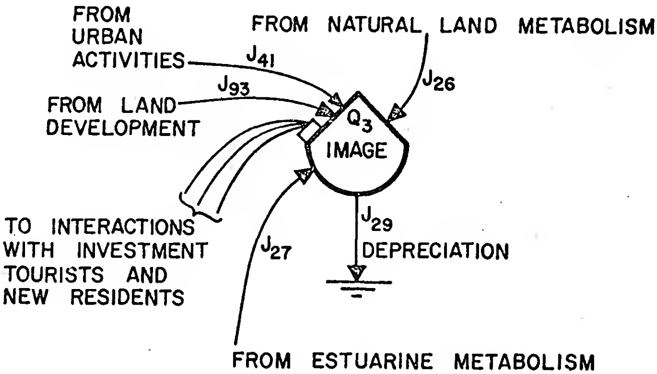

FROM URBAN ACTIVITIES
FROM NATURAL LAND METABOLISM
J_{41}
J_{26}
J_{93}
FROM LAND DEVELOPMENT
Q_3
IMAGE
TO INTERACTIONS WITH INVESTMENT TOURISTS AND NEW RESIDENTS
J_{29}
J_{27}
DEPRECIATION
FROM ESTUARINE METABOLISM

Fig. 29c. It was assumed that all available capital could be represented by a single storage (Q_4). Government input (J_{38}) was a constant flow source because government subsidies to Franklin County may be determined by external factors. Local leaders suggested multiple reasons why capital was attracted to the county. For this reason, investment was assumed to be a multiplicative function of image (which serves to integrate county activities) and external capital (I_5). Both tourist (J_{40}) and new resident money (J_{80}) entered in a constant relationship to tourists and residents entering the county. Money earned in external labor (J_{45}) was proportional to the county structure (Q_5) and the price paid for labor done outside Franklin County (P_3). Structure was used rather than population because it may better represent the ability of county people to compete for external employment. Money earned from oyster sales (J_{46}) was a multiplicative function of oyster biomass (Q_{11}) and structure (Q_5). Population (labor) was assumed to be nonlimiting and, therefore, was not included in the harvesting process. Money left the county to pay for maintenance work (J_{96}) and development of new structure (J_{93}'). The function used was explained in the description of the natural land storage. Energy flow was converted to dollars via price. Price was determined externally. Money also left the county in constant proportion to residents leaving the county.

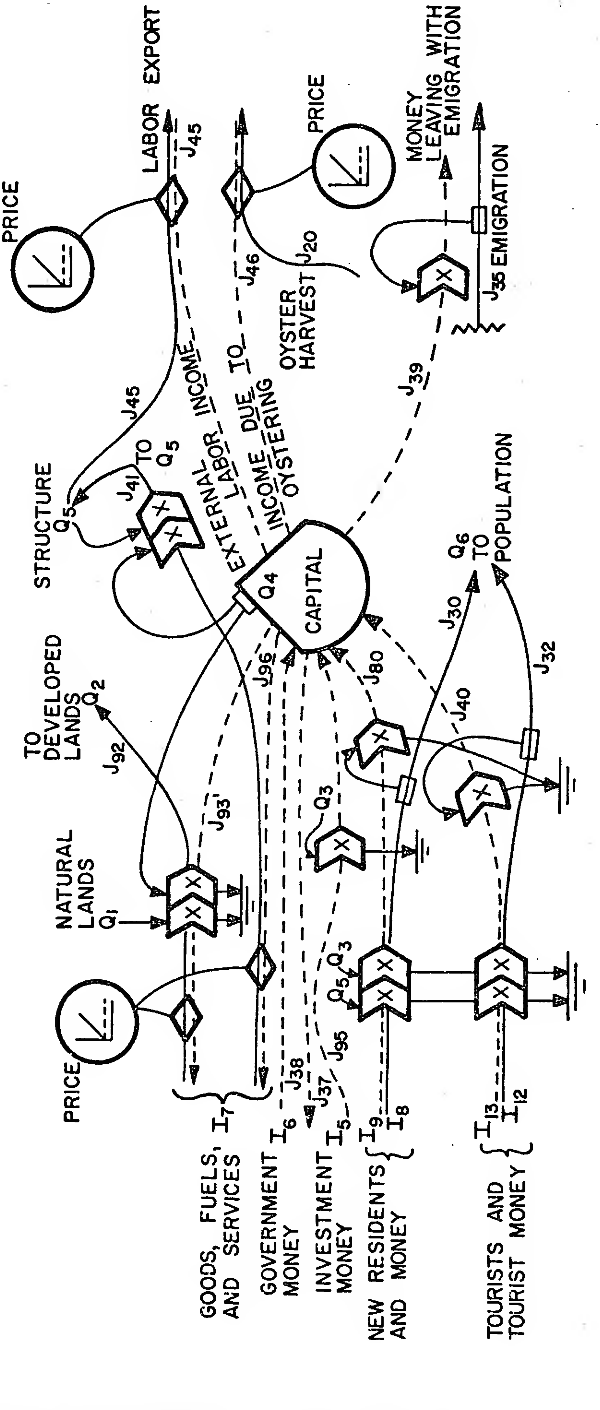

GOODS, FUELS, AND SERVICES
GOVERNMENT MONEY
INVESTMENT MONEY
NEW RESIDENTS AND MONEY
TOURISTS AND TOURIST MONEY
PRICE
NATURAL LANDS
Q_1
TO DEVELOPED LANDS
Q_2
STRUCTURE
Q_5
TO Q_5
Q_4
CAPITAL
EXTERNAL LABOR INCOME
INCOME DUE TO OYSTERING
OYSTER HARVEST
LABOR EXPORT
PRICE
PRICE
MONEY LEAVING WITH EMIGRATION
EMIGRATION
Q_6 TO POPULATION
Q_3

Fig. 29d. County structure was chosen as a state variable for use as an index of the county's ability to do work (J_{97} and J_{44}) and to show the energy requirement of maintaining (J_{41}) or adding (J_{93}) new structure which makes county activities possible. Flow J_{41} was a multiplicative function of external fuels (I_7), capital (Q_4), and the existing structure (Q_5). These were suggested by local leaders to be critical factors controlling county growth. Nonzero levels were required in all three factors for a flow to occur. A linear drain (J_{42}) was used to show losses due to normal depreciation. The square drain (J_{43}) was used to show the cost of maintaining complex structure. For each unit in a system the number of possible interactions increases as the square of the number of components. It was assumed that the cost of maintaining these interactions increased in a similar fashion. Work done in external markets was not considered to consume much structure and, therefore, J_{44} was shown as a sensor pathway. However, structure was consumed in oyster fishing (gasoline, boats, equipment) and was assumed to be a multiplicative function of both structure and adult oyster biomass (J_{47}).

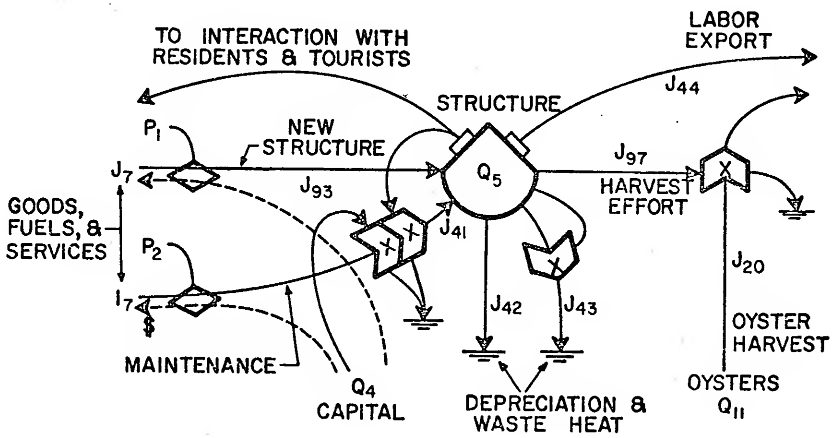

TO INTERACTION WITH
RESIDENTS & TOURISTS
LABOR
EXPORT
J_{44}
STRUCTURE
P_1
NEW
STRUCTURE
J_7
J_{93}
Q_5
J_{97}
HARVEST
EFFORT
GOODS,
FUELS, &
SERVICES
P_2
J_{41}
J_{20}
I_7
$
J_{42}
J_{43}
OYSTER
HARVEST
MAINTENANCE
Q_4
CAPITAL
DEPRECIATION &
WASTE HEAT
OYSTERS
Q_{11}

Fig. 29e. Population was represented by the hexagon unit to recognize the self-maintianing properties of such a storage. Population was chosen as a state variable because domestic wastes and coliform inputs to the bay appeared to be generally proportional to this factor. Additionally, capital entered the model in proportion to the entry of new residents and tourists and left the county in proportion to the emigration rate. Local leaders suggested that both image and structure were major factors attracting residents to the county. Thus, these inputs were multiplicative functions of both factors as well as the availibility of new residents and tourists. Birth rate (J_{31}) and death rate (J_{33}) were in constant proportion to the total population. External factors luring people out of the county were assumed to be constant and thus tourists and residents (J_{34} and J_{35}) left the county just in proportion to the total population.

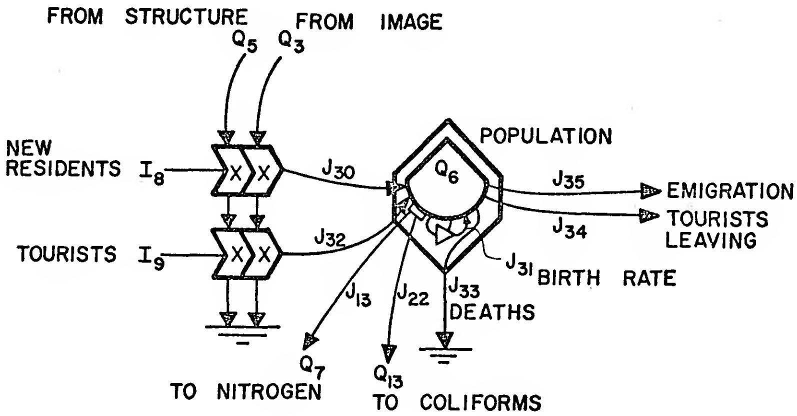
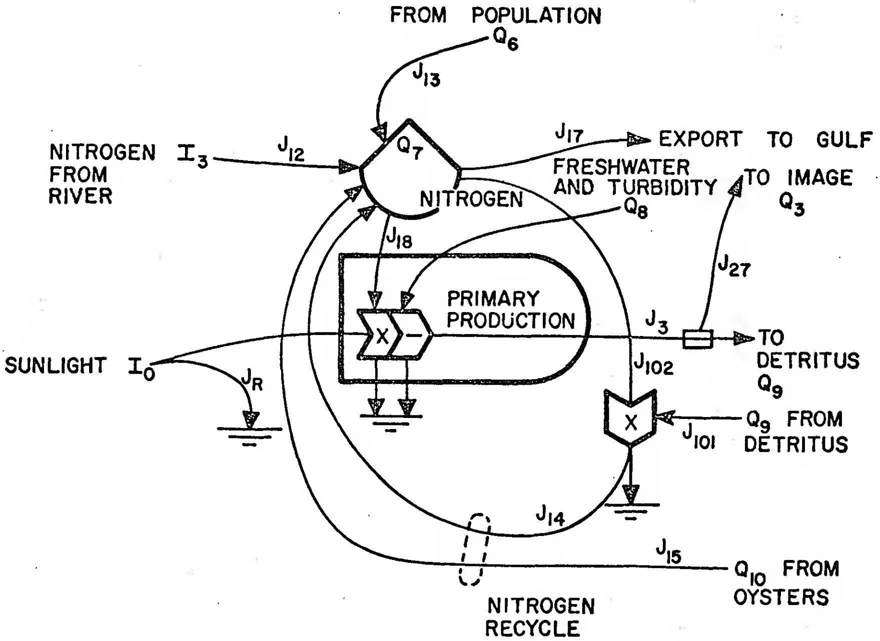
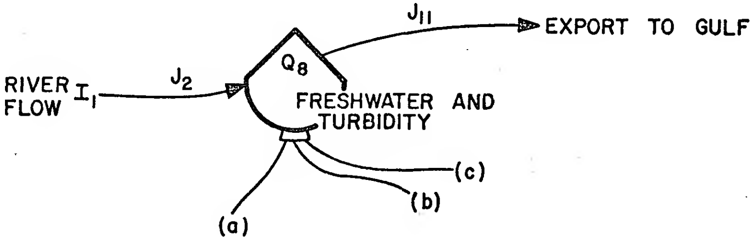

FROM STRUCTURE
FROM IMAGE
Q5 Q3
NEW RESIDENTS I8
TOURISTS I9
POPULATION
Q6
J30
J32
J35
J34
EMIGRATION
TOURISTS LEAVING
J31 BIRTH RATE
J13
J22
J33 DEATHS
Q7 TO NITROGEN
Q13 TO COLIFORMS

Fig. 29f. A nutrient storage was included because of the established requirement for nutrients in production. In-situ primary production was the main source of organic matter in the bay, at least in the summer (Appendix Table D-1). Additionally, nutrients of one kind or another often limit photosynthetic rates and are subject to changing levels due to urban or other normal seasonal factors. Nitrogen was chosen as the nutrient which may limit photosynthesis based on a review of the nutrient literature by Pomeroy _et al_. (1972). Nitrogen was used in photosynthesis as a multiplicative function of sunlight (J_0), nitrogen (Q_7), and a term ($1-Q_8$) representing the effect of turbidity in attenuating sunlight. Nitrogen was also used in microbial activity (J_{102}) as a multiplicative function of nitrogen and detritus stocks. This pathway was included to provide an alternate pathway for nutrient utilization in addition to photosynthetic uptake. The nitrogen storage had an input which was proportional to river flow. Nitrogen concentration in river water was assumed to be constant during each simulation run (Fig. 17). Pathways J_{14} and J_{15} are recycle pathways and were included because they provide the bulk of the nitrogen used in photosynthesis. Small recycle pathways were not included. Nitrogen also entered as a constant proportion of the population (J_{13}) representing sewage discharge from the towns. Nitrogen was assumed to be flushed from the bay in proportion to the stock of nitrogen present (J_{17}).



FROM POPULATION
Q6
J13
Q7
J17
EXPORT TO GULF
NITROGEN I3
FROM
RIVER
J12
FRESHWATER
AND TURBIDITY
TO IMAGE
Q3
NITROGEN
Q8
J18
J27
PRIMARY
PRODUCTION
X
J3
TO
DETRITUS
Q9
SUNLIGHT I0
JR
J102
X
Q9 FROM
DETRITUS
J101
J14
J15
Q10 FROM
OYSTERS
NITROGEN
RECYCLE

Fig. 29g. Freshwater in the bay is stored in Q_8. Turbidity was assumed to be proportional to the freshwater in the bay (Estabrook, 1973). Storage Q_8 had one externally controlled input from the river (J_2). Direct rainfall on the bay was small compared to river input and was not included. Freshwater left the bay in proportion to the freshwater in Q_8. Using only river flow to create an average salinity for the bay closely approximated field observations (Fig. 57). Three sensor flows were shown leaving the storage. Flow (a) had a turbidity effect in reducing phytoplankton photosynthesis. Flow (b) inhibited feeding by juvenile oysters in proportion to the amount of freshwater in the bay (Gunter, 1953). Flow (c) increased predator mortality in proportion to both predator biomass and freshwater in the bay as suggested by Dawson (1955b).



TO INTERACTIONS WITH PHOTOSYNTHESIS (a), JUVENILE OYSTERS (b), AND PREDATORS (c).

Fig. 29h. Detritus has been identified as constituting most of the organic matter present in both estuarine and oceanic areas (Hood, 1970). In this model, living phytoplankton biomass and microbial biomass were included as unknown percentages of the total detritus stock. Therefore, the detritus stock in this model contained most of the material available as food to estuarine food webs. Detritus stock was chosen as a state variable for this reason and because this stock changed seasonally due to naturally changing inputs and could change in other ways due to urban influences. Detritus entered the detritus storage in proportion to river flow (J_1). Detritus was also generated through phytoplankton production (J_3) as previously explained. Detritus was used in microbial activity (J_{101}) as a multiplicative function of detritus and nitrogen stocks. Microbes were represented by the hexagon symbol to show the self-maintaining nature of these organisms. The details of microbe activities have not been retained except for their activities in respiration (J_{101}) and nutrient utilization (J_{102}) which may be a major source of recycled nitrogen. Detritus was flushed from the bay (J_5) in proportion to the nitrogen stock present. Detritus was also used by juvenile oysters in proportion to the detritus present times a term regulating oyster feeding which depended on salinity. The J_4 pathway represented utilization of detritus by consumers other than oysters and microbes and was assumed to be linear.

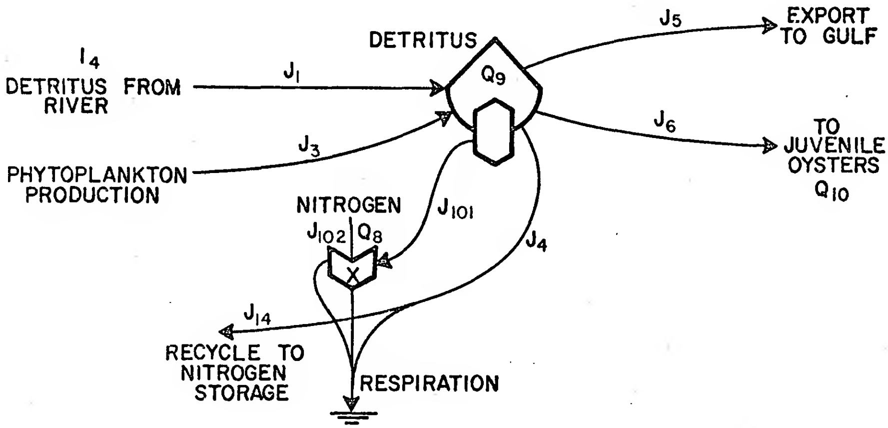

DETRITUS
Q_9
I_4
DETRITUS FROM RIVER
J_1
PHYTOPLANKTON PRODUCTION
J_3
J_5
EXPORT TO GULF
J_6
TO JUVENILE OYSTERS Q_{10}
NITROGEN
J_{101}
J_{102}
Q_8
X
J_4
J_{14}
RECYCLE TO NITROGEN STORAGE
RESPIRATION

Fig. 29i. Coliform bacteria (Q_{13}) are shown as a hexagon to recognize their self-maintaining nature. The unit has been simplified to show only inputs from the river (J_{21}) and from the urban area (J_{22}). River input of coliforms was dependent only on river flow, while input from the urban area was dependent only on population (Q_6). All losses (death and flushing) were lumped into pathway J_{23} and were proportional to the number of coliforms present. The intent of this storage was to track the average stock of coliforms, the level of which determines if oyster fishing is permitted. This is an example of a stock which does not have a large raw energy content in itself, but which has important switching actions elsewhere in the model.

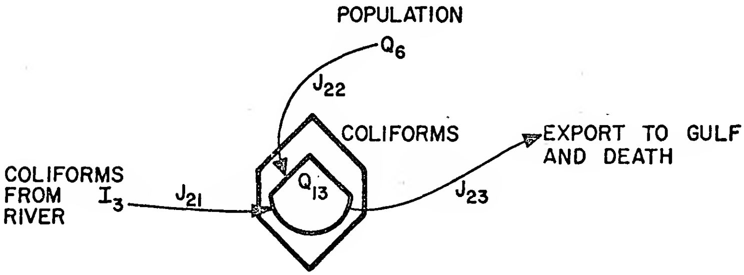
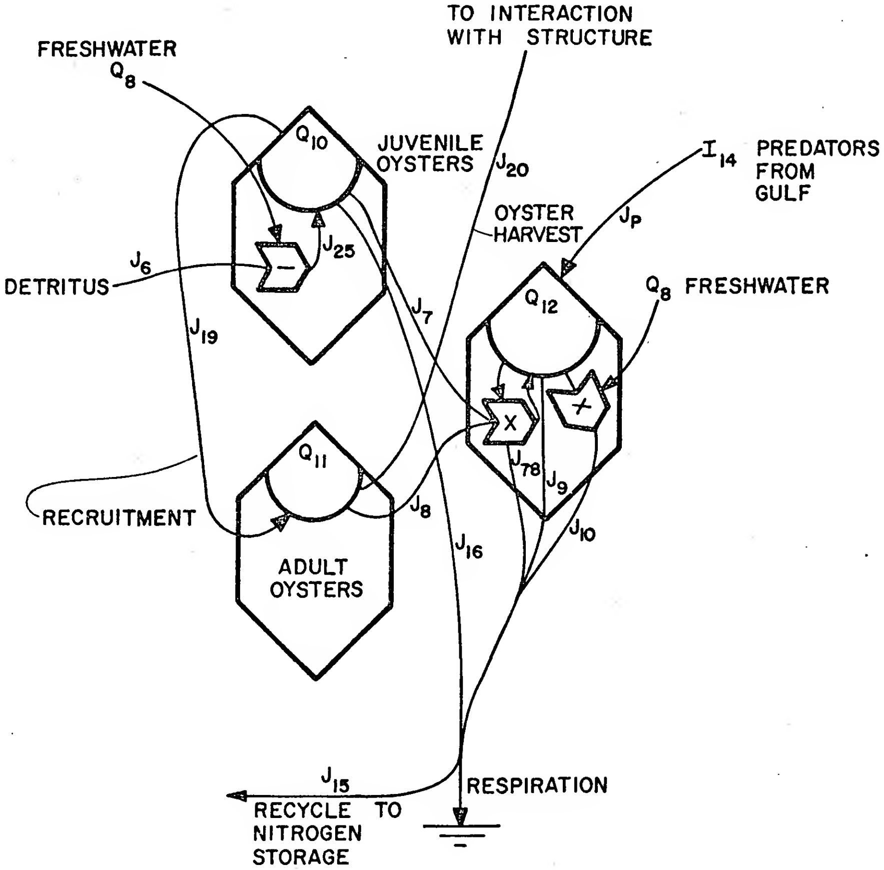

POPULATION
Q_6
J_{22}
COLIFORMS
Q_{13}
COLIFORMS FROM RIVER
I_3
J_{21}
J_{23}
EXPORT TO GULF AND DEATH

Fig. 29j. Juvenile and adult oysters and predators were represented by hexagon symbols to show the self-maintaining nature of these components. In each case the full hexagon symbol was simplified to show only processes considered essential to the simulation. Food input to juvenile oysters was a multiplicative function of food availability (Q_9) and the effect of low salinity in retarding oyster feeding ($1-Q_8$). While the exact relationship between feeding and salinity was not known, the configuration used captured at least the extremes of the relationship (Gunter, 1953). An autocatalytic feedback was not shown on juvenile oysters because, even in poor harvest years, set of juveniles was farily good and therfore was assumed to be nonlimiting (Menzel, 1973). Juvenile oyster respiration was approximated by a linear drain (J_{16}). Adult oyster recruitment (J_{19}) was assumed to depend only on the size of the juvenile stock. Predation loss was assumed to depend on both the biomass of prey (Q_{10} and Q_{11}) and predators (Q_{12}). In the case of predators, the autocatalytic feedback was required because external input pulses of predators could have significant impact on oyster stocks. If predator biomass increased for this reason, predation would increase because of the autocatalytic arrangement used. Pathway J_p was a constant source of predator biomass coming from the Gulf of Mexico. Without the seeding provided by J_p, predators would be eliminated permanently if they ever went to zero. Predator losses included both a linear respiratory drain (J_4) and a multiplicative loss which was a function of predator biomass and freshwater in the bay (J_{10}).



TO INTERACTION
WITH STRUCTURE
FRESHWATER
Q_8
Q_{10}
JUVENILE
OYSTERS
J_{20}
I_{14}
PREDATORS
FROM
GULF
OYSTER
HARVEST
J_P
J_{25}
J_6
DETRITUS
Q_{12}
Q_8 FRESHWATER
J_7
J_{19}
X
Q_{11}
J_{78}
J_9
RECRUITMENT
J_8
J_{10}
J_{16}
ADULT
OYSTERS
J_{15}
RESPIRATION
RECYCLE TO
NITROGEN
STORAGE

lands (J_{93}"), natural land metabolism (J_{26}) (shown to be dependent on the area of land available), and primary production in the estuary (J_{27}). Image had one density dependent drain to account for losses due to depreciation. Flows extend out from image to workgates controlling investment money, tourist, and new resident inputs. Flows such as these which come from the sensor symbol attached to a storage indicate that the flow was not an appreciable drain from that tank. A sensor action causes a flow along the pathway with which it interacts by drawing energy from it.

The structure storage has two inputs. The first (J_{41}) is dependent on the availability of capital, the level of structure present and the availability of goods, fuels and services. This flow represents the input required to maintain the level of structure and to add new elements to the present structure. The second input (J_{93}) which is dependent on natural lands and capital represents new structure which is added to the county when new lands are developed. Both of these work flows have inputs to image. Additionally, as new structure is added along pathway J_{93} natural lands are used (J_{92}') and converted to developed lands (J_{92}). Developed lands revert to their natural state along pathway J_{36}. Losses from the structure storage include a density dependent drain (J_{42}), a square drain (J_{43}) which becomes more important as structure becomes larger and more complicated, and a loss which is proportional to the effort involved in the oyster harvest. External labor is indicated by a sensor pathway (J_{44}).

Inputs to the capital storage include a direct input from government sources (J_{38}) (net input beyond taxes paid), and from external labor markets where input was dependent on price (P_3) paid for labor (J_{45}). Money also entered with new residents (J_{80}) and tourists (J_{40}) to the county and by investment spending in the county (J_{95}). Lastly, money entered in exchange for oysters harvested (J_{46}) with an externally-fixed oyster price (P_4). Money left the county with emigrating residents (J_{39}), interest on investments and repayment of principal on loans (J_{37}), purchases of goods, fuels, and services used for growth and maintenance (J_{96}), and for the development of new land (J_{93}'). Prices (P_1 and P_2) were also controlled externally.

Inputs to the population storage include new residents (J_{30}), tourists (J_{32}), and births (J_{31}). Losses include death (J_{33}), tourists leaving the county (J_{34}), and residents emigrating from the county (J_{35}).

Inputs to the water and plankton system include coliforms (J_{21}), nutrients (nitrogen) (J_{12}), and detritus (J_1) which enter in proportion to the input of freshwater from the Apalachicola River (J_2). River flow varies seasonally (Fig. 14). Coliforms, nutrients, and detritus concentrations were assumed constant in each run but could be changed between simulation runs. Sunlight (J_0) also varied seasonally with high and low values in May and December, respectively (Fig. 15). Predators were also introduced from the Gulf of Mexico (J_p).

The amount of freshwater in the bay is indicated by storage Q_8. When this tank is full, the bay has a salinity of 0.0 o/oo. This tank is also used as an index of turbidity, the turbidity being high when the salinity is low. This relationship was based on data from Estabrook (1973). The storage has one input from the river (J_2) and one density-dependent drain (J_{11}).

The nitrogen storage (Q_7) has inputs from the river (J_{12}) urban population (J_{13}), and recycle from respiration (J_{14} and J_{15}). Losses from this tank include uptake in photosynthesis (J_{18}), bacterial utilization (J_{102}), and flushing from the bay (J_{17}).

The coliform storage (Q_{13}) has inputs from the river (J_{21}) and urban population (J_{22}) and losses due to flushing and death (J_{23}). The number of coliforms in the bay was used to control a logic switch (L) regulating oyster harvest. When coliform numbers exceeded the Public Health Service standard (70 MPN) the switch closed and adult oysters were not harvested. Harvest was possible again when coliform numbers fell below the legal limit. The logic switches of the model provide for harvest when coliforms are below the threshold and oyster harvesting is in season (S). Oyster harvesting was permitted from September through May.

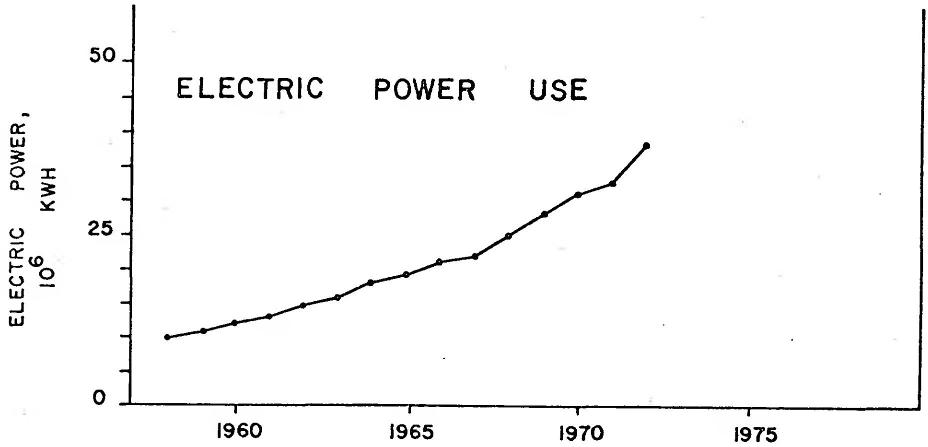
The detritus storage (Q_9) has inputs from the river (J_1) and phytoplankton production (J_3). Losses include microbial respiration (J_{101}), oyster feeding (J_6), use by other herbivores (J_4), and flushing to the Gulf of Mexico (J_5). Phytoplankton production was proportional to the product of sunlight, nutrients, and turbidity (J_3).

The oyster reef system includes juvenile oysters (Q_{10}), adult oysters (Q_{11}), and oyster predators (Q_{12}). Input to juvenile oysters (all oysters less than 3") came from the detritus storage (J_{16}). Losses include respiration (J_{16}) and predation (J_7). The adult oyster storage receives input from the juvenile oysters via recruitment and has losses to predators (J_8) and harvest (J_{20}). Oyster predators receive input from both juvenile and adult oysters and have losses due to respiration (J_9) and freshwater stress (J_{10}). Predator biomass is seeded from the Gulf of Mexico (J_p).

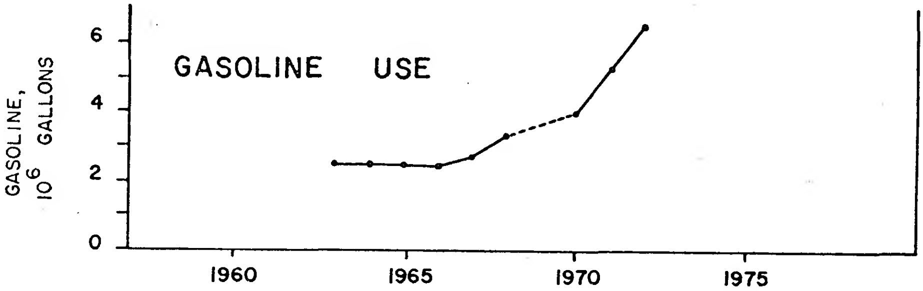
Assembled Data on Franklin County

Data used in evaluating the model in Fig. 28a were given in Table 8 with calculations and assumptions in Appendix Table D-1. Data with time sequences are given in Figs. 30-34. Given in Fig. 30 are graphs of the annual consumption of electric power, gasoline, and kerosene.

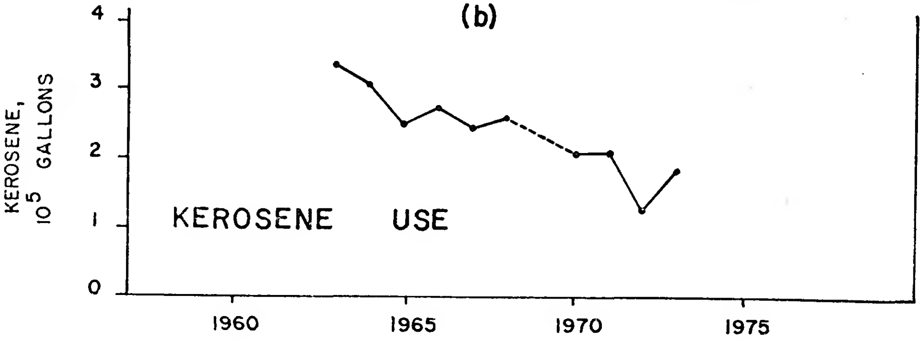
Fig. 30. Yearly consumption of fuels in Franklin County. (a) Electricity, (b) Gasoline, (c) Kerosene.


ELECTRIC POWER USE
ELECTRIC POWER, 10^6 KWH
50
25
0
1960
1965
1970
1975

(a)


GASOLINE USE
GASOLINE, 10^6 GALLONS
6
4
2
0
1960
1965
1970
1975

(b)


KEROSENE USE
KEROSENE, 10^5 GALLONS
4
3
2
1
0
1960
1965
1970
1975

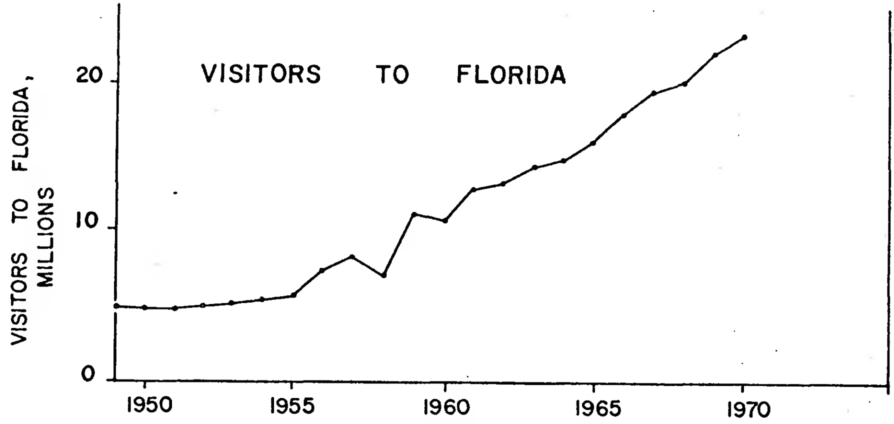
(c)

Electric power use has increased steadily over the period 1958-1972 with some indication of an increasing rate of use in 1972. Consumption of electric power almost tripled between 1960-1970. Gasoline use doubled in the five-year period prior to 1972. Kerosene use was small compared to gasoline and electricity use and annual use has declined in recent years. Time-series data were not available for bottled gas, but bottled gas use was estimated to be approximately 7.5×10^5 gal/yr in 1972 (Stapleton, 1973).

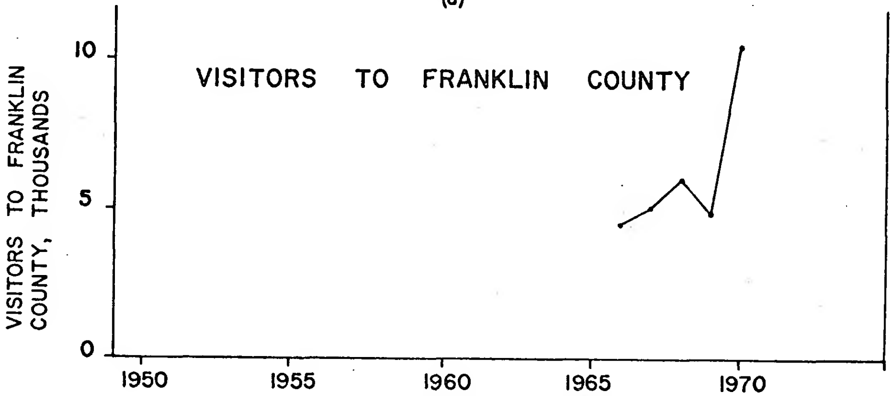
Figure 31 shows trends in the yearly number of visitors to Florida and Franklin County (Florida Tourist Study, 1970). Unfortunately, tourism data for Franklin County have not been recorded for a long period of time and after 1970 were no longer recorded on a county basis for any county in Florida. The 1970 estimate of about 11,000 visitors to the county probably underestimates total visitors because of special events such as the Apalachicola Seafood Festival, which attracts thousands of people for a short period of time. Estimated tourist expenditures in the county amounted to $\$1.7 \times 10^6$/yr in 1970.

Figure 32 shows annual trends in population, total and per capita personal income, and gross sales in Franklin County (Florida Statistical Abstract, 1973). County population has not changed dramatically in the last twenty years. Both small increases and decreases were recorded during this period. From 1900 to 1960 there was a 35%

Fig. 31. Annual number of visitors to (a) Florida, (b) Franklin County, and (c) a summary of average length of visit and expenditures.



(a)



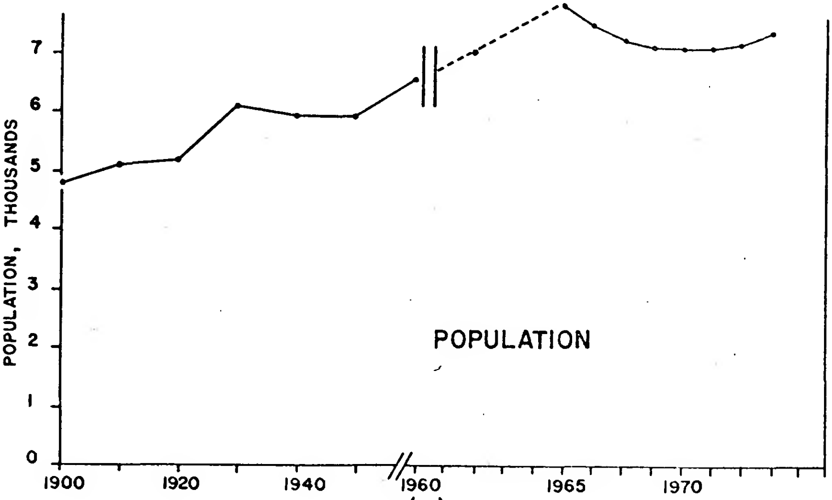
(b)

SUMMARY OF AVERAGE LENGTH OF VISIT AND EXPENDITURES

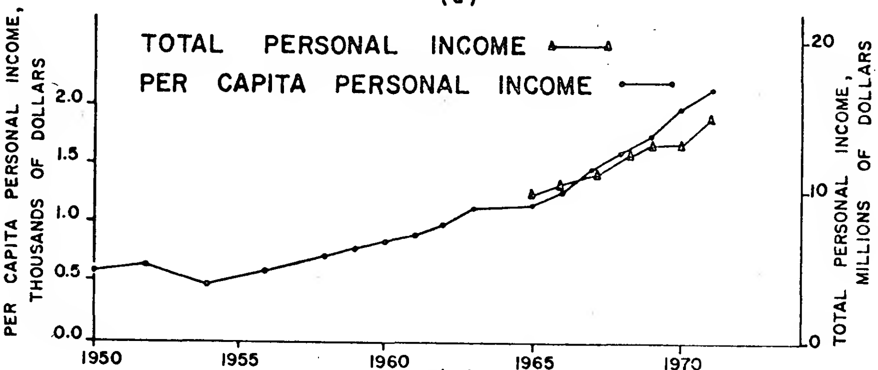
AVERAGE LENGTH OF STAY PER PERSON	12.4 DAYS
AVERAGE EXPENDITURE PER PERSON PER DAY	$ 12.63
AVERAGE EXPENDITURE PER PERSON PER STAY	$ 156.61

(c)

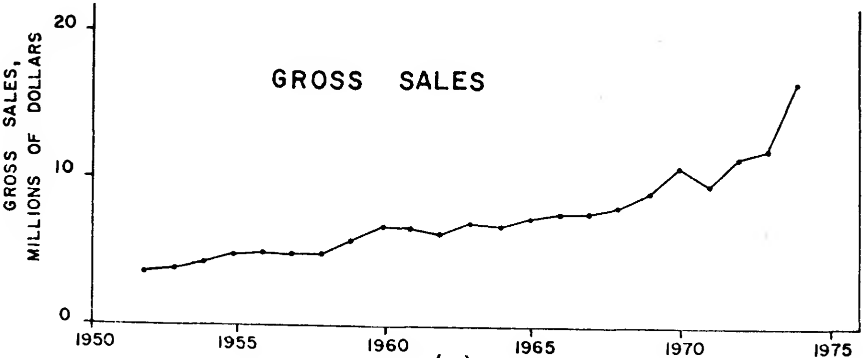
Fig. 32. Urban trends in Franklin County. (a) Population, (b) Total and per capita income, (c) Gross sales.


POPULATION
POPULATION, THOUSANDS
0
1
2
3
4
5
6
7
1900
1920
1940
1960
1965
1970

(a)


TOTAL PERSONAL INCOME
PER CAPITA PERSONAL INCOME
PER CAPITA PERSONAL INCOME, THOUSANDS OF DOLLARS
TOTAL PERSONAL INCOME, MILLIONS OF DOLLARS
.0.0
0.5
1.0
1.5
2.0
0
10
20
1950
1955
1960
1965
1970

(b)


GROSS SALES
GROSS SALES, MILLIONS OF DOLLARS
0
10
20
1950
1955
1960
1965
1970
1975

(c)

increase in population (0.6%/yr) from 4800 to 6500 people. Growth in population in the county has been very slow compared to other areas of Florida. Both total personal income and per capita personal income have increased steadily since 1955. Between 1965 and 1970 per capita income increased at a rate of about \$100/yr (8%/yr). Per capita income in Franklin County in 1970 (\$1,928) was low compared to most counties in Florida and was well below both the Florida average (\$3,661) and the United States average (\$3,933). Gross sales in the county increased slowly from 1952 ($\$3.42 \times 10^6$/yr) through 1969 ($\$9.24 \times 10^6$/yr). The average annual increase was about \$340,000/yr. From 1971 through 1974 gross sales almost doubled, going from $\$9.32 \times 10^6$/yr to $\$17.1 \times 10^6$/yr (Stalvey, 1975).

Figure 33 gives annual oyster harvest in terms of quantity, dockside value and price per pound in 1970 dollars (Rockwood, 1973). Annual harvest has varied considerably from year to year. In general, annual harvests were larger in the past 10 years than in previous periods. Dockside value of the oyster harvest has increased considerably since 1930. In general, value tracked the harvest. Price per pound for oysters (in 1970 dollars) increased by a factor of about 3 between 1930 and 1971. Prices were virtually constant from 1960 to 1968 at about \$0.35/lb (meat weight at dockside). Prices increased slowly from 1968 to 1971 reaching about \$0.43/lb in 1971. Total harvest declined during this same period.

Fig. 33. Annual oyster harvest data for Franklin County including quantity, dockside value, and price per pound in constant 1970 dollars.

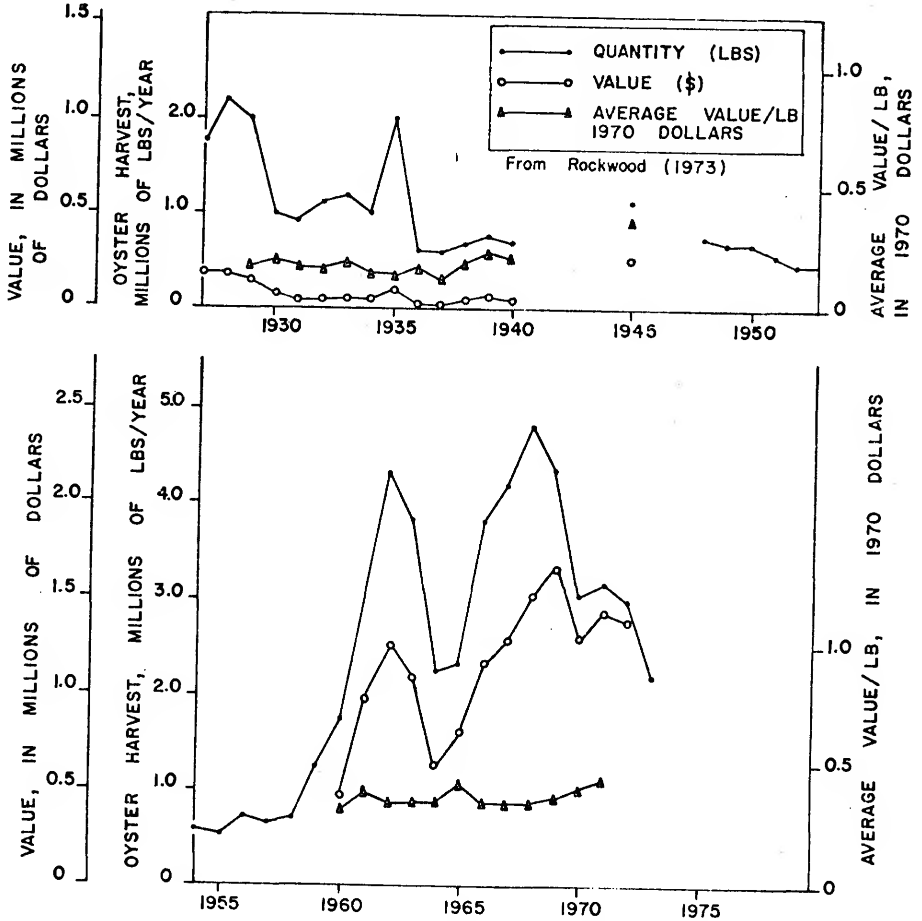

QUANTITY (LBS)
VALUE ($)
AVERAGE VALUE/LB 1970 DOLLARS
From Rockwood (1973)
VALUE, IN MILLIONS OF DOLLARS
OYSTER HARVEST, MILLIONS OF LBS/YEAR
AVERAGE VALUE/LB, IN 1970 DOLLARS
1.5
1.0
0.5
0
2.0
1.0
0
1.0
0.5
0
1930
1935
1940
1945
1950
VALUE, IN MILLIONS OF DOLLARS
OYSTER HARVEST, MILLIONS OF LBS/YEAR
AVERAGE VALUE/LB, IN 1970 DOLLARS
2.5
2.0
1.5
1.0
0.5
0
5.0
4.0
3.0
2.0
1.0
0
1.0
0.5
0
1955
1960
1965
1970
1975

Figure 34 shows annual landings and dockside value of finfish, shrimp, and blue crabs landed in Franklin County. Finfish harvest includes both food fish and trash fish (Division of Marine Resources, 1970). The sharp peaks in landings in 1952 and 1958 were the result of large menhaden landings. In recent years the dockside value of finfish landings has been less than $100,000/yr. Total shrimp landings have varied considerably from year to year, often by as much as a million pounds between successive years. Since 1950 shrimp landings have averaged about 2×10^6 lbs/yr. Dockside value prior to 1970 averaged about $500,000/yr. Since then dockside value has increased to about $1,500,000/yr in 1972. Blue crab landings have also varied considerably from year to year. From 1962 through 1972 landings averaged about 1×10^6 lbs/yr and had a dockside value of about $60,000/yr.

A great deal of additional information was required to evaluate the regional model above and beyond that given in this section. Data for which no time series information was available are given in Appendix Table D-1.

Simulation Results and Comparisons with Assembled Data

Shown in Fig. 35a and 35b are graphs from simulations of the regional model of Franklin County and Apalachicola Bay with starting conditions calculated for 1970. Seasonal trends from field data are plotted as dots on the

Fig. 34. Annual landings and dockside value of major commercial species in Franklin County. (a) Finfish, (b) Shrimp, (c) Blue crabs.

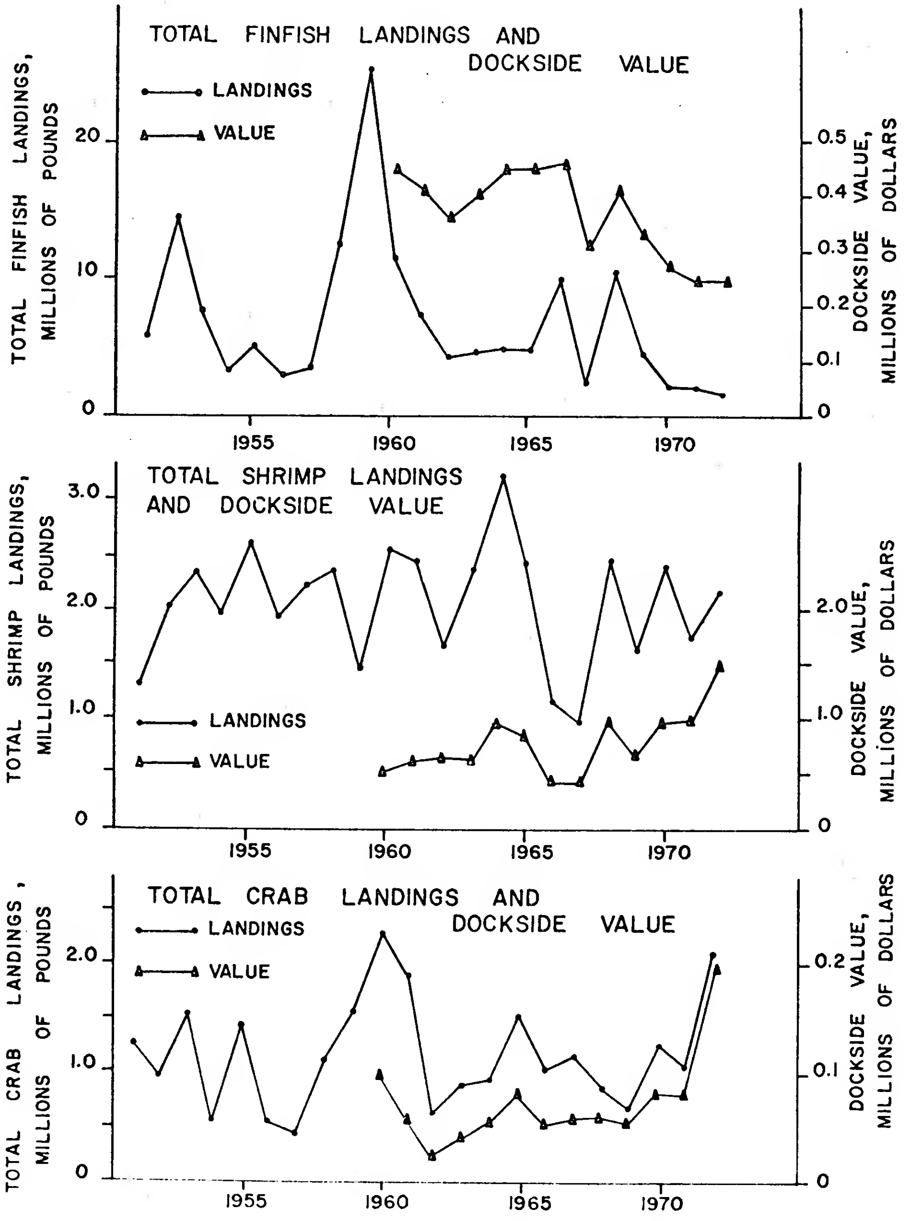
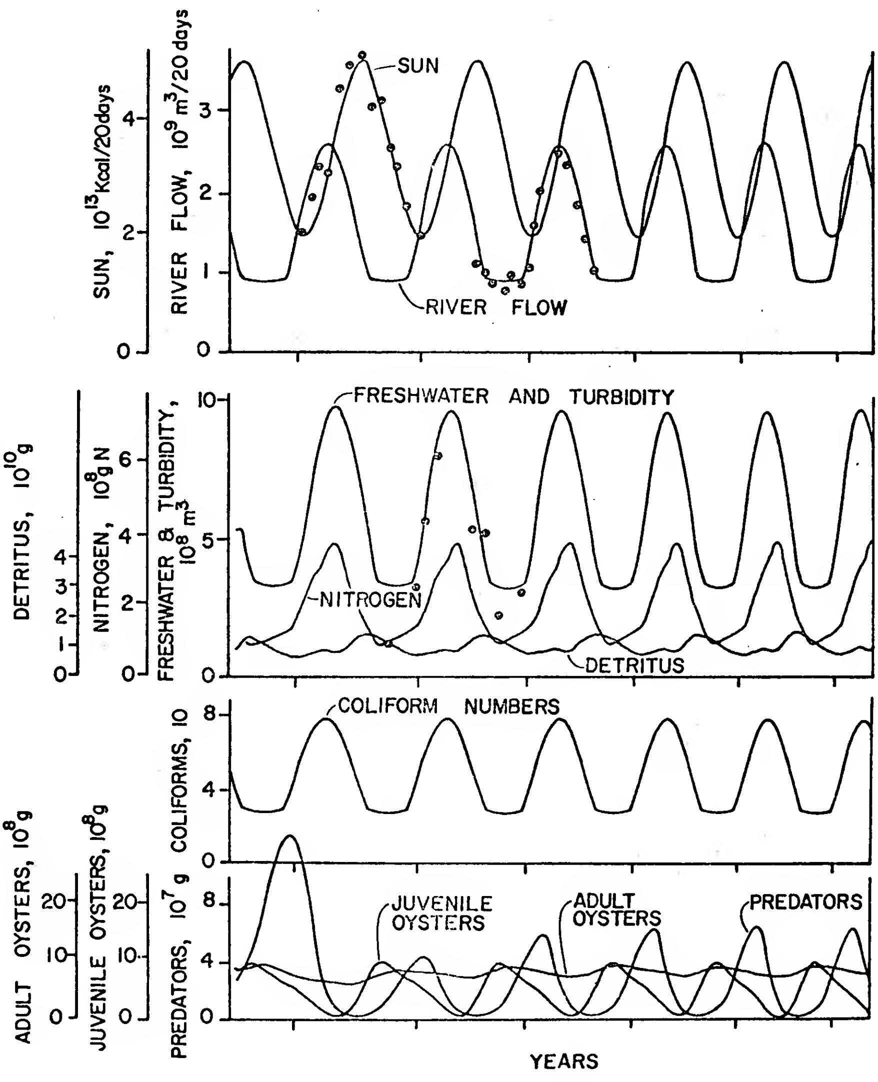
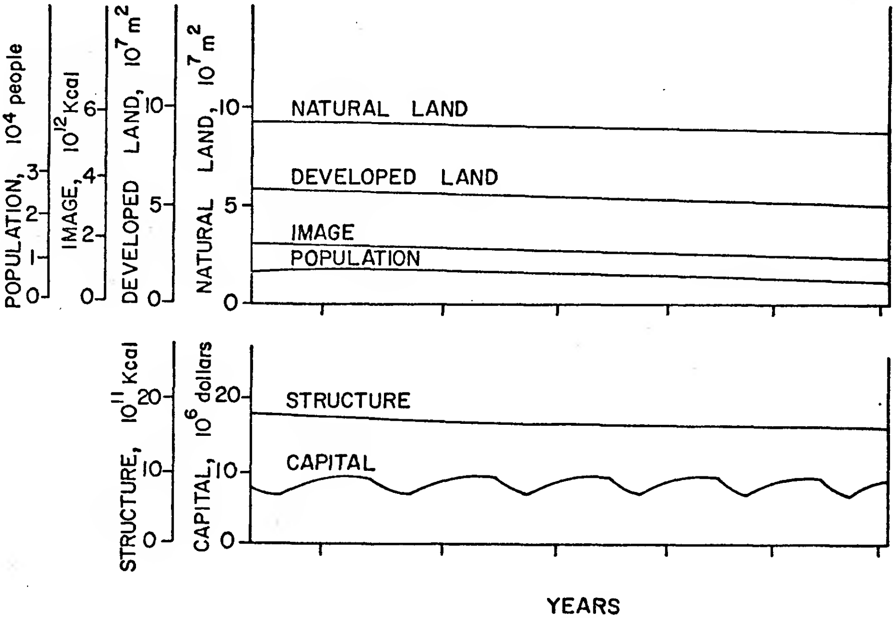

TOTAL FINFISH LANDINGS AND DOCKSIDE VALUE
LANDINGS
VALUE
TOTAL FINFISH LANDINGS, MILLIONS OF POUNDS
DOCKSIDE VALUE, MILLIONS OF DOLLARS
0
10
20
0.1
0.2
0.3
0.4
0.5
1955
1960
1965
1970
TOTAL SHRIMP LANDINGS AND DOCKSIDE VALUE
LANDINGS
VALUE
TOTAL SHRIMP LANDINGS, MILLIONS OF POUNDS
DOCKSIDE VALUE, MILLIONS OF DOLLARS
0
1.0
2.0
3.0
1955
1960
1965
1970
TOTAL CRAB LANDINGS AND DOCKSIDE VALUE
LANDINGS
VALUE
TOTAL CRAB LANDINGS, MILLIONS OF POUNDS
DOCKSIDE VALUE, MILLIONS OF DOLLARS
0
1.0
2.0
0.1
0.2
1955
1960
1965
1970

Fig. 35. Simulation results from the model in Fig. 28a using transfer coefficients calculated from 1970 data. Data points are from Figs. 14 and 15 and Appendix Table D-1. (a) Inputs of river and sunlight and responses for estuarine storages. (b) Responses within urban sectors. All storages refer to amounts in areas which are on nontimber company lands.


SUN
RIVER FLOW
SUN, 10^{13} Kcal/20days
RIVER FLOW, 10^9 m^3/20 days
FRESHWATER AND TURBIDITY
NITROGEN
DETRITUS
DETRITUS, 10^{10} g
NITROGEN, 10^8 g N
FRESHWATER & TURBIDITY, 10^8 m^3
COLIFORM NUMBERS
COLIFORMS, 10
JUVENILE OYSTERS
ADULT OYSTERS
PREDATORS
ADULT OYSTERS, 10^8 g
JUVENILE OYSTERS, 10^8 g
PREDATORS, 10^7 g
YEARS

(a)

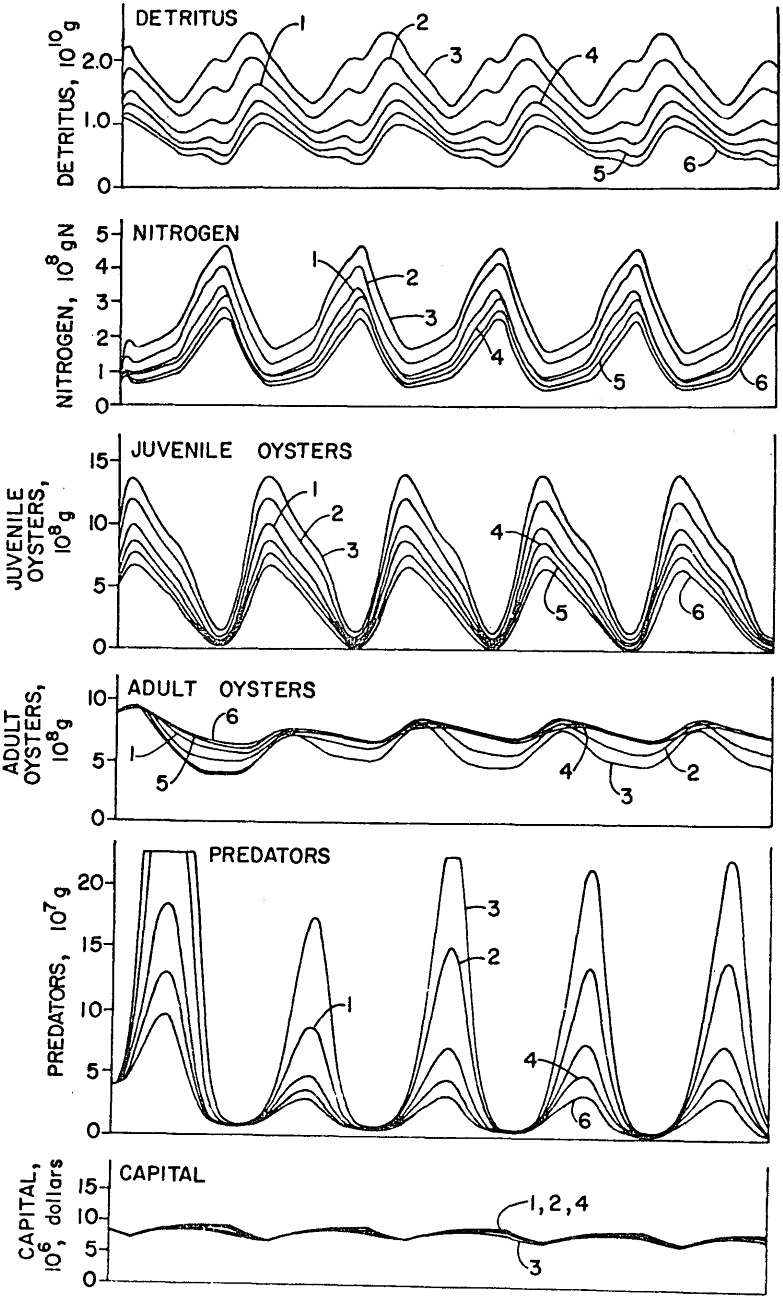

POPULATION, 10^4 people
IMAGE, 10^{12} Kcal
DEVELOPED LAND, 10^7 m^2
NATURAL LAND, 10^7 m^2
NATURAL LAND
DEVELOPED LAND
IMAGE
POPULATION
STRUCTURE, 10^{11} Kcal
CAPITAL, 10^6 dollars
STRUCTURE
CAPITAL
YEARS

(b)

diagram. Forcing functions of sunlight and river flow were set 3 months out of phase with peaks in June and March, respectively. Peak sunlight input was 5000 Kcal/m^2/day. Peak river flow corresponds to 50,000 cfs. Minimum points for sunlight and river flow occurred in December and September, respectively, and were 2400 Kcal/m^2/day and 12,000 cfs. Notice that most estuarine variables showed large seasonal variations. Urban variables, with the exception of capital, showed no noticeable seasonal variations. Seasonal changes in capital were caused by open and closed seasons for oyster harvest. The steady state pattern shown for urban variables is in agreement with qualitative observations of trends in the county.

Model responses to both increased and decreased concentrations of detritus entering the bay via river flow are shown in Fig. 36. This modification was examined to anticipate possible effects of changing detritus concentrations due to land-use changes, increased urban inputs, or damming of the Apalachicola River. Detritus, nitrogen, juvenile oysters and predators all showed higher seasonal maxima and minima under conditions of increased detritus input. Decreased minima and maxima were observed for simulation runs in which detritus concentrations were reduced below the control level. Notice that under conditions of decreased detritus input, adult oyster biomass increased slightly. However, when detritus input was increased to

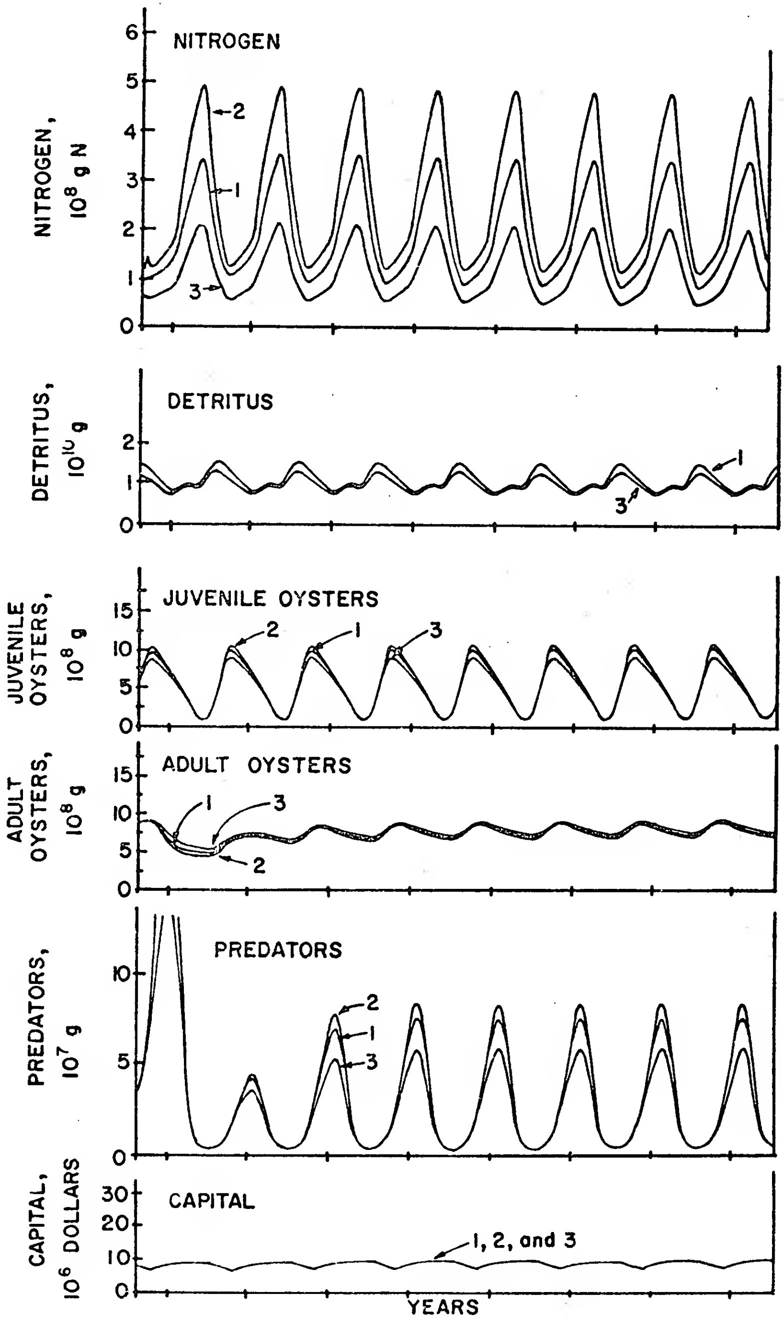
Fig. 36. Simulation results from the model in Fig. 28a with six different rates of detritus input associated with river flow. Normal input rates are given in Appendix Table D-1. (1) normal rate, (2) twice normal rate, (3) three times normal rate, (4) one-half normal rate, (5) one-fifth normal rate, (6) no detritus input.


DETRITUS
DETRITUS, 10^{10}g
2.0
1.0
0
1
2
3
4
5
6
NITROGEN
NITROGEN, 10^8gN
5
4
3
2
1
0
JUVENILE OYSTERS
JUVENILE OYSTERS, 10^8g
15
10
5
0
ADULT OYSTERS
ADULT OYSTERS, 10^8g
10
5
0
PREDATORS
PREDATORS, 10^7g
20
15
10
5
0
CAPITAL
CAPITAL, 10^6, dollars
15
10
5
0
1,2,4
3

2 and 3 times the normal input rate, adult oyster biomass developed fairly large seasonal changes and both peak and minimum adult oyster biomass was depressed below control levels. Under conditions of detritus loading the larger than usual pulse in young oyster biomass stimulated a rapid increase in predator biomass as soon as river flow began to decline. When adult oyster biomass began to increase, predator biomass was quite large and predation was heavy and occurred when the recruitment of juvenile oysters into the adult stock was approaching a seasonal minimum. The seasonal pattern of capital was depressed slightly under conditions of detritus loading.

Model responses to increased and decreased concentrations of nitrogen entering the bay via river flow are given in Fig. 37. This modification was examined in anticipation of possible nitrogen concentration changes due to changes in agricultural runoff and increased urban inputs of nitrogen. In general, storages were not very sensitive to either increased or decreased nitrogen input rates and, except for the nitrogen storage, were similar to responses observed in Fig. 35 (control conditions). Note that while the river was the major source of imported inorganic nitrogen, most of the nitrogen used in photosynthesis was supplied via nitrogen recycled from respired detritus (compare pathways J_{12} and J_{14} in Appendix Table D-1). Thus, if the composition estimates used were correct, the original

Fig. 37. Simulation results from the model in Fig. 28_a for the response of estuarine variables and capital to three different rates of nitrogen input associated with river flow. Normal input rate is given in Appendix Table D-1. (1) normal rate, (2) twice the normal rate, (3) no input of nitrogen.


NITROGEN
NITROGEN, 10^8 g N
6
5
4
3
2
1
0
2
1
3
DETRITUS
DETRITUS, 10^{10} g
2
1
0
1
3
JUVENILE OYSTERS
JUVENILE OYSTERS, 10^8 g
15
10
5
0
2
1
3
ADULT OYSTERS
ADULT OYSTERS, 10^8 g
15
10
5
0
1
3
2
PREDATORS
PREDATORS, 10^7 g
10
5
0
2
1
3
CAPITAL
CAPITAL, 10^6 DOLLARS
30
20
10
0
1, 2, and 3
YEARS

source of most inorganic nitrogen used in this system entered as nitrogen bound in organic matter.

Shown in Fig. 38 are time responses of all state variables to two-fold increases in the input rates of coliforms, nitrogen, and detritus. This modification was examined because changes in water quality often include several factors. Because of possible interactive effects, the outcome under conditions including several pollutants may be different than when impact is examined with one pollutant at a time. In this case, the response of the estuarine storages (nitrogen, detritus, juvenile and adult oysters, and predators) was very similar to those seen in Fig. 36 under conditions where the detritus input rate was twice the control rate. However, a two-fold increase in coliform input was sufficient to exceed the state's legal coliform limit. In this simulation, this resulted in closure of the fishing grounds in January. Thus, oysters were harvested and sold for only a part of the season. Because of this, capital reached a lower, but still seasonally varying steady state. The low point for capital in this run was about 20% lower than in the control run (Fig. 35). In response to the decline in capital, image, structure, and population declined to lower steady states.

Figure 39 shows adult oyster and predator biomass under conditions of no oyster harvest and no predation. This modification was examined to show the relative impact

Fig. 38. Simulation results from the model in Fig. 28a for the response of all state variables to a two-fold increase in the input rate of coliforms, nitrogen, and detritus. River flow was not adjusted from the normal condition.

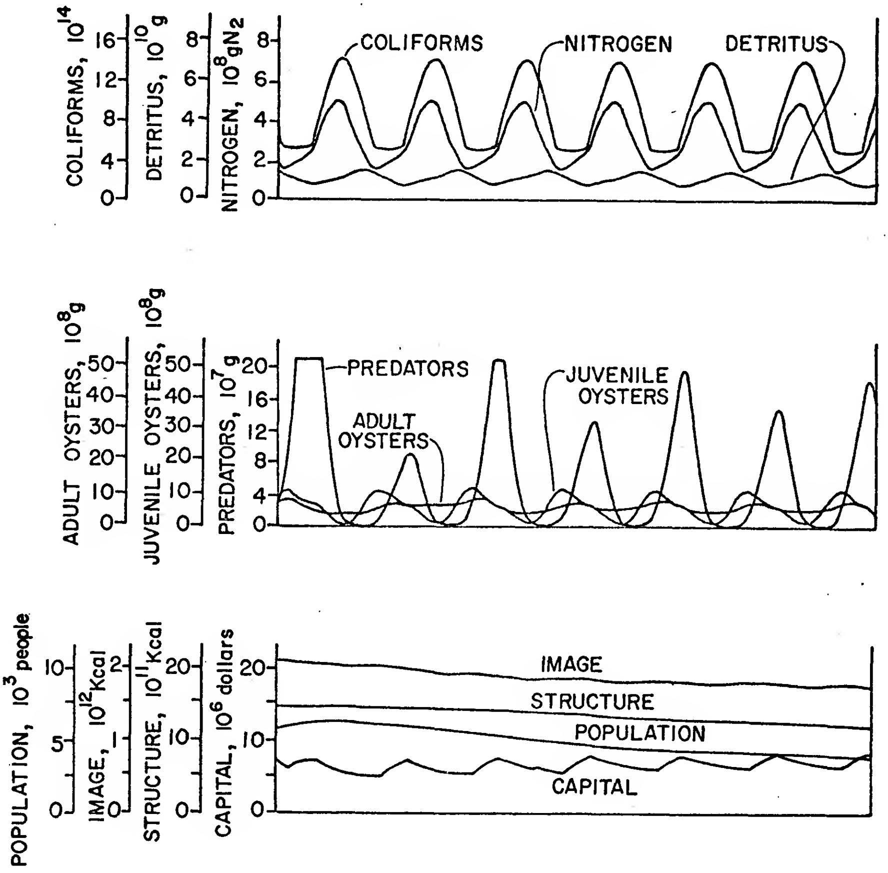
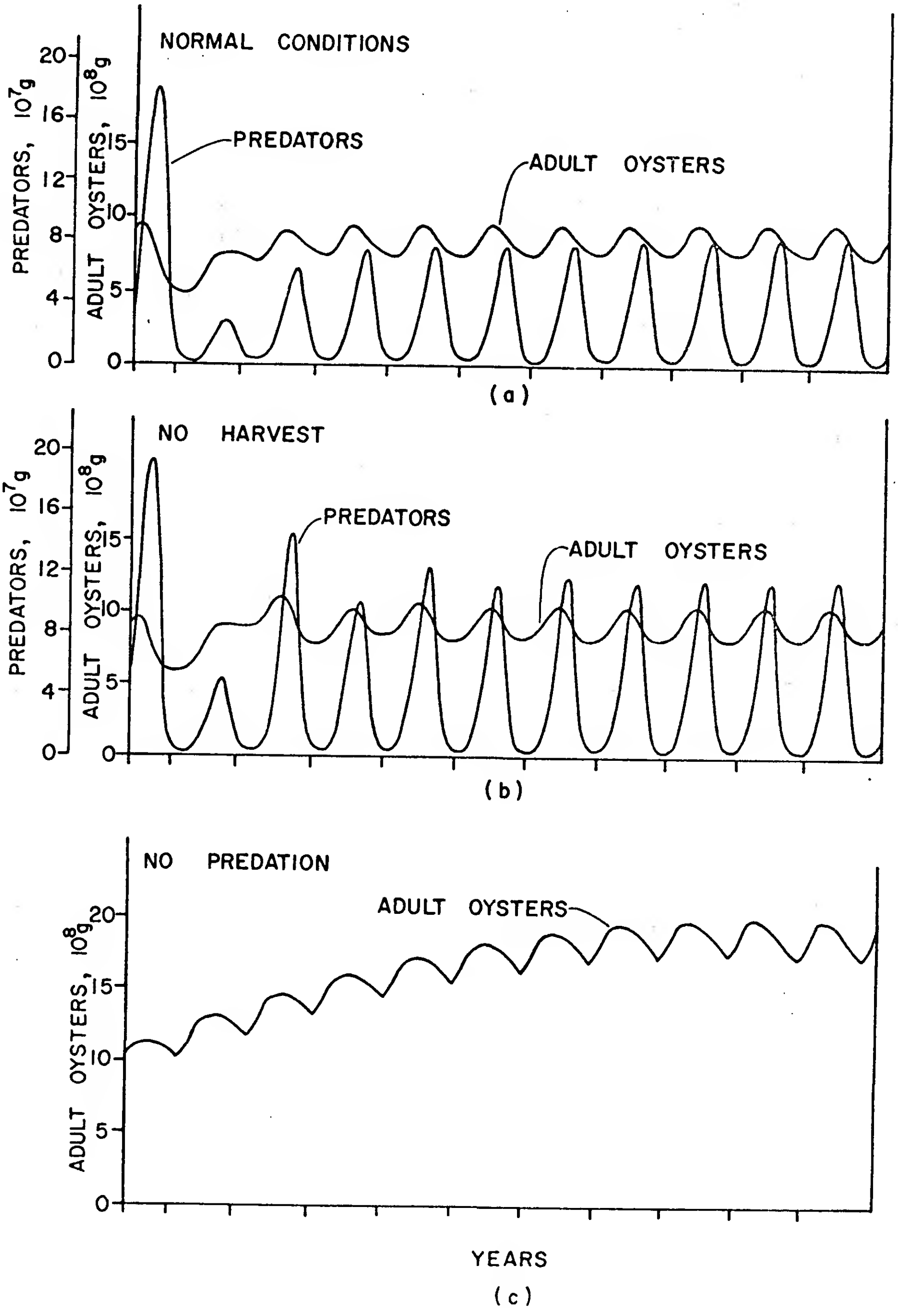

COLIFORMS, 10^{14}
DETRITUS, 10^{10}g
NITROGEN, 10^8gN$_2$
COLIFORMS
NITROGEN
DETRITUS
ADULT OYSTERS, 10^8g
JUVENILE OYSTERS, 10^8g
PREDATORS, 10^7g
PREDATORS
JUVENILE OYSTERS
ADULT OYSTERS
POPULATION, 10^3people
IMAGE, 10^{12}Kcal
STRUCTURE, 10^{11}Kcal
CAPITAL, 10^6 dollars
IMAGE
STRUCTURE
POPULATION
CAPITAL

Fig. 39. Simulation results from the model in Fig. 28a for the response of adult oysters and predators to various conditions of harvest and predation. (a) normal harvest and predation, (b) no harvest, normal predation, (c) normal harvest, no predation.

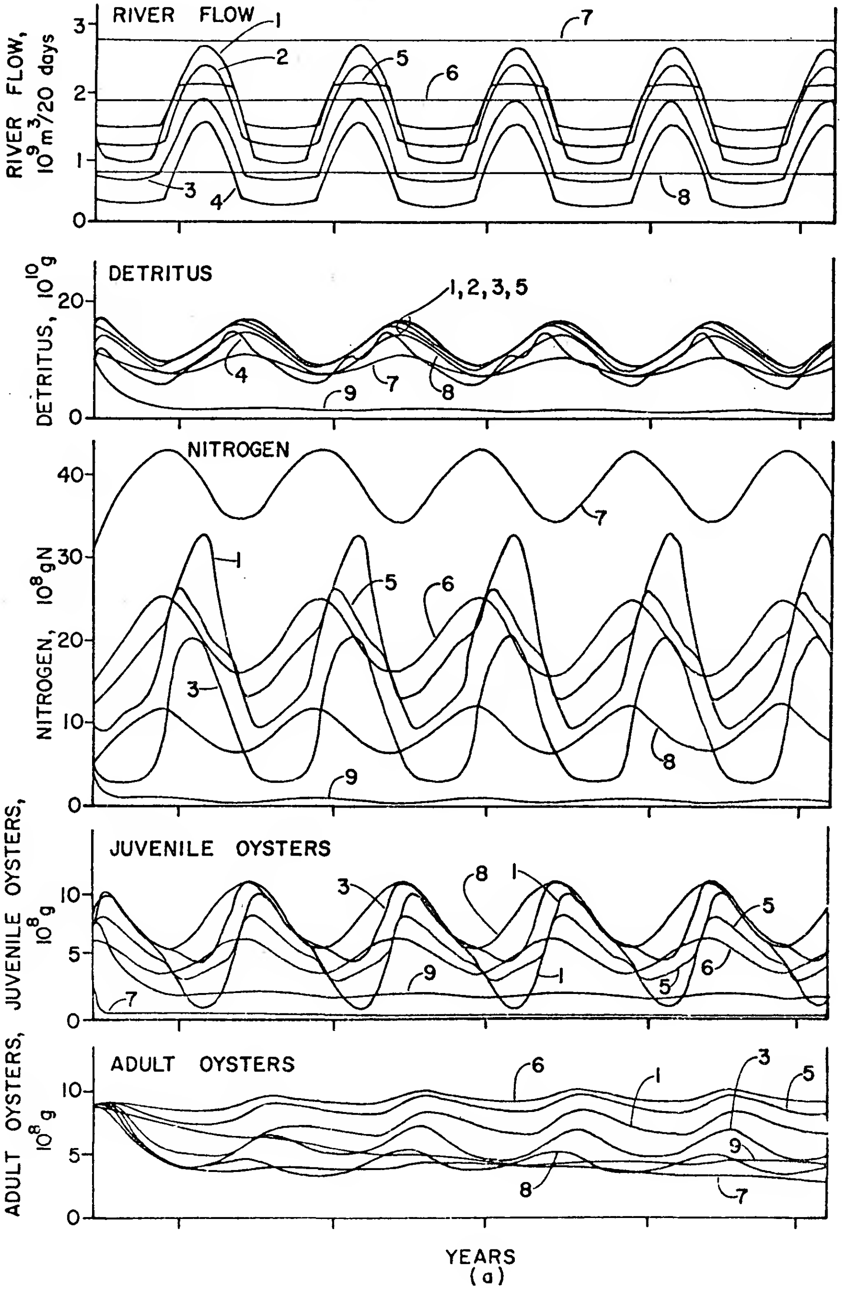

NORMAL CONDITIONS
PREDATORS
ADULT OYSTERS
PREDATORS, 10^7g
ADULT OYSTERS, 10^8g
20
16
12
8
4
0
15
10
5
0
(a)
NO HARVEST
PREDATORS
ADULT OYSTERS
PREDATORS, 10^7g
ADULT OYSTERS, 10^8g
20
16
12
8
4
0
15
10
5
0
(b)
NO PREDATION
ADULT OYSTERS
ADULT OYSTERS, 10^8g
20
15
10
5
0
YEARS
(c)

of harvest and predation on the adult oyster stock. When oysters were not harvested, oyster biomass increased only slightly, but peak predator biomass increased by 50%. However, when predation was removed, oyster biomass increased by approximately a factor of two, this indicating the dominant effect of predation in controlling oyster stocks.

Figure 40 shows the response of state variables to changes in both river flow volume and river pulse amplitude. There were three types of river flow modifications examined. These included changing the pulse height (cases 2-5), eliminating the pulse (cases 6-8), and eliminating river flow entirely (case 9). Case 1 was the normal condition. Plots of river flow curves are shown at the top of Fig. 40. Notice that adult oyster biomass increased with river flow patterns that had seasonal pulses smaller than the control pulse but that had approximately the same amount of total freshwater input (cases 5 and 6). However, river flows much higher (7) and much lower (cases 9 and 8) than the normal case produced smaller adult oyster stocks. Smaller than normal predator stocks were observed in cases 5, 6, and 7 due to freshwater stress. With no river flow, predator biomass was small because their food source was small. Whenever the juvenile oyster stock and predator stock were above normal, the adult stock was below normal. Model responses for capital, residents, and structure followed the response of adult oysters. When adult oyster biomass

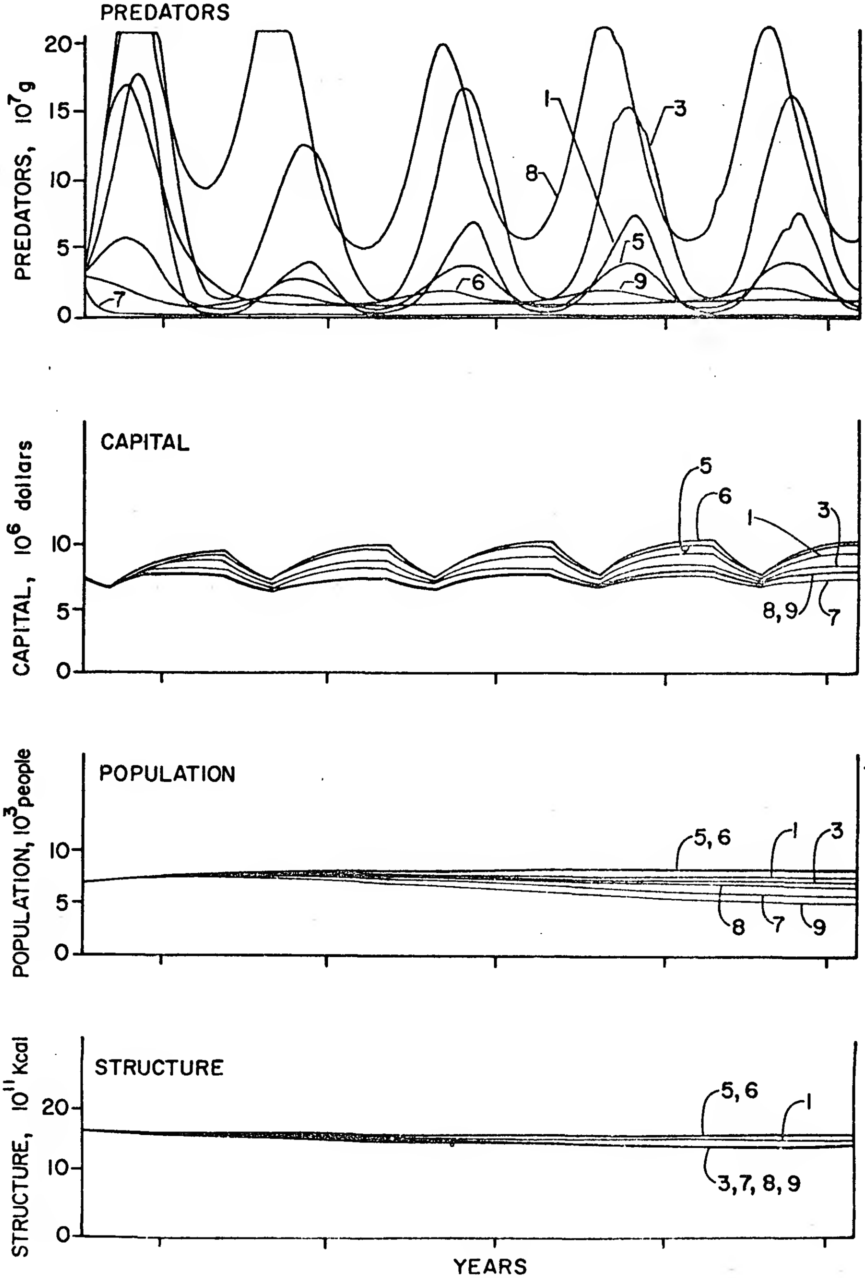
Fig. 40. Simulation results from the model in Fig. 28a with varying flow and amplitude of river pulse. Total yearly river flow volume and pulse height are given below as percentages of average river flow and pulse height. (a) Estuarine storages, (b) Urban storages.

Flow regime	Yearly volume, % of average	Pulse height, % of normal
1	100%	100%
2	86%	70%
3	65%	70%
4	42%	67%
5	105%	38%
6	114%	0.0%
7	169%	0.0%
8	44%	0.0%
9	0.0%	0.0%



RIVER FLOW
RIVER FLOW, $10^9 m^3/20$ days
DETRITUS
DETRITUS, 10^{10}g
1,2,3,5
NITROGEN
NITROGEN, 10^8gN
JUVENILE OYSTERS
JUVENILE OYSTERS, 10^8g
ADULT OYSTERS
ADULT OYSTERS, 10^8g
YEARS

(a)


PREDATORS
PREDATORS, 10^7g
20
15
10
5
0
1
3
8
5
6
9
7
CAPITAL
CAPITAL, 10^6 dollars
10
5
0
5
6
1
3
8, 9
7
POPULATION
POPULATION, 10^3people
10
5
0
5, 6
1
3
8
7
9
STRUCTURE
STRUCTURE, 10^{11} Kcal
20
10
0
5, 6
1
3, 7, 8, 9
YEARS

(b)

increased, each of the above variables increased. In the control case these variables were in steady state. Even slight decreases in oyster biomass caused declines in urban variables.

The response of adult oyster biomass, capital and structure to three different adult oyster recruitment rates is shown in Fig. 41. This modification was examined both because recruitment rates may vary and because earlier simulations indicated that all urban variables were sensitive to changes in the adult oyster stock. In this simulation the price paid for oysters and for goods, fuels and services was inflating at 10% per year. Note that increased recruitment rates increased the seasonal variation in adult oyster biomass while reduced recruitment rates leveled seasonal changes and depressed the standing stock of oysters. Capital followed a similar pattern. Note also that when prices paid for oysters (an income source to the county) and for goods, fuels, and services (a cost to the county) both increased at an annual rate of 10%, county structure went into a gradual decline and was about 30% lower after 10 years. The decline in structure was more rapid when oyster recruitment was at a tenth of the normal rate.

Shown in Fig. 42 are model responses to four different rates of government spending in the county. Increased government spending (cases 4 and 5) increased the capital in the county and caused small increases in structure

Fig. 41. Simulation results from the model in Fig. 28a for the response of (a) adult oysters, (b) capital, and (c) structure to three different rates of adult oyster recruitment. Prices for oyster sales and goods, fuels, and services purchases were both inflating at 10% per year. (1) normal recruitment rate, (2) 5 times normal recruitment rate, (3) one-tenth normal recruitment rate.

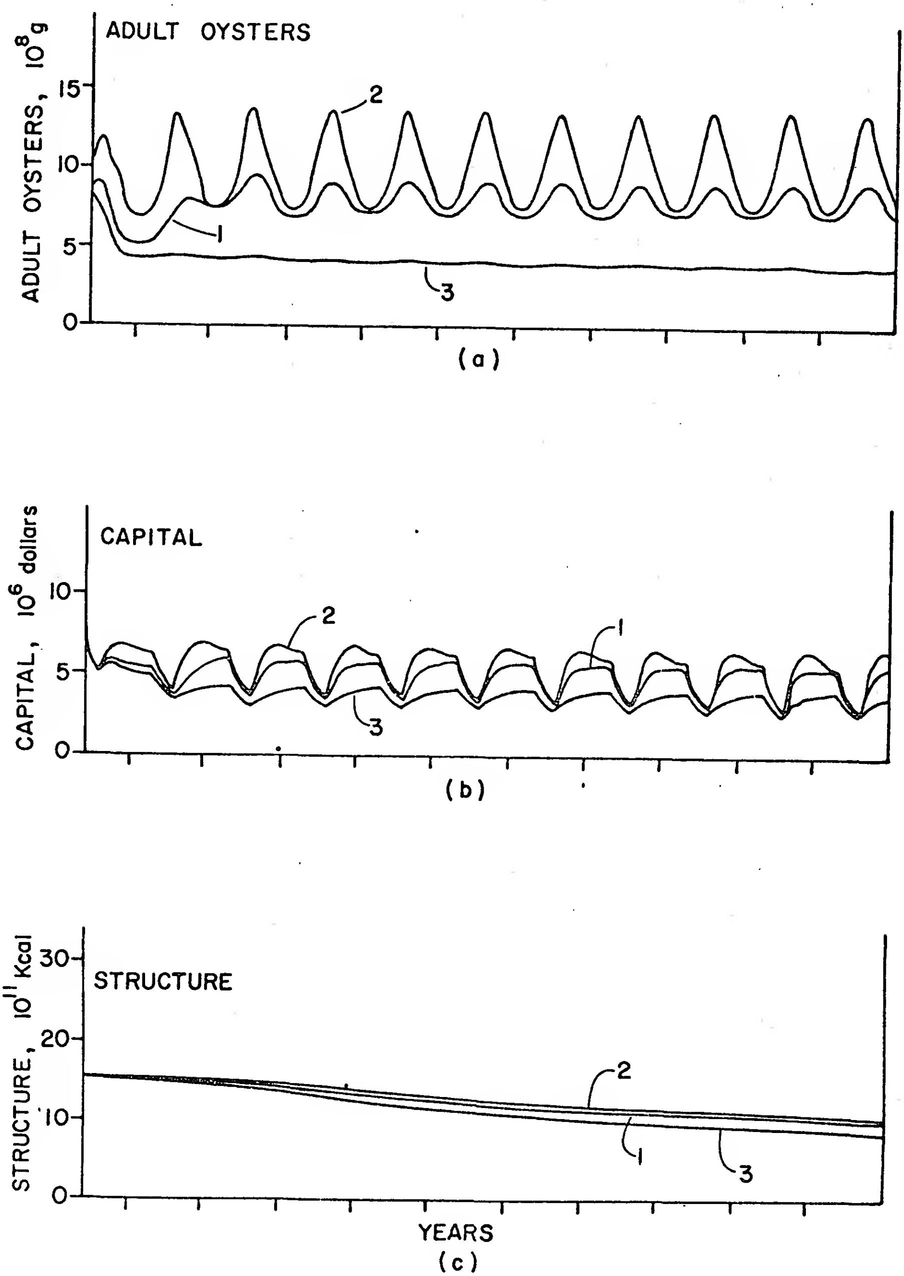
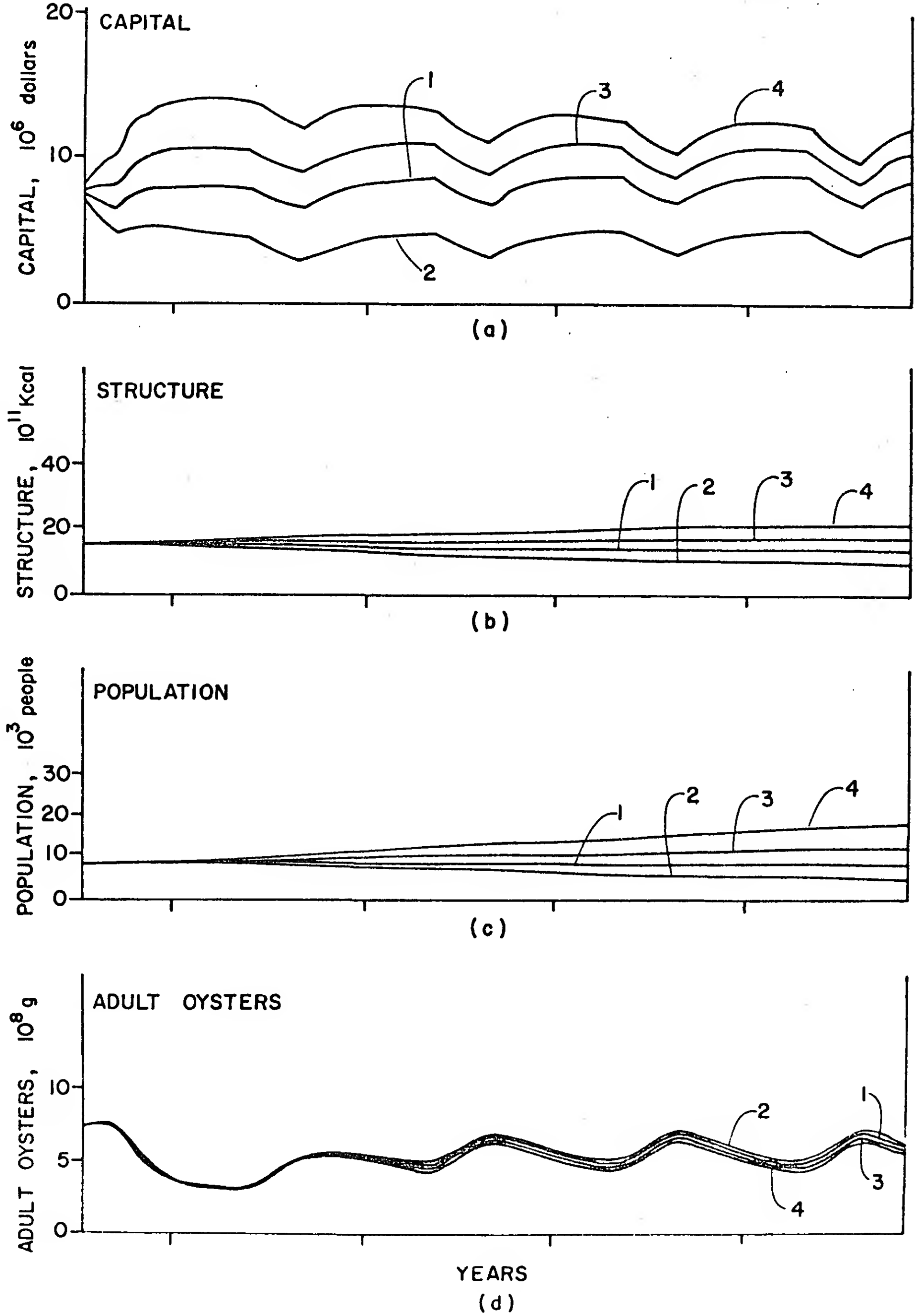

ADULT OYSTERS
ADULT OYSTERS, 10^8g
15
10
5
0
2
1
3
(a)
CAPITAL
CAPITAL, 10^6 dollars
10
5
0
2
1
3
(b)
STRUCTURE
STRUCTURE, 10^{11} Kcal
30
20
10
0
2
1
3
YEARS
(c)

Fig. 42. Simulation results from the model in Fig. 28a for the response of (a) capital, (b) structure, (c) population, and (d) adult oysters to four different rates of government spending in the county. All prices were constant. (1) normal rate of government spending, (2) no government spending, (3) 5 times the normal rate of government spending, (4) 10 times the normal rate of government spending.


CAPITAL
CAPITAL, 10^6 dollars
20
10
0
1
2
3
4
(a)
STRUCTURE
STRUCTURE, 10^{11} Kcal
40
20
0
1
2
3
4
(b)
POPULATION
POPULATION, 10^3 people
30
20
10
0
1
2
3
4
(c)
ADULT OYSTERS
ADULT OYSTERS, 10^8 g
10
5
0
1
2
3
4
YEARS
(d)

and population. In case 5 there was a 25% increase in structure and tripling of population over the 5 years the model was run. Increased government spending resulted in lower adult oyster biomass because of increased harvest effort. The changes, however, were small.

Shown in Fig. 43 are model responses to four different rates of tourist and tourist money inputs. Changes in capital, population and structure were small for an increase to 5 times the normal rate and likewise declines were small when tourist entry was zero. However, exponential growth occurred when tourist and tourist money input was increased by a factor of 10 beyond the control case. Note that in year 5 capital takes on a saw-tooth shape as a result of partial oyster industry closure due to excessive coliform levels. Note also that money earned from oyster sales was only a small part of the capital stock when the partial closure occurred. This simulation assumed that all external urban sources were in infinite supply and that all prices were constant.

Figure 44 shows simulation results for capital, structure, and image under conditions where the rate of investment money entering the county is increased but only for one year. The investment rate was readjusted to its control level after one year. This modification was examined because large, but short-term investments in tourist facilities may occur in the county. Could such an investment

Fig. 43. Simulation results from the model in Fig. 28a for the response of (a) capital, (b) population, and (c) structure to four different rates of tourist and tourist money inflow. All prices were constant. (1) normal rate, (2) no tourist or tourist money inflow, (3) 5 times the normal rate of tourist and tourist money inflow, (4) 10 times the normal rate of tourist and tourist money inflow.

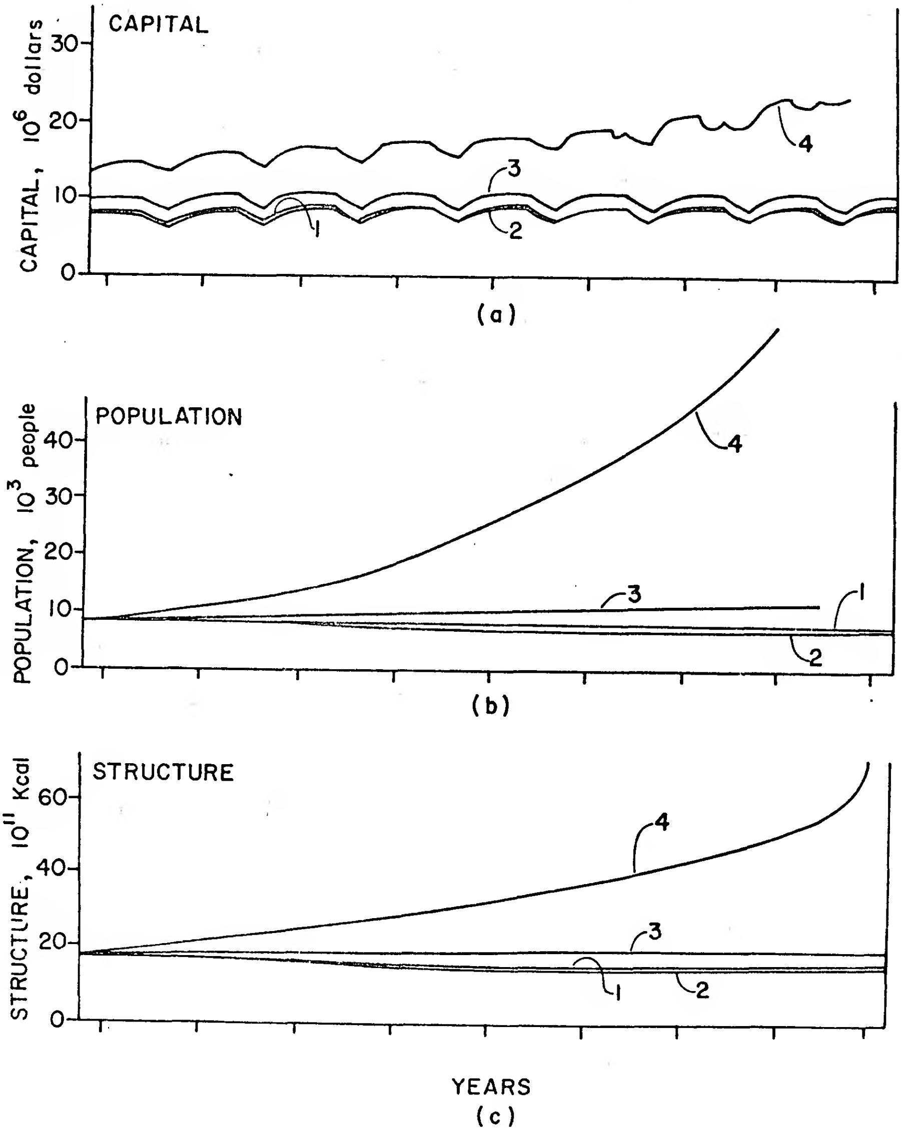
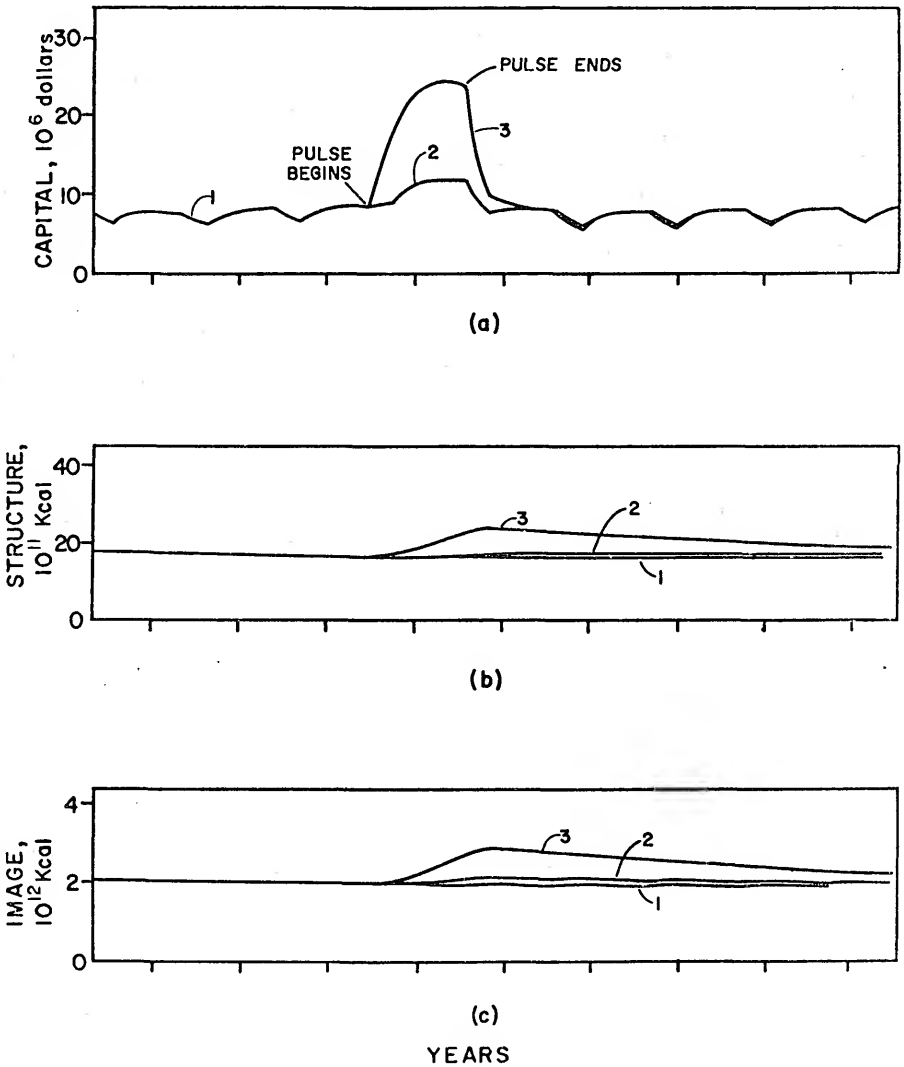

CAPITAL
CAPITAL, 10^6 dollars
0
10
20
30
1
2
3
4
(a)
POPULATION
POPULATION, 10^3 people
0
10
20
30
40
1
2
3
4
(b)
STRUCTURE
STRUCTURE, 10^{11} Kcal
0
20
40
60
1
2
3
4
YEARS
(c)

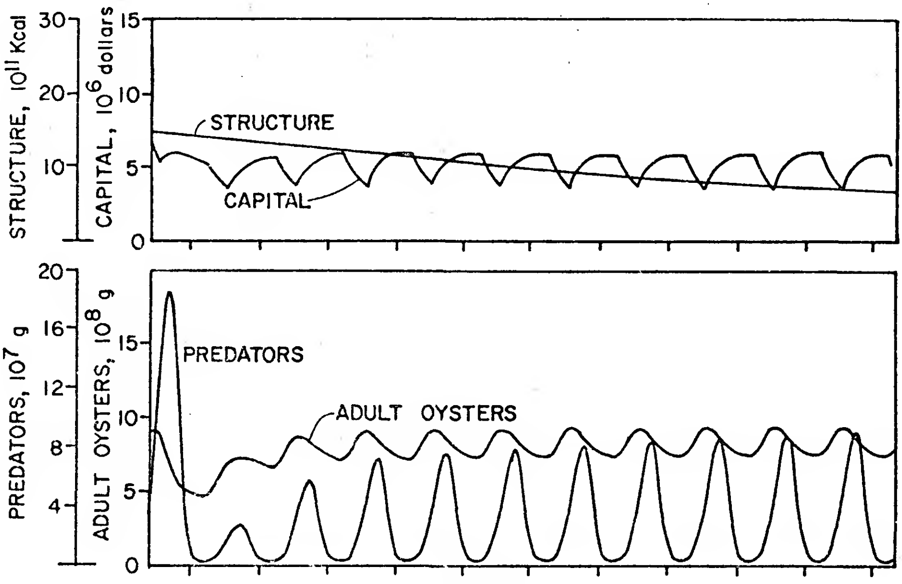
Fig. 44. Simulation results from the model in Fig. 28a for the response of (a) capital, (b) structure, and (c) image to pulses of investment with three different rates of money inflow. Higher investment rates are of one year duration. All prices were constant. (1) normal rate, (2) 10 times the normal rate, (3) 50 times the normal rate.


CAPITAL, 10^6 dollars
30
20
10
0
PULSE ENDS
PULSE BEGINS
1
2
3
(a)
STRUCTURE, 10^{11} Kcal
40
20
0
1
2
3
(b)
IMAGE, 10^{12} Kcal
4
2
0
1
2
3
(c)
YEARS

initiate long-term growth? Note that all variables under both cases (2 and 3) of increased investment responded with increased levels. The response of capital was the sharpest to increased investment both in increasing and returning to control levels. The increases observed for structure and image were smaller, took longer to reach a peak and declined to control conditions more slowly than capital stocks. In this case, large, but short-term injections of capital did not result in permanent growth or permanently higher levels of structure capital or image. If the investment continued and inflation was not severe, growth did occur as shown in Fig. 42.

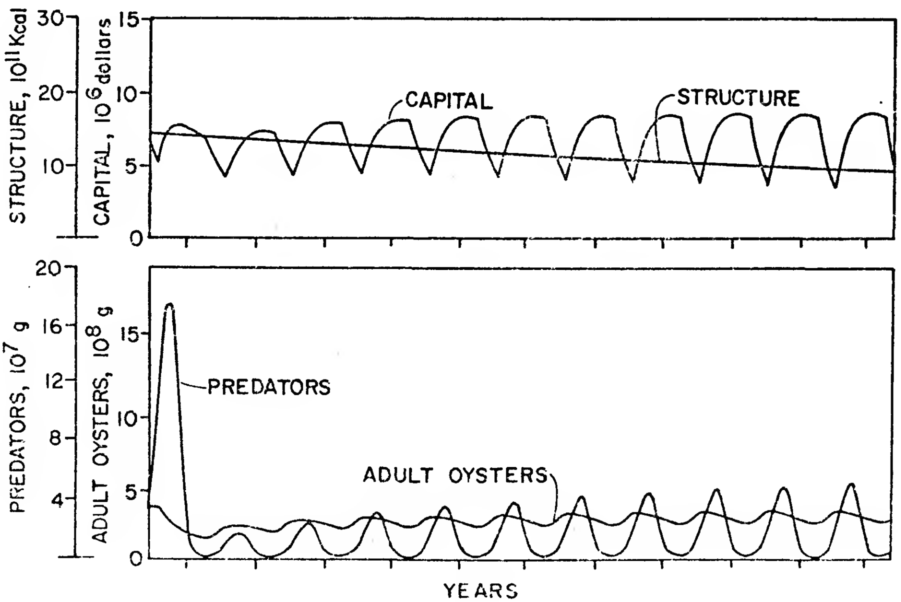
Shown in Fig. 45a are model responses when prices paid for oysters (an income source for the county) and prices paid for goods, fuels, and services (a cost to the county) were both increasing at 10% per year. Notice that over the ten-year period inflation caused a decline in structure of about 50%. Peak levels in capital declined only slightly but the seasonal change in capital increased reaching a minimum lower than observed in the control case. Inflation caused more rapid turnover of capital because both income and expenses increased. Because of this, the capital storage became sensitive to interruptions in money flows such as those associated with the seasonal closure of the oyster industry. The seasonal change in adult oyster biomass increased slightly but the average stock

Fig. 45. Simulation results from the model in Fig. 28a for the response of capital, structure, predators and adult oysters to an inflation rate of 10% per year for both purchases and sales and changes in harvest effort. (a) normal harvest effort, (b) twice normal harvest effort.



STRUCTURE, 10^{11} Kcal
CAPITAL, 10^6 dollars
STRUCTURE
CAPITAL
PREDATORS, 10^7 g
ADULT OYSTERS, 10^8 g
PREDATORS
ADULT OYSTERS
YEARS

(a)



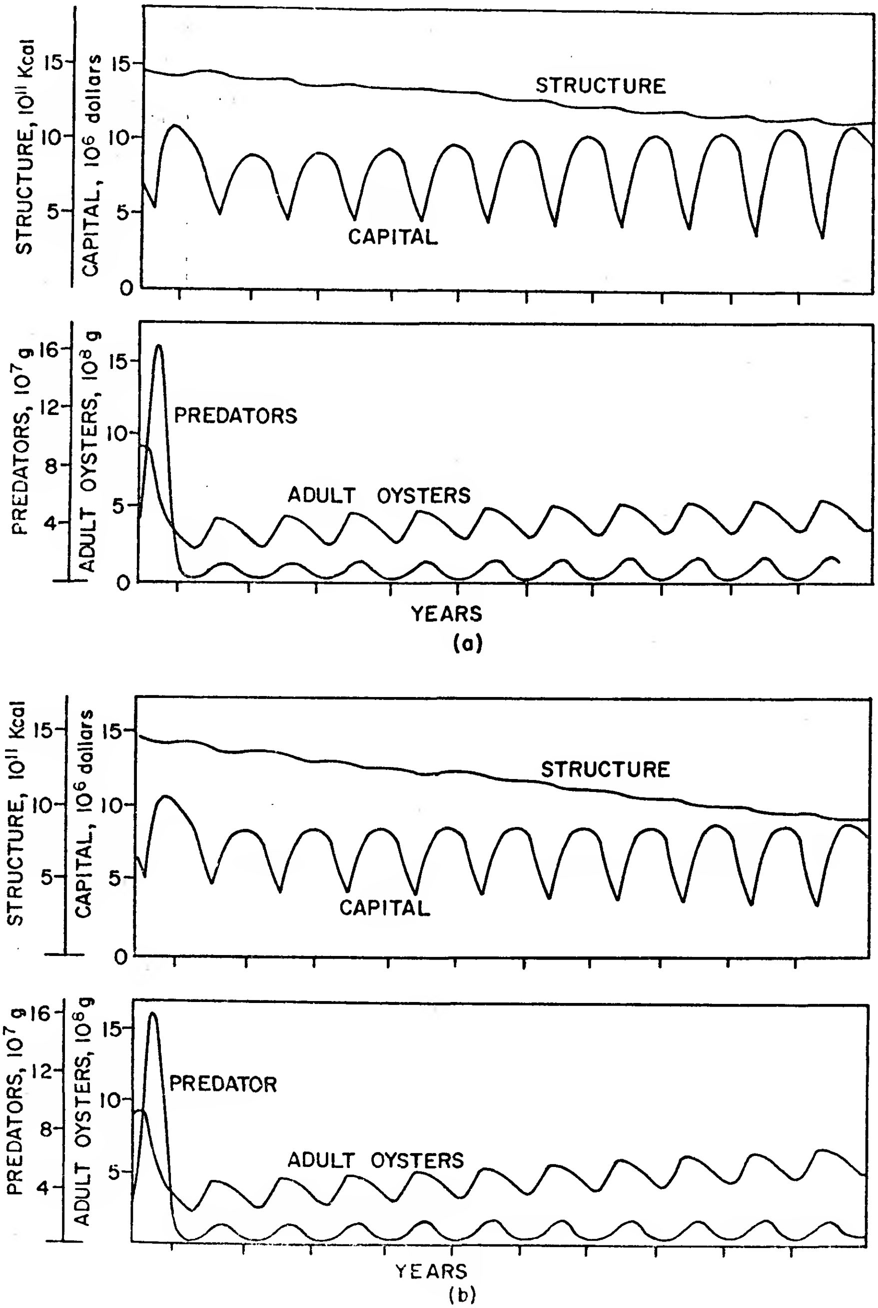
STRUCTURE, 10^{11} Kcal
CAPITAL, 10^6 dollars
CAPITAL
STRUCTURE
PREDATORS, 10^7 g
ADULT OYSTERS, 10^8 g
PREDATORS
ADULT OYSTERS
YEARS

(b)

remained about the same. In Fig. 45b a doubling in harvest effort reduced the decline in structure to 30% over the ten-year period but was not sufficient to maintain original stocks. The peak level of capital was the same as in the control case but the seasonal range in capital increased beyond that observed in Fig. 45a. Both adult oyster and predator biomasses decreased by factors of about two below those recorded for the control case. Adult oyster biomass under conditions of twice the normal harvest effort became a limiting factor. This simulation suggests that attempting to increase work efforts in periods of inflation will not stimulate growth or even maintain past levels if energy sources are limiting (oysters in this case). Such a plan may lead to instability as indicated by the capital storage.

In Fig. 46 harvest effort was increased to four times the control effort. Sales and purchases were both inflating at a rate of 10% per year. Under these conditions structure still showed some decline (20% over ten years). However, the seasonal range in capital reached "boom and bust" proportions and it may be doubtful that an economy could operate under such extreme conditions. Notice that under these extreme harvest conditions predators are virtually eliminated much the same as pests are eliminated in intensive agriculture. Oyster stocks developed a larger seasonal range and slightly higher peak levels but were still the major limiting factor. In Fig. 46b harvest effort

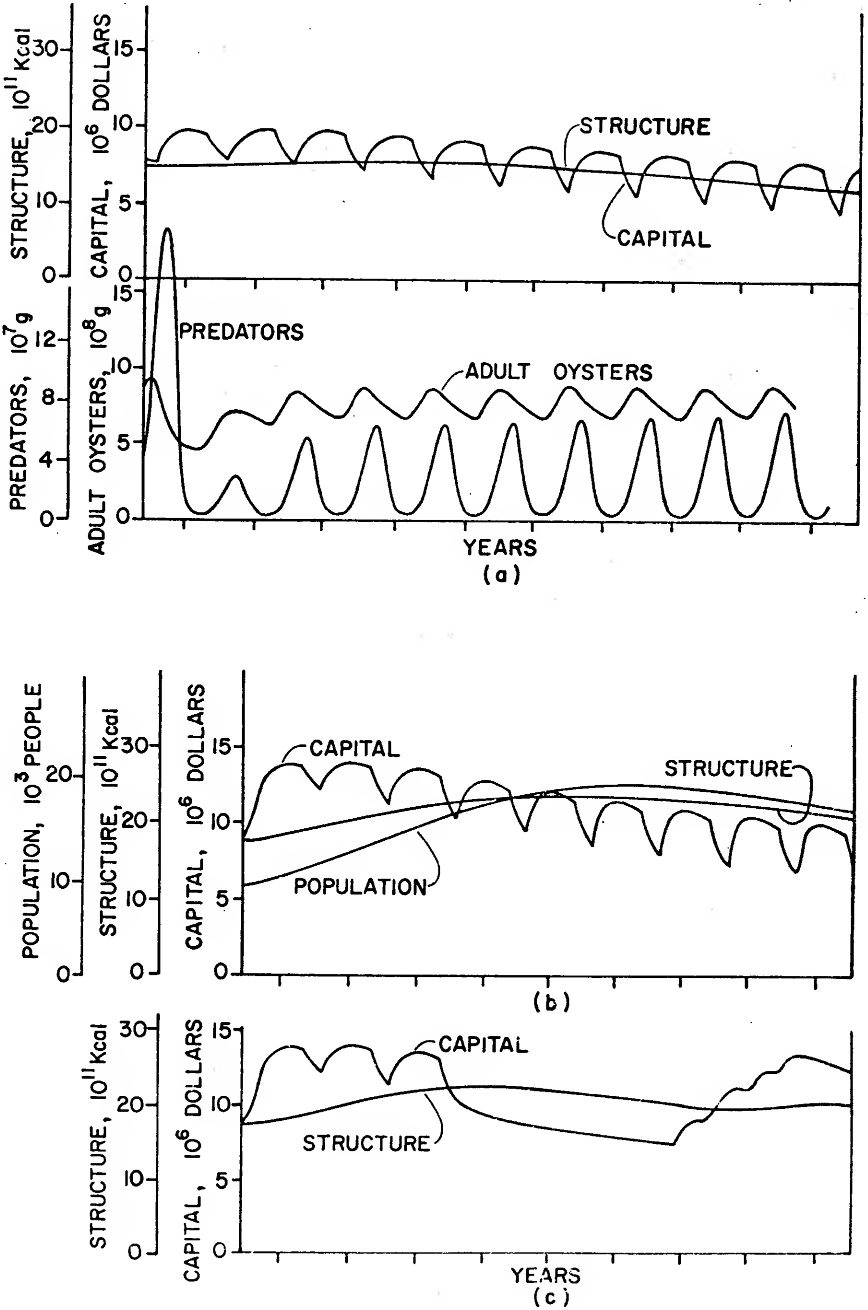
Fig. 46. Simulation results from the model in Fig. 28a for the response of structure, capital, predators, and adult oysters to harvest effort four times greater than in the control condition. In (a) both purchases and sales had inflation rates of 10% per year. In (b) purchases of goods, fuels and services (J_{93}', J_{96}) inflated at 10% per year, while oyster sales inflated at 5% per year.


STRUCTURE, 10^{11} Kcal
CAPITAL, 10^{6} dollars
STRUCTURE
CAPITAL
PREDATORS, 10^{7} g
ADULT OYSTERS, 10^{8} g
PREDATORS
ADULT OYSTERS
YEARS
(a)
STRUCTURE, 10^{11} Kcal
CAPITAL, 10^{6} dollars
STRUCTURE
CAPITAL
PREDATORS, 10^{7} g
ADULT OYSTERS, 10^{8} g
PREDATOR
ADULT OYSTERS
YEARS
(b)

was still at four times the control level but the inflation rate of oyster sales was reduced to 5% per year while the inflation rate of goods, fuels and services remained at 10% per year. In this case the decline in structure was greater than in Fig. 44a but the seasonal range in capital decreased. Adult oyster and predator biomasses were about the same as in Fig. 46a.

Shown in Fig. 47a are simulation results for structure, capital, adult oysters and predators under conditions of 10% per year price inflation for both purchases and sales but with increased investment rates. This modification was examined to estimate the level of investment required to offset the declines caused by inflation. Structure and capital have patterns similar to the control case for the first five years of the simulation and then both show slow declines. The seasonal range in capital was only slightly larger than in the control case. In this simulation an investment rate ten times the control rate offset the declines observed in urban variables in simulation runs with normal investment rates but with similar inflation rates. Figure 47b shows response under the same inflation rate conditions as in 47a but with an investment rate 20 times the control rate. Under these conditions some growth in population and structure was observed during the first six years of the simulation. However, at the end of ten years the seasonal pattern in capital was about the same as in the previous case.

Fig. 47. Simulation results from the model in Fig. 28a for the response of variables to inflation rates of 10% per year for purchases and sales with increased investment. (a) 10 times normal investment rate, (b) 20 times normal investment rate, (c) 20 times normal investment rate with temporary 3-year closure of the oyster fishery.


STRUCTURE, 10^{11} Kcal
CAPITAL, 10^6 DOLLARS
STRUCTURE
CAPITAL
PREDATORS, 10^7g
ADULT OYSTERS, 10^8g
PREDATORS
ADULT OYSTERS
YEARS
POPULATION, 10^3 PEOPLE
STRUCTURE, 10^{11} Kcal
CAPITAL, 10^6 DOLLARS
CAPITAL
STRUCTURE
POPULATION
STRUCTURE, 10^{11} Kcal
CAPITAL, 10^6 DOLLARS
CAPITAL
STRUCTURE
YEARS

(a)

(b)

(c)

Structure and population were higher than in the previous case but both were declining. Figure 47c shows the leveling effect that the loss of the oyster fishery has even when the investment rate was 20 times the control rate. The results suggest that during early stages of growth, the oyster fishery remains a key feature of the local economy. Loss of the fishery, at that stage, could completely reverse trends as shown.

Figure 48 shows the response of capital, structure, population, and image to an inflation rate of 20% per year for both sales and purchases and investment rates of 10, 30, and 50 times the control rate. In all three graphs, inflation leveled growth and caused declines to levels beneath peak values. Declines were sharpest in Fig. 48c because of temporary oyster fishery closure after the third year of the simulation. Closure was caused by coliform levels that exceeded state health limits. In Figs. 48b and 48c harvest effort increased because of increased structure. However, oysters soon became limiting and thus oyster sales did not offset the declines caused by inflating prices.

Given in Fig. 49 are long-term plots of structure, capital, image, population, adult and juvenile oysters, and predators. This simulation was done to show that county growth could be supported by the oyster fishery and that growth dependent on the resource was stable and leveled

Fig. 48. Simulation results from the model in Fig. 28a for the response of variables to an inflation rate of 20% per year for purchases and sales with increased investment inflows. (a) 10 times the normal investment rate, (b) 30 times the normal investment rate, (c) 50 times the normal investment rate.

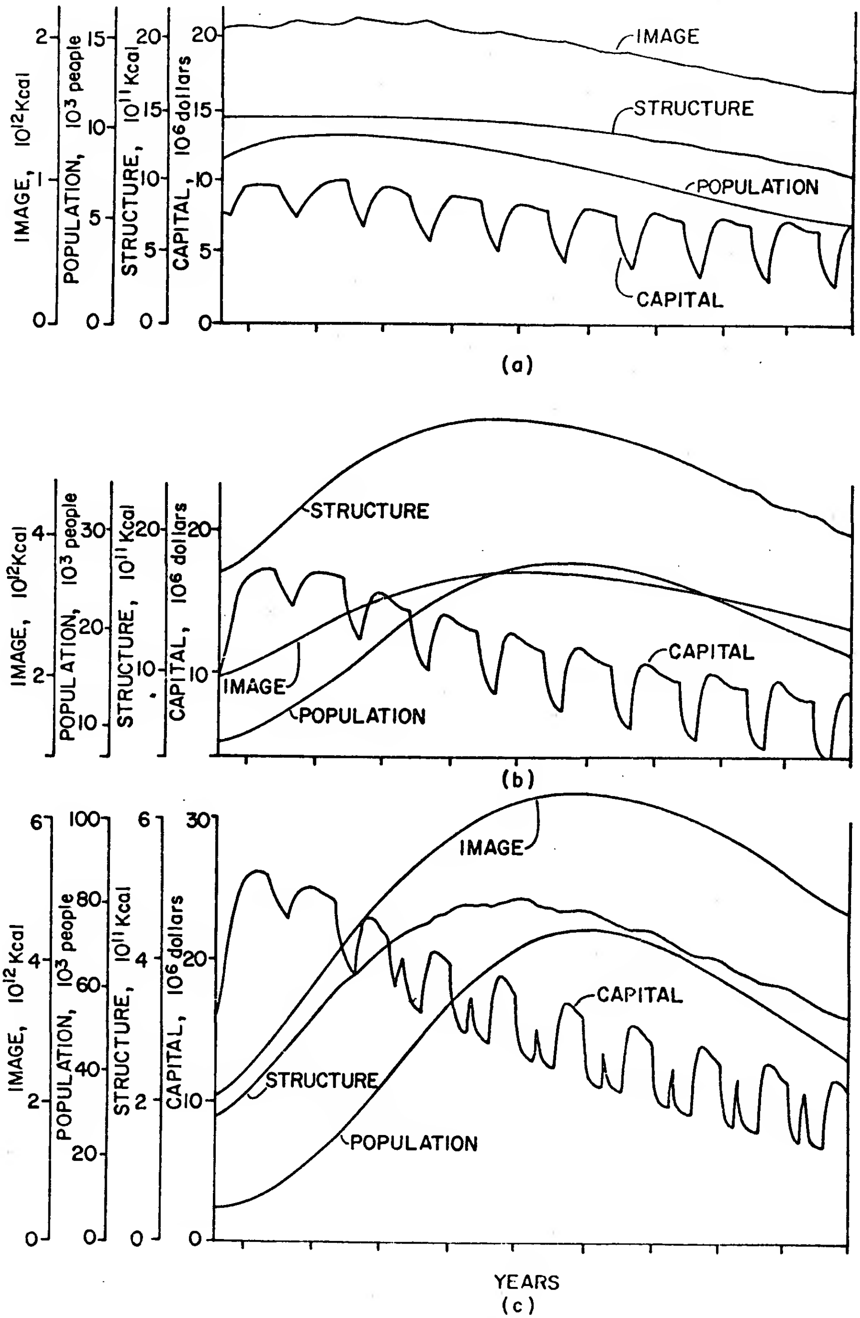
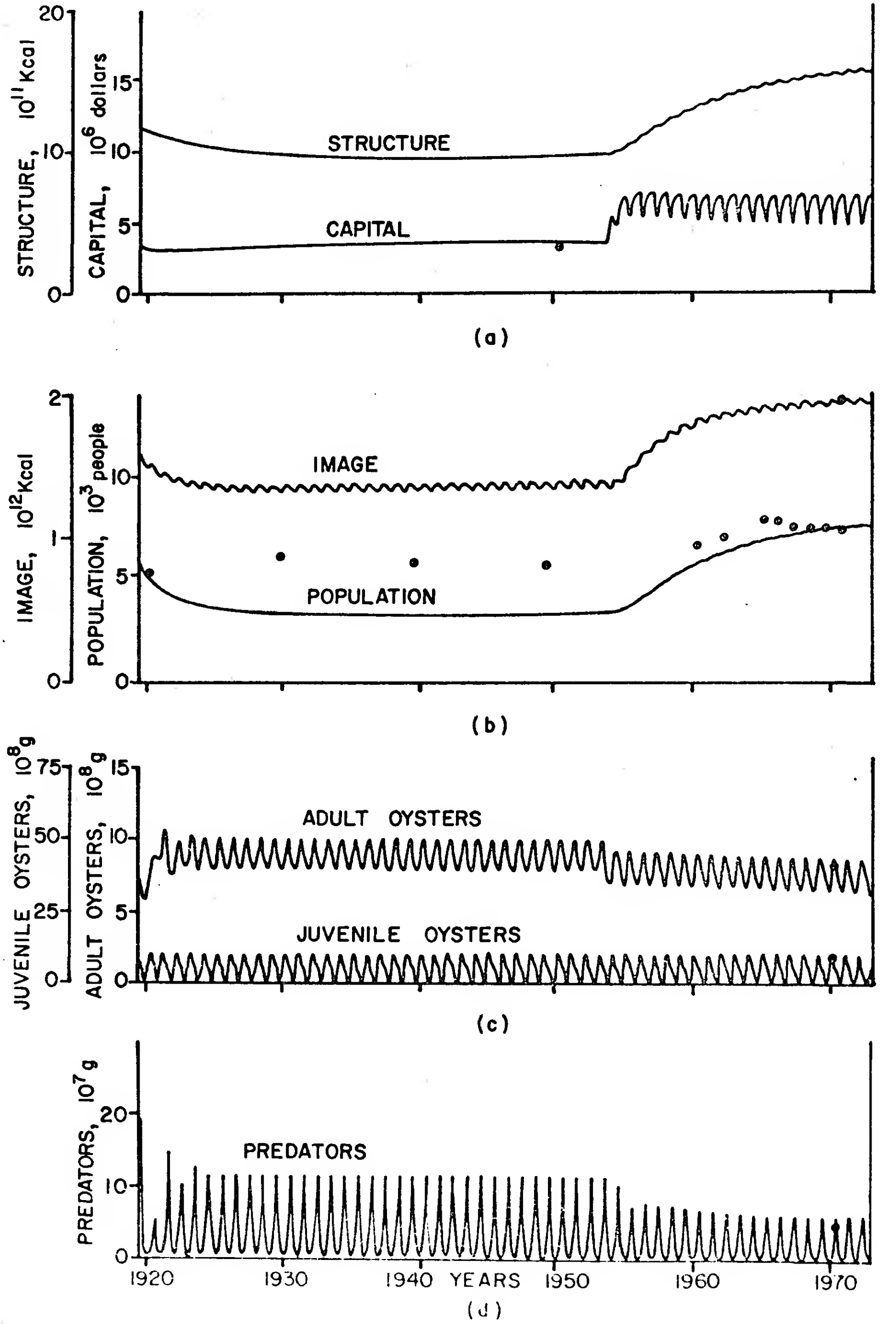

IMAGE, 10^{12} Kcal
POPULATION, 10^3 people
STRUCTURE, 10^{11} Kcal
CAPITAL, 10^6 dollars
IMAGE
STRUCTURE
POPULATION
CAPITAL
(a)
STRUCTURE
IMAGE
POPULATION
CAPITAL
(b)
IMAGE
CAPITAL
STRUCTURE
POPULATION
YEARS
(c)

Fig. 49. Historical plot obtained from simulation of model in Fig. 28a. Initial conditions for adult and juvenile oysters and predators was not readjusted for this run. Oyster harvest was initiated in 1954. Initial conditions for structure, capital, population and image were adjusted downward to levels approximating those in 1920. Historical data are given below and plotted as dots on the diagram. (a) structure and capital, (b) image and population, (c) adult and juvenile oysters, (d) predators

	level	year	reference
structure	15x10	1970	Table D-1
capital	$3x10^{6}$	1950	Franklin Co. Overall Economic Development Program, 1965.
image	2x10	1970	Table D-1
population	———	1920-1970	Fig. 32a
adult oysters	8x10g	1970	Table D-1
juvenile oysters	$9x10^{8}g$	1970	Table D-1
predators	$6x10^{7}g$	1970	Table D-1



STRUCTURE, 10^{11} Kcal
CAPITAL, 10^6 dollars
STRUCTURE
CAPITAL
(a)
IMAGE, 10^{12} Kcal
POPULATION, 10^3 people
IMAGE
POPULATION
(b)
JUVENILE OYSTERS, 10^8g
ADULT OYSTERS, 10^8g
ADULT OYSTERS
JUVENILE OYSTERS
(c)
PREDATORS, 10^7g
PREDATORS
1920
1930
1940 YEARS
1950
1960
1970
(d)

soon after the fishery was established. The oyster fishery, as a major activity in the county, was estimated to have begun in 1954 (Fig. 33). In this simulation prices were held constant. With the beginning of the oyster fishery, all urban variables showed increases and leveling at new but higher steady states. Historical data for urban variables, when available, have been plotted on the diagram.

After the beginning of the oyster fishery the adult oyster stock declined by about 20% due to new harvest losses. There was no noticeable change in juvenile oyster stocks. Both nutrient and detritus levels (not shown in Fig. 49) increased slightly in response to increased population which, in this model, resulted from increased inputs of both coliforms and nitrogen in the bay. Predator stocks decreased slightly. This was due to the new competition that developed for food (oysters) between predators and human harvestors. Unfortunately, historical data for ecological variables in this area are very scarce and it was not possible to plot field data points to support the simulation results obtained for these variables.

Energy Evaluations for Franklin County

Presented in this section are calculations of the energy basis for the primitive and present pattern of activities in Franklin County, the oyster fishery, and a proposed tourist development on St. George Island.

Calculation of Energy Basis

An inventory of energy flows entering the county was drawn in Figs. 50 and 51, tabulated for both the primitive and present patterns (Tables 9 and 10), and converted to fossil fuel equivalent flows using energy quality factors given in Table 1. Depending on the resident energy flows available for matching with fossil fuels (purchased flows) an energy investment ratio was calculated. Additionally, an energy-based carrying capacity was estimated. This was done by multiplying the natural energy flows in fossil fuel equivalents by 2.5 thus giving the amount of purchased energies the county could attract if it were to develop to a level equal to the national average.

Primitive pattern. The energy basis of the primitive pattern prior to the first cutting of local forests in about 1838 was modelled in Fig. 50 and tabulated in Table 9. The pathways shown suggest where input energies are used, but not all internal pathways are shown. Calculations, assumptions and data sources are given in notes to Table 9. In the primitive pattern, energy was contributed from rain (as it amplifies photosynthesis), wind, waves, tide, river head, energy due to the mixing of fresh river water and ocean water, and sunlight as it developes temperature gradients between the ground and above the vegetation and as it drives photosynthesis in the variety of ecosystems covering Franklin County and Apalachicola Bay.

The energy contributions of rain in generating a hydrostatic head and mixing energy are shown on the rain input pathway. The energy generated by rain interacting with other energy sources in photosynthesis is shown in the production symbols.

In the primitive condition, the fossil fuel equivalents of all inflowing energy was 3.86 x 10^{12} $Kcal_{FFE}$/yr. About 60% of the fossil fuel equivalent kilocalories of sunlight was accounted for in the estimated metabolism of natural ecosystems. On an area basis the largest system (coastal plankton) had the smallest metabolism per area. The smallest system (freshwater system) had the highest per area metabolism. Most of the potential work of the physical or chemical type was done via wind, and the free energy of mixing fresh and salt water. Tides, hydrostatic head, waves, and heat gradient declined in magnitude in the order presented. Combined, they represented about 3% of the total inputs.

Present pattern. The diagram with the present pattern of energy inputs is given in Fig. 51 and tabulated in Table 10. Total energy input was greater in the present pattern than in the primitive pattern, totalling 4.58 10^{12} $Kcal_{FFE}$/yr. Man-related additions of fuels, goods, and services were 0.721 x 10^{12} $Kcal_{FFE}$/yr. Natural metabolic work flows decreased slightly because of conversion of swamp-type forests to cleared/planted lands or pine plantations. These new systems may have higher net production

Fig. 50. Primitive pattern of energy inputs available to do work in the Franklin County region. All flows shown on the diagram are in 10^{12} fossil fuel equivalents per year.

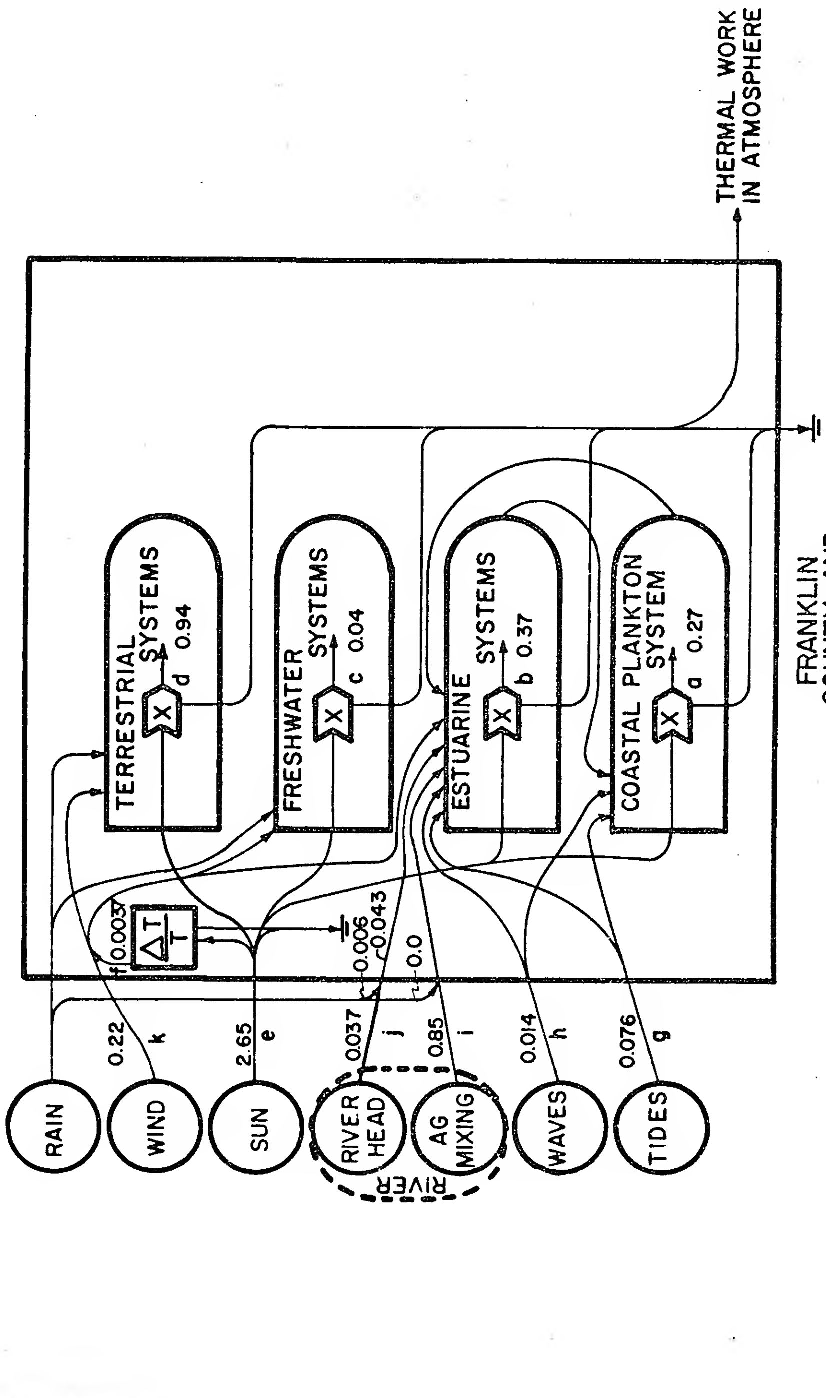

RAIN
WIND
SUN
RIVER HEAD
AG MIXING
RIVER
WAVES
TIDES
0.22
k
2.65
e
0.037
j
0.85
i
0.014
h
0.076
g
f 0.0037
ΔT/T
0.006
0.043
0.0
TERRESTRIAL SYSTEMS
d 0.94
FRESHWATER SYSTEMS
c 0.04
ESTUARINE SYSTEMS
b 0.37
COASTAL PLANKTON SYSTEM
a 0.27
X
FRANKLIN COUNTY AND APALACHICOLA BAY REGION
THERMAL WORK IN ATMOSPHERE

Fig. 51. Present (1973) pattern of energy inputs available to do work in the Franklin County region. All flows shown on the diagram are in 10^{12} fossil fuel equivalents per year.

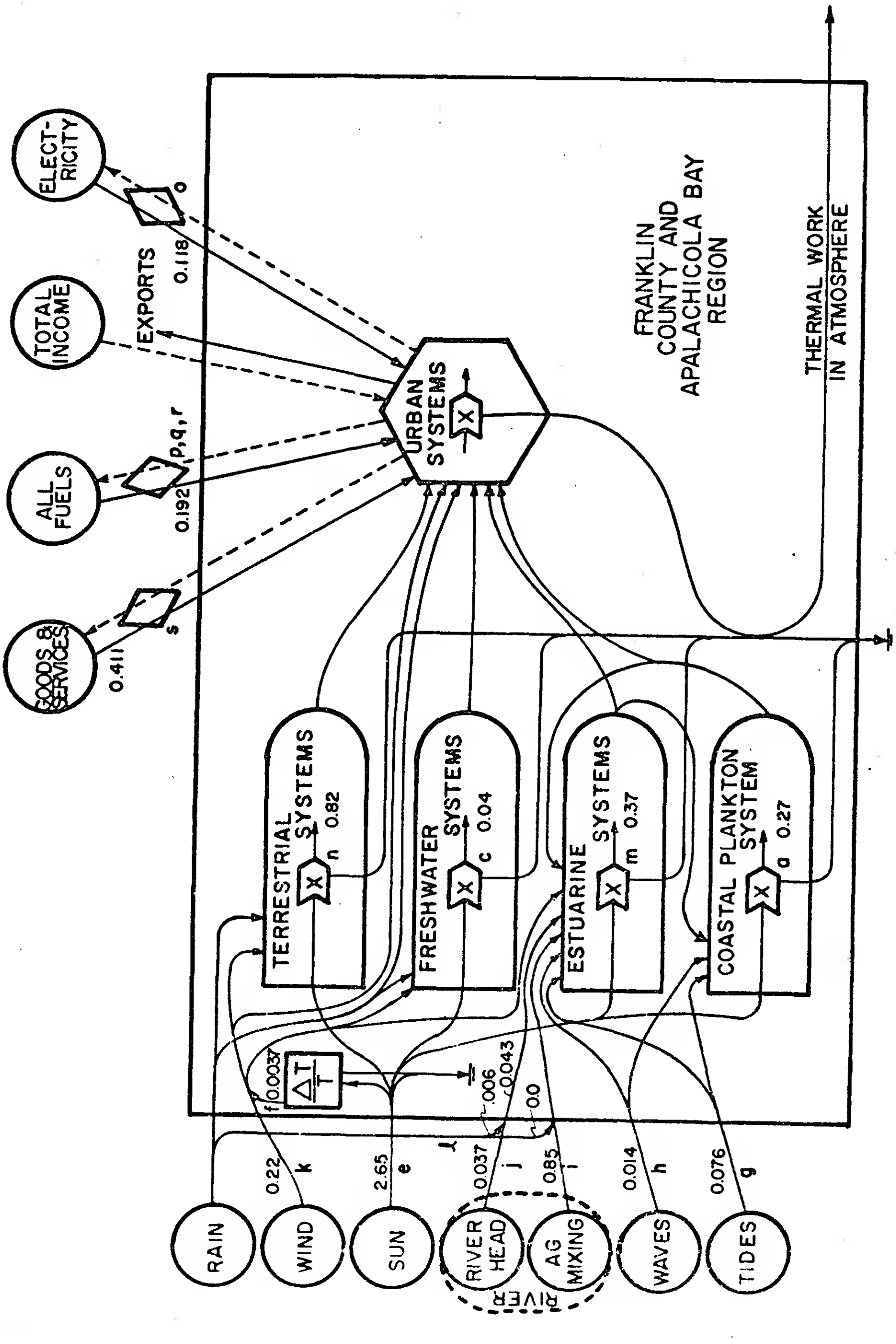

ELECT-RICITY
TOTAL INCOME
ALL FUELS
GOODS & SERVICES
0.411
s
0.192
p,q,r
EXPORTS
0.118
o
URBAN SYSTEMS
X
FRANKLIN COUNTY AND APALACHICOLA BAY REGION
THERMAL WORK IN ATMOSPHERE
TERRESTRIAL SYSTEMS
n 0.82
FRESHWATER SYSTEMS
c 0.04
ESTUARINE SYSTEMS
m 0.37
COASTAL PLANKTON SYSTEM
a 0.27
ΔT/T
f 0.0037
.006
0.043
0.0
RAIN
WIND
SUN
RIVER HEAD
AG MIXING
RIVER
WAVES
TIDES
0.22 k
2.65 e
l
0.037 j
0.85 i
0.014 h
0.076 g

Table 9

Energy flow table for the primitive pattern in the Franklin County region.

Pathway on Fig. 50	Name of Flow	Area of System, Acres	Annual Work Per Unit Area, 10^7/Kcal/acre/yr	Total Annual Work, 10^{12}Kcal/area/yr	Energy Quality Factor (See Table 1)	Annual Work in Fossil Fuel Equivalents $10^{12}Kcal_{FFE}/yr$
Contributing Natural Energy Flows						
e	Total Sunlight	897,154	591.0[e]	5300.00	2000.0	2.650
f	Heat Gradient	897,154	4.10[f]	36.78	10,000.0	0.0037
g	Tides in Estuary	127,020	0.15[g]	0.19	2.5	0.076
h	Waves on Shoreline	—	0.061[h]	0.068	5.0	0.014
	River Water					
i	Mixing Energy (ΔG)	—	—	0.256[i]	0.3	0.85
j	Hydrostatic Head	—	—	0.023[j]	0.63	0.037
k	Wind	897,154	—	1.87[k]	7.7	0.22

Table 9 - continued

Pathway on Fig. 50	Name of Flow	Area of System, Acres	Annual Work Per Unit Area 10^7/Kcal/acre/yr	Total Annual Work, 10^{12}Kcal/area/yr	Energy Quality Factor (See Table 1)	Annual Work in Fossil Fuel Equivalents $10^{12}Kcal_{FFE}/yr$
1	Rain					
	Mixing energy	—	—	~ 0[1]	0.3	$\sim$0.0
	Hydrostatic Head	—	—	0.004[1]	0.63	0.006
Metabolic Energy Flows in Natural Systems (Includes main inputs of sun and rain)						
a	Coastal Plankton System	406,400	1.33[a]	5.41	20	0.27
b	Estuarine Systems	150,742	4.85[b]	7.31	20	0.37
c	Freshwater Systems	7,428	11.20[c]	0.83	20	0.04
d	Terrestrial Systems	332,584	5.68[d]	18.89	20	0.94
				32.44		1.62

Table 10

Energy flow table for the present pattern in the Franklin County region.

Pathway on Fig. 51	Name of Flow	Area of System, Acres	Annual Work Per Unit Area, 10^7/Kcal/acre/yr	Total Annual Work, 10^{12}Kcal/area/yr	Energy Quality Factor (See Table 1)	Annual Work in Fossil Fuel Equivalents $10^{12}Kcal_{FFE}$/yr
Contributing Natural Energy Flows						
e	Total Sunlight	897,154	591.0[e]	5300.0	2000.0	2.650
f	Heat Gradient	897,154	4.10[f]	36.780	10,000.0	0.0037
g	Tides in Estuary	127,020	0.15[g]	0.190	2.5	0.076
h	Waves on Shoreline	—	0.061[h]	0.068	5.0	0.014
	River Water					
i	Mixing Energy (ΔG)	—	—	0.256[i]	0.3	0.85
j	Hydrostatic Head	—	—	0.023[j]	0.63	0.037
k	Wind	897,154	—	1.87[k]	7.7	0.22
l	Rain					

Table 10 - continued

Pathway on Fig. 51	Name of Flow	Area of System, Acres	Annual Work Per Unit Area, 10^7/Kcal/acre/yr	Total Annual Work, 10^{12}Kcal/area/yr	Energy Quality Factor (See Table 1)	Annual Work in Fossil Fuel Equivalents $10^{12}Kcal_{FFE}/yr$
	Mixing Energy	—	—	~0.0	0.3	~0.0
	Hydro-static Head	—	—	0.004	0.63	0.006
Metabolic Energy Flows in Natural Systems						
a	Coastal Plankton System	406,400	1.33[a]	5.41	20	0.27
m	Estuarine Systems	149,853	4.90[m]	7.34	20	0.37
c	Freshwater Systems	7,428	11.20[c]	0.83	20	0.04
n	Terrestrial Systems	338,451	4.83[n]	16.35	20	0.82
Energy Flows Associated with Urban Systems						
o	Electricity	—	—	0.033[o]	0.28	0.118
	Fuels					

Table 10 - continued

Pathway on Fig. 51	Name of Flow	Area of System, Acres	Annual Work Per Unit Area, 10^7/Kcal/acre/yr	Total Annual Work, 10^{12}Kcal/area/yr	Energy Quality Factor (See Table 1)	Annual Work in Fossil Fuel Equivalents $10^{12}Kcal_{FFE}/yr$
p	Gasoline	—	—	0.168[p]	1.0	0.168
q	Kerosene	—	—	0.006[q]	1.0	0.006
r	Bottled Gas	—	—	0.018[r]	1.0	0.018
s	Goods and Services	—	—	0.411[s]	1.0	0.411
						0.721

Notes to Tables 9 and 10

[a]Estimated metabolism of coastal plankton system. Average metabolism was estimated to be 9 $Kcal/m^2/day$ (McKellar, 1975).

$$(9\ Kcal/m^2/day)(365\ days/yr)(4047\ m^2/acre) =$$

$$1.33 \times 10^7\ Kcal/acre/yr$$

[b]Area weighted metabolism estimate for all estuarine systems. Included here are the oligohaline, grass flat, salt march, oyster reef, sand bar, medium salinity plankton, high energy beach, high velocity channels, high energy beach, and coastal dune systems. For metabolism estimates see Young (1974), Lehman (1974), McFarland (1963), and Table 4.

[c]Estimated metabolism for all freshwater systems. Included here are the turbid peidmont river, shallow woodland pond, and blackwater river systems. Average metabolism was estimated to be 76 $Kcal/m^2/day$ (Odum, 1956).

$$(76\ Kcal/m^2/day)(365\ days/yr)(4047\ m^2/acres) =$$

$$11.2 \times 10^7\ Kcal/acre/yr$$

[d]Area weighted metabolism estimate for all terrestrial systems. Included here are the pine scrub, high pineland, pine-palmetto flatweeds, bay swamp, river swamp, and freshwater marsh systems. For metabolism estimates see Odum *et al*. (1972), Ovington (1961), Woodwell and Whittaker (1968), Whittaker and Woodwell (1969), Westlake (1963), Bayley and Odum (1973), Bayley and Burnes (1974), Cowles (1974), and Young (1974).

[e]Total sunlight was estimated by multiplying average yearly sunlight by total area. Average sunlight input was estimated to be $4 \times 10^3\ Kcal/m^2/day$ (Odum, 1971).

$$(4.0 \times 10^3\ Kcal/m^2/day)(8.97 \times 10^5\ acres)$$

$$(4.047 \times 10^3\ m^2/acre)(365\ days/yr) =$$

$$5.30 \times 10^{15}\ Kcal/yr$$

[f] Local heat gradient work estimated by multiplying average sunlight input per area per year times Carnot ratio (ΔT = 2°C) times the total study area (Odum, 1974b).

$$(4000\ \text{Kcal/m}^2\text{/day})\left(\frac{2}{288.5}\right)(365\ \text{days/yr})(4047\ \text{m}^2\text{acre})$$

$$\times\ (897{,}154\ \text{acres}) = 36.78 \times 10^{12}\ \text{Kcal/yr}$$

[g] Potential energy of tides calculated by using the following formula. Average tidal amplitude was from Gorsline (1963).

$$W = 1/2\rho g h^2 A$$

Where ρ = density (1.0 g/cm^3)
g = gravitational acceleration (980 cm/sec^2)
h = tidal amplitude (46 cm)
A = unit surface area (1.0 m^2)

P.E. Tides=

$$(1/2)(1.0\ \text{g/cm}^3)(980\ \text{cm/sec}^2)(46\ \text{cm}^2)(10^4\ \text{cm}^2/\text{m}^2)\ \times$$

$$(2\ \text{tides/day})(2\ \text{cycles/tide})(2.4 \times 10^{-11}\ \text{Kcal/erg})\ \times$$

$$(365\ \text{days/yr})(4047\ \text{m}^2\text{/acre})(127{,}020\ \text{acres}) =$$

$$0.190 \times 10^{12}\ \text{Kcal/yr}$$

[h] Wave energy absorbed on shoreline was calculated using the following formula. Average wave height from Walton (1974).

$$\text{Power/Length of Shoreline} = 1/8\rho g^{3/2} H^{5/2}$$

Where ρ = density (1.0 g/cm^3)
g = gravitational acceleration (980 cm/sec^2)
h = average wave height (21.3 cm)

Wave Energy/yr =

$$(1/8)(1.0\ \text{g/cm}^3)(980\ \text{cm/sec}^2)^{3/2}(21.3)^{5/2}$$

$$(2.4 \times 10^{-11}\ \text{Kcal/erg})(3.15 \times 10^7\ \text{sec/yr})(100\ \text{cm/m})$$

$$(11.17 \times 10^4\ \text{meters of beach}) = 6.77 \times 10^{10}\ \text{Kcal/yr}$$

[i]Chemical free energy released due to mixing of solutions with different concentration was calculated using the following formula.

$$\Delta G \text{ cal/g solute} = nRT \ln \frac{C_2}{C_1}$$

Where n = number of moles (35 g/mole)

R = gas constant (1.99)

T = temperature (300°K)

C_1 = concentration of solute in river water (35,000 ppm)

C_2 = concentration of solute in ocean water (120 ppm)

$$\Delta G = (1/35)(1.99)(300)(2.3 \log \frac{120}{35000})$$

$$= -96.7\text{g cal/g solute}$$

$$\text{Kcal/yr} = (96.7\text{g cal/g})(120 \text{ g/m}^3)(2.21 \times 10^{10} \text{m3/yr})$$

$$\times (1 \text{ Kcal/1000g cal}) = 25.6 \times 10^{10} \text{ Kcal/yr}$$

[j]Potential energy of river head was calculated using the formula given below (Healy, 1974).

$$PE/yr = \rho ghd$$

Where ρ = density (1.0 g/cm^3)

g = gravitational acceleration (980 cm/sec^2)

h = river elevation change in Franklin County (45 cm)

d = yearly river discharge (2.21 x 10^{16} cm^3/yr)

$$PE/yr = (1.0 \text{ g/cm}^3)(980 \text{ cm/sec}^2)(45 \text{ cm}) \times$$

$$(2.21 \times 10^{16} \text{ cm}^3\text{/yr})(2.4 \times 10^{-11} \text{ Kcal/erg})$$

$$= 2.34 \times 10^{10} \text{ Kcal/yr}$$

[k]Yearly work done by winds was based on the kinetic energy of wind. An eddy diffusion coefficient of 10,000 cm^2/sec was used. Average wind velocity was 8.7 mph(Florida Statistical Abstract, 1972). This wind speed was assumed to occur 10^4 cm above ground.

$$\text{Work/yr} = \frac{1.2 \times 10^{-3}\ g/cm^3)(371\ cm/sec)^2(1 \times 10^4\ cm^2/sec) \times (2.39 \times 10^{-11}\ Kcal/erg)(3.15 \times 10^7\ sec/yr)(3 \times 10^{13}\ cm^2)}{(2)(1 \times 10^4\ cm)}$$

$$= 1.87 \times 10^{12}\ Kcal/yr$$

[l]Annual work done by rain was divided into three categories. The work done in photosynthesis was accounted for in the terrestrial and freshwater metabolism measurements and was not recounted here. The potential energy of rainwater relative to river water due to the concentration difference (mixing energy) was calculated using runoff water but not water lost due to evaporation or transpiration. Potential energy of water due to its position relative to sea level was calculated using the volume of runoff water.

(a) Mixing energy

$$\Delta G\ \text{g cal/g solute} = nRT\ln\frac{C_2}{C_1}$$

where n = number of moles (35 g/mole)
R = gas constant (1.99 g cal/deg-mole)
T = temperature (300°K)
C_1 = concentration of solute in river water (120 ppm)
C_2 = concentration of solute in rainwater (1.2 ppm)

$$\Delta G = (\frac{1}{35}\ g/mole)(1.99\ g\ cal/deg\text{-}mole)(300°K)(2.3\ \log\frac{1.2}{120})$$

$$\Delta G = -78\ g\ cal/g\ solute$$

Runoff flow estimated to be 43 cm/yr (Mann, 1975)

$$\text{Total flow/yr} = (43\ cm/yr)(\text{total area})$$

$$= (43\ cm/yr)(13.8 \times 10^{12}\ cm^2/county)$$

$$= 5.93 \times 10^{14}\ cm^3/\text{county area/yr}$$

$$= 5.93 \times 10^8 m^3/\text{county area/yr}$$

$$\text{Kcal/yr} = (78\ g\ cal/g\ solute)(1.2\ g/m^3)(5.93 \times 10^8 m^3/yr)$$

$$= 5.55 \times 10^{10}\ cal/yr$$

$$= 5.58 \times 10^7\ Kcal/yr$$

(b) Hydrostatic head

$$PE/yr = 1/2\ \rho g h d$$

where ρ = density (1.0 g/cm^3)

g = gravitational acceleration (980 cm/sec^2)

h = average elevation above sea level (610 cm)

d = yearly runoff flow (5.93×10^{14} cm^3/yr)

$$PE/yr = (1/2)(1.0\ g/cm^3)(980\ cm/sec^2)(610\ cm) \times$$

$$(5.93 \times 10^{14}\ cm^3/yr)(2.4 \times 10^{-11}\ Kcal/erg) = 4.26 \times 10^9\ Kcal/yr$$

[m]Estuarine metabolism was calculated for the present pattern as in (b) but with area weighted adjustments for metabolism of boat basins and harbors and navigation channels. There were also some area adjustments in other estuarine ecosystems (Table 3). Estimated metabolism increased only slightly.

[n]Terrestrial metabolism was calculated for the present pattern as in (d) but with area weighted adjustments for the metabolism of planted lands and pine forests. Estimated metabolism decreased slightly compared to the original pattern.

[o]Total electricity use was obtained from Florida Power Corporation (Crosthwaite, 1974).

$$(3.8 \times 10^7\ KWH/yr)(860.5\ Kcal/KWH) = 3.27 \times 10^{10}\ Kcal/yr$$

Kilocalories of electrical energy were converted to $Kcal_{FFE}$ by dividing by 0.28 (Table 1). Cost of electric power was $\$9.26 \times 10^5$/yr.

[p]Gasoline use was obtained from the Department of Revenue, Tallahassee, Florida (Thomas, 1973). Cost of gasoline was $\$1.82 \times 10^6$/yr.

$$(5.2 \times 10^6\ gal/yr)(127{,}654\ BTUs/gal)(0.253\ Kcal/BTU) = 1.68 \times 10^{11}\ Kcal/yr.$$

Kilocalories of gasoline, bottled gas, and kerosene were assumed to be $Kcal_{FFE}$ and needed no further conversions.

[q]Kerosene use was obtained from The Revenue Office, Department of Agriculture, Tallahassee, Florida (Rutledge, 1973). Cost of kerosene was $\$2.4 \times 10^4$/yr.

$(1.61 \times 10^5$ gal/yr)(141,785 BTUs/gal)(0.253 Kcal/BTU)

$= 5.7800^9$ Kcal/yr

[r]Bottled gas use was estimated by Stapleton (1973). Cost of bottled gas was estimated to be $\$2.33 \times 10^5$/yr.

$(7.5 \times 10^5$ gal/yr)(4.24 lbs/gal)$(2.17 \times 10^4$ BTU/16) x

(0.253 Kcal/BTU) $= 1.75 \times 10^{10}$ Kcal/yr

[s]The energy flow associated with goods and services was estimated by multiplying the total dollar outflow times 25,000 Kcal/dollar (Table 1).

(Total Dollar Outflow)(25,000 Kcal/dollar)

$(\$16.44 \times 10^6$/yr)(25,000 Kcal/dollar) $= 4.11 \times 10^{11}$ Kcal_{FFE}/yr.

[t]Energy investment ratio for present pattern in Franklin County.

I = Outside energy being invested (summation of all purchased energy inputs)

R = Energy flow generated from resident system (summation of all natural energy inputs)

$$\text{Investment Ratio} = \frac{0.721 \times 10^{12}\ \text{Kcal}_{FFE}/\text{yr}}{3.86 \times 10^{12}\ \text{Kcal}_{FFe}/\text{yr}} = 0.19$$

[u]Preliminary carrying capacity for present pattern in Franklin County.

$$\text{Carrying Capacity} = (2.5)(\text{natural energy input})$$
$$= (2.5)(3.86 \times 10^{12}\ \text{Kcal}_{FFE}/\text{yr})$$
$$= 9.65 \times 10^{12}\ \text{Kcal}_{FFE}/\text{yr}$$

than the swamp types, but their gross production is less (see "m" in Notes to Table 9). Other natural work flows remained as in the primitive condition.

The energy investment ratio for the present pattern was calculated to be 0.19 for the Franklin County region (Table 10, Note "t"). High quality energy (purchased goods, fuels, and services) that could be attracted to Franklin County (carrying capacity) to bring activity to the national average was calculated to be 9.65×10^{12} $Kcal_{FFE}/yr$ or some 13 times the present input (Table 10, Note "u").

Oyster Fishery

An energy basis calculation of the oyster industry was made to evaluate the combination of natural (not paid for) and purchased energies that act in support of the industry. The calculation also suggested the amount of fossil fuel-based activities elsewhere that may be matched by natural energies originating in Franklin County. Simplified energy circuit diagrams of the Franklin County oyster fishery are given in Fig. 52. Figure 52a was evaluated in energy flows measured in heat equivalents. Figure 52b was evaluated in fossil fuel equivalents to show the ability of individual flows to do work and amplify low-quality energy flows. Notes follow the figures with calculations and references.

In each figure energies are shown entering the estuary where they interact in the production of oysters and other products. Energies associated with the cultch planting program and sewage (nitrogen) are shown as additional work subsidizing estuarine production. The model of oyster harvest is shown as the product of the oyster industry and estuarine oyster stocks. Money is received for the oyster harvest and spent for goods, fuels and services for the industry. Once the oyster harvest leaves the county (indicated by the larger rectangle surrounding the estuary and oyster fishery components), additional value is added to the harvest before it reaches final retail sales and consumption.

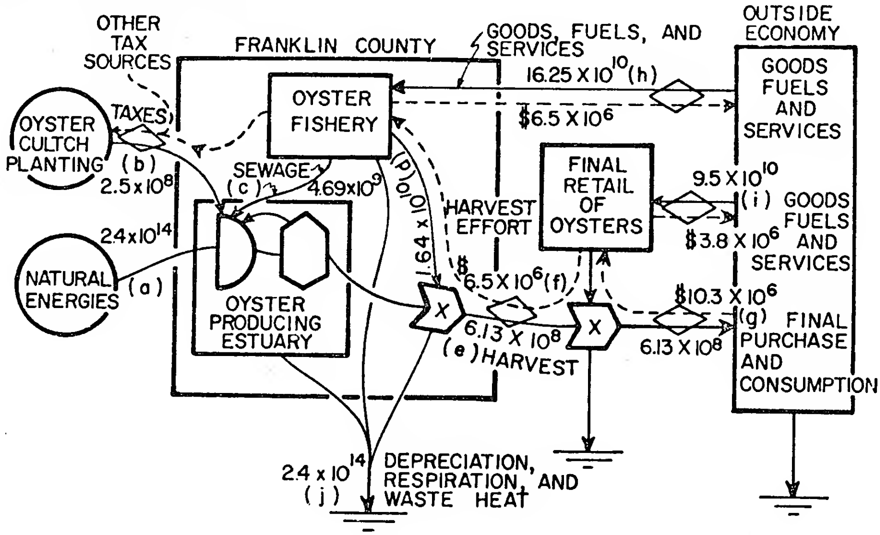
In Fig. 52b inputs to the estuary are dominated by the natural energies (1.2×10^{11} $Kcal_{FFE}/yr$). The fossil fuel equivalents provided by the cultch program and sewage effluent are quite small compared to the natural sources. In the oyster fishery, approximately 1.2×10^{11} $Kcal_{FFE}/yr$ of natural work (h) interact with 1.68×10^{10} $Kcal_{FFE}/yr$ of high-quality energies (l, m, and n). In the process about 6.13×10^{8} heat kilocalories of oysters are exchanged for $\$6.6 \times 10^{6}/yr$. Purchased energies thus represent about 14% of the total input energies. Assuming that this money will be exchanged for a mixture of goods, fuels, and services which have an energy equivalent similar to the national average, then the oyster income represents 1.62×10^{11} $Kcal_{FFE}/yr$. The energies expended in harvest returned almost ten times the equivalent energies represented by the money paid for the oysters. Most of the oysters produced in

Fig. 52. Simplified energy circuit language diagrams showing purchased and natural energy flows involved in the Franklin County oyster industry. (a) Energy flows as heat equivalents, (b) Energy flows as fossil fuel equivalents.

Energy Quality of Oysters

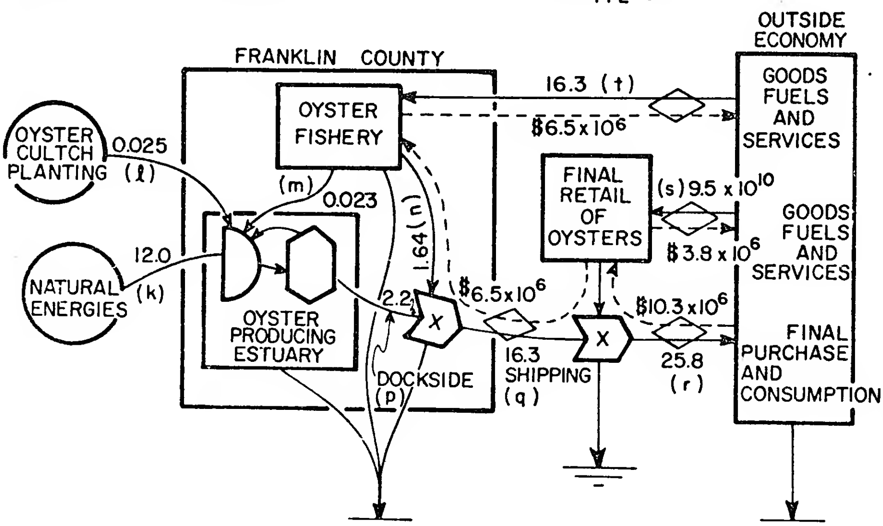
Heat calories	6.1×10^{8}	Fig. 52, footnote e
Distributed in bay	3.1×10^{9}	Fig. 52, footnote o
Concentrated at dockside	2.2×10^{10}	Fig. 52, footnote p
Shipping from county	16.3×10^{10}	Fig. 52, footnote q
Final consumption	25.8×10^{10}	Fig. 52, footnote r

HEAT EQUIVALENTS



(a)

FOSSIL FUEL WORK EQUIVALENTS (10^{10} $Kcal_{FFE}$/yr)



(b)

Notes to Fig. 52

[a]Total natural energy input acting in support of the oyster reefs in the bay was calculated by converting annual oyster uptake of organic matter back to sunlight equivalent kilocalories. Organic matter kilocalories were converted to gross photosynthesis kilocalories by multiplying by 10. These kilocalories were converted to sunlight kilocalories by multiplying by 100 (Table 1). Oyster uptake of organics is given in Appendix Table D-1.

$$\text{Kcal/yr} = (2.4\text{x}10^{11}\text{Kcal/yr})(10)(100) = 2.4\text{x}10^{14}$$

[b]Energy input associated with planting cultch to catch oyster larvae was estimated by converting yearly cost of this operation to kilocalories using 25,000 Kcal/\$. Data are from Whitfield (1973).

$$(\$10{,}000/\text{yr})(25{,}000\text{Kcal}/\$) = 2.5 \times 10^{8}\text{Kcal}_{\text{FFE}}/\text{yr}$$

[c]The energy equivalent of nitrogen entering the bay from a secondary treatment plant was calculated by converting nitrogen to organic matter via photosynthesis. (Nitrogen data are given in Table D-1).

$$(5.05 \times 10^{7} \text{ g N/yr})(20 \text{ g organic matter/g N})$$

$$(4.5 \text{ Kcal/g}) = 4.6 \times 10^{9} \text{ Kcal/yr}$$

[d]The energy equivalent of the oyster harvest effort included replacement costs of boats, motors, tongs and other boat gear, shucking and packing houses. Data were from Rockwood (1973).

$$(\$3.04 \times 10^{5}/\text{yr})(25{,}000 \text{ Kcal}/\$) = 7.6 \times 10^{9} \text{ Kcal}_{\text{FFE}}/\text{yr}$$

Expenditure of fuel was estimated to be 8.8×10^{9} $\text{Kcal}_{\text{FFE}}/\text{yr}$ (Rockwood, 1973).

$$(2.75 \times 10^{5} \text{ gal/yr})(1.27 \times 10^{5} \text{ BTU/gal})(\text{Kcal/BTU})$$

$$= 8.8 \times 10^{9} \text{ Kcal/yr}$$

Total harvest effort = 1.64×10^{10} $\text{Kcal}_{\text{FFE}}/\text{yr}$

[e]Oyster harvest for 1970 was converted directly to kilocalories using 4.5 Kcal/g (Table D-1).

$$(3 \times 10^6 \text{ lbs/yr})(4.5 \text{ Kcal/g})(454 \text{ g/lb})$$

$$(0.1 \text{ g/g dry weight}) = 6.13 \times 10^8 \text{ Kcal/yr}$$

[f]Money earned due to oyster sales was calculated as given in Appendix Table D-1.

$$\$6.5 \times 10^6\text{/yr}$$

[g]Final retail value of Franklin County oysters was estimated from data given by Colberg and Windham (1965). The money earned by oyster sales in the county (f) represented about 63 percent of final oyster value. Thus, $\$10.3 \times 10^6$ dollars were eventually paid for Franklin County oysters.

[h]Total purchase of goods, fuels, and services by those directly and indirectly involved in the oyster industry. Only a portion of the purchase is used in the harvest effort (compare (h) and (d)). It was assumed that all money earned was spent (savings were small compared to spending). The money flow to the outside economy was converted to energy flow using the ratio of 25,000 Kcal/$.

$$(\$5.5 \times 10^6\text{/yr})(25{,}000 \text{ Kcal/\$})$$

$$= 16.25 \times 10^{10} \text{Kcal}_{FFE}\text{/yr}$$

[i]As stated in the text, approximately 37% of the full value of oysters did not enter the county. This was estimated to be $\$3.8 \times 10^6$/yr (Colberg and Windham, 1965). This was converted to energy flow using the ratio of 25,000 Kcal/$.

$$(\$3.8 \times 10^6\text{/yr})(25{,}000 \text{ Kcal/\$})$$

$$= 9.5 \times 10^{10} \text{ Kcal}_{FFE}\text{/yr}$$

[j]In "heat calories" the total input flow was large compared to yields (e) and subsidies (b, c, and d). Thus, the heat lost from the system was approximated by the inputs and was assigned an approximate value of 2.4×10^{14} Kcal/yr.

[k]Natural energies (a) were converted to fossil fuel equivalents by dividing by 2000 (Table 1).

$$\frac{2.4 \times 10^{14} \text{ Kcal/yr}}{2 \times 10^{3}} = 1.2 \times 10^{11} \text{ Kcal}_{FFE}\text{/yr}$$

[l]The value given in (b) for the cultch planting program was assumed to be in fossil fuel equivalents.

$$2.5 \times 10^{8} \text{ Kcal}_{FFE}\text{/yr}$$

[m]The energy content of nitrogen input to the bay from sewage wastes was calculated in (c). This value was at the gross photosynthesis level of quality and was adjsuted to fossil fuel quality by dividing by 20 (see Table 1).

$$\frac{4.6 \times 10^{9}\text{Kcal/yr}}{20} = 2.3 \times 10^{8}\text{Kcal}_{FFE}\text{/yr}$$

[n]The value given in (d) for harvest effort was in fossil fuel equivalents.

$$1.64 \times 10^{10}\text{Kcal}_{FFE}\text{/yr}$$

[o]The energy quality of oysters in a dispersed state in the bay was calculated by assuming that 10% of oyster intake of organics was assimilated into new tissue.

$$\begin{aligned} \text{Energy Quality of Oysters (dispersed)} &= \frac{\text{assimilated material}}{\text{total intake}} \\ &= \frac{2.4 \times 10^{10}\text{Kcal/yr}}{2.4 \times 10^{11}\text{Kcal/yr}} = 0.1 \end{aligned}$$

With this assumption of assimilation efficiency, oysters in a dispersed state have an energy quality about 10 times that of net photosynthetic production. Net photosynthetic production is a factor of at least 2 less in quality than fossil fuels. Thus, this calculation indicates that oysters dispersed in nature have a quality about five times that of fossil fuels.

[p]The energy quality of oysters concentrated to dockside was calculated by taking the ratio of organic matter consumed to yields (both harvest and predation). This ratio was used because it reflects the energy input required to produce a yield which can be passed up the food web or to urban systems. Simulation results in Fig. 45 suggested that the present harvest rate was close to the carrying capacity of oyster stocks.

Energy Quality

$$\text{oysters at dockside} = \frac{\text{Yield}}{\text{Total input}}$$

where

yield = harvest yield + predation

harvest yield = $6.13\text{x}10^{8}$ Kcal/yr (as in (e) of this table)

predation = $(5\text{x}68\text{x}10^{8}\text{g/yr})(4.5\ \text{Kcal/g})$

= $2.56\text{x}10^{9}$ Kcal/yr (Appendix Table D-1 for predation losses).

Total input = $2.4\text{x}10^{11}$ Kcal/yr (as in (a) of this table).

Energy Quality

$$\text{oysters harvested} = \frac{3.17\text{x}10^{9}\ \text{Kcal/yr}}{2.4\text{x}10^{11}\ \text{Kcal/yr}} = 0.013$$

Thus, harvest yield is related to input by a factor of about 75 $\left(\frac{1}{0.013}\right)$. Input energy (net production) is lower in quality than fossil fuels by a factor of at least 2 (Table 1). Thus oyster yields are 35 times fossil fuel quality. The heat calories of oyster yield were thus multiplied by 35 to adjust them to fossil fuel equivalents.

$$(6.13\text{x}10^{8})(35) = 2.15\text{x}10^{10}\ \text{Kcal}_{FFE}\text{/yr}$$

[q]The energy content of oysters at the point of processing when they leave the county was assumed to be reflected by the price paid for the product.

$$(\$6.5 \times 10^{6}/yr)(25{,}000\ Kcal/\$)$$
$$= 16.3 \times 10^{10} Kcal_{FFE}/yr$$

[r]The energy content of the oyster after final retail sale was estimated from the price paid for the product (g, this table) using the ratio 25,000 Kcal/$.

$$(\$10.3 \times 10^{6}/yr)(25{,}000\ Kcal/\$)$$
$$= 25.8 \times 10^{10} Kcal_{FFE}/yr$$

[s]This flow represents the energy flow resulting from final processing of oysters outside of Franklin County. The money flow was taken as the difference between (q) and (r) and converted to energy flow using 25,000 Kcal/$.

$$(\$3.8 \times 10^{6}/yr)(25{,}000\ Kcal/\$)$$
$$= 9.5 \times 10^{10} Kcal_{FFE}/yr$$

[t]This flow represents the purchase of goods, fuels, and services by the oyster industry. Calculation was as in (h) of this table.

$$16.3 \times 10^{10} Kcal_{FFE}/yr$$

Franklin County are consumed outside the county. Based on value added estimates made by Colberg and Windham (1965), oyster exports ultimately were exchanged for $\$10.3 \times 10^6$. Approximately 37% of this money did not enter the county. Thus, the eventual use of oysters supported an additional $\$3.8 \times 10^6$ (9.5×10^{10} $Kcal_{FFE}$) worth of work in some other area of the country.

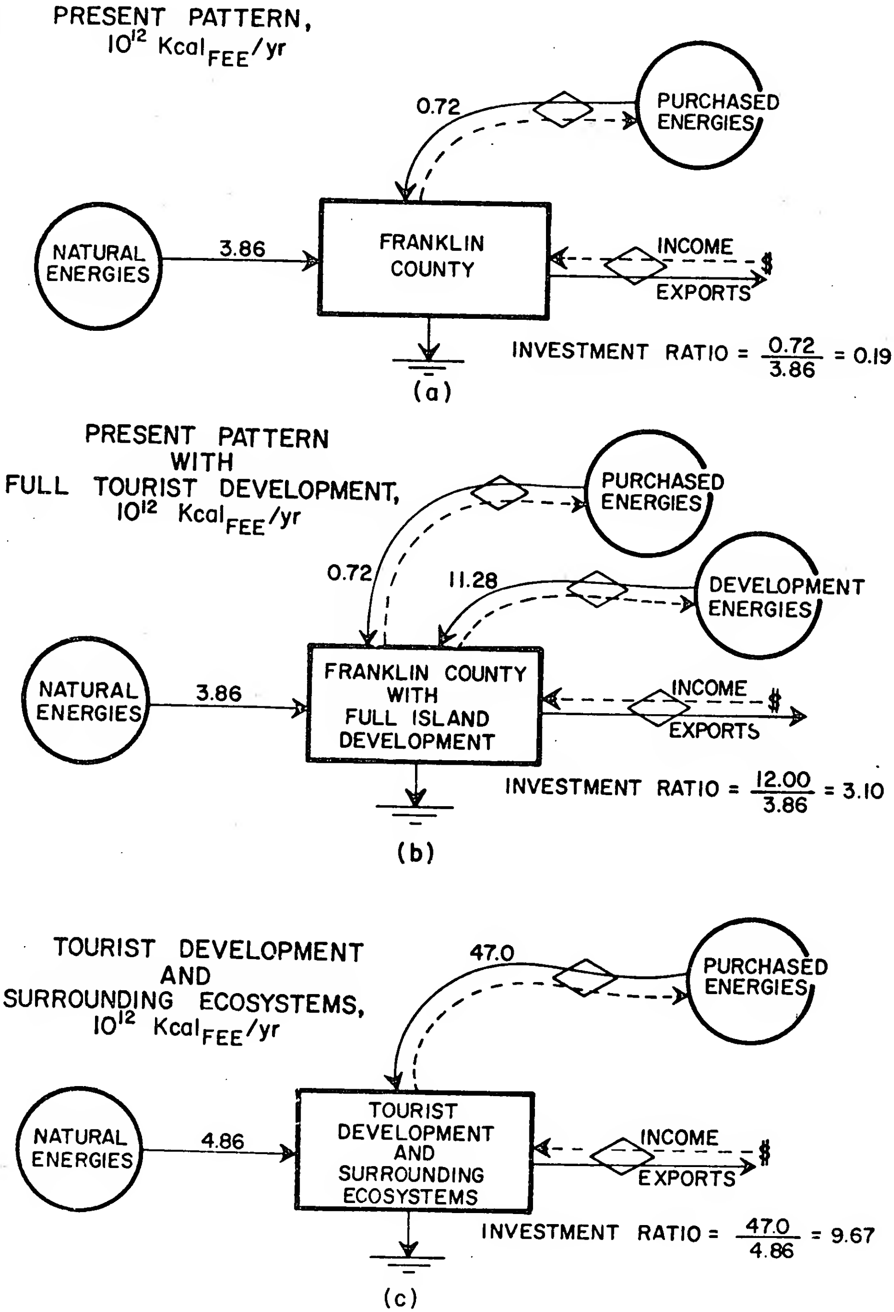
Tourist Development

Energy calculations were made anticipating the development of St. George Island as a tourist resort. Energy calculations were made to estimate the impact of adding this new feature to the full area of St. George Island and to the local area of St. George Island as presently proposed.

Three simplified models are given in Fig. 53 showing natural and purchased energy inputs to Franklin County under present conditions and under conditions that a tourist community is developed on St. George Island as proposed. Figs. 53b and 53c show urban inputs associated with the tourist development. The models show natural energy inputs on the left side of the diagram, and purchased sources entering from the top of the diagram. All flows are in fossil fuel equivalents.

Natural energy flows and energy flows associated with the present urban system are shown in Fig. 53a with documentation given in Table 10. Natural energy flows were

Fig. 53. Simplified energy circuit language diagrams showing aggregated inputs of natural and purchased energies and effect of tourist developments on St. George Island. (a) Present pattern of the county, (b) Pattern with full tourist development of St. George Island, (c) One unit of tourist development with surrounding ecosystems as defined in Fig. 54.


PRESENT PATTERN,
10^{12} $Kcal_{FEE}/yr$
0.72
PURCHASED ENERGIES
NATURAL ENERGIES
3.86
FRANKLIN COUNTY
INCOME
$
EXPORTS
INVESTMENT RATIO = $\frac{0.72}{3.86}$ = 0.19
(a)
PRESENT PATTERN WITH FULL TOURIST DEVELOPMENT,
10^{12} $Kcal_{FEE}/yr$
PURCHASED ENERGIES
0.72
11.28
DEVELOPMENT ENERGIES
NATURAL ENERGIES
3.86
FRANKLIN COUNTY WITH FULL ISLAND DEVELOPMENT
INCOME
$
EXPORTS
INVESTMENT RATIO = $\frac{12.00}{3.86}$ = 3.10
(b)
TOURIST DEVELOPMENT AND SURROUNDING ECOSYSTEMS,
10^{12} $Kcal_{FEE}/yr$
47.0
PURCHASED ENERGIES
NATURAL ENERGIES
4.86
TOURIST DEVELOPMENT AND SURROUNDING ECOSYSTEMS
INCOME
$
EXPORTS
INVESTMENT RATIO = $\frac{47.0}{4.86}$ = 9.67
(c)

large (investment ratio = 0.19). New energy flows associated with the proposed island development were estimated to be 0.468×10^{12} $Kcal_{FFE}/yr$ (Table 11). This represents a 65% increase in current urban energy flows. If the proposed tourist development were to expand and include all of St. George Island, purchased energy flows might increase to 11.28 $Kcal_{FFE}/yr$. This was estimated by assuming that the proposed 800-acre development was duplicated to cover all 20,000 acres of the island. The purchased flows given in Table 11 were multiplied by a factor of 24. Urban energy flows in the county increased to 12.0×10^{12} $Kcal_{FFE}/yr$ with the addition of the full island development. The investment ratio was 3.10 with the addition of the tourist development. This is comparable to other developed areas of Florida and is higher than the national average.

To obtain an estimate of the localized mix of natural and purchased energy flows in the proposed tourist development, an area around the site was defined (Fig. 54). Figure 55 gives a map view of the proposed 800-acre development. It was assumed that a five-mile extension on either side of the development would include most of the natural areas having exchange with the development including fishing, vistas and microclimate control. Within this area natural and purchased flows were compared as shown in Fig. 53c. Table 12 summarizes energy flows for this area. In this case, urban inputs were very large compared to natural energies. The investment ratio was 9.67.

Table 11

New urban energy flows associated with tourist development.

Name of Flow	Area of System, Acres	Annual Work Per Unit Area, 10^7Kcal/acre/yr	Total Annual Work 10^{12}Kcal/area/yr	Energy Quality Factor (see Table 1)	Annual Work in Fossil Fuel Equivalents $10^{12}Kcal_{FFE}/yr$
Energy Flows Associated with Tourist Development					
Construction					
Goods and services[a]	—	—	0.146	1.0	0.146
Operation and Maintenance					
Electricity[b]	—	—	0.030	.28	0.107
Gasoline[c]	—	—	0.065	1.0	0.065
Goods and services[d]	—	—	0.112	1.0	0.112
Urban flows developed with new tax money[e]	—	—	0.038	1.0	0.038
					0.468

Notes to Table 11

[a]The purchased energy flow associated with the development of St. George Island (800 acres; 7000 residents; 3000 dwelling units) was estimated by multiplying the dollar cost (minus advertising costs) times 25,000 Kcal/dollar. Data were from the Development of Regional Impact report prepared by Leisure Properties Limited (1974). Development costs include prorated costs of both vertical and horizontal development. Advertising costs were assumed to be spent outside the county and were not included.

Horizontal development (prorated over 20 years)

$(\$.042 \times 10^6/yr)(25,000\ Kcal/dollar)$

$1.1 \times 10^{10}\ Kcal_{FFE}/yr$

Vertical development (prorated over 20 years)

$(\$5.4 \times 10^6/yr)(25,000\ Kcal/dollar)$

$13.5 \times 10^{10}\ Kcal_{FFE}/yr$

$Total = 14.6 \times 10^{10}\ Kcal_{FFE}/yr$

[b]Annual electricity use was extrapolated from data developed by Brown and Genova (1973) for Lee County, Florida. For dwelling unit densities of 3.5 D.U./acre, electricity use was 15×10^{16} Kcal/D.U./yr. In this calculation there were 3.75 D.U./acre. Over the twenty-year period considered here there was an average of 2000 dwelling units.

$(15 \times 10^6\ Kcal/D.U./yr)(2000\ D.U.)$

$3.0 \times 10^{10}\ Kcal/yr$

[c]Gasoline use was calculated using 1000 gals/yr as the average family consumption (Ford Foundation, 1974).

$(1000\ gal/D.U./yr)(2000\ D.U.)(3.23 \times 10^4\ Kcal/gal)$

$6.46 \times 10^{10}\ Kcal_{FFE}/yr$

[d]The energy flow associated with goods and services was extrapolated from data developed for Lee County, Florida by Brown and Genova (1973). They estimated goods and services use to be 5.6×10^7 Kcal/D.U./yr for new housing at similar densitites.

$(5.6 \times 10^7 \text{ Kcal/D.U./yr})(2000 \text{ D.U.})$

$1.12 \times 10^{11} \text{ Kcal}_{FFE}\text{/yr}$

[e]Urban energy flows that would develop based on the new tax money from the island development were calculated by multiplying estimated tax receipts (Leisure Properties Limited, 1974) by 25,000 Kcal/dollar.

$(\$1.52 \times 10^6\text{/yr})(25{,}000 \text{ Kcal/dollar})$

$3.8 \times 10^{10} \text{ Kcal}_{FFE}\text{/yr}$

Fig. 54. Map showing site of tourist development on St. George Island. The area used in calculating natural energy input to the development (Fig. 53c) is also shown (13,400 acres).

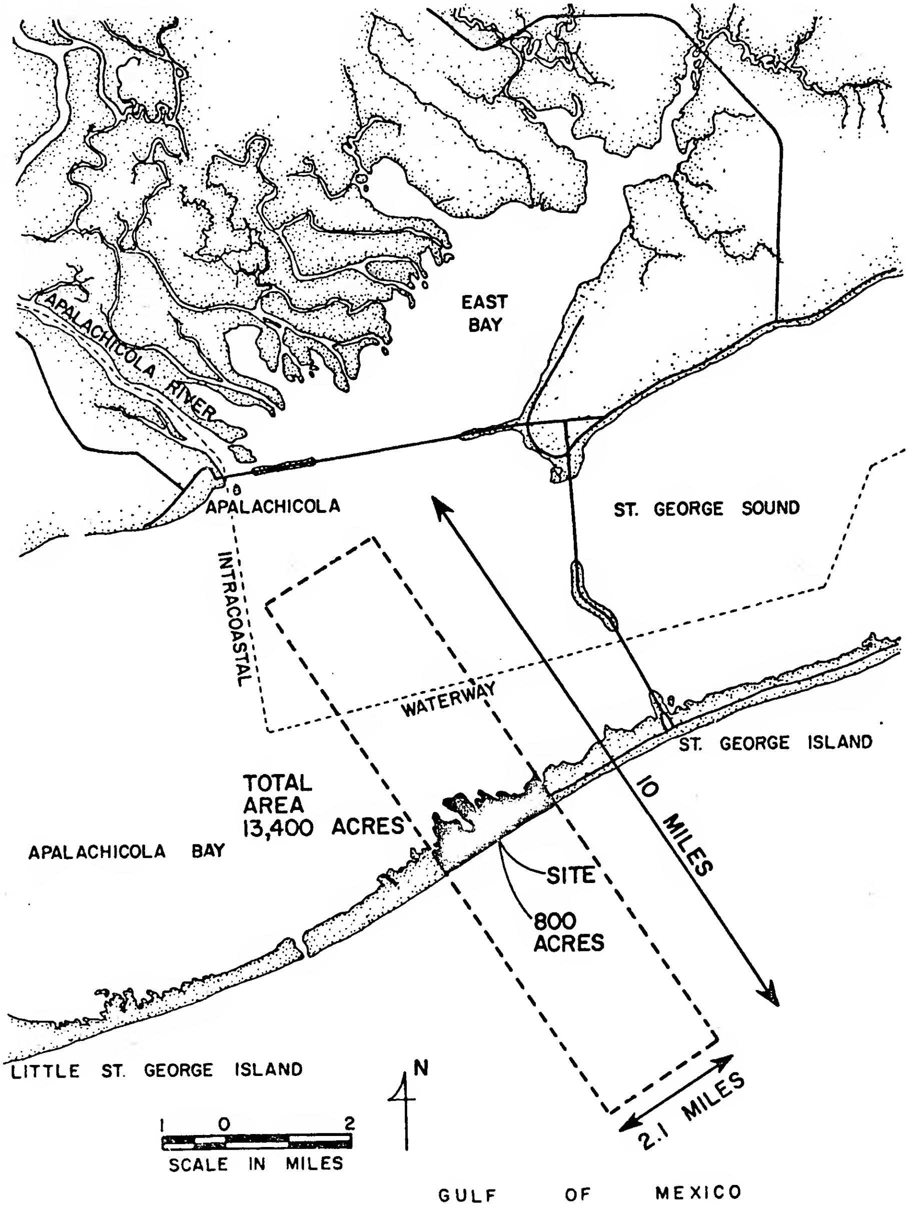

EAST
BAY
APALACHICOLA RIVER
APALACHICOLA
ST. GEORGE SOUND
INTRACOASTAL
WATERWAY
ST. GEORGE ISLAND
10 MILES
TOTAL
AREA
13,400 ACRES
APALACHICOLA BAY
SITE
800
ACRES
LITTLE ST. GEORGE ISLAND
N
1 0 2
SCALE IN MILES
2.1 MILES
GULF OF MEXICO

Fig. 55. Map view of proposed 800-acre tourist development on St. George Island. The map was adapted from one given by Leisure Properties, Limited (1974).

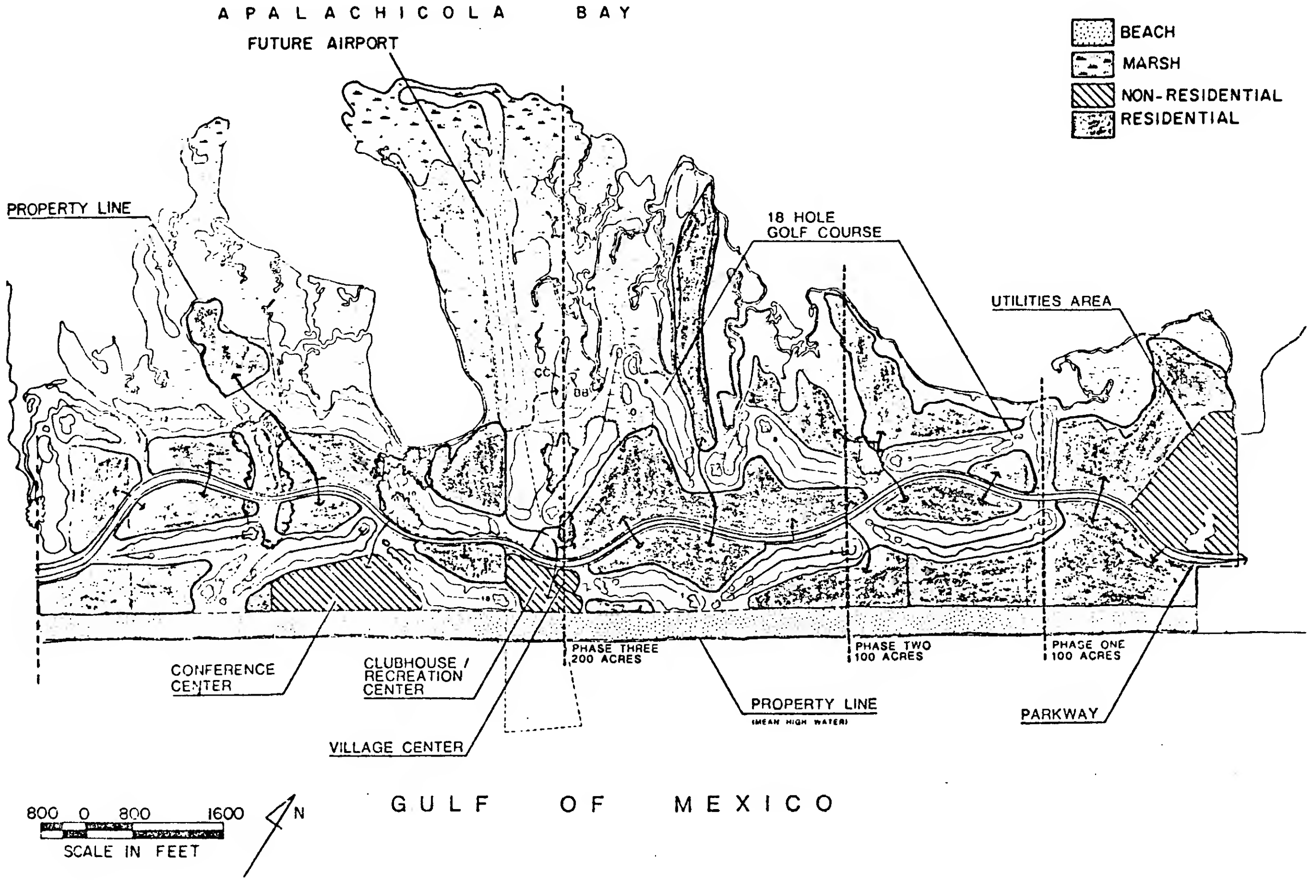

A P A L A C H I C O L A B A Y
FUTURE AIRPORT
BEACH
MARSH
NON-RESIDENTIAL
RESIDENTIAL
PROPERTY LINE
18 HOLE GOLF COURSE
UTILITIES AREA
CC
BB
PHASE THREE 200 ACRES
PHASE TWO 100 ACRES
PHASE ONE 100 ACRES
CONFERENCE CENTER
CLUBHOUSE / RECREATION CENTER
PROPERTY LINE (MEAN HIGH WATER)
PARKWAY
VILLAGE CENTER
800 0 800 1600
SCALE IN FEET
N
G U L F O F M E X I C O

Table 12

Energy flow table for localized impact of island development.

Name of Flow	Area of System, Acres	Annual Work per Unit Area, 10^7Kcal/acre yr	Total Annual Work 10^{10}Kcal/yr	Energy Quality Factor (Table 1)	Annual Work in Fossil Fuel Equivalents, 10^{10}Kcal$_{FFE}$/yr
Contributing Natural Energy Flows					
Total sunlight[a]	13,400	591.0	7920	2,000.0	3.96
Heat Gradient[b]	13,400	4.1	60	10,000.0	0.01
Tides in Estuary[c]	6,720	0.15	1.0	2.5	0.40
Waves on Shoreline[d]	3,380 (m of beach)	——	0.21	5.0	0.04
Wind[e]	13,400	0.25	3.4	7.7	0.45
Energy flows associated with tourist development (as in Table 11)[f]					46.8

[a] Total sunlight calculated as in Table 10 (e) but adjusted to 13,400 acres.

[b] Heat gradient calculated as in Table 10 (f) but adjusted to 13,400 acres.

[c] Tides in estuary calculated as in Table 10 (g) but adjusted to 6,720 acres.

[d] Waves on shoreline calculated as in Table 10 (h) but for 3,380 m of beach.

[e] Wind calculated as in Table 10 (k) but for 13,400 acres.

[f] Urban flows calculated by summing flows (a) - (e) in Table 11.

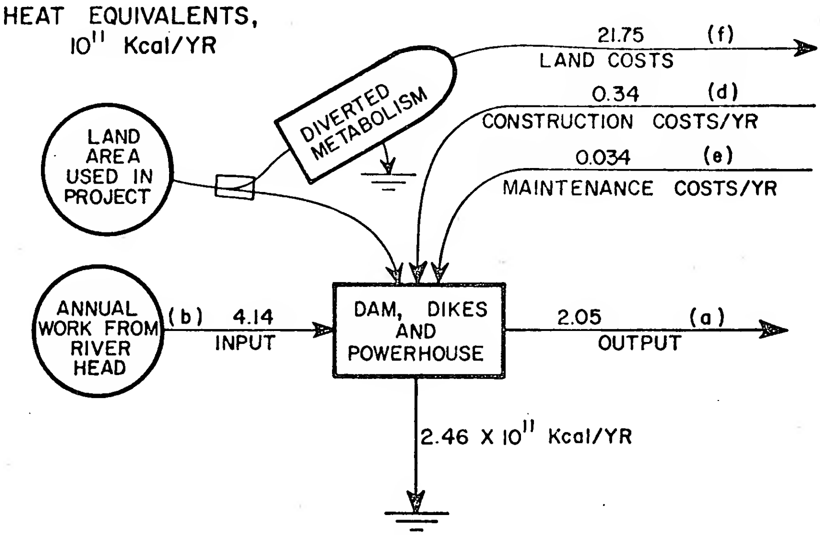
Energy Quality of Water at Jim Woodruff Dam

The methodology for calculating an energy quality ratio was presented in the Methods section. Given here is a calculation estimating the energy quality of the hydrostatic head of water at Jim Woodruff Dam on the Apalachicola River relative to fossil fuel quality work.

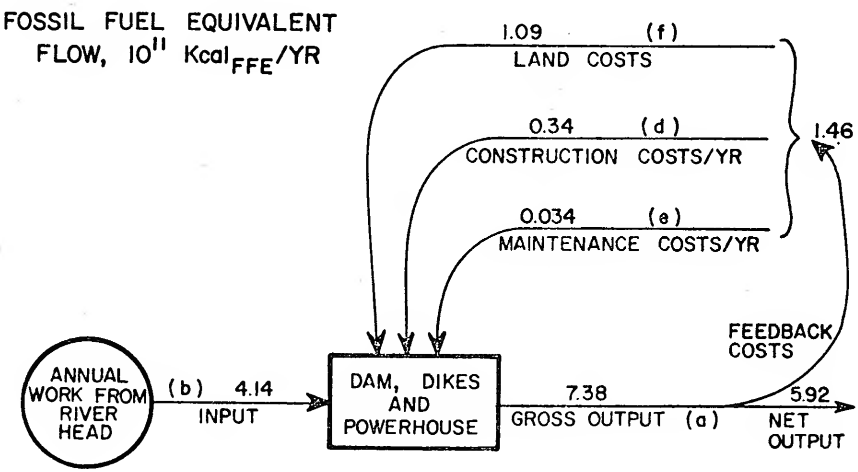
Fig. 56a and 56b are simplified diagrams of the process of converting the potential energy of river head into electricity at a hydroelectric station. Required purchased subsidies enter the conversion process at the top of the box symbol and include the prorated costs of construction and maintenance. Land costs were evaluated in terms of diverted metabolism and are shown as another energy input in Fig. 56b. Degraded heat is shown at the bottom. Annual output of electricity is shown on the right. All energy flows in Fig. 56a are in heat kilocalories with no adjustment to fossil fuel equivalents. Total energy input amounts to 4.51×10^{11} Kcal/yr. Output was 2.05×10^{11} Kcal/yr as electrical energy.

In Fig. 56b all flows except (b) have been converted to fossil fuel equivalents. Gross output was 7.38×10^{11} $Kcal_{FFE}$/yr. After subtracting the feedback costs from the gross output, net output amounted to 5.92×10^{11} $Kcal_{FFE}$/yr. River head calories are related to fossil fuel calories by the ratio of net output to input (5.92×10^{11} Kcal/yr divided by 4.14×10^{11} $Kcal_{FFE}$/yr). Thus 1.42

Fig. 56. Simplified energy circuit language diagrams showing the conversion of potential energy of river head to electricity. Letters refer to explanatory notes in Table 13. (a) Model evaluated in heat calories, (b) Model evaluated in fossil fuel equivalent kilocalories.



(a)



$$\text{ENERGY QUALITY FACTOR} = \frac{\text{NET OUTPUT}}{\text{INPUT}} = \frac{5.92}{4.14} = 1.42$$

Therefore one kilocalorie of fossil fuel work is equivalent to 0.7 kilocalories of hydrostatic head.

(b)

Kcal of fossil fuel work are equal, in work ability, to 1 Kcal of river head-type work. Data and calculations are given in Table 13.

Table 13

Documentation of energy flows given in Fig. 56.

a) Power plant output in KWH (yearly average)

238,090,000 KWH

238,090,000 KWH x 860.5 Kcal/KWH = 2.049×10^{11} Kcal/yr

A factor of 3.6 was used to convert electricity to fossil fuel equivalents (Table 1).

$(2.049 \times 10^{11}$ Kcal/yr$)(3.6) = 7.38 \times 10^{11}$ $Kcal_{FFE}$/yr

(Apalachicola River Basin Reservoir Regulation Manual, 1972)

b) Calculation of input energy

net head, full load = 30.5 ft.

turbine discharge (cfs)

1 unit operating 5,500

2 units operating 12,000

3 units operating 18,300

Average annual flow past dam = 21,311 cfs

(Apalachicola River Basin Reservoir Regulation Manual, 1972)

Calculating power developed from this flow with a head of 30.5 ft.

$$Pw = \frac{HW}{T}$$

where H = height (ft)

W = weight (lbs)

T = time interval

Pw = power (ft-lbs/sec)

Table 13 - continued

V = volume of water

w = weight (lbs/ft^3)

$Pw = HwQ$

where $Q = \frac{V}{T}$ = volumetric flow rate in ft^3/sec out of the reservoir

$Pw = HwQ$

$= (30.5\ ft)(62.3\ lbs/ft^3)(21,311\ ft^3/sec)$

$= 4.049 \times 10^7$ ft-lbs/sec

$Pw = 4.049.10^7 \text{ ft-lbs/sec} \times 1.945 \times 10^{-2} \frac{\text{Kcal/min}}{\text{ft-lbs/sec}}$

$= 7.975 \times 10^5$ Kcal/min

$Pw = 7.875 \times 10^5$ Kcal/min x 60 min/hr x 24 hr/day x 365 days/yr

$Pw = 4.139 \times 10^{11}$ Kcal/yr

(Healy, 1974)

c) Lifetime of lock-dam-hydrofacilities was estimated to be 50 yrs (Harrison, 1974).

d) Calculation of construction costs:

Powerhouse	$15,392,120	
Lock	8,940,191	
Spillways and Dikes	26,906,434	
	$51,238,745	(1953 dollars)

The dam and hydrofacility appear to operate independent of lock and because of this, the cost of the lock was not included in this calculation (Snow, 1974).

Total cost in 1953 dollars = $42,966,243

This figure was adjusted to 1973 dollars by multiplying by 1.6. This was done so that the 25,000 Kcal/dollar ratio could be used.

Table 13 - continued

Total fossil fuel investment = \$68,745,988 x 25,000 Kcal/dollar

$= 1.719 \times 10^{12}$ $Kcal_{FFE}$

Prorated cost over 50 years was 0.344×10^{11} $Kcal_{FFE}/yr$

e) Calculation of yearly maintenance costs:

Powerhouse	\$83,199/yr
Spillway and Dikes	52,981/yr
	\$136,180/yr

Converting to Kcal/yr using 25,000 Kcal/dollar

\$136,180/yr x 25,000/dollar = 0.034×10^{11} $Kcal_{FFE}/yr$

(Snow, 1974)

f) Calculation of costs associated with modified environments (conversion of forests to reservoir).

Land costs = (forest loss/yr + river loss/yr) - (reservoir gain/yr)

Loss of forest metabolism = $(33.5 \times 10^3$ acres) x $(20 \times 10^3$ Kcal/yr)$(4.046 \times 10^3 m^2$/acre)

$= 27.11 \times 10^{11}$ Kcal/yr

Loss of river metabolism = $(4.0 \times 10^3$ acres) x $(10 \times 10^3$ Kcal/yr)$(4.046 \times 10^3 m^2$/acre)

$= 1.62 \times 10^{11}$ Kcal/yr

Gain in reservoir metabolism = $(37.5 \times 10^3$ acres) x $(4.6 \times 10^3$ Kcal/yr)$(4.046 \times 10^3 m^2$/acre)

$= 6.98 \times 10^{11}$ Kcal/yr

Differential cost = $(27.11 \times 10^{11} + 1.62 \times 10^{11}) - (6.98 \times 10^{11}) = 21.75 \times 10^{11}$ Kcal/yr

Table 13 - continued

The differential cost was converted to fossil fuel quality by dividing by 20 (Table 1).

$$\frac{21.75 \times 10^{11}}{20} = 1.09 \times 10^{11} \text{ Kcal}_{FFE}/\text{yr}$$

Metabolism estimates are from Table 10.

DISCUSSION

This study considered the energetic basis of a coastal region using calculations, simulation models, and areal maps for purposes of adding to our understanding of the behavior of large open systems of man and nature. The study was also a part of a continuing effort to develop a generalized methodology for anticipating regional trends and deciding which of many alternative patterns now facing coastal zone and other areas adds to the vitality of the region. The discussion is presented in sections organized by issues which are important in the Franklin County-Apalachicola Bay region and which may have broader applications.

Main Energy Characteristics of the County

The most striking characteristic of the energy basis of the county was the major role played by natural energy inputs. In 1973 approximately 84% of all energy inputs to the county came from natural inputs. The remaining 16% was associated with goods, fuels and services for which payment was made. The ratio of urban to natural inputs (investment ratio) was 0.19. Total energy input to the region was 4.50 x 10^{12} $Kcal_{FFE}$/yr, or about 5.1 x 10^6 $Kcal_{FFE}$/acre/yr.

The investment ratio and the energy flow per area can be compared to other systems to gain perspective on the energy basis of Franklin County. Zucchetto (1975) reported an investment ratio of 3.90 for the Miami-Dade County region of Florida. The ratio for the South Florida region was 2.4 in 1974 while the overall ratio for the U.S. in 1974 was 2.5 (Odum and Brown, 1975). Franklin County would have to process about 13 times the present amount of purchased fuels to have an investment ratio similar to the national average. On a unit area basis, the Miami-Dade area had 6.7 x 10^7 $Kcal_{FFE}$/acre/yr, and the U.S. 1.7 x 10^6 $Kcal_{FFE}$/yr. On an area basis energy input in the Franklin County region was less than the Miami-Dade and South Florida areas but greater than the U.S. average. Most energy inputs to Franklin County were natural inputs.

Thus, the notion of Franklin County as a rural area (Colberg and Windham, 1965) heavily dominated by natural energy flows appears to be substantiated by quantitative energy input calculations. Inspection of maps from aerial photographs gave a similar impression. Dominant on the maps were the terrestrial, estuarine, and coastal plankton systems. Freshwater systems were less dominant but still evident in the deltaic system at the mouth of the Apalachicola River. Highly metabolic urban systems were a small feature (0.3% of the total area).

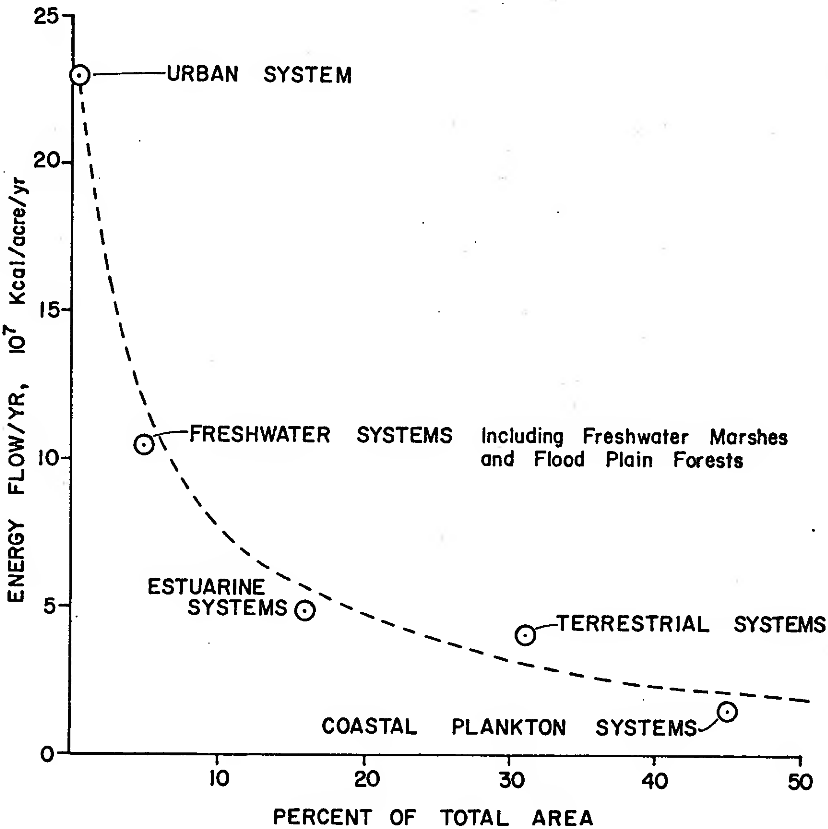
In establishing the energy basis of the study area energy flows were evaluated as they crossed the boundary into Franklin County region. Raw energy flows (representing heat content) were converted to fossil fuel equivalent kilocalories to allow comparisons between flows. On a fossil fuel equivalent basis, the largest inflow in the primitive pattern was sunlight and this accounted for about 69% of the total input. Tides, waves, mixing energy, and hydrostatic head were primarily associated with the estuary and amounted to about 1.0×10^{12} $Kcal_{FFE}/yr$ or about 26% of the total input. Wind was also a major natural input and amounted to about 5% of the total. Several observations concerning the energy input pattern are offered. First, estuaries have been often characterized as highly dynamic areas (Ketchum, 1972). In the study area the estuary occupied approximately 16% of the total area. If sunlight and wind inputs were prorated so the estuary received 16% of the total input and this was combined with the estuarine inputs given above, then the estuary received about 38% of total energy inputs. Secondly, metabolism estimates were made of each of the dominant systems (Table 10). Total metabolism was estimated to be about 1.5×10^{12} $Kcal_{FFE}/yr$. This figure represents some portion of the work done by input energies after they enter the system.

Total ecosystem metabolism represents at least 40% of the input energies. Actual work done by other inputs was not estimated inside the study area but some actions are evident, especially in the estuary where shorelines are building and eroding. The point here is that ecosystem metabolism may be the major factor in shaping and controlling landscapes by utilizing input energies.

Estimates of primitive and present patterns of energy input were calculated for the Franklin County region (Tables 9 and 10) to quantify the impact of present urban systems on the full energy budget. In the Franklin County region urban flows were small compared to natural inputs. In this area input energies in the present pattern are larger than those in the primitive pattern. This is consistent with Lotka's Principal of Maximum Power (Lotka, 1922; Odum, 1971a), which states that successful systems are those that maximize the use of energy inputs available to them. Since the present urban area seems to be a persistent part of the landscape, we would expect that total energy flow would now be greater, even though some portion of the original system has been displaced.

Given in Fig. 57 is a plot of energy flow per area for five major ecosystem types versus the percent of the total study area occupied by each ecosystem type. The largest spatial system (coastal plankton) had the smallest energy flow per unit area per year. Community metabolism

Fig. 57. Plot of energy flow per area per year versus percent of total study area in each ecosystem type. Urban energy flow per area is in $Kcal_{FFE}$/yr. Ecosystem energy flows are in Kcal/acre/yr measured at the gross photosynthesis level. Total area was 8.97×10^5 acres.



25
20
15
10
5
0
ENERGY FLOW/YR, 10^7 Kcal/acre/yr
URBAN SYSTEM
FRESHWATER SYSTEMS Including Freshwater Marshes and Flood Plain Forests
ESTUARINE SYSTEMS
TERRESTRIAL SYSTEMS
COASTAL PLANKTON SYSTEMS
10
20
30
40
50
PERCENT OF TOTAL AREA

was used as an index of work done in the system. The urban system which was small in area had the largest energy flow per area per year. The dashed line connecting the points has the general shape of an exponential curve. Odum (1974a) has suggested that exponential energy power spectra may be developed in all systems because of the requirement to maximize total system power. In maximizing total power, systems develop feedbacks from storages to capture incoming energy. Special feedbacks are developed that are of high quality to provide services that lower quality storages are not capable of delivering. In generating the high quality storages energy is lost and the total quantity of high quality energy is less. In this way exponential power spectra are developed.

Curves similar to the one in Fig. 57 have been observed in other systems including food webs as is suggested in data reported by McKellar (1975). The exact significance of this distribution on a regional scale is not clear at this point but it might be speculated that all systems are characterized by such relationships, and that regional systems are distinguished by such patterns. The figure is presented here as one way to view a relationship between energy flow/unit area in major ecosystems and the areal extent of the ecosystems in a regional pattern.

Relationship of Economy to Natural Systems

As shown in the consideration of the energy basis of the county, natural systems provide the main energy supports to the county. In Franklin County most of the money earned comes from fishery products which at present are taken from wild stocks. The total value of the oyster harvest was calculated to be $\$6.5 \times 10^6$ (Colberg and Windham, 1965) in 1970 and is worth more at the present time. Dockside value of the remaining fishery products was about $\$1.3 \times 10^6$. The full value to the county was somewhat more as this figure does not include value added in processing. Tourism in the county appeared to be mainly related to recreational opportunities including fishing in estuarine, freshwater, and offshore areas, hunting, and relaxation. The main attractions for these are provided by natural ecosystems with little or no cost. Total tourist income was estimated to be $\$1.3 \times 10^6$/yr in 1970. This may have been an underestimate as the money spent by visitors at the annual seafood festival was not included. Fishery and tourism incomes were $\$9.1 \times 10^6$ in 1970, about 60% of the total county income of about $\$16 \times 10^6$.

Feedback Required of Urban Systems

Figure 3 shows a simplified model of Franklin County and Apalachicola Bay. The diagram suggests main feedback relationships operating between urban and natural systems. These included the addition of nitrogen and coliforms to the bay from the urban area and harvest effort which may have the effect of rearranging oyster bar materials and in this way stimulating new growth. On a larger scale, exports of fishery products to areas outside the county have a return flow as nutrients, detritus, and coliforms from the river. Only some unevaluated portion of these materials are from urban areas. Also, there is a state-supported program of shell planting in the bay for purposes of developing new oyster reefs or improving the condition of existing reefs (Whitfield, 1974). Connecting flows from the estuary include fishery harvest, contribution to image which attracts tourists, residents, and capital, and assimilation of nitrogen and coliforms in sewage effluent.

To test one aspect of the feedback reinforcement theory the sensitivity of oyster stocks to increased harvest effort was estimated. As shown in Figs. 45 and 46, increasing harvest effort by factors of 2 and 4 times normal depressed the stock of adult oysters. If the model is correct, it would seem that additional urban feedbacks to the estuary and the oyster reef system would be required to increase the yield. Rockwood (1973) has proposed several methods for improving fishery yields. Whitfield (1973) has reported results of a shell planting program in Apalachicola Bay. Both sets of suggestions represent potential feedbacks from the urban sector to the producing system. Each suggestion should be evaluated to test the net yielding characteristics of the proposal. This has been done for the oyster industry in this paper.

Energy Value of Natural Pulses

Over the course of the year there is a gradual rise and fall in sunlight, temperature, river flow, productivity and other factors in Apalachicola Bay. It has been hypothesized elsewhere (Odum, 1971b) that estuarine communities have adapted periods of reproduction and growth to coincide with periods of peak production in the estuaries. Estuaries characteristically have populations of fish and shellfish moving in and out on a seasonal program that seems related to estuarine production. Such migrations have been recorded in Texas estuaries by Hellier (1962), Copeland (1965), and Odum (1967), and in Apalachicola Bay by Livingston (1975)(Fig. 18).

There may be special energy value related to pulsing seasonal programs in that populations that were dispersed over wide ocean areas become concentrated in estuarine areas and are available for harvest. Systems with pulsing inputs may be characterized by also having pulsing net yields, some of which are available to urban systems. The seasonal pulse in water and materials from the Apalachicola River may be a major factor organizing this characteristic. Because of the seasonal pulse in river flow bay, salinity and many other environmental factors change seasonally. Relatively few species are adapted to the full range of conditions found in the estuary and as a result many species are present for a short period of time when conditions are favorable and are then replaced by others. A few species such as oysters and some clams have adapted to estuarine conditions and are often present in great numbers. The river pulse which changes environmental condition may favor a system with fewer components, less spatial diversity, and large numbers of a few species. The special value of pulses, such as river flow, may be in organizing ecosystems with low diversity and large stocks of only several species.

This concept was incorporated into the regional model (Fig. 28a). Model responses were tested to changes in both the amount of freshwater entering the bay and the amplitude of the seasonal pulse. Results are shown in Fig. 40. In this simulation, pulsing river flows tended to maintain oyster stocks. River flows much higher and lower than normal and without seasonal pulses caused oyster stocks to decline. Menzel _et al_. (1957) have shown that predator stocks increased on one reef in Apalachicola Bay when the salinity pattern stabilized for several years. Adult oysters disappeared from the reef during this time. While no quantitative value has been given to the pulse of the Apalachicola River in the study area, the ability of the urban area to process purchased goods, fuels, and services and to maintain the established estuarine oyster fishery was shown in this model to be related to river pulse.

Alternative Factors Controlling Patterns in the Region

This section brings together calculations and simulation model results concerning county trends resulting from proposed or existing modifications. Included are considerations of nutrient and organic matter loading with oxygen depletions, salinity control in the bay with passes and impact on the county energy budget of adding urban housing developments to St. George Island.

Nutrient and Organic Matter Loading with Oxygen Depletions

The concentration and seasonal cycles of nitrate and ammonia were shown in Fig. 17 (Estabrook, 1973). Peak nitrate concentrations occurred in February and were generally lower than those for other river-dominated estuaries including the upper and mid-Chesapeake Bay (Carpenter *et al*., 1969), Patuxent River, Maryland (Flemer *et al*., 1970) and the Ythan estuary (Leach, 1971). In the Potomac River, nitrate plus nitrate concentrations were often 5 to 10 times the peak value observed in Apalachicola Bay. The Potomac receives sewage wastes from the Washington, D.C. area. Peak values were similar to those observed for

North Carolina estuaries (Thayer, 1969). The seasonal cycle in nitrate concentration was similar to those observed in other river-dominated estuaries (Carpenter *et al*., 1969) and temperate coastal areas with early spring overturn (Martin, 1965). Ammonia concentrations were similar to those reported for the lower portion of the Chesapeake Bay (Patten *et al*., 1963) and lower than those reported for the Patuxent River, Maryland (Flemer *et al*., 1970), which has nutrient additions from a sewage treatment plant.

Total organic carbon was measured over several days in the fall of 1973. Data were not available on a seasonal basis for organic carbon. Organic matter concentrations in the bay were higher than those in the river apparently because phytoplankton stocks were more developed in the bay. The values observed were lower than those observed in Georgia marsh creeks (Odum and de la Cruz, 1967), the upper Chesapeake Bay (Flemer and Biggs, 1971), and Chincoteague Bay, Maryland, which does not have a strong river influence (Boynton, 1974). Stocks of organic carbon were about 5 times higher than those reported for shelf waters of the Gulf of Mexico (Fredericks and Sacket, 1968). In general, nitrogen and organic carbon levels were not high compared to other coastal areas with river inputs. Total input may be much greater than indicated by the one set of measurements presented here.

Calculations used in models indicated that most nitrogen used in phytoplankton photosynthesis originally entered the bay as organic nitrogen bound in particulate or dissolved organic matter. The nitrogen from this source, when recycled, constituted about 85% of the total input to the nitrogen storage in June (compare $J_{14} + J_{15}$ and J_{12} in Table 8). Inputs from urban areas constituted only about 1% of the inorganic nitrogen entering the bay.

The diurnal activity model was evaluated with late summer data from a station in the medium salinity plankton system which includes a major portion of the bay and may be representative of average conditions in the bay. Summer data were used because temperature and salinity were high and flushing and the saturation level of oxygen were at a seasonal low. With high temperature, oxygen use in respiration may have been near a seasonal high. Thus it may be that the late summer period is most likely to experience low oxygen levels. Oxygen measurements taken over 24-hr periods during the summer of 1973 never fell below 3.9 ppm even in the East Bay where respiration was dominant. In general most stations had oxygen levels above saturation during the day and slightly below saturation at night or just before dawn. Simulation model output showed normal diurnal oxygen variations of about 2.8 ppm for the water column. Oxygen levels in the model, as in the field, did not fall below saturation even in the predrawn period.

The model indicated the possibility of nitrogen being a factor limiting photosynthesis (see gross photosynthesis plot for cases 1 and 2 in Fig. 23). Nitrogen additions may stimulate photosynthesis some, increasing daily oxygen pulses as shown in Fig. 24. However, this model was not very sensitive to nitrogen additions, and additions up to 5 times the normal rate did not cause oxygen levels to drop below saturation. Estabrook (1973) found that phosphate may have been limiting phytoplankton production during periods of calm weather in late summer. However, he suggested that phytoplankton photosynthesis was primarily controlled by temperature. While temperature may stimulate photosynthesis some directly (Williams and Murdoch, 1966) it also may be promoting the recycle of bound nutrients via respiration. The large diurnal changes in nitrogen seen in all simulations suggest recycle to be a major source of nitrogen during the summer. Iverson (1975) has suggested that there may be a substantial stock of nitrogen in the bay sediments. If this is true, remineralization of this material would be another source of inorganic nitrogen available for phytoplankton photosynthesis. A large sediment nitrogen storage would also act as a stabilizing factor in the model. Diurnal changes in inorganic nitrogen would have been reduced if this storage had been included.

Oxygen concentrations fell below saturation where detritus input was increased and when reaeration was restricted. When reaeration was reduced to 10% of the normal level and detritus input increased to 4 times the normal input rate (equivalent to river concentrations of about 20 g C/m^3) predawn oxygen levels were at about 3 ppm. These conditions might be expected for areas with higher than normal organic matter inputs and restricted circulation. If organic inputs increased and circulation became restricted, some portions of the bay might experience severe oxygen depletions before low oxygen levels were characteristic of the bay in general. If organic matter inputs to the bay began to increase the East Bay area may show signs of oxygen depletion first because the area is somewhat restricted with poorer circulation and reaeration. Diurnal metabolism measurements indicated that respiration was already dominant in this area.

Salinity Control with Dams and Passes

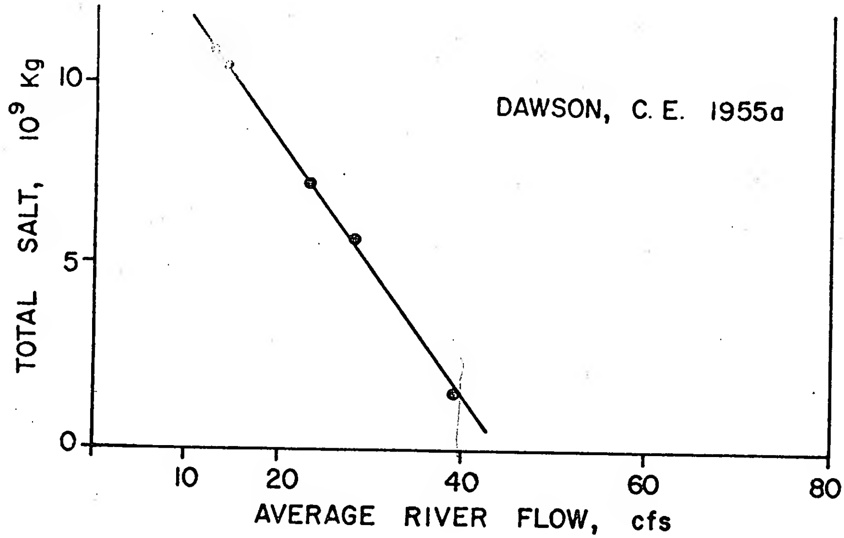
The changing salinity regime in Apalachicola Bay is an important factor in maintaining estuarine characteristics. Seasonally the average bay salinity changed from about 8 ppt in late winter to about 21 ppt in late summer. Indications are that the seasonal change in salinity due to river pulse favors oyster communities over more diverse communities with less yield found in areas with stable salinities. Several environmental modifications have been made or are planned that may affect the bay salinity pattern.

In 1965 Jim Woodruff Dam was constructed at Chattahoochee, Florida, on the Apalachicola River. Lake Seminole was formed behind the dam. Monthly average river flow for the period 1929-1972 was given in Fig. 13. No obvious changes in river flow are evident from this plot. Both before and after dam construction there were years of high and low flow. Figure 14b shows monthly river flow averaged for a 15-year period before and after dam construction. Average peak flow prior to dam construction was slightly lower than after the dam was built. Also, before the dam was built average river flow declined to low flow more slowly than after the dam was built and then rose more quickly. Statistical tests of the means for average monthly flows before and after dam construction (February, March, and November, when differences between average flows were the largest) showed no statistical difference at the 0.01 level.

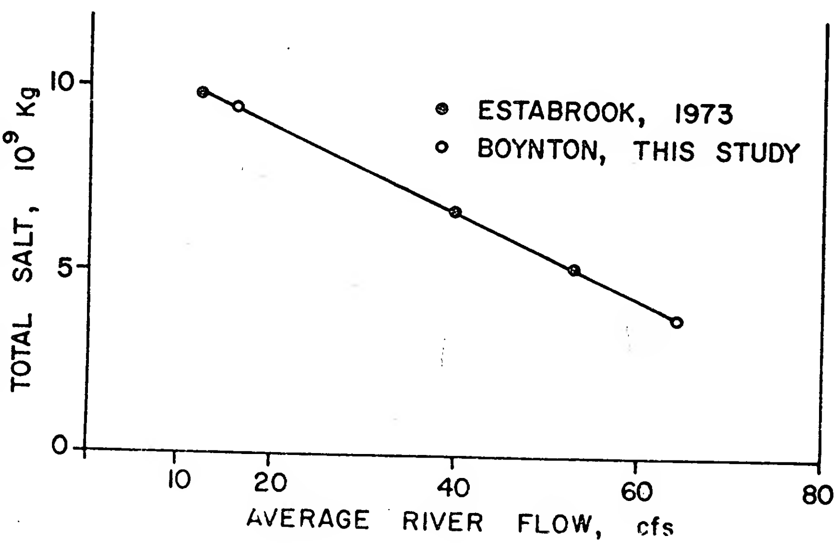
Information developed in this study and information from Estabrook (1973) and Livingston (1975) suggest that there may have been some changes in the salinity pattern in the bay related to the construction of Bob Sikes Pass (Fig. 1). Dawson (1955a) conducted a hydrographic survey prior to pass construction and reported that the bay was well mixed with salinity stratification occurring only occasionally in navigation channels and near inlets. In surveys done recently, salinity stratification was a general feature. Even during periods of high river flow there was stratification in the outer portions of the bay.

Figures 8 and 9 indicate high salinity water was associated with Bob Sikes Pass. To estimate if there have been changes in the bay salinity after construction of the pass, area weighted estimates of total salt in the bay were calculated and plotted against average river flow. Figure 58a shows data from Dawson (1955a) plotted in this way for a period just prior to the construction of the pass. Figure 58b shows data collected in 1973 plotted in the same way. Both plots indicate that total salt in the bay was inversely correlated with river flow. Comparison of the two plots suggests that during periods of low river flow there was little difference before and after the shrimp boat pass was cut. However, the plots suggest that during high river flow periods there was more salt in the bay after construction of the pass. If more salt was in the bay this suggests that the degree of mixing of bay and river water has decreased and that river water is reaching the Gulf of Mexico faster than before the pass was cut. It seems possible that the shrimp pass has caused this general increase in salinity. More data should be collected to substantiate fully the suggestion made here.

Fig. 58. Plot of total salt versus river flow. (a) Data from Dawson (1955a) taken just prior to construction of Bob Sikes Pass, (b) Data from Estabrook (1973) and this study. Average river flow was calculated using average daily river flow for a two-week period prior to salinity measurements.


DAWSON, C. E. 1955a
TOTAL SALT, 10^9 Kg
0
5
10
10
20
40
60
80
AVERAGE RIVER FLOW, cfs

(a)


ESTABROOK, 1973
BOYNTON, THIS STUDY
TOTAL SALT, 10^9 Kg
0
5
10
10
20
40
60
80
AVERAGE RIVER FLOW, cfs

(b)

Salinity control has implications for the oyster industry. It appears that oyster communities do best in areas that have seasonally changing salinities (Menzel et al., 1957). One reason for this is that many oyster predators cannot withstand low salinity water. Each year when salinity drops these species are either killed, migrate to other areas or become dormant and oyster predation decreases. Additionally, the influx of freshwater kills many fouling organisms that are attached to oyster shell. After these organisms die cultch is clean and available for new oyster spat (Gunter, 1953). Other mechanisms are also probably active that favor oyster dominance in estuarine areas with changing salinities.

Data from Menzel and Cake (1969)(Fig. 59) show a fairly clear relationship between environmental change (as indicated by salinity range) and diversity. Low diversity was associated with large yearly salinity changes. High diversity was associated with areas with stable salinities, in this case areas near the ocean. Oyster bars in Apalachicola Bay were associated with areas of moderate salinity change (15-20 ppt). Two stations were deleted from this plot. Both had diversities lower than expected. They were located at the river mouth where many factors such as sedimentation and dredging may be controlling diversity.

Shown in Fig. 60 is a long-term plot of the lowest yearly salinity recorded at two oyster bars in Apalachicola

Fig. 59. Plot of maximum salinity range per year at 13 stations in Apalachicola Bay versus yearly average species diversity recorded at that station. Data were from Menzel and Cake (1969). Diversity was reported as

$$\frac{\text{number of species}}{\sqrt{\text{number of individuals}}}$$

Numbers on the diagram correspond to station numbers reported by Menzel and Cake (1969).

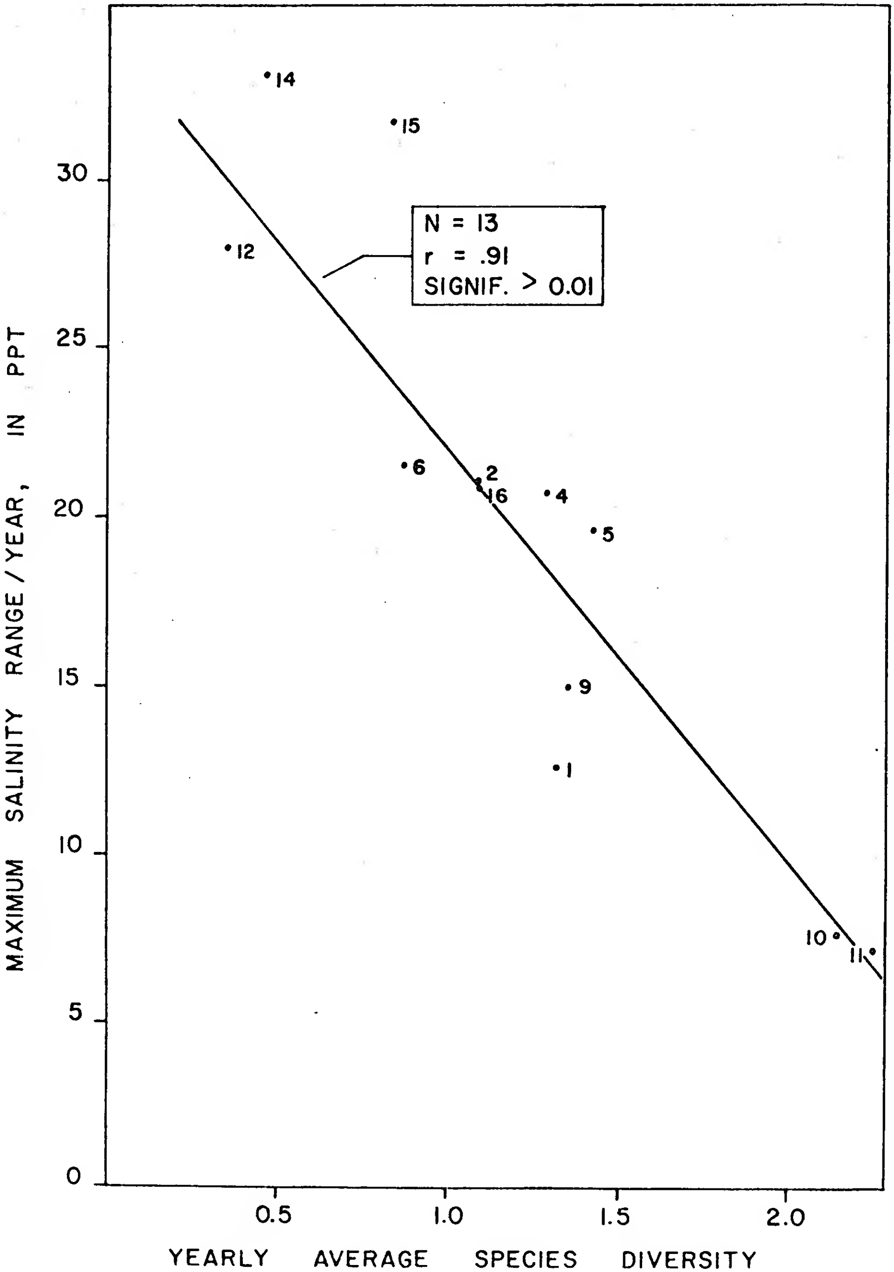
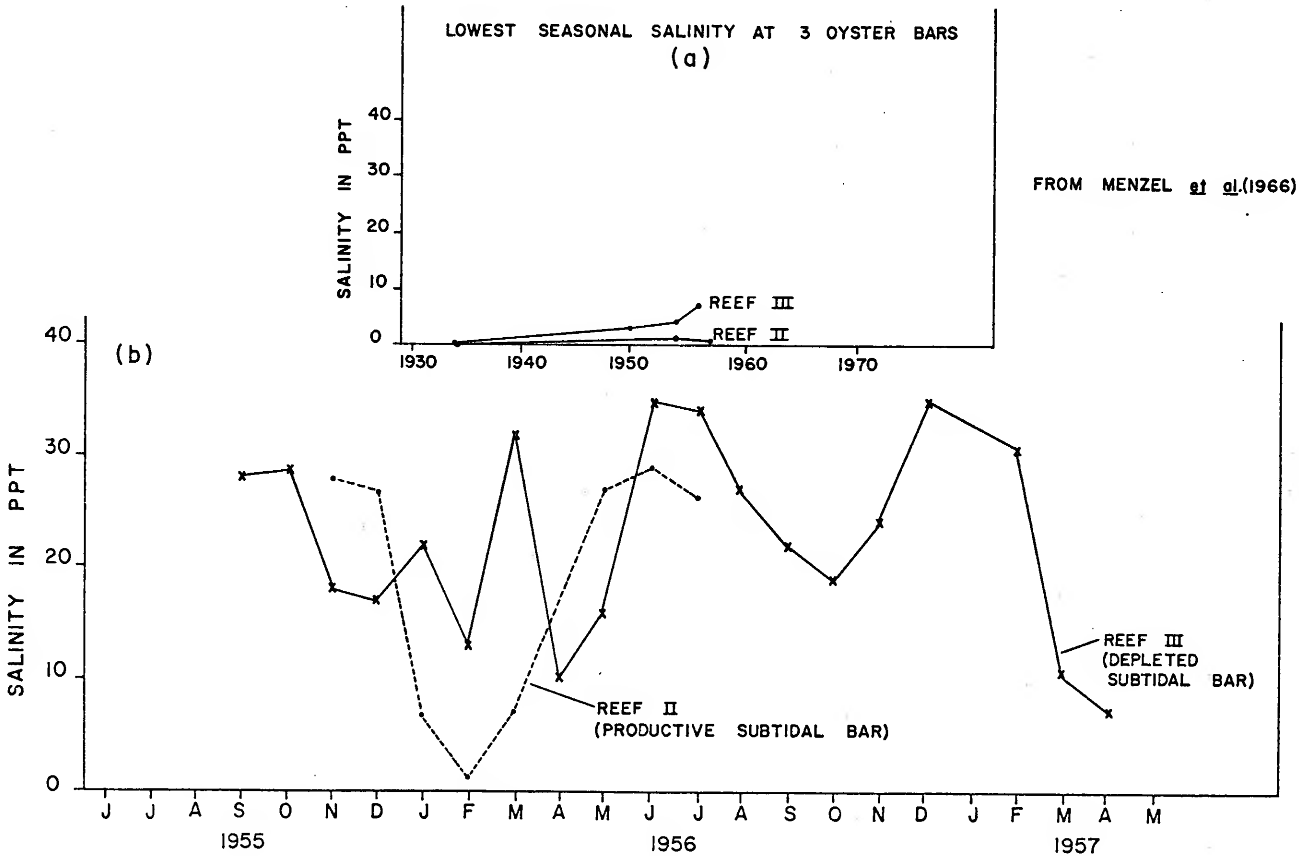

N = 13
r = .91
SIGNIF. > 0.01
MAXIMUM SALINITY RANGE / YEAR, IN PPT
YEARLY AVERAGE SPECIES DIVERSITY
0
5
10
15
20
25
30
0.5
1.0
1.5
2.0
14
15
12
6
2
16
4
5
9
1
10
11

Fig. 60. Salinity data at two oyster reefs in Apalachicola Bay. (a) Yearly lowest salinity recorded at reefs II and III, (b) Monthly salinity recorded at reefs II and III. All data are from Menzel *et al*. (1966).


LOWEST SEASONAL SALINITY AT 3 OYSTER BARS
(a)
SALINITY IN PPT
40
30
20
10
0
1930
1940
1950
1960
1970
REEF III
REEF II
FROM MENZEL et al.(1966)
(b)
SALINITY IN PPT
40
30
20
10
0
J J A S O N D J F M A M J J A S O N D J F M A M
1955
1956
1957
REEF II
(PRODUCTIVE SUBTIDAL BAR)
REEF III
(DEPLETED SUBTIDAL BAR)

Bay. Station II is near the John Gourie Bridge. Station III is near the eastern end of St. Vincent Island. Data and station numbers are from Menzel _et al_. (1966). There is some indication of increasing salinity at station III especially after construction of Jim Woodruff Dam and the boat pass. Station II does not show this trend. The lower graph in this figure shows monthly salinity values at these same oyster bars. Station II was a very productive reef, had few predators, and was subjected to a well-defined seasonal dip in salinity. Station III was depleted with only small spat present. Predators were common. Salinities at this reef did not drop as low as at Station II and were often above 30 ppt. Menzel _et al_. (1966) noted that their study was done during a dry period and this may be in part the reason for the lack of adult oysters on Reef II. This reed had previously been quite productive. Several local oystermen said that oysters were scarce in Reef III during the 1974-75 season.

The data suggest that salinities are higher and have less seasonal change now than before the pass was constructed. Since stable salinity regimes do not favor oyster production (as suggested in Fig. 59) a quantitative assessment of the boat pass and its relation to salinity and stratification may be advisable, especially if some additional loss of freshwater associated with a proposed navigation dam on the Apalachicola River can be anticipated.

If the pass proves to be a major factor in changing salinity and mixing, it may be possible to modify the pass slightly so that freshwater is retained and mixed in the bay while the recreational and commercial use of the pass can be continued.

Urban Housing Developments

The proposed island housing development has stimulated local interest in the consequences of attempting to have a fishing and recreation area coexist in close proximity to one another. Sewage disposal schemes have been proposed by the developer as well as a monitoring program to detect changes in water quality associated with the development. The impact of the new development in terms of energy flow at the county level was given in Table 11. On a yearly basis the new development represented a 65% increase in purchased energy flows in the county. Compared to energy flows in other parts of the state and nation, Franklin County would still be less developed with an investment ratio of 0.37. This ratio may be low compared to the national average reported in Odum and Brown (1975) due to calculation differences. The national ratio had natural inputs calculated by dividing annual sunlight by a factor of 2,000. Here all natural energies were summed including sunlight and thus the divisor in the investment ratio was larger. Using Odum's method the investment ratio becomes

0.45 which still indicates low levels of development relative to the national average.

In Fig. 53b a calculation was made comparing urban and natural energy inputs assuming that the proposed development was expanded to include the entire island. In this case the investment ratio became 3.1 suggesting that this level of development would overdevelop the county compared to the rest of Florida and the nation.

In Fig. 53c a third evaluation of the development was done using an area around the development rather than the whole county. If the energy flows associated with the proposed development (Fig. 55) are compared to natural energy flows in the full county, the investment ratio increases to 0.37. The implication from this may be that a development of the proposed size would not overdevelop the county. This calculation was done to see if the density of the development was high relative to surrounding areas. Could other similar developments be added to this one and not overdevelop the local area? As shown in Fig. 53c the investment ratio was quite high (9.63), well above the national average. If construction costs were not included, the ratio was still high (> 5). The ratio suggests that at the densities proposed, high-quality purchased energies will not find sufficient natural energies for matching. There may be an overdependence on purchased energy flows.

Several simulation experiments with the regional model were also aimed at estimating the impact of large developments based on external energy sources. The proposed island development is of this type because its success depends largely on excess energy being attracted from outside the county.

Figure 44 shows the impact of an attempt to develop the county which fails. In this run there was a temporary surge in building (as represented by the structure, capital, and image storages). However, it was hypothesized in this experiment that external energies (or capital with which to direct energies to Franklin County) were not available for completion of the project. The simulation shows a "boom and bust" pattern with no lasting effects. In this simulation the oyster fishery did not close because of water quality changes. Based on current information the proposed island development would have a yearly investment of about \$9.9 x 10^6/yr (about 20 times the current investment rate) and thus would be equivalent to something between cases 2 and 3 in Fig. 44. Since all prices in this simulation were constant, the effect may be more like case 2 than case 3. In fact, if energy limitations in the county as a whole are as severe as some suggest, there may be no change at all because the development will never start.

Several economists doing work in the Franklin County area (Colberg and Windham, 1965; Rockwood, 1973) have stressed the fact that the region has a limited economic base and is susceptible to economic problems should anything interfere with the fishery. According to proponents of the island development this project would provide additional employment and relieve the county dependence on fisheries. Several simulation experiments were done to investigate this problem.

In the simulation shown in Fig. 43 tourist money to the county was allowed to expand. As the simulation shows the effect of the seasonal nature of the oyster fishery lessened as the tourist input increases (case 4). In this simulation there was closure of the fishery. The impact of fishery closure was not large because when closure occurred the oyster industry was a small part of county income. Growth continued. However, in this simulation, prices were constant and the income associated with tourism was about 2 times as large as investment associated with the proposed development. In Fig. 48 the inflation rate for both purchases and sales was at 20% per year. In case (b) the investment rate was similar to the one for the proposed development. In this case the dependence on the industry was still evident as shown by the response of the capital storage. The inflation rate of 20% per year leveled growth and the decline was severe because the oyster industry was closed (indicated by the spikes in the capital storage) because of high coliform counts. In this case investment did not help the county economy over the long run because of external energy shortages and because the oyster industry was closed.

A third possible outcome was explored in the simulation shown in Fig. 47. In this case there was an inflation rate of 10% per year and investment increases to 10 and 20 times the normal rate. In cases (a) and (b) there was some growth and then a gradual decline because of continued inflation. Investments and prices for oysters and other sales would have to increase to offset the effects of inflation if growth were to continue. Case (c) shows model response under investment conditions similar to those of the proposed development and inflation rates for sales and purchases of 10% per year. It was hypothesized, however, that due to the development the oyster industry was lost for one reason or another. The simulation suggests that a development of the size proposed is not large enough to cover losses should it interfere with the oyster fishery. As shown in Fig. 47 county structure goes into a decline upon the loss of the oyster fishing even though investment in the development continued.

The decline in county structure would have been more severe if development stopped because of poor water quality conditions in the bay. It seems wise in this case to devise mechanisms for protecting both the oyster fishery and the development so as to assure coexistence of both.

Factors of Energy Investment Return

The energy return from energy investment is discussed in this section including the oyster industry and the conversion of river head to electricity.

Oyster Industry

Calculations showing the energy basis of the oyster fishery were shown in Fig. 52. The energy basis, expressed in fossil fuel equivalents, was mainly natural. Harvesting was most of the purchased energy input (about 12%). Energy in sewage from the town and planting of oyster cultch was relatively small. On an energetic basis, the present oyster industry is not highly dependent on purchased fuels within the county. Hence, the oyster industry may be less susceptible to rising fuel prices.

The matching of natural and purchased energies in the oyster industry was traced from input of natural energies to final consumption. At dockside (P) the investment ratio was 0.18 (2.2/12). When oysters left the county the ratio was 1.35 (16.3/12.0) and when consumed the ratio was 2.15 (25.8/12). The calculation suggests that the natural energies acting in support of the oyster industry eventually attract fossil fuels in the same ratio as the average of other processes in the country. This may indicate that more fuel-intensive oyster fishing will not be competitive.

Additionally, if the ratio of purchased to natural energies continues to drop, the oyster processing chain may shorten with more use of oysters in the county.

Most oyster reefs in Apalachicola Bay occur in the areas occupied by the medium salinity plankton ecosystem (Fig. 7). This area covers 80,000 acres. Rockwood (1973) suggested that this area could support many more oyster reefs than at present. Energy used in maintaining the present reefs (Fig. 52a) was compared to total sunlight input to the medium salinity plankton system. Total sunlight was used as an estimate of total energy available for oyster growth (5×10^{14} Kcal/hr of sunlight). The calculated energy use by oysters was about 2.5×10^{14} Kcal/yr. Comparison of these numbers suggests that the bay may be able to support twice the present population of oysters. Oyster bars are supported by large areas of the estuary through water movement. This points for the need for full estuarine management when considering the management of oyster reefs. If must be noted that this calculation assumed that no other energy subsidies were involved in oyster production. Higher densities could be achieved in the bay only by adding more purchased energies such as supplemental feeding. Intensive aquaculture is an example. Per area the output of oyster meat from Apalachicola Bay was about 8×10^4 Kcal/acre/yr. The harvest came from about 8,000 acres of oyster beds in the bay. The yield for pasture beef in

Florida was 20 x 10^4 Kcal/acre/yr. In beef production, about 30% of the input energy was from purchased fuels (De Bellevue, 1975). Meat production from estuarine areas compares favorably with alternatives.

Simulation results shown in Figs. 45 and 46 suggest special energy inputs to the bay would be required if oyster yields were to increase much beyond the present yield. In these simulations an increase in harvest effort by a factor of 2 caused large declines in the standing stock of oysters. If additional inputs were developed using purchased energies, output may increase but so also would dependence on fossil fuels. The cultch planting program may be an example of a mechanism for increasing yields in a fashion that is not heavily dependent on purchased fuels.

The oyster fishery represents a large net yielding process for the county. On a fossil fuel basis, total harvest effort was 1.64 x 10^{10} $Kcal_{FFE}$/yr in 1970. Oyster sales represented 1.63 x 10^{11} $Kcal_{FFE}$/yr (\$6.5 x 10^6 x 25,000 Kcal/\$). This represents a 10 to 1 return on the investment as represented by harvest effort.

Energy Costs of Basin Formation

In the calculation given in Fig. 56 the energy quality of river head came out to be 1.42 times as concentrated as fossil fuel equivalent calories. This indicates that the potential energy of elevated water is of high quality. Young et al. (1974) calculated a slightly higher ratio using information for larger dams. High quality of elevated water has been utilized for many years by the construction of hydroelectric dams on many major river systems around the world. A suitable basin is a prerequisite for most hydroelectric facilities. In the creation of the reservoir at Jim Woodruff Dam a considerable area of flat land was flooded. Some terrestrial land was converted to a use with less metabolism as a reservoir. This contribution was 75% of the total cost and may be similar to geological costs in other river systems spent on creating more relief and storage capacity.

Energetic Basis of Regional Coastal Image

What factors attract money and people to the Franklin County region? In interviews, some suggested it was the natural resources of the area. Others felt it was related to the existing structure in the area. Several combinations of rates and storages were suggested. It was hypothesized that there is in every region a factor which represents the ability of an area to attract outside investments and thus amplify that region's ability to do work. We chose to call this factor image and to make it proportional to energy flows. Image had inputs from the major work processes occurring in the county. These included inputs from estuarine and terrestrial metabolism and urban activities as represented by the major input to structure (Fig. 28a). Each input to image was adjusted so that the energy flow along the pathway was in fossil fuel equivalent kilocalories. Energy flows of different quality were weighted equally in their ability to do work.

If the attractiveness of a region is based on the energy flows available, the coastal zone would seem to have a naturally high image because there are special energy flows associated with coastal areas not generally found elsewhere. These include waves and tidal energy, potential and kinetic energy of river flow, coastal currents, mixing energy available from the concentration difference between river water and ocean water, steady winds and perhaps others not recognized here. Energy inputs to the estuarine area in Franklin County were more than twice what they were in other areas of the county. If the theory is valid, these special energy flows will attract more external investments. Over 50% of the population of the U.S. lives in counties bordering on the ocean or Great Lakes (Ketchum, 1972). Most urban centers in Florida occur in coastal areas.

In this dissertation, the image of the region was based on both urban and natural energy flows. Odum and Brown (1975) suggested that the ultimate ability of a region to attract high-quality energies depends on the amount of lower-quality natural resident energies available for interaction with high-quality flows. High-quality work can be done by high-quality flows only when there are low-quality energies with which to interact. If these are not available, the high-quality flows can not be fully used in a high-quality fashion and the system produces less to exchange for more purchased fuels.

World Conditions of Energy Prices and Future Trends in Coastal Franklin County

The conditions of world fuel prices as they may affect future trends in Franklin County were explored using the regional simulation model shown in Fig. 28a. Sharp growth trends were observed only when external energies were not limiting. These familiar trends were shown in Figs. 42 and 43.

The most dominant trend in the regional model was that growth in the urban sector leveled and declined slowly when prices were allowed to inflate at rates similar to those in the nation. This pattern was consistent under a variety of conditions. In Fig. 41 prices for oyster sales and prices for goods, fuels and services were both inflating at 10% per year. It was hypothesized that some modification could be made in the bay with little cost (perhaps similar to the cultch planting program) that would increase the recruitment of adult oysters. As shown, even increasing the recruitment rate by a factor of five was not sufficient to offset declines in the urban sector. Increasing the harvest effort (Figs. 45 and 46) did not offset declines because oyster stocks became limiting. Declines were more severe when the inflation rate of oysters was less than for goods, fuels and services (Fig. 46b). There were only small declines when the investment rate was increased to ten times the current rate and some growth when the rate was increased to 20 times the current rate (Fig. 47b). Declines and "boom and bust" trends were sharper with large investment rates and 20% per year inflation (Fig. 48). In all cases, declining energy limited long-term growth. In Fig. 43a (case 4) the oyster industry was lost due to high coliform counts. With rich energies available oyster income was only a small part of county income and loss of the industry had little effect on the growth pattern. When external energies were limiting loss of the oyster industry caused a reversal in growth trends (Fig. 47c) and a decline in structure.

Growth based on the oyster industry had a stable pattern with leveling as shown in Fig. 49, a characteristic of all runs based on internal resources. Leveling was initiated when oyster stocks declined.

When prices were allowed to inflate the yearly change in capital became more pronounced. This resulted because both inputs and outputs from the capital storage increased while the stock remained about the same. Hence the stock was sensitive to interruptions in input such as that caused by the seasonal oyster harvest. The pulse became larger when harvest effort was increased or when increased investment created new structure which required expenditures for maintenance.

This model suggests that when external energies are limiting, efforts to continue growth lead to increased turnover of capital and sensitivity to interruptions. Attempts at growth based on external investment were shown in Fig. 48. In case (a) declines were smooth and gradual. In cases (b) and (c) there was a boom and bust cycle with large yearly changes in capital and in case (c) loss of the oyster industry. The end result in all three cases was about the same. The model suggests that when external energies become limiting, as they may be now, declines in structure may result. Large investments aimed at growth were not long-lasting, created large yearly changes in capital, and in one case caused the loss of the previously successful oyster industry.

While this model predicts leveling or declines in the county due to external energy shortages, there still may be some significant growth in the area in the future. This growth, if it occurs, may be based on the redistribution of purchased energies from presently developed urban areas in other parts of the country. During initial periods of growth, based on large energy sources, there was a premium on getting assets generated with which to feed back to the energy source. Those areas with the most early assets won when in competition with other systems with smaller assets. The result was spotty development with unequal distribution of fossil fuels. However, when energy sources become limiting, as they may be at present, this advantage declines both because further efforts to process more fuels are not successful and because maintenance costs are high. The work done in these areas per unit of fuel expended may decline. Rural areas with more natural energies available for use with fossil fuels may become more competitive and attract high-quality energies away from present urban areas. High-quality energies may become more evenly spread across the landscape. It seems possible that this may happen in Franklin County because of the abundance of natural energies available.

Fisheries and Urban Economy

The future coexistence of coastal fisheries and urban development was a central issue in this paper. Simulation models and calculation results suggest several trends and strategies that may have use in Franklin County or other similar areas.

Energy calculations suggested that the support of each acre of oyster reef was derived from about five acres of estuary. The present ratio of oyster reef area to estuary in Apalachicola Bay is about one to ten. It may be possible to expand the natural oyster stock by a factor of two without the addition of large purchased energies subsidies.

The evaluation of the oyster industry suggested that about 37% of the value of oysters was exported from the county and matched with fossil fuels elsewhere. If the oysters were more fully processed in the county more high-quality energy may be attracted to the county and add to the energy basis of the area. The low ratio of purchased to natural energies suggests that there would be a good return on additional inputs of purchased energies.

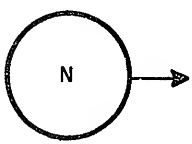
Simulation results from the regional model (Fig. 28a and Fig. 47) and investment ratio calculations suggest that addition of more purchased energies would bring the county economy into a more competitive position relative to the rest of the nation. In this sense development would be good. However, simulation results also suggest (Fig. 47c) that new developments that affect water quality, and hence the oyster industry, should be kept well insulated from the estuary. If this can be done, coexistence may be quite possible. The disposal or recycle of some wastes from urban developments might be done in the abundant wetlands in the county. This type of coupling would make purchased fuels available for other uses, and may provide a needed buffer between estuarine fisheries and urban activities.

APPENDICES

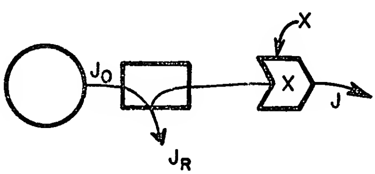
APPENDIX A

SYMBOLS USED IN MODEL DEVELOPMENT

The symbols used in diagrams of models are those of the enery circuit language developed by H. T. Odum. Each symbol has both a verbal meaning and an exact mathematical equivalent which can be found in Odum (1971a, 1972a).

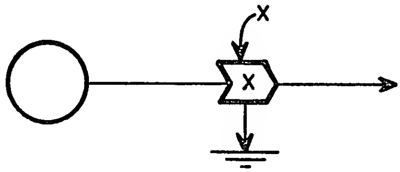


Forcing Function. An external source of energy with or without materials whose driving forces are independent of model behavior. Program can be constant, sinosoidal, etc. and is controlled from outside the model.

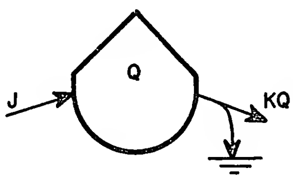


Flow Limited Forcing Function. An external source of energy with or without materials whose input can be a limiting factor due to interactions within the model.

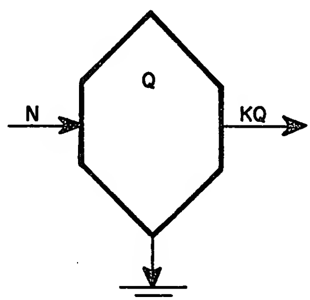
$$J_r = J_o - kJ_rX; \; J = k\left(\frac{kJ_o}{1 + kX}\right)(X)$$



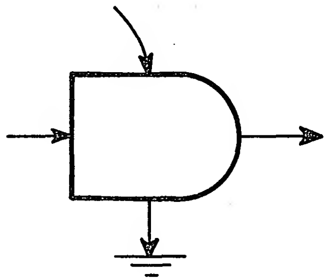
Forcing Function. An external source of energy with or without materials whose input is determined by some variable within the model (X). Inflow can only be limited by the variable with which the forcing function interacts.



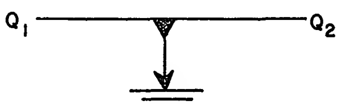
Storage Module. Represents a storage of energy of materials within a system where a quantity is stored as the balance of inflows and outflows ($\frac{dQ}{dt}$ = J - kQ) and where outflow includes depreciation.



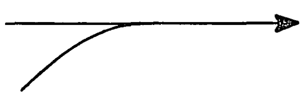
Self-Maintaining Consumer Model. A group module which represents a consumer unit including a combination of a storage module and at least one multiplier where energy stored in one or more places in the module is fed back to do work on processing input energy to that unit; response is autocatalytic if the above features are included. The group symbol is often used to organize model components. When used in this way, it does not imply additional pathways beyond those actually shown.



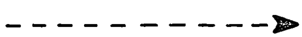
Production and Regeneration Module. A group module representing an interactive production process and storage. Normally used to depict green plant photosynthesis. On a regional scale the module represents the production and consumption of entire ecosystems (P/R). Details of relationships in a particular model are shown within the group symbol.



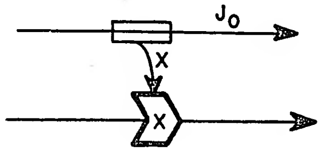
Pathway. Shows a flow of energy with or without materials which is proportional to a quantity in storage or external sources at each end ($J = k(Q_1 - Q_2)$). The heat sink represents energy losses due to frictional forces and backforce along the pathway.



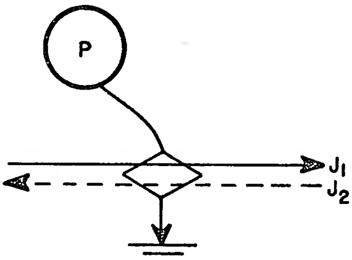
Adding Junction. Shows the intersection of two pathways capable of adding. Arrow indicates direction of flow and absence of any backforce.



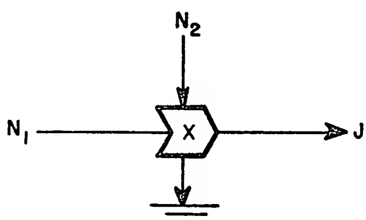
Money Pathway. Dashed line indicates a flow of money with arrow indicating direction.



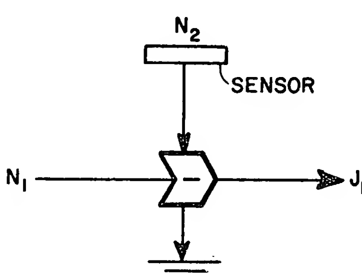
Force from a Flow Symbol. Flow rate of one pathway (J_0) delivers a force X that is proportional to the sensed flow and derives its energy from it.



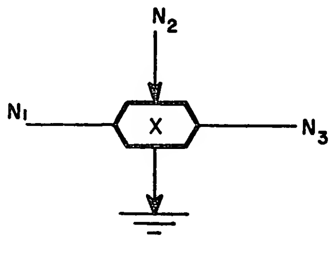
Price Transactor. Symbol indicates an economic transaction with price (P) the ratio of money flow to energy flow (J_2/J_1). Price may be constant or may vary in a variety of ways. Heat sink indicates the energy cost of maintaining transactions.



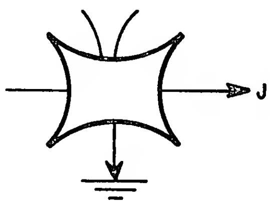
Multiplicative Workgate. Symbol indicates intersection of two pathways coupled to produce an outflow proportional to the product of the forces driving both flows. General response is a limiting factor type ($J = kN_1N_2$).



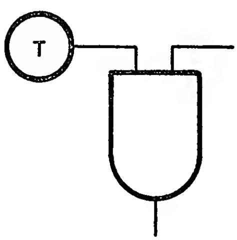
Drag Action Workgate. Symbol indicates an intersection where an increase in one flow has a retarding effect on the output flow ($J = kN_1(1 - kN_2)$). Sensor symbol indicates there is no appreciable loss from N_2 in this interaction.



Reversing Multiplier. Symbol indicates an intersection where flows may reverse direction when the downstream force is greater than the upstream force [$J = kN_2(N_1 - N_3)$]. N_2 is the common driving force variable.



Group Logic. Group symbol for on-off processes controlling flow J. Details are drawn within such as the Logic Comparator shown next. Heat sink indicates the cost of maintaining logic control.



Logic Comparator. A logic module which is on or off depending on a critical threshold (T).

APPENDIX B

ECOSYSTEM CLASSIFICATION SYSTEM

A classification of ecosystem types was developed for Franklin County and used in the land-use maps in Figs. 6 and 7. Categories were named so as to recognize dominant energy flows or vegetation types.

Urban Systems

Scraped Land. Lands cleared and prepared for development.

Light Residential. Residential areas with densities of four units per acre or less.

Medium-Dense Residential. Residential areas with densities of four units per acre or more.

Commercial and Industrial. Commercial and industrial areas within the city.

Airport. System designation used here to identify position of local airports. Airports in Franklin County not used for regular commercial traffic.

Coastal Systems

Oligohaline System. System existing at the river mouth area of estuaries (normal salinity 0.4-10 ppt). Characterized by large seasonal salinity changes due to river pulses, turbid water, and low diversity. Biomass is often high being composed of mollusks, and migrating invertebrate and fish subsystems (Copeland *et al*., 1974).

Grass Flats. Estuarine system occurring in shallow waters with moderate currents, fairly stable salinities and low turbidity. In turbid bays, grass flats occur on shallow sand bars. Characteristic plant species include *Diplanthera* and *Ruppia* in intertidal areas, and *Thalassia*, *Syringodium* and *Halophila* below water levels. *Zostera* is dominant in more temperate areas. Animal species are varied and often depend on the grass flat for part or all of their life cycle (Phillips, 1974).

Salt Marsh. Estuarine system most often characterized by dense stands of *Spartina* and/or *Juncus* with large seasonal organic matter exports to adjacent estuarine areas. Marshes develop where there are areas of intertidal soft sediments not too strongly stressed by ocean waves or winter ice. Large numbers of estuarine species utilize marsh creeks for feeding, protection and as nursery areas (Cooper, 1974).

Oyster Reef. Estuarine subsystem found where currents and tidal action bring suspended material that serves as food and eliminates waste from the reef community. Biomass of oysters and associated organisms is high, diversity moderate and metabolism high and dependent on supplies of imported organics. Most commercial oysters bars occur in the medium salinity plankton system zone or intertidally in higher salinity areas (Chestnut, 1974).

Sand Bar. Intertidal or subtidal sand areas formed by current action. Characterized by shifting sands, lack of rooted vegetation and sparse benthic populations.

Medium Salinity Plankton System. System characterized by salinities between 5-18 ppt and often located in the middle broad portion of east coast estuaries. Seasonal cycles of nutrients, temperature, phytoplankton and zooplankton production are evident in northern and temperate areas. The food web is based on phytoplankton production and supports commercial quantities of fish, shrimp, oysters and clams. These estuaries often have partial stratification with wedges of dense salt water along the bottom. Anaerobic conditions do not generally occur on the bottom although oxygen is often lower than at the surface (Bellis, 1974).

Coastal Plankton System. The coastal system is located between the estuarine zone and the open sea, extending to a depth of approximately 300 ft. Phytoplankton production is the main photosynthetic food source. Respiration and nutrient recycle is accomplished both by zooplankton and diversified benthic communities. The coastal plankton system supports commercial fisheries (Odum et al., 1974a).

High Velocity Channel. Estuarine ecosystem characterized by high velocity currents (2-20 miles/hr) and having reef-like communities of encrusting organisms along the sides of the channel. Bottoms are often swept clean. In areas where waters are clear, dense stands of attached macrophytic algae are present. High metabolic activity is facilitated by the strong water flow delivering organisms and nutrients and flushing wastes. Where high velocity ecosystems occur near open ocean areas with high salinities, diversity is moderately high (Odum et al., 1974a).

High Energy Beach. Characteristic ecosystem occurring along sandy shores receiving strong wave action. Well-sorted sands and zones with distinct chemical and physical characteristics support a specialized biota of sand dwelling (psammon) animals. Different portions of the epipsammon live on the sand and include birds, fish, etc.; the endopsammon burrow into the sand and include snails, bivalves and crustacea; mesopsammon live between sand grains and include many invertebrate classes. The beach is primarily heterotrophic, acting as a large filter extracting both particulate and dissolved organics and nutrients delivered by ocean waves (Riedl and McMahan, 1974). In this classification the high energy beach extends out to the 20 ft contour or 500 yards offshore, whichever comes first.

Coastal Dune. Includes area extending landward from the extreme high tide line to the beginning of pinelands. The vegetation is adapted to salt spray and occassional inundation. Characteristic species include sea purslane, bermuda grass, seaside-pennywort, sea ort, seaside evening primrose, saw palmetto and others. Cabbage-palms and hardwoods may be present on the leeward side of old established dunes (Kurz, 1942).

Boat Basins and Harbors. These new estuarine subsystems are often characterized by depth exceeding natural flushing capacity resulting in deposition of sediments and organic matter. Phytoplankton production is high due to high nutrient concentrations but the euphotic zone is limited and respiration generally exceeds photosynthesis. Oxygen stress on the bottom can be severe and species diversity is often low.

Dredged Navigation Channel. These new estuarine subsystems are characterized by being deeper than surrounding areas, steep-sided, and often stratified with respect to temperature, salinity, oxygen, and other factors. At times oxygen concentrations may be very low.

Freshwater Systems

Shallow Woodland Pond. Freshwater ecosystems characterized by open water with slow exchange and seasonal stratification. In ponds, the littoral zone is large compared to the limnetic and profundal zones and is the main production area. Ponds were characteristic of the study region and were probably warm monomictic with circulation in the winter (Odum, 1971). Some ponds were surrounded by cypress, and many have rooted aquatic plants, dark water and seasonal water level fluctuation. Included here are a few brackish water ponds on the barrier islands.

Rivers. Freshwater ecosystem characterized by through-flowing waters, and general absence of stratification. Attached algae and diatoms may be important producers but imported organics are generally the primary food source. Rivers characteristically export organics, recycle nutrients, and support seasonal fish and insect populations (Odum, 1971). Two types of rivers appear in the study area and include low pH, blackwater rivers carrying swamp drainage, and turbid piedmont rivers carrying upland silts and clays.

Terrestrial Systems

Pine Forest. This type includes all planted pine (slash) stands in the county in which the trees are large enough to be recognized from aerial photographs. Those areas recently planted in which trees are not recognizable from the photographs have been included in the cleared/planted type. Also included here are scattered stands of native longleaf, slash, and sand pine which could not be clearly distinguished from planted pines on aerial photographs.

Cleared/Planted Lands. This type includes lands that have been cut for timber and recently replanted in pine or allowed to naturally reestablish vegetative cover. Ground cover is characterized by young planted pines (not recognizable from aerial photographs), shrubs, grasses, and scattered mature pines and saw palmetto. No attempt was made to distinguish between wet and dry habitats, or from natural savannahs as recognized by Clewell (1971).

River Swamp. Climax hardwood system found in seasonally flooded areas with poor drainage (along creeks, rivers, sloughs, and depressions) characterized by presence of *Fraxinum caroliniana* (Carolina ash), *Taxiodium distichum* (bald cypress), *Sabal palmetto* (Cabbage palmetto), and *Ulmus floridana* (white or American elm). *Acer rubrum* (red maple), *Nyssa sylvatica* (Black tupelo), and *Liquidambar styraciflua* (Sweetgum) are major species but also occur in bay swamps. *Quercus nigra* (water oak), *Q. laurifolia* (laurel oak), *Carya aquatica* (water hickory), and *Magnolia virginiana* (sweet bay) may also occur. *Cephalanthus occidentalis* (Cottonbush), *Ilex cassine* (cassena), *Myrica cerifera* (wax myrtle) and *Carpinus caroliniana* (American hornbeam) are the major understory trees. These swamps are more fertile, less acidic, and have more flooding than bay swamps. Tree dominance is more variable than in bay swamps. Litter accumulation is slight. Soils are alluvial.

Bay Swamp. A broad classification which includes titi, bay, cypress, and blackgum dominated swamps. Soils are very poorly drained highly organic sands of the Plummer-Rutledge Association. Clewell (1971) gives a full description of each swamp type. Also included here are savannahs characterized by frequent fire, poorly-drained Plummer-Rutledge soils, and dominant herbaceous vegetation. Soil moisture is higher than in the pine-palmetto flatwoods and some bays (Clewell, 1971).

Freshwater Marsh. Characteristic vegetation includes pickerel weed (*Pontederia lanceolata*), fireflag (*Thalia geniculota L.*), water lilies (*Nymphacea spp.*), *Utricularia inflata* (blatterwort), cattail (*Typha spp.*), spike rush (*Eleocharis cellulosa*), bullrush (*Scirpus spp.*), and spatterdock (*Nuphar luteum*). Seasonally to continually inundated by water with slow water drainage. Water levels generally higher than in wet prairies (Davis, 1943).

Pine Scrub. Areas characterized by sand pine (*Pinus clausa*), scrub oaks (*Quercus myrtifolia*, *Q. chapmanii*, and *Q. virginiana var. maritina*), palmetto (*Serenoa repens*), and various lichens. Wiregrass is absent. Soils are excessively drained and sandy soils of the St. Lucie-Kureb-Rimini association (Kurz, 1942). Included here are the Franklin County barrier islands.

High Pineland. Areas characterized by longleaf pine (*Pinus palustris*) with understory of bluejack oak

(Quercus incana), sand-post (Q. margaretta), turkey oak (Q. laevis) and sand live-oak (Q. gemineta). Wiregrass (Aristida stricta) is abundant with other herbaceous species present. Fire is frequent. Soils are deep, dry sands of the Lakeland group. Also called sandhill, turkey oak ridge, or scrub oak (Clewell, 1971).

Pine-Palmetto Flatwoods. Area characterized by longleaf (P. palustris) and slash pine (P. elliottii). Ground cover of wiregrass, saw palmetto, gallberry and others. Fires are frequent in the natural situation. Soils are sandy with an underlying hardpan several feet below the surface and are predominantly of the Leon group (Clewell, 1971).

APPENDIX C

SUPPLEMENTARY INFORMATION ON THE DIURNAL ACTIVITY MODEL

Table C-1
Data used in simulation of diurnal activity model (Fig. 19).

STATE VARIABLES Notation	Name	Description and Calculations	Reference
Q_1	Phytoplankton biomass	Total dry weight of phytoplankton in water column 2.1 meters in depth. Calculation assumed a carbon:chlorophyll-a ratio of 50:1. Chlorophyll-a data were for September. $2.5\ g/m^2$ $(0.012\ g\ Chl.\ a/m^3)^a \left(\frac{50\ g\ C}{gm\ Chl.\ a}\right)^b \times$ $(2\ g\ C/g\ organics)(2.1\ meters)$	(a) Estabrook, 1973 (b) Parsons et al., 1961
Q_2	Consumer biomass	Dry weight of all consumers except microbes. Oyster biomass is included on an area-weighted basis. Biomass was evaluated for September. $7.9\ g/m^2$ $(0.5\ g/m^2)^a + (6.79\ g/m^2)^b$ $\text{oyster biomass} = \frac{\text{total weight}}{\text{bay area}}$ $\frac{14.2 \times 10^8 g/bay}{204 \times 10^6 m^2/bay} = 6.79\ g/m^2$	(a) Fig. 18, September data. (b) Table 6, Case III including both adults and juveniles

Table C-1 - continued

STATE VARIABLES Notation	Name	Description and Calculations	Reference
Q_3	Dissolved oxygen	Dissolved oxygen in water column at 1200 hours. 16.4 g O_2/m^2 (7.8 g O_2/m^3)x(2.1 m)	Fig. 10b, oxygen curve at 1200 hrs.
Q_4	Detritus	Detritus in water column 2.1 meters deep 19.7 g/m^2 (4.7 g C/m^3)(2 g C/g organics)(2.1 m)	Table 5, average for all bay stations.
Q_5	Nitrogen	Inorganic nitrogen (NO_3+NH_3) in water column 2.1 m deep 0.063 g/m^2 (0.03 g/m^3)(2.1 m)	Fig. 17, September data for NO_3 and NH_3.
FORCING FUNCTIONS			
D	Detritus input	Average input of dissolved and particulate detritus per hour from the river and various sources. Calculation assumes an 18 day turnover time for the bay water. Approximately 0.12 m^3 is exchanged from the water column per 24	

Table C-1 - continued

FORCING FUNCTIONS(cont.) Notation	Name	Description and Calculations	Reference
D (cont.)		hours if the water column is 2.1 m deep 0.039 g/hr $(0.12\ m^3/day)^a (7.8\ g/m^3)^b (\frac{1\ day}{24\ hrs})$	(a) Gorsline, 1963 (b) Table 5, average of river stations
N	Nitrogen input	Average input of inorganic nitrogen (NO_3+NH_3) from the river and urban sources. Turnover was the same as in D of this table. .0013 g N/hr $(1.250\ g\ N/m^3)^a (0.12\ m^3/day)^b (\frac{1\ day}{24\ hr})$	(a) Fig. 17 (b) Gorsline, 1963
A	Oxygen advection	Average input of dissolved oxygen due to advection. Calculation assumed advected water was saturated with O_2 at S o/oo = 17 and T = 29°C. Turnover was assumed to be the same as in D of this table. 0.035 gO_2/hr $(6.93\ g\ O_2/m^3)(0.12\ m^3/day)(\frac{1\ day}{24\ hrs})$	Estimated

Table C-1 - continued

Notation	Name	Description and Calculations	Reference
FORCING FUNCTIONS(cont.)			
A_s	Oxygen saturation value	Oxygen concentration of water column 2.1 m deep at salinity of 17 o/oo and temperature of 29°C. Saturation value is constant in this model. $(6.93\ g\ O_2/m^3)(2.1\ m)$ $14.55\ g\ O_2$	Strickland and Parsons, 1972
S	Sunlight	Sunlight incident on 1.0 m^2 of bay surface in September. 700 Kcal/m^2/hr (at 1200 hrs)	Fig. 15a
T	Turbulent energy of mixing	Assumes that turbulent energies are proportional to velocity. Velocities ranged between 0.0 and 100 cm/sec. 50 cm/sec	Gorsline, 1963
FLOWS			
J_1	Gross phytoplankton production	Hourly gross production of organic matter. Rate at 1200 hours used for starting model. Gross production was assumed to equal daytime net plus nighttime respiration.	Fig. 10b

Table C-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_1(cont.)		$0.70\ g/m^2/hr$	
		$(0.5\ g/m^2/hr)+(0.2\ g/m^2/hr)$	
J_2	Gross oxygen production	Hourly gross oxygen production. Rate at 1200 hours was used for starting model.	Fig. 10b
		$0.7\ 0\ g/m^2/hr$	
		$(0.5\ g/m^2/hr)+(0.2\ g/m^2/hr)$	
J_3	Nitrogen uptake in photosynthesis	Uptake of nitrogen in phytoplankton photosynthesis at 1200 hours. Calculation assumed that material produced was 5 percent nitrogen by weight.	Odum, 1971
		$0.035\ g\ N/m^2/hr$	
		$(0.05)(J_1)$	
J_4	Phytoplankton respiration	Hourly rate of phytoplankton respiration. Calculation assumed that phytoplankton respired 30 percent of the gross production over 24 hours.	Estimated from Fig. 10b
		$0.09\ g/m^2/hr$	
		$\frac{(7\ g\ O_2/m^2/day)(0.30)}{24\ hrs/day}$	

Table C-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_5	Oxygen use in phytoplankton respiration	Hourly uptake of oxygen in phytoplankton respiration. The respiratory quotient was assumed to be 1.0. $0.09\ g/m^2/hr$	J_4, this table
J_6	Oxygen utilization by microbes	Average hourly rate of microbial respiration. Flow included all respiration not associated with phytoplankton or consumer respiration. $0.069\ g\ O_2/m^2/hr$ $J_6 = (\text{total respiration}) - (J_5 + J_9)$ $J_6 = \dfrac{(4.6\ g\ O_2/m^2/day)^a - (0.792 + 2.16)^b}{24\ hrs/day}$	(a) Fig. 10b, 2 times night respiration (b) J_5 and J_9, this table
J_7	Detritus respiration by microbes	Average respiration of detritus by microbes. The RQ was assumed to be 1.0. $0.069\ g\ O_2/m^2/hr$	J_6, this table
J_8	Detritus utilization by consumers	Average hourly uptake of detritus by consumers. The RQ was assumed to be 1.0. $0.033\ g/m^2/hr$	J_9, this table

Table C-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_9	Oxygen utilization by consumers	Average hourly oxygen utilization by consumers. Oxygen utilization rate was assumed to be 0.085 g O_2[a] per gram of consumer biomass[b] per day. 0.033 g $O_2/m^2/hr$	(a) Day *et al.*, 1973 (b) Q_2, this table
J_{10}	Consumer assimilation	Average hourly assimilation of detritus by consumers. It was assumed that assimilation efficiency was 50 percent of intake. 0.017 $g/m^2/hr$ $(J_8)(0.50)$	Day *et al.*, 1973
J_{11}	Consumer death	Calculated to balance Q_2. Calculation assumed steady state for Q_2. 0.017 $g/m^2/hr$ $J_{11} = J_{10}$	Estimated
J_{12}	Nutrient regeneration	Average hourly rate of nutrient regeneration from phytoplankton respiration. Calculation assumed that respired material was 5 percent nitrogen by weight.	Estimated

Table C-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_{12}(cont.)		0.005 g $N/m^2/hr$ $(J_4)(0.05)$	
J_{13}	Rearation	Oxygen exchange between water and air. Rate is proportional to saturation deficit and turbulent energies available for mixing. At 1200 hours diffusion rate was approximately 0.1 g $O_2/m^2/hr$. 0.1 g/m^2/hr	Fig. 10b, taken as the difference between corrected and uncorrected curves
J_{14}	Oxygen export	Calculated by assuming that all advected oxygen (a) was exported plus the 24 hour net O_2 production (b). 0.038 g $O_2/m^2/hr$ $0.035^a + \left(\frac{0.1 \text{ g } O_2/m^2/day^b}{24 \text{ hrs/day}}\right)$	Estimated
J_{15}	Nutrient recycle	Average hourly nitrogen recycle associated with microbe respiration. Calculation assumed that respired material was 5 percent nitrogen. 0.0035 $(J_7)(0.05)$	Parsons *et al.*, 1961 Odum, 1971

Table C-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_{16}	Nutrient recycle	Average hourly nitrogen recycle associated with consumer respiration and death.	Parsons et al., 1961
		0.0020	Odum, 1971
		$(J_{11})(0.05)$	
J_{17}	Phytoplankton death	Hourly loss of phytoplankton and phytoplankton decay and excretory products to detrital pool. Calculated to balance Q_1 after respiration and flushing losses were accounted for.	Estimated
		$0.10\ g/m^2/hr$	
		$J_{17} = J_1 - (J_4 + J_{18})$	
J_{18}	Phytoplankton export	Average hourly loss of phytoplankton due to flushing to the Gulf. Calculated by assuming phytoplankton were flushed in proportion to water.	(a) Q_1, this table
		$0.01\ g/m^2/hr$	(b) Gorsline, 1963
		$\frac{(2.5\ g/m^2)^a (0.12\ m^3/day)^b}{24\ hrs}$	

Table C-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_{19}	Detritus export	Average hourly export of detritus. Calculated to balance Q_4 after other losses were accounted for. $0.037\ g/m^2/hr$ $J_{19} = (J_D + J_{17}) - (J_7 + J_8)$	Estimated
J_{20}	Nutrient export	Average hourly loss of nitrogen to the Gulf of Mexico. Calculated to balance Q_5 after other losses were accounted for. $0.0013\ g\ N/m^2/hr$ $J_{20} = (J_n + J_{13} + J_{15} + J_{16}) - J_3$	Estimated

Table C-2

Scaled differential equations and pot settings used in simulating the diurnal activity model.

Phytoplankton biomass

$$\left[\frac{\dot{Q}_1}{10}\right] = \underset{k_1}{0.05(10)} \left[\frac{J_r}{700}\right]\left[\frac{Q_5}{0.3}\right] - \underset{k_4}{0.06}\left[\frac{Q_1}{10}\right]\left[\frac{Q_3}{30}\right] - \underset{k_{17}}{0.04}\left[\frac{Q_1}{10}\right] - \underset{k_{18}}{0.004}\left[\frac{Q_1}{10}\right]$$

Consumer biomass

$$\left[\frac{\dot{Q}_2}{15}\right] = \underset{k_{10}}{0.011}\left[\frac{Q_3}{30}\right]\left[\frac{Q_4}{100}\right] - \underset{k_{11}}{0.002}\left[\frac{Q_2}{15}\right]$$

Dissolved oxygen

$$\left[\frac{\dot{Q}_3}{30}\right] = \underset{k_A}{0.001}\left[\frac{A}{0.35}\right] + \underset{k_{13}}{0.027}\left[\frac{T}{100}\right]\left[\frac{\left[\frac{A_s}{30}\right] - \left[\frac{Q_3}{30}\right]}{\left[\frac{A_s}{30}\right]}\right] + \underset{k_2}{0.168}\left[\frac{J_r}{700}\right]\left[\frac{Q_5}{0.30}\right]$$

$$- \underset{k_{14}}{0.002}\left[\frac{Q_3}{30}\right] - \underset{k_9}{0.010}\left[\frac{Q_3}{30}\right]\left[\frac{Q_4}{100}\right] - \underset{k_6}{0.021}\left[\frac{Q_3}{30}\right]\left[\frac{Q_4}{100}\right]$$

$$- \underset{k_5}{0.022}\left[\frac{Q_3}{30}\right]\left[\frac{Q_1}{10}\right]$$

Detritus

$$\left[\frac{\dot{Q}_4}{100}\right] = \underset{k_d}{0.004}\left[\frac{D}{0.4}\right] + \underset{k_{17}}{0.004}\left[\frac{Q_1}{10}\right] - \underset{k_{19}}{0.002}\left[\frac{Q_4}{100}\right] - \underset{k_7}{0.006}\left[\frac{Q_3}{30}\right]\left[\frac{Q_4}{100}\right]$$

$$- \underset{k_8}{0.003}\left[\frac{Q_3}{30}\right]\left[\frac{Q_4}{100}\right]$$

Table C-2 - continued

Nitrogen

$$\left[\frac{\dot{Q}_5}{0.3}\right] = \underset{k_N}{0.004}\left[\frac{N}{0.013}\right] + \underset{k_{12}k_4}{0.122}\left[\frac{Q_1}{10}\right]\left[\frac{Q_3}{30}\right] + \underset{k_{16}k_{11}}{0.014}\left[\frac{Q_2}{15}\right]$$

$$+ \underset{k_{15}k_7}{0.109}\left[\frac{Q_3}{30}\right]\left[\frac{Q_4}{100}\right] - \underset{k_{20}}{0.001}\left[\frac{Q_5}{0.3}\right] - \underset{k_3}{0.083(10)}\left[\frac{J_r}{700}\right]\left[\frac{Q_5}{0.3}\right]$$

Source limited sunlight inflow

$$\left[\frac{J_r}{700}\right] = \frac{\overset{k_s}{0.330}\left[\frac{S}{700}\right]}{\underset{k_p}{0.330} + \underset{k_o}{0.793}\left[\frac{Q_5}{0.30}\right]}$$

Table C-3

Maximum values for state variables and forcing functions used in diurnal activity model. Scaled potentiometer settings are given for each state variable and forcing function. Potentiometer settings for the sine wave generator are given at the bottom.

Maximum Value of State Variable	Scaled Pot Setting	Maximum Value of Forcing Function	Scaled Pot Setting
$[\frac{Q_1}{10}]$	0.210	$[\frac{A}{0.35}]$	0.001
$[\frac{Q_2}{15}]$	0.547	$[\frac{T}{100}]$	0.25
$[\frac{Q_3}{30}]$	0.547	$[\frac{D}{0.4}]$	0.004
$[\frac{Q_4}{100}]$	0.197	$[\frac{N}{0.013}]$	0.004
$[\frac{Q_5}{0.3}]$	0.20	$[\frac{As}{30}]$	0.485

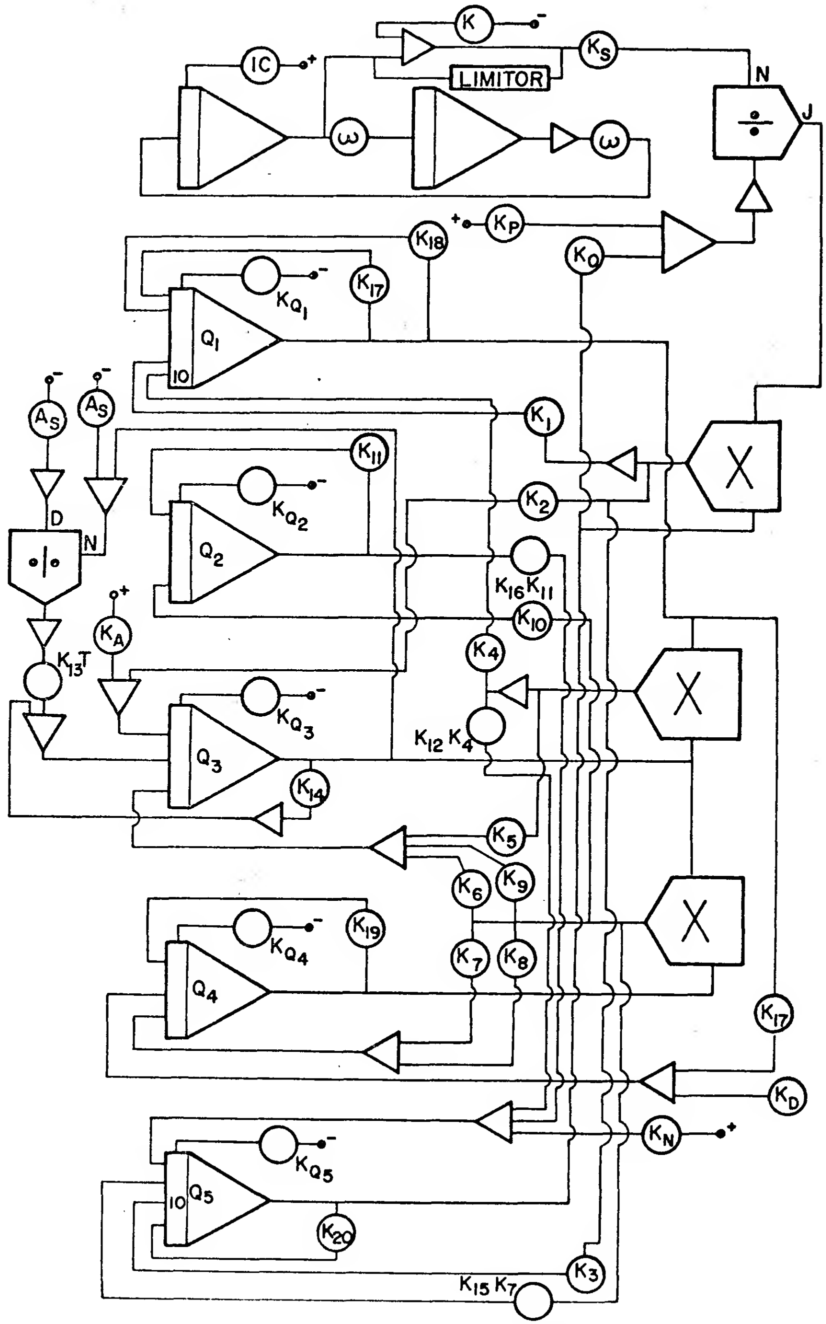
sine wave settings

I.C. = 1.00

ω = 0.262

ω = 0.262

Fig. C-1. Analog patching diagram of the diurnal activity model shown in Fig. 19. Equation coefficients are identified by numbered potentiometers.



K
LIMITOR
IC
K_S
N
J
ω
ω
K_P
K_Q
K_{18}
K_{17}
K_{Q_1}
Q_1
10
A_S
A_S
K_1
K_{11}
K_{Q_2}
K_2
D
N
Q_2
$K_{16}K_{11}$
K_{10}
K_A
K_4
$K_{13}T$
K_{Q_3}
$K_{12}K_4$
Q_3
K_{14}
K_5
K_6
K_9
K_{19}
K_{Q_4}
K_7
K_8
Q_4
K_{17}
K_D
K_N
K_{Q_5}
Q_5
10
K_{20}
K_3
$K_{15}K_7$

APPENDIX D

SUPPLEMENTARY INFORMATION ON THE REGIONAL SIMULATION MODEL OF FRANKLIN COUNTY AND APALACHICOLA BAY

Table D-1
Data used in the regional model of Franklin County and Apalachicola Bay (Fig. 28)

STATE VARIABLES Notation	Name	Description and Calculations	Reference
Q_1	Natural Land	All non-timber company land in county which was used for human habitation or structures. $9.26 \times 10^7 m^2$ (22,848 acres)x(4047 m^2/acre)	Florida Coastal Coordinating Council, 1970
Q_2	Developed Land	All non-timber company land in county which was used for human habitiation or structures. $5.84 \times 10^7 m^2$ (14,419 acres)x(4047 m^2/acre)	Florida Coastal Coordinating Council, 1970
Q_3	Image	Total attractiveness of the county based on summation and storage of the three major work processes in the county (urban, natural lands, and estuary). Storage was in fossil fuel work equivalent calories. The weighted turnover time of the three storages associated with inputs to image was 3.8 years. The initial amount in the storage was calculated by multiplying the turnover time times yearly input. 2.03×10^{12}Kcal (total input/20 days)(18.25)(3.8)	Estimated

Table D-1 - continued

STATE VARIABLES Notation	Name	Description and Calculations	Reference
Q_3(cont.)		$(3.7 \times 10^9 + 19.6 \times 10^9 + 6.2 \times 10^9)(18.25)(3.8)$ J_{26} J_{93}" J_{27}	
Q_4	Capital	Represents capital in the county and is composed of the assets of the two banks in the county. $\$77.77 \times 10^6$	Carrabelle Bank Statement, 1970 Apalachicola State Bank Statement, 1970
Q_5	Structure	Represents the non-liquid assets of the county including all buildings, services, and structures. Does not include assessed value of timber company land. Urban structure is expressed in fossil fuel work equivalent calories. Calculated as total assessed value minus value of timber land times dollar to calorie conversion factor of $25,000 Kcal/dollar. $1.41 \times 10^{12} Kcal_{FFE}$ $(\$6.8 \times 10^{7^a} - \$1.16 \times 10^{7^b})(2.5 \times 10^4 Kcal/\$)$	(a) Florida Statistical Abstract, 1972 (b) James, 1974
Q_6	Population	Total number of people living in the county plus average number of tourists visiting the county.	

Table D-1 - continued

STATE VARIABLES (cont.) Notation	Name	Description and Calculations	Reference
Q_6(cont.)		7423 people (7065 residents)[a] + (358 tourists)[b]	(a) Florida Statistical Abstract, 1972 (b) Florida Tourist Study, 1971
Q_7	Nitrogen	Average amount of NO_3 + NH_3-N in the bay in June. Average concentration was multiplied by bay volume to get total amount. 7.5×10^7 gN $(0.072\ g\ N/m^3)^a \times (1.04 \times 10^9 m^3)^b$	(a) Estabrook, 1973 (b) Gorsline, 1963
Q_8	Freshwater and Turbidity	The storage monitors the total amount of fresh water in the bay. The starting condition for this storage was June when the average bay salinity was about 17‰ or when the bay was 1/2 filled with freshwater. Turbidity was assumed to be directly proportional to the amount of fresh water in the bay. $5.2 \times 10^8 m^3$ (Bay Volume)(0.5) $(1.04 \times 10^9 m^3)^a (0.5)^b$	(a) Gorsline, 1963 (b) Estabrook, 1973

Table D-1 - continued

STATE VARIABLES (cont.) Notation	Name	Description and Calculations	Reference
Q_9	Detritus	Storage of total particulate and dissolved organic matter (dry weight) in the bay evaluated for June. Carbon was converted to organic matter using a factor of 2.0. Detritus estimate also includes living phytoplankton and zooplankton. 1.06×10^{10}g $(10.2\ g/m^3)^a (1.04 \times 10^9 m^3)^b$	(a) Table 5, average of all bay stations (b) Gorsline, 1963
Q_{10}	Juvenile Oysters	Taken as dry meat weight of all oysters less than 3 inches in length. (5.53×10^8g	Table 6, Case III
Q_{11}	Adult Oysters	Taken as dry meat weight of all oysters three inches or larger in length. 8.68×10^8g	Table 6, Case III
Q_{12}	Predators	Represents total dry weight biomass of oyster predators including stone crabs, southern oyster drill, and blue crabs. Biomass was back calculated from estimating total oyster loss to predation times a respiration rate for predators of 5 percent of total biomass per day.	

Table D-1 - continued

Notation	Name	Description and Calculations	Reference
STATE VARIABLES (cont.)			
Q_{12}(cont.)		$3.11 \times 10^7 g$ Daily input to predators = $\frac{J_7 + J_8}{20}^{a} = 1.56 \times 10^6 g$ Daily respiration represents 5 percent of total biomass[b] and thus total biomass was estimated to be $(1.56 \times 10^6 g/day)(20) = 3.11 \times 10^7 g$	(a) J_7 and J_8, (b) Day *et al.*, 1973
Q_{13}	Coliforms	Estimate of average number of coliform bacteria in the bay in June. 5.51×10^{14} coliforms $(53 \times 10^4 \text{ coliforms/m}^3)^{a} \times (1.04 \times 10^9 m^3/\text{bay})^{b}$	(a) Keyes, 1973 (b) Gorsline, 1963
FORCING FUNCTIONS			
I_0	Sunlight	Average amount of sunlight falling on the bay surface per 20 days beginning in June. 4.5×10^{13} Kcal/20 days $(500 \text{ Kcal/m}^2/\text{day})^{a} (20 \text{ days})(452 \times 10^6 m^2)^{b}$	(a) Fig. 15, June value (b) Gorsline, 1963

Table D-1 - continued

FORCING FUNCTIONS (cont.)

Notation	Name	Description and Calculations	Reference
I_1	River Flow	Average amount of freshwater entering bay from the Apalachicola River per 20 days. $1.04 \times 10^9 m^3/20$ days	Fig. 14a, June value
I_2	Coliform Concentration	Average coliform concentration in river water. Concentration was assumed to be constant through the year. $2.5 \times 10^6 m^3$	Keyes, 1973 Taylor, 1973
I_3	Nutrient Concentration	Average concentration of $NO_3 + NH_3 - N/m^3$ in river water. Concentration was assumed to be constant through the year. 0.25 g N/m^3	Fig. 17, June value
I_4	Detritus Concentration	Average concentration of both particulate and dissolved organic matter in river water (dry weight). Concentration was assumed to be constant through the year. Carbon was converted to organic matter using a factor of 2.0. $8.0 g/m^3$	Table 5, average of river samples

Table D-1 - continued

FORCING FUNCTIONS (cont.) Notation	Name	Description and Calculations	Reference
I_5	Capital Investment	Total investment capital entering the county per 20-day period. The county tax assessor estimated annual investment to be 6×10^5 dollars. 3.29×10^4 dollars/20 days	James, 1974
I_6	Government Spending	Total Federal and State money entering the county per 20-day period. Input given represents net input after state and federal taxes have been paid. 8.2×10^4/20 days State input = \$1.77 x 10^6/yr [a] Federal input = \$1.40 x 10^6/yr [b] State taxes = \$0.77 x 10^6/yr [c] Federal taxes = \$0.91 x 10^6/yr [d] Net input = \$1.49 x 10^6/yr	(a) Estes, 1973 (b) Federal Information Exchange System, 1973 (c) Stalvey, 1973 (d) Euringer, 1974
I_7	Goods, Fuels and Services	Calculated by converting dollars spent outside the county to kilocalories, using a ratio of 25,000 Kcal/dollar.	

Table D-1 - continued

FORCING FUNCTIONS (cont.) Notation	Name	Description and Calculations	Reference
I_7(cont.)		1.96×10^{10} Kcal/20 days $(J_{96}{}^{a} + J_{93}{}'^{,b})$(25,000 Kcal/dollar)	(a) J_{96}, this table (b) J_{93}', this table
I_8	Immigration	Average rate of people entering Franklin County to reside per 20-day period. Calculation assumed immigration rate was constant through the year. (376 people/yr)/(18.25 20 day units/yr)	RMBR Planning/ Design Group, 1974.
I_9	Incoming Resident Capital	Capital associated with new residents entering the county. $6,157/person	RMBR Planning/ Design Group, 1974.
I_{12}	Tourist Inflow	Average number of people entering Franklin County for recreational purposes per 20-day period. Calculation assumed that tourism was constant over the year. 576 people/20 days (10,350 tourists/yr)/(18.25 20 day units/yr)	Florida Tourist Study, 1970

Table D-1 - continued

FORCING FUNCTIONS (cont.) Notation	Name	Description and Calculations	Reference
I_{13}	Tourist Money Inflow	Average amount of money spent by tourists in Franklin County per 20-day period. 7×10^4 dollars/20 days ($\$1.27 \times 10^6$/yr)/(18.25 20 day units/yr)	Florida Tourist Study, 1970
I_{14}	Predator Inflow	Estimated rate of predator recruitment from the Gulf of Mexico. Rate was sufficient to replace amount in storage in a one-year period. 1.64×10^6g/20 days	Estimated
L	Coliform Threshold	Legal limit of coliform concentrations required to close oyster industry due to fecal pollution. 8.22×10^{14} coliforms $(790 \times 10^3/m^3)^a (1.09 \times 10^9 m^3)^b$	(a) Keyes, 1973 (b) Gorsline, 1963
S	Oyster Fishing Season	Period of the year during which oysters can be harvested (September-May).	Keyes, 1973

Table D-1 - continued

FLOWS Notation	Name	Description and Calculations	Reference
J_0	Sunlight	Average sunlight falling on the bay in June. Sunlight input was sinosoidal with peak and trough in June and December, respectively. 4.50×10^{13} Kcal/20 days	I_0, this table
J_1	Organic Matter Inflow	Average inflow rate of particulate and dissolved organic matter from the Apalachicola River (dry weight). 8.32×10^{9}/20 days $(8.0\ g/m^3)^a\ (1.04 \times 10^9 m^3/20\ days)^b$	(a) I_4, this table (b) I_1, this table
J_2	River Flow	Average 20 day river flow entering Apalachicola Bay. Calculated from June. $1.04 \times 10^{9} m^3$/20 days	I_1, this table
J_3	Phytoplankton Production	Average 20 day net primary production in Apalachicola Bay (dry weight). Calculated for June. 2.72×10^{10} g/20 days	

Table D-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_3(cont.)		(3.0 g organic matter/m^2/day)[a] (20 days) x (452 x $10^6 m^2$/bay)[b]	(a) Table 4, average of all stations (b) Gorsline, 1963
J_4	Community Respiration	Average 20 day community respiration in g dry organic matter per bay area. Calculated for June. Flow does not include respiration of oysters or predators. Calculation assumed that 75 percent of the daytime net phytoplankton production was respired in this way. $(J_3)(0.75) = 2.30 \times 10^{10}$ g/20 days	Estimated
J_5	Detritus Export	Average export of organic matter to the Gulf of Mexico per 20 day-period. Calculated to balance storage Q_9 for June. 8.50×10^9 g/20 days $J_5 = (J_1 + J_2) - (J_{101} + J_4 + J_6)$	Estimated
J_6	Food Uptake by Juvenile Oysters	Average dry weight organic matter uptake by juvenile oysters per 20-day period. Calculated to balance other losses from Q_{10} for June.	Estimated

Table D-1 - continued

FLOW (cont.) Notation	Name	Description and Calculations	Reference
J_6(cont.)		1.46×10^9 g/20 days $J_6 = J_7 + J_{16} + J_{19}$	
J_7	Predation of Juvenile Oysters	Average dry weight loss of juvenile oysters per 20 days due to predator activity. Estimated to be 40 percent of total stock per yr. 1.21×10^7 g/20 days $\frac{5.53 \times 10^8 g)(0.4)(20\ days)}{365\ days/yr}$	Menzel, 1973
J_8	Predation of Adult Oysters	Average dry weight loss of adult oysters (>3" in length) per 20 days due to oyster predator activity. Estimated to be 40 percent of total stock per yr. 1.90×10^7 g/20 days $\frac{(8.68 \times 10^8 g)(0.4)(20\ days)}{365\ days/yr}$	Menzel, 1973
J_9	Predator Respiration	Average respiration of predators per 20 days. Flow assumed that 75 percent of total respiration at 15 o/oo salinity was due to normal respiration. The remaining 25 percent was due	Q_{12}, this table

Table D-1 - continued

FLOW (cont.) Notation	Name	Description and Calculations	Reference
J_9(cont.)		to salinity stress. The respiration rate of invertebrate predators was estimated to be 5 percent of body weight per day. 2.34×10^7/20 days $(3.11 \times 10^7 g)(0.75)^a (0.05)^b (20)$	(a) Wells, 1961 (a) Menzel et al., 1966 (b) Day et al., 1973
J_{10}	Predator Stress Respiration	Predator respiration under salinity stress per 20-day period. Stress at 15 o/oo salinity was assumed to be 25 percent of total respiration. Flow was calculated for June when salinity stress was estimated to be small. $7.7 \times 10^6 g$/20 days $(3.11 \times 10^7 g/20\ days)(0.25)^a$	(a) Wells, 1961 (a) Menzel et al., 1966
J_{11}	Bay Flushing	Average freshwater export to the Gulf of Mexico per 20-day period. Calculated to balance storage Q_8. $1.04 \times 10^9 m^3$/20 days $J_{11} = J_2$	J_2, this table

Table D-1 - continued

FLOW (cont.) Notation	Name	Description and Calculations	Reference
J_{12}	River Nitrogen Input	Average nutrient (NO_3+NH_3) input per 20-day period from the Apalachicola River. Calculated for June. 2.6×10^8 g N/20 days $(0.25 \text{ g N/m}^3)^a (1.04 \times 10^9 \text{m}^3/20 \text{ days})^b$	(a) Fig. 17, average river concentration for June (b) I_1, this table
J_{13}	Nitrogen from Towns	Average flow of nutrients (NO_3+NH_3) from the towns bordering Apalachicola Bay per 20-day period. Calculation was based on current sewage discharge rates. 2.77×10^6 g N/20 days $(30 \text{ g N/m}^3)^a (3.785 \times 10^{-3} \text{m}^3/\text{gal})(1 \times 10^6 \text{gal/day})^b \times$ (20 days)	(a) Taylor, 1973 (b) McNulty *et al.*, 1972
J_{14}	Nutrient Regeneration	Nutrient regeneration per 20 days associated with J_4. Calculation assumed that respired material was 5 percent nitrogen by weight. 1.28×10^9 g N/20 days $(J_4)(0.05)^a$	(a) Parsons *et al.*, 1961 (a) Odum, E.P., 1971

Table D-1 - continued

FLOW (cont.) Notation	Name	Description and Calculations	Reference
J_{15}	Oyster Nutrient Regeneration	Total nutrient regeneration per 20 days associated with oyster metabolism. Calculation assumed that respired material was 5 percent nitrogen by weight. 7.2×10^7 g N/20 days $(J_{16})(0.05)$	Parsons _et al_., 1961 Odum, E.P., 1971
J_{16}	Oyster Respiration	Average respiration per 20 days. Calculation assumed that the oyster stock respired 5 percent of their total biomass per day. Calculation done for June. 1.34×10^9 g/20 days $(Q_{10} + Q_{11})(0.05)(20\text{ days})$ $(5.53 \times 10^8\text{g} + 8.68 \times 10^8\text{g})^a (0.05)^b (20\text{ days})$	(a) Q_{10} and Q_{11}, this table (b) Day _et al_., 1973
J_{17}	Nutrient Export	Average export of nutrients ($NO_3 + NH_3$) per 20 days from the bay to the Gulf of Mexico. This low was calculated to balance storage Q_7 in June. 1.34×10^8 g N/20 days	Estimated

Table D-1 - continued

FLOW (cont.) Notation	Name	Description and Calculations	Reference
J_{17}(cont.)		$J_{17} = (J_{12} + J_{13} + J_{14} + J_{15}) - (J_{18} + J_{102})$	
J_{18}	Nutrient Uptake	Average nutrient uptake in phytoplankton photosynthesis per 20-day period in June. Calculation assumed that organic matter produced was 5 percent nitrogen by weight. 1.36×10^9 g N/20 days $J_{18} = (J_3)(0.05)$	Parsons *et al.*, 1961
J_{19}	Adult Oyster Recruitment	Average recuitment of young oysters to adult stock. Initial stock of adults was estimated to be replaced by newly-recruited juveniles in 12 months. 2.91×10^7 g/20 days $J_{19} = \dfrac{(Q_{11})^a(20 \text{ days})}{365 \text{ days/yr}}$	(a) Menzel, 1973 (a) Ingle and Dawson, 1952
J_{20}	Oyster Harvest	Average dry weight of harvest per 20-day period. Calculation was based on 273-day season using 1970 harvest data.	Division of Marine Resources, 1970

Table D-1 - continued

FLOW (cont.) Notation	Name	Description and Calculations	Reference
J_{20} (cont.)		1.06×10^{7} g/20 days	
J_{21}	Coliform Input from River	Average input of coliforms from the Apalachicola River per 20-day period. Calculated for June. 2.6×10^{15} coliforms/20 days $(2.5 \times 10^{6} \text{ coliforms/m}^{3})^{a} (1.04 \times 10^{9} \text{m}^{3}\text{/20 days})^{b}$	(a) Taylor, 1973 (a) Keyes, 1973 (b) I_1, this table
J_{22}	Coliform Input from Towns	Average input of coliforms from towns per 20-day period. 1.89×10^{14} coliforms/20 days $(2.5 \times 10^{6} \text{ coliforms/m}^{3})^{a} (1 \times 10^{6} \text{ gal/day})^{b} \times$ $(20 \text{ days})(3.79 \times 10^{-3} \text{m}^{3}\text{/gal})$	(a) Clark and Viessman, 1966 (b) McNulty _et al._, 1972
J_{23}	Coliform Losses	Estimated loss of coliforms per 20-day period. Pathway included those lost via flushing and death. Flow was calculated to balance inputs into Q_{13}.	Estimated

Table D-1 - continued

FLOW (cont.) Notation	Name	Description and Calculations	Reference
J_{23}(cont.)		2.79×10^{15} coliforms/20 days $J_{23} = J_{21} + J_{22}$	
J_{25}	Oyster Uptake of Detritus	Total average uptake of detritus by juvenile oysters. 1.46×10^{9} g/20 days	J_6, this table
J_{101}	Microbe Respiration	Estimated amount of detritus utilized by microbes requiring enrichment with nitrogen. Estimated to be 10 percent of total plankton respiration in June. 2.56×10^{9} g/20 days $(J_4)(0.1)$	Estimated
J_{102}	Microbe Nutrient Utilization	Estimated amount of nitrogen used in flow J_{101}. It was assumed that detritus and nitrogen were used in ratio of 20:1. 1.28×10^{8} g N/20 days $(J_{101})(0.05)$	J_{101}, this table

Table D-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_{27}	Estuarine Input to Image	Flow was assumed to be proportional to phytoplankton production. Phytoplankton production of organic matter was converted to kilocalories using 4.5 Kcal/g organic matter. This value was then adjusted to fossil fuel work equivalents by dividing by 20.0 6.2×10^{9} Kcal/20 days $\frac{(J_3)(4.5\ Kcal/g)}{20^b}$	(a) J_3, this table (b) Table 1
J_{29}	Image Depreciation	Calculated to balance inputs to Q_3 2.95×10^{10} Kcal/20 days	Estimated
J_{30}	Immigration	Average immigration rate in Franklin County. Estimated rate per 20 days was calculated by dividing yearly rate by 18.25. 20.6 people/20 days $\frac{376\ people/yr}{18.25\ units/yr}$	RMBR Planning/ Design Group, 1974

Table D-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_{31}	Birth Rate	Average birth rate per 20-day period. Flow was calculated by dividing yearly births by 18.25. 6.6 people/20 days $\frac{120\ \text{births/yr}}{18.25\ \text{units/yr}}$	Florida Statistical Abstract, 1972
J_{32}	Tourist Inflow	Average number of people visiting county per 20-day period. Flow was calculated by dividing yearly tourist visit by 18.25 to obtain input rate per 20 days. 576 people/20 days $\frac{10{,}500\ \text{people/yr}}{18.25\ \text{units/yr}}$	Florida Tourist Study, 1970
J_{33}	Death Rate	Average death rate per 20-day period. Flow was calculated by dividing yearly deaths by 18.25. 4.6 people/20 days $\frac{85\ \text{people/yr}}{18.25\ \text{units/yr}}$	Florida Statistical Abstract, 1972

Table D-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_{34}	Tourist Outflow	Average outflow of tourists per 20-day period. Flow was calculated to balance J_{32}. 576 people/20 days	J_{32}, this table
J_{35}	Emigration	Average number of people leaving the county, excluding tourists per 20-day period. Flow was calculated by dividing total yearly emigration by 18.25. 18.2 people/20 days $\frac{334 \text{ people/yr}}{18.25 \text{ units/yr}}$	Florida Statistical Abstract, 1972
J_{36}	Return to Natural Land	Average rate at which developed land returns to a natural state. Natural lands do not have functioning urban structures. Rate was assumed to balance J_{92}. $5.6 \times 10^3 m^2/20$ days	Estimated
J_{37}	Investment Return	Average rate of return on investments made in the county. Rate was assumed to be 5 percent of the capital investment rate (J_{95}).	J_{95}, this table

Table D-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_{37}(cont.)		1.64×10^3/20 days $(J_{95})(0.05)$	
J_{38}	Government Spending	Flow was calculated as the net input of State and Federal money into the county. Yearly rate was divided by 18.25 to get rate per 20 days. 8.2×10^4/20 days	I_6, this table
J_{39}	Money Outflow with Emigration	Average outflow of money associated with people emigrating from the county. Yearly rate was divided by 18.25 to get rate per 20 days. 1.13×10^5/20 days (J_{35})($6,157/person)	RMBR Planning/ Design Group, 1974
J_{40}	Tourist Money Inflow	Average amount of money spent by tourists in Franklin County per 20-day period. The flow was calculated by dividing total tourist money inflow by 18.25 to get inflow per 20 days. 7.0×10^4/20 days (10,500 tourists/yr)(12.5 days/tourist)($10.00/tourist/day) $(\frac{1}{18.25})$	Florida Tourist Study, 1970

Table D-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_{80}	Money Inflow with Immigration	Average amount of capital entering the county with new residents per 20-day period. $\$1.38 \times 10^{5}$/20 days (J_{30})($6,157/person)	RMBR Planning/ Design Group, 1974
J_{41}	Maintenance of Structure	Average input of goods, fuels, and services to county structure. Includes all inputs to structure except those associated with development of natural lands. 1.89×10^{10}Kcal/20 days (J_{96})(25,000 Kcal/dollar)	Odum, 1974a
J_{41}'	Urban Input to Image	Urban input to image was assumed to be proportional to input of goods, fuels, and services (J_{41}). J_{41}' was assumed equal to the fossil fuel work equivalent quality of work and was not adjusted further. 1.89×10^{11}Kcal/20 days	J_{41}, this table
J_{42}	Linear Depreciation of Structure	Includes all depreciation of structure except that associated with oyster harvest and that associated with the square drain on structure. Flow was calculated to balance Q_5 with harvest effort and square drain subtracted out. Of the total developed land in the county 84% was low density and	Table 3, approximately 16% of urban lands are in the commercial industrial grouping.

Table D-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_{42}(cont.)		was assumed to have linear depreciation. The remaining 16% of the developed land was higher density and it was assumed that depreciation included a square drain due to the associated complexity. 1.5×10^{10}Kcal/20 days J_{42} = total inputs to $Q_5 - (J_{43} + J_{97})$	
J_{43}	Square Drain Depreciation of Structure	Flow includes depreciation due to high density. Flow was calculated to balance Q_5 with harvest effort and linear depreciation subtracted out. 2.86×10^9Kcal/20 days J_{43} = total inputs to $Q_5 - (J_{42} + J_{97})$	J_{42}, this table
J_{45}	Income Earned Outside County	Income earned by people living in Franklin County but working outside the county. Calculation assumed those working outside of the county earned the average income of Florida residents. $\$1.02 \times 10^5$/20 days $\frac{(225\text{ people})^a(\$8{,}267/\text{yr})^b(20\text{ days})}{365}$	(a) Estes, 1975 (b) Florida Statistical Abstract, 1972
J_{46}	Income Due to Oyster Sales	Flow represents total income earned due to oyster sales. Dockside value of oysters represented	

Table D-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_{46}(cont.)		approximately 18% of the full value of the oyster harvest. The remaining 82% of oyster harvest value was generated from shucking house operation, packing and shipping, and an over-all multiplier effect of 0.25. Income per 20 days was calculated assuming a 275-day harvest season. $\$4.76 \times 10^5/20$ days $\frac{(\$1.23 \times 10^6/yr)^a (20\ days)}{(0.18)^b (275\ days/season)}$	(a) Division of Marine Resources, 1970 (b) Colberg and Windham, 1965
J_{92}	Land Development	Average rate at which natural land was converted to developed land per 20-day period. $5.6 \times 10^3 m^2/20$ days $\frac{(25\ acres/yr)(4047\ m^2/acre)(20\ days)}{365\ days/yr}$	RMBR Planning/ Design Group, 1974
J_{92}'	Loss of Natural Lands	Average rate at which natural land was converted into developed land per 20-day period. $5.6 \times 10^3 m^2/20$ days	J_{92}, this table
J_{93}	Goods, Fuels and Services Used to Develop Land	Average input of goods, fuels, and services used to develop land. Calculation was based on the cost of land development being \$24,000/acre	

Table D-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_{93}(cont.)		with 25 acres being developed per year. Capital input was converted to energy flow by using the conversion ratio of 25,000 Kcal/dollar. 7.4×10^{8} Kcal/20 days $\dfrac{(\$2.4 \times 10^{4}/\text{acre})^{a}\ (25\ \text{acres/yr})^{b}\ (25{,}000\ \text{Kcal/\$/20 days})}{365\ \text{days/yr}}$	(a) James, 1974 (b) RMBR Planning/ Design Group, 1974
J_{93}'	Capital Outflow for Development of New Lands	Capital outflow required to pay for conversion of natural lands to developed lands. $\$2.96 \times 10^{4}$/20 days $\dfrac{(\$2.4 \times 10^{4}/\text{acre})^{a}\ (25\ \text{acres/yr})^{b}\ (20\ \text{days})}{365\ \text{days/yr}}$	(a) James, 1974 (b) RMBR Planning/ Design Group, 1974
J_{93}''	New Land Development Input to Image	Work flow associated with development of natural lands. Input to image from this flow was assumed to be equal to fossil fuel work equivalent quality and was not further adjusted before entering the image storage. 7.4×10^{8} Kcal/20 days $\dfrac{(\$2.4 \times 10^{4}/\text{acre})^{a}\ (25\ \text{acres})^{b}\ (25{,}000\ \text{Kcal/\$})(20\ \text{days})}{365\ \text{days/yr}}$	(a) James, 1974 (b) RMBR Planning/ Design Group, 1974
J_{95}	Investment Rate	Total investment capital entering the county per 20-day period. Rate per 20 days was	James, 1974

Table D-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_{95}(cont.)		calculated by converting yearly data to a 20-day time period. $\$3.29 \times 10^4/20$ days $\frac{(\$6.0 \times 10^5/\text{yr})(20 \text{ days})}{365 \text{ days/yr}}$	
J_{96}	Capital Outflow for Goods, Fuels, and Services	Money spent to purchase goods, fuels, and services for all uses in the county except development of natural lands. Capital spent in thes way was calculated to balance other inputs to Q_4. $\$7.6 \times 10^5/20$ days $J_{96} = (J_{40} + J_{80} + J_{95} + J_{45} + J_{46}) - (J_{39} + J_{37} + J_{93}')$	Estimated
J_{97}	Oyster Harvest Effort	Included work done in harvest of oysters including fuels expended and depreciation of boats, motors, gear, oyster houses, and cars and homes of those associated with the oyster industry. 1.74×10^9 Kcal/20 days $\frac{(\$9.55 \times 10^5/\text{yr})(25{,}000 \text{ Kcal/yr})(20 \text{ days})}{365 \text{ days/yr}}$	Rockwood, 1973

Table D-1 - continued

FLOWS (cont.) Notation	Name	Description and Calculations	Reference
J_P	Predator Inflow	Estimated rate of predator recruitment from the Gulf of Mexico. Rate was sufficient to replace amount in storage in a one-year period. 1.64×10^6 g/20 days	Estimated

Table D-2

Scaled differential equations used in simulation of the regional model of Franklin County and Apalachicola Bay, Florida.

Natural Land

$$\left[\frac{\dot{Q}_1}{15x10^7}\right] = \underset{k_{36}}{0.0001}\left[\frac{Q_2}{15x10^7}\right] - \underset{k_{92}}{0.0008}\left[\frac{I'_7}{10x10^9}\right]\left[\frac{Q_1}{15x10^7}\right]\left[\frac{Q_4}{100x10^6}\right]$$

Developed Land

$$\left[\frac{\dot{Q}_2}{15x10^7}\right] = \underset{k_{36}}{-0.0001}\left[\frac{Q_2}{15x10^7}\right] + \underset{k_{92}}{0.0008}\left[\frac{I'_7}{10x10^9}\right]\left[\frac{Q_1}{15x10^7}\right]\left[\frac{Q_4}{100x10^6}\right]$$

Image

$$\left[\frac{\dot{Q}_3}{10x10^{12}}\right] = \underset{k_{26}}{0.0006}\left[\frac{Q_1}{15x10^7}\right] + \underset{k_{27}}{(0.0045)}\underset{k_3}{(0.542)}\underset{sf^a}{(10)}\left[\frac{Y}{78x10^{16}}\right]\left[\frac{I_o}{2.5x10^{13}}\right]$$
$$+ \underset{k_{41}}{0.167}\left[\frac{I_7}{10x10^{10}}\right]\left[\frac{Q_4}{10x10^7}\right]\left[\frac{Q_5}{10x10^{12}}\right] + \underset{k''_{93}}{0.002}\left[\frac{I'_7}{10x10^9}\right]\left[\frac{Q_1}{15x10^7}\right]\left[\frac{Q_4}{10x10^7}\right]$$
$$- \underset{k_{29}}{0.015}\left[\frac{Q_3}{10x10^{12}}\right]$$

---

[a] sf = scaling factor

Table D-2 - continued

Capital

$$\left[\frac{\dot{Q}_4}{10\text{x}10^7}\right] = \underset{k_{38}}{0.00082}\left[\frac{I_6}{1\text{x}10^6}\right] + \underset{k_{95}}{0.0016}\left[\frac{I_5}{3\text{x}10^5}\right]\left[\frac{Q_3}{10\text{x}10^{12}}\right] + \underset{k_{80}}{0.049}\left[\frac{I_8}{100}\right]\left[\frac{I_9}{5\text{x}10^5}\right]\left[\frac{Q_3}{10\text{x}10^{12}}\right]\left[\frac{Q_5}{10\text{x}10^{12}}\right]$$

$$+ \underset{k_{40}}{0.025}\left[\frac{I_{12}}{1\text{x}10^3}\right]\left[\frac{I_{13}}{1\text{x}10^5}\right]\left[\frac{Q_3}{10\text{x}10^{12}}\right]\left[\frac{Q_5}{10\text{x}10^{12}}\right] + \underset{k_{46}}{0.1944}\ \underset{sf}{(10)}\left[\frac{Q_5}{10\text{x}10^{12}}\right]\left[\frac{Q_{11}}{5\text{x}10^9}\right]\left[\frac{P_4}{0.473}\right]$$

$$+ \underset{k_{44}}{0.072}\left[\frac{Q_5}{10\text{x}10^{12}}\right]\left[\frac{P_3}{4\text{x}10^{-4}}\right] - \underset{k_{37}}{0.0002}\left[\frac{Q_4}{10\text{x}10^7}\right] - \underset{k_{39}}{0.011}\left[\frac{Q_6}{7\text{x}10^4}\right]$$

$$- \underset{k_{96}}{0.69}\underset{sf}{(10)}\left[\frac{I_7}{10\text{x}10^{10}}\right]\left[\frac{Q_4}{10\text{x}10^7}\right]\left[\frac{Q_5}{10\text{x}10^{12}}\right]\left[\frac{P_2}{4\text{x}10^{-4}}\right]$$

$$- \underset{k'_{93}}{0.062}\left[\frac{I'_7}{10\text{x}10^9}\right]\left[\frac{Q_1}{15\text{x}10^7}\right]\left[\frac{Q_4}{10\text{x}10^7}\right]\left[\frac{P_1}{4\text{x}10^{-4}}\right]$$

Urban Structure

$$\left[\frac{\dot{Q}_5}{10\text{x}10^{12}}\right] = \underset{k_{41}}{0.167}\left[\frac{I_7}{10\text{x}10^{10}}\right]\left[\frac{Q_4}{10\text{x}10^7}\right]\left[\frac{Q_5}{10\text{x}10^{12}}\right] + \underset{k_{93}}{0.002}\left[\frac{I'_7}{10\text{x}10^9}\right]\left[\frac{Q_1}{15\text{x}10^7}\right]\left[\frac{Q_4}{10\text{x}10^7}\right]$$

$$- \underset{k_{42}}{0.0106}\left[\frac{Q_5}{10\text{x}10^{12}}\right] - \underset{k_{43}}{0.014}\left[\frac{Q_5}{10\text{x}10^{12}}\right] - \underset{k_{97}}{0.010}\left[\frac{Q_{11}}{5\text{x}10^9}\right]\left[\frac{Q_5}{10\text{x}10^{12}}\right]$$

Table D-2 - continued

Population

$$\left[\frac{\dot{Q}_6}{7\text{x}10^4}\right] = \underset{k_{30}}{0.011}\left[\frac{I_8}{1\text{x}10^2}\right]\left[\frac{Q_3}{10\text{x}10^{12}}\right]\left[\frac{Q_5}{10\text{x}10^{12}}\right] + \underset{k_{31}}{0.001}\left[\frac{Q_6}{7\text{x}10^4}\right] + \underset{k_{32}}{0.292}\left[\frac{I_{12}}{1\text{x}10^3}\right]\left[\frac{Q_3}{10\text{x}10^{12}}\right]\left[\frac{Q_5}{10\text{x}10^{12}}\right]$$

$$- \underset{k_{33}}{0.0006}\left[\frac{Q_6}{7\text{x}10^4}\right] - \underset{k_{34}}{0.0078}\left[\frac{Q_6}{7\text{x}10^4}\right] - \underset{k_{35}}{0.0024}\left[\frac{Q_6}{7\text{x}10^4}\right]$$

Nitrogen

$$\left[\frac{\dot{Q}_7}{75\text{x}10^7}\right] = \underset{k_{12}}{0.133(10)}\left[\frac{I_1}{20\text{x}10^8}\right]\left[\frac{I_3}{1.0}\right] + \underset{k_{13}}{0.029}\left[\frac{Q_6}{7\text{x}10^4}\right] + \underset{k_{14}\ \ sf}{0.162(100)}\left[\frac{Q_9}{10\text{x}10^{10}}\right] + \underset{k_{15}\ \ sf}{0.175(10)}\left[\frac{Q_{10}}{5\text{x}10^9}\right]$$

$$- \underset{k_{17}\ \ sf}{0.178(10)}\left[\frac{Q_7}{75\text{x}10^7}\right] - \underset{k_{18}\ \ sf}{0.362(100)}\left[\frac{Y}{78\text{x}10^{16}}\right]\left[\frac{I_o}{2.5\text{x}10^{13}}\right] - \underset{k_{102}\ \ sf}{0.161(100)}\left[\frac{Q_7}{75\text{x}10^7}\right]\left[\frac{Q_9}{10\text{x}10^{10}}\right]$$

Freshwater Turbidity

$$\left[\frac{\dot{Q}_8}{1.04\text{x}10^9}\right] = \underset{k_2\ \ sf}{0.384(10)}\left[\frac{I_1}{20\text{x}10^8}\right] - \underset{k_{11}\ \ sf}{0.20(10)}\left[\frac{Q_8}{1.04\text{x}10^9}\right]$$

Table D-2 - continued

Detritus

$$\left[\frac{\dot{Q}_9}{10\text{x}10^{10}}\right] = \underset{k_1}{0.320}\left[\frac{I_4}{20}\right]\left[\frac{I_1}{20\text{x}10^8}\right] + \underset{k_3\ \ sf}{0.542(10)}\left[\frac{Y}{78\text{x}10^{16}}\right]\left[\frac{I_o}{2.5\text{x}10^{13}}\right] - \underset{k_4\ \ sf}{0.217(10)}\left[\frac{Q_9}{10\text{x}10^{10}}\right]$$

$$- \underset{k_5}{0.80}\left[\frac{Q_9}{10\text{x}10^{10}}\right] - \underset{k_{101}\ \ sf}{0.24(10)}\left[\frac{Q_9}{10\text{x}10^{10}}\right]\left[\frac{Q_7}{75\text{x}10^7}\right] - \underset{k_6}{0.276}\left[\frac{Q_9}{10\text{x}10^{10}}\right]\left[\frac{1-Q_8}{1.04\text{x}10^9}\right]$$

Juvenile Oysters

$$\left[\frac{\dot{Q}_{10}}{5\text{x}10^9}\right] = \underset{k_{25}\ \ sf}{0.553(10)}\left[\frac{Q_9}{10\text{x}10^{10}}\right]\left[\frac{1-Q_8}{1.04\text{x}10^9}\right] - \underset{k_{19}}{0.053}\left[\frac{Q_{10}}{5\text{x}10^9}\right] - \underset{k_{16}\ \ sf}{0.257(10)}\left[\frac{Q_{10}}{5\text{x}10^9}\right]$$

$$- \underset{k_7}{0.141}\left[\frac{Q_{10}}{5\text{x}10^9}\right]\left[\frac{Q_{12}}{2\text{x}10^8}\right]$$

Adult Oysters

$$\left[\frac{\dot{Q}_{11}}{5\text{x}10^9}\right] = \underset{k_{19}}{0.053}\left[\frac{Q_{10}}{5\text{x}10^9}\right] - \underset{k_8}{0.141}\left[\frac{Q_{11}}{5\text{x}10^9}\right]\left[\frac{Q_{12}}{2\text{x}10^8}\right] - \underset{k_{20}}{0.130}\left[\frac{Q_{11}}{5\text{x}10^9}\right]\left[\frac{Q_5}{10\text{x}10^{12}}\right]$$

Table D-2 - continued

Predators

$$\left[\frac{\dot{Q}_{12}}{2\times10^8}\right] = \underset{k_7}{0.141}\underset{sf}{(0.25)}\underset{sf}{(100)} \left[\frac{Q_{10}}{5\times10^9}\right]\left[\frac{Q_{12}}{2\times10^8}\right] + \underset{k_8}{0.141}\underset{sf}{(0.25}\underset{sf}{(100)} \left[\frac{Q_{11}}{5\times10^9}\right]\left[\frac{Q_{12}}{2\times10^8}\right]$$

$$- \underset{k_9}{0.75}\left[\frac{Q_{12}}{2\times10^8}\right] - \underset{k_{10}}{0.50}\left[\frac{Q_{12}}{2\times10^8}\right]\left[\frac{Q_8}{1.04\times10^9}\right] + \underset{k_p}{0.005}\left[\frac{I_{20}}{3\times10^7}\right] .$$

Coliforms

$$\left[\frac{\dot{Q}_{13}}{15\times10^{14}}\right] = \underset{k_{21}}{0.660}\underset{sf}{(10)}\left[\frac{I_1}{2\times10^9}\right]\left[\frac{I_2}{10\times10^6}\right] - \underset{k_{22}}{0.118}\underset{sf}{(10)}\left[\frac{Q_6}{7\times10^4}\right] - \underset{k_{23}}{0.506}\underset{sf}{(10)}\left[\frac{Q_{13}}{15\times10^{14}}\right]$$

Table D-3

Scaled state variables and forcing functions and scaled initial condition pot settings used in simulating the regional model of Franklin County and Apalachicola Bay.

Maximum Value of State Variable	Scaled Initial Condition Pot Setting	Maximum Value of Forcing Functions	Scaled Pot Setting
$\frac{Q_1}{15\text{x}10^7}$	0.62	$\frac{I_0}{2.5\text{x}10^{13}}$	See Appendix Table D-2 (refer to diagram of sine wave)
$\frac{Q_2}{15\text{x}10^7}$	0.39	$\frac{I_1}{2\text{x}10^9}$	See Appendix Table D-2
$\frac{Q_3}{10\text{x}10^{12}}$	0.20	$\frac{I_2}{10\text{x}10^6}$	—[a]
$\frac{Q_4}{10\text{x}10^7}$	0.077	$\frac{I_2}{1.0}$	—
$\frac{Q_5}{10\text{x}10^{12}}$	0.141	$\frac{I_4}{20}$	—
$\frac{Q_6}{7\text{x}10^4}$	0.106	$\frac{I_5}{3\text{x}10^5}$	—
$\frac{Q_7}{75\text{x}10^7}$	0.10	$\frac{I_6}{1\text{x}10^6}$	—
$\frac{Q_8}{1.04\text{x}10^9}$	0.50	$\frac{I_7}{10\text{x}10^{10}}$	—
$\frac{Q_9}{10\text{x}10^{10}}$	0.106	$\frac{I_{7'}}{10\text{x}10^9}$	—

[a]Forcing functions with no scaled pot setting were combined with transfer coefficient pot setting. Combined values can be found in Appendix Table D-2.

Table D-3 - continued

Maximum Value of State Variable	Scaled Initial Condition Pot Setting	Maximum Value of Forcing Functions	Scaled Pot Setting
$\frac{Q_{10}}{5x10^9}$	0.110	$\frac{I_8}{1x10^2}$	—
$\frac{Q_{11}}{5x10^9}$	0.174	$\frac{I_9}{5x10^5}$	—
$\frac{Q_{12}}{2x10^8}$	0.153	$\frac{I_{12}}{1x10^3}$	—
$\frac{Q_{13}}{15x10^{14}}$	0.367	$\frac{I_{13}}{1x10^5}$	—
		$\frac{I_{20}}{3x10^7}$	—
		$\frac{J_r}{2.5x10^{13}}$	0.50
		$\frac{P_1}{4x10^{-4}}$	0.1
		$\frac{P_2}{4x10^{-4}}$	0.10
		$\frac{P_3}{4x10^{-4}}$	0.10
		$\frac{P_4}{0.473}$	0.10
		$\frac{L}{15x10^{14}}$	0.548

Fig. D-1. Analog patching diagram for the regional model of Franklin County and Apalachicola Bay, Florida. Equation coefficients are identified by numbered potentiometers. Patching for oscillating forcing functions and logic control is given in Fig. D-2.

FOR CONNECTIONS SEE APPENDIX FIGURE D-2

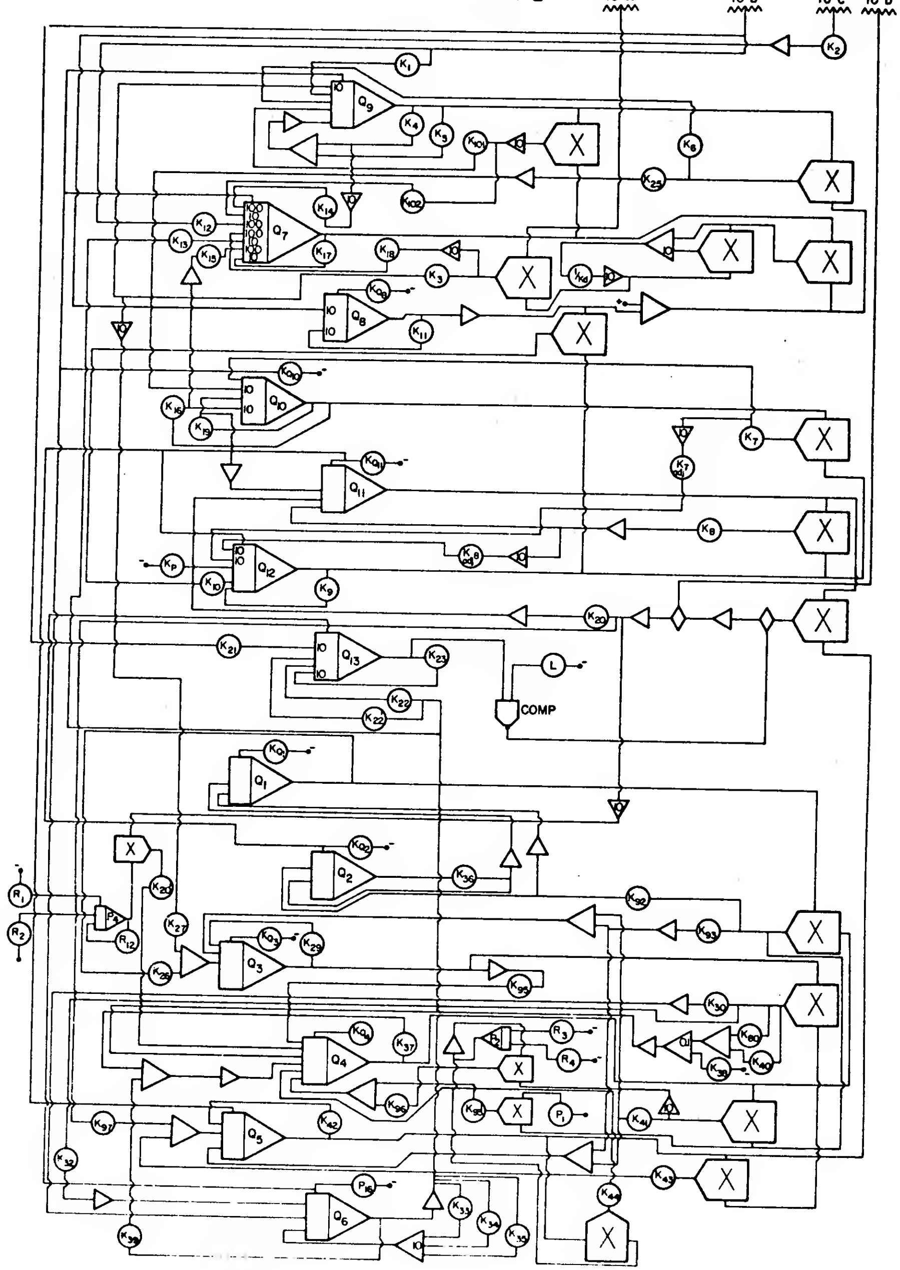
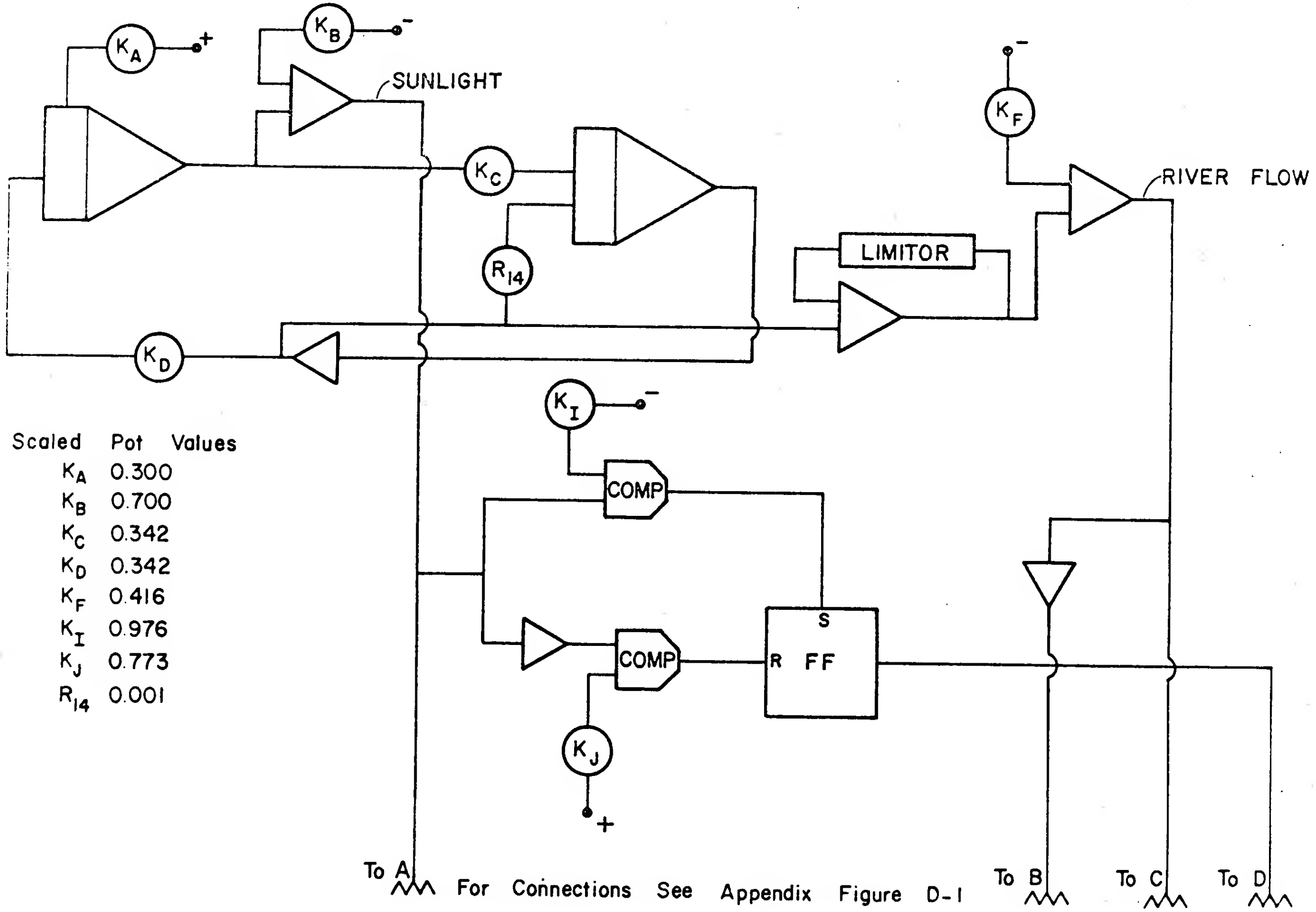


Fig. D-2. Analog patching diagram used to generate sunlight, river flow and logic control of oyster fishing season in regional simulation model of Franklin County and Apalachicola Bay, Florida. Outputs A-D on this diagram correspond to inputs A-D in Fig. D-1.



Scaled Pot Values

K_A	0.300
K_B	0.700
K_C	0.342
K_D	0.342
K_F	0.416
K_I	0.976
K_J	0.773
R_{14}	0.001

APPENDIX E

FULL-SIZED MAPS OF PRIMITIVE AND PRESENT LAND-USE PATTERNS

These maps are on file in the library of the Department of Environmental Engineering Sciences, University of Florida. Reduced versions of the maps are given as Figs. 6 and 7 in the main text.

REFERENCES

Apalachicola State Bank. 1970. Statement of condition of Apalachicola State Bank, Apalachicola, Florida.

Apalachicola River Basin Reservoir Regulation Manual. 1972. Mobile District, U.S. Army Corps of Engineers, Mobile, Alabama.

Bayley, S. and L. Burns. 1974. Condensation of marsh data gathered in the Upper St. Johns River Basin. In Carrying Capacity for Man and Nature in South Florida. First draft of final report to U. S. Dept. Interior and Florida Div. State Planning. Center for Wetlands, Univ. Florida.

Bayley, S. and H. T. Odum. 1973. Energy evaluation of water management alternatives in the Upper St. Johns River Basin of Florida. Final report to E. P. A., Region IV, Atlanta, Georgia.

Barkuloo, J. M. 1961. Distribution and abundance of striped bass, Roccus saxatili (Walbaum), on the Florida Gulf Coast. Proc. 15th Ann. Conf. So. East. Assoc. Game Fish Comm., pp. 223-236.

Bellis, V. 1974. Medium salinity plankton system, pp. 358-396. In H. T. Odum, B. J. Copeland and E. A. McMahan (eds.), Coastal Ecological Systems of the United States. The Conservation Foundation, Washington, D. C.

Boynton, W. 1974. Phytoplankton production in Chincoteague Bay, Maryland-Virginia. M. S. Thesis. Curriculum in Marine Sciences, Univ. North Carolina.

Boynton, W. R., D. Hawkins, and C. Gray. 1975. A modeling approach to regional planning in the fishery dominated economy of Franklin County and Apalachicola Bay, Florida. In C. A. S. Hall and J. Day (eds.), Models as Ecological Tools: Theory and Case Histories. Wiley-Interscience, N. Y. (In press).

Brown, M. and G. Genova. 1973. Energy indices in the urban pattern. Final Report to the Lee County, Florida Board of County Commissioners. Dept. of Architecture, Univ. Florida.

Carpenter, J. H., D. W. Pritchard, and R. C. Whaley. 1969. Observations of eutrophication and nutrient cycle in some coastal plain estuaries, pp. 210-221. In Eutrophication: Causes, Consequences, Correctives. Nat. Acad. Sci., Washington, D. C.

Carrabelle Bank. 1970. Condensed statement of condition. Carrabelle, Florida.

Chestnut, A. F. 1974. Oyster reefs, pp. 171-203. In H. T. Odum, B. J. Copeland, and E. A. McMahan (eds.), Coastal Ecological Systems of the United States. The Conservation Foundation, Washington, D. C.

Clark, J. W. and W. Viessman, Jr. 1966. Water Supply and Pollution Control. International Textbook Co., Scranton, Pennsylvania. 245 pp.

Clewell, A. F. 1971. The vegetation of the Apalachicola National Forest: An ecological perspective. Office of the Forest Supervisor, Tallahassee, Florida. 152 pp.

Colberg, M. R., T. S. Dietrich, and D. M. Windham. 1968. The social and economic values of Apalachicola Bay, Florida. Final Report to Fed. Water Poll. Cont. Admin. (Contract No. 14-12-117). Washington, D. C. 58 pp.

Colberg, M. R. and D. M. Windham. 1965. The oyster-based economy of Franklin County, Florida. U. S. Dept. Health, Educ. Welfare, Public Health Service, Washington, D. C. 23 pp.

Cooper, A. W. 1974. Salt marshes, pp. 55-98. In H. T. Odum, B. J. Copeland, and E. A. McMahan (eds.), Coastal Ecological Systems of the United States. The Conservation Foundation, Washington, D. C.

Copeland, B. J. 1965. Fauna of the Aransas Pass Inlet, Texas. Emigration as shown by tide trap collections. Publ. Inst. Mar. Sci. (Univ. Texas) 10:9-21.

Copeland, B. J. and W. R. Duffer. 1964. Use of a clear plastic dome to measure gaseous diffusion rates in natural waters. Limnol. Oceanogr. 9:494-499.

Copeland, B. J., K. R. Tenore, and D. B. Horton. 1974. Oligohaline regime, pp. 315-357. In H. T. Odum, B. J. Copeland and E. A. McMaham (eds.), Coastal Ecological Systems of the United States. The Conservation Foundation, Washington, D. C.

Cowles, S. 1974. Primary productivity of cypress trees. Rockefeller-RANN Report. Center for Wetlands. Univ. Florida.

Cox, D. T. 1970. Stream investigations, annual progress report. Florida Game and Fresh Water Fish Commission (1969-1970). Tallahassee, Florida.

Cox, D. T. and D. Auth. 1971. Stream investigations, annual progress report. Florida Game and Fresh Water Fish Commission (1970-1971). Tallahassee, Florida.

Crosthwaite, J. S. 1974. Florida Power Corp., St. Petersburg, Fla. Personal communication.

Danglade, E. 1917. Conditions and extent of the natural beds and barren bottoms in the vicinity of Apalachicola, Florida. Report U. S. Comm. Fish. for 1916. App. V:1-68.

Davis, J. H., Jr. 1943. The natural features of Southern Florida. Fla. Geol. Sur. Bull. 25. 311 pp.

Dawson, C. E. 1955a. A contribution to the hydrography of Apalachicola Bay, Florida. Publ. Inst. Mar. Sci. (Univ. Texas) 4:15-35. ✓

Dawson, C. E. 1955b. A study of the oyster biology and hydrography at Crystal River, Florida. Publ. Inst. Mar. Sci. (Univ. Texas) 4(1):280-302.

Day, J. W., Jr., W. G. Smith, P. R. Wagner, and W. C. Stowe. 1973. Community structure and carbon budget of a salt marsh and shallow bay estuarine system in Louisiana. Publ. LSU-SG-72-04. Center for Wetland Resources, Louisiana State University.

DeBellevue, E. 1975. A general systems analysis of Hendry County, Florida. M. S. Thesis. Dept. Environ. Eng. Sci., Univ. Florida (in preparation).

Division of Marine Resources. 1970. Summary of Florida Commercial Marine Landings. Dept. Natural Resources. Tallahassee, Florida.

Estabrook, R. H. 1973. Phytoplankton ecology and hydrography of Apalachicola Bay. M. S. Thesis, Dept. of Oceanography, Florida State University. ✓

Estes, J. 1973. Franklin County Agricultural Extension Agent. Apalachicola, Florida. Personal communication.

Estes, J. 1975. Franklin County Agricultural Extension Agent. Apalachicola, Florida. Personal communication.

Euringer, H. E. 1974. Public Affairs Officer. Internal Revenue Service, Jacksonville, Florida. Personal communication.

Federal Information Exchange System. 1973. Agency Operations-County Summaries for the State of Florida. Washington, D. C.

Flemer, D. A., and R. B. Biggs. 1971. Particulate organic carbon: nitrogen relationships in Northern Chesapeake Bay. J. Fish. Res. Bd. Canada 28(6):911-918.

Flemer, D. A., D. H. Hamilton, C. W. Keefe, and J. A. Mihersky. 1970. The effects of thermal loading and water quality on estuarine primary production. Chesapeake Biological Laboratory, Natural Resources Institute, Univ. Maryland. Ref. No. 71-76. 215 pp.

Florida Coastal Coordinating Council. 1970. Florida coastal zone land use and ownership map, Franklin County, Florida. Tallahassee, Florida. ✓

Florida Dept. of Commerce. 1973. Economic Development Profile. Apalachicola, Franklin County, Florida.

Florida Statistical Abstract. 1972. Prepared by Bureau of Economic and Business Research, College of Business Administration, University of Florida.

Florida Statistical Abstract. 1973. Prepared by Bureau of Economic and Business Research, College of Business Administration, University of Florida.

Florida Tourist Study. 1970. Florida Department of Commerce, Tallahassee, Florida.

Florida Tourist Study. 1971. Florida Department of Commerce, Tallahassee, Florida.

Ford Foundation. 1974. A Time to Choose America's Energy Future. Ballinger Publ. Co., Cambridge, Mass.

Franklin County Overall Economic Development Program. 1965. Franklin County Planning and Development Committee, Apalachicola, Florida.

Fredericks, A. D. and W. M. Sacket. 1968. Organic carbon in the Gulf of Mexico. Oceanography International Corp., College Station, Texas.

Gorsline, D. S. 1963. Oceanography of Apalachicola Bay, Florida, pp. 69-96. In T. Clements (ed.), Essays in Marine Geology in Honor of K. O. Emery. Univ. of Southern California Press, Los Angeles, California.

Gunter, G. 1953. The relationship of the Bonnet Carre Spillway to oyster beds in Mississippi Sound and the "Louisiana marsh," with a report on the 1950 opening. Publ. Inst. Mar. Sci. (Univ. Texas) 3(1):17-71.

Hall, C. A. S. 1972. Migration and metabolism in a temperate stream ecosystem. Ecology 53(4):585-604.

Harrison, R. C. 1974. Hydro Power Branch Operations Division. U. S. Army Corps of Engineers, Mobile, Ala. Personal communication.

Hawkins, D. E. 1973. Simulation and evaluation of a regional model of Franklin County, Florida and the Apalachicola Bay oyster industry. M. S. Thesis. Dept. Environ. Eng. Sci., Univ. Florida.

Healy, T. J. 1974. Energy, Electric Power, and Man. Boyd and Fraser Publishing Co., San Francisco. 356 pp.

Hellier, T. R. 1962. Fish production and biomass studies in relation to photosynthesis in the Laguna Madre of Texas. Publ. Inst. Mar. Sci. (Univ. Texas) 8:1-22.

Hood, D. W. (ed.) 1970. Organic Matter in Natural Waters. Occasional Publ. No. 1. Inst. Mar. Sciences, Univ. Alaska.

Ingersoll, E. 1881. The oyster industry. U. S. Fish Comm. 4:1-252.

Ingle, R. M. 1951. Spawning and setting of oysters in relation to seasonal environmental changes. Bull. Mar. Sci. Gulf and Caribb. 1(2):111-135.

Ingle, R. M. and C. E. Dawson. 1950. Variations in salinity and its relation to the Florida oyster. Salinity variation in Apalachicola Bay. Proc. Gulf and Caribb. Fish Inst. 3:35-42.

Ingle, R. M. and C. E. Dawson. 1952. Winter growth of the American Oyster, Crassostrea virginica, in Apalachicola Bay, Florida. Proc. Gulf Caribb. Fish Inst. 4:46.

Ingle, R. M. and C. E. Dawson. 1953. A survey of Apalachicola Bay, Florida. State Board of Conservation. Tech. Ser. 10:1-38.

Iverson, R. W. 1975. Department of Oceanography. Florida State University. Personal communication.

James, J. 1974. Franklin County Tax Assessor, Franklin County, Florida. Personal communication.

Jones, J. I., R. E. Ring, M. D. Rinkel, and R. E. Smith, (eds.) 1973. A summary of knowledge of the Eastern Gulf of Mexico. State Univ. System of Florida Institute of Oceanography, St. Petersburg, Florida.

Jordan, G. F. 1951. Continental slope off the Apalachicola River, Florida. Am. Assoc. Petroleum Geologists Bull. 35:1978-1993.

Jordan, G. F. 1952. Reef formation in the Gulf of Mexico off Apalachicola Bay, Florida. Geol. Soc. American Bull. 63:741-744.

Ketchum, B. H. (ed). 1972. The Water's Edge. Critical Problems of the Coastal Zone. The M. I. T. Press, Cambridge, Mass. 393 pp.

Keyes, V. 1973. Bureau of Sanitary Engineering, Florida Div. Health and Rehabilitative Services, Jacksonville, Florida. Personal communication.

Kofoed, J. W. and D. S. Gorsline. 1963. Sedimentary environments in Apalachicola Bay and vicinity, Florida. J. Sed. Petrology 33(1):205-223.

Kurz, H. 1942. Florida dunes and scrub vegetation and geology. Geol. Bull. No. 23. Florida Dept. Conservation, Florida Geol. Survey. 154 pp.

Leach, J. H. 1971. Hydrology of the Ythan Estuary with reference to distribution of major nutrients and detritus. J. Mar. Biol. Ass. U. K. 51:137-157.

Lehman, M. E. 1974. Oyster reefs at Crystal River, Florida, and their adaptation to thermal plumes. Master's Thesis. Dept. Environ. Eng. Sci., Univ. Florida.

Leisure Properties Limited. 1974. Villages of St. George. Franklin County Florida Development of Regional Impact, Residential Planned Community Development. Tallahassee, Florida.

Livingston, R. J. 1975. Chronic effects of certain chlorinated hydrocarbon insecticides on estuarine animals of the Northern Gulf coast of Florida. Final Report, Florida Sea Grant Program Project R/EM-1. Florida State University.

Livingston, R. J., R. L. Iverson, R. H. Estabrook, V. E. Keyes, J. Taylor. 1974. Major features of the Apalachicola Bay system: Physiography, biota, and resource management. Fla. Acad. Sci. (In press). ✓

Livingston, R. J. and N. P. Thompson. 1974. Chronic effects of certain chlorinated hydrocarbon insecticides on estuarine animals of the northern Gulf Coast of Florida. Progress Report, Florida Sea Grant Program Project R/EM-1. Florida State Univ.

Lotka, A. J. 1922. Contribution to the energetics of evolution. Proc. Nat. Acad. Sci. 8:147-151.

Mann, W. B. IV. 1975. Subdistrict Chief, U. S. Dept. Interior, Geological Survey, Tallahassee, Florida. Personal communication.

Martin, J. H. 1965. Phytoplankton-zooplankton relationships in Narragansett Bay. Limnol. Oceanogr. 10:185-191.

Martin, S. W. 1944. Florida During the Territorial Days. The Univ. of Georgia Press, Athens, Ga.

McConnell, W. J. 1962. Productivity relations in carboy microcosms. Limnol. Oceanogr. 7:335-343.

McFarland, W. N. 1963. Seasonal plankton productivity in the surf zone of a south Texas beach. Publ. Inst. Mar. Sci. (Univ. Texas) 9:77-90.

McKellar, H. N. Jr. 1975. Metabolism and models of estuarine bay ecosystems affected by a coastal power plant. Ph.D. dissertation, Dept. Environ, Eng. Sci., Univ. of Florida.

McNulty, J. K., W. N. Lindall, Jr., and J. E. Sykes. 1972. Cooperative Gulf of Mexico estuarine inventory and study, Florida: Phase I, Area description. NOAA Tech. Rept., NMFS Circ. 368. U. S. Dept. Commerce, Seattle, Wash.

Menzel, R. W. 1973. Department of Oceanography. Florida State University. Personal communication.

Menzel, R. W. and E. W. Cake, Jr. 1969. Identification and analysis of the biological value of Apalachicola Bay, Florida. Final report to the Federal Water Pollution Control Administration. Contract number 14-12-191. Department of Oceanography, Florida State University.

Menzel, R. W., N. C. Hulings, and R. R. Hathaway. 1957. Causes of oyster depletion in St. Vincent Bar, Apalachicola Bay, Florida. Proc. Natl. Shellfish. Assoc. 48:66-71.

Menzel, R. W., N. C. Hulings, and R. R. Hathaway. 1966. Oyster abundance in Apalachicola Bay, Florida in relation to biotic associations influenced by salinity and other factors. Gulf Research Reports 2(2):73-96.

Northwest Florida Development Council. 1972. Commercial tourism. Land absorption study. Prepared for the Coastal Coordinating Council. Tallahassee, Florida.

Oceanography International Total Carbon System. 1972. Operation manual. Oceanography International Corp., College Station, Texas.

Odum, E. P. 1971. Fundamentals of Ecology (3rd edition). W. B. Saunders Co., Philadelphia. 574 pp.

Odum, E. P. and A. A. de la Cruz. 1967. Particulate organic detritus in a Georgia salt marsh-estuarine ecosystem, pp. 383-388. In G. H. Lauff (ed.), Estuaries. American Assoc. Adv. Sci. Publ. No. 83. Washington, D. C.

Odum, H. T. 1956. Primary production in flowing waters. Limnol. Oceanogr. 1:102-117.

Odum, H. T. 1967. Biological circuits and the marine systems of Texas, pp. 99-157. In T. A. Olson and F. J. Burgess (eds.), Pollution and Marine Ecology. Interscience Publishers, New York.

Odum, H. T. 1971a. Environment, Power and Society. Wiley-Interscience, New York. 332 pp.

Odum, H. T. 1971b. Energetics of world food production, pp. 252-280. In A. E. Lugo and S. C. Snedaker (eds.), Readings on Ecological Systems: Their Function and Relation to Man. MSS Educational Publ. Co., Inc., N. Y.

Odum, H. T. 1972a. An energy circuit language for ecological and social systems: Its physical basis, pp. 139-211. In B. Patten (ed.), Systems Analysis and Simulation in Ecology. Vol. 2. Academic Press, N. Y.

Odum, H. T. 1972b. Use of energy diagrams for environmental impact statements, pp. 197-213. In Tools for Coastal Management. Proceedings of the conference, Marine Technology Society, Washington, D. C.

Odum, H. T. 1973. Energy, ecology, and economics. Ambio 2(6):20-27. Swedish Royal Academy of Science.

Odum, H. T. 1974a. Combining energy laws and corollaries of the maximum power principle with visual system mathematics. SIAM Inst. for Mathematics and Society Research Application Conference on Ecosystems. July 1-4. Alta, Utah.

Odum, H. T. 1974b. Energy cost-benefit models for evaluating thermal plumes, pp. 628-249. In J. W. Gibbons and R. R. Sharitz (eds.), Thermal Ecology. Technical Information Center, Office of Information Services, U. S. Atomic Energy Commission.

Odum, H. T. and M. Brown (eds.). 1975. Carrying capacity for man and nature in South Florida, Energy models for recommending energy, water, and land use for long range economic vitality in South Florida. Final Rept. on contract CX000130057 to Nat. Park Serv., U. S. Dept. Interior, and State of Florida Div. St. Planning, Center for Wetlands, Univ. Florida.

Odum, H. T., B. J. Copeland, and E. A. McMahan (eds.). 1974a. Coastal Ecological Systems of the United States. Vols. 1-IV. The Conservation Foundation, Washington, D. C.

Odum, H. T. and Hoskins. 1958. Comparative studies on the metabolism of marine waters. Publ. Inst. Marine Sciences (Univ. Texas) 6:159-170.

Odum, H. T., W. M. Kemp, W. H. B. Smith, H. N. McKellar, K. L. Young, M. E. Lehman, M. L. Homer, L. H. Gunderson, and A. D. Merriam. 1974b. An energy evaluation of the system of power plants, estuarine ecology, and alternatives for management. Final Report to Florida Power Corporation. Dept. Environ. Eng. Sci., Univ. Florida.

Odum, H. T., C. Kylstra, J. Zucchetto, K. Han, and T. Ballentine. 1974c. Simulation of macroenergetic models of environment, power, and society. Progress report to Atomic Energy Commission, Contract AT-(40-1)-4398. Dept. Environ. Eng. Sci., Univ. Florida.

Odum, H. T., C. Littlejohn, and W. C. Huber. 1972. An environmental evaluation of the Gordon River area of Naples, Florida and the impact of development plans. Dept. Environ. Eng. Sci., Univ. Florida.

Ovington, J. D. 1961. Some aspects of energy flow in plantations of Pinus sylvestris. Ann. Bot. 25:12-20.

Parsons, T. R., K. Stephens, and J. D. H. Strickland. 1961. On the composition of eleven species of marine phytoplankton. J. Fish. Res. Bd. Canada. 18:1001-1016.

Patten, B. C., R. A. Mulford, and J. B. Warinner. 1963. An annual phytoplankton cycle in the lower Chesapeake Bay. Chesapeake Sci. 4:1-20.

Peterson, G. R. 1967. Basic Analog Computation. The Macmillan Company, Collier-Macmillan Limited, London. 124 pp.

Phillips, R. C. 1974. Temperate grass flats, pp. 244-299. In H. T. Odum, B. J. Copeland, and E. A. McMahan (eds.), Coastal Ecological Systems of the United States. The Conservation Foundation, Washington, D. C.

Platt, T. and R. J. Conover. 1971. Variability and its effect on the 24 h chlorophyll budget of a small marine basin. Marine Biol. 10:52-65.

Pomeroy, L. R., L. R. Shenton, R. D. H. Jones, and R. J. Reimold. 1972. Nutrient flux in estuaries, pp. 274-293. In G. E. Likens (ed.), Nutrient and Eutrophication: The Limiting Nutrient Controversy. Special Symposia Vol. I. Limnol. Oceanogr. Lawrence, Kansas.

Rabinowitch, E. and R. Govindjee. 1969. Photosynthesis. John Wiley and Sons, Inc., N. Y. 273 pp.

Riedl, R. and E. A. McMahan. 1974. High energy beaches, pp. 180-251. In H. T. Odum, B. J. Copeland, and E. A. McMahan (eds.), Coastal Ecological Systems of the United States. The Conservation Foundation, Washington, D. C.

RMBR Planning/Design Group. 1974. Plan and implementation: Franklin County, Apalachicola, and Carrabelle. Dept. Community Affairs, Tallahassee.

Rockwood, C. E. 1973. A management program for the oyster resource in Apalachicola Bay, Florida. Res. Rept., Florida Dept. Nat. Resources. Contract No. N-042-44-72. Tallahassee, Florida.

Rutledge, R. 1973. Revenue Officer. Fla. Dept. Agric., Tallahassee, Fla. Personal communication.

Sawyer, F. 1974. Concise history of Apalachicola. Apalachicola Times, 31 October 89 (43):7-14.

Snow, C. H. 1974. Hydro Power Branch Operations Division. U. S. Army Corps of Engineers, Mobile, Ala. Personal communication.

Stalvey, E. W. 1973. Revenue analyst. Dept. of Revenue, Tallahassee, Florida. Personal communication.

Stalvey, E. W. 1975. Revenue analyst. Dept. of Revenue, Tallahasee, Florida. Personal communication.

Stapleton, S. 1973. Liquified petroleum gas division. Florida Insurance Commission, Tallahassee, Florida. Personal communication.

Strickland, J. D. H. and T. R. Parsons. 1972. A Practical Handbook of Seawater Analysis. Fish. Res. Bd. Canada. Bull. 167: 1-311.

Swallows, O. C. Jr. 1973. Model simulation of freshwater-saltwater mixing in the Apalachicola Bay. Masters Research Report. Dept. Environ. Eng. Sci., Univ. Florida.

Swift, F. 1897. Report of a survey of the oyster regions of St. Vincent Sound, Apalachicola Bay and St. George Sound, Florida. Dept. U. S. Fish. Comm. for 1896: 187-217.

Taylor, J. 1973. Bureau of Sanitary Engineering, Florida Div. Health and Rehabilitative Services, Apalachicola, Florida. Personal communication.

Thayer, G. W. 1969. Phytoplankton production and factors influencing production in the shallow estuaries near Beaufort, North Carolina. Ph.D. Dissertation. Zoology Dept., North Carolina State University.

Thomas, L. 1973. Revenue Officer. Dept. Revenue, Tallahassee, Fla. Personal communication.

U. S. Army Corps of Engineers. 1968. Detailed project report on breakwater at Eastpoint, Apalachicola Bay, Florida. Mobile, Ala.

Walton, T. 1974. Research Assistant, Dept. Coastal Engineering, Univ. Florida. Personal communication.

Wells, H. W. 1961. The fauna of oyster beds with special reference to the salinity factor. Ecological Monographs 31(3):239-266.

Westlake, J. C. 1963. Comparisons of plant productivity. Biol. Rev. 38:385-425.

Whitfield, W. K., Jr. 1973. Construction and rehabilitation of commercial oyster reefs in Florida from 1949 through 1971 with emphasis on economic impact in Franklin County. Special Scientific Report No. 38. Florida Dept. of Natural Resources, Marine Research Lab, St. Petersburg, Fla. 42 pp.

Whittaker, R. H. and G. M. Woodwell. 1969. Structure, production, and diversity of the oak-pine forest at Brookhaven, N. Y. J. Ecology 57:157-176.

Williams, R. B. and M. B. Murdoch. 1966. Phytoplankton production and chlorphyll concentration in the Beaufort Channel, North Carolina. Limnol. Oceanogr. 11:73-82.

Woodwell, G. M. and R. H. Whittaker. 1968. Primary production of terrestrial communities. Amer. Zool. 8:19-30.

Young, D. L. 1974. Studies of Florida Gulf Coast salt marshes receiving thermal discharges, pp. 532-550. In J. W. Gibbons and R. R. Sharitz (eds.), Thermal Ecology, AEC symposium series (Conf-730505). Oak Ridge, Tenn.

Young, D., H. T. Odum, J. Day and T. Butler. 1974. Evaluation of regional models for the alternatives in management of the Atchafalaya Basin. Status Report to U. S. Dept. of Interior, Bureau of Sport Fisheries and Wildlife. Center for Wetlands, Univ. of Florida.

Zucchetto, J. J. 1975. Energy basis for Miami, Florida and other urban systems. Ph.D. dissertation. Dept. Environ. Eng. Sci., Univ. Florida.

BIOGRAPHICAL SKETCH

Walter Raymond Boynton was born May 5, 1947, in Lawrence, Massachusetts. He received his B.S. in Biology from Springfield College, Springfield, Massachusetts in 1969. He was employed for a year and a half as a research assistant at the University of Maryland, Chesapeake Biological Laboratory. In September, 1970, he began graduate studies at the University of North Carolina, Chapel Hill, with a graduate school fellowship. He received his M.S. in Marine Sciences in March, 1974. Since the fall of 1972, he has worked towards a Ph.D. in Environmental Engineering Sciences holding first a graduate school fellowship and later graduate assistantships.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Howard T. Odum, Chairman
Graduate Research Professor of Environmental Engineering Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Patrick L. Brezonik

Patrick L. Brezonik
Associate Professor of Environmental Engineering Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Carl Feiss
Professor of Architecture and Urban Studies

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Richard L. Iverson
Assistant Professor of Oceanography
Florida State University

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Edwin E. Pyatt
Professor of Environmental Engineering Sciences

This dissertation was submitted to the Graduate Faculty of the College of Engineering and to the Graduate Council and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

August, 1975

Dean, College of Engineering

Dean, Graduate School

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

H T Odum

Howard T. Odum, Chairman
Graduate Research Professor of Environmental Engineering Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Patrick L. Brezonik

Patrick L. Brezonik
Associate Professor of Environmental Engineering Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Carl Feiss
Professor of Architecture and Urban Studies

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Richard L. Iverson
Richard L. Iverson
Assistant Professor of Oceanography
Florida State University

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Edwin E. Pyatt
Edwin E. Pyatt
Professor of Environmental Engineering Sciences

This dissertation was submitted to the Graduate Faculty of the College of Engineering and to the Graduate Council and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

August, 1975

Dean, College of Engineering

Dean, Graduate School