crystal river power plant
Environmental Considerations

final report to the
Interagency Research Advisory Committee

Florida
Power
CORPORATION

8003130708

A

CRYSTAL RIVER POWER PLANT

ENVIRONMENTAL CONSIDERATIONS

VOLUME I

OCTOBER, 1974

TABLE OF CONTENTS

VOLUME I

INTRODUCTION
Florida Power Corporation I-3

PROGRAM OVERVIEW AND STATISTICAL REVIEW I-7
Law Engineering Testing Company

POWER PLANTS AND ESTUARIES AT CRYSTAL RIVER, FLORIDA

An Energy Evaluation of the System of
Power Plants, Estuarine Ecology
and Alternatives for Management

Howard T. Odum, W.M. Kemp, W.H.B. Smith,
H.N. McKellar, D.L. Young, M.E. Lehman,
M.L. Homer, L.H. Gunderson, and A.D. Merriam

SYSTEMS ECOLOGY GROUP

Department of Environmental Engineering
Sciences
University of Florida

INTRODUCTION AND RECOMMENDATIONS I-13
H.T. Odum

ENERGY EVALUATION OF COOLING ALTERNATIVES AND REGIONAL IMPACT OF POWER PLANTS AT CRYSTAL RIVER I-29
M. Kemp

MAIN ECOLOGICAL SUBSYSTEMS OF THE ESTUARY AND THEIR ADAPTATION TO THE POWER PLANTS I-73

- A. SHALLOW INSHORE ECOSYSTEM OF BOTTOM COMMUNITIES AND THE EFFECT OF THERMAL PLUME I-77
  Wade Smith
- B. METABOLISM AND MODELS OF OUTER BAY PLANKTON ECOSYSTEMS AFFECTED BY POWER PLANT I-159
  H. McKellar
- C. OYSTER REEFS AT CRYSTAL RIVER AND THEIR ADAPTATION TO THERMAL PLUMES I-269
  M. Lehman
- D. ECOSYSTEMS OF THE INTAKE AND DISCHARGE CANALS I-361
  M. Kemp
- E. TIDAL CREEKS AND EFFECTS OF POWER PLANTS I-387
  M. Homer

TABLE OF CONTENTS

VOLUME II

AN ENERGY EVALUATION OF THE SYSTEM OF POWER PLANTS, ESTAURINE ECOLOGY, AND ALTERNATIVES FOR MANAGEMENT (CONTINUED)

F. SALT MARSH AND THE EFFECT OF THERMAL PLUME — II-1
D. Young

VALUE OF HIGHER ANIMALS AT CRYSTAL RIVER ESTIMATED WITH ENERGY QUALITY RATIOS — II-93
M. Kemp, H. McKellar, and M. Homer

MONITORING FUTURE TRENDS AND ONSET OF ADDITIONAL PLUMES WITH A METABOLISM BUOY — II-109
L. Gunderson and A. Merriam

APPENDIX A. PAPERS RECENTLY PUBLISHED IN THERMAL ECOLOGY SYMPOSIUM — II-117

APPENDIX A1. ENERGY COST-BENEFIT MODELS FOR EVALUATING THERMAL PLUMES — II-118
H.T. Odum

APPENDIX A2. STUDIES OF FLORIDA GULF COAST SALT MARSHES RECEIVING THERMAL DISCHARGES - — II-140
D.L. Young

APPENDIX A3. TOTAL METABOLISM OF THERMALLY AFFECTED COASTAL SYSTEMS ON THE WEST COAST OF FLORIDA — II-159
W. Smith, H. McKellar, D. Young, and M. Lehman

APPENDIX B. ENERGY COST-BENEFIT APPROACH TO EVALUATING POWER PLANT ALTERNATIVES — II-175
H.T. Odum

APPENDIX C. PRELIMINARY CALCULATIONS OF ENERGY QUALITY RATIOS OR WORK EQUIVALENT FACTORS — II-185
M. Kemp and W. Boynton

APPENDIX D. MODELS OF THE INTERACTION OF THE CRYSTAL RIVER POWER PLANT AND THE ADJACENT OUTER BAY ECOSYSTEM: RELATION TO COASTAL FISHERIES — II-209
H. McKellar

APPENDIX E. SALT MARSH MICROARTHROPOD POPULATIONS — II-241
E.A. McMahan and D.L. Young

TABLE OF CONTENTS

VOLUME II

FINAL REPORT TO THE FLORIDA POWER CORPORATION II-255
Dr. Samuel C. Snedaker, Principal
Resource Management Systems Program
Institute of Food and Agricultural Sciences
University of Florida
Gainesville, Florida

REPORT A. EVALUATIONS OF INTERACTIONS BETWEEN A POWER GENERATION FACILITY AND A CONTIGUOUS ESTUARINE ECOSYSTEM II-257
Samuel C. Snedaker

REPORT B. IMPINGEMENT AT THE CRYSTAL RIVER POWER GENERATION FACILITY A QUANTITATIVE ANALYSIS II-259
Samuel C. Snedaker

REPORT C. SEDIMENT COMPOSITION AND DISTRIBUTION AT CRYSTAL RIVER POWER PLANT: EROSION VS. DEPOSITION II-309
Daniel J. Cottrell

REPORT D. COMPARISONS OF THE BENTHIC FLORA IN ESTUARIES ADJACENT TO THE CRYSTAL RIVER POWER GENERATION FACILITY II-377
Robin F. Van Tine

VOLUME III

FINAL REPORT TO THE FLORIDA POWER CORPORATION
SUBMITTED BY
Dr. Samuel C. Snedaker,
Principal Investigator (continued)

REPORT E. BENTHIC INVERTEBRATE COMPARISONS IN TWO ESTUARIES ADJACENT TO THE CRYSTAL RIVER POWER GENERATION FACILITY III-1
Gary Evink and Barbara Green

REPORT F. COMPARISON OF SELECTED VERTEBRATE POPULATIONS IN TWO ESTUARIES ADJACENT TO THE CRYSTAL RIVER POWER GENERATION FACILITY III-1
Clayton A. Adams

REPORT G. EFFECTS OF IMPINGMENT AND ENTRAPMENT ON THE CRYSTAL RIVER BLUE CRAB, CALLINECTES SAPIDUS RATHBUN, POPULATION III-107
Clayton A. Adams, Michael J. Oesterling and
Samuel C. Snedaker

APPENDIX A. PHYLOGENETIC LISTING OF ESTUARINE SPECIES AT CRYSTAL RIVER, FLORIDA III-147
Clayton A. Adams, Gary L. Evink, Michael J. Oesterling,
William Seaman and Robin Van Tine

TABLE OF CONTENTS

VOLUME III

APPENDIX B1 IMPINGEMENT DATA RECORD III-165
Clayton A. Adams, Charles J. Bilgere
and Samuel C. Snedaker

APPENDIX B2 IMPINGEMENT DATA SUMMARIES III-315
Clayton A. Adams, Charles J. Bilgere
and Samuel C. Snedaker

INDEPENDENT ENVIRONMENTAL STUDY OF THERMAL EFFECTS
OF POWER PLANT DISCHARGE
Dr. Kendall L. Carder
Principal Investigator
Department of Marine Science
University of South Florida

"NATURAL HEATING OF SALT MARSH WATERS IN THE AREA OF THE CRYSTAL RIVER POWER PLANT" - TECHNICAL REPORT #3 III-379
Ronald H. Klausewitz, Steven L. Palmer, Bruce A. Rodgers, and
Kendall L. Carder

RESULTS ON BATHYMETRY AND BOTTOM TYPE ANALYSIS OF THE CRYSTAL RIVER POWER PLANT DISCHARGE BASIN - TECHNICAL REPORT #5 III-413
Bruce A. Rodgers, Ronald H. Klausewitz, and Thomas J. Keller

VOLUME IV

ZOOPLANKTON RESEARCH
Dr. Frank J. Maturo, Jr.
Principal Investigator
University of Florida Marine Laboratory
Gainesville, Florida

A SUPPLEMENTARY ZOOPLANKTON SURVEY AT THE CRYSTAL RIVER PLANT SITE IV-1
Frank J. Maturo, Jr., John W. Caldwell, and William Ingram III

EFFECTS OF POWER PLANT ENTRAINMENT ON MAJOR SPECIES OF COPEPODS IV-69
Frank J. Maturo, Jr., Ray Alden and William Ingram III

APPENDIX A DATA TABLES IV-103

APPENDIX B BIOLOGICAL PARAMETERS GRAPHS IV-105

APPENDIX C NET MORTALITY GRAPHS IV-151

APPENDIX D CONTOUR GRAPHS IV-205

APPENDIX E FECUNDITY RATE ANALYSIS IV-209

APPENDIX F GROWTH CURVES IV-215

TABLE OF CONTENTS

VOLUME IV

EFFECTS OF POWER PLANT ENTRAINMENT ON MAJOR SPECIES OF COPEPODS IV-235
MEASUREMENT OF ZOOPLANKTON MORTALITY USING ADENOSINE TRI-PHOSPHATE AS A VIABLE BIOMASS INDICATOR.
Frank J. Maturo, Jr. and Richard D. Drew

EFFECT OF POWER PLANT OPERATION ON SHALLOW WATER COASTAL ZOOPLANKTON IV-265

Frank J. Maturo, Jr. John W. Caldwell and William Ingram III

GENERAL OBJECTIVES IV-269

OBJECTIVE 1 SOURCE AND DISCHARGE AREAS OF CRYSTAL RIVER POWER PLANT'S COOLING WATER IN RELATION TO ZOOPLANKTON SAMPLING STATIONS IV-282
Richard Cullen and Ron DuBose

OBJECTIVE 2 STANDING CROP ESTIMATES IV-282
Tom Chaney

OBJECTIVE 3 PRODUCTION OF ZOOPLANKTON POPULATIONS AT CRYSTAL RIVER IV-287
Ray Alden and Frank Hearne

OBJECTIVE 4a CTENOPHORE STANDING CROP AND PREDATION IV-299
Eric F. Hallquist

OBJECTIVE 4b CHAETOGNATH PREDATION IV-306
Alex Smart

OBJECTIVE 4c DECAPOD PREDATION IV-312
Alex Smart

OBJECTIVE 5 A COMPARISON OF POWER PLANT PREDATION AND NATURAL PREDATION IV-331
Richard Cullen and Ronald DuBose

OBJECTIVE 6 STATISTICAL ANALYSIS OF NATURAL AND POWER PLANT INFLUENCES ON ZOOPLANKTON COMMUNITIES AT CRYSTAL RIVER. IV-334
William Ingram

OBJECTIVE 7 COMPARISON OF ZOOPLANKTON DIVERSITY OF SEVERAL AREAS IN THE EASTERN GULF OF MEXICO IV-392
Herbert Hickox and Arthur Wenderoth

TABLE OF CONTENTS

VOLUME IV

PHYTOPLANKTON RESEARCH
Dr. Thomas L. Hopkins
Principal Investigator
Department of Marine Science
University of South Florida

PHYTOPLANKTON ECOLOGY IN THE VICINITY OF THE FLORIDA POWER CORPORATION GENERATING PLANT AT CRYSTAL RIVER, NOVEMBER, 1973 - APRIL, 1974. IV-419
Robert A. Gibson, J.O. Roger Johansson, Mark E. Gorman and Thomas L. Hopkins

APPENDIX I IV-445

CRYSTAL RIVER POWER PLANT

ENVIRONMENTAL CONSIDERATIONS

INTRODUCTION

This report concludes two and one-half years of study at Florida Power Corporation's Crystal River Power Plant. Its purpose is to serve as a decision making tool for regulatory agencies of the State of Florida and the federal government. In particular, the Atomic Energy Commission and the Environmental Protection Agency are required to evaluate the power plant's effect on the local and regional environments prior to issuance of an operating license and a discharge permit. This report describes the baseline conditions found at the two existing fossil fuel units thereby serving as a basis for accessing the interaciton with the environment of Unit 3, an 855 MWe Nuclear Power unit. In addition, this research formed the basis for the setting of plant operating limitations which will assure that existing ecosystems of the receiving waters are not significantly altered.

Environmental projects at the Crystal River Plant began shortly after Florida Power applied to the AEC for the license to construct Unit 3 in August, 1967. In a letter to the AEC, the Department of the Interior (Fish and Wildlife Service) expressed concern that the proposed once-through cooling might be detrimental to the marine environment. As a result, Florida Power Corporation committed to conduct a study of the effects on the environment at Crystal River attributable to the two existing units as a proviso to issuance of the nuclear plant construction permit in September, 1968. This survey was initiated by the Florida Department of Natural Resources under contract with the Company and resulted in some half dozen publications growing out of a year and a half study. Detailed hydrographic mapping of the discharge plume was begun in June, 1970.

In compliance with the NEPA legislation of 1969, Florida Power submitted its original Environmental Report in the Fall of 1970. On September 9, 1971, as a result of the Calvert Cliff's decision, the AEC published its revised Appendix D to 10CFR Part 50, which required holders of construction permits issued prior to January 1, 1970, to "Show Cause" why construction should not be stopped pending the completion of an environmental review. Florida Power filed the required statement October 15, 1971, and advised the AEC that it intended to submit a new environmental report incorporating the substance of the original report and containing the information required in the revised Appendix D. On November 23, Florida Power was notified that construction would not be halted. The new environmental report was docketed January 4, 1972. Three volumes were submitted on that date and in response to further questions, two more volumes were compiled. Eight months later, in September, 1972, the AEC Draft Environmental Statement was issued.

It became evident from the concerns expressed in the draft statement that the federal regulatory agencies were relatively unaware of much of the environmental research which was currently being conducted at Crystal River and which had been done in the past despite several years of widely circulated reports. As a result, Florida Power docketed a technical description/discussion of research at Crystal River in March, 1973.

To resolve differences and identify problem areas in the existing research, on May 10th, a meeting was held between Florida Power and the

AEC, EPA, NOAA and the Department of the Interior. At this meeting, a revised research program was outlined which to a great degree was consistent with the research then in progress. The AEC Final Environmental Statement, issued later in May, concluded that an operating permit should be issued but that Florida Power should produce an acceptable environmental research program capable of establishing baseline ecological data from which an evaluation of the effect of the operation of Crystal River 3 could be made prior to November, 1974. An additional goal was to provide sufficient information to make an assessment of cooling alternatives for the plant.

The Company began to implement the revised program, continuing to utilize resources from within Florida, particularly the state university system, the keywords being accessibility and credibility. On June 11th, Florida Power docketed the proposal describing the implementation of the revised research program which would comply with the expressed concerns of the federal agencies. The scope went beyond that for the third unit to a consideration of the impact of units 1, 2, and 3. This was to ensure that the EPA would be supplied data acceptable in making its assessment for the discharge permit (NPDES) for all three units. On June 27, 1973, the most significant meeting to date was held at the AEC offices in Bethesda, Maryland with federal participation which included the AEC, Department of Interior, EPA. and NOAA. At this meeting, the revised research program was essentially accepted. Two exceptions required that the direction of the plankton program be modified and ongoing independent statistical analysis of the program be performed. Finally, the concept of an interagency team to give direction to and monitor research progress was formalized. The need for the interagency team was strongly supported by Mr. Nathaniel P. Reed, the Assistant Secretary of the Interior for Fish, Wildlife and Parks, and Mr. Jack Ravan, Region IV Administrator of EPA. By September, the plankton program and a statistical overview proposal had been accepted.

On October 15, 1973 the AEC officially designated the membership of the Interagency Governmental Subgroup (the interagency team). This team has met once each quarter since its inception. At these meetings, the researchers elaborated on their findings and the interagency team could make comments and criticisms of any part of the program. Because all the principals were present, it was possible t resolve program issues immediately thereby avoiding much of the delay in approval usually associated with this type of program. The importance of the concept of continual governmental participation through such an interagency subgroup cannot be overstated. It allowed the federal agencies an improved method to insure that the proper environmental information was being generated to assure the technical basis for responsible licensing decisions. In addition, by continued governmental participation, those who must make these decisions are well enough informed to make judgements. From the Company's standpoint, Florida Power has the assurance that the data and methods are acceptable to the concerned agencies, without risk of loss in time and can be confident that permits will not be delayed as a result of inadequate enviornmental information.

This report stresses only those areas where the existing environment and the power plant interact, primarily those immediate to the intake and discharge canals. Specific studies included (1) a survey of the benthic, pelagic, and planktonic communities of the intake and discharge canals, the inner bay area (that area under the plant's influence) and the outer bay; (2) the effects of entrainment on plankton dominants; (3) a modelling of all major communities to identify the major components and pathways; and finally (4) a benefit-cost analysis which looks at the power plant and its system at the regional level. A uninvolved third party was enlisted to provide overview and to evaluate statistical procedures. Supporting information to aid in the assessment of cooling alternatives is supplied in the appended reports by the consulting firms of Gilbert and Associates and Dames & Moore. A benefit-cost analysis of alternate cooling schemes vs. the designed once-through system is also incorporated.

PROGRAM OVERVIEW AND STATISTICAL REVIEW

LAW ENGINEERING TESTING COMPANY

In response to a request by Florida Power Corporation, Law Engineering Testing Company contracted to participate in The Crystal River Environmental Research Program to Meet Current Federal Requirements. Responsibilities in this program included acting as a disinterested third party for purposes of:

A. Meeting with individual principal investigators as requested by Florida Power Corporation preliminary to obtaining final year of data in the Crystal River study. These meetings were for purposes of obtaining information on various objectives, proposed statistical models, and tests.

B. Reviewing quarterly data of various phases of the Environmental Research Program at Crystal River for purposes of providing statistical control and overview functions. After each review, a summary report was furnished to Florida Power Corporation.

C. Meeting with individual principal investigators during the course of the study as requested by Florida Power for purposes of providing statistical consultation.

D. Meeting with interagency personnel as needed and requested for purposes of discussing objectives, statistical models and significance likely to be obtained therefrom on each phase of the Crystal River Research Program.

These responsibilities have been fulfilled to date and are represented by a series of summary reports submitted to Florida Power Corporation. These professional services were supplied by Drs. Don E. Henley, Limnologist and Robert T. Lackey, Statistician.

POWER PLANTS AND ESTUARIES AT CRYSTAL RIVER, FLORIDA

An Energy Evaluation of the System of Power Plants, Estuarine Ecology, and Alternatives for Management

Howard T. Odum, W. M. Kemp, W. H. B. Smith, H. N. McKellar,
D. L. Young, M. E. Lehman, M. L. Homer, L. H. Gunderson, and A. D. Merriam

Contract #
GEC-159
918-200-188.19

with the

Florida Power Corporation

and

Systems Ecology Group

Department of Environmental Engineering Sciences

University of Florida

Gainesville, Florida 32611

A Report to Florida Power Corporation
and Government Agencies concerned
with Licensing

October, 1974

TABLE OF CONTENTS

1. Abstract

2. Introduction and Recommendations - H.T. Odum

3. Energy Evaluation of Cooling Alternatives and Regional Impact of Power Plants at Crystal River - M. Kemp

4. Main Ecological Subsystems of the Estuary and Their Adaptation to the Power Plants.

   A. Shallow Inshore Ecosystem of Bottom Communities and the Effect of Thermal Plume - Wade Smith

   B. Metabolism and Models of Outer Bay Plankton Ecosystems Affected by Power Plant - H. McKellar

   C. Oyster Reefs at Crystal River and Their Adaptation to Thermal Plumes - M. Lehman

   D. Ecosystems of the intake and discharge canals - M. Kemp

   E. Tidal creeks and effects of power plants - M. Homer

   F. Salt marsh and the effect of thermal plume - D. Young

5. Value of Higher Animals at Crystal River Estimated with Energy Quality Ratios - M. Kemp, H. McKellar, and M. Homer

6. Monitoring Future Trends and Onset of Additional Plumes with a Metabolism Buoy - L. Gunderson and A. Merriam

7. Appendices:

   A. Papers recently published in Thermal Ecology Symposium

   A1. Energy Cost-Benefit Models for Evaluating Thermal Plumes - H.T. Odum

   A2. Studies of Florida Gulf Coast Salt Marshes Receiving Thermal Discharges - D.L. Young

   A3. Total Metabolism of Thermally Affected Coastal Systems on the West Coast of Florida - W. Smith, H. McKellar, D. Young, and M. Lehman

   B. Energy Cost-Benefit Approach to Evaluating Power Plant Alternatives - H.T. Odum

   C. Preliminary Calculations of Energy Quality Ratios or Work Equivalent Factors - M. Kemp and W. Boynton

   D. Models of the Interaction of the Crystal River Power Plant and the the Adjacent Outer Bay Ecosystem: Relation to Coastal Fisheries - H. McKellar

   E. Salt Marsh Microarthropod Populations - E. A. McMahan and D. L. Young

1. ABSTRACT

This is the report of a contract between the Systems Ecology group of the Department of Environmental Engineering Sciences, University of Florida and the Florida Power Corporation summarizing many studies of the estuaries at Crystal River and the impact of the power plants. Models, energy evaluations, and measurements of five estuarine ecosystems were used for an evaluation including the effects of entrainment, temperature, circulation, and economic costs on the shallow inshore bottom dominated bays, deeper bays where plankton is more important, oyster reefs, salt marshes, and intake and discharge canals as well as the larger power shed region. Impact on the estuary was compared with impact of proposed cooling towers to determine which alternative maximized generation of total value by the combined system of man's economy and the production processes of nature. An energy cost-benefit procedure showed a cooling system utilizing the estuary to have much greater value than a system of cooling towers.

2. SUMMARY AND RECOMMENDATIONS

This is an evaluation of the present and proposed systems of power plants and estuary at Crystal River, Florida. After seven years of operation the power plants, the adjacent estuary, and the circulation of water between plant and estuary have developed patterns of marine life involving adaptation of ecosystems to the plant and vice versa. The plant is like a giant consumer, absorbing some of the plankton and swimming life, returning them as nutrient materials to the estuary along with some increase in temperature and current velocity. This circulation has been substituted for the coastal circulation that existed before the plant and its barrier were constructed. A new plant now under construction (Unit #3) will increase the flow and thus the area of influence of the consumer (power plant) interactions. This report summarizes studies of the several estuarine ecological subsystems affected by the plant and suggests the changes that may follow with the additional plant. The observed and possible positive and negative effects of the plants on the estuary are compared with alternatives such as cooling towers using a new energy cost-benefit approach. The economic vitality of the region served by the Florida Power Corporation is dependant on maximizing the total useful work including that of man and that of nature in the estuarine ecosystems. The losses in useful work associated with the estuarine impact are far less than the losses that would result with building cooling towers.

Ecological subsystems studied include (1) a shallow inshore bay dominated by bottom plants and animals, (2) marshes with their tidal creeks into which larger fishes, shrimp, and crabs come and go, (3) oyster reef bars, (4) the deeper waters further out, in which plankton ecosystems are more important with fewer bottom organisms, and (5) the new ecosystems in and along the power plant intake and discharge canals. Measurements of predominant organisms, the general diversity of life, overall metabolism and energy budgets, and nutrient cycles that are a part of these, show relatively small differences in the areas affected by the plant and areas measured nearby. Only the inshore bay ecosystem in the direct path of the outflow showed a significant decrease of about 50% in total metabolic work and related indices. The area of this shallow bay exhibiting depressed metabolism under present conditions of once-through cooling of two units is about 175 acres.

Simplified overall energy models were used to provide perspective on the interaction of parts of ecosystems, the effect of more circulation, the effects of temperature, and plant impact. Computer similations were run on each of the subsystems to determine consistency of the concepts of how the estuary works with observed data. As finalized, the computer graphs of seasonal change produced by the models were giving patterns similar to the observed seasonal trends of data. These model studies included the action of temperature as an accelerator of constructive processes and as a disordering destructive process as is well established in biological studies of temperature effect on life. These models were simulated with conditions expected for the new plant (greater flow and slightly increased temperature). The effects on the general productivity were predicted to be within 30% of the present condition.

If built, cooling towers for units 1, 2, and 3 would require a flow of money of 17 million dollars per year and thus an energy diversion of 540 x 10^9 Kcal of fossil fuel equivalent work per year. Presently, the effect of the two operational units is a reduction of present estuarine energy flow in units of equivalent ability to do work only about 1 % as much as the energy flow associated with cooling towers. If the effect on the estuary increases to 64 x 10^9 Kcal as predicted in this report from the increased discharge of Unit 3 the factor favoring estuarine cooling becomes 50 to 1. The energy flowing throughout our national economy to supply 17 million dollars worth of goods and services to build and maintain a cooling tower is estimated to be 70% from purchased fossil fuels and 30% from the free services to the economy from work of the environment such as absorbing and recycling wastes. In other words, 30% of the energy cost of the cooling towers is environmental impact elsewhere. This effect in 100 x 10^9 Kcal of fossil fuel work equivalents per year is about 2 times greater than the 64 x 10^9 Kcal/yr of impact on the estuary.

In summary, energy evaluations show that the system of power plants and estuarine cooling as they are after an adaptation period is economically and ecologically more competitive than the proposed alternatives of cooling towers. The estuarine ecosystems after adaptation are somewhat different from unaffected ones, but within the range of energy budget, metabolism, diversity and productivity of fishery species of other Gulf Coast estuaries.

Calculations were made to show the power needs for the region using the new concept of energy investment matching. The carrying capacity of the Crystal River Power plant region for economic development based on purchased energy sources from outside is calculated as that level with as high a ratio of natural free energy contribution to match purchased energy as competitors.

This ratio (natural to bought work rates) is about 1.0 bought to 0.4 natural for the United States (1970). Since this ratio is declining along with world fuel supplies, the maximum carrying capacity for fossil fuel work is estimated to be declining from present value of 45.3×10^{12} (FFWE) Kilocalories per year. Allowing 43%* of this for electric power generation and converting to electrical units, the ultimate power needs of the region served by Crystal River units are calculated to be 1890 megawatts, similar to the capacity of the present plants and those under construction. This calculation predicts little further power plant development, although there may be further economic development in the less populated areas around the plants. The impact of the plant on the estuary should not be judged as one of many yet to come.

For the start-up of the third plant, we recommend that any judgement as to the effects be reserved until after the initial transitional period of adaptation is over. In order to allow observation of the adaptation. Since the new adaptations that will follow the addition of flow from the third power plant will require at least one year, we recommend monitoring for key indices of the ecosystems through a two year transition period. A buoy for continuously measuring total metabolism has been constructed and is now operational for scanning each of the affected ecosystems by rotating every week. (See section 6 of this report). Zooplankton diversity, larger fishes caught by nets in marsh creeks, and visual scanning of bottom ecosystems are additional techniques for a long range, low cost, monitoring of the estuary during the transition.

---

* Percent for United States in 1970,

SUMMARY

SHALLOW INSHORE ECOSYSTEM OF BOTTOM COMMUNITIES AND THE EFFECT OF THE POWER PLANT DISCHARGE PLUME

Wade Smith

The heated discharge of Florida Power Corporation's power plants near Crystal River, Florida first flows into a shallow estuarine basin of about one meter average depth consisting primarily of benthic animals and plants, and expecially one species of seagrass, Halodule wrightii (formerly Diplanthera wrightii). This bottom dominated ecosystem is influenced by oyster reefs on its boundaries and mud bottoms adjacent to the salt marshes on the landward edge. (See Fig. 1, 2, and 3.) As part of a larger project to assess the environmental impact of these plants and a third under construction, total community metabolism has been measured since the summer of 1972 in this basin and similar benthic dominated areas to the south and north. Measurements from this study and data from concurrent studies by others were combined with models and computer simulations to evaluate the effects of present and future plants.

Total community metabolism was measured with the complete diurnal method and a more approximate dawn-dusk-dawn method. A marked seasonal pattern of daytime net photosynthesis, night respiration, and gross production was evident in the control areas with lowest values in winter, highest in summer and fall. Values in the control area were similar regardless of season. Winter values were similar in the two areas, but were 2 to 3 times higher in the control areas during spring, summer, and fall.

The range in values of gross production of 2 to 10 g O_2/m^2.da measured in the Crystal River region are very similar to those measured in the many different types of bay systems of the Texas coast (Odum and Hoskins, 1958; Odum and Wilson, 1962), falling within the lower two-thirds of the range of values recorded there (Odum, 1967). Odum (1963) reports seasonal patterns and levels of metabolism for Redfish Bay, a Thallassia and Halodule dominated Texas bay which is much like the control areas at Crystal River.

Light and dark bottle measurements of water column metabolism excluding larger organisms indicated the benthic dominance of metabolism except in spring. In the discharge bay water column metabolism ranged from 3.10 g O_2/m^2·da to 0.81 g O_2/m^2·da, being highest in spring based on only two measurements, and considerably lower in summer and fall. In the control areas the average value ranged from 3.14 g O_2/m^2·da to 0.54 g O_2/m^2·da and was also highest in spring and lower in the fall.

Plankton production was a larger portion of total production in the discharge area than in the control areas ranging from 75% of total production in the spring to 23% in the summer and fall. In the control area it was 33% in the spring and 7% in the fall.

SUMMARY

METABOLISM AND MODELS OF OUTER BAY ECOSYSTEMS AFFECTED BY THERMAL PLUME

Hank McKellar

This chapter evaluates the effects of the coastal power plant at Crystal River, Florida on the outer bay ecosystem. Considered were the net effects of the thermal discharge, canal spoil banks, and plankton entrainment on ecosystem energy flow. An energy circuit model was proposed for the bay ecosystem's structures, functions, and interfaces with influences from the power plant. The major energy flows and storages of the model were evaluated with field measurements and with supporting information in the literature. Evaluated models for both "discharge" and "control" bays were compared to show differences due to the new design of ecosystem parts and processes which developed in adaptation to power plant influence.

Power plant influence on total biological energy flow was small with less than 10% difference in annual averages of community gross primary production (5.58 and 5.22 g. organic matter/m^2/day in the control and discharge bays, respectively). During August, September, and October, net daytime production in the discharge bay was significantly lower than in the control bay by about 15%, possibly indicating some degree of photosynthetic inhibition following the warmest months of the year. Some evidence was also found indicating a spring time stimulation of respiration and photosynthesis in the discharge bay.

In general, bottom metabolism in the control bay was more important than the plankton. Gross planktonic production usually comprised less than 50% of the total community gross production. Power plant influence in the discharge bay apparently led to more plankton dominance in community energy flows with gross planktonic production generally greater than 50% of community production. Annual average gross planktonic production was 1.93 and 3.06 g/m^2/day for the control and discharge bays, respectively.

Rates of zooplankton respiration per unit body weight were found to change significantly from winter to summer (0.006 g/g/day and 0.028 g/g/day, respectively) although no differences could be shown between control and discharge bays. Daily oxygen consumption by zooplankton was between 3% and 9% of total planktonic respiration and between 0.5% and 1.5% of total community respiration.

Planktonic chlorophyll-a in both bays fluctuated from winter concentrations around 1 mg/m^3 to spring and summer peaks around 5 mg/m^3. Although no consistent differences were demonstrated between the two bays, the annual average in the discharge bay (2.97 g/m^3) was about 34% higher than in the control bay (2.21 g/m^3).

Total phosphorus in the water column fluctuated from winter concentrations around 30 mg/m^3 to spring and summer values around 60 mg/m^3. During most of the year, concentrations in the discharge bay were 20 to 40% higher than in the control bay. This trend was offset by higher levels in the control bay during spring phytoplankton blooms. Annual averages of total phosphorus were 40.9 mg/m^3 amd 44.1 mg/m^3 for the control and discharge bays, respectively. Dissolved inorganic phosphorus was consistently higher in the discharge bay by about 10% indicating possible effects of increased temperatures on recycling inorganic fractions.

Chlorophyll-a and total phosphorus concentrations in the power plant canals were similar to those found in the bays. As was found for the discharge bay, the discharge canal always had higher concentrations of dissolved inorganic phosphorus than the intake canal.

Distinct gradients of chlorophyll and phosphorus concentrations were found across the continental shelf adjacent to the power plants. Chlorophyll-a concentrations in inshore waters were found to be more than an order of magnitude higher than concentrations found at stations over the outer shelf. Similarly, total phosphorus at inshore stations was 30 to 80% more concentrated and particulate phosphorus was 100 to 200% more concentrated than in offshore waters. The seaward effect of power plant influence on these materials could not be distinguished from the gradients.

The combined information on system metabolism and organisms biomasses indicated that the total system turnover rate during the summer was faster in the discharge bay. Total organism biomass (48.5 g/m^2) in the discharge bay was about 30% lower than in the control bay at 66.8 g/m^2. With similar rates of total metabolism, respiration per unit biomass was correspondingly higher in the discharge bay. Total system turnover times for the control and discharge bays were 15 and 11 days respectively.

SUMMARY

OYSTER REEFS AT CRYSTAL RIVER, FLORIDA AND THEIR ADAPTION TO THERMAL PLUMES

M. E. Lehman

Intertidal oyster reefs receiving thermal effluent from power plants were compared with those unaffected nearby. Field measurements of biomass gave area-weighted estimates of 253.4 g/m^2 (dry meat weight) for the thermal area, and 256.4 g/m^2 for the control area. The American oyster, Crassostrea virginica, comprised 78% of the total consumer biomass in the thermal area, and 47% in the control area. Lower species diversity in the thermally-affected area may reflect the greater oyster dominance. Spawning rates of oysters were similar in both areas with less seasonal variation in the plume-warmed waters. Total community respiration of reefs in the thermal plume was 20.9 $g/m^2/day$. Respiration of reefs not in the thermal plume was 15.7 $g/m^2/day$. Underwater metabolic rates of thermally-affected reefs were six times greater than rates during exposed periods at low tides. The underwater rate was three times the exposed rate for reefs not receiving thermal effluent.

Simple models evaluated and simulated to help understand present conditions showed increased turnover times of storages in the thermal model. Over-all structure and function were similar in the two models. Simulation of future adaptation to additional thermal influence suggested a dampening of seasonal variation in certain standing stocks with some stocks being reduced. Increased temperatures as much as 4°C altered reef stocks less than 20%.

The value of oyster reefs in the energy budget of the estuary was calculated for use in environmental impact statements. Similarities of reef system structure and function, and comparable energy budgets, of thermally-affected and unaffected reefs, suggests successful adaptation of reefs at Crystal River to thermal plumes.

SUMMARY

ECOSYSTEMS OF THE INTAKE AND DISCHARGE CANALS

W.M. Kemp

The power plant's intake and discharge canals represent significant components of the coastal areas near Crystal River. The ecosystems within the canals have developed in response to the energy sources and stresses provided by the power plant. Because of their proximity to the power plant and since they are strongly influenced by plant activities, the canals offer a reasonable point at which to monitor the effects of power plant operation. Field work from June to January, 1974, and computer simulations are presented which attempt to characterize these ecosystems.

Total gross primary production in the canals ranged from 6 to 22 g/m^2/day. Average primary production in the intake canal was 35% greater than in the discharge canal, perhaps owing to the greater depth of the euphotic zone in the intake canal and to thermal and chlorine stresses in the discharge canal. Also, P/R ratios were slightly higher in the intake canal.

Gross planktonic productivity ranged from 0.17 to 16.9 g/m^2/day and was about 2.5 times greater in the intake canal than in the discharge canal. Planktonic production accounted for about 36% of the total production in the intake canal and about 21% in the discharge canal.

Total animal biomass in the discharge canal, dominated by a littoral community of oysters, barnacles and crabs, was about 70% greater than in the intake canal system. The intake canal intertidal animal community was dominated by the small porcelain crab, Petrolisthes sp. with mud and stone crabs contributing substantially to the overall biomass. The intake

canal benthic intertidal animal community was 46% more diverse than the discharge canal.

An energy circuit model is proposed which illustrates some major characteristics of this ecosystem, with emphasis of consumer components. Simulations were performed to test the model's response to varying rates of plankton input, benthic consumption of plankton and detritus, fish immigration, fishing pressure, and water flow.

SUMMARY

CHARACTERISTICS OF TIDAL CREEKS RECEIVING THERMAL DISCHARGE

Mark Homer

Results of the first months of sampling are included in this report. Fish biomass levels in the control creek peaked in July at 4.6 g wet weight/m^2, while discharge creek fish biomass reached its highest level in September at 3.7 g/m^2.

Lower diversity levels for the first five months of sampling were found in the discharge creek. Diversity in species per 1000 ranged from 9.5 to 20.5 in the discharge area and from 13.5 to 23.5 in the control creek.

Preliminary measurements were made at planktonic and sediment metabolism using light and dark bottle methods. Gross production ranged from 1.83 to 2.29 g O_2/m^3/day in the discharge creek area and from 1.29 to 2.82 g O_2/m^3/day in the control area. 24 hour respiration ranges were 1.34 to 2.16 g O_2/m^3/day in the discharge creek and 1.24 to 2.21 g O_2/m^3/day in the control creek. These values were similar to those measured in the shallow inshore bay system of basin #1.

A few preliminary fish production values were calculated for two species of resident killifish, <u>Fundulus grandis</u> and <u>F. similis</u> of age class 0. In the control areas, production values for <u>F. grandis</u> ranged from -0.22 to 18.9×10^{-2} g wet wt/m^2/mo, while those for <u>F. similis</u> ranged from 1.35 to 21.34×10^{-2} g wet wt/m^2/mo. In the discharge area <u>F. grandis</u> production values ranged from -0.21 to 1.51×10^{-2} g wet wt/m^2/mo, while those for F. similis ranged from -0.05 to 13.54×10^{-2} g wet wt/m^2/mo.

ACKNOWLEDGMENT

The authors acknowledge field and laboratory assistance from W. Auffenberg, T. Ballentine, J. Bernardi, G. Bevis, C. Bilgere, N. Black, W. Boynton, S. Brown, J. Caldwell, T. Chaney, J. Cox, D. Dorman, R. Drew, R. Dubose, T. Gayle, D. Hinck, J. Huffaker, J. Murray, J. Peck, F. Ramsey, D. Rohe, M. Sell, S. Simonet, H. Tyus , and J. Zucchetto.

Technical assistance and advice were provided by C. Adams, R. Beyers, K. Dugger, C. High, S. Jones, W. Huber, F. Maturo, M. Oesterling, S. Snedaker, R. Stanford, E. Striker, P. Brezonik, J. Fox, and S. Snedaker loaned the use of field equipment and supplies. The State University System's Institute of Oceanography in St. Petersburg and Florida State University's Department of Oceanography in Tallahassee provided research vessels and crews for work in the deeper bays and offshore areas. Florida Power Corporation's D. McMullin and W. Trowell maintained smaller boats used in this study. Secretarial work was done by J. Breeze, B. Barnard, B. Dawson, N. McMann, and N. Russell.

3. ENERGY EVALUATION OF COOLING ALTERNATIVES AND REGIONAL IMPACT OF POWER PLANT AT CRYSTAL RIVER, FLORIDA *

W.M. Kemp

Department of Environmental Engineering Sciences
University of Florida, Gainesville 32611

In keeping with the requirements set forth in the National Environment Policy Act(NEPA,1969) Florida Power Corporation has established and supported a multifaceted research program to investigate the impact of the Crystal River electric power generating plant on the region with which it interacts. Together, the various components of this research effort are intended to characterize the relationship of the existing two-unit plant with its environment. In addition, effort has been made to project this understanding to anticipate any further impact which would result from the operation of the third unit . Future research monitoring programs will be maintained to detect any further environmental changes.

To assist in organizing the many aspects of this project, models have been developed as a format for assuring comprehensiveness of the field program and for understanding the interrelationships of the research tasks and of the parameters being measured. Model simulations have helped to predict the general consequences of proposed power plant changes and have led to identification of sensitive ecosystem parameters for further scrutiny. This report provides such models and data synthesis toward an understanding

---

* The concepts provided in this report include inputs from many participants of this and related projects in the Systems Ecology Program at the University of Florida. A summary of the important concepts can be found in Odum, H.T.. Energy, Value, and Money, in C. Hall and J. Day (eds.), Models as Ecological Tools: Theory and Case Histories (in press) Special contributions from C. Kylstra, W. Boynton, S. Bayley, and J. Zucchetto are gratefully acknowledged.

of the effects of the power plant on the estuary. An overall evaluation of the impact of the Crystal River power plant on its regional environment under several management alternatives is quantified using an energy cost benefit analysis technique.

Methods and Concepts of Environmental Impact Analysis and Regional Planning

The concept of environmental impact assessment was developed to "insure that presently unquantified environmental amenities and values may be given appropriate consideration in decision making along with economic and technical considerations " (NEPA , 1969). The mandate of this law requires that environmental impact assessment be directed toward regional design and planning for a vital economy of both man and nature. It is essential in this planning process that impact of human activity on "natural" work functions be understood so that man's structures and functions can be designed to maximize the sum of both nature's and man's work, coupled together in the regional economy. We suggest that the overriding notion which dictates surviving patterns, and upon which all planning effort must be based is the Lotka maximum power principle. Our efforts to evaluate the role of the Crystal River power plant in its regional environment through modeling and energy cost-benefit calculations are rooted in the essence of the Lotka principle. The following few paragraphs are provided to explain this principle and its corollaries as preface and explanation to our methods of environmental impact assessment.

Lotka Principal of Maximum Power for Regional Design

The Lotka principle states that any system will tend to prevail, prosper, and survive in competition with alternatives if it utilizes all its energy resources to maximize its useful work value. In order to maximize its value a system must build adequate structure to maintain flexibility in competitive functions and channel its energies into feedback pathways which further increase its total power budgets. Furthermore, a system of man and nature such as a region containing estuaries, power plants, and human settlements makes best use of its available energies by building intricate structures which emphasize partnerships, symbioses and diverse functions, and avoid unnecessary waste. Translated specifically into management questions in the Florida Power Corporation power shed, the pattern of power plant, man, estuary, and the economy of circulating money which develops a compatible fabric, maximizing the useful work of the entire region, will maintain an economically competitive position and ultimately be regarded as reasonable, correct, and desirable by component individuals who adapt as part of the surviving system.

Converting Energy Values to Work Values Using Energy Quality

It has been recognized for some time in the fields of engineering and physics that all types of energies do not possess equal ability to perform work (Tribus and McIrvine 1971; Evans, 1969). In such a large, diverse region as that which is directly influenced by Crystal River, there is a broad spectrum of many kinds of energies contributing various work functions in the system. The analysis presented in this report tabulates and compares magnitudes of energies flowing into and out from the region, and attempts to establish management schemes which will maximize the overall work value of these energies to the system.

Since measurements and reported data are usually given in terms of energy flows rather than "useful work accomplishments" but since it is the latter in which Lotka's principle and our analysis are ultimately interested, the general ability of a given flow of a given kind of energy to do a unit of work becomes a key issue. We therefore introduce the notion of energy quality which we define as the ability of a unit amount of energy to perform a unit of work (work value). On a relative scale the energy quality or "work concentration" for one energy type can be quantified in terms of another type. An energy quality ratio (EQR),then, is the ratio of the work values of two different energy types, and a system of energy quality ratios can be developed with the work concentration of a given energy type being set equal to unity. This energy type is thus given unit quality and is then usedas the common basis to which all other energies are compared.

Only when energies of various quantities, concentrations and sorts are converted to a common basis using energy quality ratios is their work value comparable. We calculate these EQR's (work concentration factors) by investigating a given work process which can be performed by more than one energy type. The kilocalories of energy (in terms of heat content) required to do this work by a given kind of energy is inversely proportional to its quality. A recent paper by Odum (1974) provides an example calculation in which it is shown that electrical energy is about 3.6 times as concentrated to support work as is the thermal energy of coal. It costs about 3.6

calories of energy in the form of coal (including cost of maintaining the installations involved in the conversion) to make one calorie of electricity. Calculations for all of the energy quality conversion ratios used in this report are given in Appendix C.

Some of these work concentration factors are calculated from only one of two examples, but others utilize numerous data sets to document mean EQR's. It is thought that the energy quality ratios will vary some depending on the actual concentration of energy per unit area, that is, 150 feet of water head can generate electricity more efficiently that can 25 feet of head. Therefore energy concentrations common to northern Florida were used wherever possible. While the exact magnitudes of these energy quality ratios are somewhat variable from situation to situation, we are confident that those used in this report are reasonable.

In an earlier report (Odum <u>et al</u>., 1973) the EQR of primary production of sugar was set equal to 1.0 and work concentration factors were related to it as a common basis for comparison of work value. Calculations in this report utilize the EQR for the work of fossil fuel energy as the common level for comparison, since fossil fuel work dominates most regional sytems in this country. Where relevant, totals are also given in terms of 1973 U.S. dollars, realizing that most readers will have a better sense of the work associated with dollar rather than fossil fuel magnitudes. Table 1 summarizes the energy quality ratios used in this report as calculated in Appendix C.

Table 1. Energy Quality Ratios (Work Equivalents) for Various Kinds of Energy Flows at Concentrations Typical for Florida.*

Energy Type	Reference to Appendix C	Sugar Equivalents	Fossil Fuel Work Equivalents
Sunlight	1	0.01	7×10^{-4}
Winds	1	1.8	0.13
Tides	2	6	0.4
Waves	3	3	0.2
Water Head	4	25.5	1.7
Water as Dilutant	5	15	1
Sugar	7	1	0.07
General Water Kinetic Energy	6	0.2	0.014
Wood	7	2	0.14
Coal	7	10 } 15	0.7
Fuel Oil	7	20	1.4
Electricity	7	50	3.6
Dollars		45×10^4	3×10^4

* Work equivalents are generally greater for energy flows found in high concentrations - viz., the amount of work per Kcal of water head is greater for a larger head than for a smaller.

Mixtures of High and Low Energy Quality

Within the network of both "natural" ecological systems and the economic systems of man, as well as within the combined systems of both which must be considered in regional evaluations, many components of varied energy qualities occur working together. The work of lower energy quality units and functions develops higher quality ones, which in turn feedback special services of management and recycle for the effective functioning of the whole system. For example, in biological systems one observes food chains converging in the high quality functions of larger complex animals that have management roles in the ecosystem. The pattern of distribution for these various system components whose energies are of different qualities emerges in a distribution resembling the classical power spectra of molecular energies, ocean wave frequencies, or turbulent eddy energies.

The extent to which high quality components can be developed in a system (both in terms of level of quality and numbers of units at the highest qualities) is dependent on the magnitude of the total energies available to the whole system. Higher quality units are more energy expensive to maintain, and the expense increases with quality in an apparent logarithmic fashion. High quality functions must be supported and maintained by a broad base of lower quality work functions.

When a system is complex, branched, and running on several main sources of energy, one must develop models and diagrams to suggest what are the main means by which the overall condition of surviving maximum power is developed. An example of such a complex system is the food web of the estuary at Crystal River. Fig. 1. in Section 5 of this report is a diagram of this system. In Fig. 3. of Section 5 the trophic web system is rearranged into general work functions. Since all work functions are of equal value to the overall operation of the system, the higher trophic levels which process less energy have a greater work value per unit energy.

Transitions and Steady State

When a modification is made in a regional pattern, there may be transition periods in which subsystems change and substitute as part of the adapting and selecting processes, ultimately leading to a new kind of steady state that maximizes power under the new conditions. For ultimate planning, the temporary losses as one system replaces another should not be the primary long range questions as to desirability of alternatives, although they must be included in calculating the total loss or gain in replacement. Evaluation of the impact of adaptation to new conditions required a diversion of energy and will usually be manifest as a temporary negative to the total system. For example, a significant impact could result from starting up a power plant or in stopping it after adaptation, but the main issue should be the nature of the new steady state after adaptation has occurred.

At Crystal River there has been an adaptation period of over 7 years since the initial plant operation, and the adapted system which is well tuned to its environment (including the Crystal River power plant) has had sufficient time to develop. Under the additional special energy conditions associated with the power plant, (ultimately from fossil and nuclear fuels), certain changes in the estuarine ecosystems have occurred with new adaptations developing and replacing some previous ones. The new external energies, while displacing some previous values, are also the basis for additional work value to the region. The energy users that will prevail are the ones which make the best use of the combined energies in accordance with the Lotka principle.

Ultimate Evaluation on Large Scale

In evaluating alternatives and making choices in management questions, such as the best method for cooling a power plant, the ultimate decision must be determined by that alternative that will maximize the power of the overall larger scale system of estuary, terrestrial system, and human economy all considered together. The various economic decisions of man are a part of the overall self design process for maximum work value but typically do not consider the large supporting and free energy flows of nature. In evaluating the environmental impact of the Crystal River power plant, the scale of analysis must be one-step broader than the local area of impact. This is because significant work value effects result from energy exchanges across the local boundaries of that area. While components interact at the scale of their own system, the system which they comprise further interacts as a component in a larger system, and so on, through a cascading hierarchy. Fig. 1a and b and 2a and b illustrate the regional scale for analysis of power plant effects, and Table 4 gives the method used for calculating the areal extent of this region.

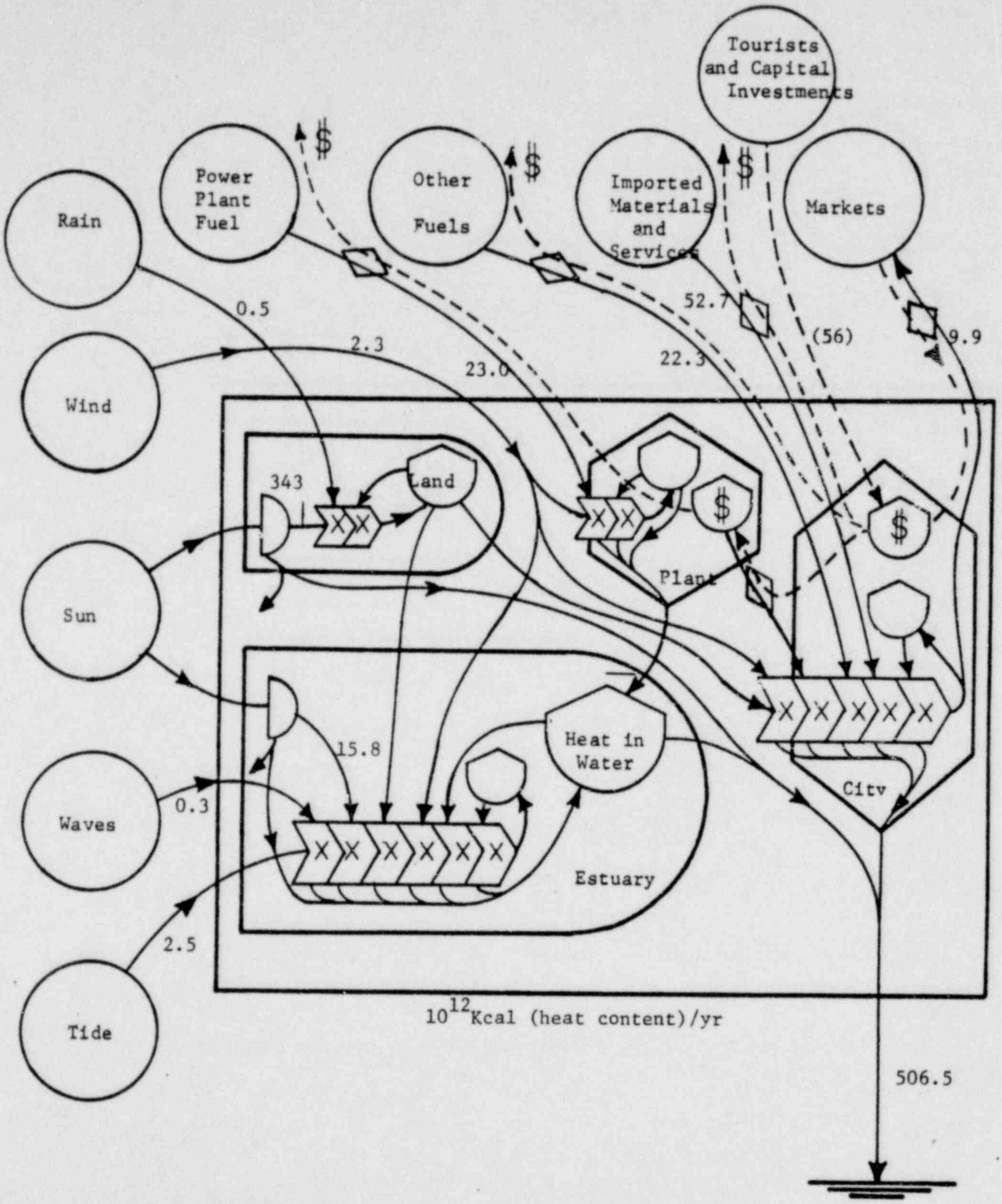


Fig. 1a. Energy diagram for region associated with Crystal River power plant with energy inflows and outflows evaluated in terms of heat content.

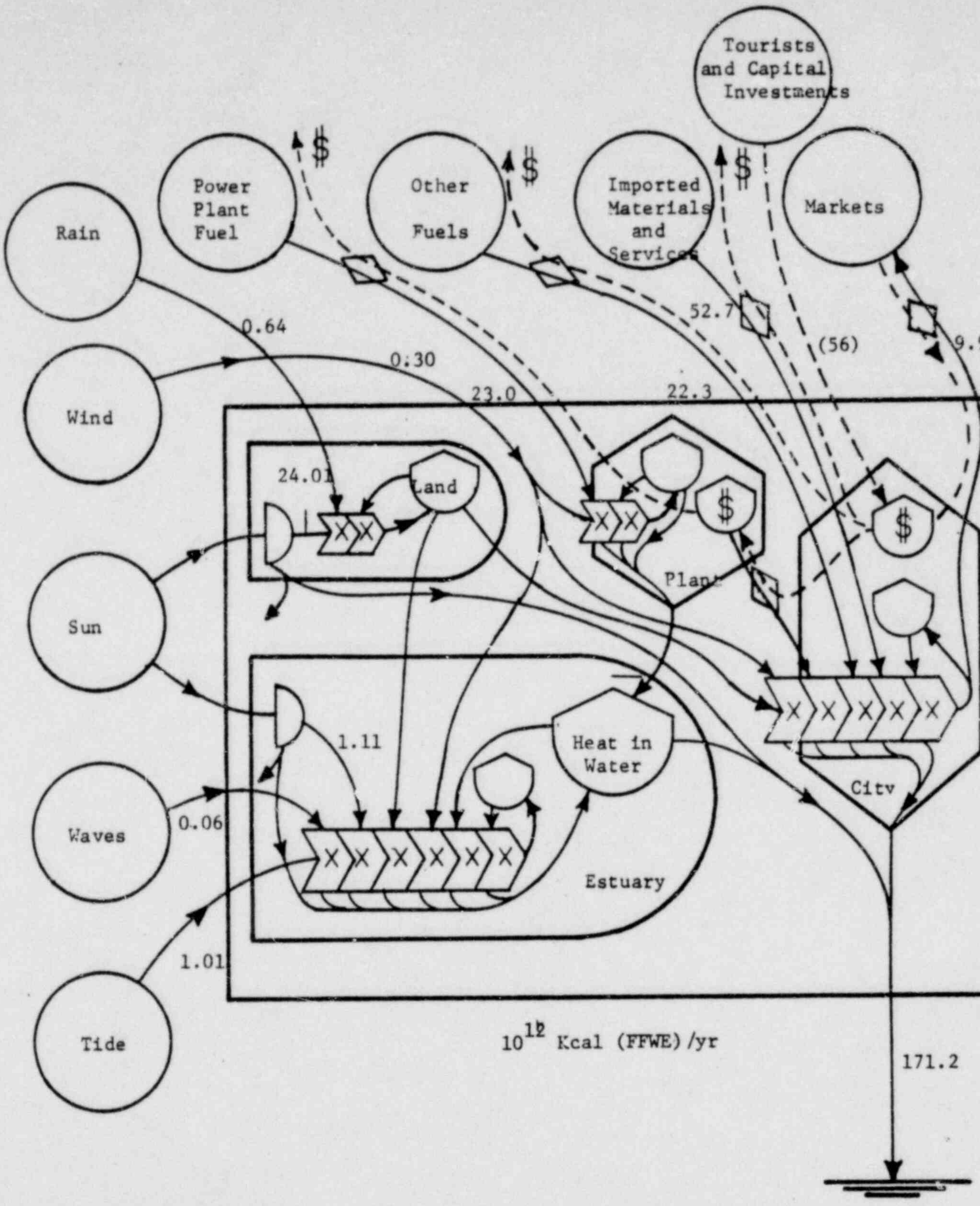


Fig. 1b. Energy diagram for region associated with Cryatal River power plant with energy inflows and outflows evaluated in terms of fossil fuel work equivalents.

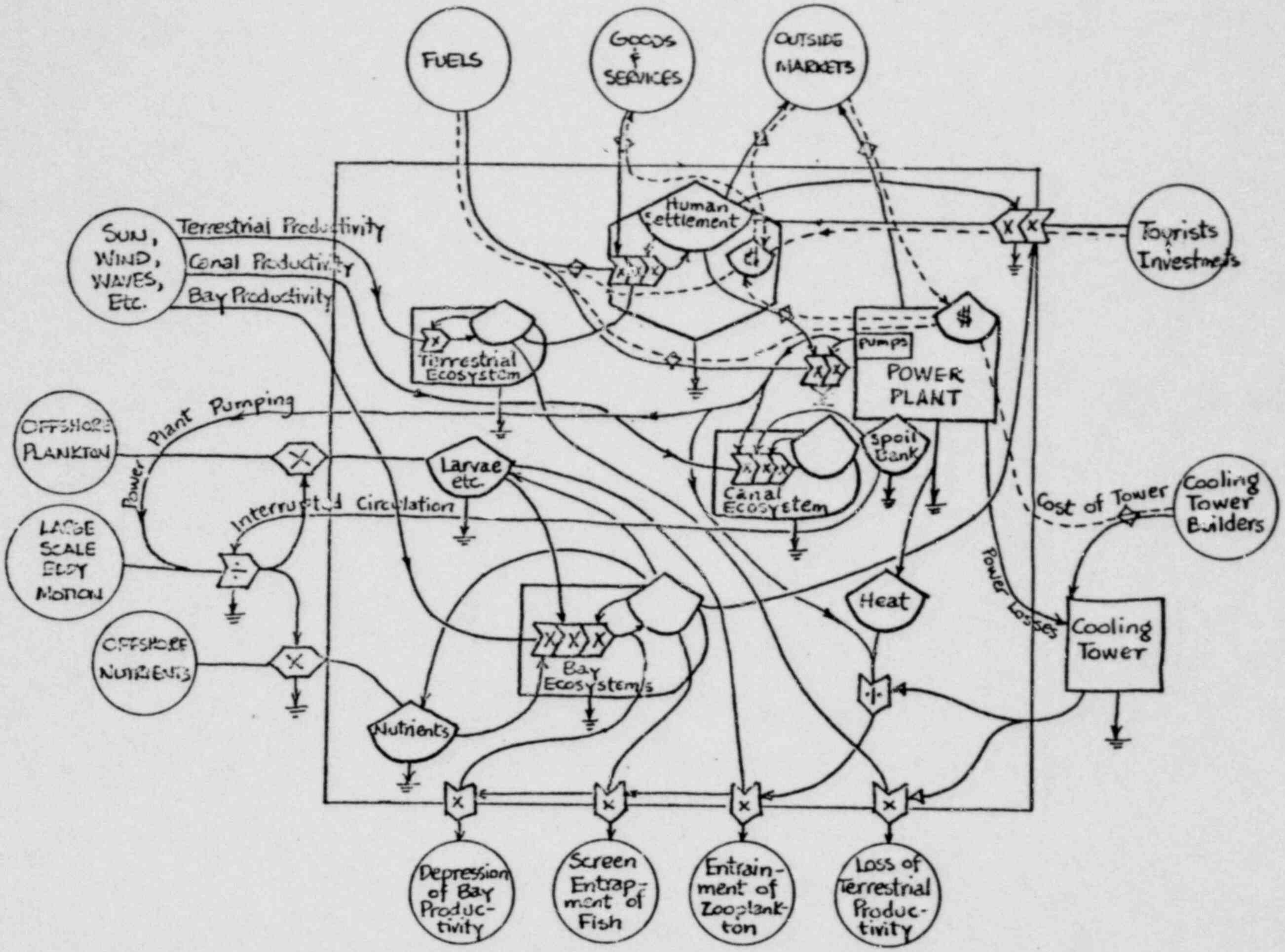


Fig. 2a. Energy diagram of Crystal River power plant emphasizing the effects of management alternatives.

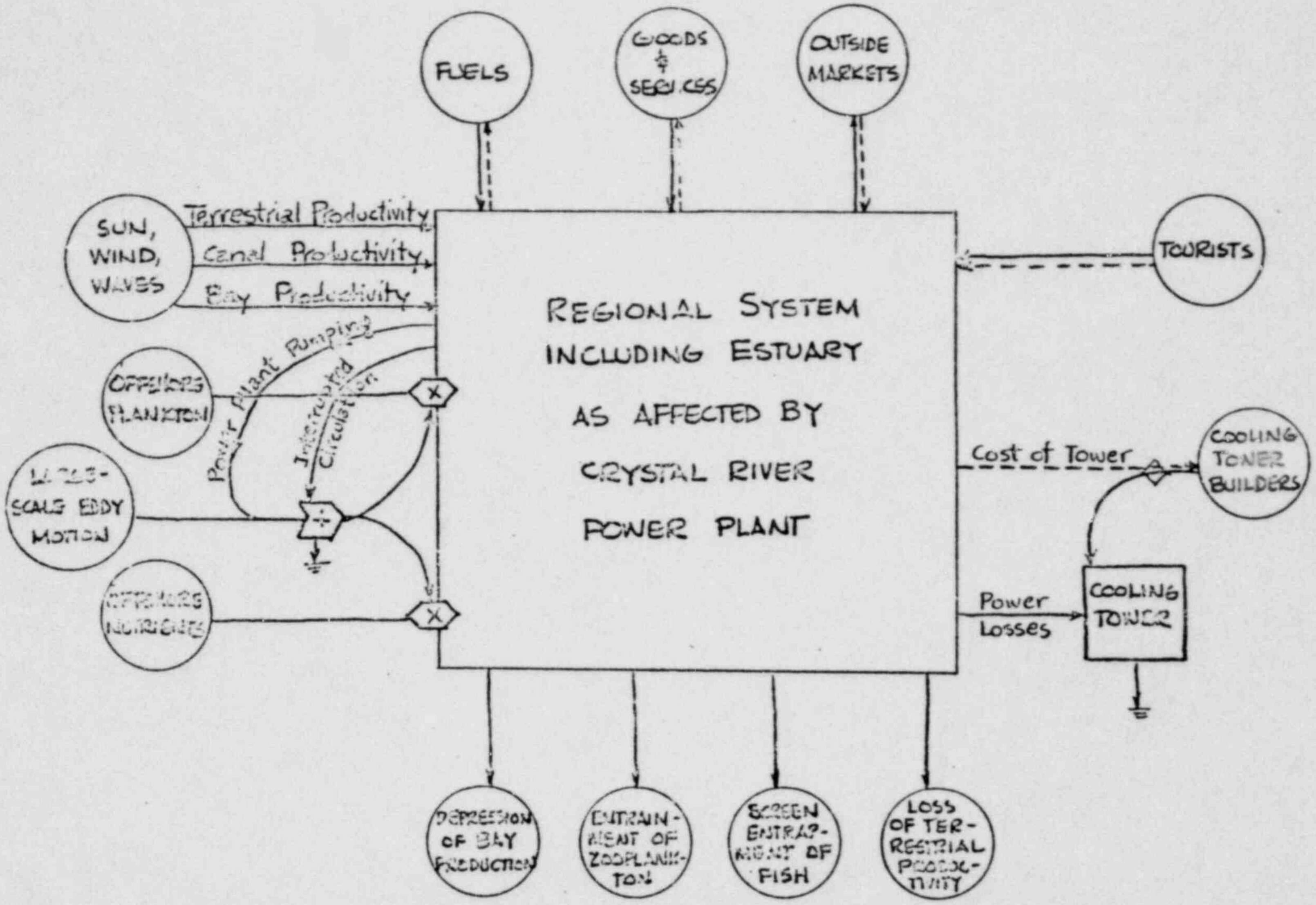


Fig. 2b. Energy "White box" diagram of Crystal River power plant emphasizing losses and gains to regional system under various management alternatives

Table 4. Calculation of Terrestrial[a] and Marine[b] Areas Affected by Crystal River Power Plant.

TERRESTRIAL REGION AREA

A_1 = area land region = $A_{ps} \left(\frac{G_{cr}}{G_{ps}}\right)$

A_{ps} = Area of 32 counties in Florida Power Corp. Power Shed
= 23,878 mi^2

G_{cr} = Electric Power generating capacity of Crystal River plant (3 units)
= 1690 Mw

G_{ps} = Electric Power generating capacity of all power plants in 32 county area.
= 4453 Mw

$$A_1 = 23{,}878 \text{ mi}^2 \times \left(\frac{1690}{4453}\right) = 9062 \text{ mi}^2$$

[a]This calculation is based on the assumption that the land region affected is that portion of the total Florida Power Corporation power shed equivalent to the fraction of the total Florida Power Corporation power generation provided by the Crystal River Plants.

MARINE REGIONAL AREA

A_m = Area Marine region = $L_{cr} \times h$

$$L_{ce} = L_s \left(\frac{G_{cr}}{G_{ps}}\right) : \ h = Q \times T/\ L_{cr}/\ d : \ d = \frac{h}{6080}$$

L_s = length of shoreline in power shed = 308 mi.

L_{cr} = length of shoreline affected by Crystal River = 117 mi.

Q = Crystal River plant water flow = 2940 $ft.^3/sec.$

T = estimated life of plant = 30 yrs.

d = depth of volume affected by Crystal River distributed over A_m = 4.97 ft.

h = width of area affected by Crystal River = 30,218 ft.

$$A_m = (30{,}218 \text{ ft.}) \times (4.97 \text{ ft.}) = 1.867 \times 10^{10} \text{ ft.}^2 = 1.74 \times 10^9 \text{ m}^2$$

[b]The affected marine area is calculated assuming that the maximum water volume affected would be that which is pumped through the power plants during their operational life. It is also conservatively assumed that no water parcel is ever pumped more than once. The length of the coastal water area affected is calculated by pro-rating the total coastline in the power shed by the fraction power contribution by Crystal River units.

Subsystems

Model building for the purpose of evaluating contributions to maximum work value is complicated by subsystems that develop specialized adaptations to particular combinations of energy flow of man and nature. At Crystal River, where shallow bay ecosystems, deeper plankton-dominated ecosystems, oyster bars, and salt marshes interact with one another as subsystems of the greater estuary, the power plant is yet another susbystem that has some similarities to a reef of plankton consumers. New ecosystems are developing in the power plant canals as a result of the unique combination of pumping, channeling, barge stirring, and thermal energies occurring there. Each of these old and new subsystems including the power plant technology itself becomes linked to the other systems as the plastic ecological components go through an adapting and selecting process. The total work value which results is maximized as symbioses develop between subsystems so that the energies of one help functions of the other. The subsystem interconnections cycles, population management service, migrations, and spatial and temporal timing of behavior in harmonious schemes. Any overview of energy flows and regional design toward maximum work value (and thus, survival) requires models that recognize symbiotic pathways of functional exchange in systems as they ultimately emerge surviving from the adaptive and self designing process. Figure 1 in the preface to Section 4 illustrates the interrelationship between subsystems in the estuary adjacent to the Crystal River power plant.

Energy Cost Benefit Table

Once a model for energy pathways and the main subsystems is drawn and evaluated for each alternative of special energy management application (Figs. 1a & b, and Figs. 2a & b) one may summarize the total work done by tabulating the total energy inputs after conversion to the same concentration level. Each alternative considered affects its own particular energy gains and losses. In many cost-benefit analyses such as for Crystal River, the changes in work value associated with various alternative plans, although significant in themselves, are small in comparison with the total regional work value. Therefore, a tabulation includes just the changes in work value for each alternative related to some base (e.g. primitive) conditions. The system with the higher total energy flow per area per year is the one that will ultimately survive since it is the system with the higher resources for itself and its ability to withstand competitions from without and from within. It is the system that provides the most total real work to the combined pattern of man and nature. The system with less total work will falter in economic and ecological competition.

Energy Budget for the Coastal Zone Region Influenced by the Crystal River Power Plant

Given in Figs. 1a & b is a general model of the main energy flows in the region influenced by the operation of the Crystal River power plant. The main energy flows into and out of the regional system are given in terms of their raw heat content (Fig. 1a) and their respective fossil fuel work equivalents (Fig. 1b). Corresponding to these diagrams the main components to the regional energy budget are listed in Table 2. The details of calculation for these energy flows are given in the footnotes following the table.

Table 2. Energy Budget for Region[a] Affected by Crystal River Power Plants

Source	Foot-note	Heat Content (Kcal x 10^{12}/yr)	Energy Quality Ratio (fossil fuel)	Work Value Fossil Fuel Equivalents (x 10^{12})
<u>Free</u>:				
Wind	1	2.3	0.13	0.30
Tides	2	2.5	0.4	1.0
Waves	3	0.3	0.2	0.06
Fresh Water Head	4	0.2	1.7	0.34
Freshwater (as dilutant)	5	0.3	1.0	0.30
Productivity				
- Land	6	343.0	0.07	24.01
- Estuary	7	15.8	0.07	1.11
Subtotal Free		362.4		27.12
<u>Purchased</u>:				
Power Plant Fuel Crystal River	8	+23.0[b]	1	23.0
Others	9	(44.6)	1	(44.6)
Other Fuels	10	+22.3[b]	1	22.3
Goods & Services Imported	11	+52.7[b]	1	52.7
Exported	12	-9.9[b]	1	-9.9
Tourists & Cap. Invest.	13	+56.0[b]	1	56.0
Subtotal Purchased		144.1		144.1
Total		506.5 x 10^{12}Kcal/yr		171.2 x 10^{12}Kcal/yr

[a] See Table 4 for calculation of size of affected region.

[b] Fossil fuel work equivalents.

Footnotes to Table 2

(1) Wind: Power, P_{wd} = (drag) x (velocity) = $D \cdot u = 1/2\ p \cdot A \cdot u^3 \cdot C_f$

$C_f = (1.89)(1.62 \log \frac{l}{K_s})^{-2.5}$; K_s = roughness coeff. = 4 x ht of vegetation

A = surface area = 9062 mi^2 = $2.53 \times 10^{11} ft^2$; $l = 5.67 \times 10^5 ft$

$C_f = .002$; Assume mean wind speed u = 7.33 fps

$$P_{wd} = 1/2(2.3 \times 10^{-3} \frac{lb}{ft^3})(7.33 \frac{ft}{sec})^3 \ (2.53 \times 10^{11} ft^2)(.002) \times (3.15 \times 10^7 \frac{sec}{yr})(3.24 \times 10^{-4} \frac{Kcal}{ft\text{-}lb})$$

$$P_{wd} = 2.34 \times 10^{12} Kcal/yr$$

(2) Tides: Power, $P_r = pgA\frac{h^2}{2}$

h = 91.4 cm; A = $1.77 \times 10^{13} cm^2$; g = 980 cm/sec^2; p = 1.025 g/cm^3

$$P_r = (1.025\ g/cm^3)(980\ cm/sec^2)(1.77 \times 10^{13} cm^2)\ \frac{(91.4\ cm)^2}{2} \times (2.38 \times 10^{-11} \frac{Kcal}{erg})(1410 \frac{tides}{yr})$$

$$P_r = 2.49 \times 10^{12} Kcal/yr$$

(3) Waves: Power, $P_{wv} = 1/8\ pg^{3/2}H^{5/2}\ell$ (for shallow waves, $\frac{H}{L} < \frac{1}{20}$)

$\rho = 1.025\ g/cm^2$; g = 980 cm/sec^2; H = 30 cm; $\ell = 1.88 \times 10^7 cm$

$$P_{wv} = 1/8\ (1.025\ g/cm^3)(980 cm/sec^2)^{3/2}\ (30cm)^{5/2}(1.88 \times 10^7 cm) \times (3.15 \times 10^7\ sec/yr)\ (2.38 \times 10^{-11} Kcal/erg)$$

$$P_{wv} = 0.27 \times 10^{12} Kcal/yr = 3.8 \times 10^6 ft\text{-}lb/day/ft$$

(4) Fresh Water Head: Power, $P_{FH} = 1/2\ p \cdot g \cdot V \cdot h$

$P = 1.0\ g/cm^3$; $g = 980\ cm/sec^2$

V = volume of fresh water running off and infiltrating in region x

= rainfall x area x fraction runoff = $(50\frac{in}{yr})(.083\frac{in}{ft})(2.53 \times 10^{11} ft^2) \times 31.5 \frac{1}{x} 10^6 \frac{yr}{sec})(.28)$

= $0.29 \times 10^{12} ft^3/yr = 0.82 \times 10^{16} cm^3/yr$

h = mean height of water = mean elevation of region = 100 ft

$$P_{FH} = 1/3)1\ g/m^3)(980\ cm/sec^2)(30.48 \times 10^2 cm)(0.82 \times 10^{16} cm^3/yr) \times (2.38 \times 10^{-11} \frac{Kcal}{erg})$$

Footnotes to Table 2 (continued)

(5) Fresh Water Dilutant: Power, $P_{FD} = \Delta F \times V \times m_s = (nRT \ln \frac{C_1}{C_2}) \times V \times m_s$

$n = 1$ mole/35gm; R = gas constant = 1.99 cal/mole°K

T = annual mean water temp = 20°C = 293°K

C_1 = freshwater delta conc. of dissolved solute = 120 ppm

C_2 = solute conc. of seawater as sink = 35,000 ppm

V = total freshwater in region = $2.95 \times 10^{10} m^3$/yr (rain)

$$P_{FD} = (\frac{1 \text{ M}}{35 \text{ gm}})(1.99 \times 10^{-3} \frac{\text{Kcal}}{\text{M}^{\circ}\text{K}})(293^{\circ}\text{K}) \ln(\frac{120}{35{,}000})(120 \text{g/m}^3)(2.95 \times 10^{10} \text{m}^3/\text{yr})$$

$$= 0.34 \times 10^{12} \text{Kcal/yr}$$

(6) Land Productivity: Power, $P_{LP} = A_L \times M$

A_L = area of affected land region = $2.35 \times 10^{10} m^2$

M = typical mean metabolism for pine flatwoods = 40 Kcal/m^2/day

$$P_{LP} = (2.35 \times 10^{10} \text{m}^2)(40 \text{ Kcal/m}^2/\text{day})(365 \text{ day/yr})$$

$$= 343 \times 10^{12} \text{Kcal/yr}$$

(7) Marine Productivity: Power, $P_{MP} = A_M \times M$

A_M = area of affected marine region = $1.74 \times 10^9 m^2$

M = typical outer bay metabolism = 25 Kcal/m^2/day

$$P_{MP} = (1.74 \times 10^9 \text{m}^2)(25 \text{ Kcal/m}^2/\text{day})(365 \text{ day/yr})$$

$$= 15.8 \times 10^{12} \text{Kcal/yr}$$

(8) Power Plant Fuels: Power, $P_{PC} = C \times p \times f \times K_{FF}$

C = per capita electric consumption = 8.5×10^3 Kwh/cap/yr

p = population of region - 2.3×10^6

f = fraction of population served by Crystal River = .38

K_{FF} = fossil fuel equivalent of electric power = 3.6

$$P_{PC} = (8.5 \times 10^3 \frac{\text{Kwh}}{\text{cap}}/\text{yr})(860 \frac{\text{Kcal}}{\text{Kwh}})(2.3 \times 10^6 \text{cap})(.38)(3.6)$$

$$= 23 \times 10^{12} \text{Kcal/yr (FFWE)}$$

Footnotes to Table 2 (continued)

(9) Power Plant Fuels: Power, $P_{PO} = P_{PC}(\frac{1-f}{f})$

$$P_{PO} = 2.3 \times 10^{12} \frac{Kcal}{yr} (\frac{.62}{.38}) = 37.5 \times 10^{12} Kcal/yr$$

(10) Other Fuels: (Gasoline, Natural Gas, Liquid Fuels):

$$P_{OF} = (C_G + C_{NG} + C_{LF}) \times P$$

C_G = consumption of gasoline - 15.9 x 10^6Kcal/person/yr

C_{NG} = " " natural gas - 1.98 x 10^6Kcal/person/yr

C_{LF} + " " liquid fuels - 7.66 x 10^6Kcal/person/yr

$$P_{OF} = (15.9 + 1.98 + 7.66) \times 10^6 \ (.88 \times 10^6 cap)$$
$$= 22.3 \times 10^{12} Kcal/yr$$

(Fuels burned in electric power generation are subtracted)

(11) Imported Goods and Services: Power, P_I = I(f)(1-e)(S0

I = total dollars paid for imports in Florida = \$16.88 x 10^9/yr

f = fraction of Florida population in region = .13

e = fraction of budget spent on fuels = .10

S = conversion of dollars to Kcal = 30,000 $\frac{Kcal}{\$}$

$$P_I = \$16.06 \times 10^9/yr \ (.13)(.90)(30,000\frac{Kcal}{\$}) = \$1.88 \times 10^9/yr$$
$$= 5.63 \times 10^{13} \ Kcal/yr$$

(12) Exported Goods and Services: Power, P_E = E(f)(S)

E = total dollar value of exports from Florida = \$2.54 x 10^9/yr

f = .13 ; S = 30,000 Kcal/\$

$$P_E = \$2.54 \times 10^9/yr \ (.13)(30,000 \ Kcal/\$)$$
$$= \$3.31 \times 10^8/yr \ (30,000) = 9.9 \times 10^{12} \ Kcal/yr$$

Footnotes to Table 2 (continued)

(13) Tourists and Capital Investments: Power, $P_{TC} = D_I(f)S - P_E$

D_I = total dollars coming into Florida =

f = fraction of Fla. population in region

$$P_{TC} = \$16.88 \times 10^9/\text{yr}(.13)(30{,}000 \frac{\text{Kcal}}{\$} - 9.9 \times 10^{12} \frac{\text{Kcal}}{\text{yr}}$$

$$= 56 \times 10^{12}\ \text{Kcal/yr} = \$187 \times 10^7/\text{yr}\ (30{,}000 \frac{\text{Kcal}}{\$})$$

The 32-county area served by Florida Power Corporation is shown in Fig. 3, a relatively rural area of Florida having towns, agriculture, forestry plantations, lakes, estuaries, swamps, and other non-human ecosystems. The region considered to be influenced by the Crystal River power plant operation is taken as that portion of these 32 counties (and each subsystem therein) represented by the fraction of the total electric power generated in the FPC power shed which would be provided by the Crystal River plant. The affected marine area is taken as a function of the total volume of water pumped by the 3 generating units in a 30-year lifetime. This volume is spread over the Gulf shelf along a coastline equal to a prorated portion of the total coastline in the 32 counties. Table 4 details the specifics of this method used in calculating the size of the region of power plant influence.

Figs. 1a & b provide some perspective on the value and importance of the power plant system to the overall system of man and nature, both in terms of heat energy and fossil fuel work value. Included in the diagram is the work of the sun in photosynthesis and stirring air masses, the input of potential energy of rain as a flowing mass and chemical dilutant, the energy transferred to the earth from friction of winds, the inflow of waves and tides onto the coast, the input of various fossil fuels including coal and oil to run the power plants, the import and export goods and services, and the influx of tourists and investment dollars.

The Crystal River power plant fuel consumption is about 5% of the regional energy budget in terms of heat content, but accounts for over 13% of the work done in the region. Natural energies represent about 72% of the regional energy in terms of heat content, but only 15% of the regional work value. Inversely, purchased energy accounts

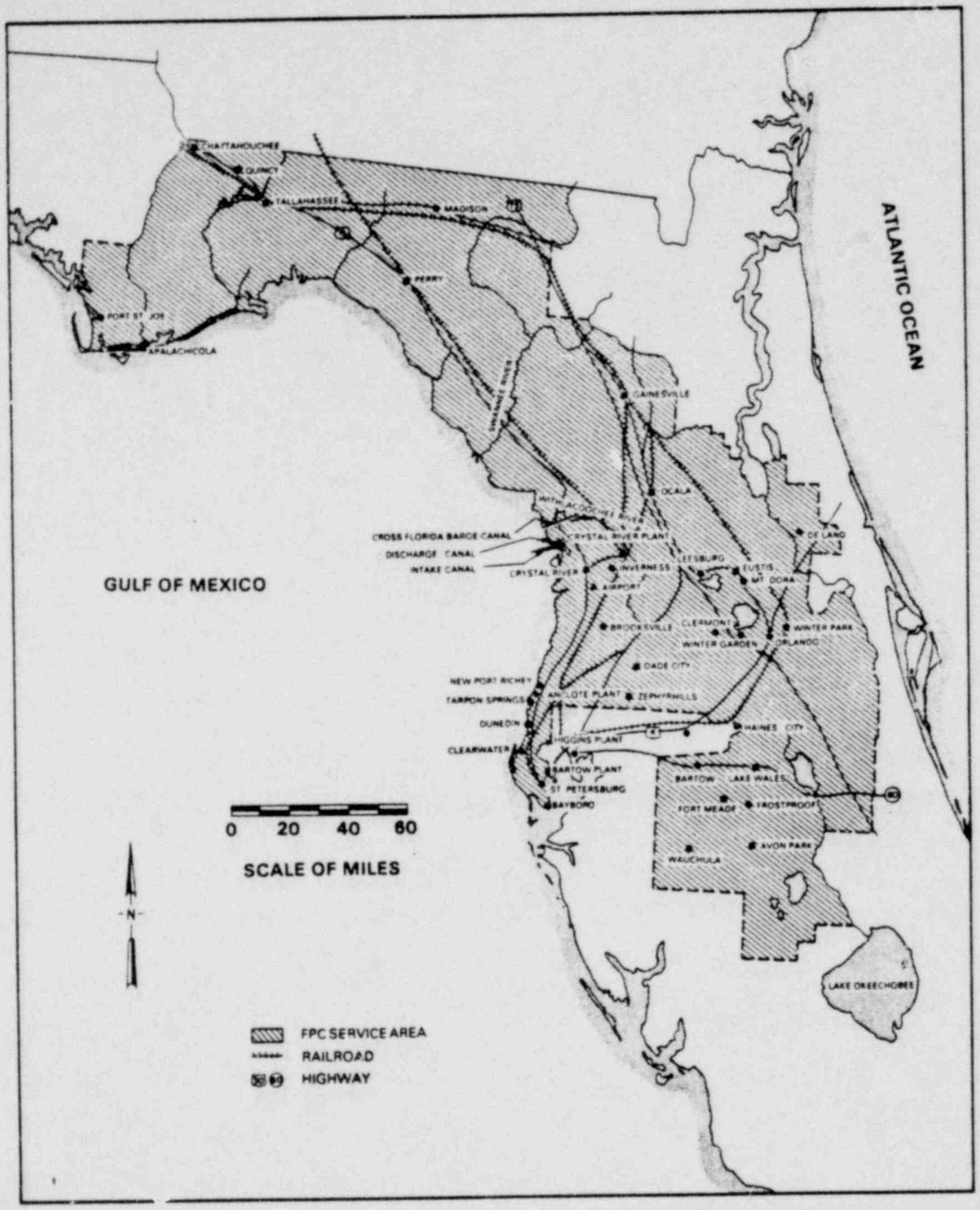


Fig. 3. Florida Power Corporation 32 county service area.

for 28% considering heat content, but 85% in terms of work equivalents. The total work value of the region is equivalent to some 171.2×10^{12} fossil fuel kcal/yr (5.7 billion 1973 U.S. dollars).

Energy Cost Benefit Calculation of Cooling Alternatives

As an integral part of the overall environmental impact analysis various alternative schemes for managing the power plant cooling water flow must be evaluated, balancing gains and losses to the regional work economy associated with each alternative. Government regulatory agencies have suggested that cooling towers be considered as possible means for mitigating losses of nature's work value resulting from the cooling water flow of the power plant. Table 3 provides a comparison of the total work value lost to the system resulting from 3-unit power plant operation under three management alternatives. In terms of fossil fuel equivalents of work value, the use of mechanical draft cooling towers (the cheapest technological alternative) for unit 3 results in some eighty times greater loss to the region than using the estuary for cooling. Cooling towers for all three units give a loss of work value of about 160 times the losses incurred without cooling towers. The money which would be invested in cooling tower construction, operation and maintenance represents a diversion of fossil fuel energy from other possible investments into the economy of man and nature which would return a greater income to the system. By way of comparing magnitudes of investments, the cost of cooling towers for all three units is about equivalent (in terms of work value) to complete inhibition of primary productivity in the entire estuary region assigned to the power plant (about $1.8 \times 10^9 m^2$ or 600 mi^2).

Table 3. Changes in Regional Annual Energy Budget Associated with Management Alternatives for Cyrstal River Power Plants

		Estuary Cooling			Cooling Tower Unit 3			Cooling Towers All Units		
Affected Energy Flow	Footnote	Heat Kcal (x 10^9)	EQR	Fossil Fuel Work Equivalents (x10^9)	Heat Kcal (x10^9)	EQR	Fossil Fuel Work Equivalents (x 10^9)	Heat Kcal (x10^9)	EQR	Fossil Fuel Work Equivalents (x 10^9)
Land Productivity										
Construction Land	1	-22.6	0.070	-1.58	-23.2	0.070	-1.62	-23.80	0.070	-1.66
Salt Spray Effects	2	-	-	-	-43.3	0.070	-0.30	- 8.65	0.070	-0.61
Estuary										
Potential Energy in Residual Heat	3	(560[b]		-	(160)[b]	-	-	-	-	-
Plant Stirring	4	+0.03	0.014	+0.0004	+0.004	0.014	+0.00006	-	-	-
Interrupted Circulation	5	-0.01	0.014	-0.0001	-0.01	0.014	-0.0001	-0.01	0.014	-0.0001
Ecosystems Displaced by Canals	6	-19.4	0.070	-1.36	-19.4	0.070	-1.36	-19.4	0.070	-1.36
Canal Metabolism	7	+13.2	0.070	+0.92	+11.0	0.070	+0.77	+ 6.6	0.070	+0.46
Depressed Inner Bay Metabolism	8	- 7.8	0.070	+0.55	- 3.9	0.070	-0.27	-	-	-
Screen Wash Mortality	9	- 1.0	0.070	-0.07	- 0.5	0.070	-0.035	-	-	-
Entrainment Mortality	10	-11.45	0.070	-0.80	- 5.61	0.070	-0.39	-	-	-
Subtotal of losses to ecosystem				-3.44			-3.21			-3.20
Cooling Towers					-276.0	1.0	-276.0	-539.0	1.0	-539.0
Power Plant		(230,000)[b]			(230,000)[b]			(230,000)[b]		
Total Change in Heat Content		-49.0			-361.42			-571.5		
TOTAL CHANGE IN FOSSIL FUEL WORK VALUE				-3.44 ($0.11 x 10^6/yr)[a]			-279.21 ($9.3 x 10^6/yr)[a]			-542.2 ($18.07 x 10^6/yr)[a]

[a] Converted to 1973 U.S. dollars by ratio 3 x 10^4Kcal: $1 (Odum, 1974)

[b] Numbers in parentheses not included in totals.

Footnotes to Table 3.

(1) Construction Land Productivity Loss:

Unit 3: Power, $Pc_1 = Ac_2 \times M$

Ac_1 = Area covered by construction = $3 \times 10^5 ft^2 = 1.58 \times 10^6 m^2$

M = Metabolism of ecosystems displaced = 60 $Kcal/m^2/day$

$Pc_1 = (1.58 \ \times 10^6 m^2)(60 Kcal/m^2/day)(365 \frac{day}{yr}) = 232 \times 10^8 Kcal/yr$

Units 1-3: Power, $Pc_2 = Ac_2 \times M$

Ac_2 = Area covered by construction = $1.61 \times 10^6 m^2$

$Pc_2 = (1.61 \times 10^6 m^2)(60 Kcal/m^2/day)(365 \frac{day}{yr}) = 238 \times 10^8 Kcal/yr$

(2) Depressed Land Productivity from Salt Spray

Unit 3: Power, $Ps_1 = (R^2 \ )(\delta)\ M$

R = radius of area in which salt spray addition equals background rate of salt deposition.

δ = assumed mean rate of productivity inhibition = .25

M = metabolism of affected terrestrial ecosystems = 60 $\frac{Kcal}{m^2/day}$

Background salt deposition rate = 0.125 $lb/m^2/yr$

Maximum salt deposition rate from towers = 4.8 lb/acre/mo
= 0.140 $lb/m^2/yr$

R (at max. rate) = 0.5 Km

$Ps_1 = (7.9 \times 10^5 M^2)(.25)(60 \ Kcal/m^2/day)(365 \ days/yr) = 4.33 \times 10^9 Kcal/yr$

Units 1-3:

$Ps_2 = 2 \times Ps_1 = 8.65 \times 10^9 Kcal/yr$

Footnotes to Table 3. continued

(3) Potential Energy in Residual Heat: $P_t = T \times C \times Q \times \quad \times \frac{T}{T}$

T = change in temperature across condensers

C = specific heat of water

Q = flow rate of water

= density of water

T = absolute temperature

Units 1-3:

$$Pt = (8^{o}C)(1\frac{cal}{g^{o}C})(7.1 \times 10^{6}\frac{m^{3}}{day})(1.02 g/cm^{3})(10^{6}\frac{cm^{3}}{m^{3}})(10^{-3}\frac{Kcal}{cal})(\frac{8^{o}}{293^{o}}) 365 \text{ day/yr}$$

$$= 5.6 \times 10^{11}\frac{Kcal}{yr}$$

Units 1-2:

$$Pt = (6^{o}C)(1\frac{cal}{g^{o}C})(7.1 \times 10^{6}\frac{m^{3}}{day})(1.02 g/cm^{3})(10^{6}\frac{cm^{3}}{m^{3}})(10^{-3}\frac{Kcal}{cal})(\frac{6^{o}}{293}) 365 \text{ day/yr}$$

$$= 1.6 \times 10^{11}\frac{Kcal}{yr}$$

(4) Plant Stirring: $Pke = 1/2 \quad Qv^{2}$

v = velocity of plume

Units 1-3:

$$Pke = 1/2(1.02 g/cm^{3})(7.1 \times 10^{12}\frac{cm^{3}}{day})(30\frac{cm}{sec})^{2} x (365\frac{day}{yr})(2.38 \times 10^{11}\frac{Kcal}{erg})$$

$$= 0.3 \times 10^{8}\frac{Kcal}{yr}$$

Units 1-2:

$$Pke = 1/2(1.02)(3.6 \times 10^{12})(15)^{2}(365)(2.38 \times 10^{-11})$$

$$= 0.04 \times 10^{8}\frac{Kcal}{yr}$$

Foonotes to Table 3 continued

(5) Circulation Interrupted by Spoil Banks

This is the calculated loss of kinetic energy of estuary waters diverted into frictional heat loss due to drag of canal spoil banks.

$Pke = 1/2\ RdV^3$ = Power of kinetic energy

= mass of water g/cm^3

R = east-west horizontal length of affected zone

d = depth (cm)

V. = velocity (cm/sec)

A. Water Movement Not Interrupted by Spoil Banks

Assume a horizontal velocity profile of constant mean velocity from eng of spoil banks to 0.5m from coast (boundary layer).

1) Area outside boundary layer

$V = 5$ cm/sec

$Pke_1 = 1/2\ (1.020\ g/cm^3) \times (5cm/sec)^3 \times (4.5 \times 10^5 cm) \times (200\ cm)$

$= 5.74 \times 10^9$ erg/sec $\times 3.15 \times 10^7$ sec/yr $\times 2.38 \times 10^{-11}$ Kcal/erg

$= 4.30 \times 10^6$ Kcal/yr

2) Area inside boundary layer

$V = 2.3$ cm/sec

$Pke_2 = 1/2(1.020\ g/cm^3) \times (2.5\ cm/sec)^3 \times (.5 \times 10^5 cm) \times (100cm)$

$= 3.98 \times 10^7$ ergs/sec $\times 3.15 \times 10^7$ sec/yr $\times 2.38 \times 10^{-11}$ Kcal/erg

$= .30 \times 10^6$ Kcal/yr

Total P_A (area inside + Area outside) $= Pke_1 + Pke_2 = 4.60 \times 10^6$ Kcal/yr

Footnotes to Table 3 continued

B. Water Movement Interrupted by Spoil Banks

Assume that as flow streamlines move west to sweep around spoil banks, they create a back-eddy on the southwest side of the spoil bank/shore intersection. Velocities are reduced due to frictional drag.

1) Zone outside of back-eddy ($R = 3.5 \times 10^{5}$cm)

$V = 2.5$ cm/sec

$Pke = 1/2\ (1.02) x (2.5)^{3} x (3.5 \times 10^{5}) x (200)$

$= (5.6 \times 10^{8}) x (3.15 \times 10^{7}) x (2.38 \times 10^{-11})$

$= 4.2 \times 10^{5}$Kcal/yr

2) Zone within back-eddy ($R = 1.5 \times 10^{5}$cm)

$V = 1.0$ cm/sec

$Pke = 1/2\ (1.02) x (1)^{3} x (1.5 \times 10^{5}) x (100)$

$= (.77 \times 10^{7}) x (3.15 \times 10^{7}) x (2.38 \times 10^{-11})$

$= .58 \times 10^{5}$Kcal/yr

Total $P_B = Pke_1 + Pke_2 = .468 \times 10^{6}$Kcal/yr

Difference in Pke with spoil banks $= P_B - P_A$

$Pke_{net} = .468 \times 10^{6}$Kcal/yr $- 4.60 \times 10^{6}$Kcal/yr $= -4.12 \times 10^{6}$Kcal/yr

Total loss in available power prior to spoil bank emplacement equals 2 times calculated Pnet, assuming mirror image effect on other side of spoil banks.

Total $(P_{ke})_{net} = 2(-4.12 \times 10^{6}$Kcal/yr$) = -\ .0824 \times 10^{8}$Kcal/yr

Footnotes to Table 3. continued

(6) Ecosystems Displaced by Canals

Production = A x P x D

A = Area displaced (m^2)

P = productivity of displaced system ($Kcal/m^2$)

[40 $Kcal/m^2/day$ for land]

[25 $Kcal/m^2/day$ for marine]

D = time in days

A. Terrestrial systems

1) Area of plant = $1.68 \times 10^6 ft^2 = 1.55 \times 10^6 m^2$

$Pt = (1.55 \times 10^6 m^2)(40Kcal/m^2/day)(365 \text{ days/yr})$

$= 2.26 \times 10^{10}$ Kcal/yr

B. Marine systems

1) Area of discharge canal = $5.3 \times 10^6 ft^2 = 4.93 \times 10^5 m^2$

2) Area of intake canal = $17.5 \times 10^6 ft^2 = 1.62 \times 10^5 m^2$

$Pm = (2.13 \times 10^6 m^2 (x) 25Kcal/m^2/day)(365 \text{ days/yr})$

$= 1.94 \times 10^{10}$ Kcal/yr

Total production displaced = Pt + Pm

$= 4.20 \times 10^{10}$Kcal/yr

Footnotes to Table 3. continued

(7) Canal Metabolism

Metabolism - GPP x A x K x D

GPP = Gross Primary Production (mean annual)

A = Area in canals (m^2)

$K = \frac{Kcal}{gO_2} = 4.5$

D = time in days (365)

A. Units 1 and 2 operating:

1) Intake canal: ($A = 5.62 \times 10^5 m^2$)($GPP = 9\ gO_2/m^2/day$)

$M_I = (9)x(5.62 \times 10^5)x(4.5)x(365)$

$= 8.32 \times 10^9 \frac{Kcal}{yr}$

2) Discharge canal: ($A = 1.47 \times 10^5 m^2$)($GPP = 11\ gO_2/m^2/day$

$Mp = (11)x(1.47 \times 10^5)x(4.5)x(365)$

$= 2.64 \times 10^9 \frac{Kcal}{yr}$

3) Total metabolism = $M_I + M_D = 1.10 \times 10^{10} \frac{Kcal}{yr}$

B. Units 1, 2, 3 operating:

Based on model predictions metabolism increases by 20%

$M = (1.2)x(1.10 \times 10^{10} \frac{Kcal}{yr}) = 1.32 \times 10^{10} \frac{Kcal}{yr}$

C. No Circulating Water Flow

Based on model predictions metabolism decreases by 40%

$M = (.6)(1.10 \times 10^{10} \frac{Kcal}{yr}) = .66 \times 10^{10} \frac{Kcal}{yr}$

Footnotes to Table 3. continued

(8) <u>Depressed Inner Bay Metabolism</u>

The annual mean total community metabolism for the shallow inner bay ecosystem was measured to be 50% lower for the discharge area than for the control area. (see Smith, Section 4A, Fig. 22)

Production bay = $(M_C - M_D)\ A_B$

M_C = metabolism of control area = 1.22×10^4 Kcal/m^2/yr

M_D = metabolism of discharge area = $.65 \times 10^4$ Kcal/m^2/yr

A_B = Area of inner bay system = $6.9 \times 10^5 m^2$

$P = [1.22 \times 10^4) - (.65 \times 10^4)](6.9 \times 10^5)$

$= [.57 \times 10^4](6.9 \times 10^5)$

$= 3.9 \times 10^9 \frac{Kcal}{yr}$

Footnotes to Table 3 continued

(9) Screen Wash Mortality

$P = B \times EQR$

B = Biomass lost in 1 yr (extrapolated from gms wet wt/52 days)

EQR = Energy Quality Ratio (see section 5 for derivation)

1) Batfish

$P = (6.61 \times 10^5)x(29.8)$

$= 8.9 \times 10^7$

2) Burrfish

$P = (1.57 \times 10^5)x(25.3$

$= 1.8 \times 10^7$

3) Blue Crab

$P = (.98 \times 10^5)x(29.7)$

$= 1.3 \times 10^7$

4) Cowfish

$P = (.49 \times 10^5)x(29.5)$

$= .7 \times 10^7$

5) Pinfish

$P = (.41 \times 10^5)x(23.7)$

$= .4 \times 10^7$

6) Tunicate

$P = (.41 \times 10^5)x(11.2)$

$= .2 \times 10^7$

7) Silver Jenny

$P = (.38 \times 10^5)x(27.8)$

$= (.5 \times 10^7)$

8) Squid

$P = (.32 \times 10^5)x(36.4)$

$= (.5 \times 10^7)$

9) Silver Perch

$P = (.29 \times 10^5)x(31.3)$

$= (.4 \times 10^7)$

Footnotes to Table 3 continued

10) Scaled Sardine

$P = (.25 \times 10^5) \times (24.4)$

$= (.3 \times 10^7)$

11) Jack

$P = (.17 \times 10^5) \times (33.5)$

$= (.3 \times 10^7)$

12) Mullet

$P = (.11 \times 10^5) \times (12.7)$

$= .1 \times 10^7 \text{Kcal/yr}$

13) Atlantic Threadfin

$P = (46.2 \times 10^5) \times (24.4)$

$= 50.7 \times 10^7 \text{ Kcal/yr}$

14) Other

$P = (1.43 \times 10^5) \times (25)$

$1.67 \times 10^7 \text{Kcal/yr}$

$P_{total} = 0.67 \times 10^9 \frac{\text{Kcal}}{\text{yr}}$ = work equivalent loss/yr

Biomass total = 59.6×10^5 grams/yr = amt lost/yr

Total loss of Biomass through Screen Wash =

$B_L = (59.6 \times 10^5 \text{g/yr}) \times (5 \text{ Kcal/gm}) = 29.8 \times 10^6 \frac{\text{Kcal}}{\text{yr}}$

Value of this mass as detritus

$Vm = (29.8 \times 10^6 \text{Kcal/yr}) \times (\text{EQR detritus}) = .17 \times 10^9 \frac{\text{Kcal}}{\text{yr}}$

Total Annual Loss of Value to Region = $P_{total} - Vm$

$= .67 \times 10^9 \frac{\text{Kcal}}{\text{yr}} - .17 \times 10^9 \frac{\text{Kcal}}{\text{yr}} = 0.5 \times 10^9 \frac{\text{Kcal}}{\text{yr}}$

Footnotes to Table 3. continued

(10) Entrainment Mortality for Zooplankton:

$P_E = N \times m \times Q \times M \times K \times R \times EQR$

N = numerical density (individuals/m^3)

m = mass per individual (K9/individuals

M = metabolism per mass (Kcal/kg·day)

K = entrainment mortality

R = loss of metabolism (day /replace)

Q = daily circulating water flow (m^3/day)

EQR = energy quality ratio (see section 5 for derivation)

Units 1 and 2 Operating:

Copepods -

$$P = 10.769 \frac{\text{ind}}{m^3} \times .68 \times 10^{-8} \frac{\text{kg}}{\text{ind}} \times 500 \frac{\text{Kcal}}{\text{kg}\cdot\text{day}} \times .3 \text{ kill} \times 10 \frac{\text{day}}{\text{replace}} \times$$
$$\times 3.4 \times 10^6 m^3/\text{day} \times 11.1 \times 365 \text{ days/yr}$$

$$= 1.51 \times 10^{5} \frac{\text{Kcal}}{\text{yr}}$$

Fish Eggs and Larvae -

$$P = ss \frac{\text{ind}}{m^3} \times 1.18 \times 10^{-8} \frac{\text{Kg}}{\text{ind}} \times 250 \frac{\text{Kcal}}{\text{Kg}\cdot\text{day}} \times .90 \text{ kill} \times 20 \frac{\text{day}}{\text{replace}} \times$$
$$\times 3.4 \times 10^6 m^3/\text{day} \times 11.1 \times 365 \text{ days/yr}$$

$$= 1.61 \times 10^{7} \frac{\text{Kcal}}{\text{yr}}$$

Chaetognaths and Medusae -

$$P = 171 \frac{\text{ind}}{m^3} \times 1.98 \times 10^{-8} \text{Kg/ind} \quad 250 \frac{\text{Kcal}}{\text{Kg}\cdot\text{day}} \times .30 \text{ Kill} \times 20 \frac{\text{day}}{\text{replace}} \times$$
$$\times 3.4 \times 10^6 m^3/\text{day} \times 24.0 \times 365 \text{ days/yr}$$

$$= 1.51 \times 10^{8} \frac{\text{Kcal}}{\text{yr}}$$

Foonotes to Table 3 continued

Veligers, Trochophores, Mysids, etc.-

$$P = 2279 \frac{ind}{m^3} \times .68 \times 10^{-8} \frac{kg}{ind} \times 250 \frac{Kcal}{Kg.day} \times .30 \text{ kill} \times 20 \frac{day}{replace} \times$$

$$3.4 \times 10^6 \frac{m^3}{day} \times 20.4 \times 365 \text{ days/yr}$$

$$= 4.13 \times 10^8 \frac{Kcal}{yr}$$

Juvenile Fish -

$$P = 0.4 \frac{ind}{m^3} \times \text{[illegible]}^{4} \frac{kg}{ind} \times 250 \frac{Kcal}{kg \cdot day} \times .90 \text{ kill} \times 20 \frac{day}{replace} \times$$

$$3.4 \times 10^6 \text{ m}^3\text{/day} \times 24 \times 365 \text{ days/yr}$$

$$= 4.56 \times 10^9 \frac{Kcal}{yr}$$

<u>Units 1, 2, and 3 Operating</u>

Copepods-

$$P = 10769 \frac{ind}{m^3} \times .68 \times 10^{-8} \frac{kg}{ind} \times 500 \frac{Kcal}{kg \cdot day} \times .3 \text{ kill} \times 10 \frac{day}{replace} \times$$

$$7.1 \times 10^6 \text{ m}^3\text{/ day} \times 11.1 \times 365 \text{ day/yr}$$

$$= 3.16 \times 10^9 \frac{Kcal}{yr}$$

Fish Eggs and Larvae-

$$P = 22 \frac{ind}{m^3} \times 1.18 \times 10^{-8} \times 250 \frac{Kcal}{Kg \cdot day} \times .9 \text{ kill} \times 20 \frac{day}{replace} \times$$

$$7.1 \times 10^6 \text{ m}^3\text{/day} \times 11.1 \times 365 \text{ days/yr}$$

$$= 3.36 \times 10^7 \frac{Kcal}{yr}$$

Chaetognaths and Medusae -

$$P = 171 \frac{ind}{m^3} \times 1.98 \times 10^{-8} \frac{Kg}{ind} \times 250 \frac{Kcal}{Kg \cdot day} \times .3 \text{ kill} \times 20 \frac{day}{replace} \times$$

$$7.1 \times 10^6 \text{ m}^3\text{/day} \times 20.4 \times 365 \text{ days/yr}$$

$$= 2.68 \times 10^8 \frac{Kcal}{yr}$$

Footnotes to Table 3 continued

Veligers, Trochophores, Mysids, etc. -

$$P = 2279 \frac{ind}{m^3} \times .68 \times 10^{-8} \frac{Kg}{ind} \times 250 \frac{Kcal}{Kg \cdot day} \times .3 kill \times 20 \frac{day}{replace} \times 7.1 \times 10^6 m^3/day \times 14.3 \times 365 \text{ days/yr}$$

$$= .86 \times 10^9 \frac{Kcal}{yr}$$

Juvenile Fish -

$$P = .4 \frac{ind}{m^3} \times 10^{-4} \frac{Kg}{ind} \times 250 \frac{Kcal}{Kg \cdot day} \times .9 \text{ kill} \times 20 \frac{day}{replace} \times 7.1 \times 10^6 m^3/day \times 20.4 \times 365 \text{ days/yr}$$

$$P = 9.52 \times 10^9 \frac{Kcal}{yr}$$

Total 1 & 2 Operating = $6.76 \times 10^9 \frac{Kcal}{yr}$

Total 1,2,3 Operating = $1.38 \times 10^{10} \frac{Kcal}{yr}$

Percent value of biomass converted to detritus = .17

Total loss of value (1 & 2 Operating) = $5.61 \times 10^9 \frac{Kcal}{yr}$

Total loss of value (1,2,3 Operating) = $11.45 \times 10^9 \frac{Kcal}{yr}$

Power Needs for a Vital Economy Estimated from the Ratio of Energy Invested to Work Returned

The ratio of the total work output (work of nature, W_n, plus work of man, W_f) of a system to the fossil fuel investment (W_f) in that system all converted to fossil fuel work equivalents gives an indication of the overall return for invested fossil fuel capital.

$$\frac{W_n + W_f}{W_f}$$

The ratio approaches infinity in primitive societies and declines toward unity as the system becomes more and more dependent on bought energies such as fossil fuel.

Among competing systems of man and nature with approximately equivalent amounts of fossil fuel to invest, the surviving system will be that which invests the fossil fuel energy in such a way as to produce the maximum system work without destroying the balance between man's and nature's work value. In the hierarchal fabric which finds systems embedded within larger systems which are imbedded within still larger systems, and so on, the adaptive investment ratio to guide the design of one system is determined by the investment ratio of the larger system, as long as energy resources of the larger system remain relatively constant. Referring to numbers given in Table 2 and considering only the fuels burned versus terrestrial productivity, the investment ratio for the Crystal River power plant region is:

$$\frac{78.89\text{kcal/yr} + 149.3\text{kcal/yr}}{149.3\text{kcal/yr}} = 1.53$$

This number is considerably higher than that which has been previously calculated for Florida (1.25) and even higher than the investment ratio as calculated for the entire U.S. (1.41)(Kylstra, 1974). This indicates that the region considered still has room for fossil fuel investment (that is, unit 3 at Crystal River) without becoming non-competitive in the larger Florida system in which it functions. This conclusion, of course, assumes that energy resoruces, specifically net fossil fuel available, will remain constant during the period of investment. The fact that we have been experiencing disproportionate increases in fuel cost (by a factor of four in three years) indicates that fossil fuel available for development investment in the U.S. has declined markedly. With the fuels that support so much of our economy becoming scarce, it is mandatory that we plan our fossil fuel investments in terms of priorities. Such priorities must be established (in accordance with the Lotka principle) on the basis of the specific increased monetary or natural work value which would result for the regional economy.

Cooling towers for all three units at Crystal River would reduce losses to the environment in fossil fuel work equivalents by:

$$(3.44-3.20)\text{x}10^9\text{kcal/yr} = 0.24\text{x}10^9\text{kcal/yr}$$

With an investment of $539\text{x}10^9$kcal/yr the annual return is about 0.05%, which is poor compared to returns available from other investment opportunities.

Our calculations indicate that there is substantial loss of ecosystem work resulting from power plant operation at Crystal River ($3.44\text{x}10^9$ fossil fuel equivalent kcal/yr, or $110,000/yr for proposed three unit operation). This is about 0.002% of the total regional work budget. Considering the construction and operation of cooling towers as an investment which would mitigate part of this loss by diverting fossil fuels from other investment opportunities; the return on this investment would be 0.05%. The total loss in work value to the ecosystem is less than 1% of the diversion of fossil fuel capital resulting from the cooling tower alternative (for all three units). By the objective criteria presented in this analysis, cooling towers are a poor investment for the total work budget (and thus survival) of this region.

LITERATURE CITED

Bureau of Economic and Business Research. 1973. Florida Statistical Abstract. College of Business Adminstration. Univ. of Florida, Gainesville, Florida. Univ. of Florida Press

Evans, R.B. 1969. A proof that essergy is the only consistent measure of potential work (for work systems). Ph.D. Thesis.Dartmouth College

Federal Power Commission. 1970. The 1970 National Power Survey. Part III. U.S. Govt. Printing Office. Washington, D.C. 20402

Gutfreund, P.D. and P. Urone. 1972. Salt deposition from salt water cooling towers. Dept. of Environmental Engineering Sciences, Univ. of Florida, Gainesville, Florida. Unpub. Ms.

Kylstra, D.C. 1974. Energy analysis as a common basis for optimally combining man's activities and nature. Paper presented to, the National Symposium on Corporate Social Policy. October 5, 1974. Chicago, Illinois

Littlejohn, C. 1974. Bureau of State Planning, Department of Administration, Tallahassee, Florida. Personal communication.

McKellar, H.N. 1974. Personal communication, Department of Enviornmental Engineering Sciences. University of Florida. Gainesville, Florida

National Environmental Policy Act. 1969. Public Law 91-190, 91st Congress, S. 1075 Jan 1, 1970.

Odum, H.T., W. Smith, H. McKellar, D. Young, M. Lehman, and W. Kemp. 1973. Preliminary presentation of models to show interactions of power plant and estuary at Crystal River, Florida and energy costs and benefits for alternatives of management of cooling waters. Progress Report to Florida Power Corporation and Licensing Agencies Concerned with Planning at Crystal River, Florida

Odum, H.T. 1974. Energy quality concentration factors for estimating equivalent abilities of energies of various types to support work. Dept. of Environmental Engineering Sciences. Univ. of Florida, Gainesville Florida. Unpub. Ms.

Odum, H.T. Energy value, and money. (in) C. Hall and J. Day (eds) Models as Ecological Tools: Theory and Case Histories (in press).

Tribus, M. and E.C. McIrvine. 1971. Energy and information. Scientific American 224 (3): 179-190

United States Atomic Energy Commission. 1972. Draft Environmental Statement by the Directorate of Licensing. U.S. Atomic Energy Commission. Related to the proposd operation of Crystal River Unit 3 by the Florida Power Corporation. Docket No. 50-302. U.S. Atomic Energy Commission, Washington, D.C.

United States Atomic Energy Commission. 1972. Draft Environmental Statement by the Directorate of Licensing. U.S. Atomic Energy Commission Related to the Proposed Operation of Turkey Point Plant by the Florida Power and Light Corporation. U.S. Atomic Energy Commission, Washington, D.C. Dockets No. 50-250 and 50-251

Woodwell, G.M. and Whittaker, R.H. 1968. Primary production in terrestrial communities. Amer. Zool., 8:19-30

Woodwell, G.M. and Botkin, D.B. 1970. Metabolism of terrestrial ecosystems by gas exchange techniques: The Brookhaven approach. In: Studies in Ecology (D.E. Reichle, ed) Springer-verling, New York. pp. 73-85

Yaalon, D.H. and J. Lomas. 1970. Factors controlling the supply and the chemical composition of aerosols in a near-shore and coastal environment. Agricultural Meteorology 7:443-454.

Zucchetto, J.J. 1974. Personal communication. Department of Environmental Engineering Sciences. University of Florida. Gainesville, Florida

4. MAIN ECOLOGICAL SUBSYSTEMS OF THE ESTUARIES AND THEIR ADAPTATION TO THE POWER PLANTS

Although the questions of management alternatives must be decided on the larger overall scale as already discussed, the present procedures and laws, the habits of thinking of most scientists and environmental managers in our culture, and the design of the research programs at Crystal River as required by agencies are oriented downward to the parts and processes within the estuary and its relation to the plant. Since it is the further responsibility of this component of our research team to help the visualization and planning of these smaller scaled detailed efforts by providing models for portrayal and understanding of the subsystems, six are identified:

1. Inner bay with bottom communities
2. Outer bay with plankton associations
3. Oyster reef
4. Canal Ecosystems
5. Tidal Creeks
6. Salt Marsh

The ecosystems that form the estuary include the shallow inner waters dominated by bottom plants and organisms, deeper waters with plankton roles more dominant, oyster reefs, special ecosystems developing in the canals under influence of energies of water flow and plant action, the salt marsh into which warm waters exchange, and the tidal creeks interacting with both the salt marsh and bay ecosystems. For the first five of these subsystems a summary system ecological model is given with stocks and flows enumerated. Supporting tables show the source of these numbers within the current report of various investigators or elsewhere. These diagrams and tables include many of the varied data. Then in the narrative that goes with each system, the diagrams are discussed in terms of turnover rates, comparisons with control areas, and estimated effects of temperature directly and as partially cancelled by recycle and push-pull effect of temperature affecting all parts of the system. Included in these considerations are questions about plant actions on plankton turbidity, metabolism, nutrients, and other organisms.

Fig. 1 shows the main ecosystems of the power plant region. These include the intake area south of the spoil banks and the thermally affected discharge area to the north, the developing ecosystems of the power plant canals affected by plant pumping and heat loading, and offshore systems linked by advective exchange driven by large scale eddy motion with those inshore. The power plant pumps water, materials, and organisms in its role as a large coastal consumer, processing and returning them in a different form with added heat to reenter the cycles of the regional ecosystems.

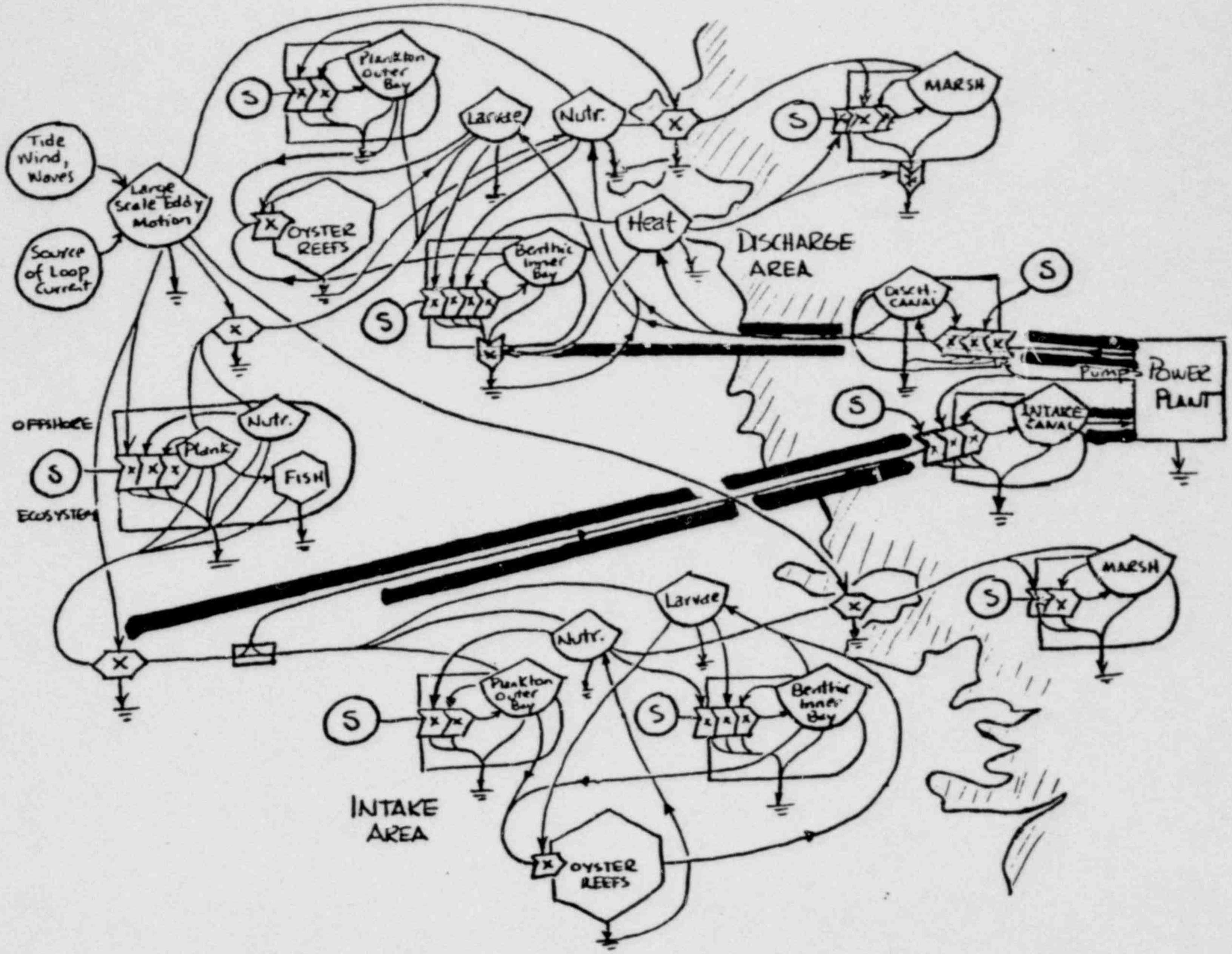


Fig. 1. Main ecosystems of the power plant region

4A. SHALLOW INSHORE ECOSYSTEM OF BOTTOM COMMUNITIES AND THE EFFECT OF THE POWER PLANT DISCHARGE PLUME

Wade Smith
Department of Environmental Engineering Sciences
University of Florida
Gainesville,32611

INTRODUCTION

The heated discharge of Florida Power Corporation's power plants near Crystal River, Florida first flows into a shallow estuarine basin of about one meter average depth consisting primarily of benthic animals and plants, and especially one species of seagrass, Halodule wrightii (formerly Diplanthera wrightii). This bottom dominated ecosystem is influenced by oyster reefs on its boundaries and mud bottoms adjacent to the salt marshes on the landward edge. (See Fig. 1, 2, and 3.) As part of a larger project to assess the environmental impact of these plants and a third under construction, total community metabolism has been measured since the summer of 1972 in this basin and similar benthic dominated areas to the south and north. Measurements from this study and data from concurrent studies by others were combined with models and computer simulations to evaluate the effects of present and future plants. These projects included: Measurements and modeling of the deeper aquatic systems in which plankton played a more important role, the salt marsh system, oyster reef associations, and canal systems; measurements of biomass of stocks such as resident bay fishes, marsh creek fishes, benthic invertebrates and

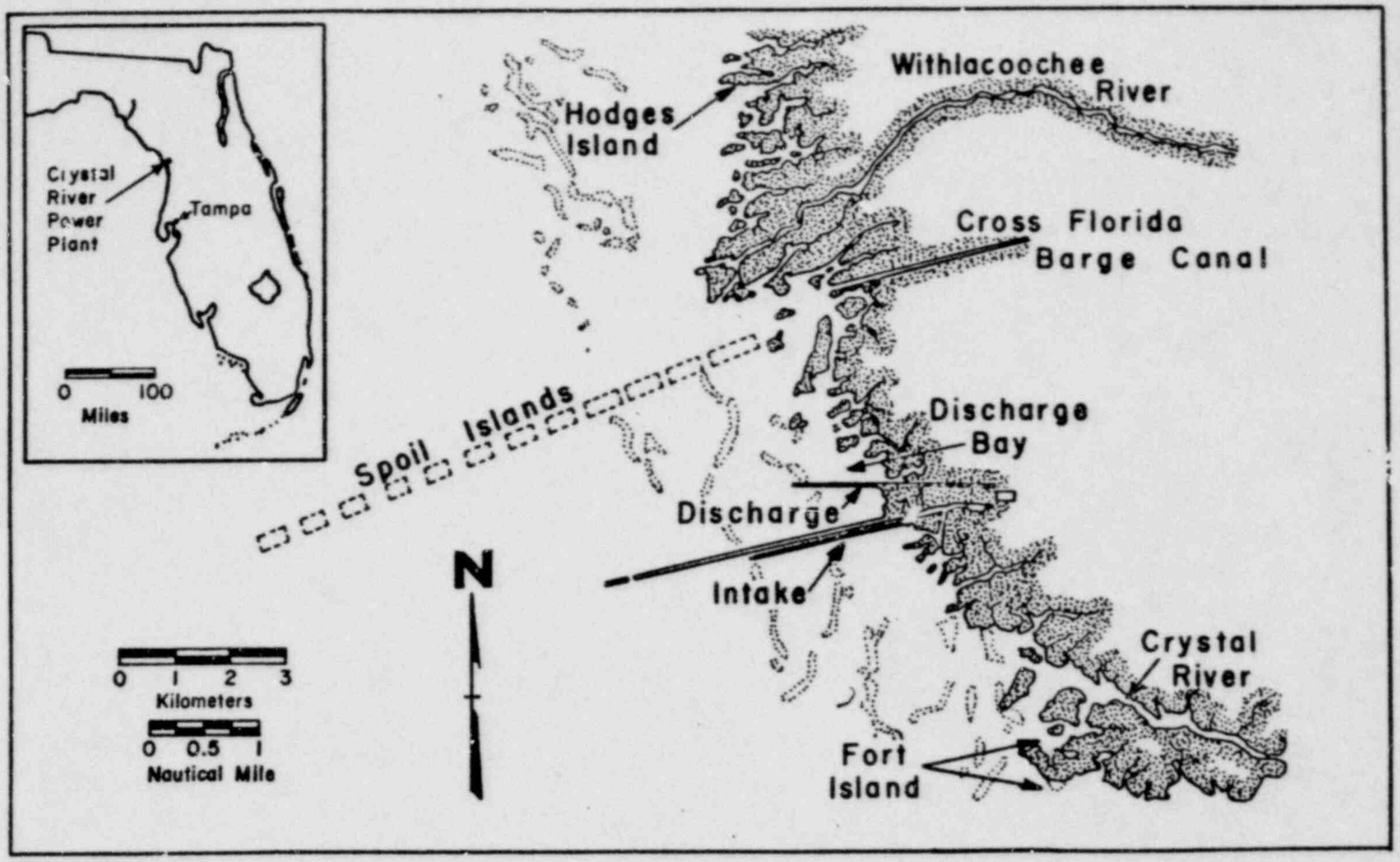


Fig. 1. Florida Power Corporation's Crystal River plant in relation to the major features of the regional coastline. Oyster bars are indicated by dotted lines.

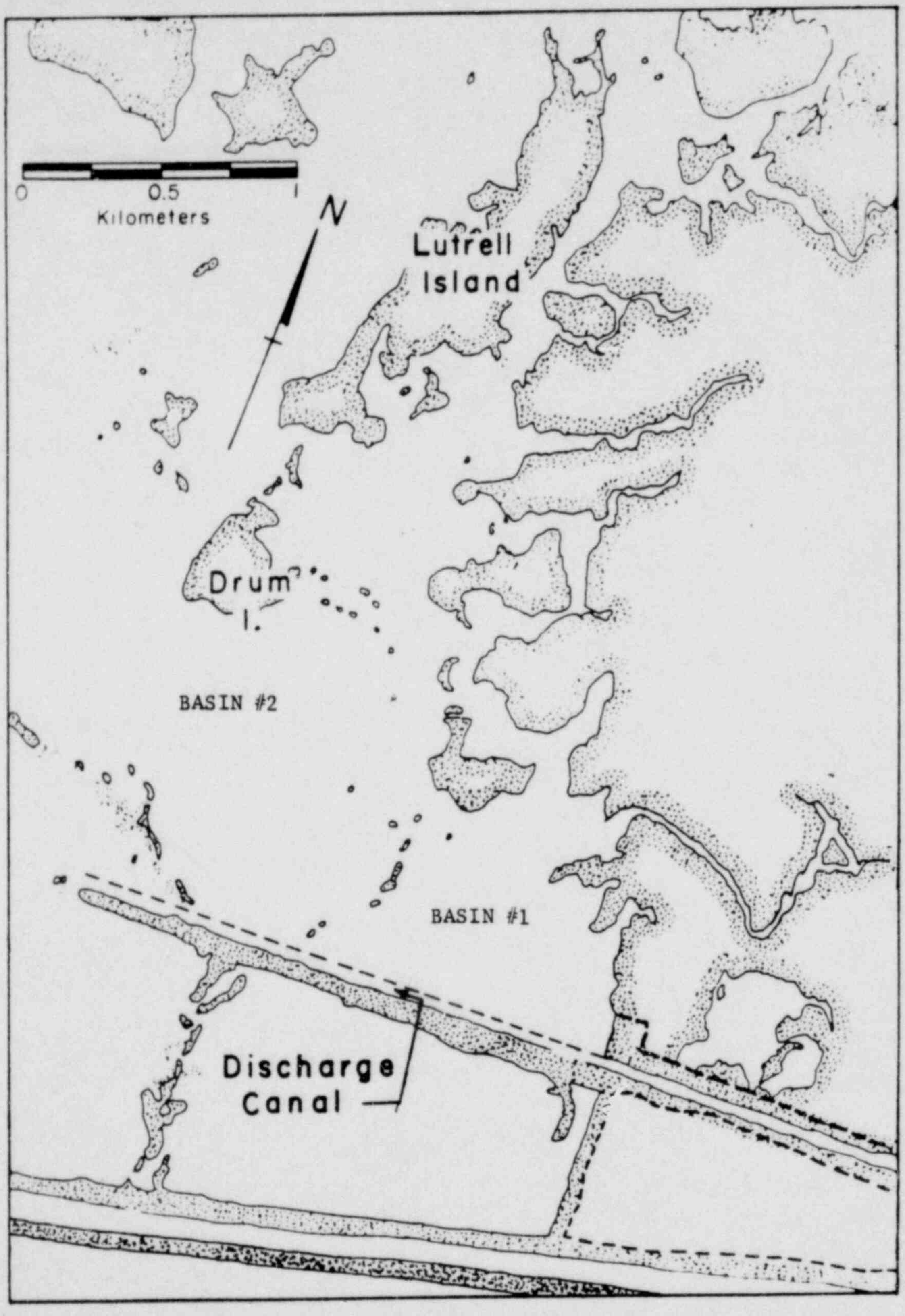


Fig. 2. Thermally affected discharge area showing location of the shallow system of basin #1 dominated by seagrass.

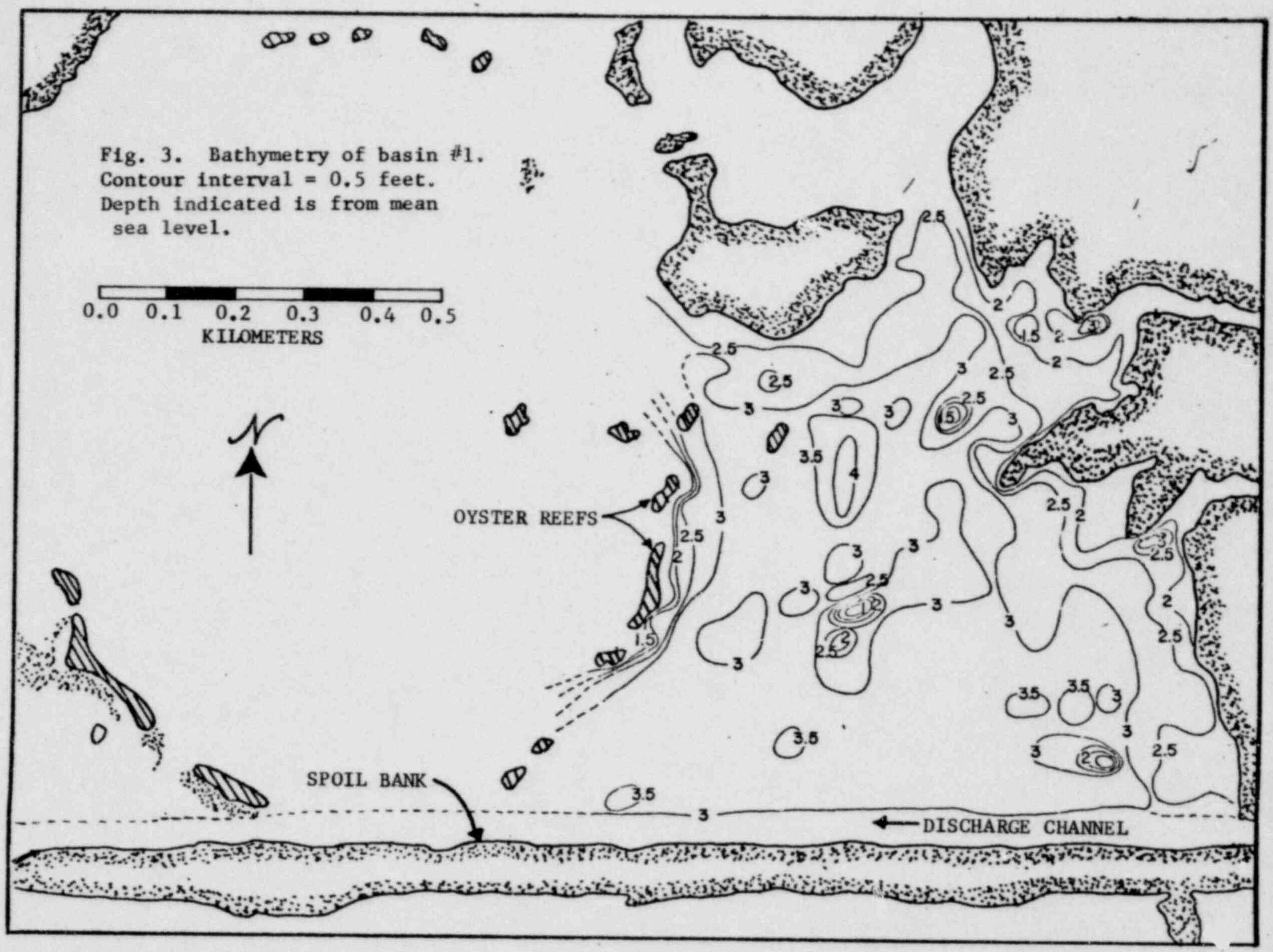


Fig. 3. Bathymetry of basin #1. Contour interval = 0.5 feet. Depth indicated is from mean sea level.

seagrass and macroalgae; seasonal measurement of nutrient levels; seasonal zooplankton stocks; impingement of organisms or the barrier screens of the intake pumps.

Some questions considered in this study were:

1) What is the effect of heated effluent on total community metabolism as a measure of overall adaption and level of work functions developed under these conditions as compared to those of other nearby coastal areas?

2) What are the differences in levels and composition of standing stocks in the thermally affected and unaffected areas. How does this indicate system adaptation in the affected area?

3) What are the relative magnitudes of flows between stocks? How do turnover times compare between systems?

Reported here are results of the metabolism studies and synthesis of data relating to this shallow system from other project tasks.

METHODS

Metabolic Measurements

Community metabolism was measured with both complete diurnal sampling runs following Odum and Hoskins (1958), Odum and Wilson (1962), and Odum (1967), and an abbreviated method using dawn-dusk-dawn oxygen measurements (McConnell, 1962). Oxygen was measured by the azide modification of the Winkler technique (Standard Methods, 1971) but adapted for use with smaller sample collection bottles.

Mini-Winkler Field Kit and Winkler Method Modification

Because of the large number of samples to be processed and the need for compactness, a mini-Winkler field kit developed at the University of Texas

Institute of Marine Sciences was used in this study. Standard flat-topped 125ml reagent bottles were used for sample collection in place of 300ml BOD bottles. Samples were fixed with 0.5 ml of manganous sulfate and azide reagent carried in dropping bottles in the field kit. After acidification with 0.5 ml concentrated sulfuric acid 100 ml subsamples were titrated with 0.0125N sodium thiosulfate. This normality allowed direct reading of ml of titrant as mg/1 of oxygen.

Sources of variability between replicate pairs of oxygen samples could have arisen from many sources. Since the small reagent bottles used were of an inexpensive nature variation in their individual volumes was expected. A test of 54 bottle subsample of those in use gave an average volume of 122.8 ml with a standard deviation of 1.66 ml (see Table 1). Because each bottle was filled from separate samples of bay water taken 30 seconds to one minute apart variations due to water mass differences could also have occured. Other sources of variation could have included differences in reagent volumes added and differences in sample volumes titrated. Actual differences in titrant volume encountered between replicate pairs of samples were small, however. Based on a subsample of 486 replicate pairs 72.6% differed by 2 drops (0.1 ml) or less. Since titrant volume was generally in the range of 4-8 ml, this gave an average error of 1.3-2.5%. Loss of accuracy due to increased sources of variability was, therefore, considered minimal, and was far outweighed by convenience in handling in the field. Thus, more samples were processed permitting better statistics in estimating values for the whole bay.

Complete Diurnal Sampling of Oxygen

Stations were sampled approximately every three hours over a 24-hour period. Two buckets of surface water were collected about one minute apart

Table 1 . Average volume of water sample bottles used in diurnal oxygen analysis

Bottle No.	Volume (ml)	Bottle No.	Volume (ml)	Bottle No.	Volume (ml)
115	125.0	77	123.0	118	125.0
132	124.8	31	123.0	40	125.5
25	121.7	45	122.7	123	120.4
149	125.7	146	121.7	28	121.0
68	122.5	145	121.1	120	125.5
76	123.5	18	125.3	155	122.2
124	121.3	29	122.9	147	123.0
157	121.3	148	123.0	67	124.8
38	122.0	156	122.7	158	121.0
143	120.9	47	122.0	88	125.2
16	120.9	85	125.8	48	120.9
11	122.4	49	122.9	133	121.4
86	120.9	140	125.0	10	123.8
74	122.5	125	124.9	162	122.0
159	120.9	84	125.7	46	120.4
22	123.5	69	123.0	71	121.0
59	121.8	64	121.8	33	122.8
63	122.0	50	121.3	144	125.0

Average volume = 122.8 ml
Standard dev. = 2.7

at each station and sample bottles were filled from the bottom by siphoning through rubber tubing. Late night samples were sometimes stored without acidification for titration the following morning. Time, temperature, salinity, and depth were noted at each station.

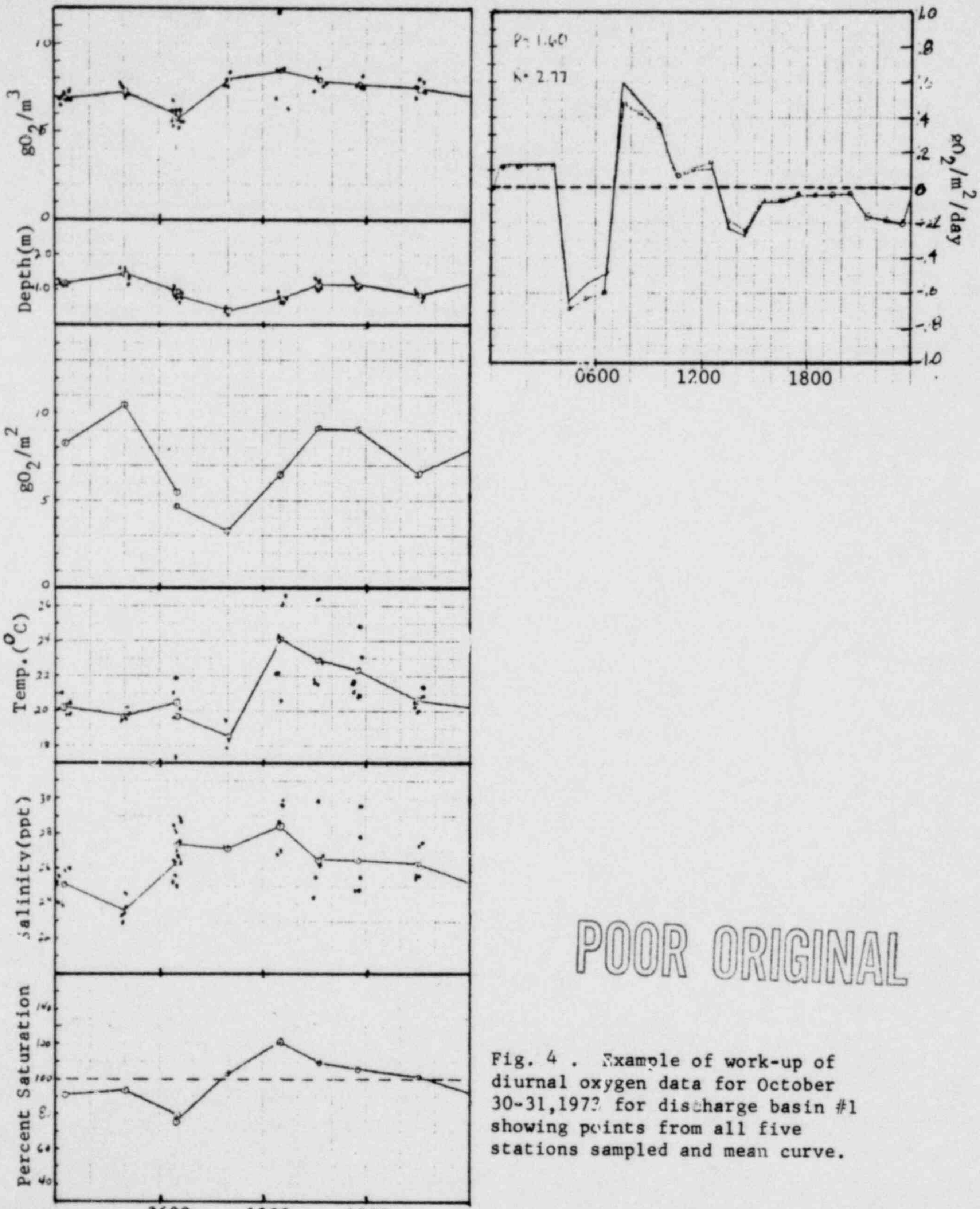
The effect on the Winkler method of saving fixed oxygen samples with or without adding acid was tested because of controversy surrounding the proper procedure. Thirty bottles were filled with salt water from a thoroughly mixed bucket and immediately fixed with the manganous sulfate and azide reagents. A group of ten bottles was picked at random, acidified, and titrated within 30 minutes. The remaining bottles were split into two groups, one group of ten bottles received acid while the other group did not. After storing in the dark for eight hours acid was added to the latter group and both groups were titrated. Table 2 gives the results of the three treatments. Differences between treatments were significant (95% level) but were considered too small to have any effect on the measurements.

Because of the large tidal flushing. advection of water masses from outside areas was important. In order to assess this effect on the diurnal oxygen curve in the study areas four or five stations were sampled in the early part of the project. Measurements showed a general similarity in the daily increase and decrease of oxygen at all stations suggesting that advection was from areas of similar metabolism, and it was decided that any errors introduced by advection were small, and the number of stations was sometimes reduced to two or three. See Fig. 4 for example of separate points and the mean curve.

Diurnal metabolism graphs were constructed using a standard format to allow easy visual comparison of all diurnal samples taken at Crystal River as well as with others in the literature (see Fig. 4). Several different workups of data were employed as the study progressed. At first, a graph for each station was plotted. Oxygen per square meter was obtained by multiplying

Table 2. Results of technique test of Winkler method to determine effect of presence or absence of acid in fixed bottles which have been saved for 8 hours.

	Bottles fixed, acidified, and titrated immediately (ml. titrant)	Bottles fixed and acidified immediately. Titrated 8 hours later (ml. titrant)	Bottles fixed immediately. Acidified and titrated 8 hours later. (ml. titrant)
	5.41	5.45	5.46
	5.37	5.40	5.49
	5.40	5.46	5.50
	5.47	5.43	5.45
	5.52	5.45	5.52
	5.55	5.43	5.45
	5.45	5.45	5.55
	5.45	5.40	5.45
	5.45	5.40	5.45
	5.43	5.42	5.46
Average	5.45	5.43	5.48
Std. Dev.	0.0540	0.0233	0.0355



POOR ORIGINAL

Fig. 4 . Example of work-up of diurnal oxygen data for October 30-31,1973 for discharge basin #1 showing points from all five stations sampled and mean curve.

oxygen concentration (g/m^3) by depth at that time. Percent saturation was calculated for the temperature and salinity at each time using the formula of Truesdale, et al., (1955). The divergence of Truesdale's saturation values from those presented in Standard Methods (1955) was reviewed by Churchill, et al., (1962), who showed deviations at temperatures less than 25°C. Maximum deviations, however, were less than 5% of the Standard Methods values so the errors incurred in this study by using Truesdale's values were considered small. Average curves were constructed from individual station curves by averaging hourly values for oxygen concentration, depth, temperature, and salinity. Oxygen per square meter and per cent saturation were then calculated from the averaged data. After this initial testing of data, individual station graphs were no longer done.. Instead, only the average graph was done but with individual station points also plotted on it. Each oxygen point represented the mean of duplicate Winklers.

An oxygen rate of change curve was constructed from the graph of average oxygen per square meter. The amount of change of oxygen during each hour was measured and plotted on the half-hour. This raw curve reflected changes in oxygen concentration under one square meter due to changing depth from tide exchange and diffusive exchange with the atmosphere, as well as photosynthesis and respiration. The effect of changing depth was eliminated by multiplying the incremental depth change for each hour by the average oxygen concentration during that hour. This value was added to the rate curve if the tide was falling or subtracted if the tide was rising.

The final adjustment to the rate of change curve was for oxygen lost or gained by diffusion between the water and atmosphere. At Crystal River the rate of diffusion tended to be largely a function of tidal current velocity and was measured at various stages of the tidal cycle using a small nitrogen filled plastic dome, which floated on the water surface (Hall, 1970, based on original work of Copeland and Duffer, 1964). A field oxygen probe measured the return of oxygen to the dome from the water under the normal conditions of underwater circulation. The diffusion rate as $g/m^2/hr/100\%$ deficit was calculated from the area of water surface covered, volume of the dome, and the observed saturation value of dissolved oxygen in the water. This was the maximum rate of diffusion into oxygen-free water or out of water 200% saturated with oxygen. Fig. 5 shows a typical diffusion measurement, Table 3 shows a sample calculation, while Table 4 gives the diffusion measurements made in this study. Because of the small number of measurements taken, assigning diffusion rates to time periods on the graph was a combination of actual measured values and estimates based on field experience with the general magnitudes of tidal currents at different stages of the tidal cycle in the study areas. The actual diffusion correction for each hour was calculated by multiplying the maximum rate selected for that hour by the actual saturation deficit during that hour.

This laborious method was soon modified to a faster procedure. Average oxygen concentration, temperature, depth, salinity, and percent saturation were plotted as before, but the areal oxygen curve was not calculated. The rate of change curve was obtained by multiplying the hourly rate of change of oxygen concentration by the average depth at that hour giving the rate of change on an areal basis. The adjustment for diffusion was made as before. In all methods the final rate of change graph showed the rise of oxygen due to net photosynthesis during the day and decrease due to respiration at night. Net daytime photosynthesis was taken as the area under the rate of change curve above the zero rate of change line. Night time respiration was taken as the area under the

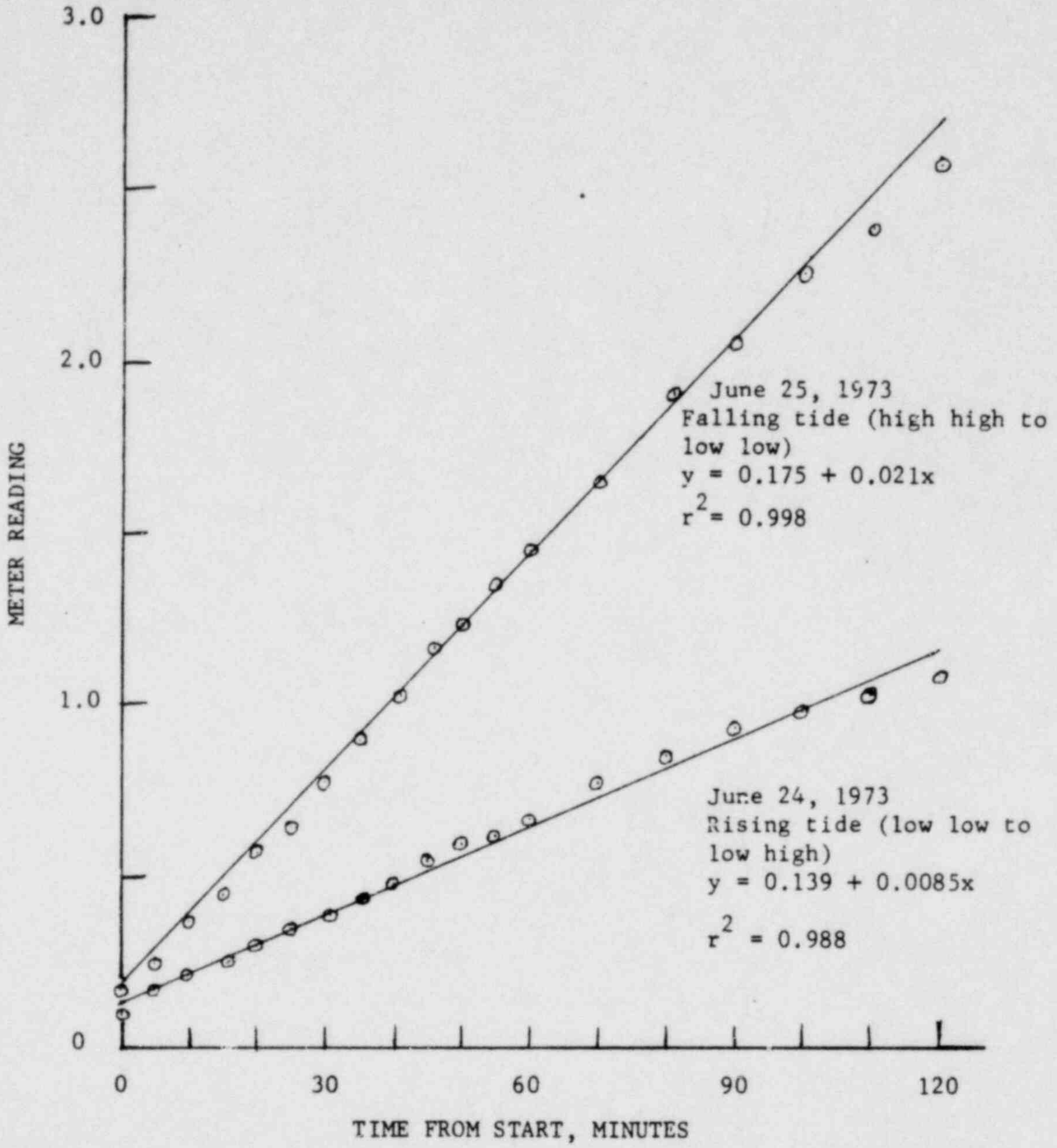


Fig. 5. Plot of oxygen meter reading with time for two diffusion experiments conducted at Fort Island. Meter was adjusted to read 10 when calibrated in air. Line through points was obtained by computing a linear regression.

Table 3. Example of calculation of diffusion constant from data obtained from floating dome experiment at Fort Island, June 25, 1973

Volume of dome = 4.5 liters

Surface area of water covered = 0.1024 m^2

Average percent saturation during run = 87.6%

From regression equation, rate = 12.6%/hr/0.1024m^2/87.6% sat.

If dome full of air about 20% of volume would be oxygen:

$$(4500\text{ml})(0.2) = 900 \text{ ml } O_2$$

After 1 hour 12.6% of that amount of O_2 had diffused in:

$$(900 \text{ ml})(0.126) = 113.4 \text{ ml } O_2/\text{hr}/0.1024 \text{ m}^2/87.6\% \text{ sat.}$$

Correction of volume to STP:

$$113.4 \text{ ml} \times \frac{273^{o}K}{308^{o}K} = 100.51 \text{ ml at STP}$$

Weight of oxygen:

$$100.51 \text{ ml} \times \frac{32 \text{ g}}{22400 \text{ ml}} = 0.144 \text{ g}O_2 \text{ at STP}$$

K = 0.144 gO_2/0.1024 m^2/hr /87.6% sat. = 1.40 gO_2/m^2/hr/87.6% sat.

K = 1.60 gO_2/m^2/hr/100% deficit

Table 4. Diffusion Rates Measured in the Power Plant Discharge and Fort Island Study Areas

Location	Date	Tidal Stage	Wind	Diffusion Rate ($gO_2/m^2/hr/100\%$ deficit)
Discharge Bay	Oct. 10, 1972	Falling.Low high to high low	Brisk white caps	0.78
Discharge Bay	June 28, 1973	Falling.High high to low low	Brisk	0.53
Discharge Bay	July 26, 1973	Falling.High high to low low	Moderate	0.54
Discharge Bay	September 12, 1973	Slack high tide	Calm to light	0.13
Discharge Bay	September 12, 1973	Falling.High high to low low	Calm	0.24
Discharge Bay	September 12, 1973	Falling.High high to low low	Light	0.44
Fort Island	June 24, 1973	Rising.Low low to low high	Light	0.55
Fort Island	June 25, 1973	Falling.High high to low low	Light	1.60

rate of change curve below the zero rate of change line.

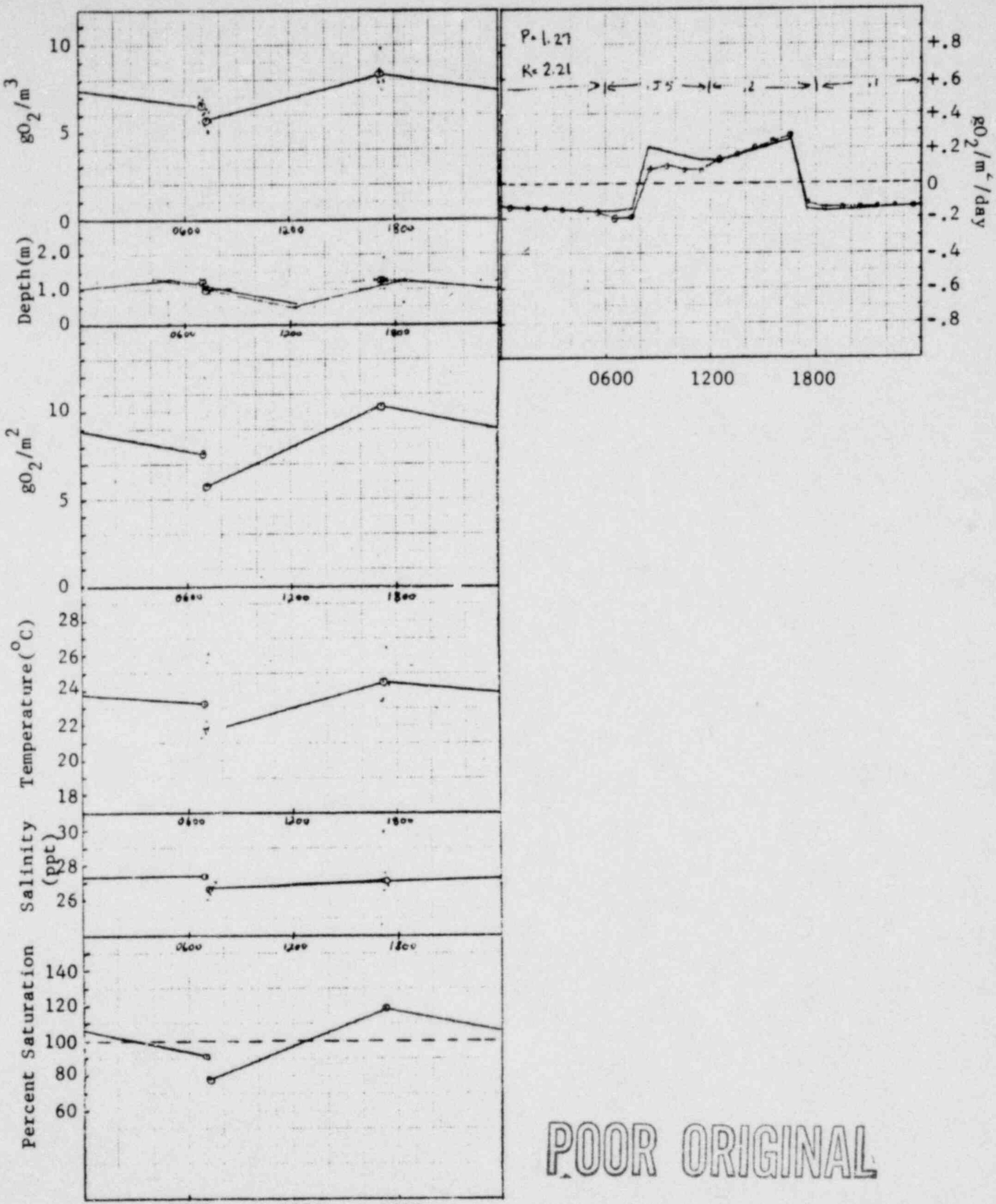
Dawn-Dusk-Dawn Measurements

In order to gain more data as a check on day to day variability of total metabolism and to reduce the amount of field labor involved the dawn-dusk-dawn method was used after the first year. The low point of oxygen at dawn, the high point at dusk, and the low point the following dawn were measured as a short cut method of approximating the true diurnal curve. Experience in the field showed that the time of the minimum and maximum was not always at dawn or dusk. Clouds in the east at sunrise tended to delay the onset of rising oxygen by an hour or more. Similarly, afternoon thunderstorms often caused the downturn of oxygen well before dusk. Even on clear days full diurnal curves showed that oxygen concentration often would not increase any more in the last 2 hours before sunset. The times of dawn and dusk sampling, then, was often adjusted to the prevailing conditions. Dawn samples were delayed if the morning was cloudy in the east. Dusk samples were generally taken about 1 1/2 hours before dusk.

Water samples were drawn, fixed, and titrated as described before. Diurnal graphs of averaged data were drawn in the same way as for full diurnals but used only three points. Fig. 6 gives an example.

Light-Dark Bottle Measurements

Light and dark bottles studies were [illegible] in the later stages of the project to estimate the metabolic component of the water column as apart from bottom and fishes. 300 ml BOD bottles were suspended at about 0.5 m depth with small chains secured to a four foot length of 3/4 inch PVC pipe floated at each end by a plastic milk carton. Generally, five replicates each of both light and dark bottles were put out as soon as the



POOR ORIGINAL

Fig. 6. Example of graphical workup of dawn-dusk-dawn diurnal data for November 1-2, 1973 in the thermally effected basin #1.

dawn diurnal run was completed and picked up at the same time the following day. Fixation and titration were as in Standard Methods (1971) except that only a 100 ml subsample was titrated because of the 0.0125N thiosulfate used. The increase in the light bottle was taken as 24 hour net production, the decrease in the dark bottle was taken as 24 hour respiration, and the sum of the oxygen gained plus that used up was taken as gross photosynthesis.

RESULTS

For purposes of synthesis, increasing understanding of total system structure and function, and assessing the nature of the adapted and surviving system which has developed under the influence of the thermal plume, data from other tasks of the Crystal River project as well as that gathered in this phase are presented here. Data for control areas comes from two different sites. Biomass data was gathered by Snedaker in basin #6 just south of the intake dike while diurnal metabolism data was measured in a bay near Fort Island just to the south of the mouth of the Crystal River (see Fig. 1).

Diurnal and Season Patterns of Data from Other Portions of Crystal River Project

Sunlight

Fig. 7 gives average daily insolation by month for the period 1961-72 measured at Tampa, Florida 90 miles to the south (U.S. Weather Bureau, 1967). Peak insolation months (about 6000 $Kcal/m^2 \cdot day$) were April and May at the very end of the winter-spring dry season. Daily summer values were lower

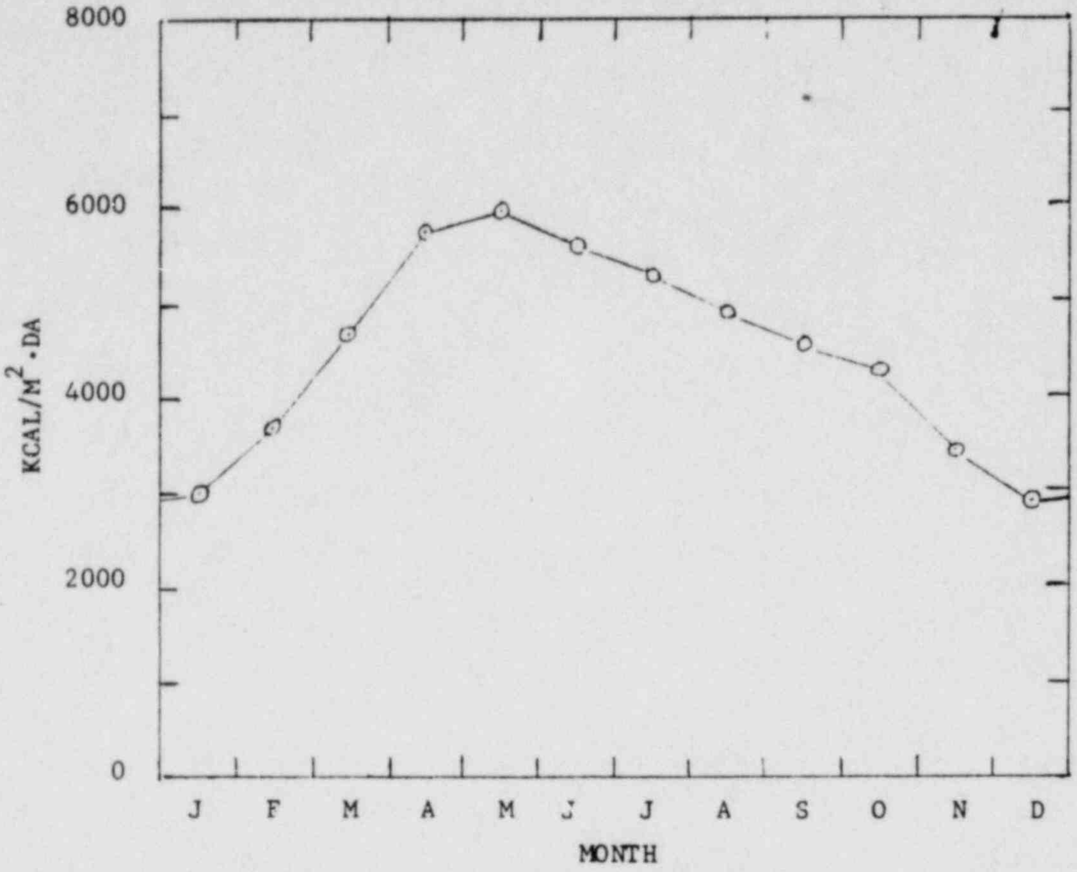


Fig. 7. Average daily insolation by month (1961-1972) at Tampa, Florida (U.S. Weather Bureau, 1969).

probably due to frequent afternoon thunderstorms. Fig. 8 gives a typical summertime pyranometer tracing for Crystal River showing afternoon thunderstorms reducing insolation.

Air Temperature

Fig. 9a gives monthly mean, maximum, and minimum daily temperatures at Tampa (taken from Fla. Power Corp., 1972). Diurnal variation was smallest during the summer months when the climate was primarily under the influence of the Bermuda high pressure system and frontal systems usually remained well north of the area. Minimum temperatures dropped sharply in October as cold fronts began penetrating into Florida and remained low through the winter when the climate was characterized by cold snaps following each frontal passage with warming until the penetration of the next cold air mass.

Precipitation

Monthly mean and maximum 24 hour precipitation at Tampa is presented in Fig. 9b (taken from Fla. Power Corp., 1972). About 60% of the yearly rainfall occurred from June through September, the rest falling over an extensive eight month dry period extending through May.

Wind Direction and Speed

Wind rose diagrams by season are given in Fig. 10 (Fla. Power Corp., 1972). Summer winds are predominantly westerly and easterly as influenced by the large scale circulation about the shifting position of the Bermuda high pressure cell and by the more local regional land-sea breeze system. With the change in the fall and winter to weather patterns dominated by frontal systems the predominant wind direction shifted to northerly directions. Average wind speed (Table 5 , Fla. Power Corp., 1972) was lowest in the summer and highest in fall and winter, probably due to the strong winds associated with frontal passages.

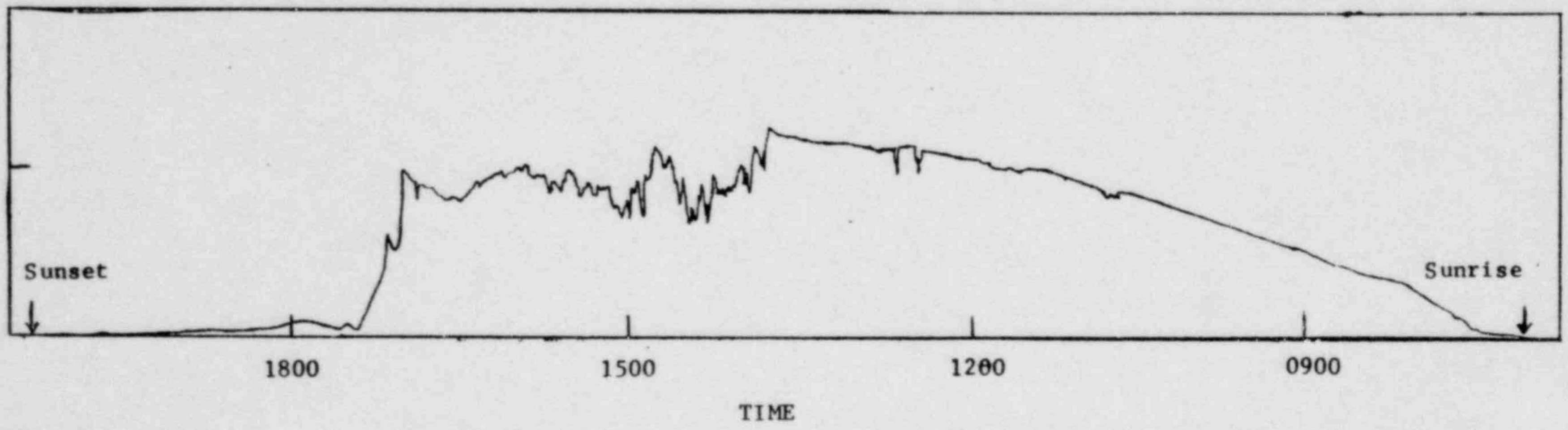


Fig. 8. Pyranometer tracing for August 2, 1974 at Crystal River site showing effect of afternoon thunderstorms on daily insolation.

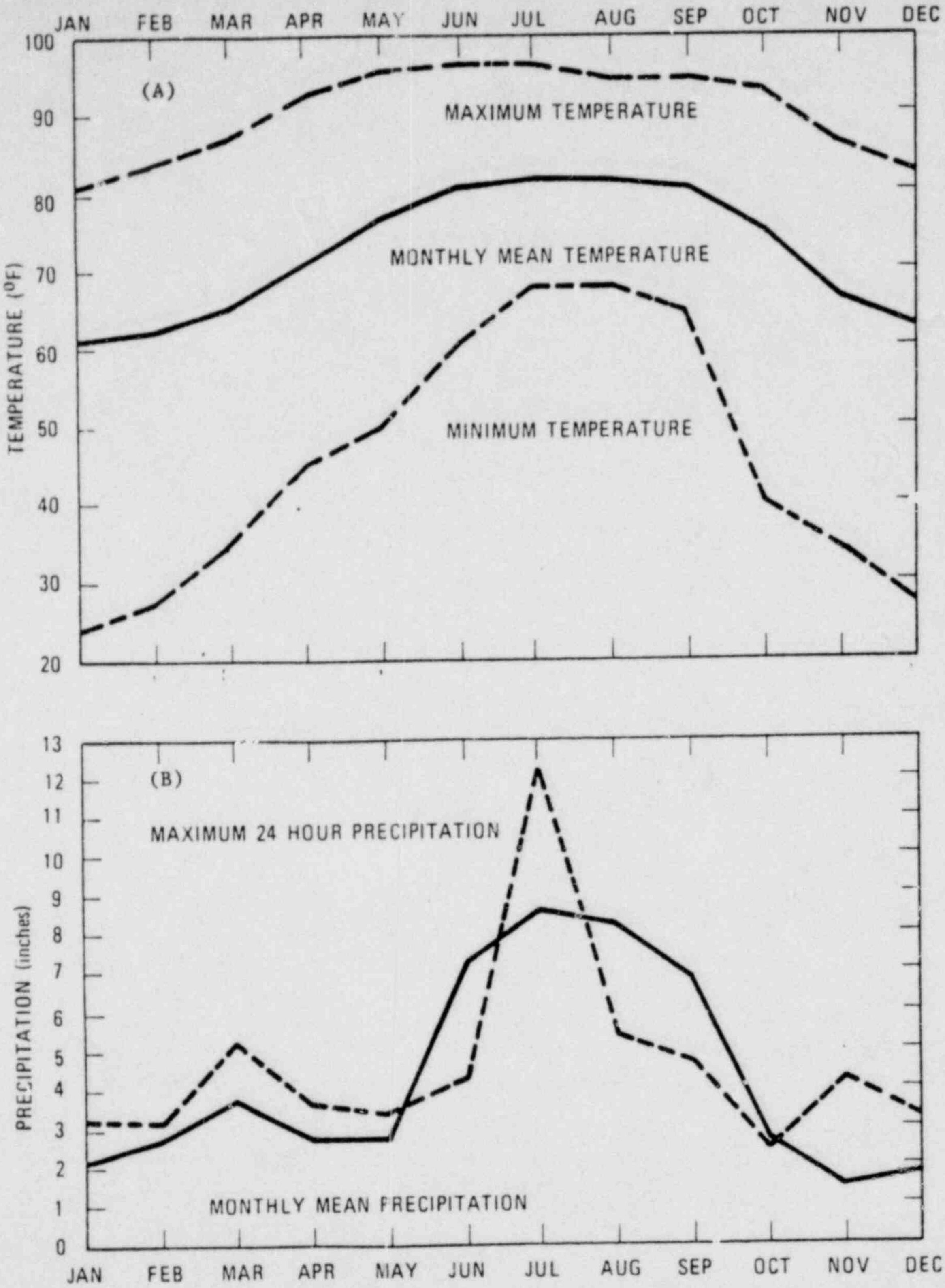


Fig. 9. Climatic data for Tampa, Fla. A) mean monthly temperature with minimum and maximums. B) monthly mean and maximum 24 hour precipitation. (Fla. Power Corp., 1972)

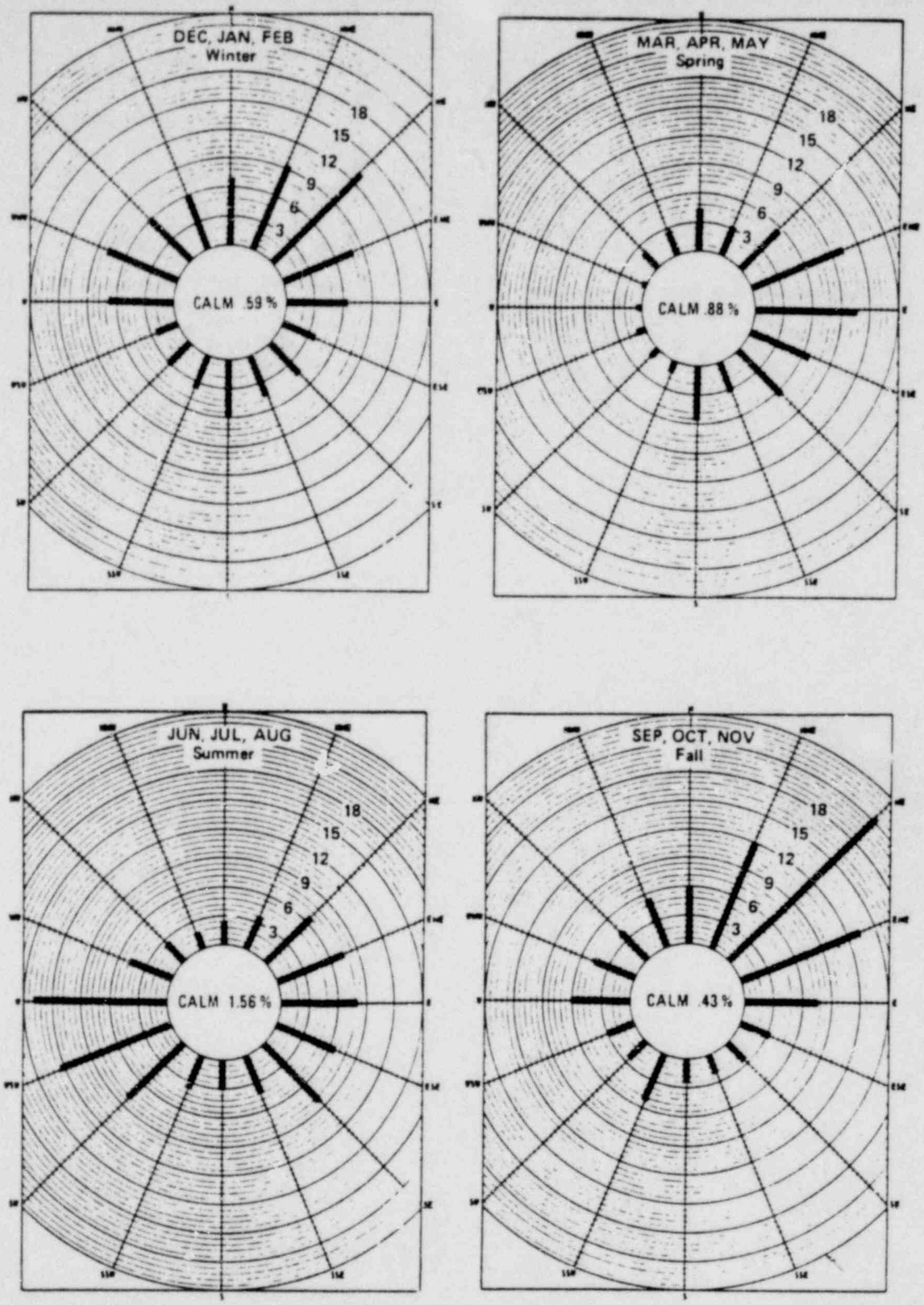


Fig. 10. Wind direction by season at Crystal River site. Bars give percent of readings occurring from each compass bearing (Fla. Power Corp., 1972).

Table 5. Seasonal average wind speed at Crystal River site (Fla. Power Corp., 1972).

	Average Wind Speed (mph)	Frequency of Calms (%)
Spring	11.1	0.88
Summer	9.5	1.56
Autumn	12.0	0.43
Winter	12.0	0.59
Annual	11.4	0.75

Water Temperatures

Weekly average water temperatures at various locations in the discharge canal, discharge study area, and intake area are given in Fig. 11. Buoy locations are given in Fig. 12. Weekly average power plant load for units 1 and 2 and temperature rise across the condensers for unit 1 is shown in Fig. 13. The seasonal ambient water temperature cycle was indicated by buoy K located at the Gulf end of the south intake dike (Fig. 11) and water entering the intake pumps (Fig. 13). For 1973 lowest temperatures of 12 to 15°C occurred in January and February rising through the spring to a plateau of 28-30°C in the summer months of June through September. Rapid cooling began in October. These data are very similar to monthly average data for Cedar Key 25 miles to the north (25 year record).

Discharge area temperatures (Fig. 11) had the same seasonal pattern as ambient areas but with a consistant temperature increase due to the thermal plume. Canal temperatures (buoys F and G) were about 5°C higher than ambient, corresponding to the average temperature rise across the power plant condensers. Over the shallow inner bay, (buoys GA, GB, GC) the average temperature increase was only about 3°C over ambient, probably due to evaporative and radiative cooling and mixing with some ambient water.

Diurnal temperature patterns are given in Fig. 13 for four days in late May, 1974. Ambient daily change (buoy K) was about 3°C. Canal temperatures (buoy G) was about 5°C above ambient but the pattern was variable. Tidal effects were evident in the record with buoys G and GD exhibiting opposite behavior. In the canal (buoy G) surface temperature decreased at high tide, probably as cooler offshore water flowed in over the warmer but more saline and dense plume. At the north boundary of the discharge plume (buoy GD) a rising tide pushed warm

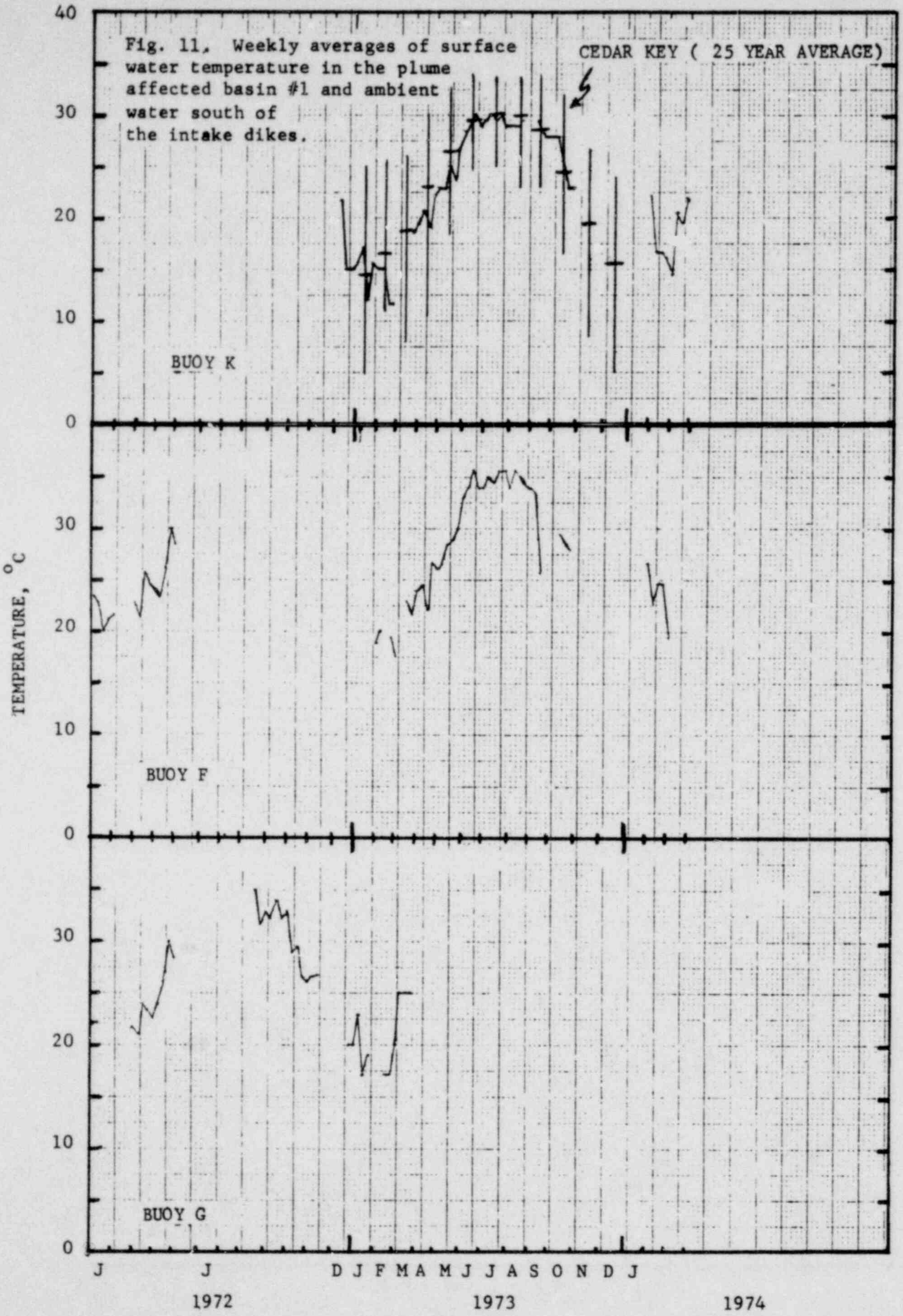


Fig. 11. Weekly averages of surface water temperature in the plume affected basin #1 and ambient water south of the intake dikes.

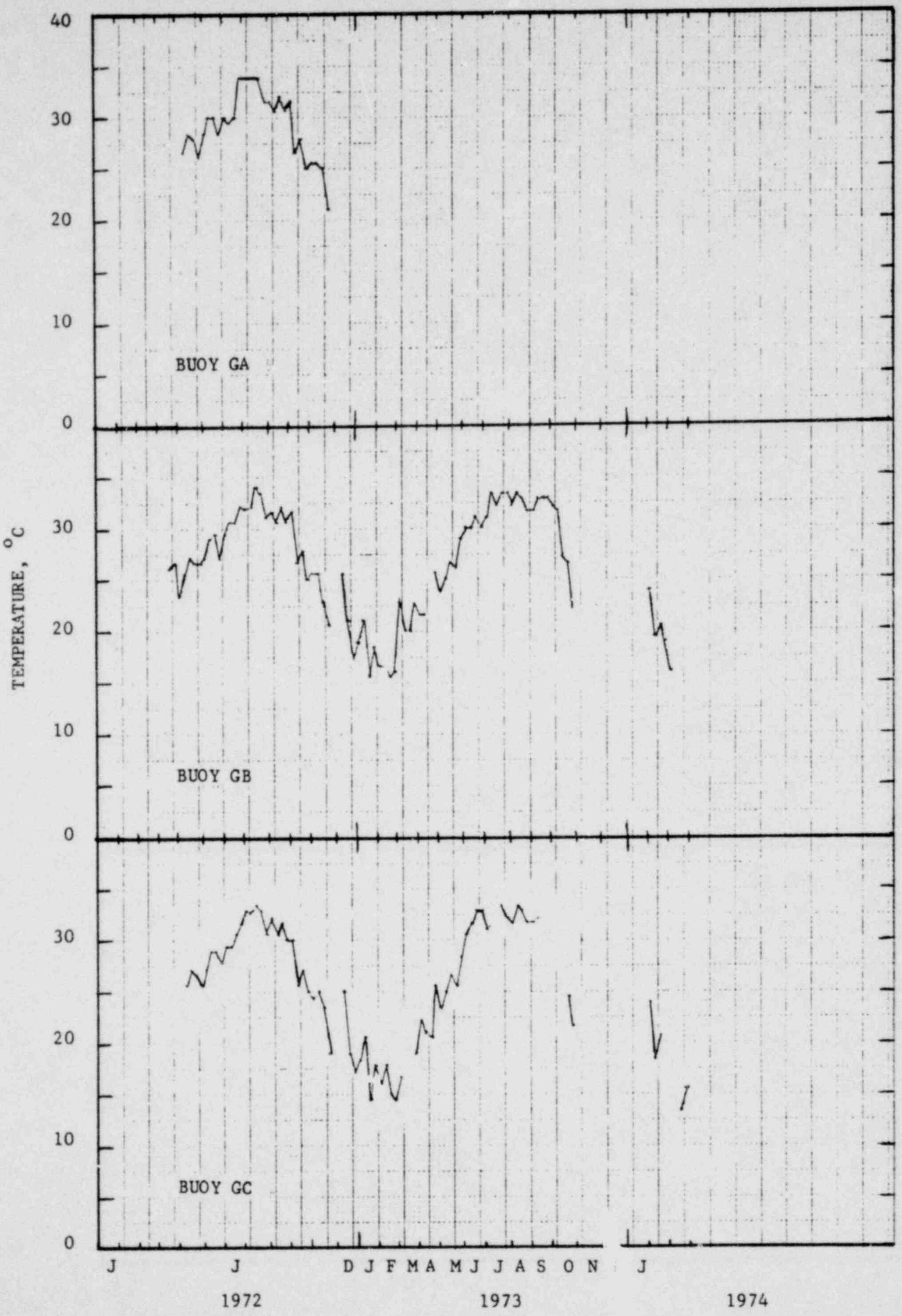


Fig. 11 continued.

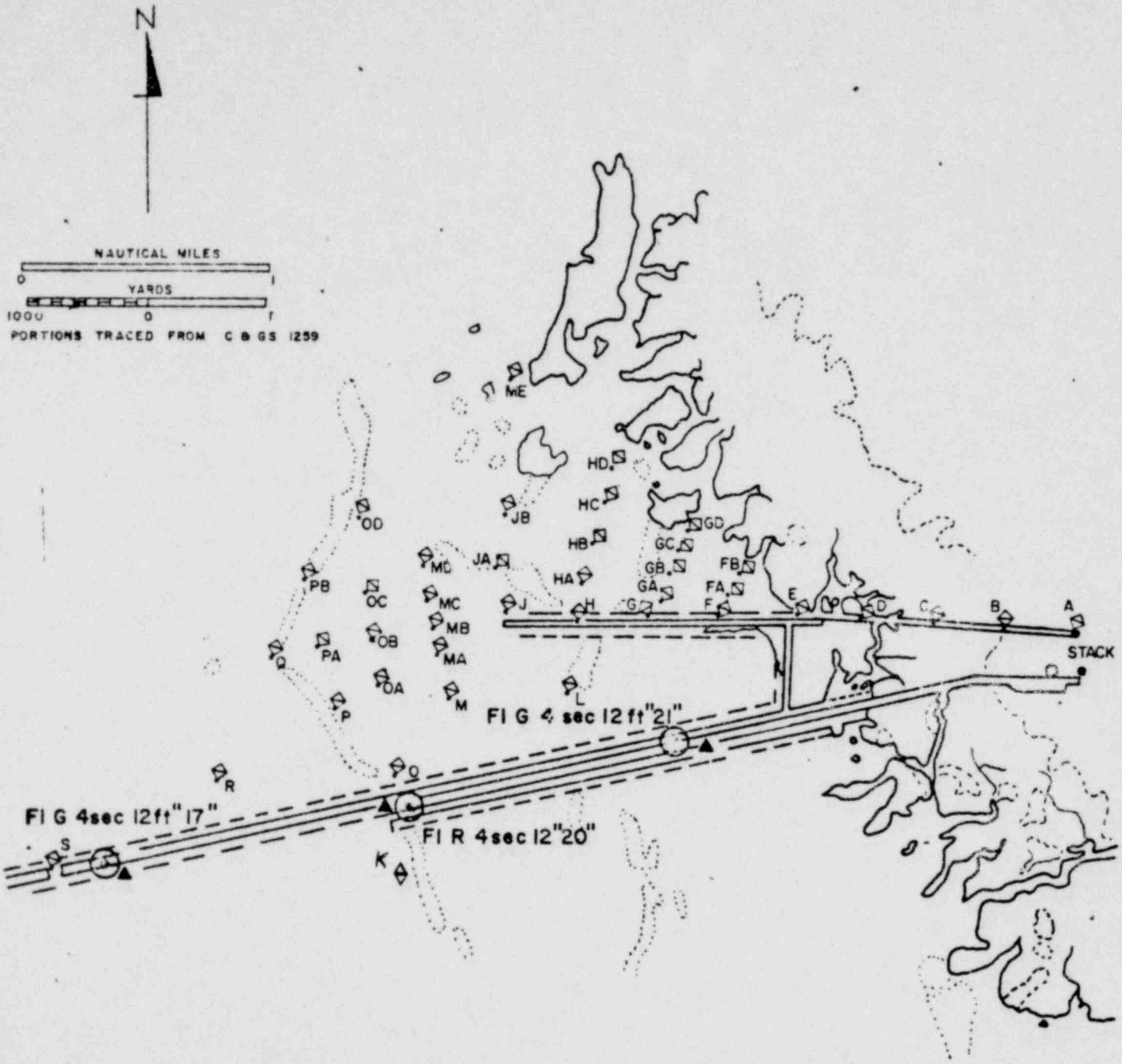


Fig. 12 . Map of locations of temperature sensing buoys in vicinity of power plant.

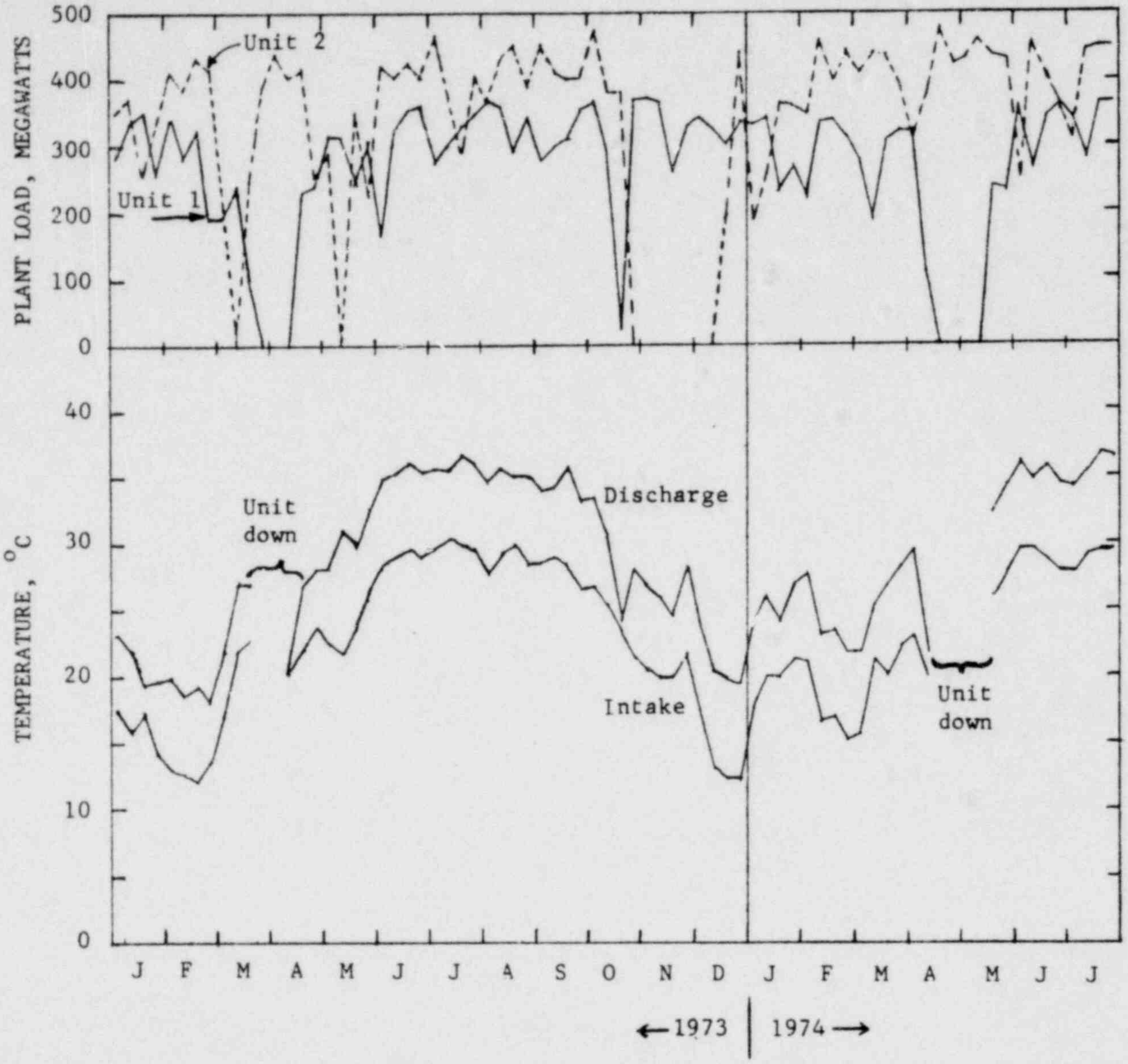


Fig. 13. Weekly average of plant load for Units 1 and 2, and Unit 1 intake and disch rge temperature.

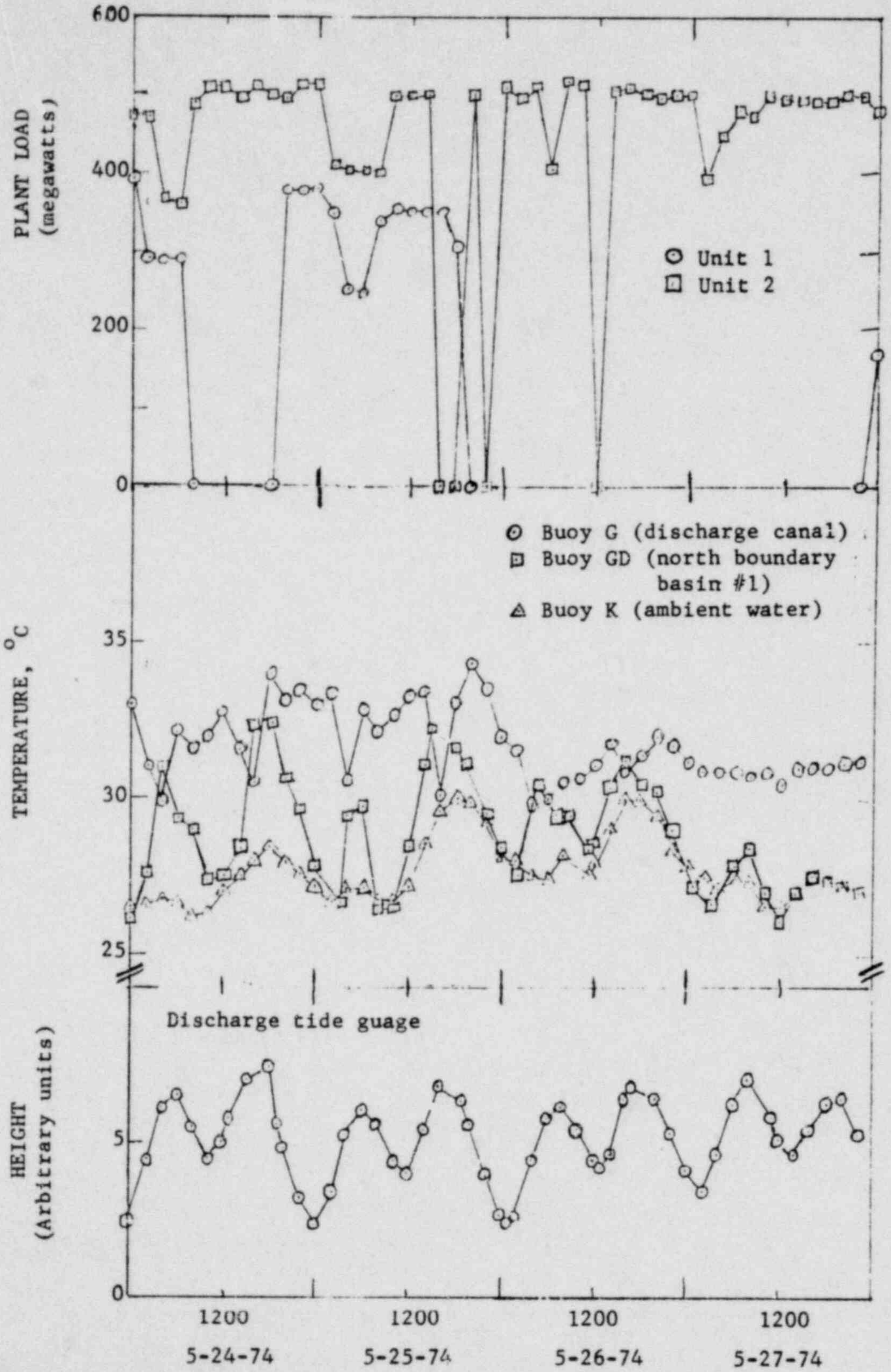


Fig. 14. Plots of power plant loads, water temperatures at three locations, and tidal stage in the discharge area for May 24-27, 1974. Buoys G and GD were in the discharge area and buoy K was in the intake area (see Fig. 12).

plume water across the bay, which finally reached the buoy sensor at full tide stage. The temperature quickly dropped to ambient as cooler water from the north flowed past on the falling tide.

The effect of plant load on temperature is apparent in the data pattern for May 26 and 27 when unit 1 went offline while unit 2 continued to operate at a fairly constant load factor. Since both units continued to pump ambient water, the canal temperature dropped several degrees because of dilution of the heat from unit 2. Because of mixing and cooling the plume reaching buoy GD dropped closer to ambient levels. Very little solar heating was evident for May 27 because of the cloudy conditions for that day.

Benthic Macrophytes

Seasonal patterns of biomass of benthic macrophytes in basin #1 affected by the thermal discharge and in basin # 6 south of the intake dike are given in Fig. 15. Biomass in basin #1 was composed almost entirely of the seagrass Halodule wrightii except during the winter of 1972-73 when mixed Ectocarpaceae were present in abundance. It did not return, however, during the milder winter of 1973-74. Basin #6 had a larger standing stock with macrophytic algae becoming much more important. See report by Van Tyne for more detail and discussion.

Resident Fishes

Seasonal values of biomass and numbers of fishes caught in drop nets in basin #6 are given in Fig. 16. See discussion by Adams elsewhere in this report for more detailed data and analysis.

Nutrients

An indication of nutrient levels in basin #1 may be indicated by measurements at the mouth of the discharge canal (Fig. 17).

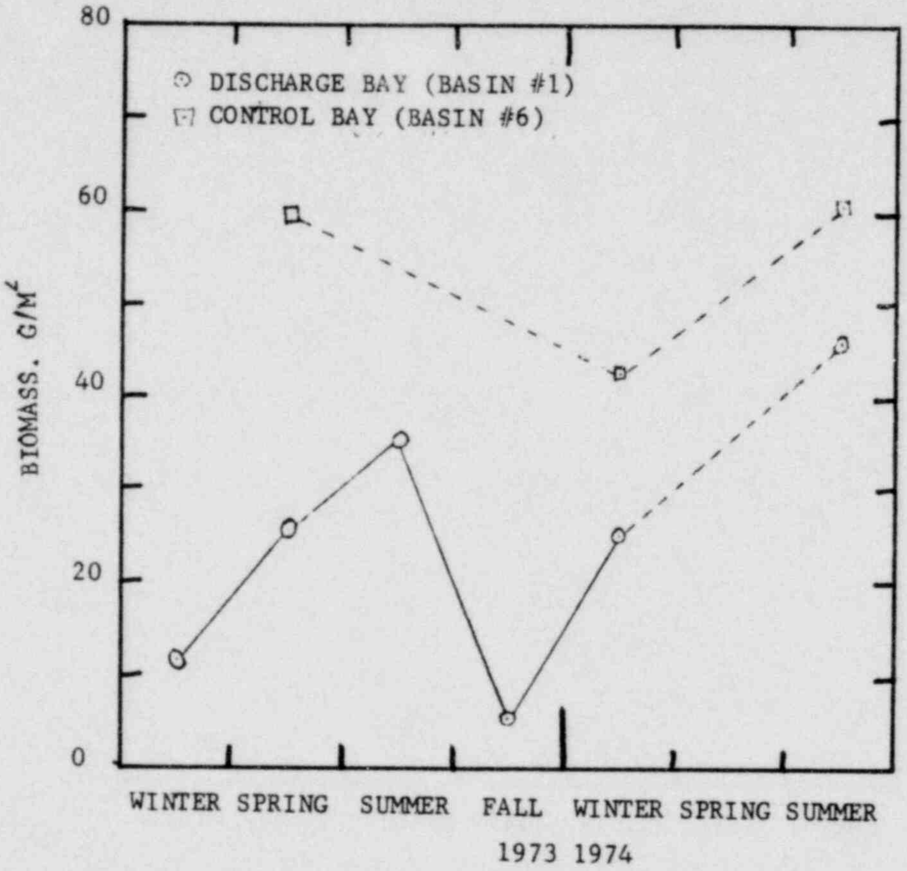


Fig. 15 . Seasonal biomass of benthic macrophytes in discharge bay (basin #1) and south control area (basin #6). Data from Van Tyne, this report.

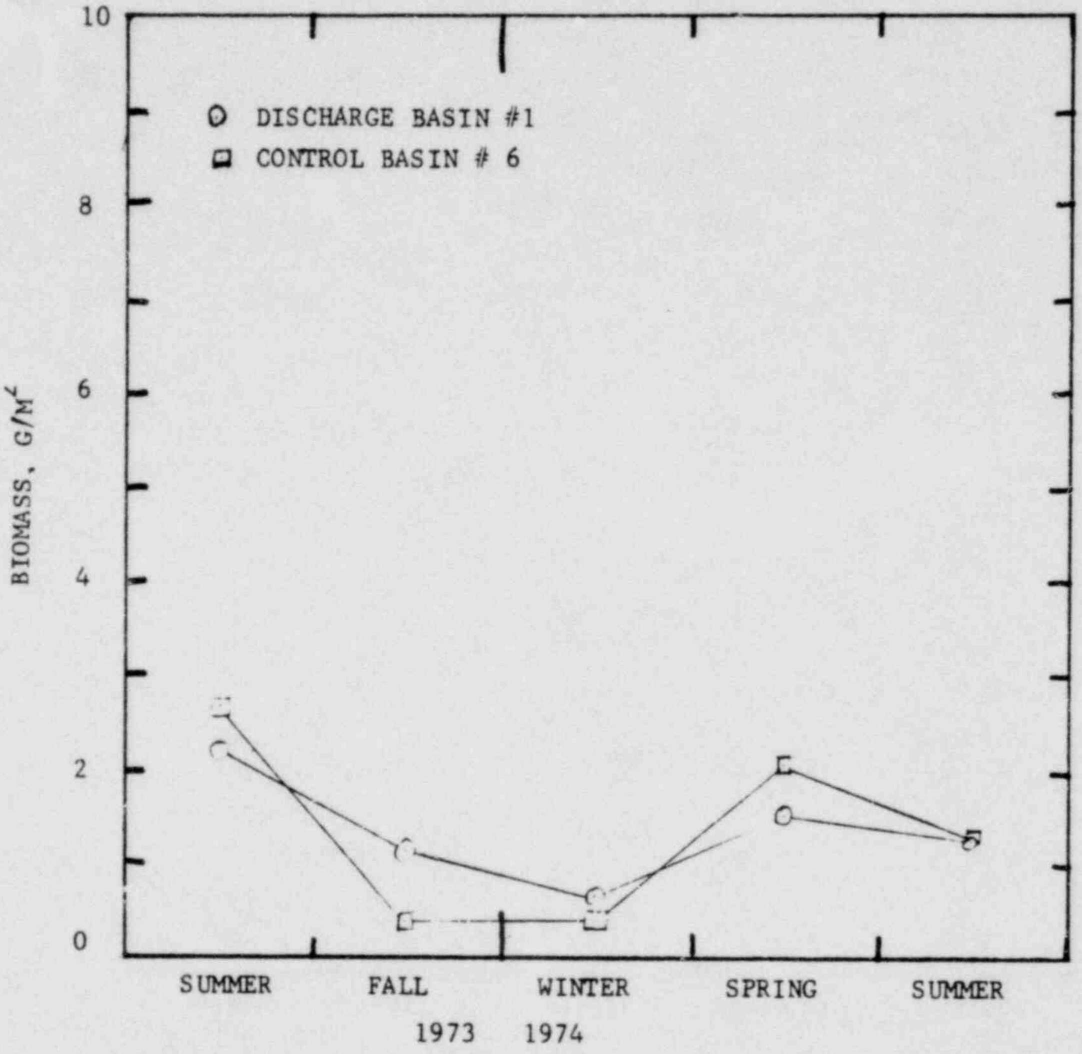


Fig. 16 . Plot by season of dry weight of fishes caught by drop nets in discharge bay basin #1 and control bay #6. Data is preliminary from Adams, this report.

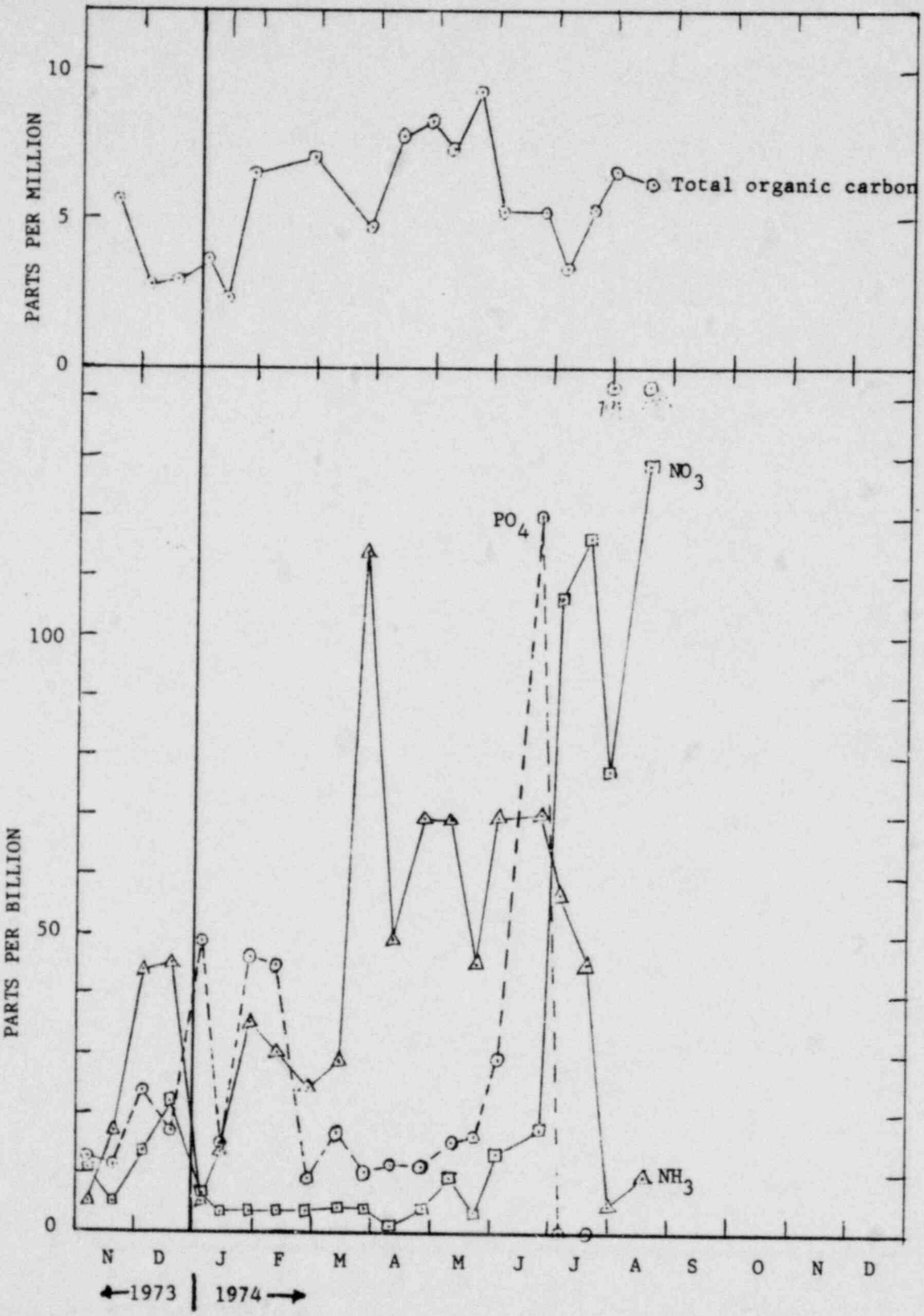


Fig. 17. Measurements of nitrate, phosphate, ammonia, and total organic carbon at the mouth of the discharge canal (station F). Data from Gibson, this report.

Total Metabolism Measurements

All total metabolism measurements obtained by the free water diurnal methods and water column metabolism as measured by light-dark bottles are given in Tables 6 and 7 for the discharge bay and unaffected bays. The total metabolism measurements are plotted graphically by date in Fig. 18 and 19, and all data for the three years have been combined and plotted on one 12 month graph in Fig. 20 and 21 .

Daytime Net Photosynthesis

Seasonal averages of daytime net photosynthesis are shown in Fig. 21 for the discharge and control bays indicating a seasonal trend in both areas. In the discharge bay highest net production occurred in the spring, was somewhat lower in summer, and lowest in the fall. However, the seasonal differences were not significant at the 95% level. In the control bays the highest value also occurred in the spring, with lower values in the summer and fall, and lowest in winter. T-tests ($\alpha = 0.05$) showed that winter was significantly different from the other seasons, spring was different from summer but not from fall, while summer and fall were not different.

Comparing the two areas showed that spring, summer, and fall values of net production in the control bays were generally 1.5 to 2.5 times those in the discharge area with almost identical values in the winter. Spring and fall values were significantly different between areas while winter and summer values were not.

Nighttime Respiration

Fig. 22 gives night respiration by season for the control and discharge areas. A marked seasonal pattern was evident in the control area. The

Table 6 .

Record of Metabolism by Diurnal Free Water Metabolism and Bottle Measurements in Plume Affected Inner Bay Area (Basin 1)

Date	Method *	Daytime Net Photosynthesis ($gmO_2/m^2 \cdot da$)	Night Respiration ($gmO_2/m^2 \cdot da$)	P + R ($gmO_2/m^2 \cdot da$)	Change in Light Bottles (mg/1)	Change in Dark Bottles (mg/1)	Gross Production (gmO_2/m^3)	Insolation ($Kcal/m^2 \cdot da$)
<u>Winter</u>:								
Dec. 14-15, 1972	D	2.42	2.53	4.95				
Jan. 22-23, 1973	D	0.90	1.11	2.01				
Jan. 31- Feb. 1, 1973	D	1.24	3.60	4.84				
	Mean	1.52	2.41	3.93				
	Std. Dev.	0.80	1.25	1.67				
<u>Spring</u>:								
May 10-11, 1973	DDD	4.83	4.28	9.11				
May 11-12, 1973	DDD	2.88	3.29	6.17				
May 24-25, 1973	DDD	2.57	1.12	3.69				6500
May 25-26, 1974	DDD	1.68	0.70	2.38				6409
May 26-27, 1974	DDD	2.28	1.79	4.07	+1.15	-0.39	1.54	5834
June 14-15, 1972	D	1.33	1.71	3.04				
June 29-30, 1972	D	2.27	2.17	4.44				
June 17-18, 1973	D	3.24	2.40	5.64				
June 18-19, 1973	DDD	2.14	0.89	3.03				
June 19-20, 1973	DDD	0.00	1.31	1.31				
June 20-21, 1973	DDD	2.39	1.90	4.29	+2.47	-2.18	4.65	
June 21-22, 1973	D	1.72	2.50	4.22				
June 22-23, 1973	DDD	0.96	1.19	2.15				
	Mean	2.18	[illegible]4	4.12	1.81	1.29	3.10	
	Std. Dev.	1.17	[illegible]1	2.02	0.93	1.27	2.20	

Table 6 (cont'd)

Date	Method*	Daytime Net Photosynthesis ($gmO_2/m^2 \cdot da$)	Night Respiration ($gmO_2/m^2 \cdot da$)	P + R ($gmO_2/m^2 \cdot da$)	Change in Light Bottles (mg/1)	Change in Dark Bottles (mg/1)	Gross Production (gmO_2/m^3)	Insolation ($Kcal/m^2 \cdot da$)
Summer:								
July 7-8, 1972	D	3.15	2.29	5.44				
July 26-27, 1973	DDD	3.51	2.64	6.15	+0.71	-0.30	1.01	6115
Aug. 2-3, 1972	D	5.96	4.16	10.12				
Aug. 2-3, 1973	DDD	0.92	1.25	2.17	+0.51	-0.06	0.57	2889
Aug. 22-23, 1973	D	1.14	1.96	3.10				
Aug. 23-24, 1973	DDD	1.16	1.27	2.43	+0.86	-0.36	1.22	
Aug. 24-25, 1973	DDD	1.43	1.48	2.91				
Aug. 25-26, 1973	DDD	0.10	2.27	2.37				
Aug. 26-27, 1973	DDD	0.56	1.78	2.84				
Aug. 27-28, 1973	DDD	1.09	2.57	3.66				
	Mean	1.90	2.17	4.12	0.69	0.24	0.93	
	Std. Dev.	1.78	0.86	2.49	0.18	0.16	0.33	
Fall:								
Oct. 29-30, 1973	DDD	1.12	1.60	2.72	+0.54	-0.22	0.76	
Oct. 30-31, 1973	D	1.60	2.77	4.37	+0.47	-0.23	0.70	
Oct. 31- Nov. 1, 1973					+0.68	-0.19	0.87	3850
Nov. 1-2, 1973	DDD	1.27	2.21	3.48	+0.55	-0.36	0.91	4490
	Mean	1.33	2.19	3.52	0.56	0.25	0.81	
	Std. Dev.	0.25	0.59	0.84	0.09	0.08	0.10	

* DDD - Dawn-dusk-dawn method
D - Full diurnal curve method

Table 7

Record of Metabolism by Free Water Diurnal Metabolism and Bottle Measurements in Fort Island Area Away from Plume.

Date	Method^2	Daytime Net Photosynthesis ($gmO_2/m^2 \cdot da$)	Night Respiration ($gmO_2/m^2 \cdot da$)	P + R ($gmO_2/m^2 \cdot da$)	Change in Light Bottles (mg/l)	Change in Dark Bottles (mg/l)	Gross Production (gmO_2/m^3)	Insolation ($Kcal/m^2 \cdot da$)
Winter:								
Feb. 13-14, 1973	D	2.03	1.25	3.28				
Feb. 22-23, 1973*	D	1.48	1.68	3.16				
	Mean	1.76	1.47	3.23				
	Std. Dev.	0.39	0.30	0.69				
Spring:								
May 25-26, 1974	DDD	5.36	4.47	9.83	+1.81	-0.54	2.35	6409
May 26-27, 1974	DDD	4.72	4.29	9.01	+1.67	-0.60	2.27	5834
June 25-26, 1974	DDD	1.93	3.05	4.98	-2.11	-3.48	1.37	3037
June 26-27, 1973	DDD	5.09	5.37	10.46	+0.70	-0.46	1.16	6543
June 26-27, 1973	D^1	6.20	5.67	11.87				6343
June 27-28, 1973	DDD	5.17	5.75	10.92				6144
June 28-29, 1973	DDD	5.63	4.96	10.59	+0.58	-0.22	0.80	6648
	Mean	4.87	4.79	9.66	0.53	1.27	1.57	
	Std. Dev.	1.38	0.95	2.25	1.58	1.47	0.69	

Table 7 (cont'd)

Date	Method[2]	Daytime Net Photosynthesis ($gmO_2/m^2 \cdot da$)	Night Respiration ($gmO_2/m^2 \cdot da$)	P + R ($gmO_2/m^2 \cdot da$)	Change in Light Bottles (mg/l)	Change in Dark Bottles (mg/l)	Gross Production (gmO_2/m^3)	Insolation ($Kcal/m^2 \cdot da$
Summer:								
Aug. 02-03, 1972	D	4.18	5.94	10.12				
Aug. 16-17, 1972	D	3.54	5.69	9.23				
Aug. 10-11, 1972*	D	2.60	3.40	6.00				
Aug. 24-25, 1973	D	3.95	6.22	10.17				
Aug. 26-27, 1973	DDD	1.55	6.87	8.42				
Aug. 27-28, 1973	DDD	3.77	7.33	11.10				
	Mean	3.27	5.91	9.18				
	Std. Dev.	1.00	1.37	1.80				
Fall:								
Nov. 12-13, 1973	DDD	2.14	3.41	5.55	+0.10	-0.17	0.27	3100
Nov. 13-14, 1973	DDD	3.97	4.35	8.32	+0.17	-0.12	0.29	4140
Nov. 14-15, 1973	DDD	4.30	4.15	8.45	+0.13	-0.12	0.25	4280
Nov. 15-16, 1973	DDD	3.36	5.09	8.45	+0.21	-0.06	0.27	
	Mean	3.44	4.25	7.69	0.15	0.12	0.27	
	Std. Dev.	0.95	0.69	1.64	0.05	0.05	0.10	

* Hodges Island

1 Single Station

2 DDD - dawn-dusk-dawn method

D - full diurnal curve method

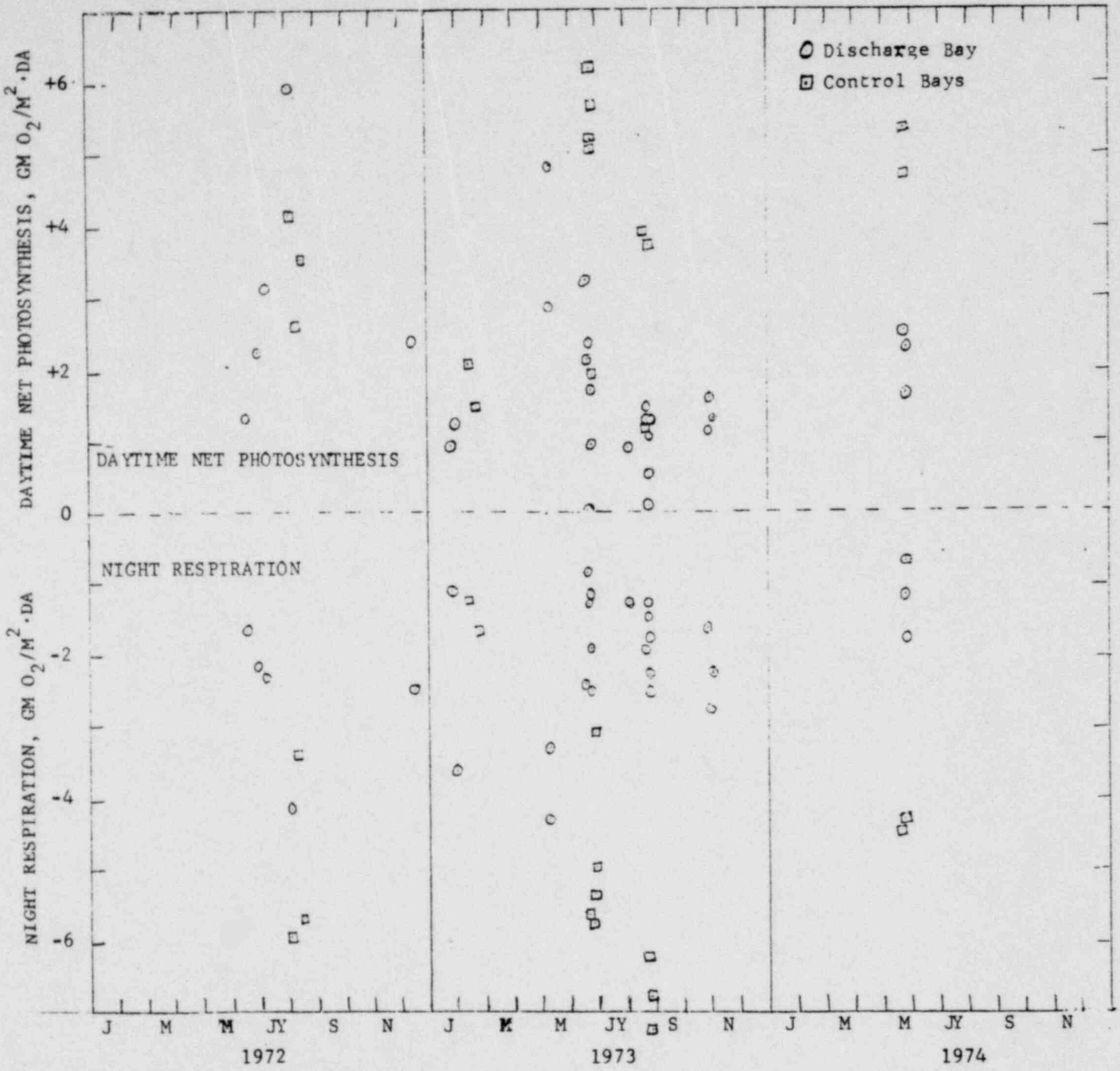


Fig. 18 Three year plot by sample date of daytime net photosynthesis and night respiration in the discharge and control areas.

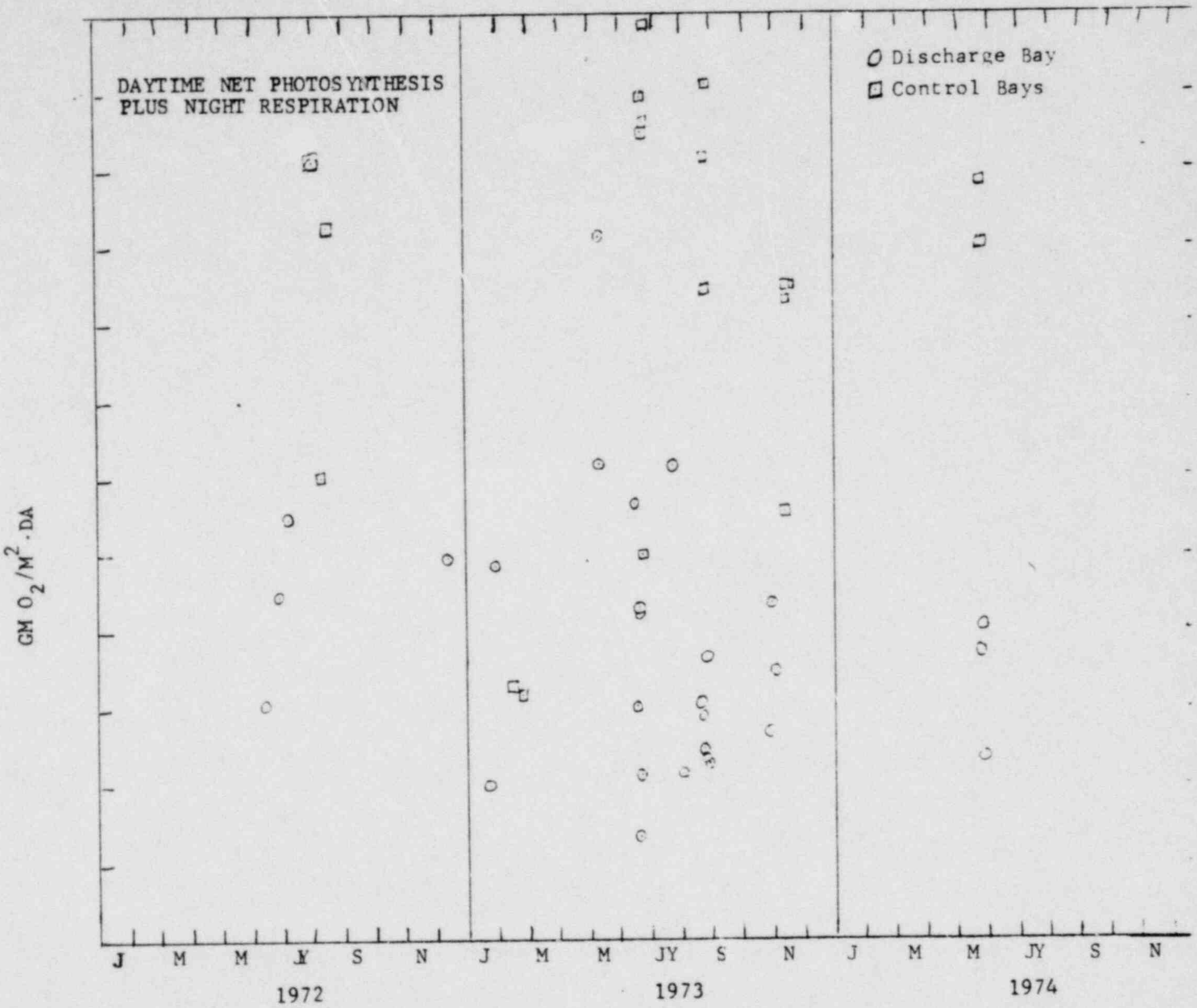


Fig. 19 Three year plot by sample date of daytime net photosynthesis plus night respiration (P + R) in the discharge and control areas.

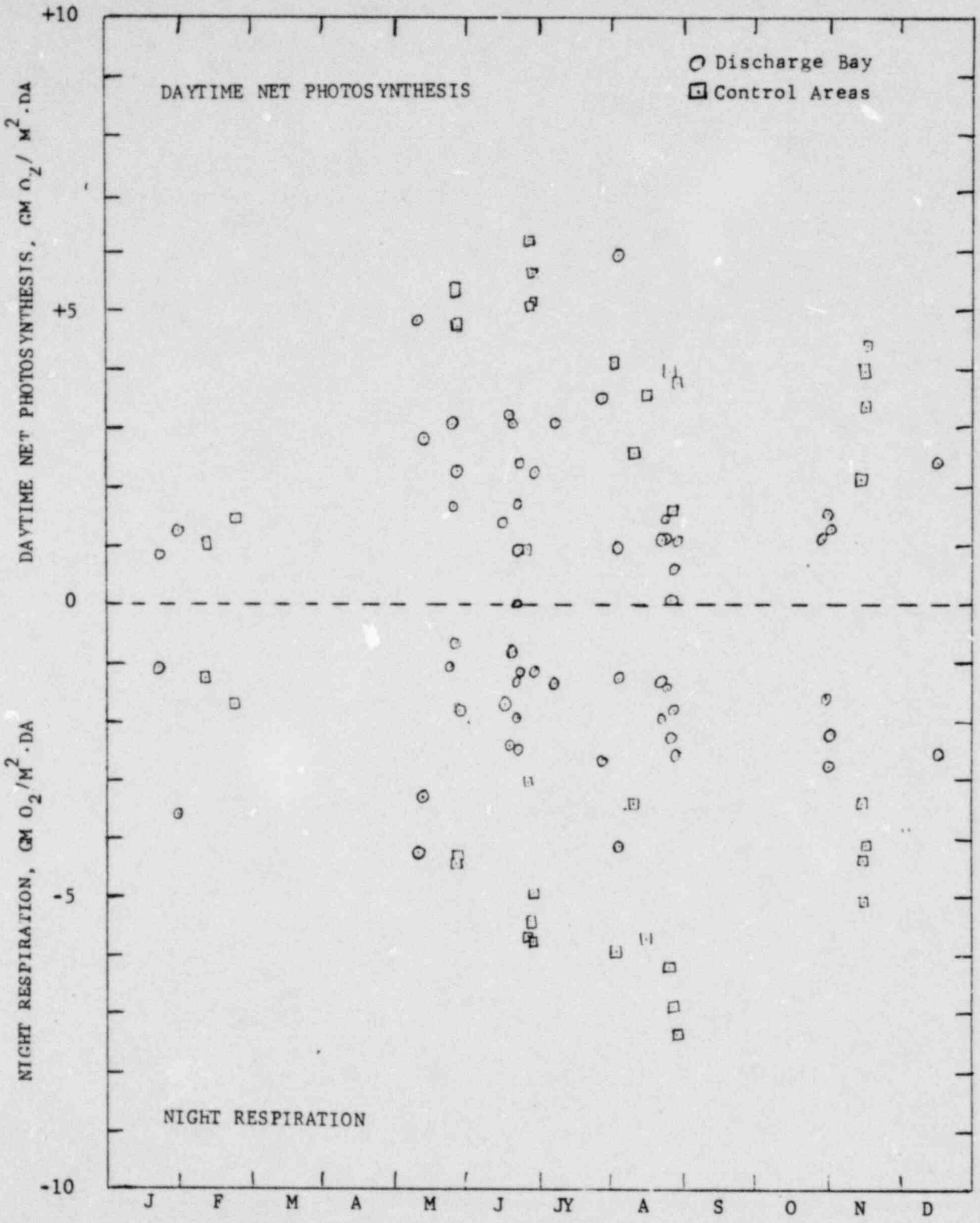


Fig. 20. All daytime net photosynthesis and night respiration values from Tables 6 and 7 and Fig. 18 plotted on 12 month graph.

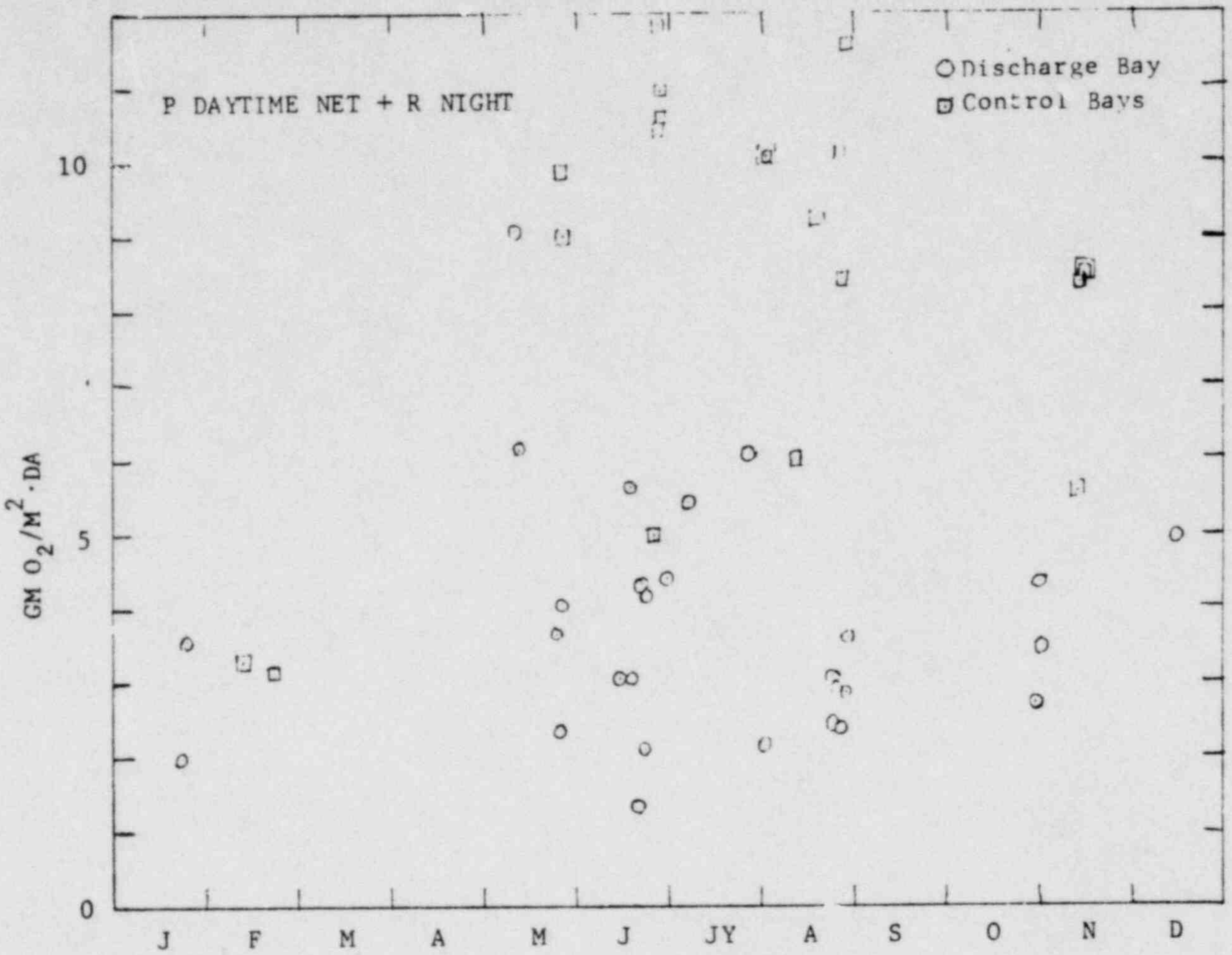


Fig. 21. All daytime net photosynthesis plus night respiration values from Table 6 and 7 and Fig. 19 plotted on 12 month graph

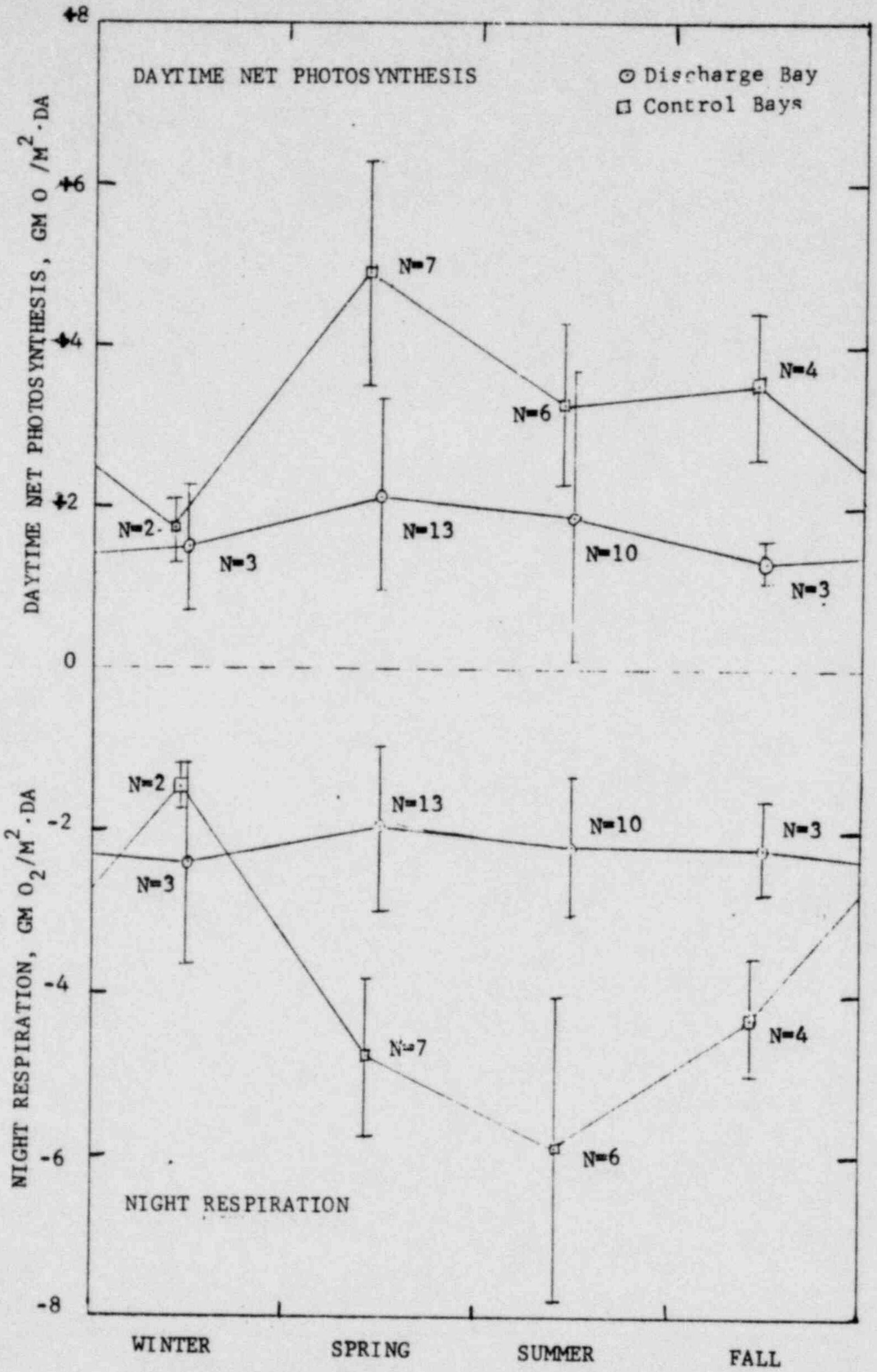


Fig. 22. Seasonal averages of daytime net photosynthesis and night respiration in basin #1 and control bays. Bars about points represent plus and minus one standard deviation. Spring is defined as May and June measurements, summer as July and August values.

lowest value (1.47 $gO_2/m^2 \cdot day$) occurred in winter, increased to 4.79 $gO_2/m^2 \cdot day$) in spring, reached its highest value (5.91 $gO_2m^2 \cdot day$) in summer, and declined again in the fall to 4.25 $gO_2/m^2 \cdot day$. T-tests (95% level) showed that spring, summer, and fall were not significantly different from each other while all were significantly different from winter.

In the discharge area night respiration values stayed almost constant, varying between only 1.94 $gO_2/m^2 \cdot day$ and 2.41 $gO_2/m^2 \cdot day$ over the four seasons. T-tests showed no significant difference between any seasons.

Comparing the two areas in winter showed the controls to be lower than the discharge bay but not significantly different (95% level). During spring, summer, and fall night respiration in the central bays was larger and significantly different from the discharge bay.

Daytime Net Photosynthesis Plus Night Respiration

If nighttime respiration was assumed to be the same as daytime respiration, then the sum of daytime net photosynthesis and night respiration was a measure of gross production. Fig.22 gives a plot of daytime net photosynthesis plus night respiration by season for the discharge and control bays. Average P + R in the discharge bay showed virtually no variation with season, remaining about 4 $gO_2/m^2 \cdot day$. There was no statistical difference between seasons (95% level).

The control bays showed a seasonal pattern of average P + R, being lowest in winter (3.23 $gO_2/m^2 \cdot day$), highest in spring (9.66 $gO_2/m^2 \cdot day$) and declining some in summer and fall. There was no significant difference (95% level) between spring, summer, and fall values, but they were all significantly different from the winter value.

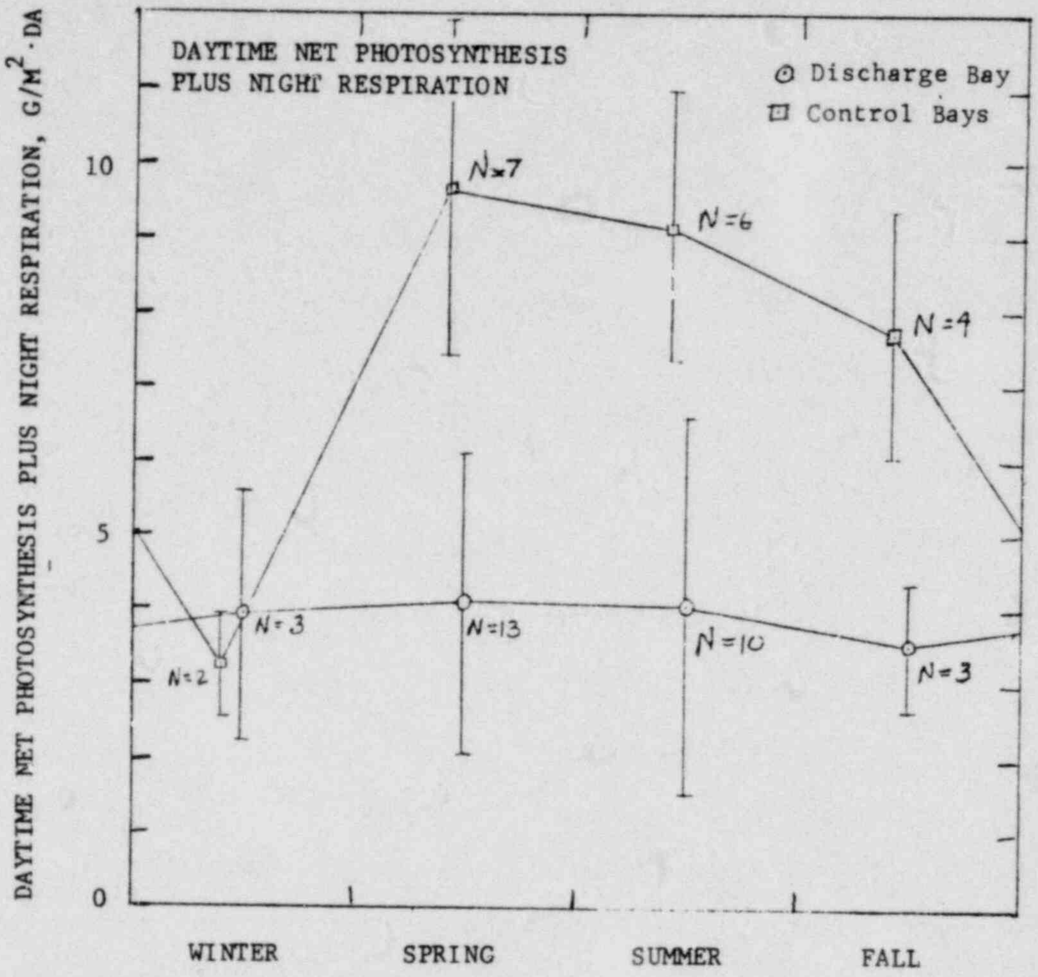


Fig. 23 . Seasonal averages of daytime net photosynthesis plus night respiration (P + R) in plume affected basin #1 and unaffected control bays. Bars about points represent plus and minus one standard deviation.

Average winter P + R in the control area was slightly lower than that of the discharge bay but the difference was not significant at the 95% level. Control area values were larger during spring, summer, and fall than those obtained in the discharge are, the difference being significant at the 95% level.

P/R Ratio

P/R ratios calculated two different ways are given in Fig. 24a and 24b. The first ratio (Fig. 24a) would indicate if the net gain of photosynthetic product manufactured during the day was sufficient to satisfy nighttime respiration requirements. Fig. 24b involved the assumption that daytime respiration was similar to that measured during the night. It measured whether total photosynthetic product produced was sufficient to satisfy total respiratory requirements. The patterns exhibited were similar in both calculations. In the discharge bay the P/R ratio was less than one during winter, summer, and fall, increasing to greater than one in the spring. The control bays had a ratio greater than one during winter and spring, dipping below one in summer and fall. The ratio was lowest during the summer.

Light and Dark Bottle Measurements

Light and dark bottle measurements of water column metabolism excluding larger organisms are given in Table 6 and 7 for the discharge bay and control bays. Relatively few measurements were made with none available for the winter period in both areas or for the summer period in the control bays. In the discharge bay water column metabolism ranged from $3.10\ gO_2/m^2 \cdot da$ to $0.81\ gO_2/m^2 \cdot da$, being highest in spring based on only two measurements, and considerably lower in summer and fall. In the control

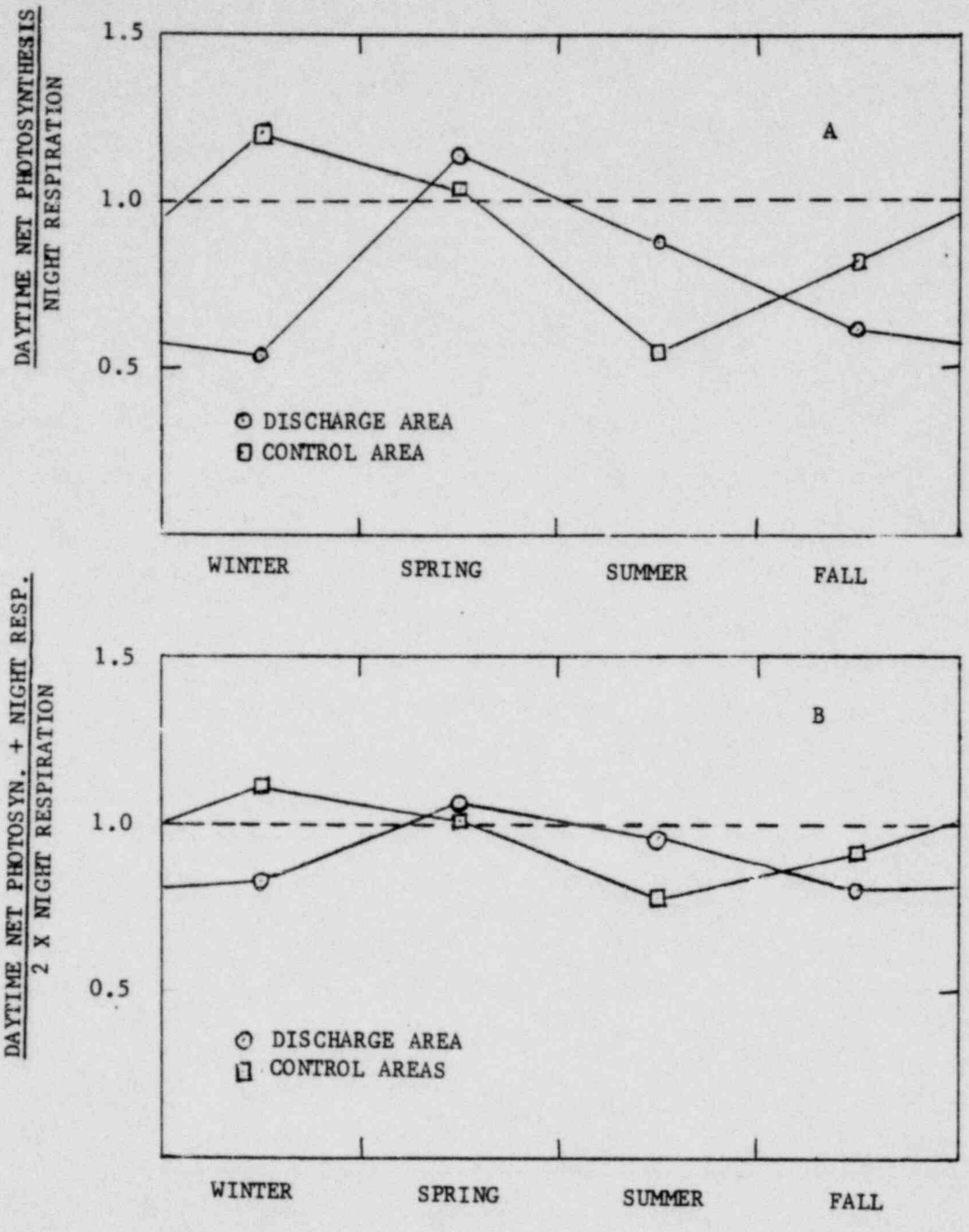


Fig. 24 . Seasonal trends of P/R ratio in plume affected basin #1 and Fort Island control bays. A) ratio of daytime net photosynthesis to night respiration. B) ratio of daytime net photosynthesis plus night respiration to two times night respiration.

areas the average value ranged from 3.14 $gO_2/m^2 \cdot da$ to 0.54 $gO_2/m^2 \cdot da$ and was also highest in spring and lower in the fall.

Plankton production was a larger portion of total production in the discharge area than in the control areas ranging from 75% of total production in the spring to 23% in the summer and fall. In the control area it was 33% in the spring and 7% in the fall.

DISCUSSION

Evaluated Seasonal Models

Energy diagrams have been drawn for the plume affected basin #1 and the Fort Island and basin #6 control areas to compile overall project data in one place and to aid synthesis in the mind's eye for gaining a comprehensive overview of the effect of the thermal discharge on the shallow system of basin #1. These diagrams are presented by season in Fig. 25 a-d and Fig. 26a-d. The numbers are drawn from various tables and graphs in this and other project reports or calculated as indicated. The components were chosen to represent the major stocks and flows being measured.

Total Metabolism Measurements

Comparison with other systems

The range in values of gross production of 3 to 10g $O_2/m^2 \cdot da$ measured in the Crystal River region are very similar to those measured in the many different types of bay systems of the Texas coast (Odum and Hoskins, 1958; Odum and Wilson, 1962), falling within the lower two-thirds of the range of values recorded there (Odum, 1967). Odum (1963) reports seasonal patterns and levels of metabolism for Redfish Bay, Thallassia and Halodule dominated Texas bay which were much like the control areas at Crystal River. Hellier (1962) reported summer values of gross production for the

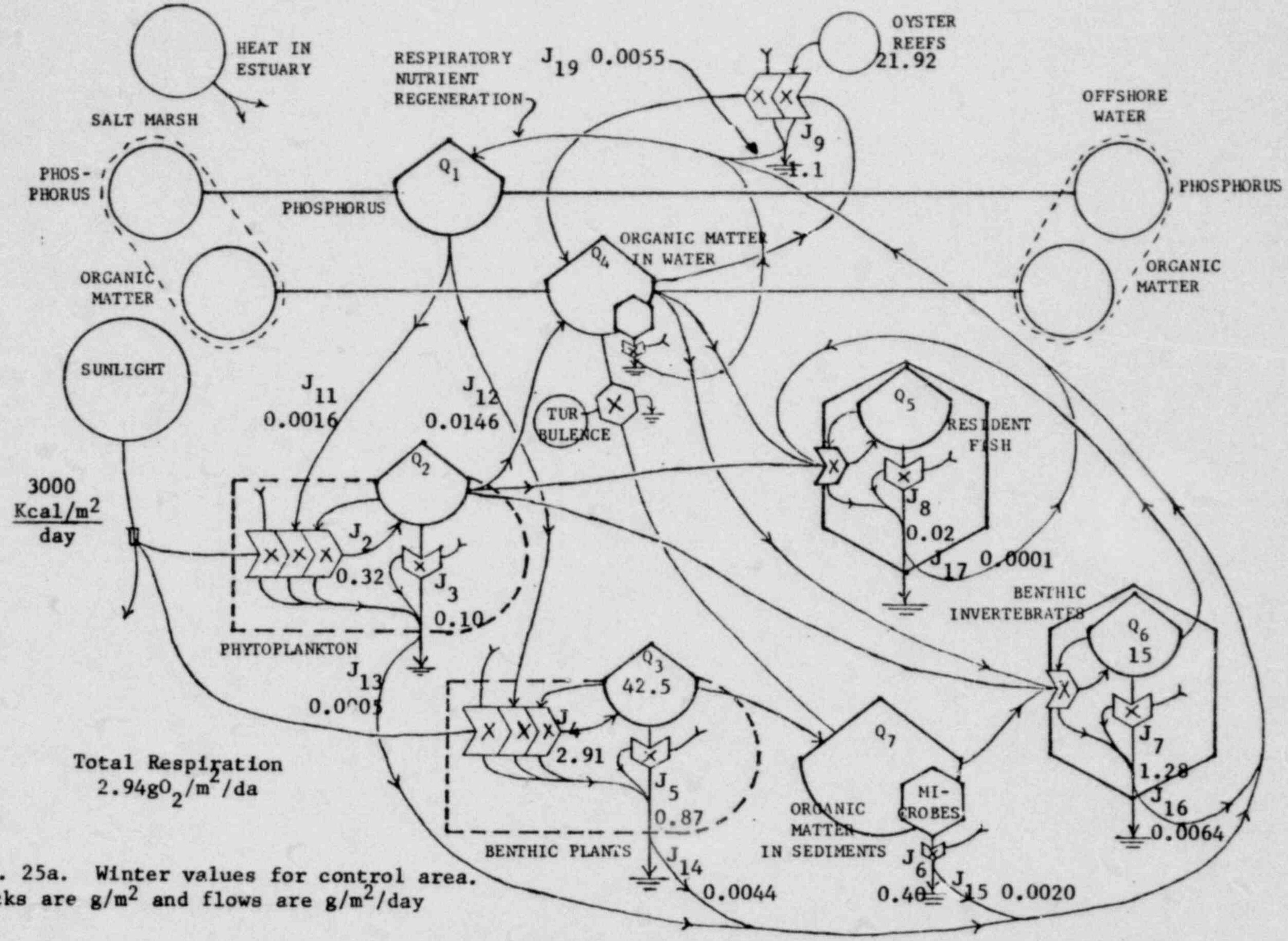


Fig. 25a. Winter values for control area.
Stocks are g/m^2 and flows are g/m^2/day

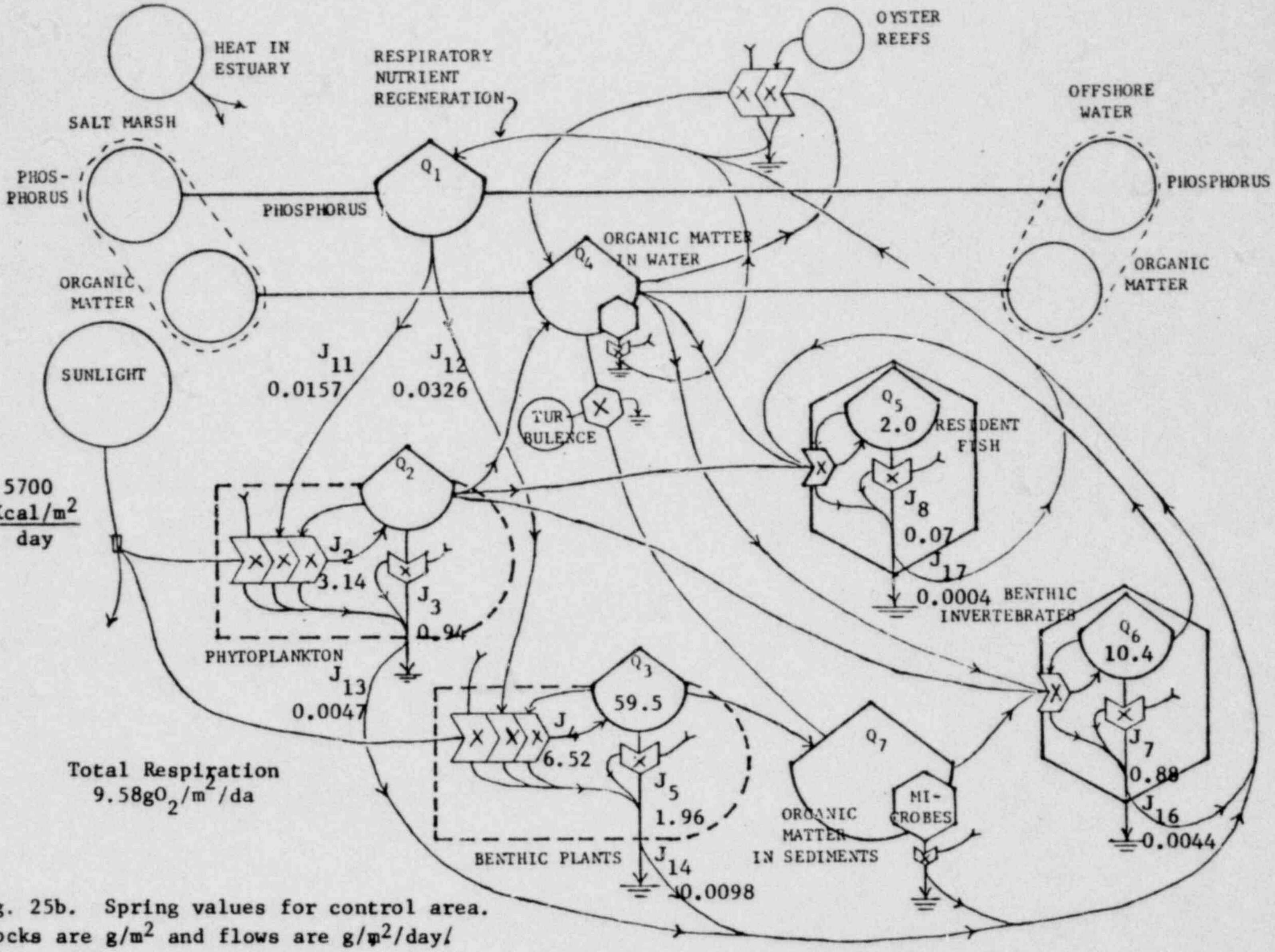


Fig. 25b. Spring values for control area. Stocks are g/m^2 and flows are g/m^2/day/

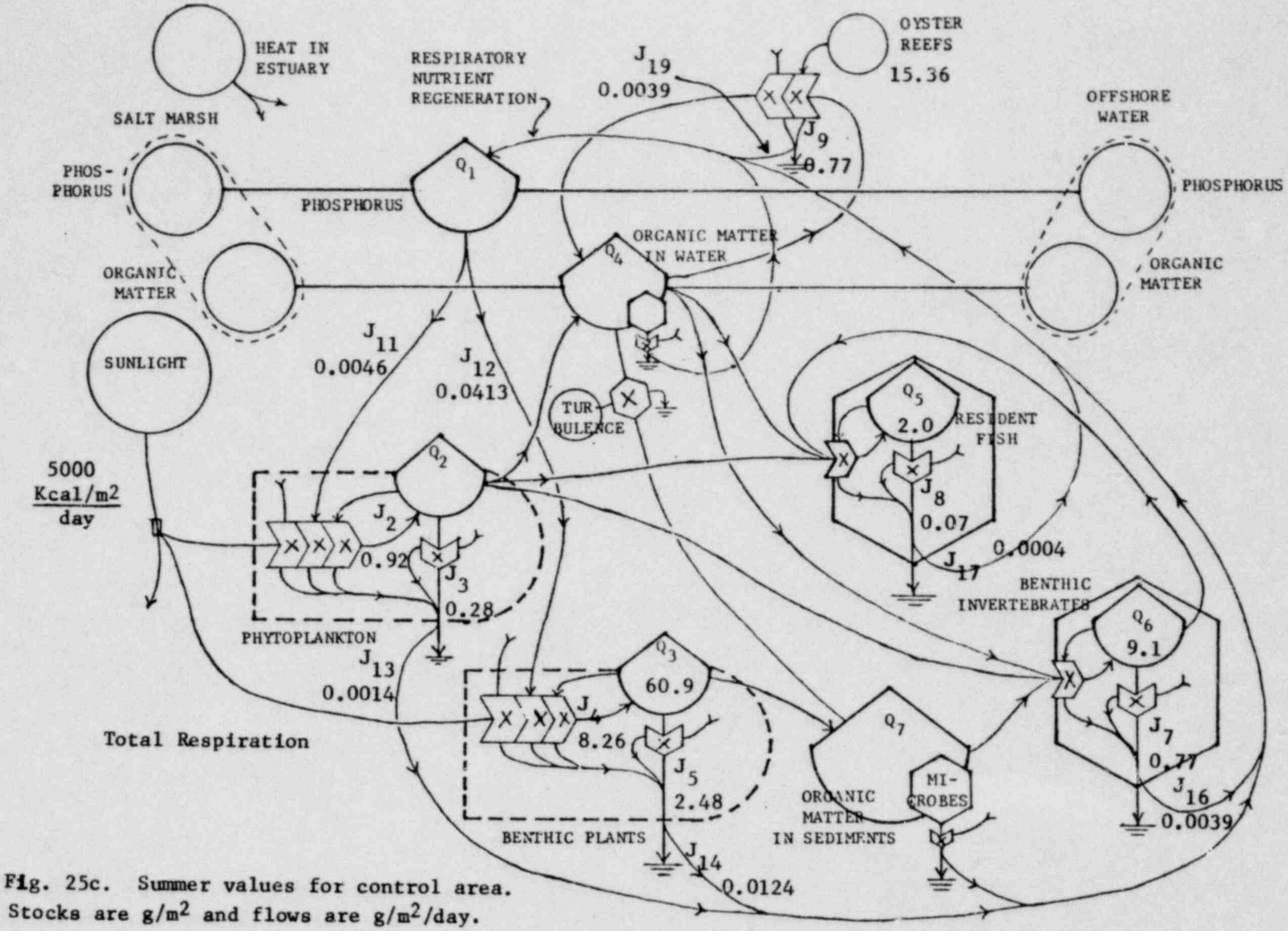


Fig. 25c. Summer values for control area. Stocks are g/m^2 and flows are $g/m^2/day$.

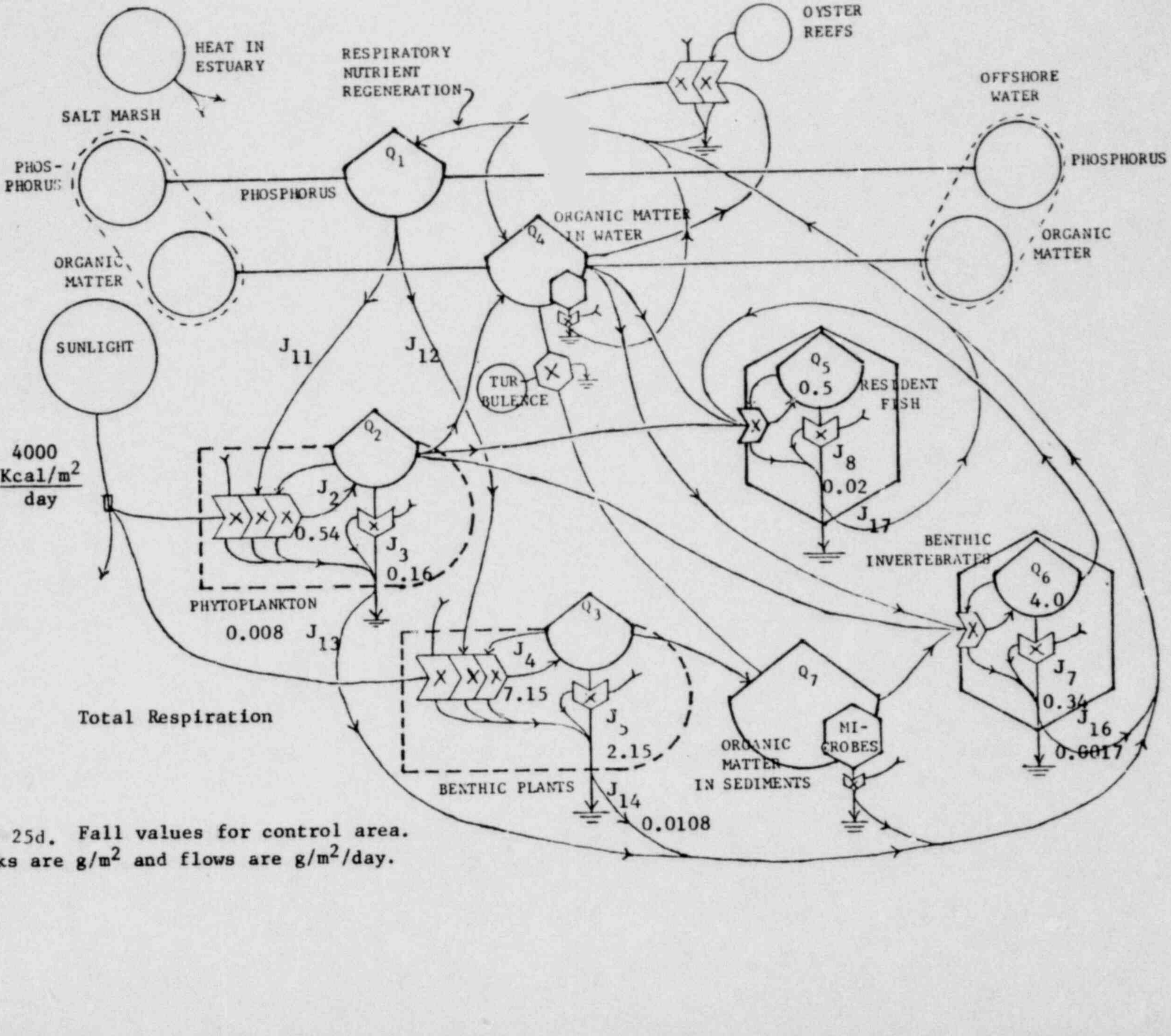
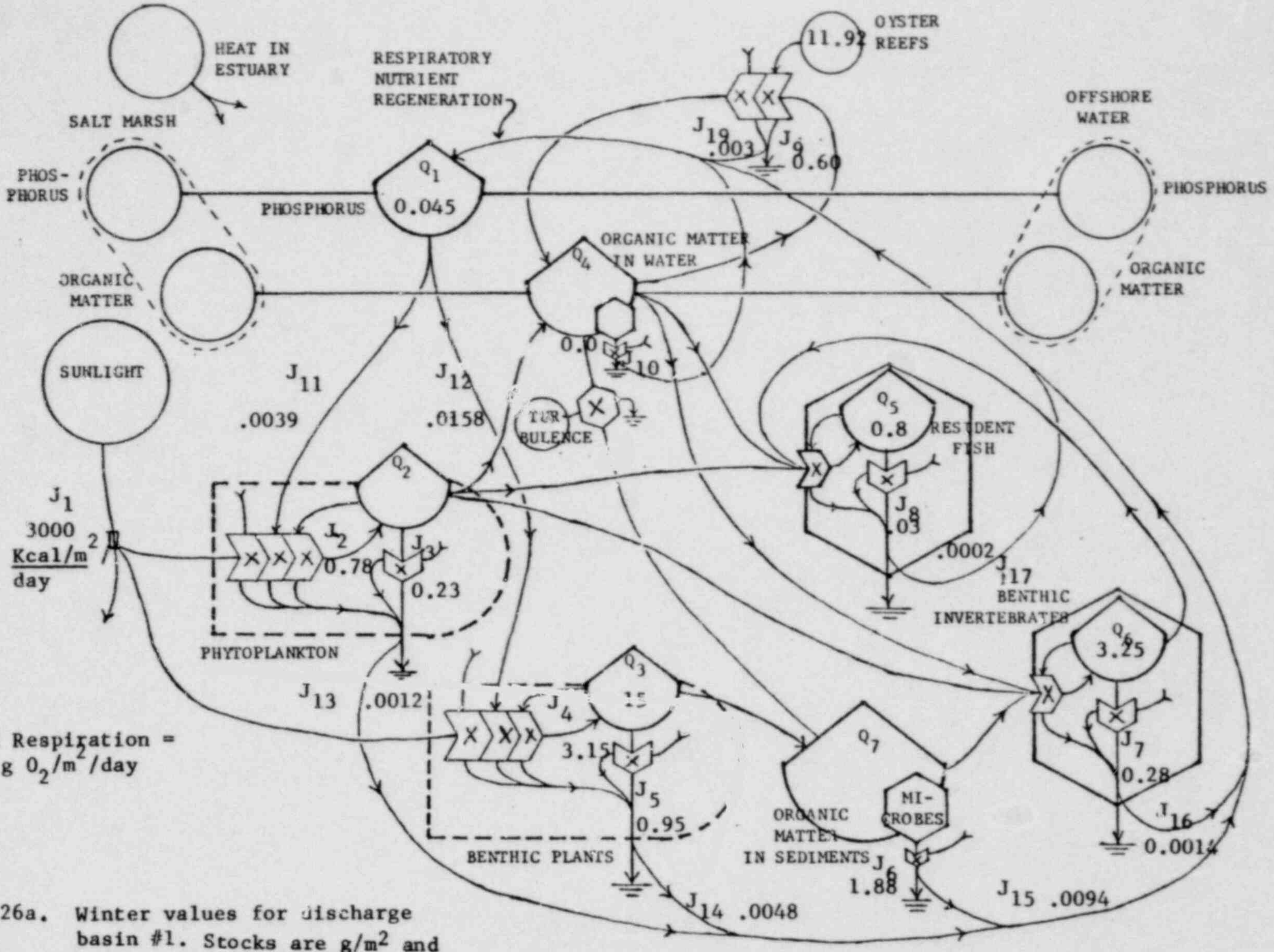
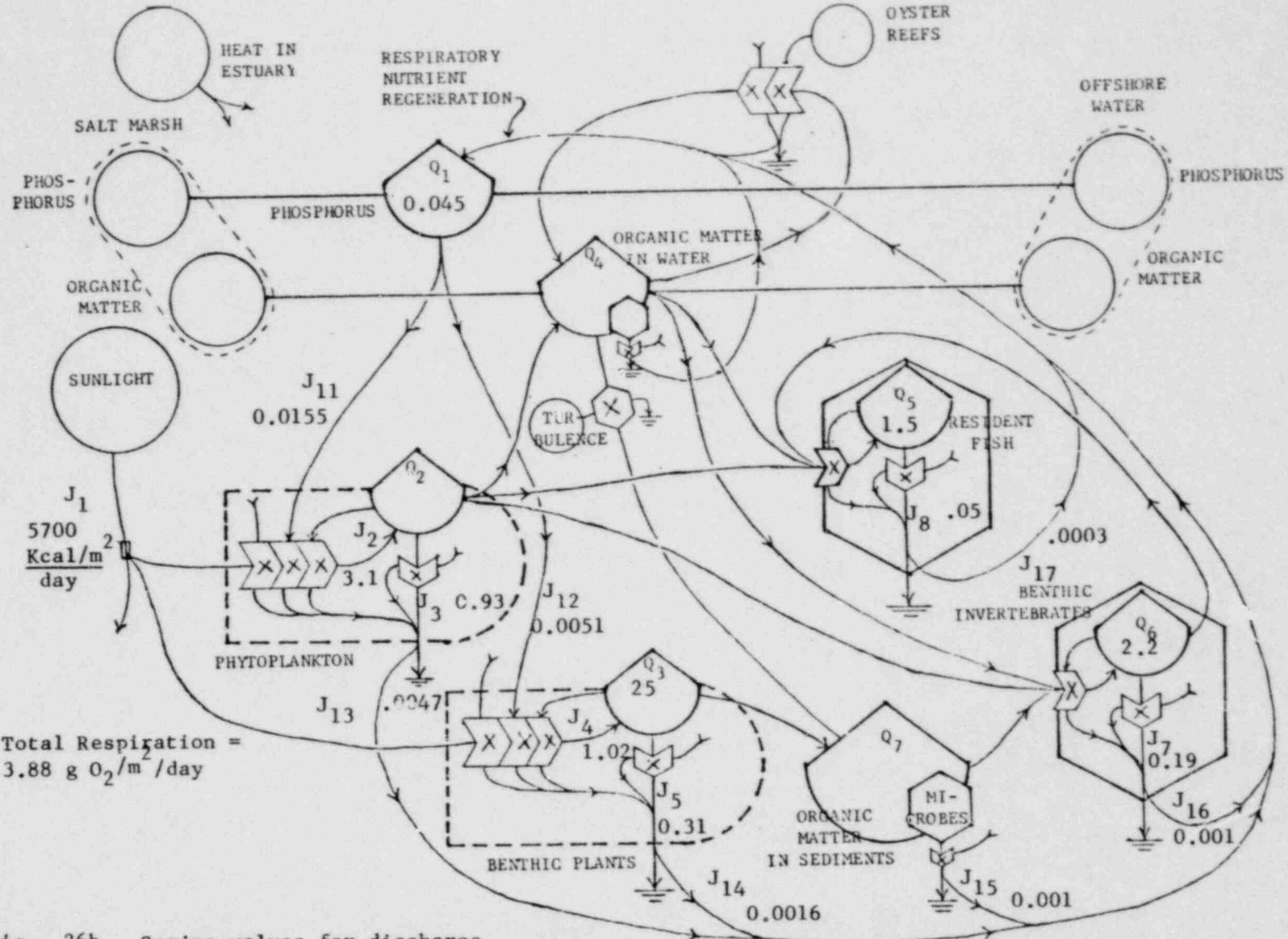


Fig. 25d. Fall values for control area.
Stocks are g/m^2 and flows are g/m^2/day.



Total Respiration = 4.82 g O_2/m^2/day

Fig. 26a. Winter values for discharge basin #1. Stocks are g/m^2 and flows are g/m^2/day



Total Respiration = 3.88 g O_2/m^2/day

Fig. 26b. Spring values for discharge basin #1. Stocks are g/m^2 and flows are g/m^2/day.

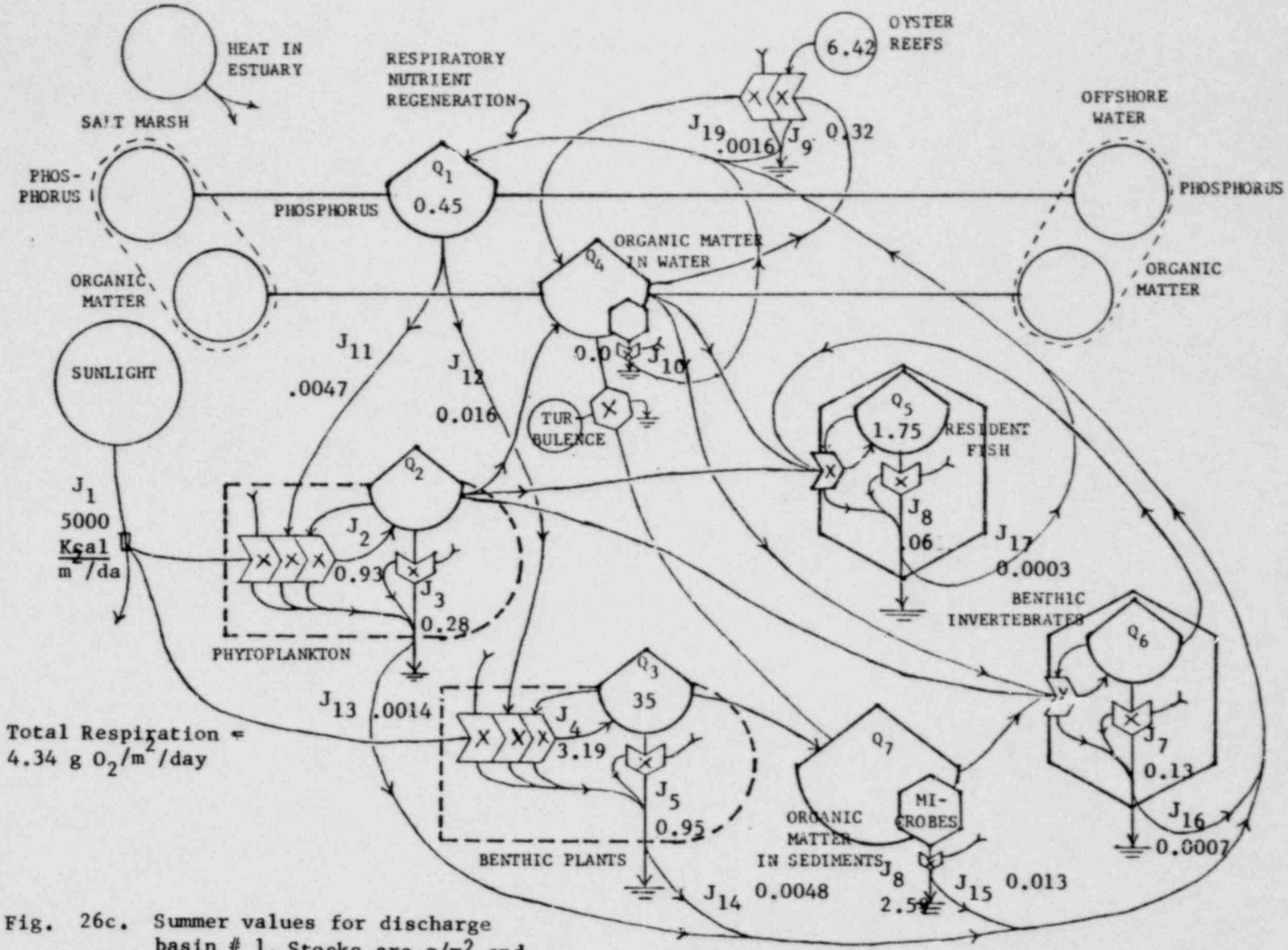


Fig. 26c. Summer values for discharge basin # 1. Stocks are g/m^2 and flows are g/m^2/day.

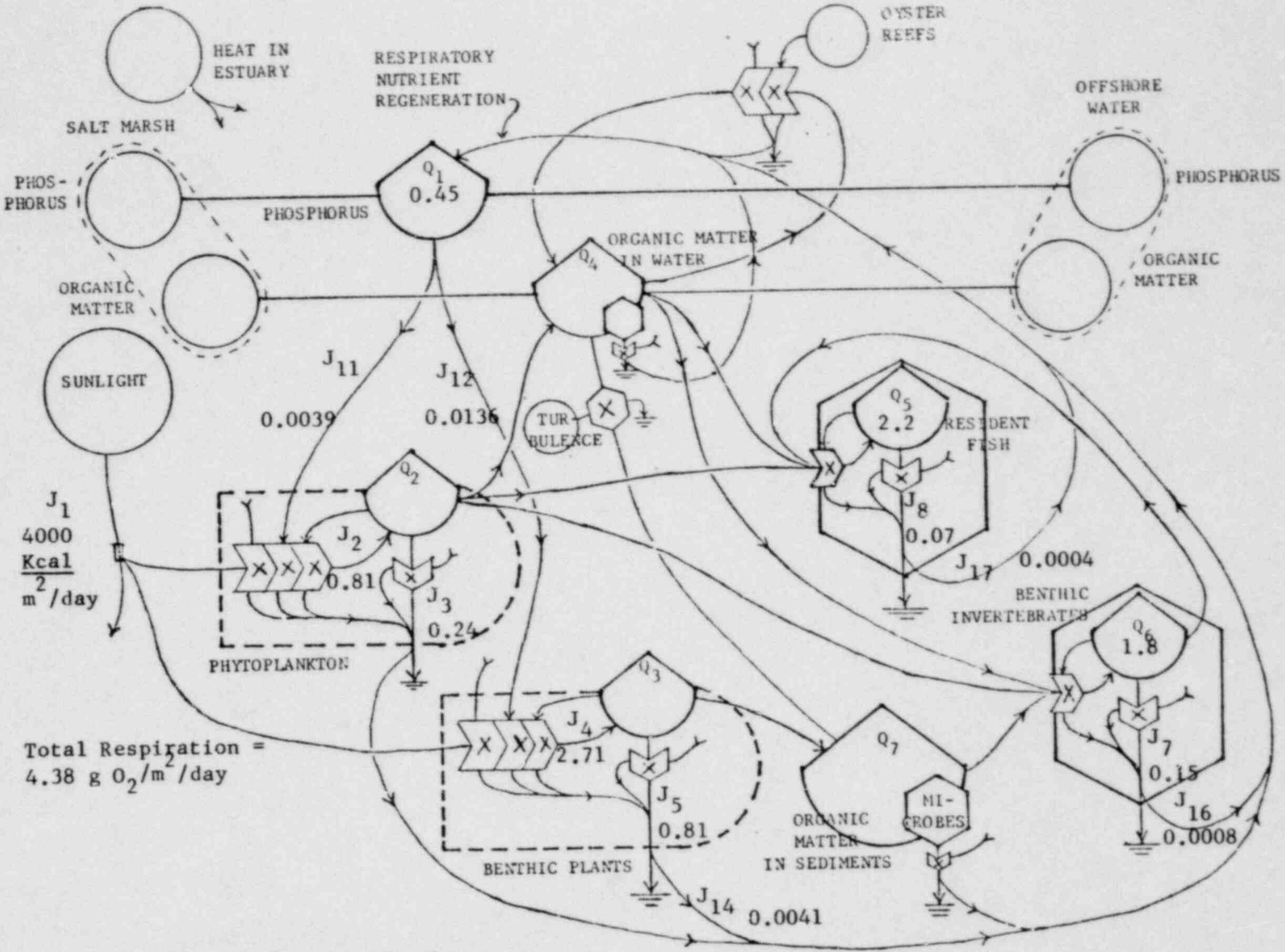


Fig. 26d. Fall values for discharge basin # 1. Stocks are g/m^2 and flows are g/m^2/day.

Table A. Calculations of numbers presented in Fig. 25a-d and 26a-d.

Storage	Description	Calculation	Reference
Q_1	Total phosphorus in bay water		
Q_2	Phytoplankton biomass		
Q_3	Benthic macrophyte biomass		Van Tyne, this report
Q_4	Organics in water column		
Q_5	Resident fish		Adams, this report
Q_6	Benthic invertebrates		Evink, this report
Q_7	Organic matter in sediments		

Table A continued.

Flow	Description	Calculation	Reference
J_1	Average seasonal insolation		
J_2	Gross production of phytoplankton	Seasonal average from Tables 6 or 7 of light and dark bottles. Assumed to be 10% of total gross production if no bottle data available.	
J_3	Phytoplankton respiration	Assumed to be 30% of gross production	
J_4	Benthic macrophyte gross production	Seasonal average total system gross production (P+R) from Table 6 or 7 minus phytoplankton gross production	
J_5	Benthic macrophyte respiration	Assume 30% of gross production	Day, 1973
J_6	Sediment microbe respiration	Remainder after all other respirations including dark bottle were subtracted from seasonal total respiration in Table 6 or 7.	
J_7	Respiration of benthic invertebrates	Assume respiration rate of 0.085 g dry wt. respired/ g dry wt./day.	Day, 1973
J_8	Respiration of resident fish	Assume turnover of 12 times per year.	Day, 1973
J_9	Oyster reef respiration	Assume respiration of 5% dry body wt./day	Day,1973
J_{10}	Respiration of water column microbes	Dark bottle value minus calculated phytoplankton respiration.	
J_{11},J_{12}	Phosphorus taken up in photosynthesis	Assume phosphorus 0.5% of organic matter	
J_{13}-J_{19}	Phosphorus regenerated by respiration	Assume phosphorus 0.5% of organic matter.	

upper Laguna Madre, Texas, a hypersaline Halodule dominated system, which were two to three times Crystal River control data while winter metabolism was similar in the two areas.

Seasonal patterns in control areas at Crystal River

Seasonal trends of metabolism in the Crystal River coastal region as indicated by data from the control bay measurements (Fig. 21 and 22), show low photosynthesis in winter, a pulse of net productivity in spring corresponding to the yearly peak of sunlight in April and May (see Fig. 7), and lower values in summer and fall with reduced insolation due to afternoon convective clouds and storms. Respiration was also low in winter, increased greatly in spring along with net photosynthesis, peaked in summer, and declined again in fall possibly being influenced by the temperature regime, which peaks in August. High respiration in summer possibly reduced net productivity. Light-dark bottle measurements (Table 7) in the control areas, although incomplete, tend to reinforce this pattern of a pulse of spring productivity. When daytime net photosynthesis and night respiration were added together as a measure of gross production of organic matter (Fig. 22) the spring pulse of net gain was not as sharp, as productivity remained high through both spring and summer.

A P/R ratio (Fig. 23) greater than one in winter indicated a net gain in organic matter during this season, but it probably was small because of the level of metabolism. Although net photosynthesis reached its seasonal high in spring, the P/R ratio was only slightly greater than one since total respiration had also increased indicating a close coupling of organic matter production and total respiratory demand during this "spring dinner" period. The dominance of respiration over production during summer and fall may result from increased sediment microbial respiration of accumulated organic material from winter and spring during the period of highest seasonal temperature.

Seasonal patterns in the thermally affected basin #1

Patterns of metabolism in the thermally affected basin #1 were remarkably constant compared to the unaffected area.(Fig. 21 and 22). An increase in net photosynthesis is evident in the spring although the difference was not statistically significant at the 95% level. Respiration tended to be highest in the winter possibly attributable to stimulation from the higher temperatures. The seasonal differences, however, were not statistically significant.

Since metabolism values were similar in winter in the two areas (Fig. 21 and 22), and assuming worst case conditions, lower values in spring, summer, and fall could be possibly attributed to a depressing effect of the power plant heat loading during these seasons.

P/R ratios (Fig. 23) were less than one in all seasons except spring indicating utilization of an external source of organic matter such as detritus exported from the surrounding salt marshes and organisms killed by the power plant and flushed in by advection of the discharge plume. The ratio rose above one in spring indicating a spring pulse of productivity as occurred in the control areas.

Seasonal Model of the Shallow Inshore Benthic Dominated Ecosystem

Fig. 27 diagrams a model of the inshore system of basin #1 and #6 used for an analog computer simulation reported in a previous report (December 1973) using more preliminary data than now available. The model has been aggregated so that all fish have been lumped into one compartment, phytoplankton have been eliminated, and the relationship of microbes to the detrital organic matter compartment has been simplified. Table 8 gives the calculations and sources of the values of the flows and storages listed on themodel diagram. The simulation was done on an EAI 680 analog computer.

The model consists of five biological storages internal to the model (benthic plants, total phosphorus, organic matter, benthic invertbrates, and fish) and one external component (oyster reefs). With the exception of organic matter these components were chosen because they are the ones being measured at Crystal River as part of the overall project. The dynamics of oyster reefs were not included because of the more detailed model being done by M. Lehman (see his section in this report). However, their role in filtering food, contributing to the detrital pool, and regenerating nutrients are included. Zooplankton have been considered part of the benthic invertebrate compartment because no separate data were available for the inner bay area. Phytoplankton have been excluded from the model because measurements have shown them usually to contribute 20% or less of the total metabolism.

Of the total driving force of sumlight energy falling on the estuary (J_o) some is absorbed by the primary producers (J_1) and fixed into organic matter (J_2) at a rate which is a function of the level of sunlight energy, the stock of nutrient (phosphorus) available, the temperature driving the reactions, and the quantity of plant structure for capturing the available insolation.

Fig. 27
Benthic Dominated
Inner Bay System
of Basin #1

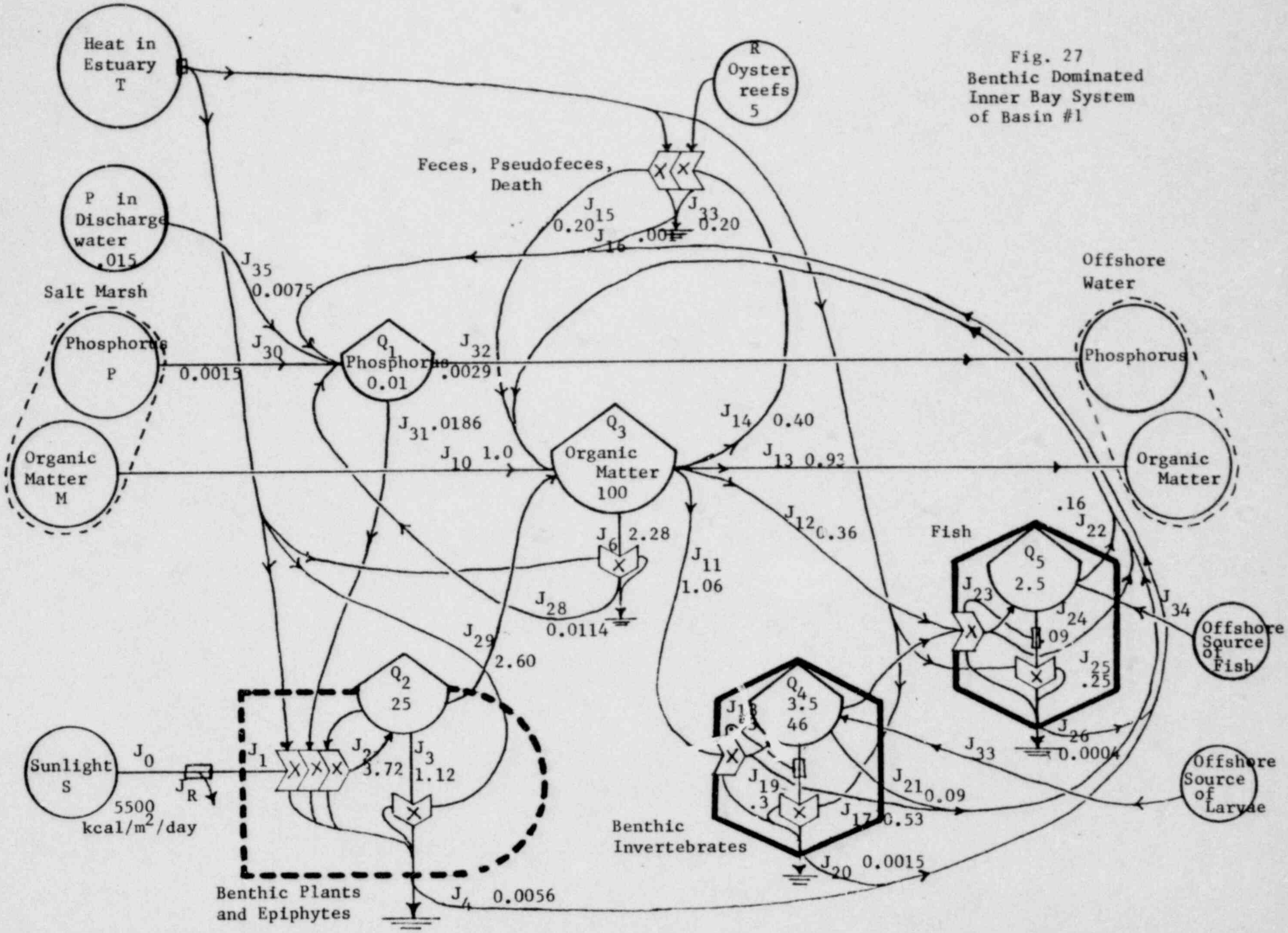


Table 8 Description, calculations, and source of values of stocks and flows used for simulation of Inner Bay system.

Storage	Description	Calculation	Reference
Q_1	Total phosphorus in bay water	Measured at Crystal River site	Smith, 1973
Q_2	Benthic macrophyte biomass	Measured at Crystal River site	Snedaker, 1973
Q_3	Organic matter in water column and sediments	Estimate	
Q_4	Benthic invertebrate biomass	Measured at Crystal River site. Venturi pump samples plus core samples. Core samples unavailable. Assumed to be of same order as venturi pump value. Therefore, total biomass 2x venturi value.	Snedaker, 1973
Q_5	Fish biomass	Measured at Crystal River site by drop net method. Assume dry wt. 25% of wet weight	Snedaker, 1973
R	Oyster reef biomass	Measured at Crystal River site	Lehman, 1973

Table 8 (cont.)

Flow	Description	Calculation	Reference
J_1	Total sunlight reaching ground	Average of measured values for 2-week period in June, 1973, 5500 kcal/m^2/day	Young, 1973
J_2	Gross photosynthesis of bottom plants	Total metabolism measurements minus phytoplankton component as measured with light-dark bottle measurements	
		Summertime average gross metabolism - $4.65gO_2/m^2$/da	Smith, 1973
		Light-dark bottle gross productivity - $1.86gO_2/m^2$/da	Smith, 1973
		$4.65gO_2/m^2$/da - ($1.86gO_2/m^2$/da)(0.5m) = $3.72gO_2/m^2$/da	
J_3	Phosphorus loss offshore due to flushing	By difference at steady state: $J_{28} + J_{30} + J_{16}$ $+ J_{26} + J_{29} + J_4 = J_{31} + J_{32}$ 0.0215 g/m^2/da = 0.0186 g/m^2/da + J_{32} J_{32} = 0.0029 g/m^2/da	
J_4	Phosphorus released by plant respiration	Assume phosphorus to be 0.5% of organic matter (3.72g/m^2/da)(0.005) = 0.0056 g/m^2/da	
J_6	Bacterial respiration	By difference after subtraction calculated respiration of benthic plants, benthic invertebrates, oysters, and fish from measured total respiration. Total respiration - $J_3 - J_{19} - J_{24} - J_{33} \approx J_6$ 4.52g/m^2/da - 1.12 - 0.3 - 0.09 - 0.73 = 2.28g/m^2/da	

Table 8 (cont.)

Flow	Description	Calculation	Reference
J_{10}	Organic matter input from marsh	Detrital export from marsh = $1.0g/m^2/m^2$ of marsh area/day. Assume marsh area about the same as inner bay area Input to inner bay = $1.0g/m^2/day$.	Young, 1973
J_{11}	Ingestion of organic matter by benthic invertebrates	Sum of J_{17} and J_{18}. $0.53g/m^2/day + 0.53g/m^2/day = 1.06g/m^2/da$	
J_{12}	Ingestion of organic matter by fish	By difference. $T_{25} + J_{23} - J_{22}$ $0.53g/m^2/day + 0.25g/m^2/day - 0.14g/m^2/day =$ $0.36g/m^2/day$	
J_{13}	Loss of organic offshore	By difference at steady state: $J_{29} + J_{10} + J_{27}$ $+ J_{25} + J_{21} + J_{17} = J_{11} + J_{12} + J_{13} + J_{14}$ $4.83g/m^2/day = 3.9g/m^2/day + J_{13}$ $J_{13} = 0.93g/m^2/day$	
J_{14}	Ingestion of organics by reef organisms	Steady state population so that $J_{14} = J_{33} + J_{15} = 0.2 + 0.2 = 0.4\ g/m^2/day$	
J_{15}	Feces, pseudofeces, death	Assume steady state population so that $J_{15} = J_{33} = 0.20g/m^2/day$	
J_{16}	Phosphorus recycled by reef respiration	Assume phosphorus 0.5% organic matter $(0.2\ g/m^2/day)(0.005) + 0.001\ g/m^2/day$	

Table 8 (cont.)

Flow	Description	Calculation	Reference
J_{17}	Feces production of benthic invertebrates	Assume 50% assimilation efficiency of ingestion Therefore, $J_{17} = J_{18} = 0.53 g/m^2/day$	
J_{18}	Gross assimilation by benthic invertebrates	Assume 15% of standing stock per day $(3.5/m^2)(0.15/da) = 0.53\ g/m^2/day$	
J_{19}	Respiration of benthic invertebrates	Assume respiration rate of 0.085 g dry wt. respired/g dry body wt/day	Day, 1973
J_{20}	Phosphorus released by benthic invertebrate respiration	Assume phosphorus 0.5% of organic matter $(0.3 g/m^2/day)(0.005) = 0.0015 g/m^2/day$	
J_{21}	Mortality	Assume 2.5% of standing stock per day $(3.5\ g/m^2)(0.025/day) = 0.09\ g/m^2/day$	
J_{22}	Predation loss to fishes	Assume 4% of standing stock per day $(3.5 g/m^2)(0.04/day) = 0.14\ g/m^2/day$	
J_{23}	Gross assimilation by fish	Assume to be 10% of standing stock per day $(2.5 g/m^2)(0.1) = 0.25\ g/m^2/day$	
J_{24}	Respiration of fish	3.6% of dry body wt. per day $(2.5\ g/m^2)(0.036) = 0.09\ g/m^2/day$	Prosser and Brow.., 1961
J_{25}	Feces production of fish	Assume assimilation efficiency of total food intake to be 50%, i.e., the same as J_{23}	

Table 8 (cont.)

Flow	Description	Calculation	Reference
J_{26}	Phosphorus released in respiration of fish	Assume phosphorus to be 0.5% of organic matter $(0.09 g/m^2/day)(0.005) = 0.00045\ g/m^2/day$	
J_{27}	Mortality (all causes)	Assumed to be difference between respiration and gross assimilation $(J_{23} - J_{24} + J_{27})$ $0.25\ g/m^2/day - 0.09\ g/m^2/day = 0.16\ g/m^2/day$	
J_{28}	Phosphorus released in microbe respiration	Assume phosphorus is 0.5% of organic matter $(2.28\ g/m^2/day)(0.005) = 0.0114\ g/m^2/day$	
J_{29}	Flow of plant biomass into organic matter pool	By difference assuming steady state $J_2 = J_3 + J_{29}$ at steady state $J_{29} = J_2 - J_3$ $J_{29} = 3.72 - 1.12 = 2.60\ g/m^2/day$	
J_{30}	Phosphorus input from salt marsh	$1.0\ g/m^2/day$ = detrital input from marsh (see calculation for J_{10}). Assume 1g or detritus comes from 1g of live plant. *Juncus roemerianus* is 0.15% phosphorus. Assume 90% of phosphorus lost from plant upon death. Therefore, 1g detritus would have released: $(1.0g/m^2/da)(0.0015) = 0.0015g\ P/m^2/day$	
J_{31}	Uptake of phosphorus by plants in photosynthesis	Assume phosphorus is 0.5% of organic matter produced in gross photosynthesis (J_2) $(3.72\ g/m^2/day)(0.005) = 0.0186\ g/m^2/day$	

Table 8 (cont.)

Flow	Description	Calculation	Reference
J_{32}	Loss of phosphorus to offshore water	By difference assuming steady state Total inputs = total outputs $0.0241 g/m^2/day = 0.0186 g/m^2/day + J_{32}$ $J_{32} = 0.0241 - 0.0186 = 0.005\ g/m^2/day$	
J_{33}	Reef respiration	Assume total biomass = $100 g/m^2$ of reef area. Use respiration rate of $7.5 g/m^2/day$ Assume reef area is 5% of bay area and submerged 12 hrs/day $(7.5 g/m^2/day)(0.05)(0.5) = 0.20\ g/m^2/day$	

The organic matter produced becomes available to consumers after flowing (J_{29}) into an organic detritus pool (Q_3). In addition to cycling through the consumers (J_{11}, J_{12}, J_{14}) where some is assimilated this detrital pool has a constant inflow from the adjacent salt marshes (J_{10}) and loses a portion permanently to offshore waters (J_{13}).

Respiration pathways are a function of the temperature acting on the metabolic pathways and the quantity of biomass respiring. The benthic invertebrate and fish consumers react to their temperature affected respiratory rate by adjusting their food gathering activities in proportion to their respiration rate. Respiration also regenerates phosphorus, which is recycled into the phosphorus pool within the water column (Q_1). Phosphorus also flows in at a constant rate from the salt marshes (J_{30}) and is lost permantly offshore (J_{32}).

The first simulation of this model using as initial conditions summer values for the plume affected inner bay area gave responses shown in **Fig. 28.** The light and temperature regimes at Crystal River were approximated with sime wave forcing functions. Light had a seasonal high of 5500 Kcal/m^2/da at the end of June and a seasonal low at the end of December of 2500 Kcal/m^2/da. The temperature function lagged 3 months behind light reaching a high of 35°C at the end of August and a low of 16°C at the end of March.

The storage component of benthic plants and its epiphytic associations followed a seasonal pattern which tracked primary production. Their maximums occured in late summer with the peak occuring just before maximum temperature. These maximum values were very close to the measured values at Crystal River. The decline through the fall reached a broad minimum lasting through the winter. The ensuing spring rise in rate and biomass was somewhat steeper then the decline of the previous fall. The minimums were much lower than measured values both biomass and gross production dropping by a factor of 3 or 4 while temperature and light dropped only by about 2 times. Observed at Crystal River but not yet included in this model is the change of dominance in the benthic plants from Halodule wrightii in the late spring, summer, and fall to an Ectocarpaceae in the winter and early spring. This species substitution may be a system mechanism for making use of the still relatively abundant wintertime light energy source and thereby increase winter metabolism. Inclusion of this observed behavior in the model may raise the low minimums of biomass and gross production.

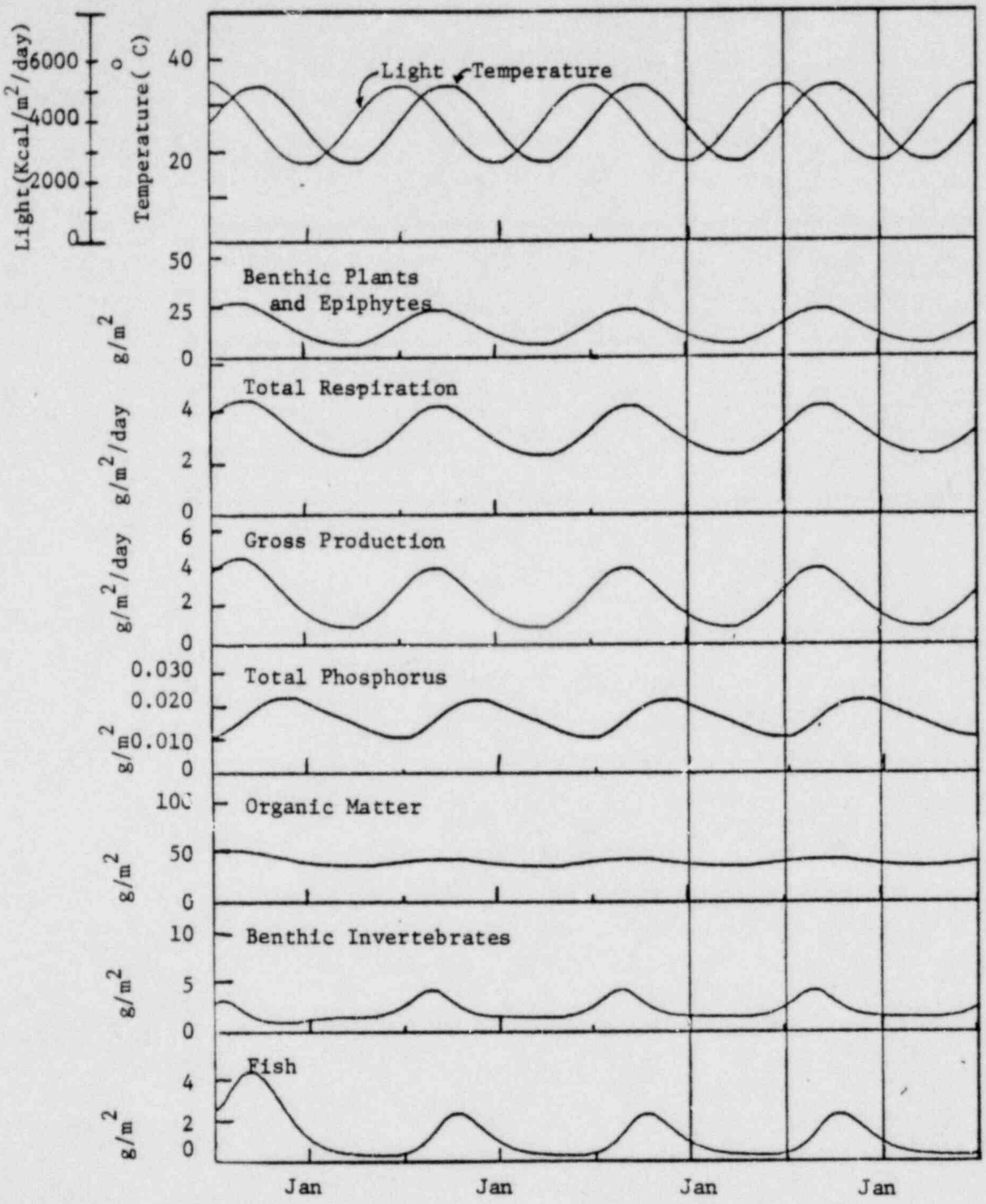


Fig. 28. Initial simulation run of inner bay model.

Total respiration closely tracked gross production and plant biomass since the major contributors to this rate were plant and microbial respiration in this simulation. The seasonal variation in total respiration was similar to measured values. The ratio of gross production to total respiration (P/R ratio) varied from about 1 in the summer to about 0.5 in the winter, a seasonal variation similar to observed data.

Total phosphorus exhibited a sharp rise in level through the summer, peaking in the fall, and slowly declining until the next summer. The few measurements so far taken at Crystal River indicate a fairly constant level of total phosphorus in the water column throughout all seasons. Incorporation of physical flushing by tides and the discharge plume into the model coefficients should level out the behavior of this component. The current model is probably more similar to a closed system such as a reservoir.

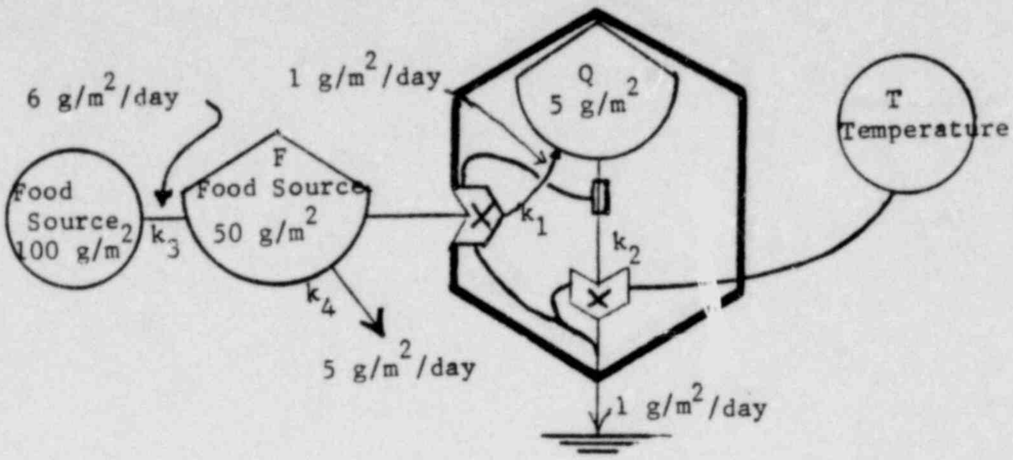
Organic matter exhibited only a small fluctuation due to the large storage relative to the inflows and outflows.

The consumer populations of the benthic invertebrates and fish could not be maintained unless a small outside source of biomass was added. The summer peaks corresponded fairly well with measured values but overall behavior was not like the observed patterns.

A Model of Temperature and a Metabolism-Sensed Energy Inflow

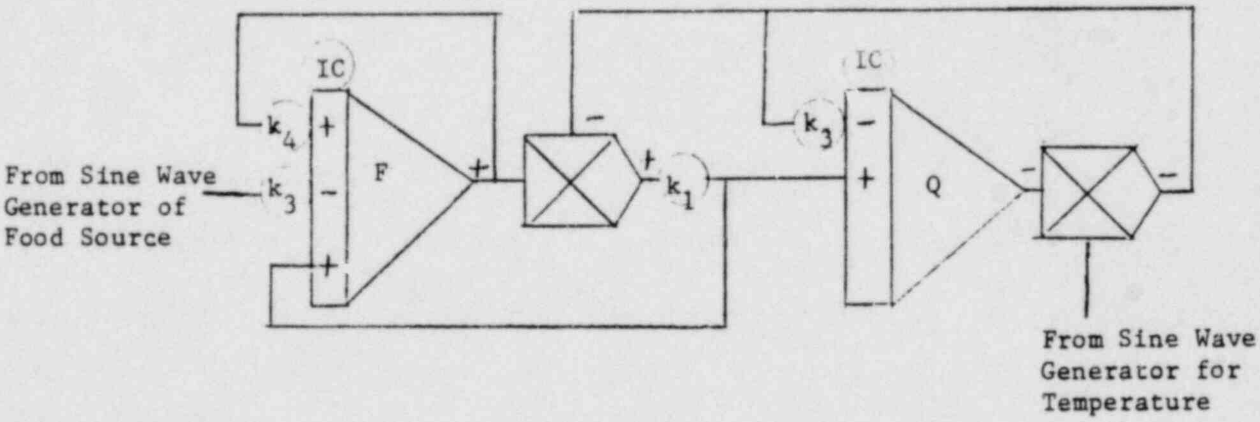
In order to refine and improve the large system model, submodels of the producer and consumer components were simulated in isolation. The goal of this effort was to test ideas about these modules concerning the role of temperature on their function and to gain a better understanding of their dynamics in the context of the larger model.

A submodel of the consumer compartment and the results of its simulation are given in Figs. 29-34. In this configuration temperature directly affected the pathway of respiratory metabolic disordering. As this drain increases with temperature the organism must increase its input of energy to compensate. The pathway of structural rebuilding and maintainence was postulated to vary directly with the rate of structural degradation. With a constant rate of food addition to the food tank this submodel had the property of decrease in the steady-state level of biomass with increasing temperature (Fig. 30). This behavior may result from the limited food source being drawn upon (constant



$$\dot{Q} = k_1 F (k_2 QT) - k_2 QT$$

$$\dot{F} = k_3 S - k_1 F(k_2 QT) - k_4 F$$



Pot Setting

k_1 = 0.104

k_2 = 0.104

k_3 = 0.018

k_4 = 0.030

ICF = 0.500

ICQ = 0.100

Figure 29. Energy model, equations, and analog diagram of consumer module with the effect of temperature disordering and a metabolism-sensed energy inflow.

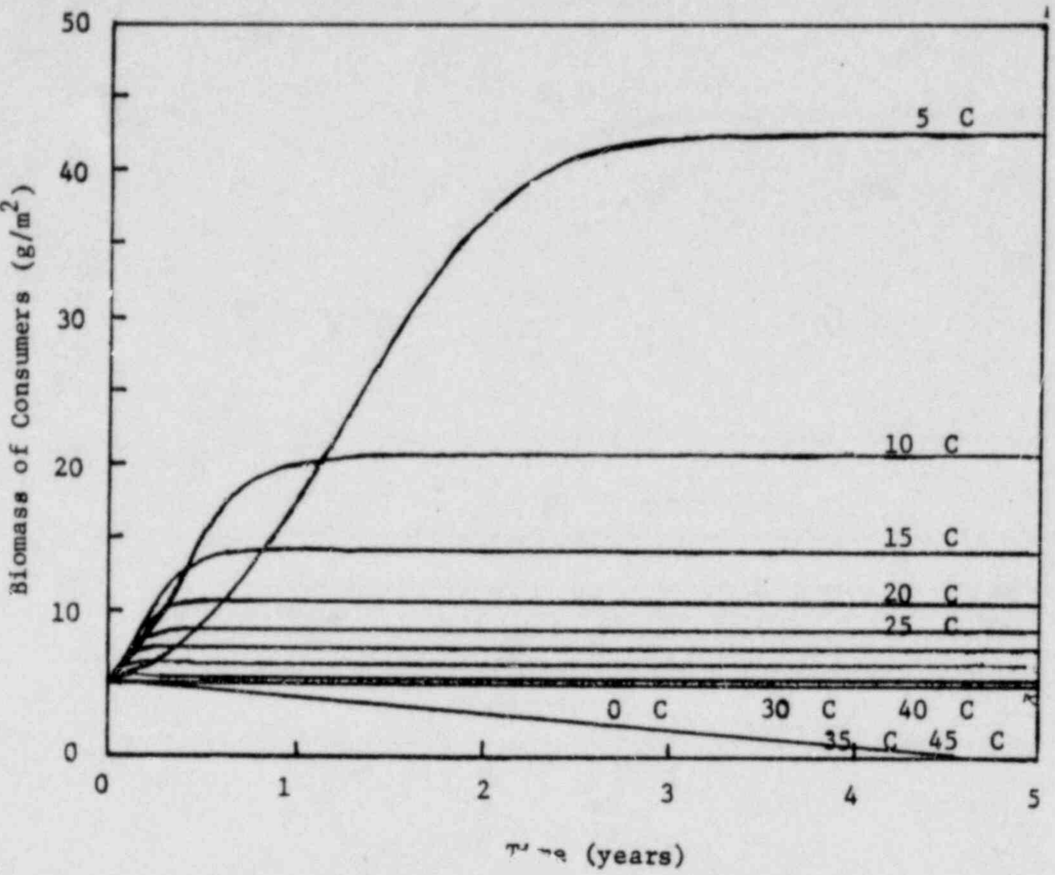


Fig. 30. Variation of steady state consumer biomass level with temperature. Food inflow held constant.

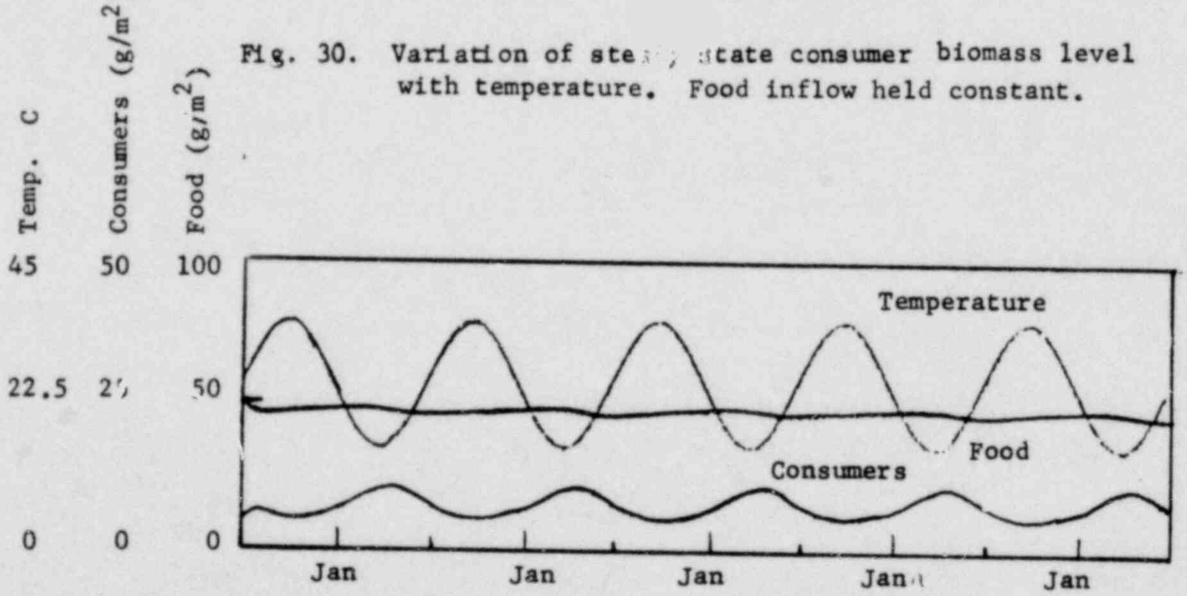


Fig. 31. Seasonal pattern of food and consumer stocks with temperature.

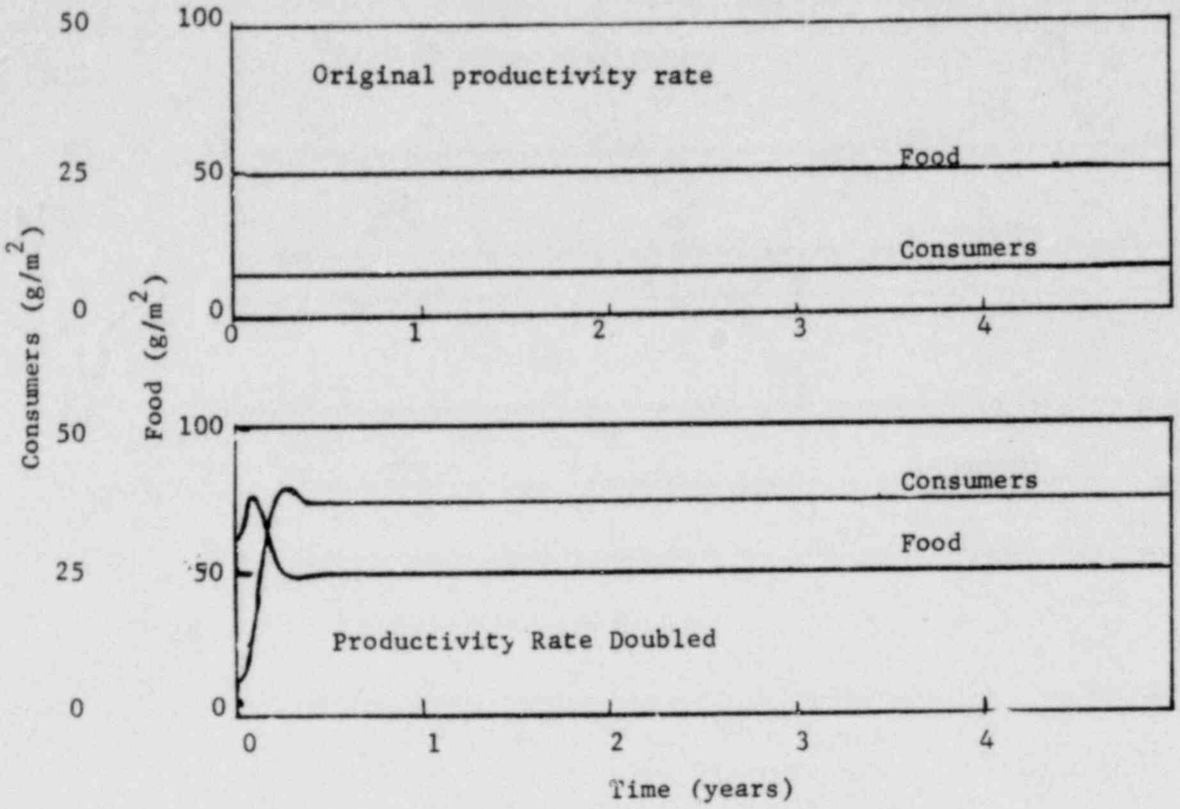


Fig. 32. Effect of the doubling of productivity on the steady state level of consumer biomass with constant temperature.

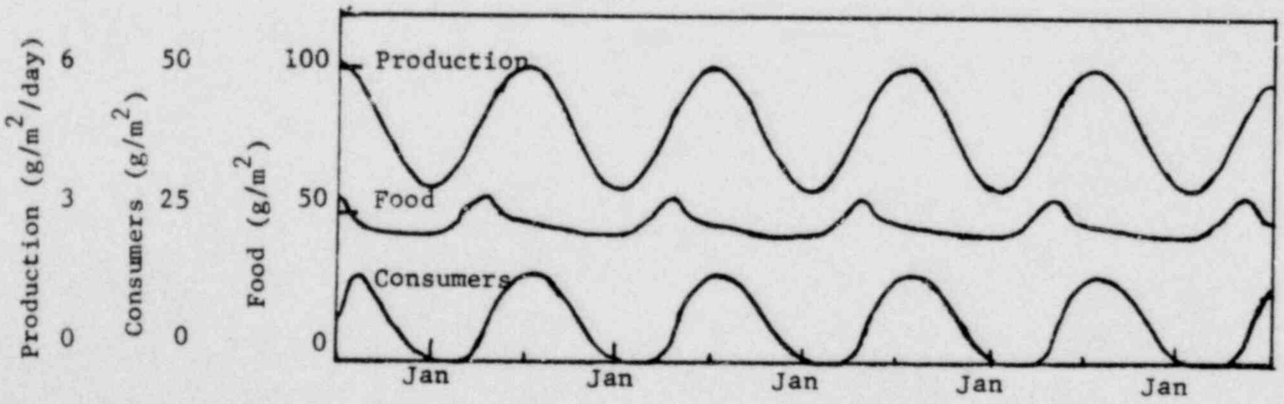


Fig. 33. Seasonal pattern of consumer and food stocks with seasonally varying productivity.

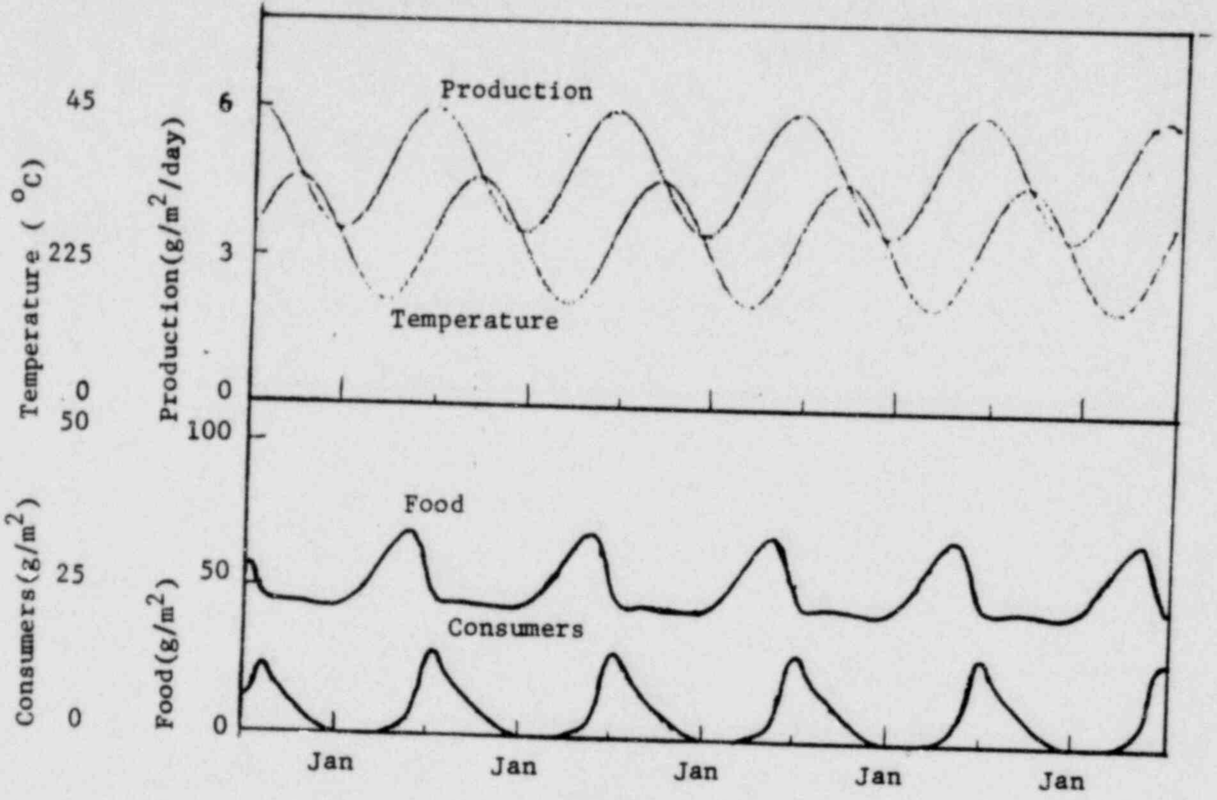


Fig. 34. Seasonal patterns of food and consumer stocks with seasonally varying productivity and temperature.

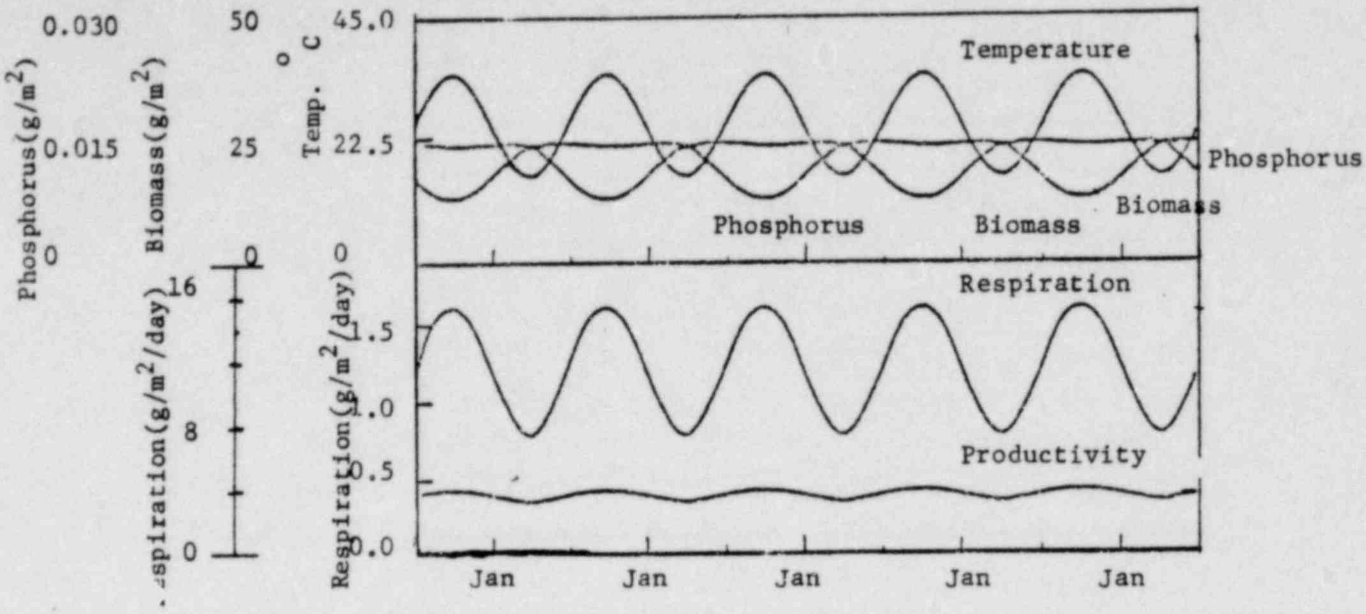


Fig. 36. Seasonal pattern with varying temperature and constant light.

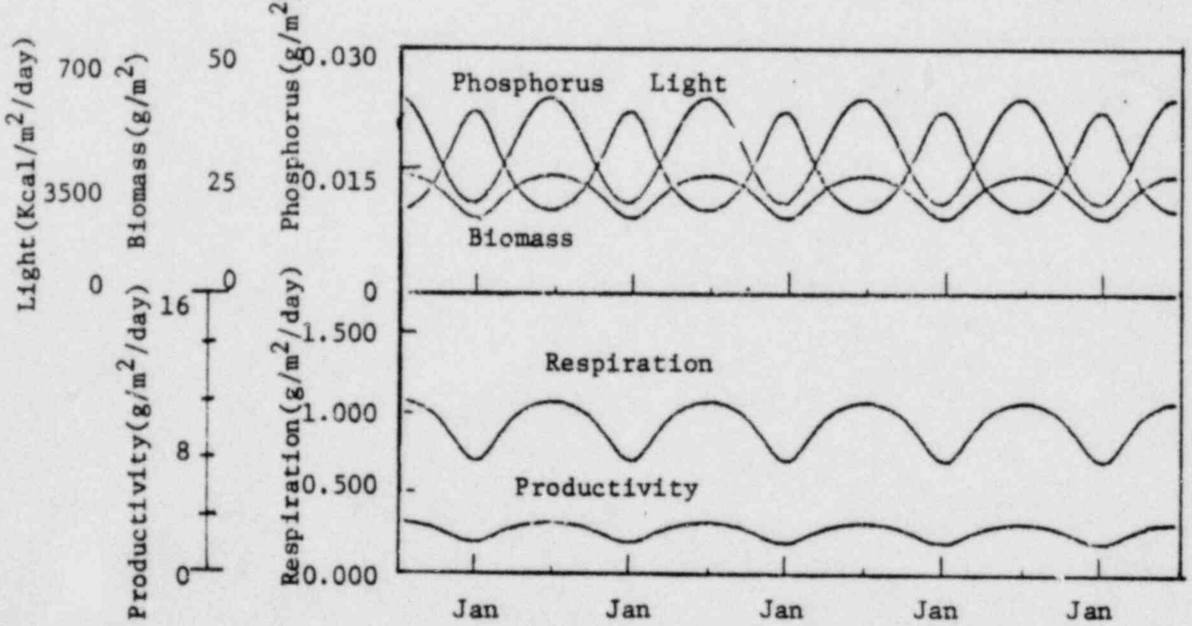


Fig. 37. Seasonal pattern with varying light and constant temperature.

flow source) becoming limiting preventing the rebuilding of structure from keeping up with the drain. **Fig.** 31 showed this as a seasonal pattern with biomass acting inversely to temperature over a four-year period.

The great sensitivity of this configuration to the rate at which food was added to the food tank (productivity) is seen in **Fig.** 32. At a constant temperature increasing productivity by a factor of 2 greatly increased consumer biomass. Simulated as a seasonally varying cycle of productivity with temperature held constant gave a response as shown in **Fig.** 33.

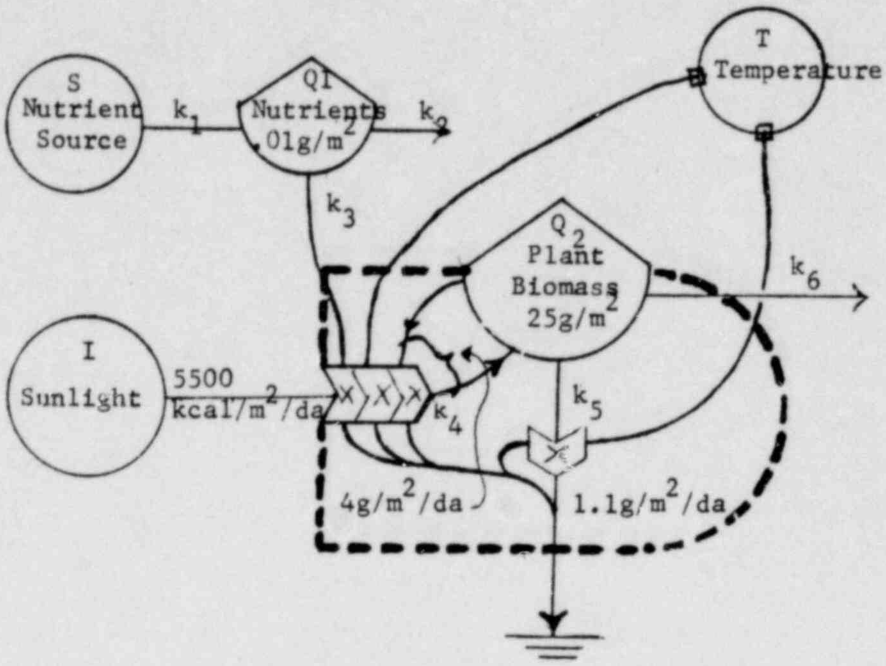
A seasonal pattern of varying production and temperature gave results graphed in Fig 34. Production was programmed to follow seasonal pattern like sunlight (high in late June, low in late December) with temperature lagging 3 months behind. The standing stock of food rose rapidly with production while the stock of consumers lagged behind. Once temperatures rose, food was rapidly grazed back and consumer biomass quickly added. Consumers declined in the fall and winter.

Overall behavior of this configuration does not correspond very well with observed patterns in nature. The sensitivity of biomass to food availability was too great, which may be result of the 5-day turnover time chosen for this submodel. However, a consumer with these coefficients could possibly exist if it were to migrate away during periods of low temperature and productivity, returning when conditions were suitable once again. Its ability for rapid growth could then take maximum advantage of available food.

Push-Pull Effect of Temperature on a Producer Module with an Unlimited Energy Source

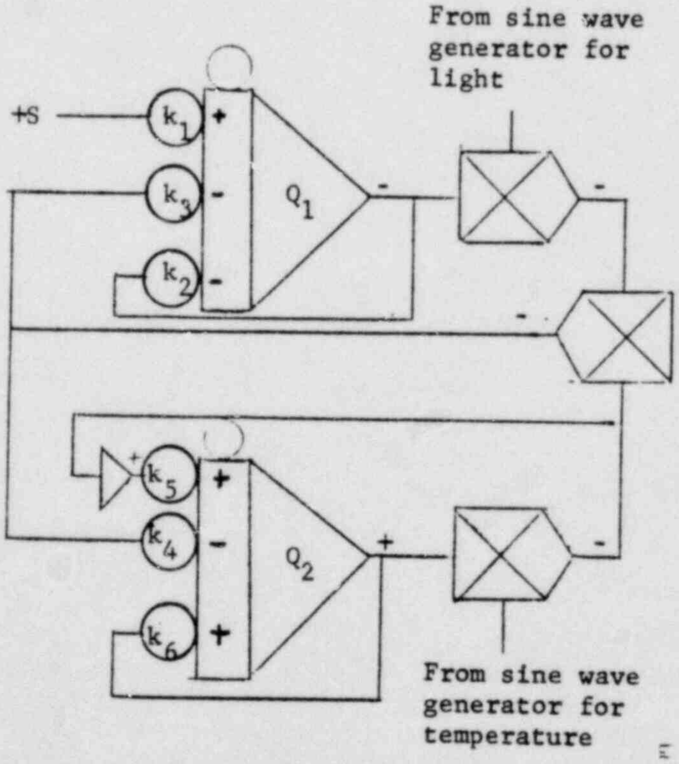
Shown in **Fig.** 35 is a submodel of the producer compartment illustrating the push-pull effect of temperature acting on both the photosynthetic and respiratory sides of the storage compartment. This simulation assumed that in an adapted plant the coefficient of the respiratory drain due to temperature is not larger than the corresponding temperature induced increase in the rate of photosynthetic rebuilding. In this case the effect of temperature on the disordering pathway is set equal to the effect on the synthesis pathway.

Fig. 36 and 37 graph the model response to the variation of one forcing function while holding the other constant. With varying temperature and constant light (Fig. 36) respiration and production vary with temperature. Since the push equals the pull, however, biomass remains constant. In the opposite



$$Q_1 = k_1S - k_2Q_1 - k_3ITQ_1Q_2$$

$$Q_2 = k_4ITQ_1Q_2 - k_5Q_2T - k_6Q_2$$



	Pot Setting
k_1	0.240
k_2	0.165
k_3	0.244
k_4	0.318
k_5	0.023
k_6	0.035
ICQ_1	0.333
ICQ_2	0.500

Fig. 35. Energy model, equations, and analog diagram of producer module testing the push-pull effect on both constructive and disordering pathways drawing on an unlimited energy source.

condition of constant temperature and varying light respiration, biomass, and production track the light pattern (Fig. 37).

Combining varying light with varying temperature lagging three months behind gives model responses graphed in Fig. 38. Productivity and biomass rose rapidly in the spring as light increased but the respiratory drain was still small with the low temperature, remained high through the summer, and declined through the fall and winter when both temperature and light were declining. Respiration lagged productivity tending to follow the temperature function. This simulation indicated that this small sub-model had some of the basic patterns observed in many real estuaries. Not modelled here is the coupling of consumer populations to this seasonal pattern and their role in nutrient regeneration. Addition of these components in a larger model may tend to make total system respiration track production more closely.

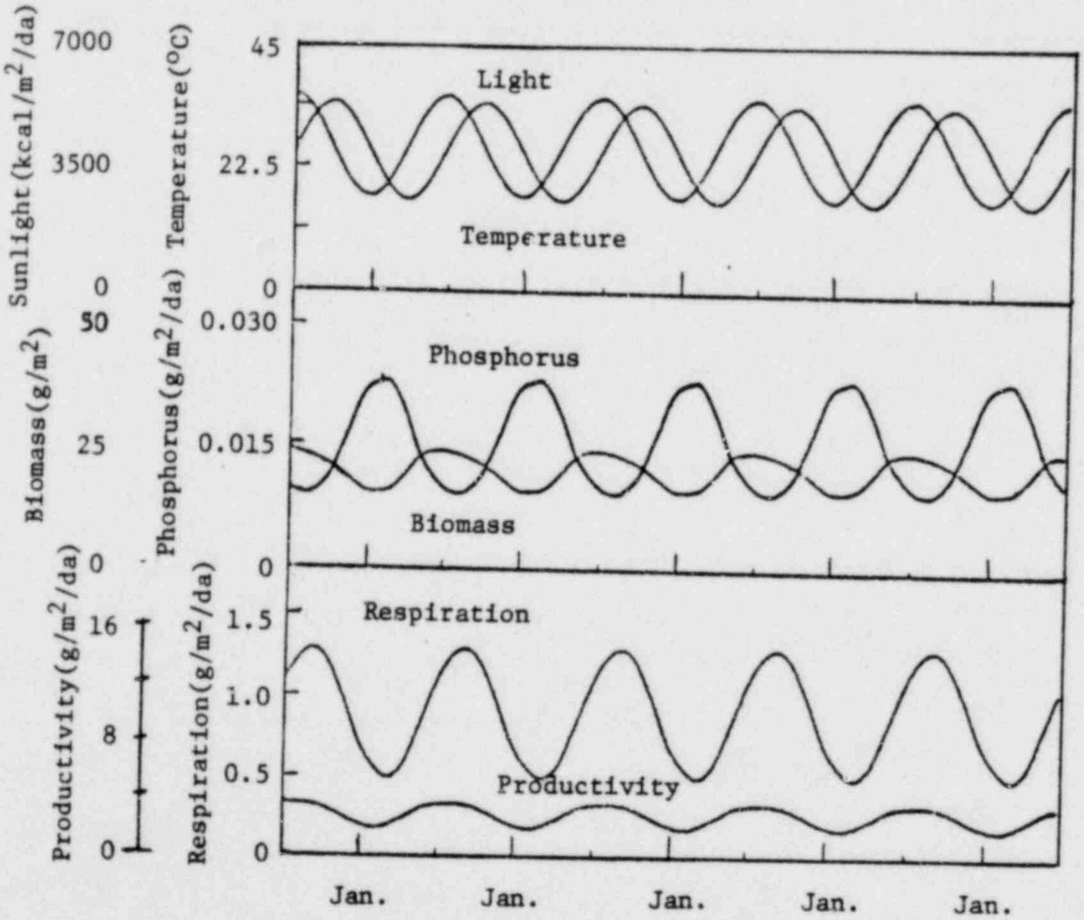


Fig. 38. Responses with seasonal variations in light and temperature.

LITERATURE CITED

American Public Health Association. 1955. Standard Methods for the Examination of Water, Sewage, and Industrial Wastes, 10th Ed., New York.

American Public Health Association. 1971. Standard Methods for the Examination of Water and Wastewater, 13th ed., New York.

Churchill, M.A., R.A. Buckingham, and H.L. Elmore. 1962. The Prediction of Stream Reaeration Rates. Tennessee Valley Authority, Div. of Health and Safety, Environmental Hygiene Branch. Chattanooga, Tennessee

Copeland, B.J., and W.R. Duffer. 1964. The use of a clear plastic dome to measure gaseous diffusion rates in natural waters. Lumnol. Oceanog. 9:494-499.

Day, J.W., W.G. Smith, P.W. Wagner, W.C. Stowe. 1973. Communnity structure and carbon budget of a salt marsh and shallow bay estuarine system in Louisiana. Publication no. LSU-SG-72-04, Center for Wetland Resources, Louisiana State University, Baton Rouge, La.

de la Cruz, A.A. 1973. The role of tidal marshes in the productivity of coastal waters. ASB Bulletin 20 (4): 147-156.

Florida Power Corporation. 1972. Crystal River Unit 3. Applicant's environmental report. Vol. 1.

Hall, C.A.S. 1970. Migration and metabolism in a stream ecosystem. Ph. D. thesis. Dept. of Zoology. Univ. North Carolina.

Lehman, L.E. Progress report to Florida Power Corporation and licensing agencies concerned with planning at Crystal River, Florida. December, 1973.

McConnell, W.J. 1962. Productivity relations in carbon microcosms. Limnol. Oceanogr. 7:835-343.

Odum, H.T. 1967. Biological circuits and the marine ecosystems of Texas, p. 99-157. T.A. Olson and F.J. Burgess [eds.], Pollution and Marine Ecology. Interscience publishers.

Odum, H.T., and C.M. Hoskins. 1958. Comparative studies on the metabolism of marine waters. Publ. Inst. Mar. Sci. Univ. Tex. 5:16-46.

Odum, H.T. and R.F. Wilson. 1962. Further Studies on Reaeration and Metabolism of Texas Bays, 1958-60. Publ. Inst. Mar. Sci. Univ. Tex. 8:23-55.

Prosser, C.L., and F.A. Brown. 1961. Comparative Animal Physiology. W.B. Saunders Co. Philadelphia, 688 p.

Smith, W.H.B. Progress Report to Florida Power Corporation and licensing agencies concerned with planning at Crystal River, Florida. December, 1973.

Snedaker, S.C. 1973. Fall enviornmental progress report. Florida Power Corporation.

Truesdale, G.A., A.L. Downing, and G.F. Lowden. 1955. The solubility of oxygen in pure water and sea water. J. Appl. Chem. 5:53-62.

U.S. Water Bureau. 1967.

Young, D.L. Progress report to Florida Power Corporation and licensing agencies concerned with planning at Crystal River, Florida. December, 1973.

4B. METABOLISM AND MODELS OF OUTER BAY ECOSYSTEMS AFFECTED BY THERMAL PLUME

Hank McKellar

Department of Enviornmental Engineering Sciences
University of Florida
Gainesville, Florida 32611

INTRODUCTION

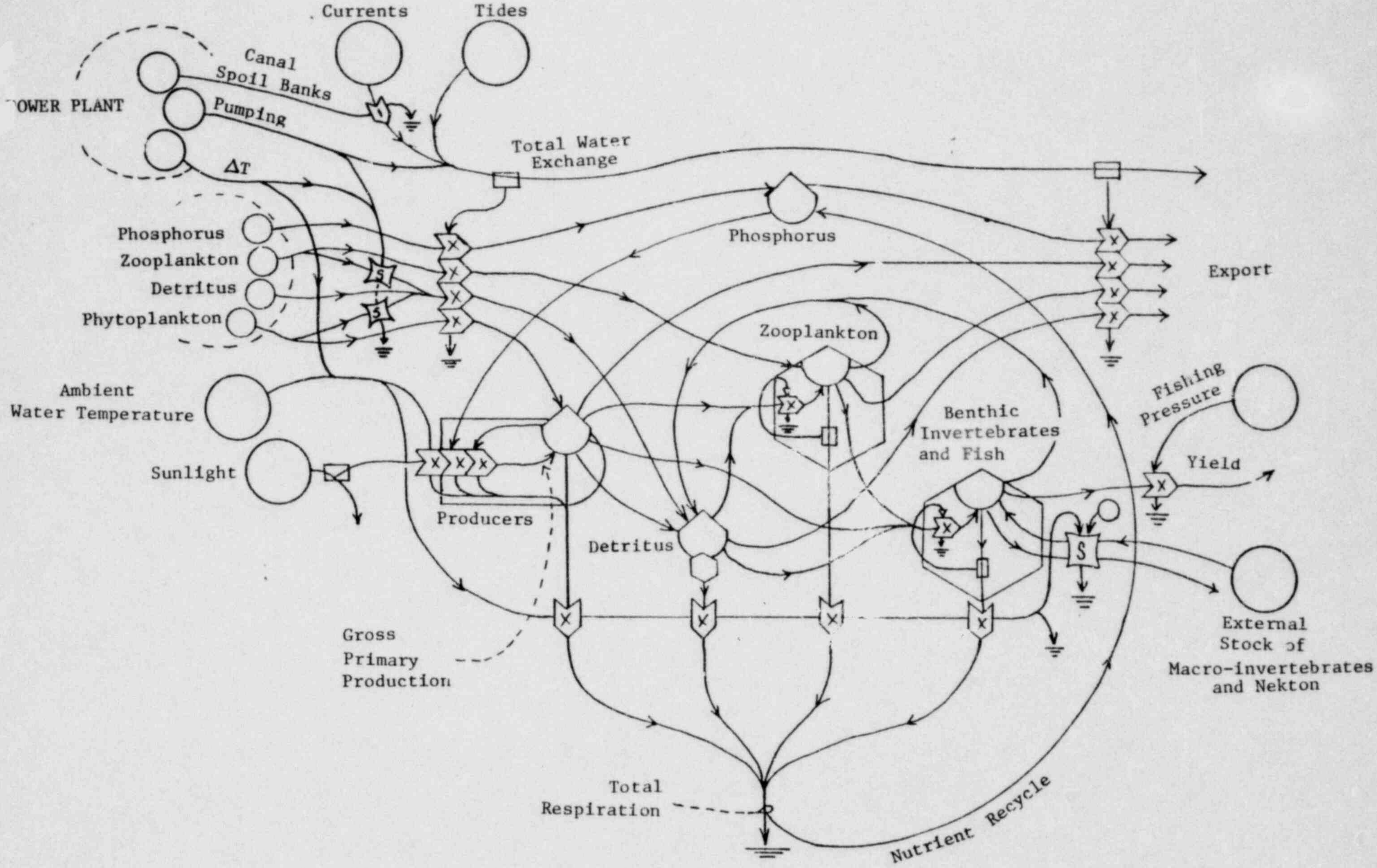
Present technological societies now face a transition from conditions of abundant energy supplies and rapid growth to a steady state with limited energies. Survival through the transition and into the steady state will depend on a new partnership between man and nature with optimum combinations of natural energies and fossil fuel based technologies (Odum, 1971; 1973). Therefore, the need is urgent to understand, predict and plan for viable interfaces between natural ecosystems and technology. Presented here is an effort to evaluate the effects of a coastal power plant on an adjacent marine bay and to develop a model for understanding and prediction.

The Coupling of Estuarine Ecosystems with Coastal Power Plants

Due to the large volumes of cooling water necessary for fossil-fuel and nuclear driven power plants, it has been desirable for power companies to locate generating stations in coastal environments. The heat and water exchange added with the thermal plume plus effects of plankton entrainment represent additional driving energies to which the affected marine ecosystems must re-design and adapt.

Proposed in Fig. 1 is a general energy circuit model of the major parts and processes of an estuarine bay ecosystem and its interactions with a coastal power plant. Such models have been shown to be a powerful tool in evaluating overall impacts of man-nature interactions and

Fig. 1. An energy circuit diagram of the outer bays near Crystal River. The diagram specifies external driving forces, internal storages, pathways of energy exchange, and their interactions. The power plant influences involve four main interactions; Δ T increases bay water temperature, ΔT and pumping causes a switch from plankton import to detrital import due to entrainment mortality, pumping adds to the general water exchange through the bay, and the spoil banks interrupt coastal currents and thereby inhibit water exchange.


Currents
Tides
Canal
Spoil Banks
POWER PLANT
Pumping
ΔT
Total Water
Exchange
Phosphorus
Zooplankton
Detritus
Phytoplankton
Phosphorus
Export
Zooplankton
Ambient
Water Temperature
Sunlight
Producers
Benthic
Invertebrates
and Fish
Fishing
Pressure
Yield
Detritus
External
Stock of
Macro-invertebrates
and Nekton
Gross
Primary
Production
Total
Respiration
Nutrient Recycle

in environmental planning (Odum, 1962; Odum, Littlejohn, and Huber, 1972). This model specifies energy exchanges among five major compartments of energy storage in the marine system and their relationships to external energies, including the power plant. The power plant is shown to interact as functions of the thermal plume (ΔT), the physical water exchange due to the *pumping* of cooling waters, and the physical structure of the canal *spoil banks*.

Water temperature in the bay, as influenced by ambient water temperatures and the heat added by the power plant (ΔT) was a major determinant of total energy flow through the bay system. A major effect of temperature is to increase biological exchanges involved with community primary production, respiration, and corresponding nutrient recycle. Up to a certain limit, heat is expected to stimulate primary production through the enzymatic process of photosynthesis (Jorgensen and Nielson, 1969). Heat also stimulates respiratory activities of producers and consumers. Nicol (1967) summarizes respiratory responses of a wide range of marine organisms documenting two to three-fold increases with each 10^{o}C rise in temperature. Higher levels of general activity in swimming, feeding, and reproduction. Fig. 1 shows zooplankton, benthic invertebrates, and fish with a property which increases their self-maintaining feed-back energies in proportion to their own respiration rates, thereby providing an adaptive response to effects of higher temperatures.

A major issue concerning the metabolic responses of organisms to higher temperatures is the net effects on total community metabolism of the energy *costs* associated with increased respiration and the *benefits* of increased photosynthesis and trophic transfers. Copeland and Davis (1972) found that total community metabolism in heated artificial pools containing estuarine water and biota was higher than in similar unheated pools. The heated systems were more autotrophic during the summer and more heterotrophic during the winter.

Temperature also serves as an information source which triggers migration of larger organisms to and from the bays. Many invertebrates and fish leave the estuarine bays during the winter and head for the warmer deeper waters of the Gulf. Those organisms and their young return again in the spring in time for the vernal bloom of estuarine productivity (Gunter. 1945; Simmons, and Hoese, 1959; Copeland, 1965; Odum, 1967). Summer emigrations also occur when temperatures exceed normal maximum preferences. These temperature related movements represent programmed responses of estuarine organisms to maximize their utilization of seasonal energy pulses. These responses are shown in Fig. 1 as a temperature controlled switch on the migratory exchanges of larger consumers with external stocks.

The actual volume of water pumped by the power plant and the physical structure of the associated canals and spoil banks alter patterns of water exchange. In un-affected bays water exchange with the sea and adjacent bays is due to tidal action and advective currents. Rates at which plankton, nutrients, and detritus are imported to the system are proportional to their external concentrations and the magnitude of water exchange. Export rates are similarly related to concentrations within the system and water exchange.

Plankton populations and nutrient stocks generally have rapid turnover times in marine systems and, therefore, tend to fluctuate suddenly with small changes in the environment. For these compartments, water exchange serves as a stabilizing energy which spreads out local concentrations and moderates large fluctuations. Such effects may, thereby, add to the stability of the entire system. Fig. 1 shows effects of power plant operation on water exchange. The volume of power plant pumping adds to the total water exchange and the physical structure of the associated canals and spoil banks may inhibit water exchange by interrupting longshore currents. Again, the model points out issues of energy costs and benefits associated with power plant influence.

Plankton are entrained in the power plant cooling waters and the corresponding mechanical and thermal shock and effects of chlorination cause some degree of stress on the entrained organisms (Morgan and Stross, 1969; Heinle, 1969, Carpenter, Peck, and Anderson; 1972; Fox and Moyer, 1972, Carpenter, et al, 1974). Entrainment mortality is shown in Fig. 1 as a switch from plankton imports to detritus imports to the receiving bay. This effect may tend to decrease planktonic involvement in the receiving systems while contributing to detrital exchanges and nutrient recycle.

In summary, this proposed model points out several component issues concerning the net effects of energy costs and benefits to estuarine bays as they interact with coastal power plants. **If the energies added by the power plants represent a resource with which the ecosystem may interact then the system's use of its total available energies may increase (Odum, 1974). Otherwise the energies added by the power plant may be a stress on the system. The encompassing issue addressed in this study concerns the functioning of the entire bay ecosystem as a coordinated unit. Does the system which self-designs and adapts to power plant influences develop structures and functions capable of maintaining its original levels of energy flow?**

This study is an effort to evaluate this issue for the outer bay ecosystems affected by power plants near Crystal River, Florida.

Plan of Study

The interface design between the outer estuarine bays and the Crystal River power plants was examined through ecosystems models evaluated by field measurements and other available data. The conceptual model shown in Fig. 1 was presented as

(a) a visual summary of the issues to be evaluated,

(b) an inventory of the total energies driving the system, the dominent internal storages, and the critical pathways of energy exchange; and as

(c) a structural basis for collecting and comparing data from " affected" and "control" bays.

Total community metabolism, as determined from diurnal oxygen curves, was taken as an indication of the ecosystem's ability to process its total available energies. Comparisons of metabolism between bays affected by the power plants and similar control bays indicated the degrees to which the affected system had changed with respect to those abilities.

Metabolism studies conducted at sites in the outer discharge and control bays are indicated in Fig. 2. Studies were initiated in June, 1972, and were performed at approximately quarterly intervals through May, 1974, thereby establishing the general seasonal trends of metabolism.

Since plankton were an important component of the outer bay ecosystems, efforts were made to partition total metabolism between its planktonic components and the remaining benthic and nektonic components.

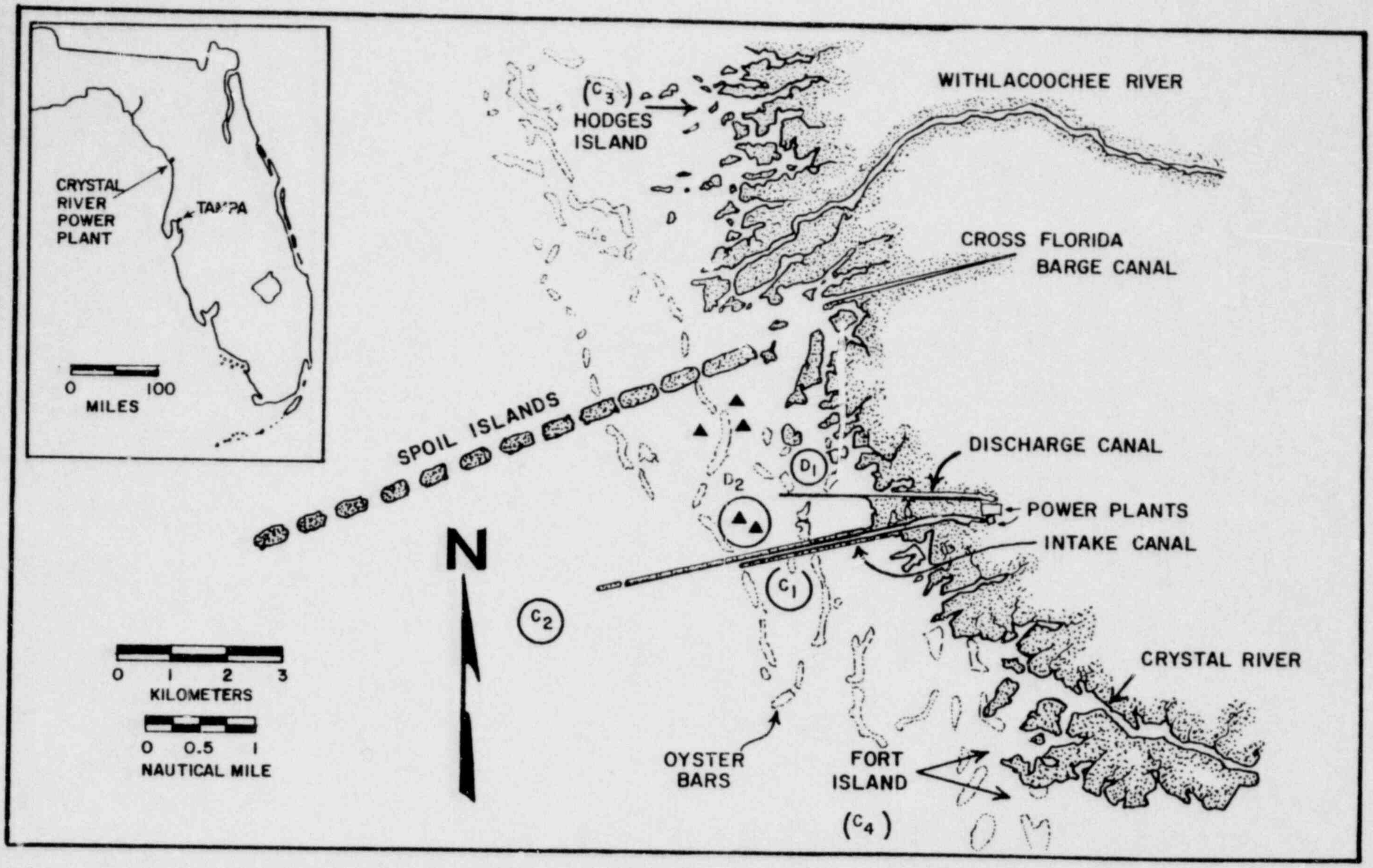


Fig. 2. Crystal River power plants in relation to the major features of the regional coastline. Study sites are indicated for the outer discharge bays (D) and outer control bays (C).

Zooplankton respiration and corresponding turnover rates were estimated by measurement to determine their relative importance in the total energy flow of the bay system.

Light penetration through the water column and concentration of phosphorus fractions and planktonic chlorophyll in the bays were also measured to augment the interpretation of metabolism data.

To determine the transition of water mass characteristics from off-shore environments up to these bays and the possible seaward extent of power plant effects, phosphorus, chlorophyll, and zooplankton concentrations were determined in transects from stations on the outer continental shelf to the bays near the power plants.

Concurrent with these studies, investigations were conducted by other researchers on biomass of macrophytes, benthic invertebrates, fish, and zooplankton in the bays and power plant canals (Snedaker, et al, 1973-74

Concurrent with these studies, investigations were conducted by other researchers on biomass of macrophytes, benthic invertebrates, fish, and zooplankton in the bays and power plant canals (Snedaker, _et_ _al_, 1973-72; Maturo, _et_ _al_, 1972-73; Drew, 1974). This additional information was combined with the metabolism data and other supporting measurements from the outer control and discharge bays. Using this data base along with information in the literature, and with some necessary calculations and assumptions, the energy circuit model in Fig. 1 was completely evaluated for both the outer discharge and control bays. The evaluated models thereby provided a direct visual comparison of the differences in energy flows, storages, and rates of systems turnover.

METHODS

Field Measurements

Total Community Metabolism

The metabolic activity of the total outer estuarine community was determined from diurnal oxygen changes in the free water with two methods modified from Odum (1956) and Odum and Hoskin (1958). The first method involved the analysis of full diurnal oxygen curves with date from several stations. The second method was an abbreviation of the first which involved estimating daily oxygen changes from samples taken at times near dawn and dusk (McConnell, 1962). Both types of analysis required corrections for oxygen diffusion across the air-water interface and allowances for tidal fluctuations in depth. A total of 43 metabolism studies were performed in the outer estuarine areas near Cyrstal River. The major areas of data collection were the outer discharge area (D_1) and the outer control area (C_1) where 84% of the total metabolism values were obtained.

Full Diurnal Oxygen Curve Procedure

For each determination of total community metabolism three to five stations were monitored for dissolved oxygen, temperature, salinity, and water depth. Stations in the outer discharge area (D_1) are given in Figure 3. Stations were visited at approximately 3-hour intervals throughout a 24 hour period. Dissolved oxygen was determined on duplicate water samples (taken approximately 1 minute apart) by the Azide Modification Method (APHA, 1971). Values obtained from stations within an area were averaged for each sampling time, thus obtaining an averaged diurnal curve for each parameter.

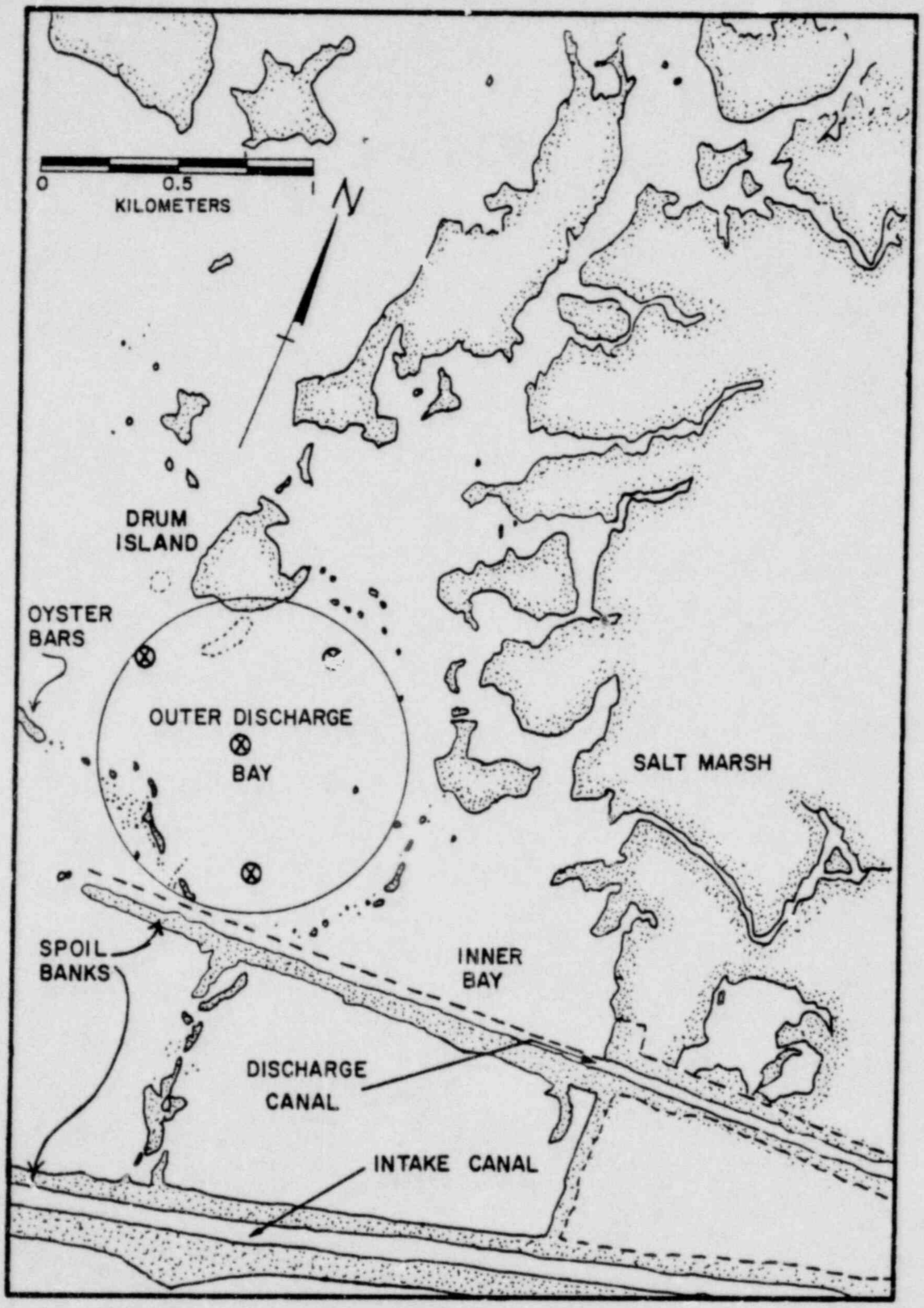


Fig. 3. Thermally affected area with the shallow inner bay dominated by benthic sea grass and the outer discharge bay (D_1 in Fig. 2) X's indicate sampling stations.

On several occasions an oxygen probe (Yellow Springs Instrument Model 51-A) was used to facilitate oxygen determinations at various depths in the water for the diurnal analysis. Use of the probe enabled continuous oxygen monitoring at a single station rather than intermittent sampling at several stations. For these diurnals, the small variations in oxygen were observed while the generality gained from multiple station diurnals was sacrificed.

Typical diurnal variations in these parameters are shown in Figure 4. The percent oxygen saturation for each combination of dissolved oxygen, temperature, and salinity was calculated using the formula of Truesdale, Downing, and Lowden (1955). At temperatures less than 25°C values given by this formula are known to differ slightly from those given by APHA (1971) as reviewed by Churchill, Elmore, and Buckingham (1962). However, the maximum deviations were less than 5% of the Standard Methods values so errors incurred by using Truesdale's formula were considered negligible. Truesdale's formula proved to be more useful in this study because it provided saturation values for water temperatures above 35°C.

Observed oxygen changes were considered to be due to community metabolism and atmospheric exchange across the air/water interface. Although community metabolism and atmospheric exchange generally influence dissolved oxygen in proportion to water surface area, the corresponding additions or losses of dissolved oxygen are mixed throughout the water column. Therefore, the observed change in oxygen concentration between each hour (Fig. 4a) were multiplied by the average depth of the water column during that time interval (Fig. 4 b) to obtain the rate of oxygen change in $g/m^2/hr$ (Fig 4f, solid line). Atmospheric exchange was determined (see Oxygen Diffusion,

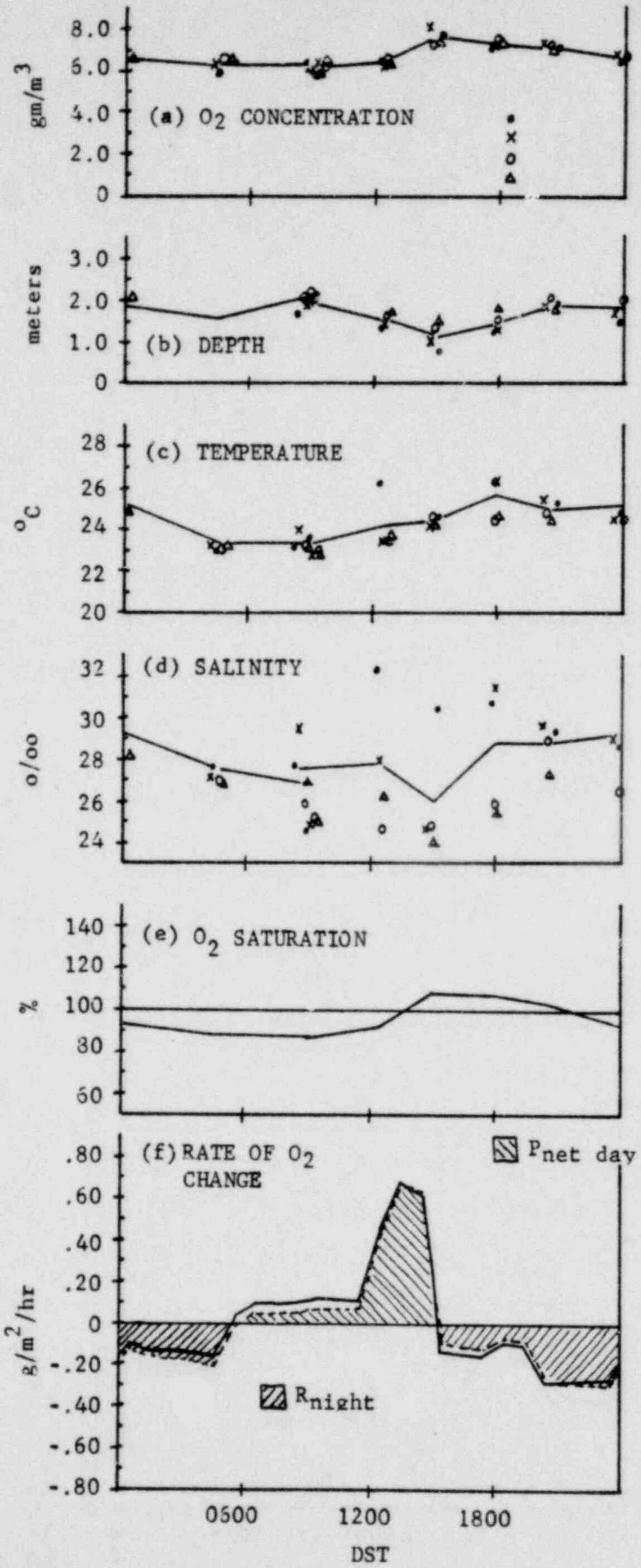


Fig. 4. Results of a full-diurnal metabolism study. Outer discharge bay, D-1, 19-20 October, 1973

below) and subtracted from the observed rate of oxygen change. The corrected curve (Fig. 4f dashed line) thereby represented oxygen changes due to the net effects of photosynthesis and respiration. The integrated area defined by the corrected curve above the zero rate-of-change line during the day [illegible]presented net daytime community photosynthesis ($P_{net\ day}$). The area b[illegible] zero rate of change line represented nighttime community respira[illegible]$_{c}$).

Odum and Hoskin (1958) cautioned researchers on the use of the free-water diurnal oxygen curve procedure in open estuarine areas where large net exchanges of water masses with different oxygen regimes may lead to considerable errors in calculating total metabolism. However, oxygen concentrations at different stations within each study area were generally similar (Fig. 4c), indicating that the exchanging water masses had similar metabolic histories. Therefore, the general procedure for calculating total metabolism did not involve a special correction for net water mass advection, although some error was involved.

Dawn-Dusk Procedure

The full diurnal oxygen curve procedure was abbreviated in order to cover more area and to obtain metabolism estimates for several days in succession during each study period. For this abbreviated procedure, stations were sampled only at times near dawn, dusk, and the following dawn (or dusk-dawn-dusk) during a 24-hour period. Samples were taken, as before, for dissolved oxygen, water depth, temperature, and salinity. Oxygen concentrations observed at times near dawn and dusk were taken as the best estimates of the daily oxygen minimum and maximum, respectively. These measurements thereby provided points for an estimated diurnal curves for oxygen, depth, temperature, and saturation (Fig. 5).

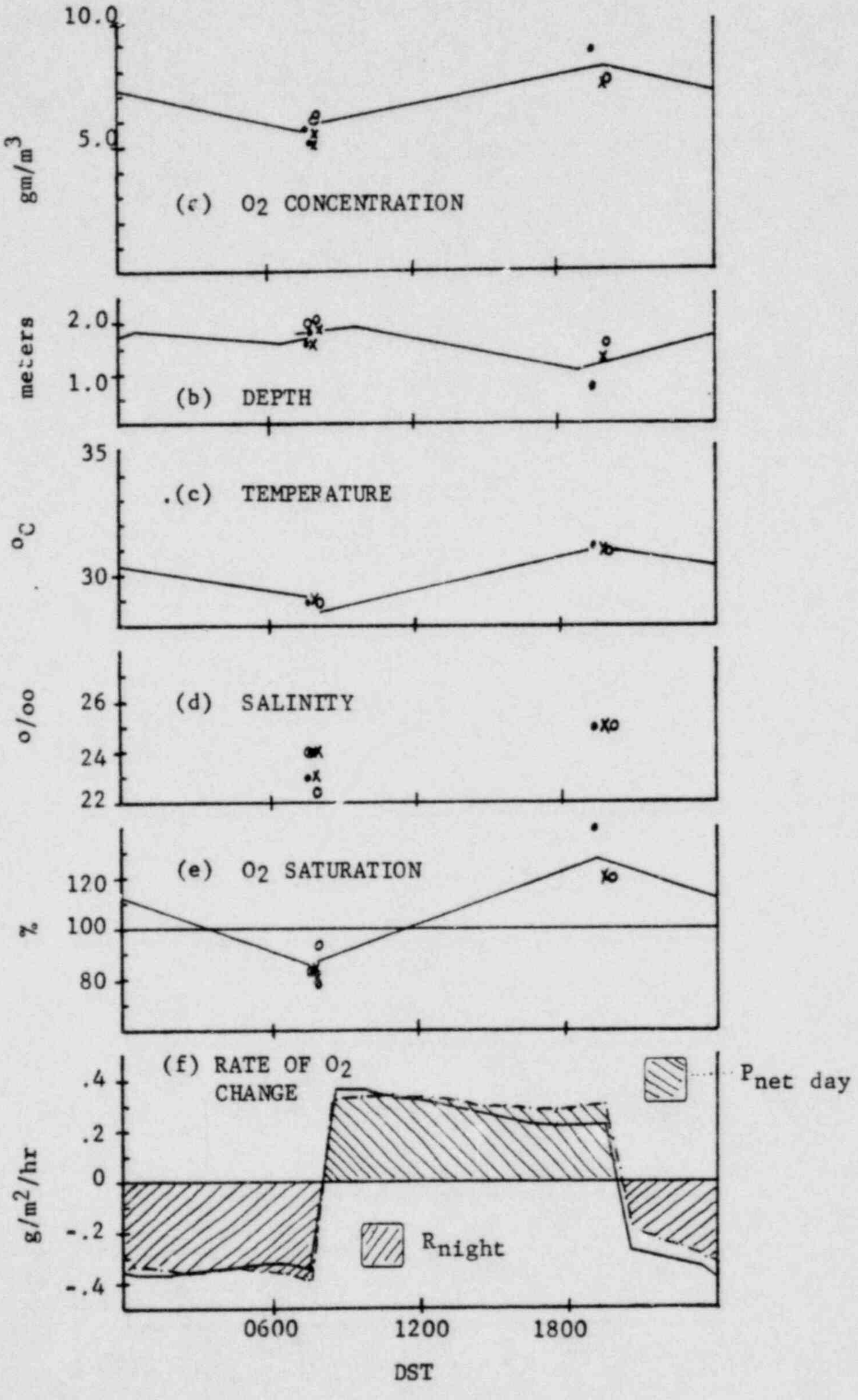


Fig. 5. Results of a dawn-dusk metabolism study. Outer control bay, C-1, 9-10 August, 1973

Dawn-dusk estimates of diurnal curves have been used in previous metabolism studies in carboy microcosms (McConnell, 1962), shallow artificial pool microcosms (Whitworth and Lane, 1969), and in shallow marine ponds (Smith, 1971) where oxygen changes were not affected by tidal action and net water advection. The semi-diurnal tidal patterns in the open estuarine bays at Crystal River required additional considerations in interpreting dawn-dusk data. Oxygen changes were measured on a volume basis and multiplied by the depth to obtain rates of oxygen change on a basis of surface area. Therefore, care was taken to establish the actual times and magnitudes of tidal depth changes. The depth curve (Fig. 5b) was calculated from the observed depth measurements (see data points) and the expected tidal depth changes as indicated by published tide tables for the Crystal River area (U.S. Dept. Commerce, 1972-1974).

Figure 5 illustrates the direct comparisons of the dawn-dusk procedure with the full diurnal analysis (Fig. 4) although such graphical representation was not necessary for metabolism calculations from dawn-dusk samples.

The net oxygen diffusion during the day in gO_2/m^2 was calculated as

$$D_{day} = (K)(\overline{S}_{day})(t_{day})$$

where K was the diffusion constant in $g/m^2/hr/100\%$ saturation deficit, $\overline{S}_{day}$ was the average percent saturation deficit during the day (= $(S_{dawn} + S_{dusk})/2$), and t_{day} was the time between dawn and dusk in hours. Net daytime photosynthesis ($P_{net\ day}$) in $g/m^2/day$ was calculated as

$$P_{net\ day} = ([O_2]_{dawn} - [O_2]_{dusk})(\overline{Z}_{day}) - D_{day}$$

where $[O_2]_{dawn}$ and $[O_2]_{dusk}$ were the oxygen concentrations observed at dawn and dusk, respectively, and $\overline{Z}_{day}$ was the average daytime depth of the water column through which changes in oxygen per m^2 were integrated. $\overline{Z}_{day}$ was calculated by averaging hourly depths from dawn to dusk as determined in depth plots such as in Figure 5b. Nighttime respiration was calculated in a similar manner for the interval between dusk and dawn minus the net nighttime oxygen diffusion.

Sixty-three percent of all the total metabolism estimates were obtained by the dawn-dusk procedure. To evaluate the differences between metabolism estimates obtained through this abbreviated procedure and full diurnal analyses, a subsample of full diurnal curves was analyzed according to the dawn dusk procedure. Stations along the full diurnal curves taken 1-2 hours after sunrise and 1-2 hours before sunset were taken as dawn and dusk samples. Corresponding metabolism estimates were calculated and compared with estimates obtained through integrating the full diurnal curve. Resulting differences are shown in Fig. 6.. Occasionally, the dawn-dusk estimates were 30-40% lower than those obtained by full diurnal analyses. These deviations occured on dates when oxygen concentrations began to decline several hours before dusk due to cloudy and/or rainy conditions. The corresponding "dusk" sample underestimated the oxygen maximum. However, dawn-dusk estimates were generally less than 10% below those from full diurnals. The average difference between these 18 pairs of values was 0.25 g/m^2, which was not significant at a 95% confidence level. However, when wide deviations occured, estimates obtained by the dawn-dusk procedure were low.

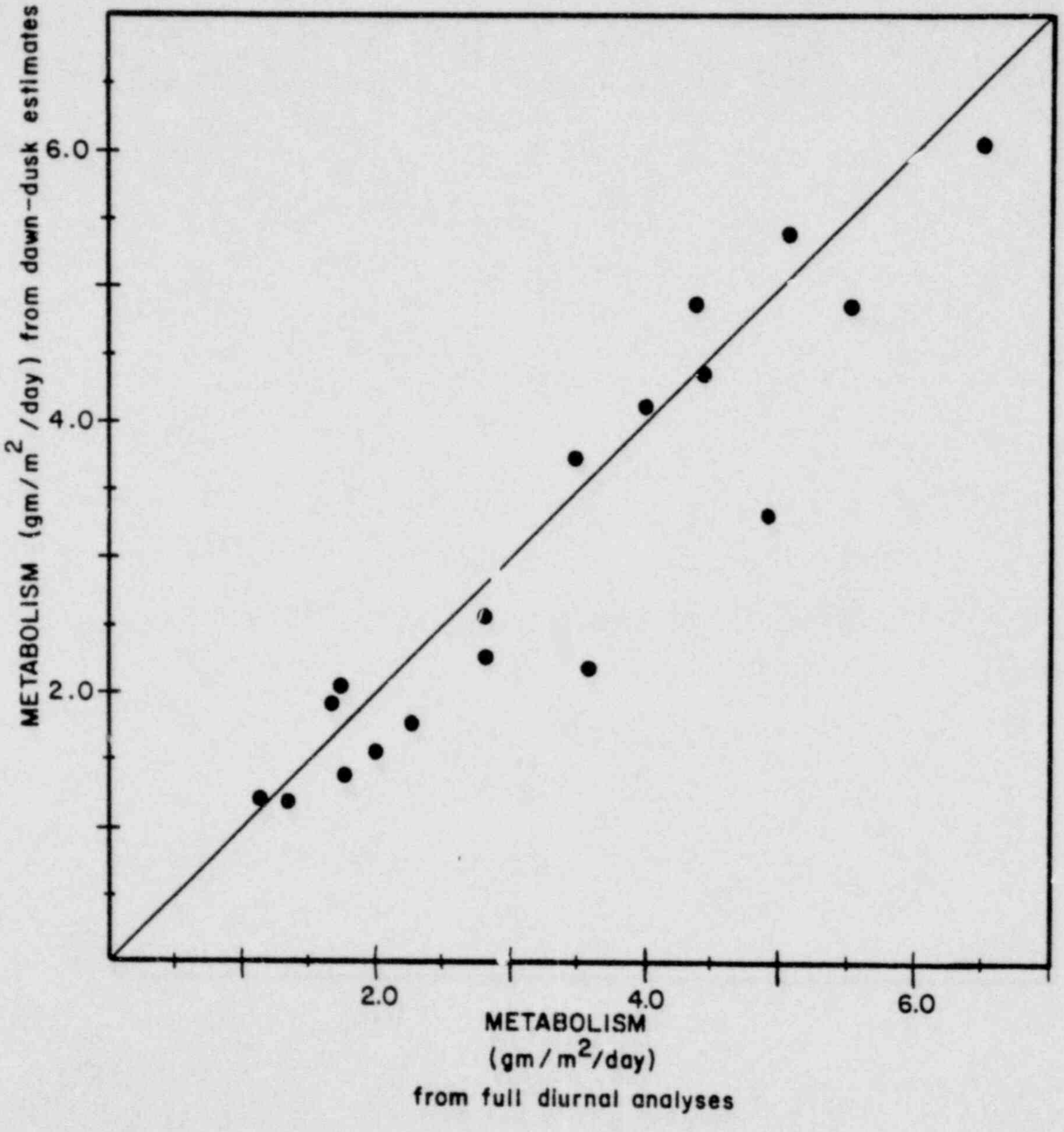


Fig. 6. Total community metabolism estimates obtained from full diurnal oxygen curve analyses verses estimates obtained from dawn-dusk calculations on the same days.

Oxygen Diffusion

Oxygen diffusion (D) in $g/m^2/hr$ was calculated as a linear function of the deviation of the dissolved oxygen concentration from saturation.

$$D = KS$$

where S was the percent dissolved oxygen saturation deficit and K was the oxygen diffusion coefficient in $g/m^2/hr$ at 100% saturation deficit (Odum and Hoskin, 1958).

Diffusion coefficients were determined from gas exchange into a floating plastic dome with a method based on original work by Copeland and Duffer (1964) and further developed by Hall (1970) and Day (1971). In general, a small plastic dome with an oxygen probe inside was floated on the water surface. An initial oxygen meter reading was obtained representing 100% saturated air. The dome was then purged with N^2 gas until the O^2 meter reading was close to zero. Oxygen meter readings were recorded at short intervals for one to two hours thereby documenting return of oxygen toward saturation. For this duration, oxygen return to the dome was generally linear as shown by the results from seven diffusion experiments (Fig. 7). With the observed rise in percent oxygen saturation in the dome, diffusion coefficients were calculated as follows:

$$K = \frac{(v)(\rho(O_2)) \times (\ \%\ O_2 \text{ saturation in dome})}{(A)(t)(\overline{\%\text{ sat. def.}})}$$

where K = diffusion coefficient in g $O_2/m^2/hr$ at 100% saturation deficit; v = volume of air in dome initially displaced by oxygen (ml) = volume of dome X .2 (air = 20% oxygen); (O_2) = density of oxygen corrected to air temperature; A = area of water surface covered by the dome; t = duration of the experiment; and $\overline{\%\text{ sat. def.}}$ = average percent saturation deficit between the dome and the water for the duration of the experiment.

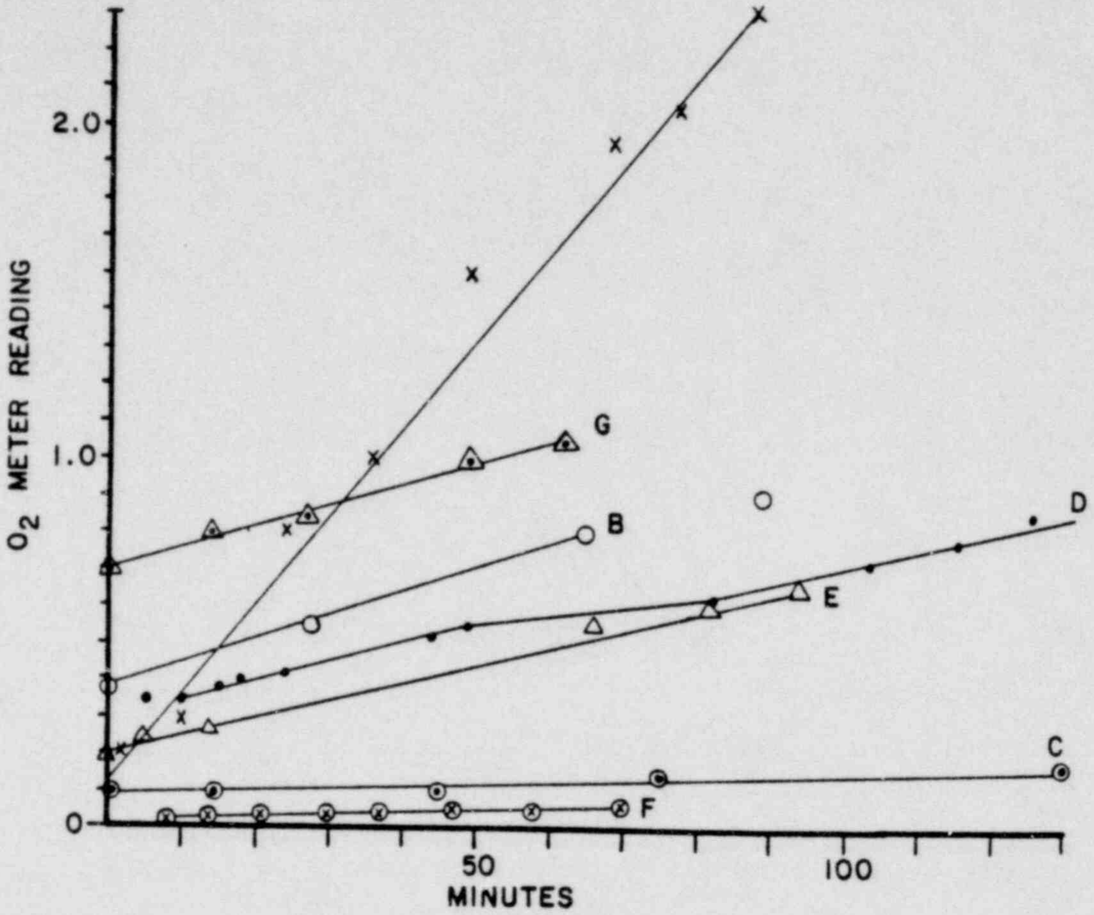


Figure 7. Oxygen return to a Nitrogen-filled plastic dome in experiments to determine oxygen diffusion coefficients (K).

Key	Area	Date	Tide	K
A	Outer Discharge Area (D_2)	13 Dec., 1972	Ebb	4.75
B	" " " "	" " "	Slack	0.98
C	" " " "	" " "	Flood	0.07
D	" " " (D_1)	10 July, 1973	Ebb	0.39
E	" " " "	" " "	Flood	0.31
F	" " " "	20 Oct., 1973	Early Flood	0.04
G	Outer Control Area (C_1)	11 July, 1973	Slack	0.38

The highest diffusion coefficient was observed during an ebbtide with fairly strong current velocities (Fig. 7a). The lowest K values (Fig. 7c and f) were observed during flood tides when currents were generally weak and variable.

Based on these data the following diffusion coefficients were used in metabolism corrections for diurnal curves obtained in the outer bays at Crystal River.

(a) In the areas where the majority (84%) of the total metabolism measurements were taken (areas D_1 and C_1; Fig. 2) a coefficient of K = 0.35 $b/m^2/hr$ at 100% sat. def. was used for diffusion corrections for all tidal stages. This value was also used for correcting the single diurnal curve obtained at Hodges Island (control Area C Fig. 2). Diffusion corrections using this value usually represented less than 5% of the observed oxygen changes.

(b) Diffusion measurements were not available for the outer stations at Fort Island (Control Area C_4; Fig. 2). However, diffusion values obtained for the inner areas at this location were approximately three times higher than in the inner discharge area (Smith, 1974). Also, these measurements indicated an approximate two-fold increase of ebb-tide diffusion coefficients over those observed during flood tides. Assuming similar relationships between diffusion coefficients for the <u>outer</u> discharge area (C_1) and those for the <u>outer</u> stations at Fort Island, a K value of 1.00 was used for diffusion corrections during ebb-tides and a value of 0.50 was used for corrections during flood tides. This combination led to diffusion corrections generally less than 10% of the observed oxygen changes.

(C) Data in Fig. 7a, b, and c indicated that diffusion coefficients were relatively high in discharge area D_2, especially during ebb-tides. For the two metabolism studies in this area a K value of 4.75 was used during ebb-tides and a value of 0.5 was used during rising tides. Since control area C_2 (Fig. 2) was further offshore and unprotected from oyster bars and spoil banks, these relatively high diffusion coefficients were also used for the single metabolism study at that location. These values led to diffusion corrections which were 15 to 60% of the observed oxygen changes.

Total Plankton Metabolism

Levels of net primary production and total respiration of the plankton community were determined by oxygen changes in light and dark bottles. Dark bottles were prepared by completely covering 300 ml BOD bottles with one layer of black electrical tape and a second layer of silver duct tape. Tops were covered with 2 layers of aluminum foil during experiments. Approximately 5 gal. of water were collected in a plastic bucket, mixed thoroughly, and siphoned into triplicate pairs of light and dark bottles. Two additional bottles were also filled for determination of the initial oxygen concentration. The light and dark bottles were incubated on station by suspending them at a depth of approximately 0.5 m for 24 hours. The oxygen changes in the light bottles were multiplied by the average water depth to obtain an estimate of net planktonic production (g/m^2/day) for the 24 hour period (P_{net-24}). Similarly, the changes in the dark bottles were taken as total planktonic respiration over the 24 hours (R_{24}).

Oxygen Uptake by Concentrated Zooplankton

Zooplankton respiration was estimated based on oxygen changes in BOD bottles to which portions from concentrated zooplankton samples were added. Zooplankton samples were collected by filtering 5 to 10 m^3 of water through a 202 μ mesh (relaxed) zooplankton net. The concentrated sample was diluted to a known volume (1000 ml) with raw sea water and mixed gently. Small portions (5-10 ml) of the diluted zooplankton sample were carefully added to 3 partially filled BOD bottles which were then filled with sea water, stoppered, and suspended in the water on site for incubation. Three additional bottles were filled only with sea water as controls. The remainder of the zooplankton sample was preserved with buffered formalin to be later dried at 60°C for 1-2 days and weighed. To account for variability between zooplankton tows, this entire procedure was generally performed in duplicate resulting in the incubation of 6 bottles with concentrated zooplankton and 6 control bottles.

The bottles were allowed to incubate for 5-6 hours during the winter and 2-4 hours during the summer. After incubation, the bottles were examined to determine if the zooplankton were still moving and then analyzed for dissolved oxygen. Results were discarded when O_2 dropped below 3 g/m^3 and/or zooplankton died during incubation. This occurred once in 18 experiments. Zooplankton respiration was calculated as

$$R = \frac{(\Delta O_2)(v)}{(t)(V)(f)(Z)}$$

where R was the respiration rate in g O_2/g dry wt./hr., ΔO_2 was the observed oxygen change in the BOD bottles (g/m^2), v was the volume of the BOD bottles ($3 \times 10^{-4} m^3$), t was the duration of the experiment (hrs), V was the volume of water concentrated for the zooplankton sample (m^3), [illegible] was the fraction of the zooplankton sample placed in the BOD bottles, and Z was the concentration of zooplankton in the open water column (g dry wt/m^3).

Zeiss (1963) showed that respiration of some planktonic species (Daphnia magna) increased significantly during concentrated conditions while other species (Calanus finmarchicus) showed no metabolic change with concentration. Some error was possibly introduced in this present study since effects of concentration were not accounted for. The degree to which zooplankton were injured or killed by collection also contributed error which was not accounted for in these experiments.

Light Penetration

The penetration of sunlight through the water column was determined from submarine photometer data and from secchi disc observations.

With the submarine photometer (T.S. Submarine Illuminance Meter S/N 88/30) light intensity was measured at 0.1 m depth intervals from the water surface to the bottom. Each measurement was compared with surface illumination as indicated by a "deck" cell. The percent of surface light remaining at each depth interval was then calculated and plotted as shown in Fig. 8. Light intensity generally decreased exponentially with depth through the water column as expressed by

$$I_2 = I_1 e^{-k \, (Z_2 - Z_1)}$$

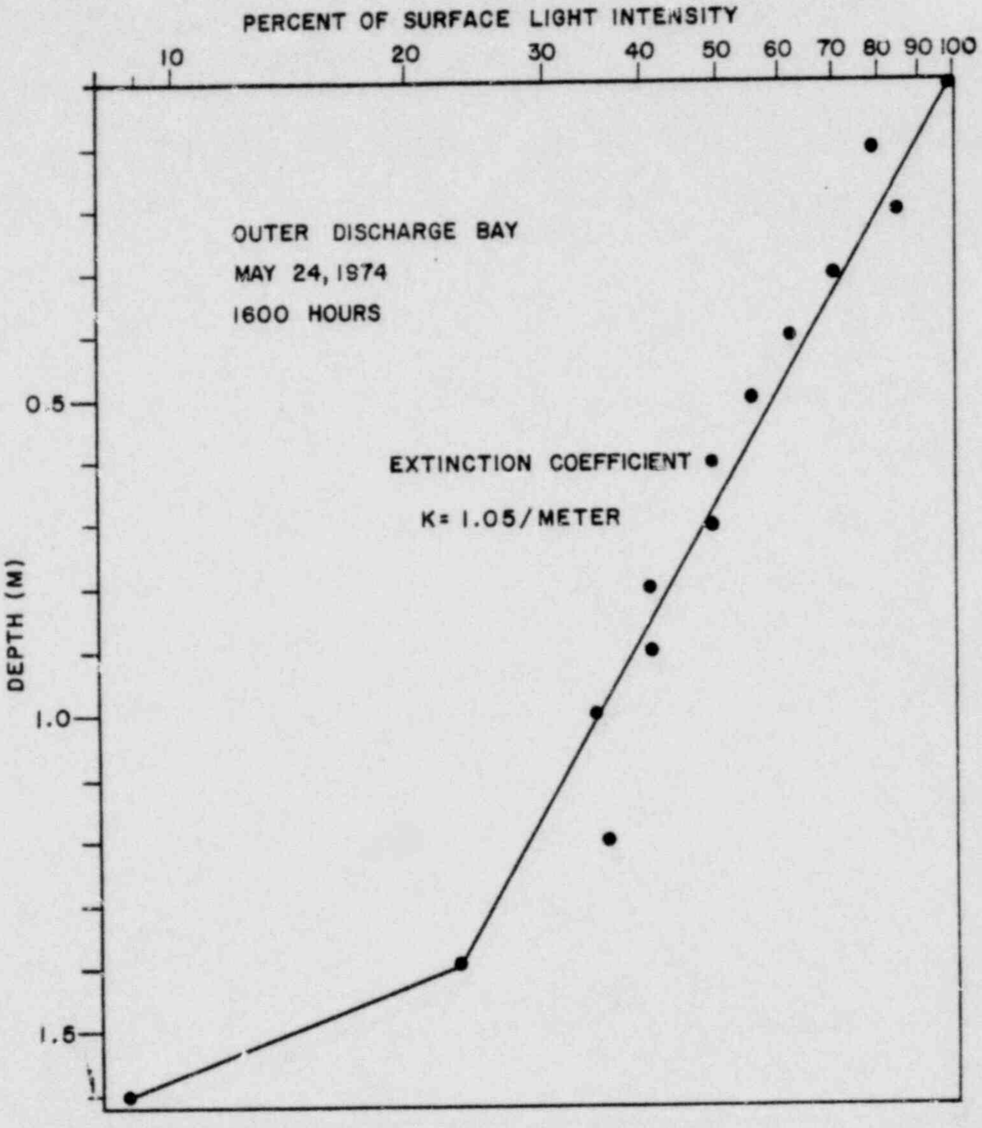


Fig. 8. Example of light penetration data obtained with a submarine photometer.

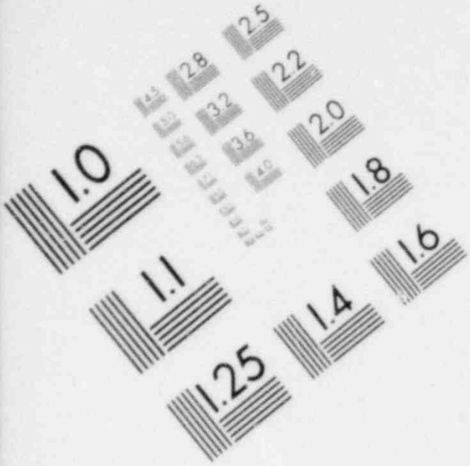
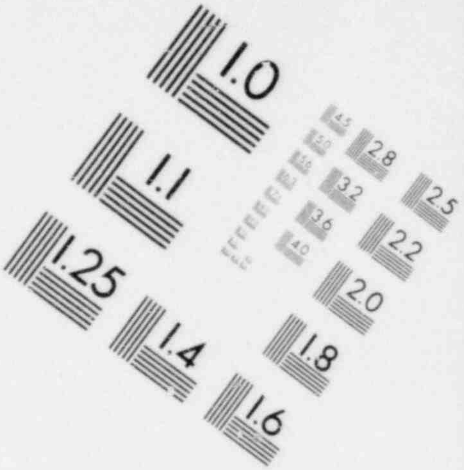
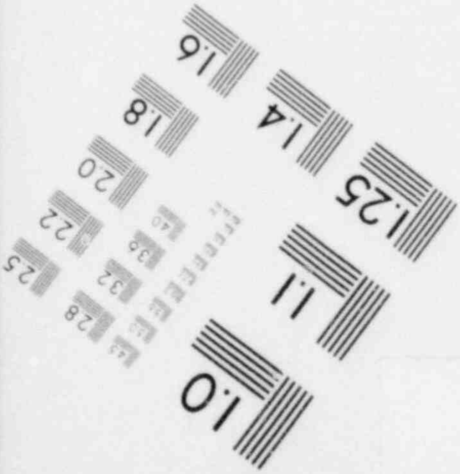
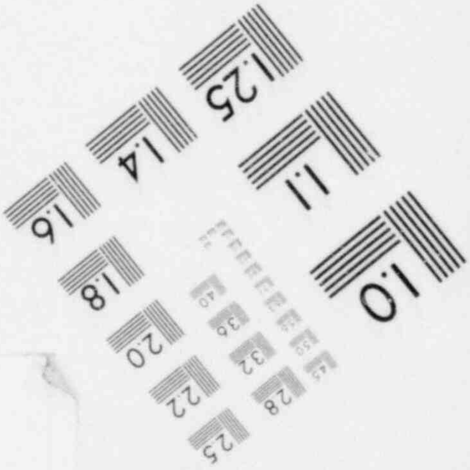



IMAGE EVALUATION
TEST TARGET (MT-3)

MICROCOPY RESOLUTION TEST CHART

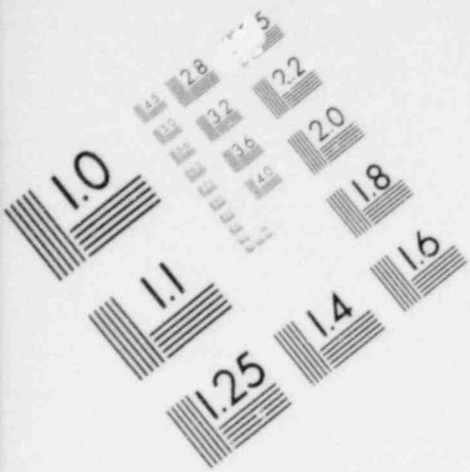
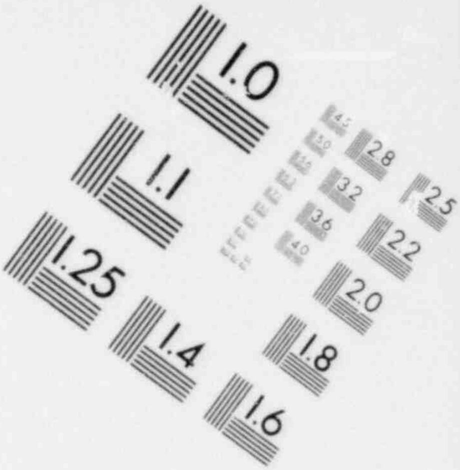
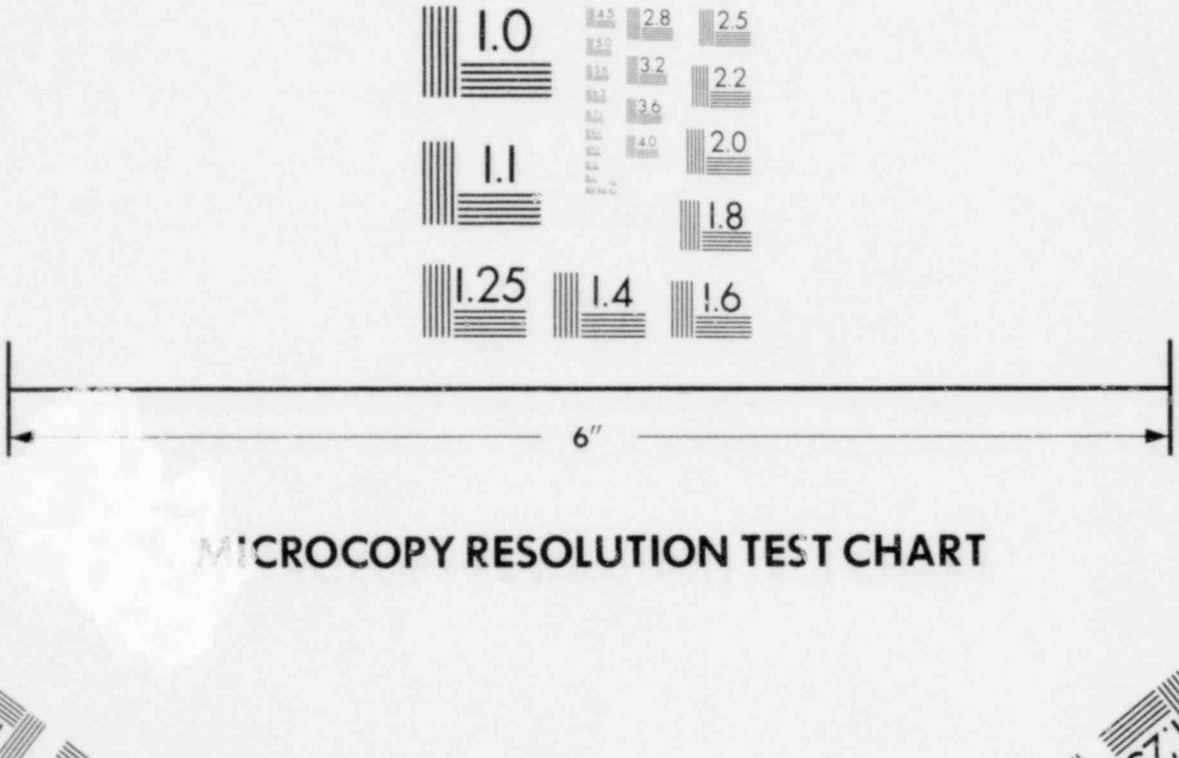
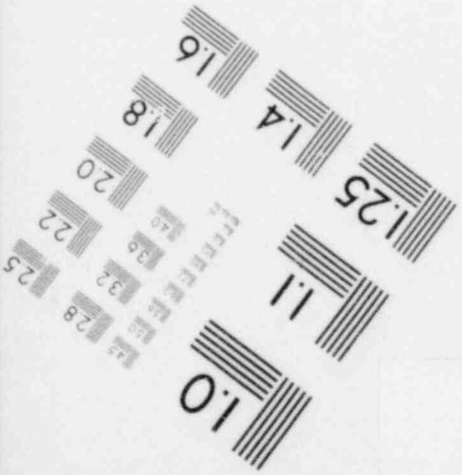
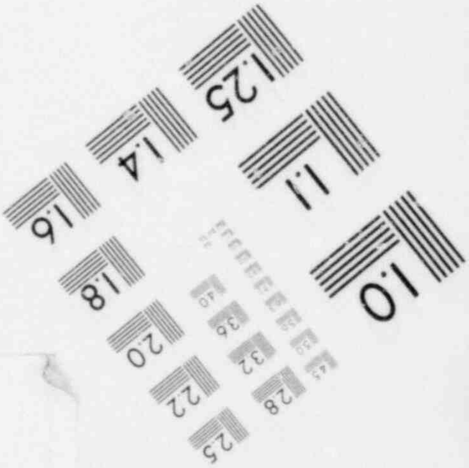



IMAGE EVALUATION
TEST TARGET (MT-3)



MICROCOPY RESOLUTION TEST CHART

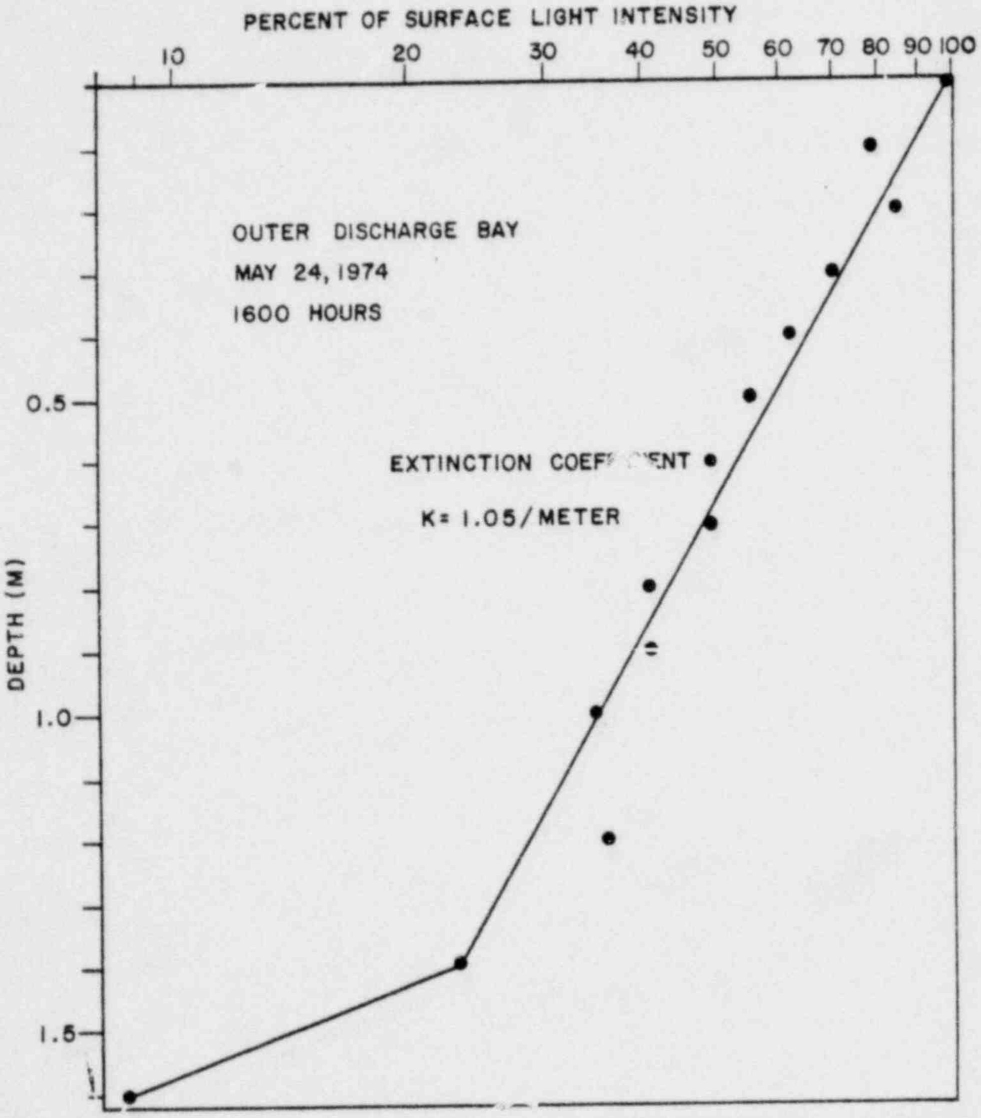


Fig. 8. Example of light penetration data obtained with a submarine photometer.

where I_2 is the light remaining at depth Z_2, I_1 is the light intensity at a lesser depth (Z_1), and K is the light extinction coefficient in meters^{-1}. Therefore with data as plotted in Fig. 11 the extinction coefficient was calculated as

$$K = \frac{\ln (I_1/I_2)}{Z_2 - Z_1}$$

When the secchi disc was used, light extinction coefficients were calculated as

$$K = 1.7/d$$

where d was the depth at which the secchi disc disappeared.

Phosphorous and Planktonic Chlorophyll

At approximately quarterly intervals, water samples were taken from 6 stations in the vicinity of the Crystal River power plants and analyzed for phosphorus fractions, planktonic chlorophyll, and pheo-pigments. At each sampling data duplicate samples were taken from 2 stations in the control area just south of the intake canal spoil banks (area C1, Fig. 2), one station in the intake canal, one at the mouth of the discharge canal, and two stations in the outer discharge area (D1, Fig. 2). Approximately 4 liters of water were collected from a depth of about 20 cm for each sample. Duplicate samples were collected from each station about 1 min. apart. Samples were placed on ice and kept in the dark until they were filtered for analysis 1-2 hours after collection.

Total phosphorus was determined on unfiltered samples by the persulfate oxidation method of Menzel and Corwin (1965). Total dissolved phosphorus was determined also by the persulfate oxidation method performed on samples that had been filtered through a 0.45 μ, acid washed, membrane filter. Dissolved inorganic phosphorus was determined on filtered water by the single-solution, molybdenem-blue method of Murphy and Riley (1962). Samples for dissolved inorganic phosphorous determinations were preserved with 40 mg/l mercuric chloride and refrigeration. Analyses were performed within one week of collection. Suspended particulate phosphorus was taken as the difference between total phosphorus and total dissolved phosphorus. Dissolved organic phosphorus was taken as the difference between total dissolved phosphorus and dissolved inorganic phosphorus.

One to two liters of sample water were also filtered through glass-fiber filters which were frozen and kept in the dark for later chlorophyll determinations. For analysis, the filters were homogenized in 90% acetone, placed in the dark, and refrigerated for pigment extraction. After at least one hour the samples were centrifuged and the supernatant was analyzed spectrophotometrically for chlorophyll-a and pheo-pigments (Lorenzen, 1967).

Distribution of Phosphorus, Chlorophyll, and Zooplankton Across the Gulf Shelf

Using Florida State University research vessel, R/V Tursiops, samples were taken in transects across the Gulf shelf from approximately 100 miles out in the open Gulf to the vicinity of the Crystal River power plants. Fig. 9 shows the station locations and Fig. 10 shows the slope of the continental shelf along this transect.

At offshore station A single samples were taken at the surface, 10m, 25 m, 50 m, and 80 m from a water column approximately 100 m deep. At offshore station B samples were taken at surface, 10, 25, and 45 m from a total depth of 50 m. At all other stations water samples were taken only from the surface and bottom in water columns 5-10 m deep. All samples were analyzed in duplicate for phosphorus fractions and chlorophyll as described above.

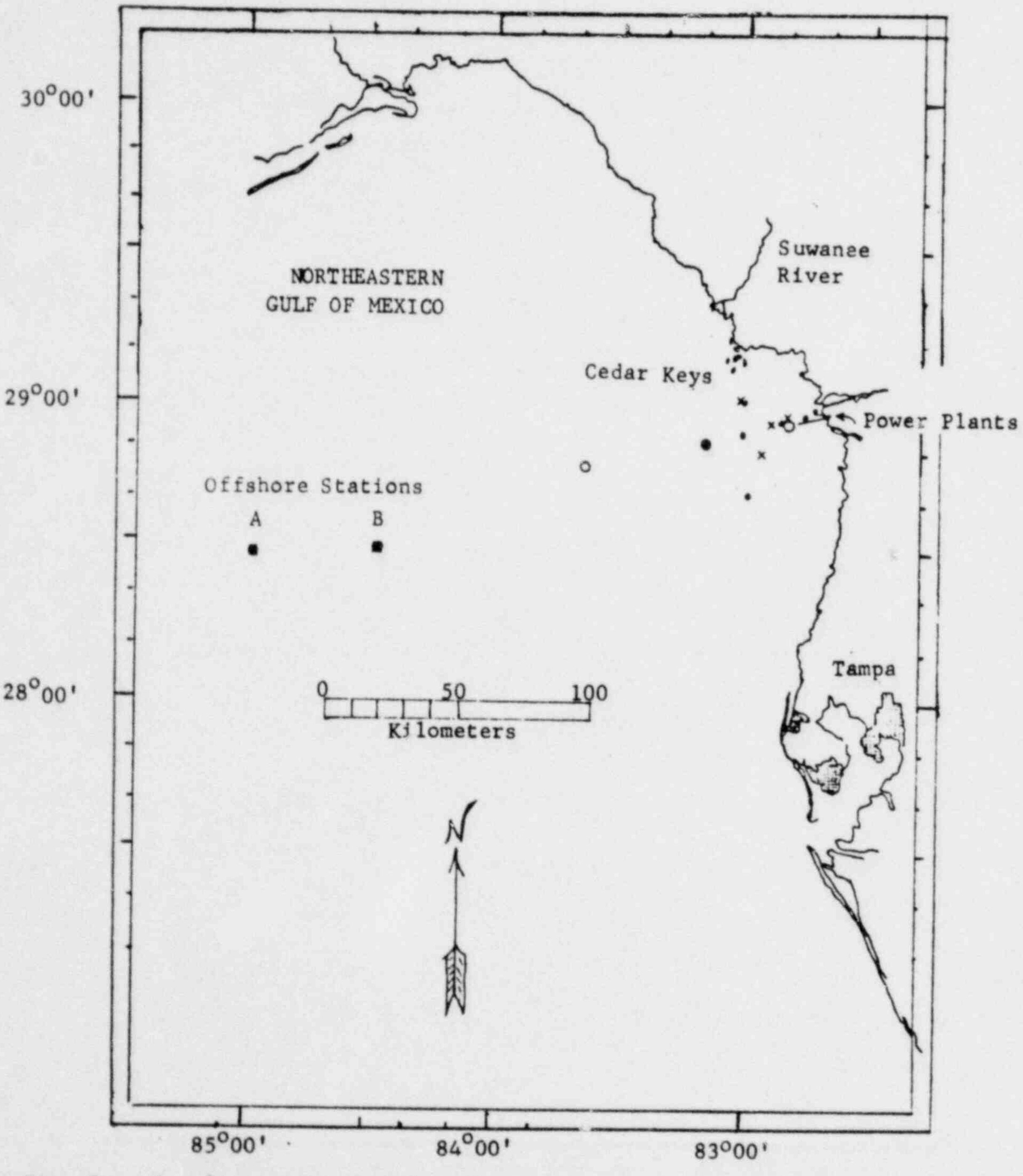


Fig. 9. Sampling stations taken from R/V Turisops on the Northeastern Gulf of Mexico continental shelf., November 25,1972 (o), March 18-19, 1973 (x), June 1-2, 1973 (.).

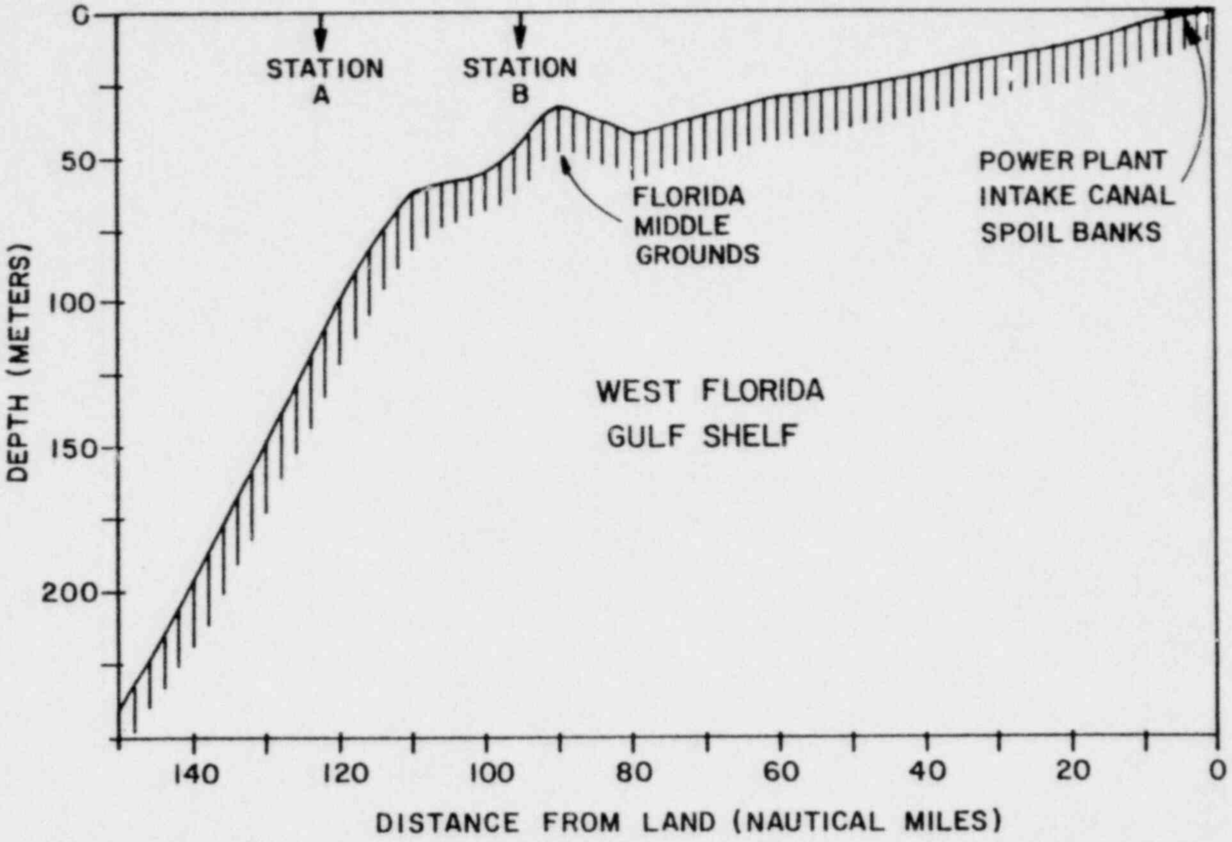


Fig. 10. Continental shelf profile from the open Gulf of Mexico at 28°29'N, 84°57'W to the West Florida Coast at the Crystal River power plants (28°58'N, 82°44.5'W)

Zooplankton samples were collected at the deeper stations (A and B) by vertical plankton tows with a 0.5m, 202 u mesh-size plankton net. At shallower stations, zooplankton samples were collected by towing the net horizontally behind the ship underway at approximately 0.5-1.0 knot. Zooplankton samples preserved in borax buffered formalin for later drying and weighing.

Systems Comparisons

The data obtained as described above were combined with other available data to evaluate the major components of the energy circuit diagram. Data on organism biomass, needed to quantify internal energy storages in primary procedures, zooplankton, macro-invertebrates, and fish, were collected by other researchers under contract with Florida Power Corporation. These and other data from the Crystal River bays were available in quarterly Environmental Progress Reports.

The quantified energy diagrams for the discharge and control bays facilitated the direct comparison of data from the two systems. With this format data were organized to indicate differences between the discharge and control systems with regards to total energy flow, componenet biomass, exchange rates, and metabolic turnover rates. For comparison, compartment storages were generally expressed in units of grams organic matter/m^2. Accordingly, exchange rates were expressed in g/m^2/day. Storage and flows of nutrients were expressed in units of grams of total phosphorus per m^2.

RESULTS

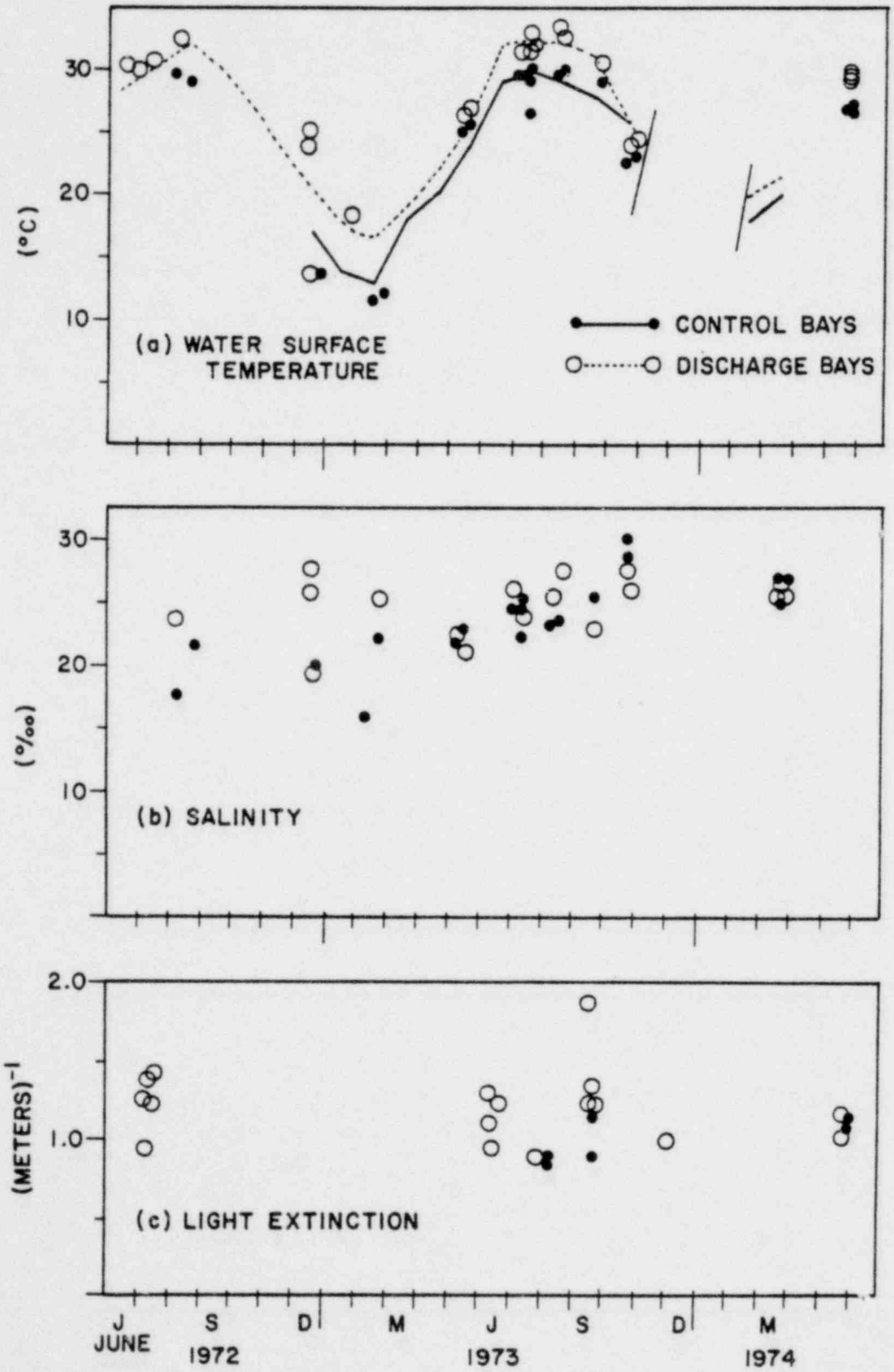
The effects of the Crystal River power plants on the outer bay ecosystems were studied through systems models which were evaluated with direct field measurements. The energy circuit diagram in Fig. 1 was presented as a conceptual model summarizing ecosystem structures and functions and interactions with the power plant. Given here, are the results of field measurements with which major variables in the model were quantified. Completely evaluated energy diagrams are presented which enable direct comparison between the control and discharge bay systems with respect to energy flows and storages.

Field Measurements

Temperature, Salinity, and Light Penetration

Water immediately discharged from the power plants was generally 5-6°C warmer than ambient water temperatures. Although patches of undiluted plume water were often observed in the outer discharge bay, average temperatures generally reflected considerable mixing of the plume with water masses of ambient temperature (Fig. 11a). When both of the power plants were operating, the thermal discharge volume was about 3.5×10^6 m^3/day (640,000 gallons/min.) and the water in the outer discharge bay retained an average temperature about 3°C warmer then water in the outer control bays. When only one of the two power plants was on line (such as in May, Sept., Oct., 1973) the thermal discharge volume was reduced by about 50% with a corresponding reduction in the average temperature differences between the discharge and control bays. Maximum temperatures for both control and discharge bays (30° and 33°C,

Fig. 11. Water temperature, salinity, and light extinction in the outer control and discharge bays. (a) Water temperature is shown with data points representing average diurnal temperatures measured during metabolism studies. Lines are drawn monthly temperature means from continuous temperature recordings provided by Florida Power Corporation. (b) Salinity points represent average diurnal values measured during metabolism studies. (c) Light extinction coefficients were calculated from secchi disc depths (d) where $(K=1.7/d)$ and from submarine photometer data $(K=(\ln (I_1/I_2))/Z_2-Z_1))$


30
20
10
(°C)
(a) WATER SURFACE TEMPERATURE
CONTROL BAYS
DISCHARGE BAYS
30
20
10
(°/oo)
(b) SALINITY
2.0
1.0
(METERS)$^{-1}$
(c) LIGHT EXTINCTION
J
JUNE
S
1972
D
M
J
1973
S
D
M
1974

respectively) were observed in August (1972 and 1973) with a minimum temperature of 12°C recorded in February. Diurnal variations of water temperature were generally within a range of 2°C about the mean diurnal temperature in the control bays and 3-4°C about the mean in the discharge bay (McKellar, 1974).

Salinity in the outer bays fluctuated between 20 and 30 o/oo (Fig. 11b). Before spring, 1973, control data were taken from the bays near the Withlacoochee and Crystal Rivers (See Fig. 2). Salinities at these sites were about 5 o/oo lower than in the bays near the power plants. From May 1973 through May 1974 control data were taken from the outer bay just south of the intake canal spoil banks of the power plant. Here, salinities averaged about 25 o/oo and were similar to those measured in the outer discharge bay. Diurnal variations of salinity were usually within a range of 4-5 o/oo about the average in both bays (See McKellar, 1974).

Data from secchi disc observations and submarine photometer readings were used to calculate light extinction coefficients for the bays (Fig. 11c). The average extinction coefficient found for the outer discharge bay was 1.2 ± 0.2 mater $^{-1}$. This value indicated that about 10% of sunlight at the water surface reached a depth of 2m (the average depth of the outer bays). The few measurements taken in the outer control bay showed an average extinction coefficient of 1.0 ± 0.1 meter^{-1} indicating that about 14% of the surface light reached a 2m depth. The differences in light penetration found between the control and discharge bays were not significant.

Total Community Metabolism

Estimates of community gross primary production and total community respiration were based on seasonal measurements of total community metabolism in the outer discharge and control bays. These data are summarized in Fig. 12 and 13 and Table 1. A tabulation of all data obtained in these metabolism studies is provided in McKellar (1974) which includes the dates, locations, number of stations and type of procedure used, diurnal ranges and means of water depth, temperature, and salinity.

Seasonal trends of community metabolism in the discharge and control bays were generally similar (Fig. 12). Winter-time lows were 1.5 to 2.0 g/m^2/day and summer-time highs were 3.5 to 4.0 g/m^2/day for both net daytime photosynthesis and nighttime respiration. However, the paired data for August, September, and October (1973) showed with 99% confidence that net daytime photosynthesis was consistently lower in the discharge area during these months. Also, with a lower degree of statistical confidence (80%) the paired data in May, 1974 indicated a higher rate of nighttime respiration in the discharge bay.

If daytime respiration was at least as large as nighttime respiration a minimal estimate of total community respiration would be $(2 \times R_{night})$. A corresponding estimate of total community gross primary production would be the sum of net daytime photosynthesis and nighttime respiration $(P_{net\ day} + R_{night})$. This approximation of gross production for the control and discharge bays showed seasonal fluctuations with a summer average of 7-8 g/m^2/day and a winter average of 3-4 g/m^2/day (Fig. 13). Again the trends for the thermally affected bays and control bays were very similar although some evidence existed indicating a possibly late summer and fall depression and a springtime stimulation of gross primary production in the discharge bays. The combined data for fall 1972 and 1973 (Table 1) provided 80% confidence for expecting that gross primary production was slightly lower in the discharge bays. The paired data for May, 1974 also provided similar levels of confidence indicating higher levels of gross primary production in the discharge bays in the spring (1974).

The ratio of net daytime photosynthesis to nighttime respiration indicated the degree of autotrophy or heterotrophy in these systems (Table 1). There were no significant differences between the P/R ratios in the control and discharge bays and none of the averaged ratios were significantly different from unity. These results indicated an overall balance of organic production and consumption in the outer bays near the power plant.

Plankton Metabolism

Light and dark bottle experiments were performed in winter, summer, and fall, 1973 and again in spring, 1974. A summary of these results (Table 2) shows the levels and relative importance of plankton metabolism in these estuarine bays. Details of these data are available in McKellar (1974).

Winter data indicated that plankton metabolism in the control and discharge bays was similar showing low levels of gross primary production

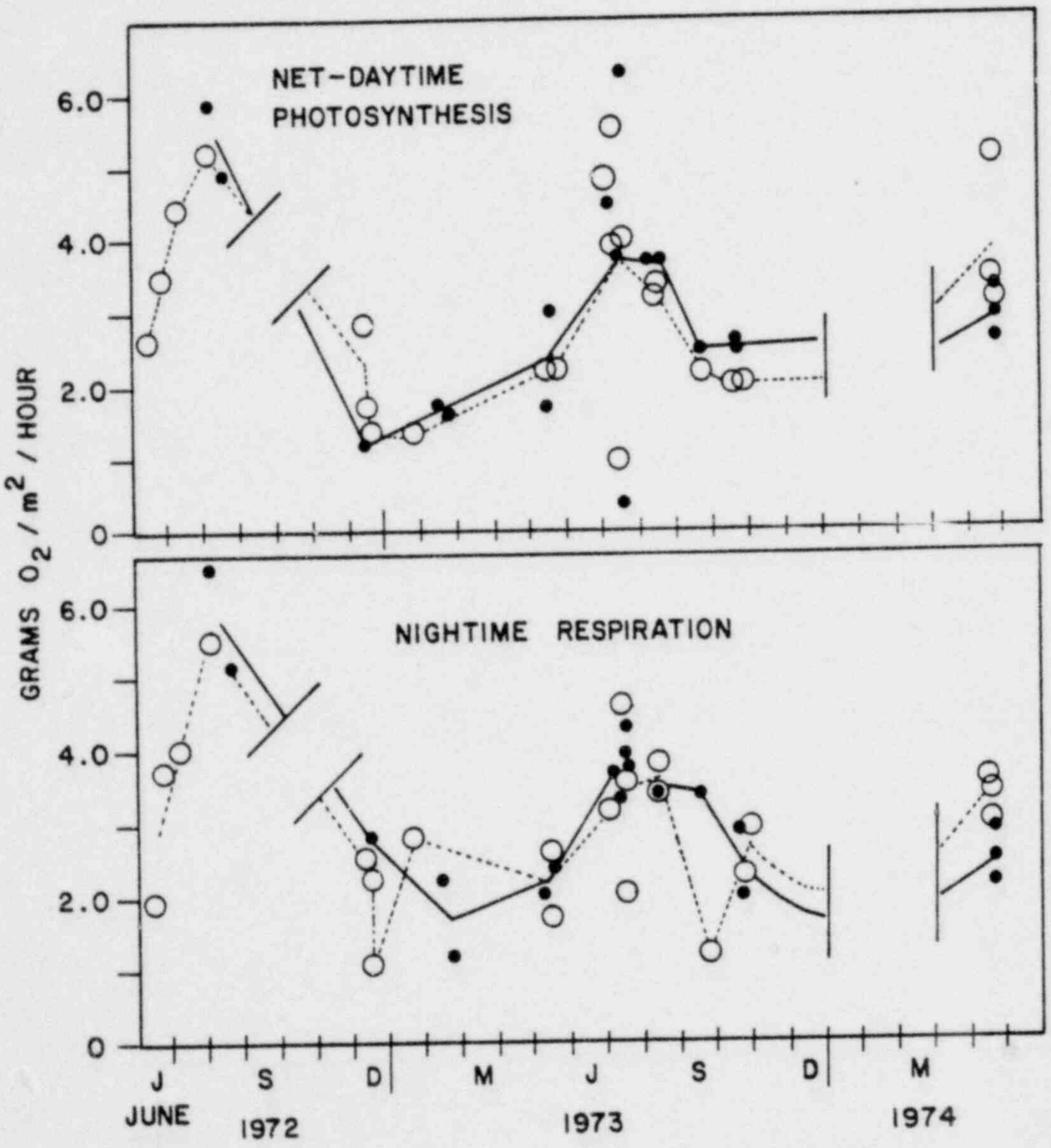


Fig. 12. Net daytime community photosynthesis and nighttime community respiration in the outer control (●---●) and discharge (O---O) bays.

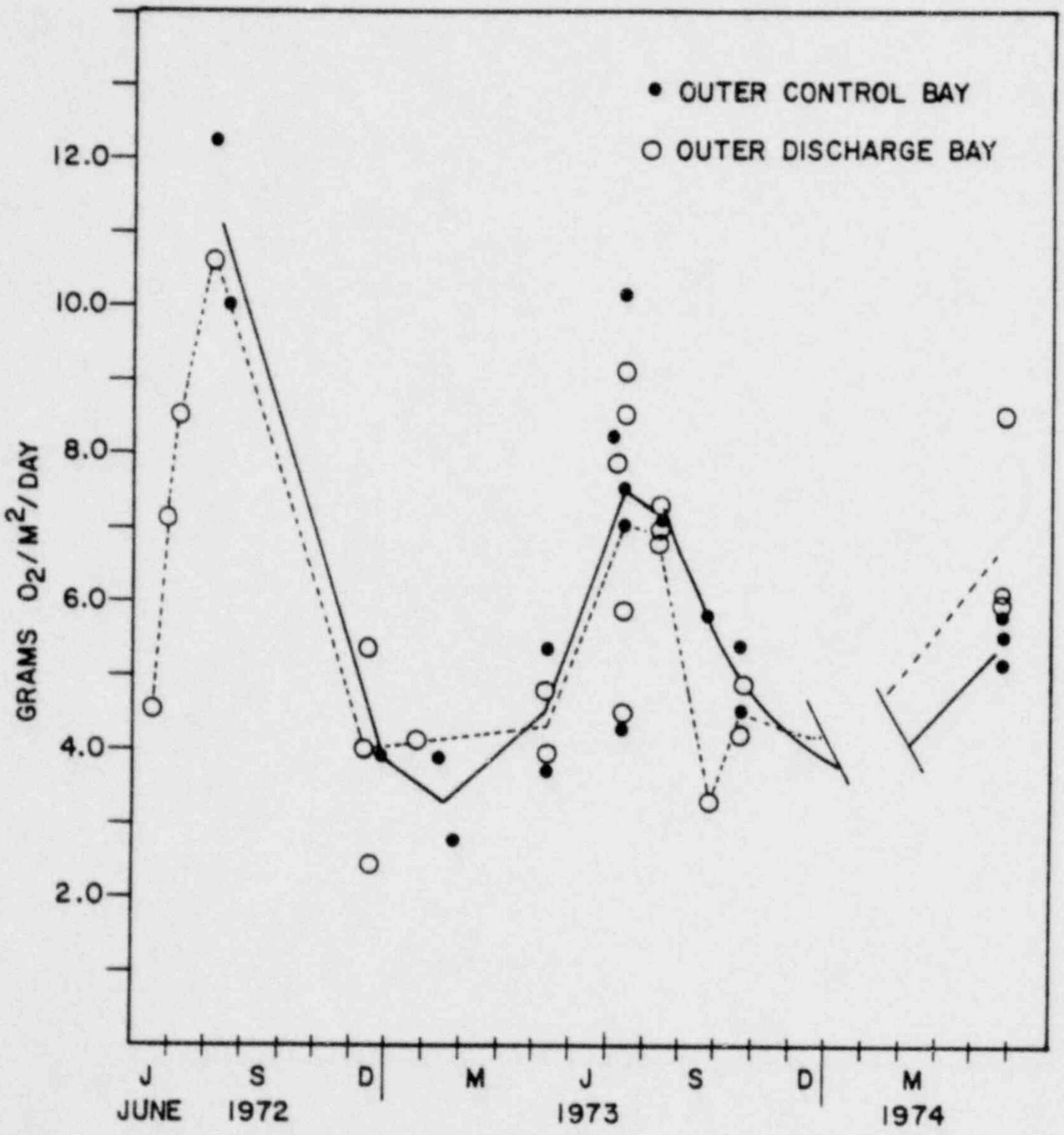


Fig. 13. Estimates of total community gross primary production calculated as $P_{net\ day} + R_{night}$.

Table 1.

Seasonal Averages of Total Community Metabolism ($gO_2/m^2/day$) in the Outer Control and Discharge Bays, 1972-1974.

			P Net Daytime Production		R Nighttime Respiration		P+R		P/R	
Season	Bay	n	Mean	(S. D.)	Mean	(S. D.)	Mean	(S. D.)	Mean	(S. D.)
Summer	Control	9	4.05	(1.74)	4.20	(1.02)	8.25	(2.30)	0.97	(.40)
	Discharge	11	3.75	(1.27)	3.57	(1.02)	7.32	(1.89)	1.08	(.42)
Fall	Control	3	2.52*	(0.045)	2.79	(0.70)	5.31*	(0.71)	0.94	(.24)
	Discharge	5	2.15*	(0.40)	2.24	(0.63)	4.39*	(0.80)	1.05	(.42)
Winter	Control	3	1.52	(0.31)	2.06	(0.83)	3.58	(0.66)	0.88	(.51)
	Discharge	2	1.32	(0.032)	1.96	(1.19)	3.28	(1.16)	0.83	(.52)
Spring	Control	5	2.74	(0.62)	2.41	(0.36)	5.15	(.82)	1.14	(.26)
	Discharge	5	3.20	(1.20)	2.68	(0.63)	5.88	(1.75	1.18	(.24)
Annual Mean	Control		2.71		2.87		5.58		0.98	
	Discharge		2.61		2.61		5.22		1.04	

n - Number of diurnal studies performed.
S.D. - Standard Deviation.
* Indicated control and discharge values are significantly different with 80% confidence as shown by two-sample t-tests.

Table 2.

Seasonal Averages of Plankton Metabolism (g O_2/m^2/day) in the Outer Control and Discharge Bays.

			$P_{net\ 24}$		R_{24}		P_{gross}	
Season	Bay	n	Mean	(S.D.)	Mean	(S.D.)	Mean	(S.D.)
Winter 1973	Control	3	0	(.30)	0.31	(.32)	0.31	(.14)
	Discharge	2	−0.47	(.36)	0.97	(.70)	0.50	(.35)
Summer 1973	Control	2	0.04*	(.50)	1.17	(.06)	1.21*	(.43)
	Discharge	2	3.58*	(.26)	1.03	(.22)	4.61*	(.10)
Fall 1973	Control	2	0.71	(.32)	0.76	(1.02)	1.55	(.7)
	Discharge	2	1.27	(1.05)	2.52	(1.79)	3.78	(2.80)
Spring 1974	Control	1	4.14		0.51		4.65	
	Discharge	1	2.85		0.52		3.37	
Annual Mean	Control		1.24		0.69		1.93	
	Discharge		1.80		1.26		3.06	

n - Number of light and dark bottle experiments.

S.D. - Standard deviations.

* indicates control and discharge values were significantly different with 95% confidence as shown by two-sample t-tests.

(^{P}gross $<$ 1.0 g/m^2/day), and some net consumption of organic matter (^{P}net 24 $<$ 0). Data for all other seasons generally showed strong autotrophic tendencies (^{P}net 24 $>$ 0) for plankton communities in both bays with net daily production values of 3 to 4 g/m^2/day in the spring and summer.

Summer values in the control bays showed an approximate 4-fold increase of both gross planktonic porduction and respiration over winter values. In the discharge bay, respiration was similar to winter values, but gross production had increased approximately 10-fold. Whereas respiration in the two systems was similar gross production and corresponding levels of net production were significantly higher in the discharge bay during the summer studies. Average fall metabolism values in the discharge bay were not significantly different from those in the control bays. The single experiment in bay system for spring, 1974 showed similar respiration rates but higher rates of gross and net production in the control bay.

On an average, the outer control bay was more benthic dominated with planktonic production generally comprising less than 50% of the total community gross production (^{P}net day + ^{R}night, Table 1). The outer discharge bay was apparently more plankton dominated where planktonic production was generally more than 50% of community production.

Oxygen Consumption by Concentrated Zooplankton

Zooplankton biomass and rates of oxygen consumption were determined during the winter and late summer. Results of these studies indicate the seasonal trends of zooplankton respiration in the outer bays. These data are presented in detail in **McKellar (1974)** and are summarized here in Table 3.

In general, the agreement of oxygen uptake among replicate bottles in each experiment was good with a mean coefficient of variation usually less than 20% (see Appendix). Although agreement between separate experiments during

Table 3.

Biomass and Oxygen Consumption of Concentrated Zooplankton in the Outer Control and Discharge Bays.

				Biomass* (g dry wt/m^3)		Oxygen Consumption (g O_2/g dry wt/hr)**		
Season	Bay	Temperature (°C)	n	Mean	(S.D.)	Mean	(S.D.)	(g O_2/m^2/day)***
Winter	Control	13.2 - 14.2	3	0.066	(.023)	0.006	(.002)	0.019
Summer	Control	29.0 - 30.2	7	0.086	(.046)	0.023	(.019)	
	Discharge	30.9 - 33.0	7	0.058	(.042)	0.033	(.020)	
	(Combined)	29.0 - 33.0	14	0.072	(.042)	0.028	(.018)	0.097

* Biomass in the open water column.

** Oxygen consumption while concentrated in BOD bottles.

*** Calculated for the open water column with a 2m depth, (g dry wt/m^3) x (g O_2/g dry wt/hr) x (24 hr/day) x (2m) the winter was also good (Table3) variations during the summer were large with standard deviations representing 60 to 90% of the mean oxygen uptake value.

Even though some of the summer experiments showed oxygen uptake rates which were similar to those found in winter, the combined summer average for control and discharge bays was almost five times higher than the winter average (99% confidence).

Daily oxygen consumption by zooplankton per m^2 during the winter was about 3% of total planktonic respiration (see Table 2, R_{24}) and about 0.5% of total community respiration (see Table 1, 2 x R_{night}). The relative magnitude of zooplankton respiration had increased by summer to a combined summer average representing about 9% of total planktonic respiration and about 1.3% of total community respiration.

Chlorophyll and Phosphorus

Outer Bays. Chlorophyll-a fluctuated in both bays from winter time concentrations around 1 mg/m^3 to spring and summer peaks around 5 mg/m^3 (Fig. 14). On a given date large differences in chlorophyll concentration existed between the control and discharge bays. At the measured peak of the spring phytoplankton bloom in the control bay chlorophyll concentrations were ca. 3 mg/m^3 higher than in the discharge bay. In early may, August, and early December, chlorophyll concentrations in the discharge bay were ca. 2 g/m^3 higher than in the control bay. Chlorophyll-a concentrations perhaps reflected rates of planktonic productivity which were found to be higher in the control bay during the spring and higher in the discharge bay during the summer (table 2).

The stock of degraded chlorophyll (pheo-pigments) followed the general seasonal trends of chlorophyll-a with fluctuations from undetectable concentrations to nearly 2 mg/m^3 (Fig. 14). No apparent differences were shown between control and discharge bays with respect to the relation between chlorophyll-a and its degradation products.

The seasonal trends of chlorophyll-a were also reflected by changes of total phosphorus in the water column (Fig. 15a) which varied from winter concentrations around 30 mg/m^3 to spring and summer values around 60 mg/m^3. As was found for chlorophyll-a, the maximum total phosphorus concentration was measured in the control bay during the spring and in the discharge bay during the summer. The annual mean concentrations of total phosphorus were similar for both bay systems (Table 4).

Seasonal fluctuations in total phosphorus were due mainly to changes in suspended particulate phosphorus (Fig. 15b). Particulate phosphorus usually comprised most of the phosphorus in the water column with an exception being shown by the December samples when total phosphorus in both bays was more evenly distributed among all three fractions. Seasonal fluctuations of particulate phosphorus resembled those found for chlorophyll (Fig. 14).

Dissolved inorganic phosphorus was consistently higher in the discharge bay throughout the year (Fig. 15). Paired t-tests for the sampling dates in 1973 showed that dissolved inorganic phosphorus in the discharge bay was significantly higher (95% confidence) with a mean difference of about 4 mg/m^3. The maximum differences were found in August and September when water temperatures were near the seasonal maximum (Fig. 11a) and minimum differences were found in February and May.

Canals. Measurements of chlorophyll and phosphorus fractions in the intake canal and at the mouth of the discharge canal indicated possible changes in these materials as they passed through the power plants and into the plume-receiving bays. These data are shown in Figs. 16 and 17.

Concentrations of chlorophyll-a in the two canals were very similar (Fig. 16) with seasonal changes resembling those observed in the control bay (Fig. 14).

This relationship might be expected since a significant portion of the cooling water intake comes from bay areas just seaward of the outer control bay (see Fig. 2).

Concentrations of phosphorus in the power plant canals are shown in Fig. 17. The annual average concentrations of total phosphorus in the intake and discharge canals (39.9 and 44.0 mg/m^3, respectively) were very similar to annual averages in the control and discharge bays, respectively. Of the annual means, particulate phosphorus comprised about 50% of the total in the intake canal and about 40% in the discharge canal. Dissolved inorganic phorphorus in the intake canal comprised about 10% of the total; whereas in the discharge canal, this fraction was consistently about 10% higher than in the intake canal and comprised about 20% of the total phosphorus. This trend possibly indicated higher rates of phosphorus regeneration in the warmer waters of the discharge canal.

Distribution of Phosphorus, Chlorophyll, and Zooplankton Across the Gulf Shelf

Phosphorus, chlorophyll, and zooplankton concentrations were measured during cruises across the continental shelf to the vicinity of the Crystal River power plants. Cruises were made in November (1972), March, and June, 1973) when data were collected to examine the lateral structure of cross-shelf gradients. Station locations were shown in Fig. 12 and detailed tabulation of the results are available in Appendix C. Also given in Appendix C are graphs showing some seasonal changes in the vertical structure of waters over the outer shelf.

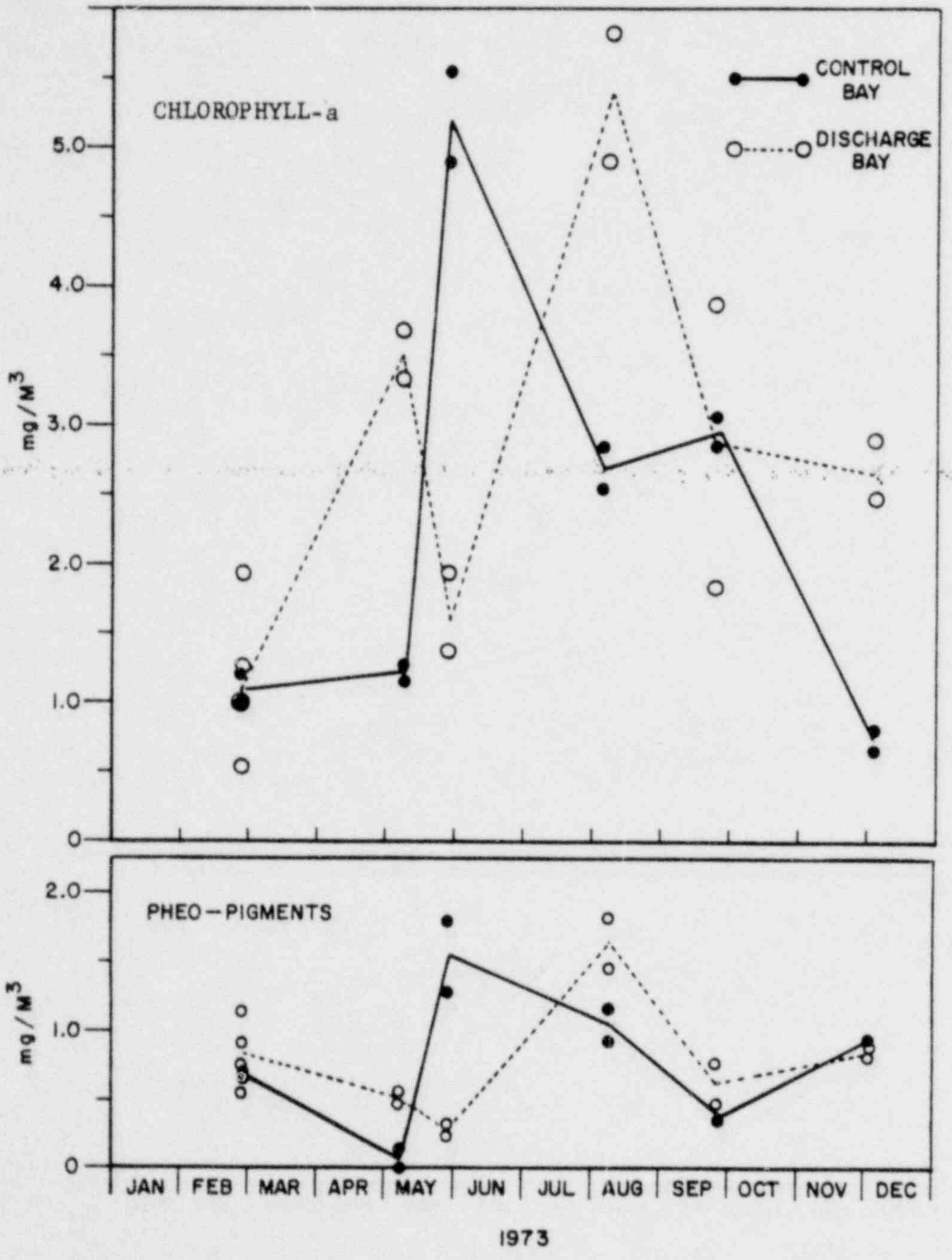


Fig. 14. Chlorophyll-a and pheo-pigment concentrations in the outer bays. Each point represents the average of duplicate samples take at a single station.

Table 4.

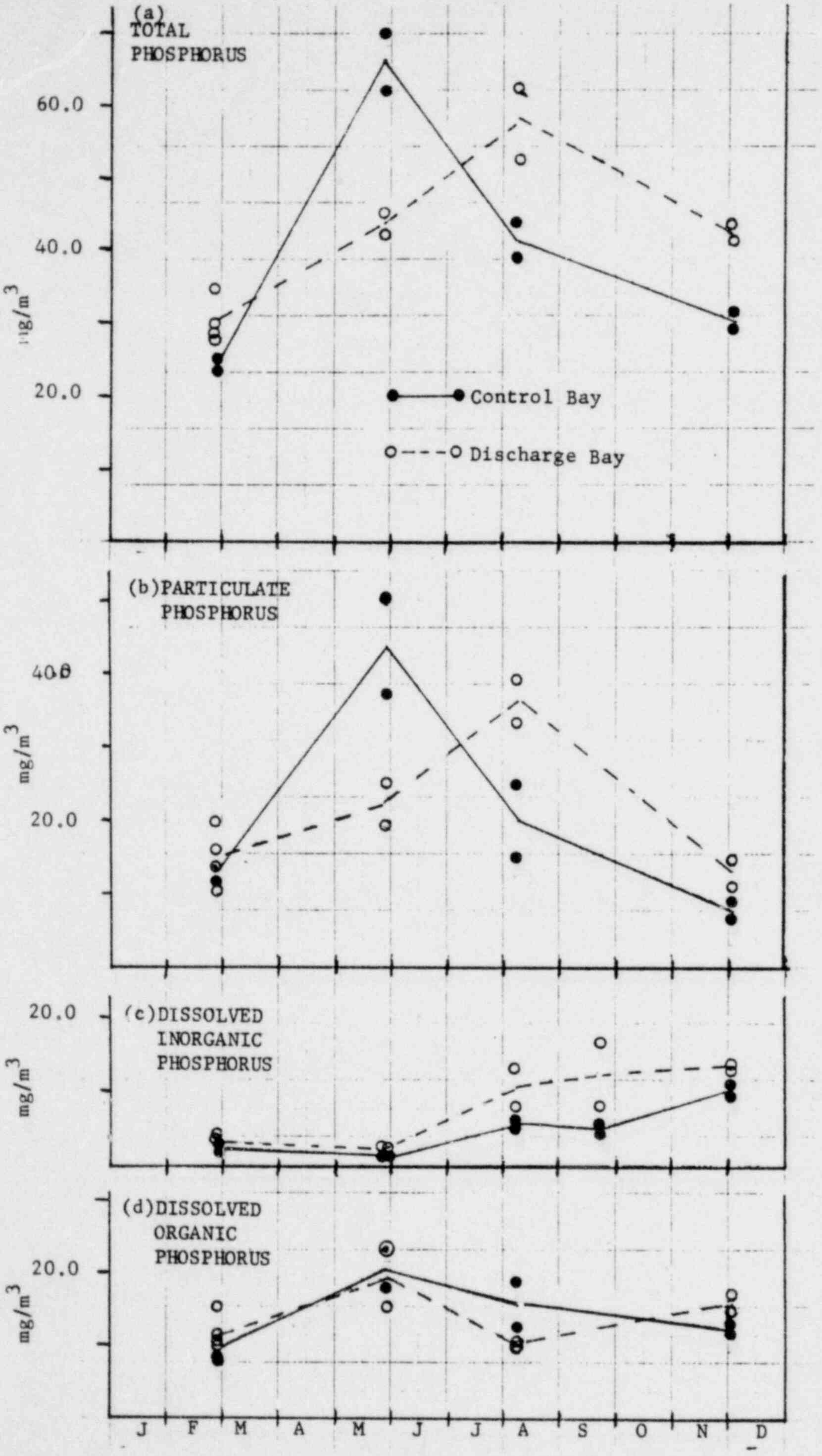
Seasonal Averages of Chlorophyll-a and Total Phosphorus (mg/m^3) in the Outer Control and Discharge Bays (1973).

		Chlorophyll-a			Total Phosphorus		
Season	Bay	n	Mean	(S.D.)	n	Mean	(S.D.
Winter	Control	2	1.10	(0.14)	2	24.2	(1.2)
	Discharge	4	1.17	(0.60)	4	30.4	(3.1)
Spring	Control	4	3.22	(2.33)	2	66.3	(5.9)
	Discharge	4	2.57	(1.12)	2	44.3	(1.9)
Summer	Control	2	2.67	(0.12)	2	42.3	(3.7)
	Discharge	2	5.37	(0.27)	2	58.8	(8.4)
Fall	Control	4	1.86	(1.29)	2	30.7	(1.9)
	Discharge	4	2.76	(0.83)	2	42.8	(1.9)
Annual Mean	Control		2.21			40.9	
	Discharge		2.97			44.1	

n - Number of duplicate samples taken

S.D. - Standard Deviation

Fig. 15. Phosphorus concentrations in the outer bays (1973)
(a) Total phosphorus in the water column, (b) suspended particulate phosphorus, (c) dissolved inorganic phosphorus (d) dissolved organic phorphorus. Each point represents the average of duplicate samples taken at a single station.


(a) TOTAL PHOSPHORUS
60.0
40.0
20.0
mg/m^3
Control Bay
Discharge Bay
(b) PARTICULATE PHOSPHORUS
40.0
20.0
mg/m^3
(c) DISSOLVED INORGANIC PHOSPHORUS
20.0
mg/m^3
(d) DISSOLVED ORGANIC PHOSPHORUS
20.0
mg/m^3
J
F
M
A
M
J
J
A
S
O
N
D

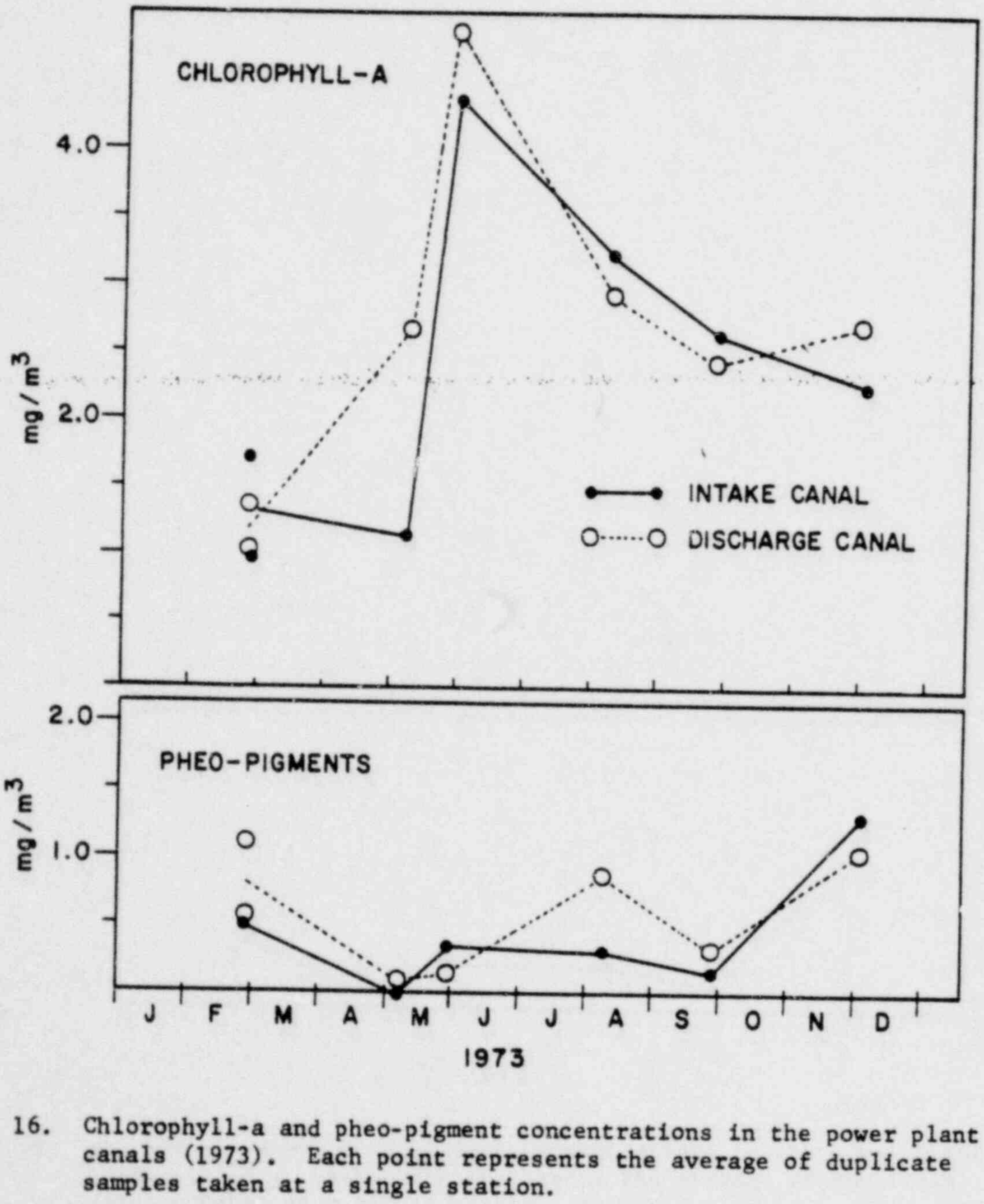
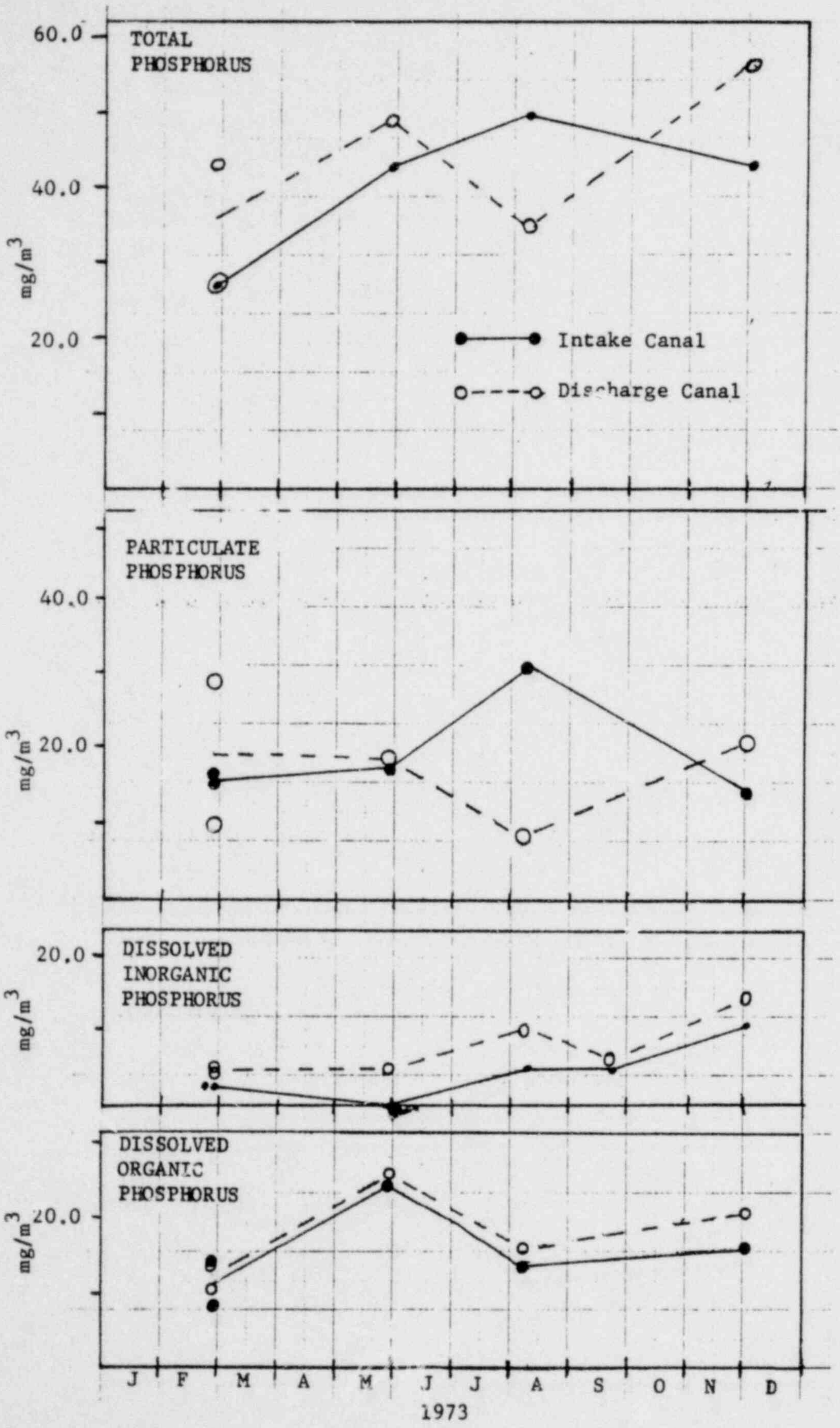


Fig. 16. Chlorophyll-a and pheo-pigment concentrations in the power plant canals (1973). Each point represents the average of duplicate samples taken at a single station.

Fig. 17. Phosphorus concentrations in the power plant canals (1973). (a) Total phosphorus in the water column, (b) suspended particulate phosphorus, (c) dissolved inorganic phosphorus (d) dissolved organic phosphorus. Each point represents the average of duplicate samples taken at a single station.


TOTAL
PHOSPHORUS
60.0
40.0
20.0
mg/m^3
Intake Canal
Discharge Canal
PARTICULATE
PHOSPHORUS
40.0
20.0
DISSOLVED
INORGANIC
PHOSPHORUS
DISSOLVED
ORGANIC
PHOSPHORUS
J F M A M J J A S O N D
1973

Distributions of temperature, salinity, plankton, and phosphorus across the Gulf shelf showed some transitions of water mass properties from the outer shelf to the coastal waters near the power plants. Cross-shelf gradients are shown in Fig. 18, 19, and 20 and are summarized in Table 5.

Temperature gradients across the Gulf shelf indicated the heat buffering property that was provided for shallow inshore areas through water exchange with the outer shelf. In November, the water over the outer shelf was about 6-7°C warmer than the cool water (13.5°C) at the most landward station about 7 miles from land (Fig. 18). Four months later, in March, the temperatures over the outer shelf and in coastal water were about the same at 20-21°C (Fig. 19). By June outer shelf water was 5 to 6°C cooler than the 30°C inshore waters that were not affected by the thermal plume (Fig. 20).

In general, concentrations of chlorophyll, phosphorus and zooplankton increased from the offshore stations, across the shelf, toward the coastal bays. In particular, chlorophyll-a concentrations in inshore waters during March and June were more than an order of magnitude higher than concentrations found over the outer shelf. Also, total phosphorus at the inshore stations was 35% to 80% more concentrated and particulate phosphorus was 100 to 200% more concentrated than in offshore waters. Fluctuations of total phosphorus across the shelf generally corresponded to changes in suspended particulate phosphorus which coincided with changes in chlorophyll and zooplankton.

Zooplankton were patchy in water masses within 25 miles of land. Concentrations were found ranging from levels characteristic of offshore populations (0.01 to 0.03 g/m^3) to concentrations as high as 0.29 g/m^3. Statistical comparisons of cross-shelf zooplankton concentrations showed no significant differences.

Evidence of lateral eddy exchange between offshore and coastal water masses was provided by the cross-shelf salinity distribution found in June (Fig. 20).

Salinity dropped at an average rate of 1 o/oo per 8 nautical miles from 95 miles seaward to land. The isolated salinity peak of 33 o/oo water at a station about 15 miles from land indicated the intrusion of an offshore eddy into waters of lower salinity (26-28 o/oo). This pocket of more saline water coincided with an abrupt drop in concentrations of phosphorus fractions and chlorophyll-a.

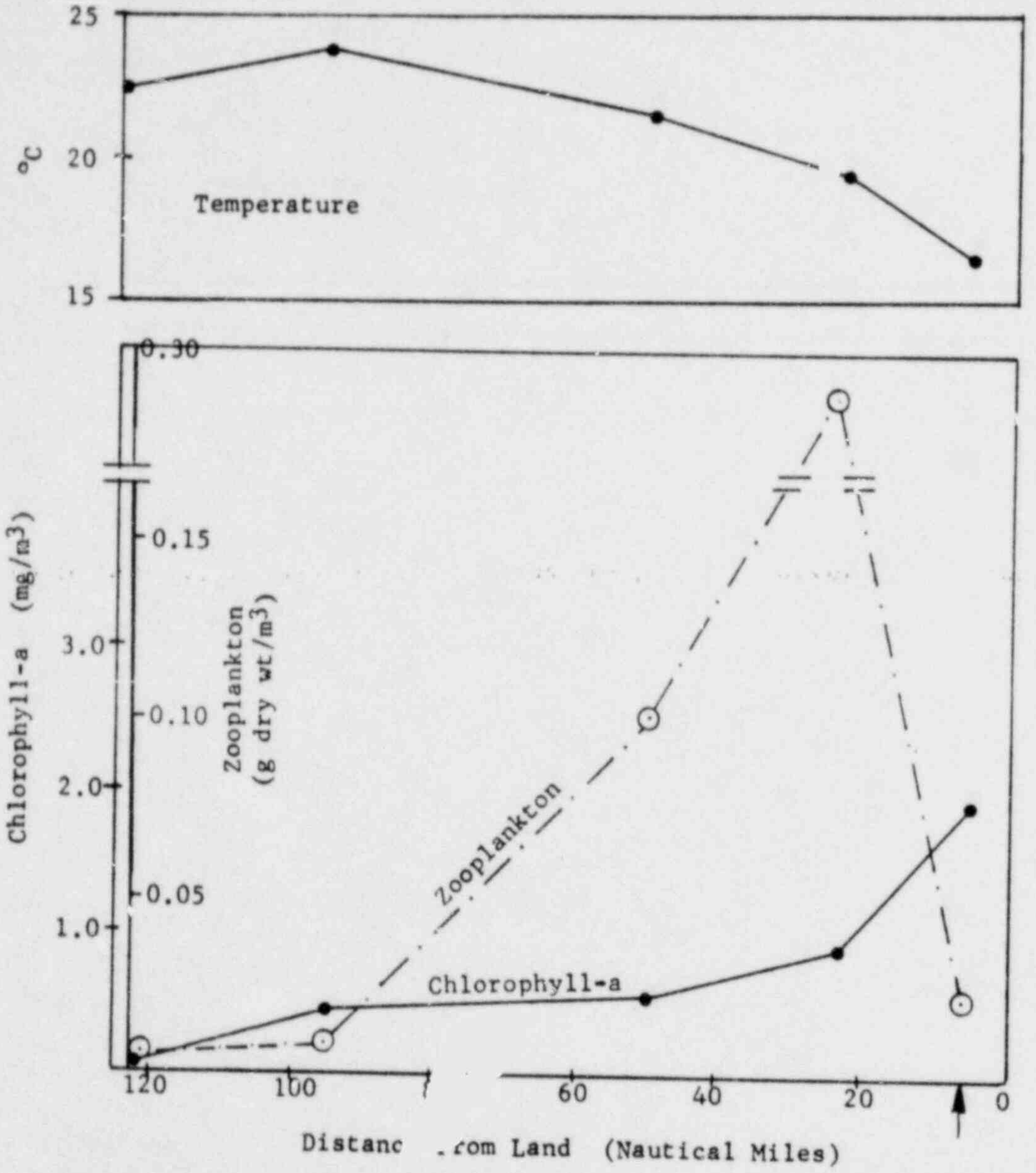


Fig. 18. Distributions of water temperature, chlorophyll, and zooplankton along a transect from the outer Gulf shelf to the vicinity of the Crystal River power plants, November 25,1972. Each point represents the weighted averages for the entire water column. The arrow on the lower right indicates the seaward extent of the power plant intake channel and spoil banks.

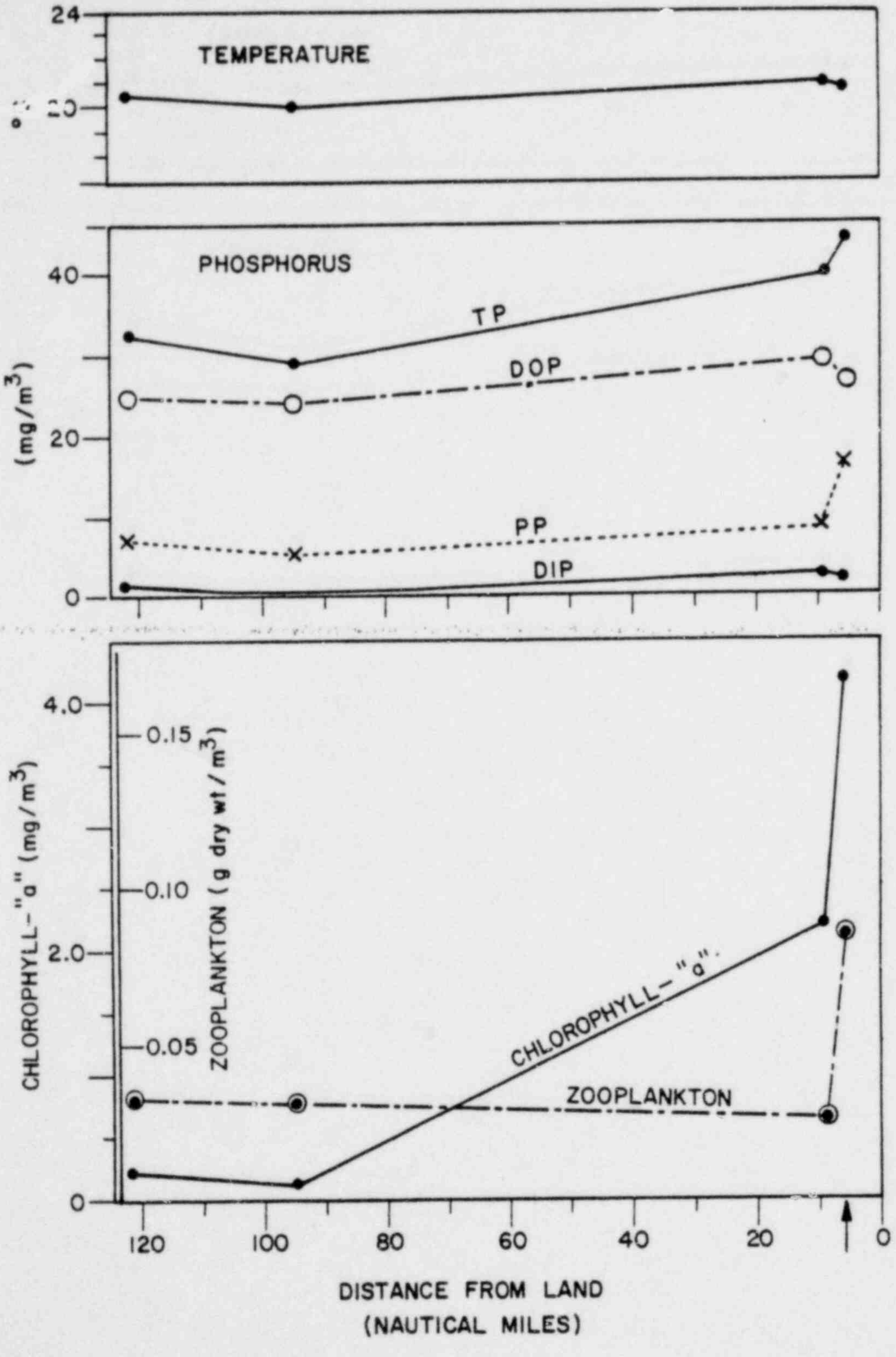


Fig. 19. Distributions of water temperature, phosphorus fractions, chlorophyll and zooplankton along a transect from the outer Gulf shelf to the coast near the Crystal River power plants, 18-19 March, 1973.

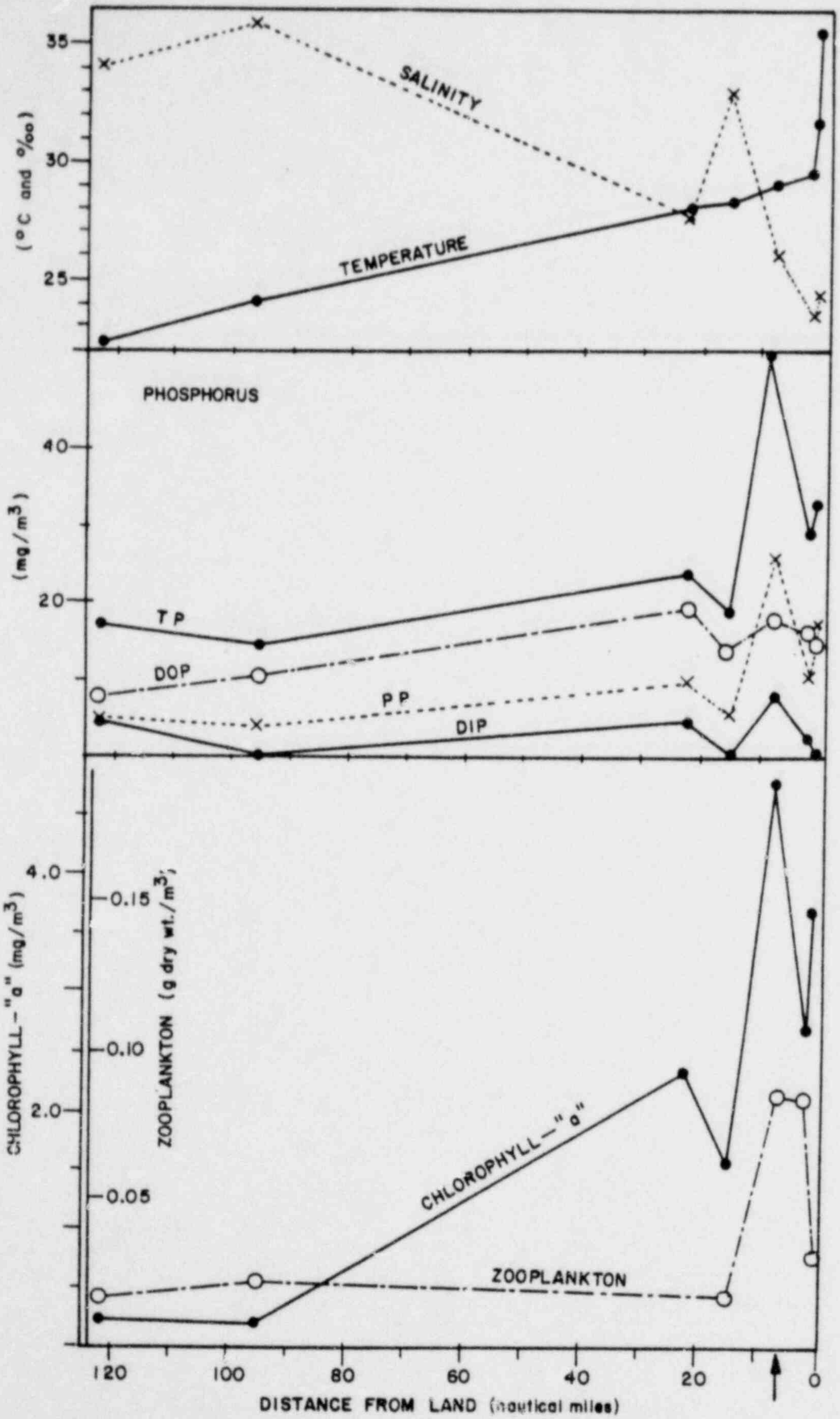


Fig. 20. Distributions of water temperature, salinity, phosphorus fractions and chlorophyll, and zooplankton along a transect from the outer Gulf shelf to the coast near the Crystal River power plants, 1-2 June, 1973.

Table 5.

Differences in Chlorophyll-a, Zooplankton, and Phosphorus Concentrations Between Inshore and Offshore Stations on the Gulf Shelf. Inshore values represent averages of stations taken within 25 nautical miles of land; offshore values are averages of stations 95-122 nautical miles from land (stations A and B, Fig. 11). Means are of the depth weighted averages for the entire water column at n number of stations.

		25 Nov., 1972		18-19 Mar., 1973		1-2 June, 1973	
		Mean	(n, S. D.)	Mean	(n, S. D.)	Mean	(n, S. D.)
Chlorophyll-a (mg/m^3)	Inshore	1.29	(2, .51)	2.96*	(4, .84	2.66*	(7, 1.22*)
	Offshore	0.28	(2, .20)	0.19*	(2, .06)	0.19*	(2, .03*)
Zooplankton (g/m^3)	Inshore	.156	(2, .189*)	.059	(4, .047*)	.065	(6, .037)
	Offshore	.007	(2, .003*)	.032	(2, .001*)	.018	(2, .003)
Total Phosphorus	Inshore			1.35*	(4, .06)	0.97	(7, .36)
	Offshore			1.00*	(2, .07)	0.52	(2, .06)
Particulate Phosphorus	Inshore			0.42	(4, .12)	0.43	(7, .23)
	Offshore			0.20	(2, .03)	0.14	(2, .03)
Dissolved Inorganic Phosphorus	Inshore			0.09	(4, .03)	0.08	(7, .10)
	Offshore			u	(2, -)	0.08	(2, .10)
Dissolved Organic Phosphorus	Inshore			0.85	(4, .07)	0.51	(7, .10)
	Offshore			0.79	(2, .01)	0.30	(2, .06)

* Indicates that values inshore stations were significantly different from offshore stations with 95% confidence as shown by two -sample t-tests and F-tests.

Evaluated Energy Flow Diagrams for the Outer Bays

Data presented in the previous sections were combined with other available data to evaluate the models shown in Fig.'s 21 and 22. These quantified diagrams represent the best available estimates for energy storages and flows in the outer control and discharge bays during summer conditions. The most reliable values (based on measurements taken at Crystal River) are shown in bold print and the least reliable ones are in parentheses. Data from other research projects under contract with Florida Power Corporation which were used in these models are summarized in the appendix to this section (Appendix 4B-A) Appendix A. The values for all the driving forces, storages, and flows shown in Fig.'s 21 and 22 are listed in Appendix 4B-B with component discriptions and the necessary calculations, assumptions, and references needed to fully evaluate the models.

Comparison of Fig's 21 and 22 indicates the major differences in system structure and function between the outer control and discharge bay ecosystems. Higher water temperatures and the altered pathways of water exchange represent the major changes in external driving forces to which the discharge bay system has adapted.

Water Exchange

Exchange of external water masses with the water in these open estuarine bays was the main driving force for the import and export of materials and organisms. Since the outer bay was defined as an area of 1 km^2 (see Fig. 3) with an average depth of 2 m, then the volume of the outer bay was about $2 \times 10^6 m^3$. The complete physical flushing of this volume due to tides, currents, and (in the discharge bay) plume exchange was on the order of 1 to 2 times per day. The exact total volume of water exchange is still uncertain due to the lack of information on mean longshore currents and the effects of the power plant on them.

Producers

Cross primary production (J_{GP}) in the discharge bay was about 10% lower than in the control bay during the summer with a corresponding 20% decrease in producer biomass (Q_1). Complete turnover of producer biomass due to organic production (Q_1/J_{GP}) occured every 5-6 days in both bays. Respiration per unit producer biomass also appeared to be similar in both bays with a respiratory turnover time of producer biomass of about 10 days.

Consumers

Zooplankton biomass (Q_2) in both control and discharge bay systems was less than 1% of the biomass of the total consumer biomass ($Q_2 + Q_3$) and their metabolism (J_{R2}) was about 1% of total system respiration. Although biomass was not measured directly in the outer discharge bay, biomass was estimated to be about 30% lower than in the control bay considering entrainment mortality (Drew, 1974), biomass levels in the discharge channel (Maturo, et al 1973-74), and estimated rates of water exchange (see Appendix D, E, and F). Water exchange was a major factor in determining zooplankton biomass due to water exchanges was less than 1 day. Respiratory turnover time for zooplankton biomass (Q_2/J_{R2}) was about 1.5 days. This rapid metabolic turnover time is consistent with literature values for small zooplankton species (such as Acartia tonsa) in warm water. A. tonsa was often the dominant zooplankton species in these bays (Maturo, et al, 1973-74).

Benthic invertebrates and fish biomass in the discharge bay was about 50% lower than the biomass in the control bay. Although oyster biomass in the discharge bay was actually higher than in the control bay (Lehman, 1974; Appendix D) the biomass of other benthic invertebrates (shrimp, crabs, polychaetes, etc) and fish was much lower in the thermally affected bays. This possibly indicates higher rates of emigration of mobile organisms from the discharge bays during the hottest part of the year. This pathway is indicated by the emigration estimate on J_{30} (Fig. 22).

Total System

Excluding the detritus and microbial components (Q_4), for which mass estimates were not available, the total biomass of organisms in the discharge bay was about 48.5 g/m^2 ($Q_1 + Q_2 + Q_3$). This value was almost 30% lower than the total organism biomass in the control bay (66.8 g/m^2). However, respiration per unit biomass for these compartments was about 30% higher in the discharge bay. Accordingly, the metabolic turnover time for total system biomass (excluding detritus) in the control bay was about 30% longer than in the discharge bay. Turnover times were 15 and 11 days, respectively, for the control and discharge bays.

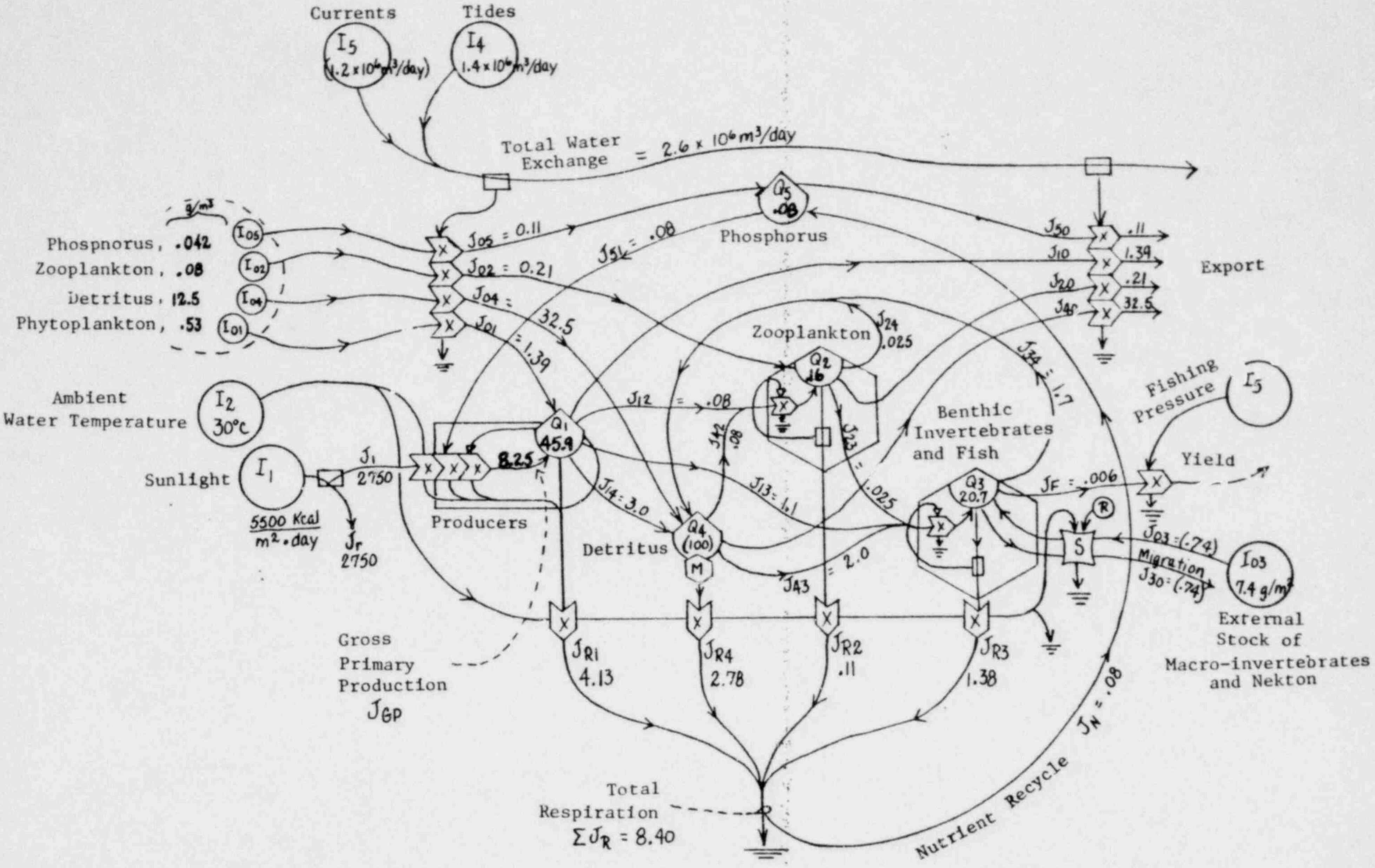


Fig. 21. Evaluated energy circuit model for the outer control bays: Summer conditions

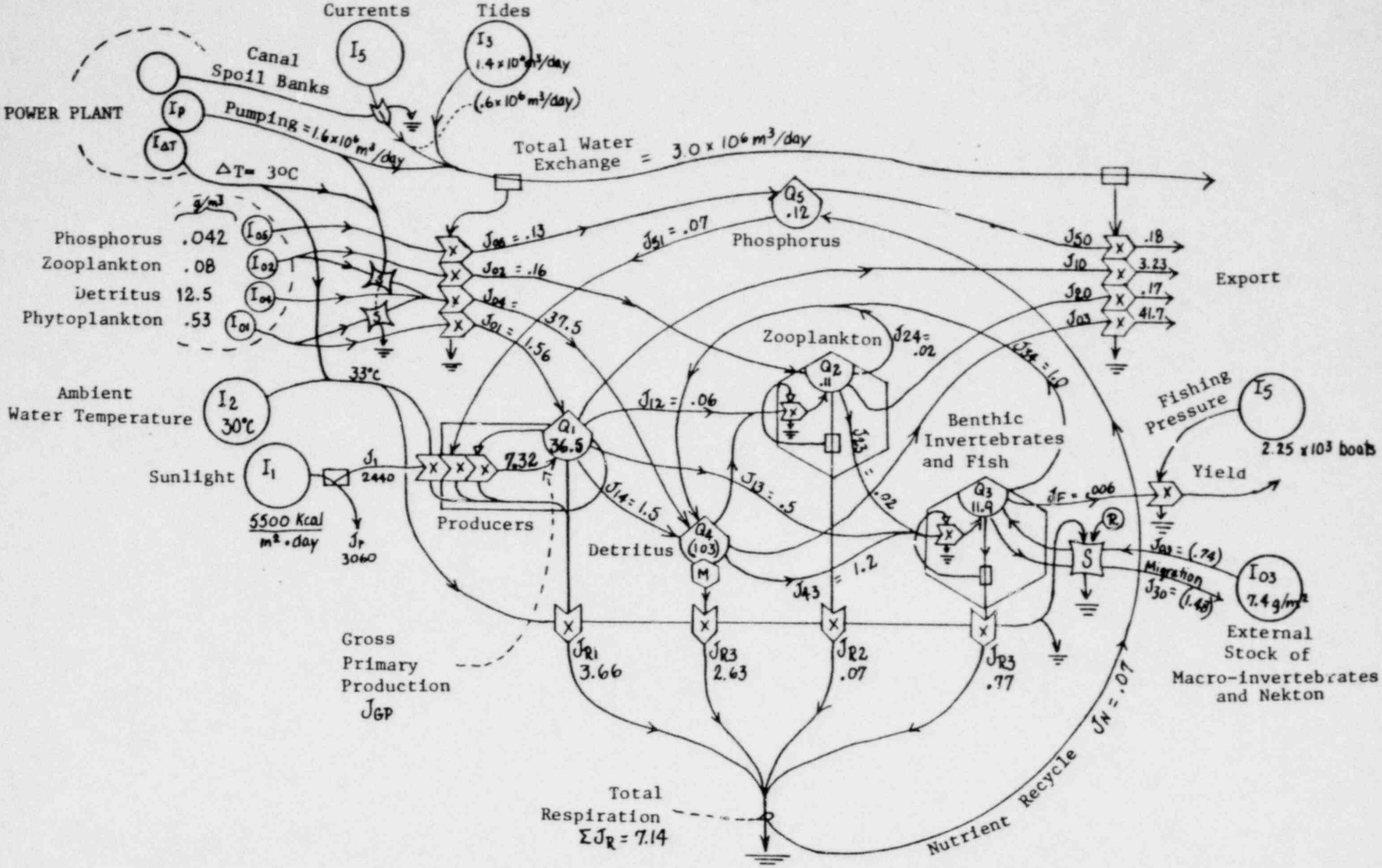


Fig. 22. Evaluated energy circuit model for outer discharge bay: Summer conditions

<u>Simulated Control Conditions</u>. Representing the model response to control conditions, a three-year simulation of the model with given initial conditions is shown in Fig. 24. The simulated curves were traced directly from the output of an X-Y recorder.

The generated sunlight curve is shown to fluctuate between 2100 and 4200 Kcal/m^2/day reaching a maximum in mid-summer (end of July) and reaching its minimum at the end of December. The generated temperature curve is shown to lag approximately three months behind sunlight in its annual fluctuation between a 30^{o}C maximum in early fall and a 13^{O}C minimum in early spring.

The simulated gross primary productivity (J_p) fluctuated between a late summer peak of about 8 to 8.5 g/m^2/day and a minimum during late winter and early spring of about 4 g/m^2/day. These simulated values closely resembled actual measurements of community metabolism for the outer bay (Fig. 13).

Simulated total respiration also showed fluctuations similar to those indicated by the data with maxima and minima around 9 and 4 g/m^2/day occurring slightly later than those for primary production. P/R ratios of the simulated curves appeared to fluctuate aroun 1.0, being slightly greaterthan 1.0 when productivity was maximum and slightly less than 1.0 when respiration was maximum.

Simulated producer biomass fluctuated between a minimum in late winter-early spring (20-25 g/m^2) to a peak in mid-summer (50 g/m^2) showing a slightly

Simulations

An outer bay model was programmed and simulated to test its validity and predictive responses to future power plant conditions. The simulation model (Fig. 23) was simplified by assuming that water exchange (bay flushing) and fishing pressure were constant for a given simulation and that organism migrations (J_{03} and J_{30}) were independent of temperature changes Therefore, for each simulation, the model emphasized the net effects on metabolism and trophic exchanges of seasonal oscillations of sunlight and temperature. Three simulations were performed representing different degrees of power plant influence on water temperature and bay flushing.

The mathematical representation of this model is given in Table 6. The driving force of sunlight was generated as a cosine function of time. The temperature function was generated with a 3 month lag behind sunlight.

Using an initial set of conditions for forcing functions, standing stocks, and exchange rates, the coefficients in the equations were calculated, the equations were scaled for programing on an Applied-Dynamics analog computer, and preliminary simulations of the model were performed. Appendix 4B-C and its accompanying footnotes list these values along with the necessary documentations, calculations, and assumptions.

Table 6. External driving force functions and differential equations for Outer Bay Model

Forcing Functions

Sunlight, $Io = \cos wt$; period = 1 year

Temperature, $T = \cos(wt + \phi) + \Delta T$; $\phi = 90° = 3$ months

ΔT = power plant influence

State Variables

Rate of Change =		Gross Production	+	Import	-	Export	- Losses to next trophic levels	-	Death	- Respiration
Producers, $\dot{Q}_1$	=	$K_pI_r{}^* Q_5Q_1T$	+	Jo_1	-	$K_{10}Q_1$	$- K_{12}Q_1(K_{R2}Q_2T)$	-	$K_{14}Q_1$	$- K_{R1}Q_1T$
Zooplankton, $\dot{Q}_2$	=	$K_{12}Q_1(K_{R2}Q_2T)$ $+K_{42}Q_4(K_{R2}Q_2T)$	+	Jo_2	-	$K_{20}Q_2$	$- K_{23}Q_2(K_{R3}Q_3T)$	-	$K_{24}Q_2$	$- K_{R2}Q_2T$
Benthic Invert's and Nekton. $\dot{Q}_3$	=	$K_{23}Q_2({}_{R3}Q_3T)$ $+K_{13}Q_1(K_{R3}Q_3T)$ $+K_{43}Q_4(K_{R3}Q_3T)$	+	Jo_3	-	$K_{30}Q_3$	$- K_FQ_3$	-	$K_{34}Q_3$	$- K_{R3}Q_3T$
Organic Detritus and Microbes, $\dot{Q}_4$	=	$K_{14}Q_1$ $+K_{24}Q_2$ $+K_{34}Q_3$	+	Jo_4	-	$K_{40}Q_4$	$- K_{42}Q_4(K_{R2}Q_2T)$ $K_{43}Q_4(K_{R3}Q_3T)$			$- K_{R4}Q_4T$
Phosphorus, $\dot{Q}_5$	=	$K_{15}(K_{R1}Q_1T)$ $+K_{25}(K_{R2}Q_2T)$ $+K_{35}(K_{R3}Q_3T)$	+	Jo_5	-	$K_{50}Q_5$	$- K_{51}I\ Q_5Q_1T$			

$^*I_r = Io - K_1(K_pI_rQ_5Q_1T)$

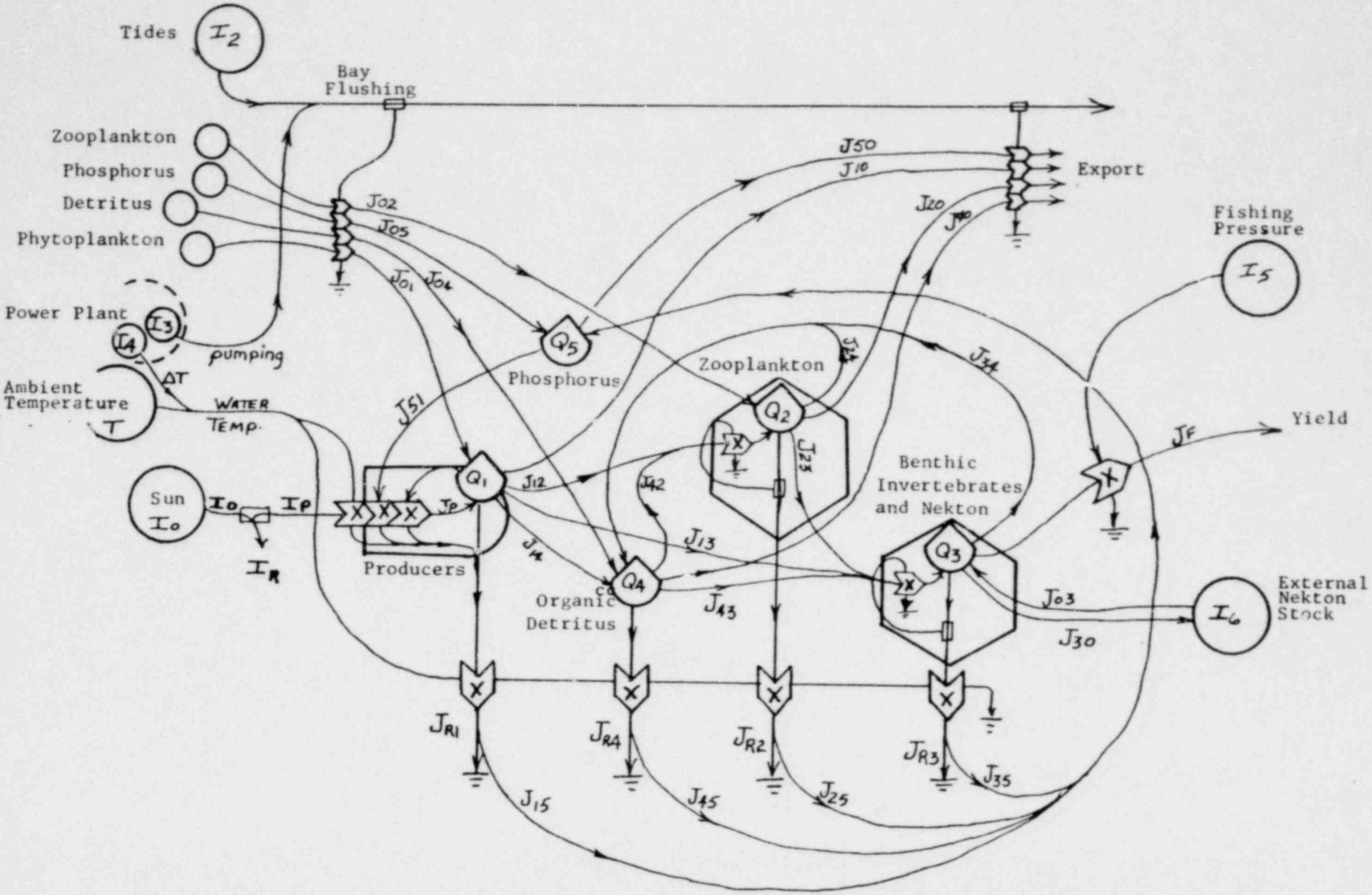


Figure 23. Circuit Diagram of Energy Flow Through the Outer Bay Ecosystem Showing Forcing Functions, Internal Storages, and Pathways of Energy Exchange. Pathways are numbered such that flow from storage X to storage Y is identified by J_{xy}.

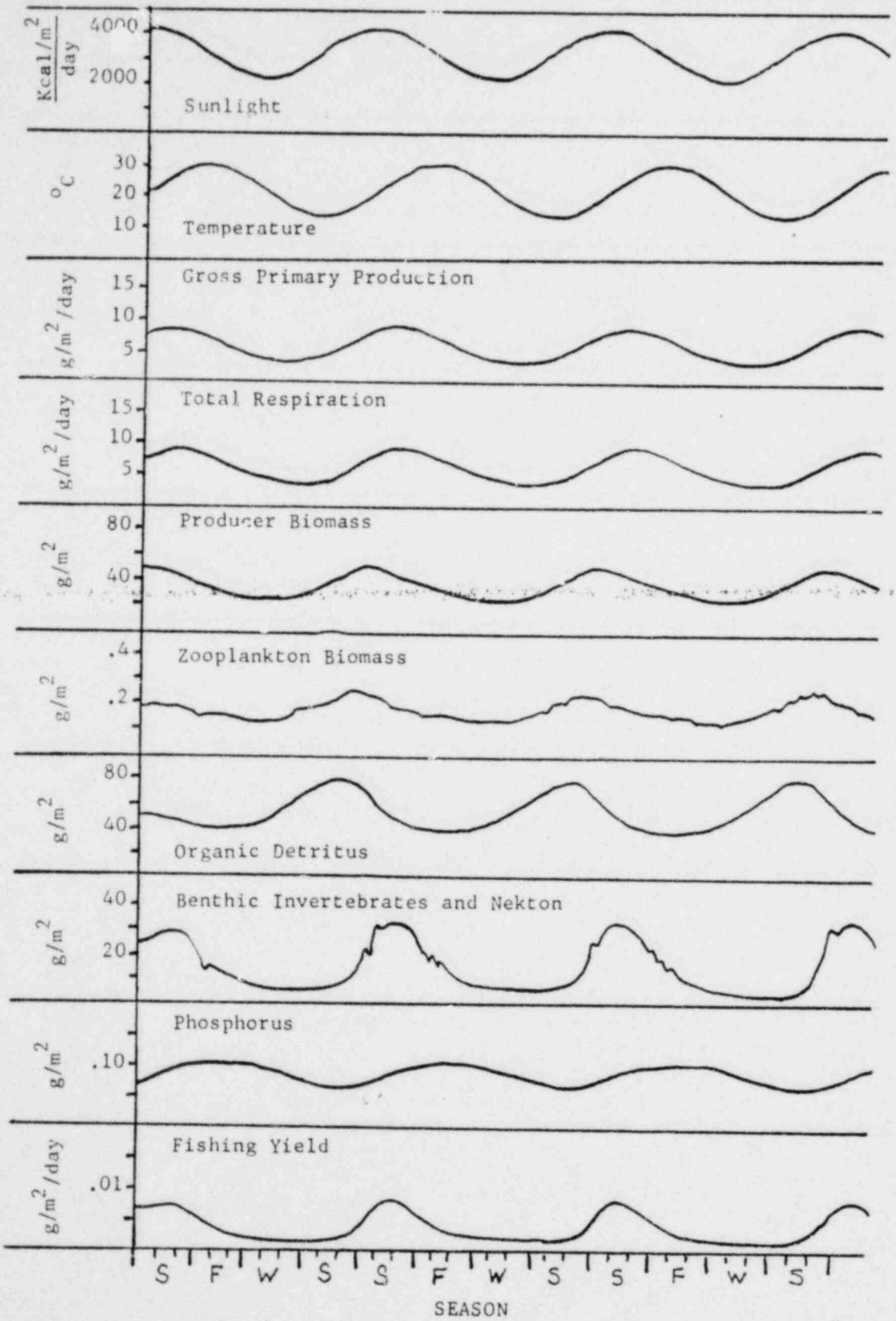


Figure 24. Simulated Outer Bay Model Response to Control Conditions (ambient temperature and a 2 x 10^6 m^3/day flushing volume)

influenced regeneration more than a function of utilization and depletion during times of high primary production.

Since fishing pressure (I_5) in this model was constant, the fishing yield was linearly proportional to the standing stock of higher consumers. Therefore, the daily catch followed the rise and fall of nekton and benthic invertebrate biomass with a peak yield of about .008 g/m^2/day in late summer. Future work in modeling the fishery and yield must account for seasonal pulses in fishing pressure and migrations of important fishery species in order to obtain more accurate simulations. As presented here the model lacks such programmed pulses and does not include, for example, mechanisms simulating the mullet fishery with high winter yields. The simulated pulse in yield shown in Fig could possibly correspond to the blue crab landings during the summer which dominate both the volume and value of the Citrus county fishery.

Simulated Effects of Units 1 and 2. **Figure 25** shows the model response to a 3^{o}C rise in temperature and an approximate doubling of the water volume flushing through the outer bay. These conditions attempt to simulate the effects of the operation of power plant Units 1 and 2 on the original "control" ecosystem. For contrast the control condition is plotted with a solid line and the new conditions are plotted wi : the dotted line.

Gross primary productivity under the new conditions was slightly higher than the control productivity from mid-winter to late summer with a maximum difference of only about 1 g m^2/day during the spring. During the rest of the year productivity was not affected. With natural variation of day-to-day community production, this change would probably not be detectable in field studies.

Total respiration was 1.0 to 1.5 g/m^2/day higher throughout the year with the new conditions. Again, this slight increase would possibly be undetectable due to natural variations of this parameter.

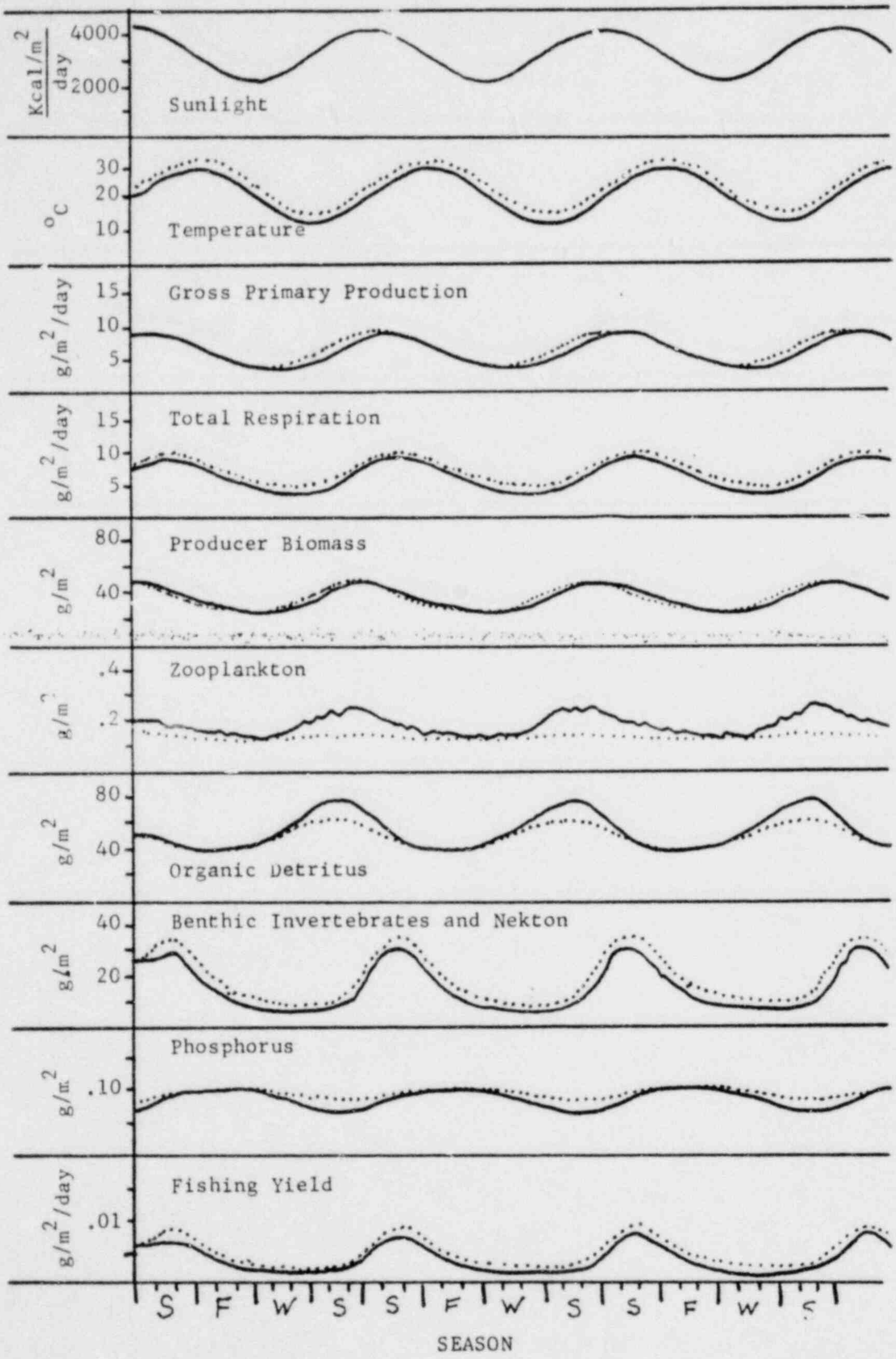


Figure 25. Simulated Outer Bay Model Response to Control Conditions (solid lines) and Response to Conditions Imposed by the Operation of Power Plant Units 1 and 2 (dotted lines). Units 1 and 2 cause a 3^{o}_{C} temperature rise and an additional 3.5 x 10 m /day flushing volume.

Plant biomass was relatively un-affected by the new conditions with only slightly higher levels during the spring (10%) and slightly lower levels during late summer and fall. Snedaker et al. (1973) found that the average benthic macrophyte biomass was about 25% lower in the discharge estuary than in the intake (control) estuary during the summer. However, the natural variance of macrophyte biomass samples would possibly not render this difference significant. Nevertheless, it will be of considerable interest in future simulations to examine the combinations of coefficients or model alterations which might lead toward a significant change in producer biomass.

Zooplankton biomass was much lower during the late spring and early winter and fluctuations were much dampened in comparison with the original control simulation. Both the dampening of fluctuations and the lowering of the biomass were much under the influence of bay flushing. Future simulations will attempt to isolate the partial effects of temperature and flushing rates.

Organic detritus was about 10-15% lower during the spring maximum with the new conditions, reflecting higher rates of decomposition (respiratory regeneration) and faster rates of transfer to higher consumers.

Benthic invertebrates and nekton reached higher levels throughout the year under the new conditions. The greatest difference from control conditions was during the late summer maximum when this compartment was about 15% higher than the control condition. Evidently the effects of higher temperatures and flushing rates stimulated the transfer of food to the higher consumers more than they enhanced respiratory losses. Again, some logic controlled migrations such as those involved with temperature preferences must be considered for future simulations.

With the new conditions total phosphorus was higher by about 20-25% during the spring and early summer but was un-affected during the fall maximum. The stimulus to phosphorus regeneration imposed by the new conditions was thus greater during times of low ambient temperature than during times when temperature were highest.

Fishing yields, again reflecting nekton and benthic invertebrate biomass, was about 10% higher for the new conditions than for the control. Again, the use of logic controlled temperature preferences and migrations will add to the validity of the model in future preductions of fishery yields.

Simulated Effects of Unit 3. The simulations shown in **Figures 24 and 25** show certain patterns that are very similar to those documented by existing data while other trends are not as well documented and possibly need additional work and study. However, the model does have properties of the real ecosystem under study at Crystal River and some insight may be gained now in an attempt to simulate patterns that might emerge when Unit 3 begins operation.

The actual discharge water from the power plant will not be much warmer than the water discharged now by Units 1 and 2. However, the volume and velocity of discharge will approximately double thus jetting a greater amount of plume water to the outer areas of the discharge bays. It is estimated, therefore, that with the approximate doubling of water volume flushing through the outer bay an additional 3°C rise in termperature will occur with the operation of Unit 3.

Figure 26 shows with solid lines the simulated patterns under present conditions (with Units 1 and 2) in contrast to resultant patterns under conditions imposed by Unit 3 (dotted lines). The main features indicated by the simulation of Unit 3 conditions were:

(a) Gross primary productivity was not affected

(b) Total respiration showed an additional 1-2 g/m^2/day increase

(c) Plant biomass was slightly lower (by about 5 g/m^2) through the summer and early fall when temperatures were highest.

(d) Zooplankton biomass was slightly lower and annual variations were almost entirely eliminated.

(e) Benthic invertebrates and nekton were again higher throughout the year.

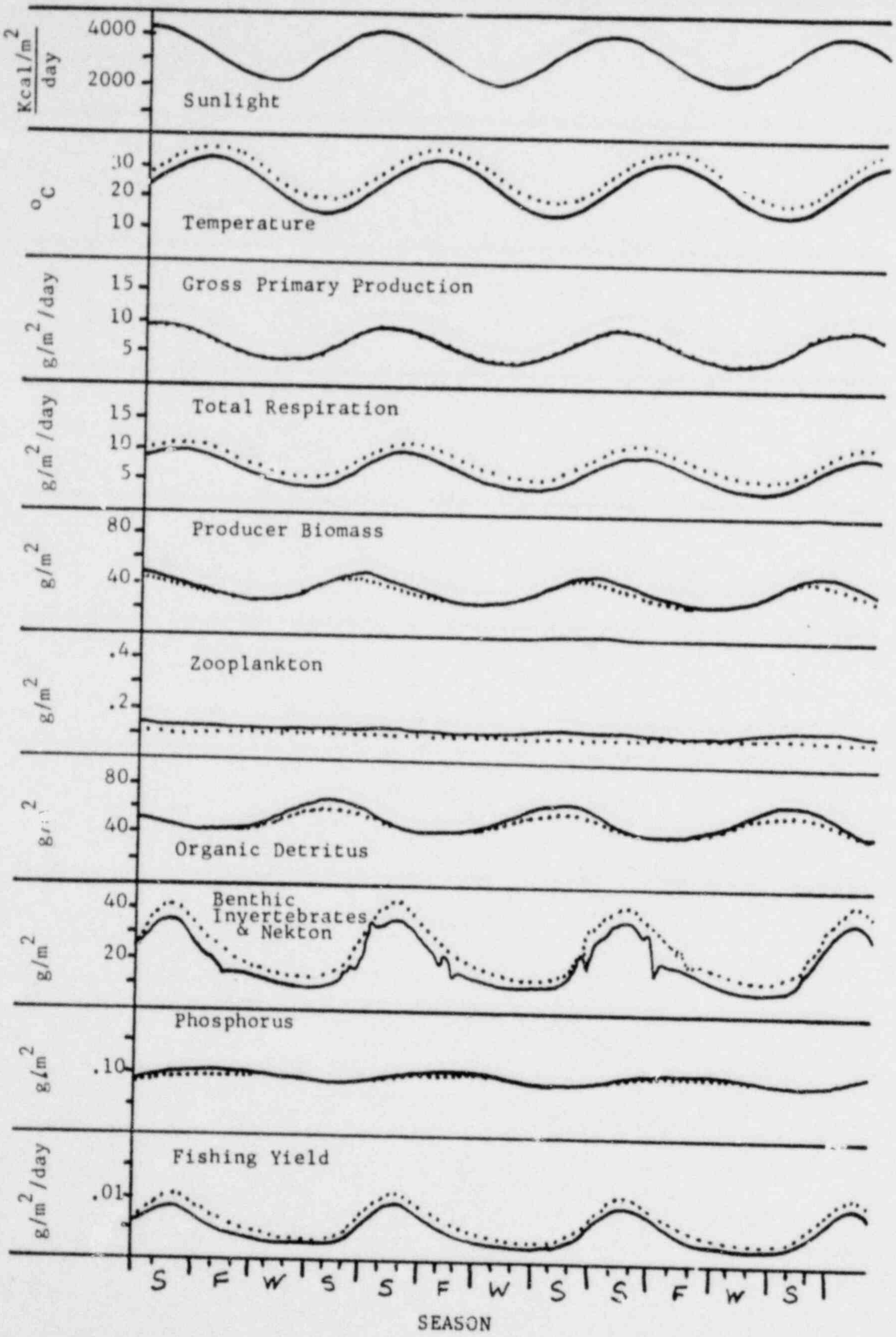


Figure 26. Simulated Outer Bay Model Response to Conditions Imposed by Units 1 and 2 (solid lines) and Response to Conditions Imposed with the Operation of Power Plant Unit 3 (dotted lines). Unit 3 is expected to cause an additional 3°C rise in temperature and an additional 3.7×10^6 m^3/day flushing volume.

(f) Phosphorus concentrations were not significantly affected

While these results do not yet constitute a definite prediction, they do demonstrate the utility of the model and the potential for such predictive use.

LITERATURE CITED

American Public Health Association. 1971. Standard methods for the examination of water and wastewater.

Carpenter, E.J., B.B. Peck, and S.J. Anderson. 1972. Cooling water chlorination and productivity of entrained phytoplankton. Mar. Biol. 16:37-40.

Carpenter, E.J., B.B. Peck, and S.J. Anderson. 1974. Survival of Copepods passing through a nuclear power station on northeastern Long Island Sound U.S.A. Mar. Biol. 24:49-55

Churchill, M.A., H.L. Elmore, and R.A. Buchkingham. 1962. The prediction of stream reareration rates. J. San Eng. Div. ASCE 88 (SA4): 1-46

Copeland, B.J. and W.R. Duffer. 1964. Use of a clear plastic dome to measure gasseous diffusion rates in natural waters. Limnol. Oceanogr. 9:494-499

Copeland, B.J. 1965. Fauna of the Aransas Pass inlet, Texas. I. Emigration as shown by tide trap collections. Pub. Inst. Mar. Sci. Univ. Texas 10:9-21

Copeland, B.J. and H. Lee Davis. 1972. Estuarine ecosystems and high temperatures. Water Resources Inst. Univ. North Carolina. Rept. #68

Dawson, C.E. 1955. A study of the Oyster biology and hydrography at Crystal River, Florida. Pub. Inst. Mar. Sci., Univ. Texas 4:279-302

Day, John W., Jr. 1971. Carbon metabolism of estuarine ponds receiving treated sewage wastes. Ph.D. dissertation, Curriculum in Mar. Sci. Univ. North Carolina 128 p.

Drew, Richard. 1974. Evaluation of ATP assay in zooplankton entrainment mortality studies. Master's thesis, Dept. Environ. Eng. Sci., Univ. Florida

Fox, J.L., and M.S. Moyer. 1972. Effects of Power Plant Chlorination on Marine Microbiota. Final contract report to Florida Power Corp. Dept. Environ. Eng.Sci. Univ. Fla.

Florida Power Corporation. 1972. Applicant's environmental report. Operating license stage. St. Petersburg, Florida

Grimes, C.B. 1971. Thermal addition studies of the Crystal River stream electric station. Fla. Dept. Natural Resources. St. Petersburg, Fla. Prof. Pap. Ser. No. 11.

Gunter, G. 1945. Studies of Marine fishes of Texas. Publ Inst. Mar Sci. Univ. Texas 1:1-190

Hall, Charles A.S. 1971. Migration and metabolism in a stream ecosystem. Ph.D. dissertation, Dept. of Zool., Univ North Carolina

Heinle, D.R. 1969. Temperature and zooplankton. Ches. Sci. 10:186-209

Jorgensen, E.G., and E. Steemann Nielsen. 1965. Adaptation in plankton algae. p. 38-46. In C.R. Goldman (ed). Primary productivity in aquatic environments. Mem. Inst. Ital. Inbrobiol., 18 suppl. Univ California Press, Berkeley

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

Lorenzen, C.J. 1967. Determination of chlorophyll and pheo-pigments: Spectrophotometric equations. Limnol. Oceanogr. 12:343-346

McConnell, W.J. 1962. Productivity relations in carboy mocrocosms. Limnol. Oceanogr. 7:335-343

McKellar, H.N.,Jr. 1974. Metabolism and Models of outer estuarine bay ecosystems affected by a coastal power plant. Ph.D. dissertation. Dept. Environ. Eng. Sci. Univ. Florida

McNulty, J.K., W.N. Lindall, and J.E. Sykes. 1972. Cooperative Gulf of Mexico estuarine inventory and study, Florida: Phase I, Area description. NOAA Technical Report, NMFS Circ-368.

Maturo, F.J., J.W. Caldwell, W. Ingram. 1973-74. Studies of zooplankton populations in thermally affected and control waters near the Crystal River power plants. Univ. Florida Mar. Lab., Dept. Zool., Univ. Florida

Menzel, D.W., and N. Corwin. 1965. The measurement of total phosphorus in sea water based on the liberation of organically bound fractions by persulfate oxidation. Limnol. Oceanogr. 10:280-282

Morgan, R.P., and R.G. Stross. 1969. Destruction of phytoplankton in the cooling water supply of a steam electric station. Ches. Sci. 10:165-171

Murphy, J. and J.P. Riley. 1962. A modified single-solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27:31-36

Nicol, J.A. Colin. 1967. The biology of marine animals. 2nd ed. John Wiley and Sons, Inc. New York

Odum, E.P. 1971. Fundamentals of ecology. 3rd ed. John Wiley and Sons, Inc. New York

Odum, H.T. 1956. Primary production of flowing waters. Limnol. Oceanogr. 1:102-117

Odum, H.T., and C.M. Hoskin. 1958. Comparative studies on the metabolism of marine waters. Bub. Inst. Marine Sciences. Univ. Texas 6:159-170.

Odum, H.T. 1967. Biological Circuits and the marine systems of Texas, p. 990157. In T.A. Olson and F.J. Burgess (eds), Pollution and marine ecology. Interscience

Odum, H.T. 1971. Environment, power, and society. Wiley-Interscience. 332 p.

Odum, H.T. 1972. An energy circuit language for ecological and social systems: its physical basis. p. 139-211. In B.C. Patten (ed), Systems analysis and simulation in ecology, vol 2. Academic Press

Odum, H.T. 1973a. Energy, ecology, and economics. Ambio 2:220-227. Swedish Royal Academy of Science

Odum, H.T. 1973b Marine ecosystems with energy circuit diagrams. In C.J. Nihoul (ed), NATO conference on modelling and the sea. June, 1973. Oporto, Portugal

Odum, H.T. 1974. Energy cost-benefit models for evaluating thermal plumes, p. 628-649. In J.W. Gibbons and R.R. Sharitz (eds), Thermal ecology, AEC symposium series, (CONF-730505).

Reifsnyder, W.E., and H.W. Lull. 1965. Radiant energy in relation to forests. Tech. Bull. No. 1344. U.S. Dept. Agr., Forest Ser. 111 pp.

Smith, Martha A. 1971. Productivity of marine ponds receiving treated sewage. Master's thesis, Dept. Zool, Univ. North Carolina 225 p.

Simmons, E.G., and H.D. Hoese. 1959. Studies on the hydrography and fish migrations of Cedar Bayou, a natural tidal inlet of central Texas coast. Pub. Inst. Mar. Sci. Univ. Texas 6:56-80

Snedaker, S.C., C.A. Adams, L.A. Burns, G.L. Evink, M.J. Oesterling, W. Semann, R. van Tine. 1973-74. Benthic marine ecology, fish biomass, and blue crab migrations in the thermally-affected and control bays near the Crystal River power plants. Agr. Exp. Sta. Res. Man. Univ. Florida

State of Florida Board of Conservation. Salt water fisheries division, Division of Mar. Resources. 1970

Steele, J.H., and I.E. Baird. 1965. The chlorophyll-a content of particulate organic matter in the northern North Sea. Limnol. Oceanogr. 10:261-267

Stanford, R. 1974. Personnal comminication. Agr. Exp. Sta., Resource Management, Univ. Florida

Truesdale, G.A., A.L. Downing, and G.E. Lowden. 1955. The solubility of oxygen in pure water and sea water. J. Appl. Chem. 5:53-62

United States Department of Commerce, NOAA. Tide tables for the east coast of North and South America. 1972-1974

Whitworth, Walter R., and Thomas H. Lane. 1969. Effects of toxicants on community metabolism in pools. Limnol. Oceanogr. 14:53-58

APPENDIX 4B-A

SUMMARY OF DATA FROM OTHER RESEARCH PROJECTS AT CRYSTAL RIVER USED TO QUANTIFY MODELS

		Standing Stock (g organic matter/m^2)			
Item	Season	Control Bay	Discharge Bay	Reference	Assumptions
Benthic Macrophytes	Summer, 1973	44.8	36.3	Snedaker, et al 1973-74	1 g organic matter/g dry wt
Zooplankton	Summer, 1972	0.16		Maturo, et al. 1973-74	"
	Fall, 1972	0.15			"
	Winter, 1973	0.06			"
	Spring, 1973	0.19			"
Oysters and Reef Organisms	Annual Arg.	6.1	6.5	Lehman, 1974	g/m^2 in overall bay = .03x g/m^2 on reefs (Reefs = 3% of bay area).
*Benthic Macro-Invertebrates	Winter, 1973		2.0	Snedaker, et al 1973-74	0.55g org matt/g dry wt
	Summer, "	3.6	0.8		
	Fall, "	2.1	0.7		
	Spring "	5.2	1.2		
*Vertebrates (Fish)	Summer, 1973	1.9	1.5	"	0.90 g org matt/g dry wt
	Fall, "	0.3	0.8	"	"
	Winter, "	0.3	0.5	"	"
Organics in the Water	Summer, 1973	26.0	30.9	Stanford, 1974	2 g org matt/g org carbon

*Benthic macro-invertebrates and fish were sampled only in the shallow inner bays at Crystal River.

APPENDIX 46-3

EXTERNAL DRIVING FORCES, STORAGES, AND FLOWS IN EVALUATED OUTER BAY MODELS (Figs. 21 and 22).

I. Outer Control Bay Model (Fig. 21)

EXTERNAL DRIVING FORCES:

Notation	Description	Calculations and Assumptions	References
I_1	Sunlight	I_1 = average insolation in southeast U.S., e-July = 5500 kcal/m^2/day	Reifsnyder and Lull, 1965
I_2	Ambient water temperature	I_2 = average summer temperature = 30° C	Grimes (1971) and **Fig. 11**
I_3	Tidal water exchange	I_3 = (average tidal range) x (area of bay) x (tides per day) x (tidal exchange coefficient)^a $= (1.0m)(1 \times 10^6 m^2)(2/day)(0.70)$ $= 1.4 \times 10^6\ m^3/day$	(a) **McKellar, 1974**
I_4	Advective water exchange	I_4 = (mean longshore current velocity)^a x (average depth of bay) x (length of bay boundary) x (advective exchange coefficient)^b	(a) Assumption (b) Assumed to be similar to tidal exchange coefficient
I_5	Fishing Pressure	Assumed to be proportional to the numbers of sport and commercial boats registered in Citrus County $I_5 = 2.25 \times 10^3$ boats	Fla. Bd. Con. Salt Water Fish. Div. Mar. Res., 1970

EXTERNAL DRIVING FORCES (cont.):

Notation	Description	Calculations and Assumptions	References
I_{01}	External concentration of phytoplankton	See footnote 1 I_{01} = (Chlorophyll-a conc. in control bay)^a x (carbon : chlorophyll-a ratio)^b x (organic matter : carbon) = (.00267 g/m^3)(100)(2) = .53 g/m^3	(a) Table 4, summer control (b) Steele & Baird, 1965
J_{01}	Import of phytoplankton due to water exchange	$J_{01} = \frac{(I_{o1}, \text{ above})(I_3 + I_4, \text{ above})}{(\text{Bay area})}$ = (.53 g/m^3)(2.6 x 10^6 m^3/day)/10^6 m^2 = 1.39 g/m^2/day	
I_{02}	External concentration of zooplankton	See footnote 1 $I_{02} = \frac{(\text{Zooplankton stuck in control bay})^a}{(\text{Bay depth})}$ = (.16 g/m^2)/(2m) = 0.08 g/m^3	(a) Maturo, et.al. 1973-74 Appendix 4B-A
J_{02}	Import of zooplankton due to water exchange	J_{02} = (I_{02}, above)($I_3 + I_4$, above)/bay area = (.089/m^3)(2.6 x 10^6 m^3/day)/ 10^6 m^2 = 0.21 g/m^2/day	

EXTERNAL DRIVING FORCES (cont.):

Notation	Description	Calculations and Assumptions	References
I_{03}	External density of migrating invertebrates and fish	Assumed to be the density of macro-benthic invertebrates and fish in the control bays I_{03} = (Macroinvertebrates + fish)[a] $= 3.6\ g/m^2 + 3.8\ g/m^2$ $= 7.4\ g/m^2$	(a) Snedaker et.al.,1973-74 footnote 2
J_{03}	Invertebrate and fish migration	J_{03} Assumed to be about 10% per day of the external stock of invertebrates and fish = (.10)(I_{03}, above) $= (.10)(7.4\ g/m^2)$ $= 0.74\ g/m^2/day$	
I_{04}	External concentration of detritus	I_{03} = [(Total density of organics in control bay water)[a] ÷ bay depth] - (phytoplankton concentration)[b] $= (26\ g/m^2/2m) - .53\ g/m^3$ $= 13\ g/m^3 - .53\ g/m^3$ $= 12.5\ g/m^3$	See footnote 1 (a) Stanford, 1974 Appendix 4B-A (b) I_{01}, this table
J_{04}	Import of detritus due to water exchange	J_{04} = (I_{03}, above)($I_3 + I_4$, above)/bay area $= (12.5\ g/m^3)(2.6 \times 10^6\ m^3/day)/10^6\ m^2$ $= 32.5\ g/m^2/day$	

EXTERNAL DRIVING FORCES (cont.):

Notation	Description	Calculations and Assumptions	References
I_{05}	External concentration of phosphorus	I_{05} = (Total phosphorus conc. in control bay water)^a = .042 g/m^3	See footnote 1 (a) Table 4, summer control
J_{05}	Import of phosphorus due to water exchange	J_{05} = (I_{05}, above)(I_3 + I_4, above)/bay depth = (.042 g/m^3)(2.6 x 10^6 m^3/day)/10^6 m^2 = .11 g/m^2/day	

INTERNAL STORAGES:

Q_1	Total producer biomass	Q_1 = Phytoplankton + benthic macrophytes Phytoplankton = (Chlorophyll-a concentration)^a x (carbon : chlorophyll ratio)^b x (organic matter : carbon ratio) x (bay depth) = (2.67 mg/m^3)(100)(2)(2m) = 1.07 g/m^2 Benthic macrophytes = 44.8 g/m^2 (c) Q_1 = 45.9 g/m^2	(a) Table 4, summer contro (b) Steele and Baird, 1965 (c) Snedaker, et.al., 1973 74 Appendix 4B-A
Q_2	Zooplankton biomass	Q_2 = (0.16 g/m^2)	Appendix 4B-A
Q_3	Benthic invertebrates and fish	Oysters and reef organisms = (6.1 g/m^2)^a Benthic macroinvertebrates = (10.8 g/m^2)^b Fish = (3.2 g/m^2)^b Q_3 = total = 20.7 g/m^2	(a) Appendix 4B-A (b) See footnote 3

INTERNAL STORAGES (cont.)

Notation	Description	Calculations and Assumptions	References
Q_4	Detritus stock with associated microbes	Q_4 = water column detritus and bottom detritus water column detritus = (total organics in the water)[a] - (phytoplankton)[b] $= (26.0\ g/m^2) - (1.07\ g/m^2)$ $= 24.9\ g/m^2$ Bottom detritus = $75\ g/m^2$ (c) $Q_4 = 100\ g/m^2$	(a) Stanford, 1974 **Appendix 4B-A** (b) See Q_1, phytoplankton, above (c) Assumption
Q_5	Total phosphorus in the water	Q_5 = (Total phosphorus conc.)[a] x (bay depth) $= (0.042\ g/m^3) \times (2m)$ $= 0.08\ g/m^2$	(a) Table 4, summer control
FLOWS:			
J_1	Light used in photosynthesis	Assuming that peak production during the summer uses 50% of incident solar radiation $J_1 = 2250\ kcal/m^2/day$	
J_r	Light remaining for additional photosynthesis	$J_r = I_1 - J_1$ $= 5500 - 2250\ kcal/m^2/day$ $= 2250\ kcal/m^2/day$	

FLOWS (cont.):

Notation	Description	Calculations and Assumptions	References
J_{GP}	Total community gross primary production	$J_p = {}^{P}net + {}^{R}night$ $= 8.25$ g/m^2/day (gO_2 = g org. matter)	Table 1, summer control bay
R	Total community respiration	$J_R = {}^{R}night \times 2$ $= 8.40$ g/m^2/day	Table 1, summer control bay
J_{R1}	Producer respiration	J_{R1} Assumed to be 50% of J_p $= 4.13$ g/m^2/day	E.P. Odum, 1971
J_{R2}	Zooplankton respiration	J_{R2} = (Q_2, this table) x (0.028 g O_2/g dry wt./hr)^a x (24 hr/day) = (0.16 g/m^2)(0.028 g/g/hr)(24 hr/day) = 0.11 g/m^2/day	(b) Table 3, combined summer average
J_{R3}	Benthic invertebrate and fish respiration	J_{R3} Assumed to reflect a metabolic turnover time of 15 days J_{R3} = (Q_3, this table)/ (15 days) = 1.38 g/m^2/day	
J_{R4}	Respiration of detritus with associated microbes	$J_{R4} = J_R - (J_{R1} + J_{R2} + J_{R3})$ $= 8.40 - (4.13 + 0.11 + 1.38)$ $= 2.48$ g/m^2/day	

FLOWS (cont.):

Notation	Description	Calculations and Assumptions	References
J_N	Phosphorus recycle from community respiration	Assuming that respired organic matter was 1% phosphorus $J_N = (.01)(8.40) = .08\ g/m^2/day$	
J_{10}	Export of phytoplankton due to water exchange	$J_{10} = \frac{(\text{Phytoplankton stock})^a \times (I_3 + I_4,\ \text{above})}{(\text{Bay area})(\text{Bay depth})}$ $= \frac{(1.07\ g/m^2)(2.6 \times 10^6\ m^3/day)}{(106\ m^2 092m)}$ $= 1.39\ g/m^2/day$	(a) See Q_1, this table
J_{12}	Zooplankton grazing	Calculated to give an organic balance to the compartment $J_{12} = 0.08\ g/m^2/day$	Footnote 4
J_{1}	Benthic invertebrates and fish grazing	Calculated to give an organic balance to the compartment $J_{13} + 1.0\ g/m^2/day$	Footnote 4
J_{14}	Producer death and transfer to detritus	Calculated to give an organic balance to the compartment $J_{14} = 3.0\ g/m^2/day$	Footnote 4
J_{20}	Zooplankton export due to water exchange	$J_{20} = \frac{(\text{Zooplankton stock})^a (I_3 + I_4,\ \text{above})}{(\text{Bay area})(\text{Bay depth})}$	(a) See Q_2, this table
J_{23}	Zooplankton loss to benthic invertebrates and fish	Calculated to give an organic balance to the compartment	Footnote 4

FLOWS (cont.):

Notation	Description	Calculations and Assumptions	References
J_{24}	Zooplankton death and feces transfer to detritus	Calculated to give an organic balance to the compartment $J_{24} = .025\ g/m^2/day$	Footnote 4
J_{30}	Benthic macro-invertebrate and fish emigration	Assumed to be 10% per day of the standing stock of benthic macro-invertebrates and fish $J_{30} = (.10)(3.6\ g/m^2 + 3.8\ g/m^2)^a$ $= (.10)(7.4\ g/m^2)$ $= 0.74\ g/m^2/day$	(a) Footnote 2
J_{34}	Benthic invertebrates and fish death, and feces transfer to detritus	Calculated to give an organic balance to the compartment $J_{34} = 1.7\ g/m^2/day$	Footnote 4
J_F	Commercial and sport fishery harvest	Commercial fishing harvest = .004 $g/m^2/day$ Commercial fishing harvest = .002 $g/m^2/day$ $J_F = .006\ g/m^2/day$	Footnote 5
J_{40}	Detritus export due to water exchange	$J_{40} = \frac{(\text{detritus in the water})^a \times (I_3 + I_4, \text{above})}{(\text{Bay area})(\text{Bay depth})}$ $= \frac{(24.9\ g/m^2)(2.6 \times 10^6 m^3/day)}{(10^6\ m^2)(2m)}$ $= 32.5\ g/m^2/day$	(a) See Q_4, this table

FLOWS (cont.):

Notation	Description	Calculations and Assumptions	References
J_{43}	Benthic Invertebrates and fish consumption of detritus	Calculated to give an organic balance to the compartment $J_{43} = 2.0\ g/m^2/day$	Footnote 4
J_{50}	Phosphorus export due to water exchange	$J_{50} = \frac{(Q_5,\ above) \times (I_3 + I_4,\ above)}{(Bay\ area)(Bay\ depth)}$ $= \frac{(.08\ g/m^2)(2.6 \times 10^6\ m^3/day)}{(10^6\ m^2)(2m)}$ $= 0.11\ g/m^2/day$	
J_{51}	Phosphorus uptake by producers	Assuming that the organic matter fixed by community production (J_{GP}) was 1% to phosphorus $J_{51} = (.01)(J_{GP},\ this\ table)$ $= (.01)(8.25\ g/m^2/day)$ $= .08\ g/m^2/day$	

APPENDIX 4B-B (cont'd)

II. Outer Discharge Bay Model (Fig. 22)

EXTERNAL DRIVING FORCES:

Notation	Description	Calculations and Assumptions	References
I_1	Sunlight	$I_1 = 5500$ Kcal/m^2/day (same as for control bay model	See Appendix E-1, above
I_2	Ambient Water Temperature	$I_2 = 30^oC$ = temperature in discharge bay if power plants shut down	" " " "
I_T	Temperature increase due to thermal discharge	$I_T = 3^oC$	Fig. 16
I_3	Tidal water exchange	Assumed to be similar to control bay tidal change $I_3 = 1.4 \times 10^6 m^3/day$	See Appendix 4B-B,I above
I_4	Water exchange due to longshore currents, advective exchange	Assuming a 50% reduction due to spoil banks $I_4 = (.5)(I_4 \text{ in control bay})^a$ $= (.5)(1.2 \times 10^6 m^3/day)$ $= 0.6 \times 10^6 m^3/day$	See I_4, Appendix 4B-B,I above
I_P	Water exchange due to power plant pumping	I_P = (total volume of water pumped by the power plants)^a x (plume exchange coefficient)^b $= (3.5 \times 10^6 m^3/day)(.28)$ $\approx 1 \times 10^6 m^3/day$	(a) F.P.C. 1972 (b) **McKellar, 1974**

EXTERNAL DRIVING FORCES (cont'd):

Notation	Description	Calculations and Assumptions	References
I_5	Fishing pressure	Assumed to be proportional to the number of commercial and sport fishing boats registered in Citrus County - same as for control bay $I_5 = 2.25 \times 10^3$ boats	
I_{01}	External concentration of phytoplankton	$I_{o1} = 0.53\ \text{g/m}^3$ (same as for control bay)	See footnote 1 and I_{o1}, Appendix 4B-B,I above
J_{01}	Impact of phytoplankton due to water exchange	$J_{o1} = \frac{(I_{o1}\text{,above})(\text{ total water exchange})^{a}}{\text{bay area}}$ $= (.53\ \text{g/m}^3)(3 \times 10^6\text{m}^3\text{/day})/10^6\text{m}^2$ $= 1.56\ \text{g/m2/day}$	(a) $I_3 + I_4 + I_p$, this table; See footnote 6
I_{02}	External concentration of zooplankton	$I_{o2} = .08\ \text{g/m}^3$ (same as for control bay)	See I_{o2}, Appendix 4B-B,I above; and footnote 1
J_{02}	Impact of Zooplankton due to water exchange	Assuming 100% entrainment mortality with power plant pumping (I_P) during the summer $J_{o2} = \frac{(I_{o2}\text{, above})(I_3 + I_4\text{, above}) + (\underline{0}\ I_{o2})(I_P)}{\text{bay area}}$ $= \frac{(.08\ \text{g/m}^3)(2\text{x}10^6\text{m}^3\text{/day}) + 0}{10^6\text{m}^2}$ $= 0.16\ \text{g/m}^2\text{/day}$	Drew, 1974

EXTERNAL DRIVING FORCES (cont'd):

Notation	Description	Calculations and Assumptions	References
I_{03}	External density of migrating invertebrates and fish	$I_{03} = 7.4\ g/m^2$ (same as for control bay)	See Appendix **4B-B,I** above
J_{03}	Invertebrate and fish immigration	$J_{03} = 0.74\ g/m^2/day$ (same as for control bay)	" " "
I_{04}	External concentration of detritus in the water	$I_{04} = 12.5\ g/m^3$ (same as for control bay)	" " "
J_{04}	Import of detritus due to water exchange	$J_{04} = \frac{(I_{03}\text{, above})(I_3 + I_4 + I_P\text{, above})}{\text{Bay area}}$ $= (12.5\ g/m^3)(3 \times 10^6 m^3/day)/10^6 m^2$ $= 37.5\ g/m^2/day$	
I_{05}	External concentration of phosphorus	$I_{05} = .042\ g/m^3$ (same as for control bay)	" " "
J_{05}	Import of phosphorus due to water exchange	$J_{05} = \frac{(I_{05}\text{, above})(I_3 + I_4 + I_P\text{, above})}{\text{bay area}}$ $= (.042\ g/m^3)(3 \times 10^6 m^3/day)/10^6 m^2$ $= .13\ g/m^2/day$	

EXTERNAL DRIVING FORCES (cont'd):

Notation	Description	Calculations and Assumptions	References
Q_1	Total producer biomass	Q_1 = phytoplankton + benthic macrophytes phytoplankton = (chlorophyll-a)^a x (carbon: chlorophyll ratio)^b x (organic matter: carbon ratio) x (bay depth) = (5.37 g/m^3)(100)(2)(2m) = 2.15 g/m^2 macrophytes = 34.3 g/m^2 (C) Q_1 = 36.5 g/m^2	(a) Table 4, summer discharge (b) Steele & Baird, 1965 (c) Snedaker *et al*, 1973-74 Appendix 4B-A
Q_2	Zooplankton biomass	Assuming a 30% reduction from control bay values Q_2 = 0.11 g/m^2	footnote 7
Q_3	Benthic invertebrate and fish biomass	Oysters and reef organisms = 6.5 g/m^2 (a) Benthic invertebrates = 2.4 " (b) Fish = 3.0 " (b) Q_3 =11.9 g/m^2	(a) Appendix 4B-A (b) " " & footnote 3
Q_4	Detritus stock	Q_4 = water column detritus + bottom detritus water column detritus = (total organics)a - (phytoplankton)b = (30 g/m^2) - (2.15 g/m^2) = 27.8 g/m^2 bottom detritus = 75 g/m^2 (same as was assumed for control bay) Q_4 = 103 g/m^2	(a) Stanford, 1974; Appendix 4B-A (b) see Q_2 above

EXTERNAL DRIVING FORCES (cont'd):

Notation	Description	Calculations and Assumptions	References
Q_5	Total phosphorus in the water	Q_5 = (total phosphorus conc.)^a x (bay depth) = (.059 g/m^3)(2m) = 0.12 g/m^2	(a) Table 4, summer discharge
FLOWS:			
J_1	Light used in photosynthesis	J_1 = 1996 Kcal/m^2/day -(estimate based on assumption stated for J_1 in the control model	See J_1, Appendix 4B-B,I
J_r	Light remaining for additional photosynthesis	$J_r = I_1 - J_1$ = (5500 - 1996) = 3504 Kcal/m^2/day	
J_{GP}	Total community gross primary production	$J_{GP} = P_{net\ day} + R_{night}$ = 7.32 g/m^2/day	Table 1, summer discharge bay
R	Total community respiration	$R = R_{night}$ x 2 = 7.14 g/m^2/day	Table 1, summer discharge bay
J_{R1}	Producer respiration	J_{R1} = Assumed to be 50% of J_{GP} = 3.66 g/m^2/day	E.P. Odum, 1971
J_{R2}	Zooplankton respiration	J_{R2} = (Q_2, this table)(.028g/g dry wt/hr)^a(24 hr/day) = (.11 g/m^2)(.028 g/g/yr)(24 hr/day) = 0.07 g/m^2/hr	(a) Table 3, combined sum summer average

FLOWS (cont'd):

Notation	Description	Calculations and Assumptions	References
J_{R3}	Benthic invertebrate and fish respiration	Assuming a metabolic turnover time of 15 days J_{R3} = (Q_3, this table)(/(15 days) $J_{R3} = (11.9\ g/m^2)/(15\ days)$ $= 0.77\ g/m^2/day$	
J_{R4}	Respiration of detritus and associated microbes	Calculated as a difference $J_{R4} = R - (J_{R1} + J_{R2} + J_{R3})$ $= 7.14\ g/m^2/day - (3.66 + .07 + .77)$ $= 2.63\ g/m^2/day$	
J_N	Phosphorus re-cycle from community respiration	Assuming that respired organic matter was 1% phosphorus $J_n = (.01)(\ R)$ $= (.01)(7.14\ g/m^2/day)$ $= (.07\ g/m^2/day)$	
J_{12}	Zooplankton grazing	Calculated to give an organic balance to compartment $J_{12} = 0.06\ g/m^2/day$	footnote 4
J_{13}	Benthic invertebrates and fish grazing	Calculated to give an organic balance to the compartment $J_{13} = 0.5\ g/m^2/day$	"

FLOWS (cont'd):

Notation	Description	Calculations and Assumptions	References
J_{14}	Producer death and transfer detritus	Calculated to give an organic balance to the compartment J_{14} = 1.5 g/m^2/day	footnote 4
J_{23}	Zooplankton loss to benthic invertebrates and fish	Calculated to give an organic balance to the compartment J_{23} = 0.02 g/m^2/day	"
J_{24}	Zooplankton death and feces transfer to detritus	Calculated to give an organic balance to the compartment J_{24} = 0.02 g/m^2/day	"
J_{30}	Macro-invertebrate and fish emigration	Assuming that are moving away from plume-affected area during the warmest part of the year at a rate twice that of immigration J_{30} = (2)(J_{03}, this table) = (2)(.74 g/m^2/day) = 1.48 g/m^2/day	
J_{34}	Macro-invertebrates and fish death and feces transfer to detritus	Calculated to give an organic balance to the compartment J_{34} = 1.0 g/m^2/day	"
J_F	Commercial and sport fishery harvest	Commercial fishery harvest = .004 g/m^2/day Sport " " = .002 " J_F = .006 g/m^2/day	footnote 5

FLOWS (Cont'd):

Notation	Description	Calculations and Assumptions	Reference
J_{42}	Zooplankton consumption of detritus	Calculated to give an organic balance to the compartment $J_{42} = .06\ g/m^2/day$	footnote 4
J_{43}	Invertebrate and fish consumption of detritus	Calculated to give an organic balance to the compartment $J_{43} = 1.2\ g/m^2/day$	"
J_{50}	Phosphorus export due to water exchange	$J_{50} = \frac{(Q_5, \text{ above})(I_3 + I_4 + I_P, \text{ above})}{(\text{bay area})(\text{bay depth})}$ $= \frac{(.12\ g/m^2)(3 \times 10^6 m^3/day)}{(10^6 m^2)(2m)}$ $= 0.18\ g/m^2/day$	
J_{51}	Phosphorus uptake by producers	Assuming that the organic matter fixed by community production was 1% phosphorus $J_{51} = (.01)(J_{GP}, \text{ above})$ $= (.01)(7.32\ g/m^2/day)$ $= .07\ g/m^2/day$	

Footnotes to Appendix 4B-B

1. Water exchange in the outer bays due to tidal action and longshore advection was considered to be among water masses which were similar to the outer control bay. Therefore, external concentrations of phytoplankton, organic detritus and phosphorus were estimated from measurements taken in the outer control bay.

Power plant pumping provided an additional mechanism of water exchange in the outer discharge bay. In general there was little difference in the concentration of phytoplankton and total phosphorus between the power plant canals and the outer control bay (see Fig.'s 19,20,21,22). Therefore, for these models the external concentrations of materials for the discharge bay was also assumed to be the same as for the control bay.

2. The stock of migrating organisms in the bays was assumed to be represented by mobile benthic macro-invertebrates **(Appen. 4B-A)** and fish. The drop-net sampling of fish biomass by Snedaker, <u>et al</u> (1973-74) was assumed to be 50% efficient. Therefore, fish biomass was taken as two times the values listed in Appendix D.

3. The total benthic invertebrate standing stock in the bays was represented by benthic macro-invertebrates (as listed in Appendix D) plus large meiofauna. A core sample during the winter 1973 (Snedaker, <u>et al</u>, 1973) indicated that meiofauna biomass was approximately twice the biomass of other benthic, macro-invertebrates. Therefore, the total biomass of benthic invertebrates in the bays was assumed to be three times the values listed for benthic macro-invertebrates in **Append. 4B-A** stated in footnote 3, fish biomass for the models was taken as two times the values listed in Appendix **4B-A,**

4. The tidal metabolic energy budget of the system was indicated by total community metabolism. Some indication of component respiration of each compartment was specified under the assumptions stated above (J_{R1} through J_{R4}). This combined information indicated certain limits on the internal exchanges for each compartment if an organic balance existed in the system for each compartment. The evaluation of the internal organic exchanges for the model were subjected to this organic balance and certain judgements were made concerning the nature of each flow as follows:

(a) Much of the energy flow through estuarine ecosystems occurs via detrital pathways. For the model the flow rate of producer biomass into detritus (J_{14}) was assumed to be about 3 times the rate of direct grazing by higher consumers.

(b) Consequently, higher consumers were assumed to graze on detrital material at rates about twice the rate of direct grazing on plant material.

(c) Zooplankton were assumed to feed on producers (phytoplankton) and detritus particles in equal proportions at a rate about equal to their body weight per day.

5. Fishery statistics were obtained from the Summary of Florida Commercial Marine Landings, Florida State Board of Conservation (1971) and were used as follows:

Finfish: = (1.325×10^6 lbs/yr)(.2 dry wt/wet wt)(.9 organic matter/ dry wt) = $.235 \times 10^6$ lbs organic matter/yr

Shellfish - (3.096×10^6 lbs/yr)(.5 dry wt/wet wt)(.56 organic matter/ dry wt) = $.850 \times 10^6$ lbs organic matter/yr

Total = 1.0×10^6 lbs organic matter/yr = 5.54×10^8 g organic matter/yr

Total commercial fishery landings for Citrus County = 1.5 $g/m^2/yr$ = .004 $c/m^2/da$. Sport fishing landings may be as high as 50% of commercial landings (from literature cited by Taylor et al, 1973) = .002 $g/m^2/day$. Therefore, the overall daily average of fish landings for the outer bay area may be on the order of .006 $g/m^2/day$.

6. Detriment to phytoplankton entrained in the power plant cooling waters occurs primarily during chlorination. Fox and Mayer (1972) found an average of 40% reduction in primary production in water immediately discharged from the power plant. However these adverse effects could not be found at the end of the discharge canal. Therefore, the import of phytoplankton to the discharge bays from power plant pumping was assumed to reflect only the additional volume of water exchange with no entrainment mortality.

7. Maturo et al (1973-74) found zooplankton concentrations in the discharge channel about 50% of concentrations found in the control bays during the summer. Concentrations in the outer bays should be somewhat higher than in the canals because of substantial mixing with waters other than the plume. If a density of .11 g/m^2 is assumed (30% reduction) a reasonable organic balance can be calculated with the corresponding rates of water exchange.

APPENDIX 4A-C

Summer Outer Control Bay Values for Forcing Functions, Initial Standing Stocks, And Exchange Rates (Fig. 23) Used in Simulations. Notation: C_f = bay flushing coefficient = 0.5 for tidal flushing only (footnote 1). Z_b = average depth of the outer bay = 1.8 m.

Forcing Functions	Value	Explanation
I_0 Sunlight	Initial: 4200 kcal/m^2/da Range: 2100 - 4200	Approximate range of insolation at 30°N, 65-77°W (Hedgepeth, 1957)
I_R Light available for additional production	Initial: 21°C	Initial estimate assuming that primary production used approx. 50% of I_o during mid-summer (see text)
I_1 Ambient water temperature	Initial = 21°C Range = 13-30°C	Approx. yearly range in outer bay (Grimes 1971)
I_2 Tidal flushing	2 X 10^{6}m^3/day (constant)	Calculation: Outer bay area (1 X 10^{6}m^2) X tidal range (1m) X 2 tides/day (See footnote 1)
I_3 Power plant pumping	0	
I_4 Power plant heat	$\Delta T = 0$	
I_5 Fishing pressure	"constant"	Arbitrary value providing a proportional fishing yield of J_F (see below)
I_6 External nekton stock	"constant"	Arbitrary value providing an immigration of nekton at a rate of J_{o_3} (see below)
J_{01} Flushing import of producers	.54 g/m^2/da	Source concentration of phytoplankton = 0.6 g/m^2 (annual average chlorophyll-a = 3mg/m^3 = .6g org/m^2 (footnote 2)). Flushing import = .6 X C_f X Z_b (footnote 1)
J_{02} Flushing import of zooplankton	.045 g/m^2/da	Source concentration of zooplankton = .05 g/m^3 (average zooplankton conc. south of intake canal (Maturo, 1973)) Flushing import = .05 X C_f X Z_b (footnote 1)
J_{03} Flushing import of Detritus	1.52 g/m^2/da	(footnote 3)
J_{05} Flushing import of phosphorus	.042 g/m^2/da	Source concentration of total phosphorus = 1.5 μg-at/ℓ = .47 g/m^3 average annual concentration (Odum et al., 1973) Flushing import = .47 X C_f X Z_b (footnote 1)

Standing Stocks	Value	Explanation
Q_1 Producers	46.2 g/m^2	Benthic plants = 45.2 g/m^2 (from Snedaker et al., 1973; assuming dry wt. of plants = organic matter) Phytoplankton = 1.0 g/m^2 (summer chlorophyll-a = 2.7 mg/m^3; Odum, et al., 1973) (2.7mg chl-a/m^3)(Z_b)=4.9mg chl-a/m^2 $\widetilde{=}$ 1.0g org/m^2 Total = 46.2 g/m^2
Q_2 Zooplankton	0.16 g/m^2	Estimate from several spot-check tows in the outer bay with a 202 μ mesh net, assuming dry wt = organic matter as shown by Bé et. al. (1971).
Q_3 Benthic Invertegrates and nekton	25g/m^2	Oysters & reef organisms = 21.0 g/m^2 (Lehman, pers. comm.) Macroinvertebrates = 3.0 g/m^2 (Snedaker, et al., 1973) Vertebrates (fish) = 1.0 g/m^2 (Snedaker, et al., 1973)
Q_4 Organic Detritus & Microbes	50 g/m^2	Initial estimate assuming detritus stock in estuarine system to be approximately equal to the standing stock of producers,Q_1
Q_5 Total phosphorus	.07 g/m^2	Summer total phosphorus concentration = 1.38 mg-at/m^3 (Odum, et al., 1973) (1.38mg-at/m^3)(Z_b)(31mg/mg at)(.001g/mg) = .07

Flows	Value	Explanation
J_P Gross primary production	7.4 $g/m^2/da$	Summer average gross community primary production (Odum, et al, 1973)(see footnote 4)
J_{R2} Zooplankton respiration	.03 $g/m^2/da$	Initial estimate assuming a metabolic turnover time of about 5 days which is consistent with some values in Raymont (1963)
J_{R3} Benthic Inv. and nekton respiration	1.2 $g/m^2/da$	Initial estimate assuming a 20-day turnover time for larger consumers.
J_{R4} Organic Detritus & microbe respiration	2.0 $g/m^2/da$	Representative rate of 0_2 consumption by marine detritus 1.6 mg 0_2/g detritus/hr (Hargrave, 1972) (1.6mg 0_2/g/hr)(.001g org/mg 0_2)(Q_4)(24hr/da) $\cong$ 2.0
J_{R1} Producer Respiration	4.3 $g/m^2/da$	Total community respiration = 7.5 $g/m^2/da$ (Odum et al, 1973; footnote 3) minus ($J_{R2} + J_{R3} + J_{R4}$) = 4.3
J_{10} Export of planktonic producers by flushing	.50 $g/m^2/da$	Standing stock of phytoplankton = 1.0 g/m^2 (see Q_1) Flushing export = 1.0 X C_f (footnote 1)
J_{12} Zooplankton grazing	.03 $g/m^2/da$	Initial estimate under organic balance constraints for the compartment (footnote 5)
J_{13} Higher consumers grazing on producers	1.1 $g/m^2/da$	Initial estimate under organic balance constraints for the compartment (footnote 5)
J_{14} Producer death & transfer to detritus pool	2.1 $g/m^2/da$	Initial estimate under organic balance constraints for the compartment (footnote 5)
J_{15} Producer release of phosphorus to water	.04 $g/m^2/da$	Assuming that respired organic matter (J_{R1}) is 1% phosphorus (.01)(4.3) $\cong$ .04
J_{20} Zooplankton export by flushing	.08 $g/m^2/da$	Q_2 (.16) X C_f (.5) = .08 (Footnote 1)
J_{23} Higher consumer grazing on zooplankton	.005 $g/m^2/da$	Initial estimate under organic balance constraints (footnote 5)
J_{24} Zooplankton death & transfer to detritus pool	.005 $g/m^2/da$	Initial estimate under organic balance constraints (footnote 5)

Flows	Value	Explanation
J_{25} Zooplankton release of phosphorus to water	.0003 g/m^2/da	Respired organic matter (JR_2) assumed to be 1% phosphorus
J_{30} Nektonic emigration	.42 g/m^2/da	Initial estimate set equal to immigration
J_{34} Benthic invertibrates and nekton death, pseudofeces, etc. and transfer to detrital pool	1.7 g/m^2/da	Initial estimate under organic balance constarints (footnote 5)
J_F Fishing yield	.006 g/m^2/da	Total commercial yield = .004 g/m^2/da sport fishery = .002 .006 (footnote 6)
J_{40} Detrital export by flushing	1.16 g/m^2/da	Initial estimate (see footnote 3)
J_{42} Zooplankton grazing on detritus	.01	Initial estimate under organic balance constraints (footnote 5)
J_{43} Benthic invertebrates and nekton grazing on detritus	1.8 g/m^2/da	Initial estimate under organic balance constraints (footnote 5)
J_{45} Respiratory regeneration of phosphorus from benthic invertebrates to nekton	.01 g/m^2/da	Respired organic matter assumed to be 1% phosphorus J_{R3} (1.2) X .01 $\cong$ .01 (footnote 1)
J_{50} Phosphorus export by flushing	.035 g/m^2/da	Q^5(.07) X C_f(.5) = .035 (footnote 1)
J_{51} Phosphorus uptake by producers	.07 g/m^2/da	Primary organic production assumed to be 1% phosphorus. J_P (7.4) X .01 $\cong$ .07

Footnotes to Appendix 4B-C

1. Whereas this appendix lists only those values used for simulation of control conditions the general relationship for all conditions of bay flushing are as follows:

Bay flushing is defined with a flushing coefficient, C_f.

$C_f(\text{day}^{-1}) = K_m \times V_f/V_b$ where V_f = volume of water flushing through the outer bay (I_2 and/or I_3)

K_m = fraction of V_f mixed with bay water (assumed here to be 0.5)

V_b = Volume of bay ($2 \times 10^6 m^3$)

The following relationships exist for conditions investigated in these simulations.

Condition	C_f	Flushing volume (m^3/day)
A, tidal flushing only	.500	2.0×10^6
B, tides + Units 1 & 2	1.375	5.5×10^6
C, tides + Units 1, 2, 3	2.300	9.2×10^6

The flushing import of materials suspended or dissolved in the water is determined by the product of C_f, the source concentration of the material (g/m^3) and the average depth of the outer bay (Z_b). Accordingly, export of materials from the system due to flushing is equal to the product of C_f and the areal concentration (g/m^2) of the material in the outer bay. The flushing import and export of detritus represents a special case discussed in footnote 3.

2. Chlorophyll-a concentrations were converted to organic matter equivalents by assuming (a) 100 g carbon/g chlrophyll-a (Steele and Baird, 1967) and (b) 2 g/organic matter/g carbon.

3. Influx of organic detritus to the outer bay was assumed to be from three sources (a) that suspended in the water column, (b) that exported from the salt marsh, and (c) that exported from the inner bay.

Boynton and Kemp (1973, pers. comm.) found an average particulate organic matter content in the water column to be approximately 0.74 g/m^3. Chlorophyll-a during the summer indicated an approximate 0.56 g organic matter/m^3 as phytoplankton. Therefore, the organic detritus in the water column was approximately 0.18 g/m^3. Influx of detritus in the water column due to tidal flushing =

$$.18 \text{ X } C_f \text{ X } Z_b = 0.16 \text{ g/m}^2\text{/day}.$$

Influx of organic detritus to the outer bay from the marsh was estimated using data from Odum et al (1973) to be o.36 g/m^2/day. Values on marsh export were reduced by 1/2 assuming that 50% of that export reaches the outer bay.

Influx of organic detritus to the outer bay from the inner bay was estimated as 1.0 g/m^2/day (initial guess).

Influx from the water column and from the inner bay was assumed to be proportional to C_f as flushing energies increased with the operation of the power plants. Influx from the marsh was assumed to be constant.

Export of detritus from the outer bay due to tidal flushing was assumed to be equal to import from the water column and from the inner bay. Export increased in proportion to C_f with the operation of the power plants.

4. The diurnal curve method of measuring community metabolism yields values for Net Daytime Production ($P_{net\ day}$) and Nighttime Respiration (R_{night}). If rates of <u>daytime</u> respiration are assumed to be similar to R_{night} then the best estimate of <u>total</u> respiration is R_{night} X 2, given 12 hours of daylight and 12 hours of darkness. Accordingly, the best estimate of gross production was $P_{net\ day} + R_{night}$.

5. The total metabolic energy budget of the system was indicated by total

community metabolism. Some indication of component respiration of each compartment was specified under the assumptions stated above (J_{R1} through J_{R4}). This combined information indicated certain limits on the internal exchanges for each compartment if an organic balance existed in the system for each compartment. The evaluation of the internal organic and nutrient exchanges for the model were subjected to this organic balance and certain judgements were made concerning the nature of each flow as follows:

(a) The flow rate of producer biomass into detritus (J_{14}) was assumed to be about twice the rate of direct grazing by higher consumers. This assumption was reasonable since much of the energy flow through estuarine ecosystems occurs via detrital pathways.

(b) Consequently, higher consumers were assumed to graze on detrital material at rates about twice the rate of direct grazing on plant material.

(c) Zooplankton were assumed to graze directly on producer biomass at a rate about 3 times the rate of grazing on detritus. Most of the detritus in this system is assumed to be larger pieces of decomposing marsh grass, sea grasses, and benthic algae rather than fine, suspended particles.

6. Fishery statistics were obtained from the Summary of Florida Commercial Marine Landings, Florida State Board of Conservation (1971) and were used as follows:

Finfish = (1.325×10^6 lbs/yr)(.2 dry wt/wet wt)(.9 organic matter/dry wt) = $.235 \times 10^6$ lbs organic matter/yr

Shellfish = (3.096×10^6 lbs/yr)(.5 drywt/wet wt)(.56 organic matter/dry wt) = $.850 \times 10^6$ lbs. organic matter/yr

Total $\cong 1.0 \times 10^6$ lbs organic matter/yr = 5.54×10^8 g organic matter/yr

Total area of Citrus County estuary = 3×10^8 m^2 (McNulty et al, 1972).
Total commercial fishery landings for Citrus County = 1.5 g/m^2/yr = .004 g/m^2/da.

Sport fishing landings may be as high as 50% of commercial landings (from literature cited by Taylor et al, 1973) = .002 g/m^2/day. Therefore, the overall daily average of fish landings for the outer bay area may be on the order of .006 g/m^2/day.

4C. OYSTER REEFS AT CRYSTAL RIVER, FLORIDA AND THEIR ADAPTION TO THERMAL PLUMES

M. E. Lehman

Department of Environmental Engineering Sciences
University of Florida
Gainesville 32611

INTRODUCTION

Measurements of structure and function of oyster reefs in and out of the thermal plume were made to characterize their overall properties of mass, metabolism, and diversity as an ecological unit. Simple models were evaluated and simulated to help understand present ecosystems and to suggest the response and adaptation of the oyster reef with additional power plant effluents. For ecological perspective and for use in impact studies the value of oyster reefs was calculated by estimating their role in the energy budget of the larger estuary.

Study Area

Measurements were taken in two areas. The thermally impacted area north of the power plant discharge channel and the control area south of the intake canal shown in Fig. 1 and Fig. 2 respectively. Six reefs in the discharge bay and five reefs in the control area were chosen.

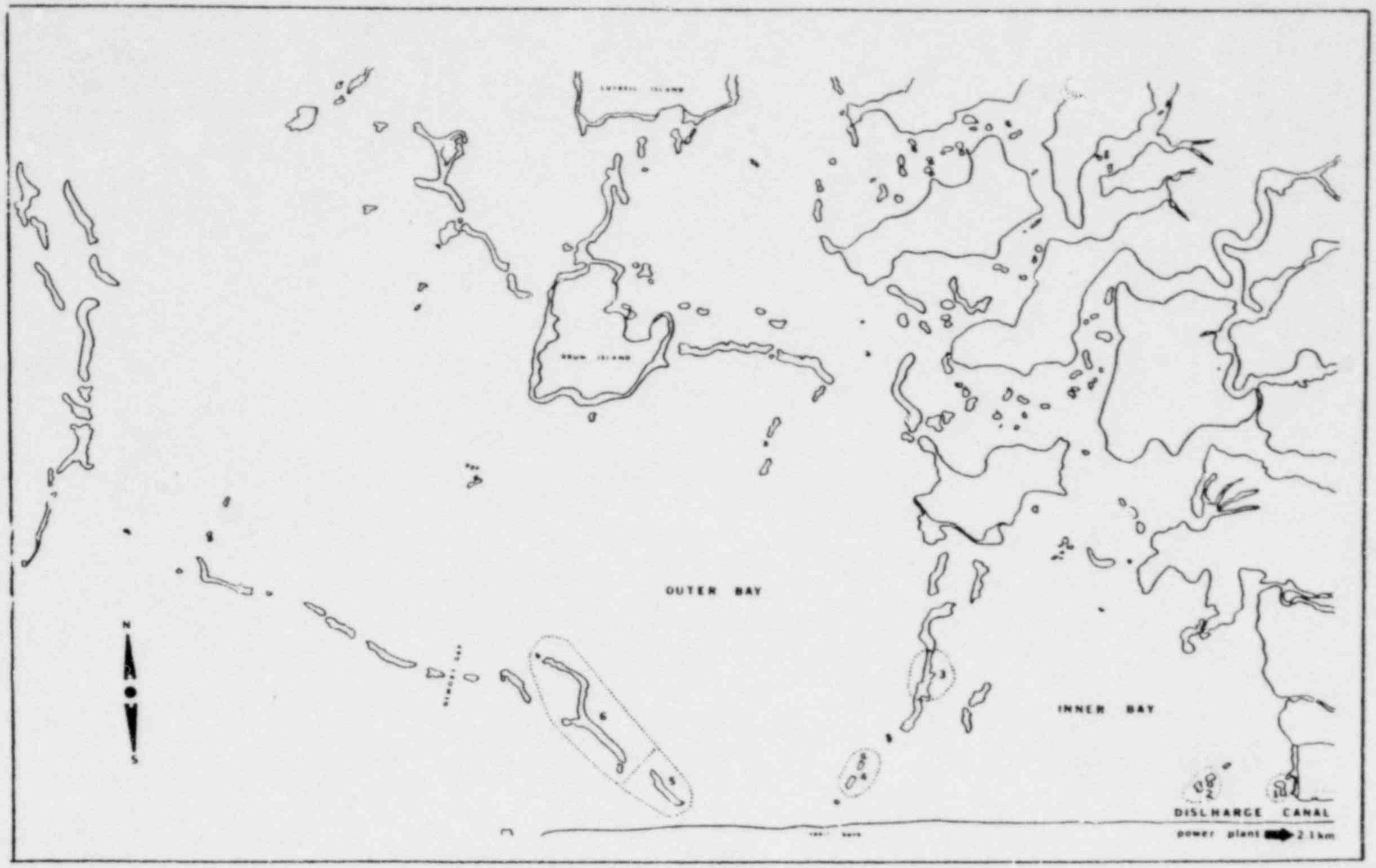


Figure 1. Crystal River Oyster Reef Sampling Sites in Discharge Bay. Note Reefs 1-6.

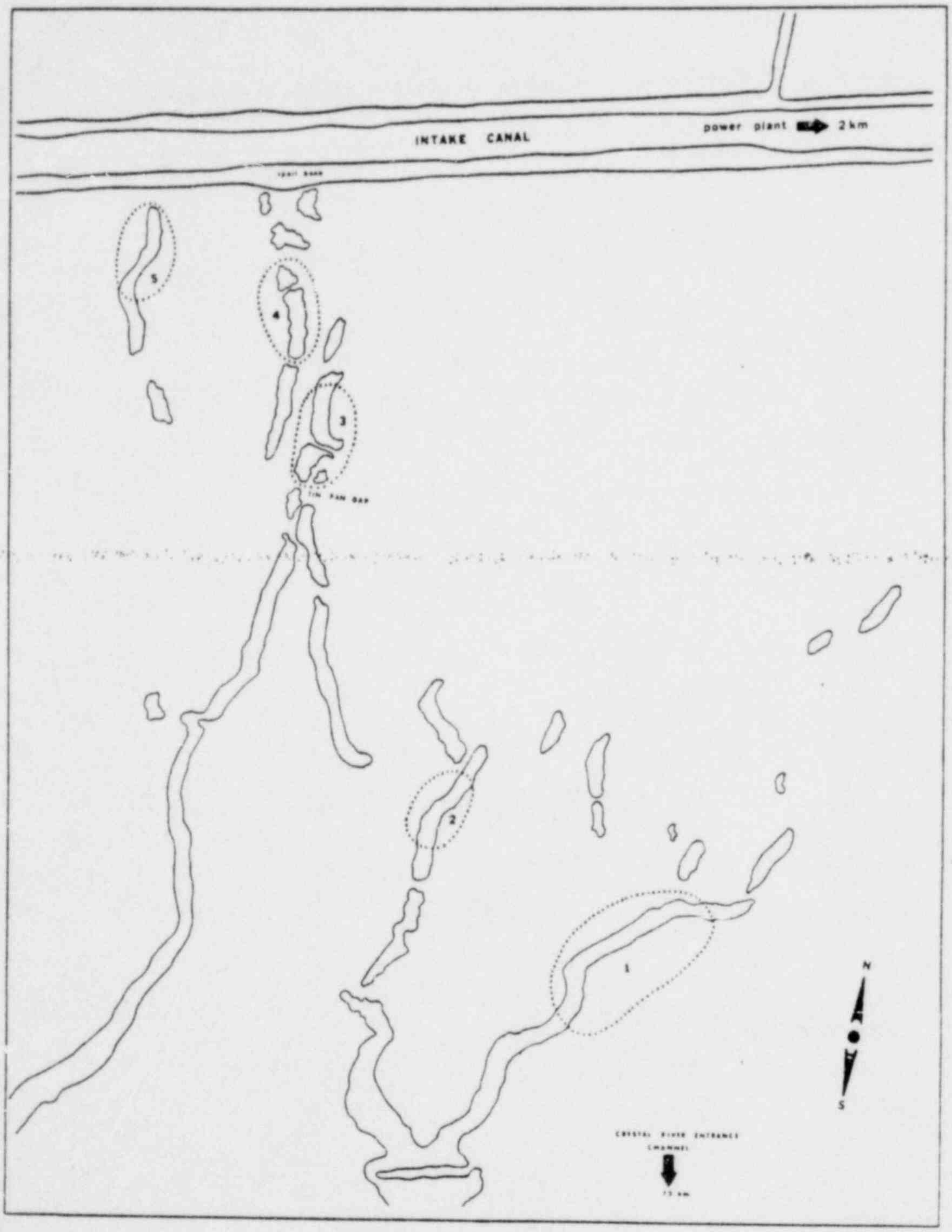


Figure 2. Crystal River Oyster Reef Sampling Sites in Control Area. Note reefs 1-5.

POOR ORIGINAL

METHODS

Field measurements were made of reef organism numbers and biomass, reef metabolism and diversity, and 'set' of oyster larvae.

Biomass and Numbers

Measurements of biomass of oyster reef organisms from samples in the discharge bay and control area were made during two seasons of the year. A total of six biomass samples were collected in each area; four summer samples and two winter samples. Duplicate samples were taken from one reef in each area to check sampling variability.

Samples were selected from zones of highest organism density by a random toss of a quarter meter square quadrant. One control cample was taken from a lower density zone on a reef fringe. All organisms and structure within the quadrant were removed to a depth of 10 cm, transported to the lab and frozen consolidated. Samples from which relationships of oyster weight and height were determined were processes fresh. All conspicuous organisms from these samples were counted, identified and weighed. Dry weights of organisms were taken after one week at 105°C. Area-weighted values of oyster reef standing crop calculated for each bay were used in the simulation models.

Diversity

Number of species per thousand individuals as an indicator of community diversity was determined by counting the first 1000 organisms encountered on each oyster reef. The species diversity of the macroinvertebrate community was measured by this method for six reefs in the thermal discharge area and five reefs in the control areas over the summer and winter seasons. Duplicate counts were made during the summer. Data on species per thousand were translated into several other diversity indices.

Representatives of each species encountered on the reef were collected, preserved, and identified. A species list contrasted organisms collected in the thermally-affected area with those in the control area.

Larval Set

Estimates of larval setting rates were made for oyster larvae by two methods. Spat in biomass samples were counted and weighed to determine differences in standing stocks with season. In the second method counts were made of set on shell placed on the reef. Wire 'cages' were attached to the reef substrate (Fig. 3). Each cage contained a quarter square meter of oyster reef structure loosened from the reef and placed inside the anchored cage. Sets were removed, counted, and weighed from four spat cages in each area for three periods of the year; May-June, June-Dec., and Dec.-May.

Metabolism

Reef metabolism was measured by two methods. One when reefs were exposed to air, and another when reefs were underwater.

Exposed Reefs with CO_2 Gas Exchange

Changes in carbon dioxide concentration in the air flowing over plant and animal ecosystems have been sensed by using infrared gas analyzers (IRGA) as measures of metabolism of the communities. During the summer of 1973, an

Fig. 3. Reefs at Crystal River showing spat cages, July 20, 1973. a. discharge area, reef 5. b. control area, reef 4.

IRGA unit was operated in the salt marshes bordering on the discharge bay and control area (Young, 1974b). Proximity of the oyster reefs to the marshes afforded an opportunity to investigate metabolism of oyster reefs during periods of low tides. Two quarter meter square samples were removed from reefs in the discharge bay and transported to the gas metabolism unit. Each sample was placed inside a gas metabolism chamber at its approximate reef elevation, and hourly carbon dioxide changes were measured over a 24-hour period (Fig. 4). Similar measurements were made for two reef samples in the control area.

Calculations of diurnal rates of respiration and photosynthesis and details of the complete sampling apparatus have been described by Odum (1970), Lugo (1969), and Young (1974 a). A basic equation used for CO_2 calculations was:

$$\text{g C/m}^2\text{/hr.} = \frac{(\text{diff.})(\text{flow})}{(\text{area})} \left(\frac{273}{T}\right)\left(\frac{P}{760}\right)\left(\frac{12 \text{ g C/mole}}{22.4 \text{ l/mole}}\right)\left(\frac{60 \text{ min/hr}}{10^6}\right)$$

where diff. = difference in ambient CO_2 concentration and chamber CO_2 concentration calibrated to some standard gas such as 300 (ppm) gas.

flow = air flow rate through chamber, liters/min.

area = area of reef, square meters

T = absolute temperature

P = atmospheric pressure, mm Hg

Fig. 4a. Measurement of CO_2 exchange with gas analysis. Plastic bag with oysters.

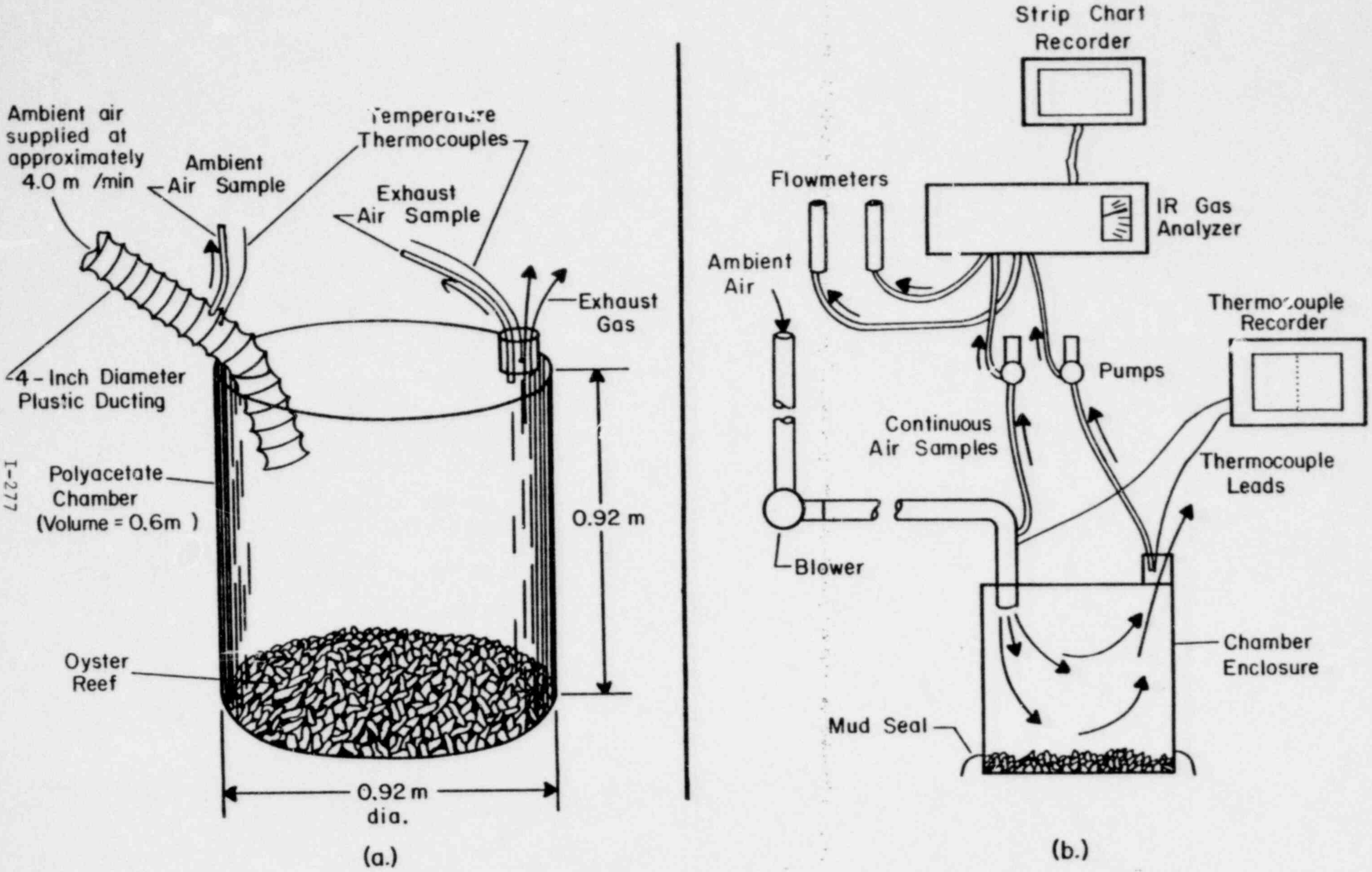


Fig. 4b. Schematic of IRGA unit used on exposed reef assemblages.

One of the calculations made from field data is offered as an example (Control Area, August 7, 1973):

Time	Flow	Press.	Temp°C	CO_2chamber	CO_2ambient
1824	1361 ℓ/min.	760 mm Hg	31.7	280.5 ppm	278.5 ppm

$$\text{Rate} = \frac{(278.5 - 280.5 \text{ ppm})(1361)\ell/\text{min.})}{.2500 \text{ m}^2} \left(\frac{273°\text{K}}{304.7°\text{K}}\right)\left(\frac{760}{760}\right)$$

$$\times \left(\frac{12 \text{ g C/mole}}{22.4/\text{mole}}\right)\left(\frac{60 \text{ min/hr}}{10^6 \text{ppm}}\right)$$

$$= 30.85 \times 10^{-2} = -.31 \text{ g C/m}^2\text{/hr (negative sign implies respiration)}$$

A total of seventeen hourly respiration measurements were obtained for each sample in the discharge bay; eighteen in the control bay. The difference in number of measurements and hours sampled reflects periods of high tide when the reef communities in the chambers were submerged and no significant changes in CO_2 concentration were recorded.

Rate of change curves plotted for each dial measurement were integrated to obtain respiration values in units of g C/m^2/day for the bay. After each metabolism measurement, biomass of chamber samples was determined by methods previously described, and respiration values of g C/g dry wt/day calculated.

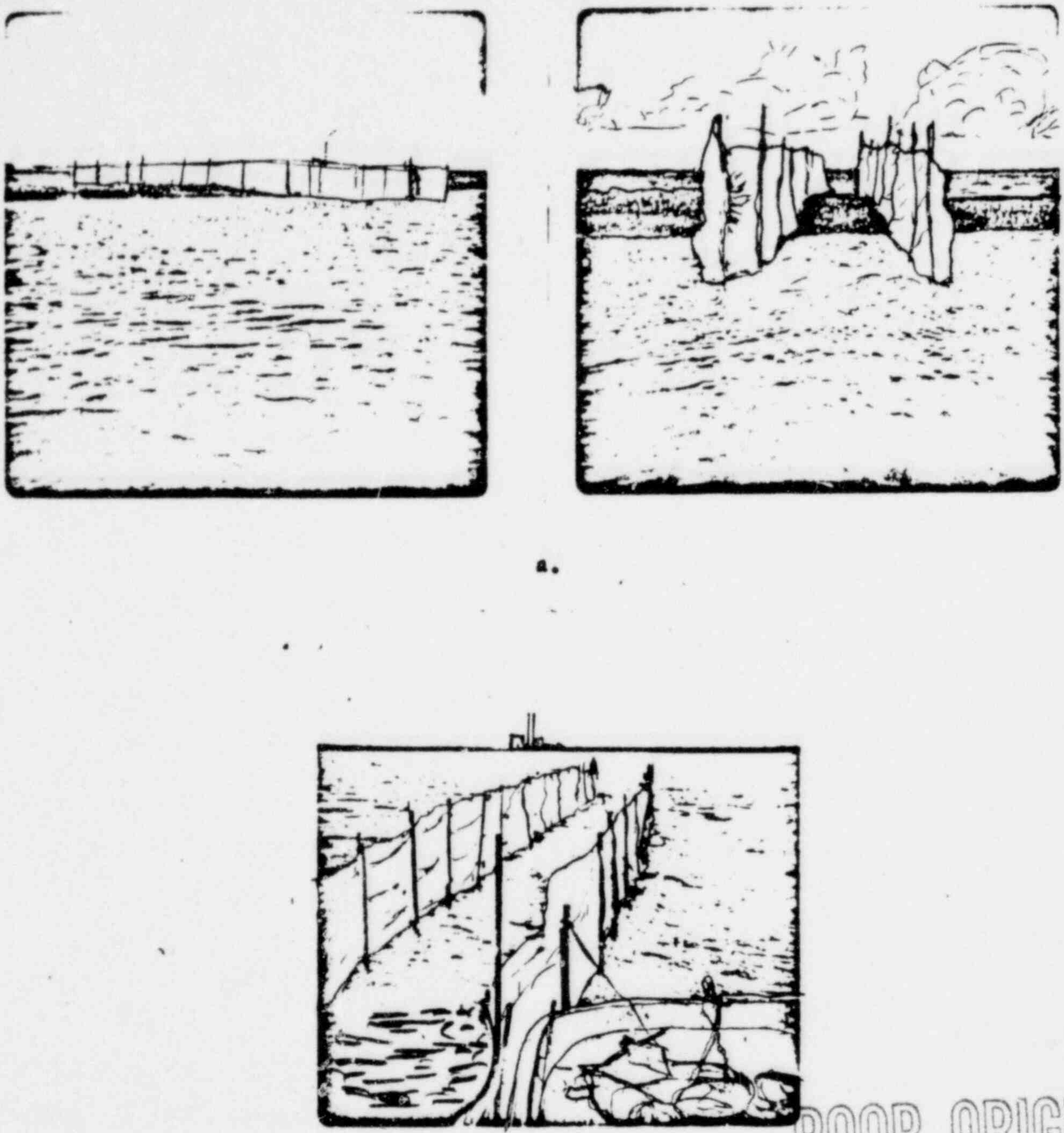
Underwater with Artificial Channels

Upstream-downstream changes in flowing waters have been used to measure community metabolism for a variety of ecosystems; coral reefs (Odum and Odum, 1955), turtle grass beds and freshwater springs (Odum, 1956, 1957), streams

(Hall, 1971) and mussel beds (Nixon et al, 1971). The methods described by these authors were adopted to measure underwater respiration of the oyster consumer community on two reefs, one thermally-affected and the other natural.

Review of the main metabolic processes in the tidal stream flowing over the reefs indicated that the observed upstream-downstream change in oxygen would be the algebraic sum of the primary production, the respiration, the diffusion into or out of the water, and advection into the sides of the tidal stream. A channel of polyacetate sheets and steel posts was constructed paralled to current flow across the reef to remove lateral advection and diffusion effects (Fig. 5). Diffusion (reaeration) measurements were made using a floating plastic dome at the midpoint of the channel stream (Fig. 6) followed methods by Hall (1971) based on the earlier work of Copeland and Duffer (1974). Diffusion rates were calculated as $g/m^2/hr/100\%$ saturation deficit for seventeen measurements over a tidal cycle. From these measurements, a multiple regression equation was calculated relating diffusion, current speed, and depth. This graph was used to estimate diffusion rates for sampling periods when no diffusion data were taken. Oxygen concentration was measured at the upstream and downstream ends of the channel by analysis of quadruplicate water samples using azide modification of the Winkler method (Standard Methods, 1971) adapted for 125 ml collection bottles. Measurements of temperature, salinity, current speed (fluorescein dye), and depth were also made with each set of samples.

Underwater community metabolism with artificial channels was followed hourly and sometimes on the half hour over three consecutive tidal cycles during July, 1974. This effort included 23 measures of metabolism in the



a.

b.

Fig. 5. Channel used to measure underwater metabolism. a. Photographs of reef 6, discharge bay, July 7, 1974, at low tide. b. at reef 4, control area, July 4, 1974, high tide. Note power plants in background.

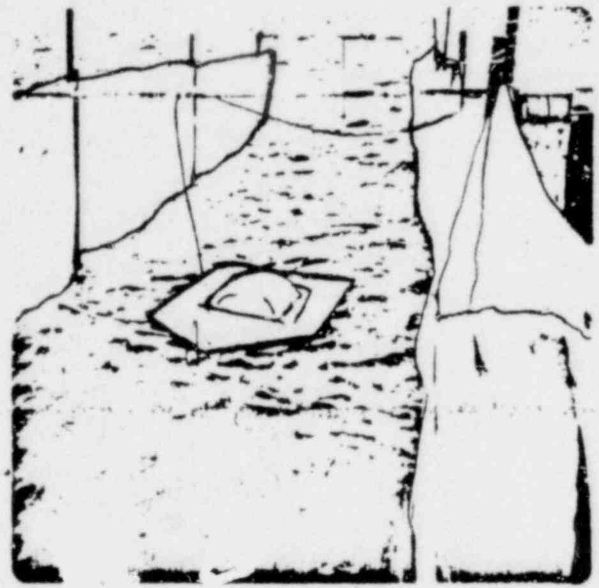


Fig. 6. Artificial channel with diffusion dome. Photograph at reef 6, discharge bay, July 7, 1974.

discharge bay, and 17 in the control area. Calculation of one of these metabolic rates is illustrated:

$$g\ O_2/m^2/hr = [(\frac{g\ O_2/m^3}{\text{res. time}})(\text{depth})] \pm (\text{diffusion correction})$$

where, ($g\ O_2/m^3$) = difference between upstream and downstream value; plus (+) implies downstream greater than upstream and minus (-) implies downstream less than upstream.

res. time = time difference between upstream and downstream station based on current speed; residence time (in channel) of water volume sampled.

depth = average depth of water flowing over reef during sample.

diff. correction = diffusion rate x saturation deficit (for conditions of current, depth, temperature and salinity during sample). The degree of saturation of water column determines sign: (-) undersaturation , (+) oversaturation.

(Discharge Bay, July 7, 1974)

Time	Current	$g\ O_2/m^3$	Res. time	Depth	% Sat.	Diffusion
1830	.214 m/sec	-.11	.026 hr	.71 m	117.68%	3.59 $g/m^2/hr/100\%$ sat. def.

$$\text{Rate} = [\frac{(-.11\ g\ O_2/m^3)}{(.026\ hr)}\ (.71m)] \pm [(+.18\ \text{sat. def.})(3.59\ g\ O_2/m^2/hr/100\%\ \text{sat. def.})]$$

$$= [(-4.23\ g\ O_2/m^3/hr)(.71\ m)] + (.64\ g\ O_2/m^2/hr)$$

$$= -3.00\ g\ O_2/m^2/hr) + (.64\ g\ O_2/m^2/hr)$$

$$= -2.36\ g\ O_2/m^2/hr\ (\text{neg. sign implies respiration})$$

Integration of the rate of change curves of hourly rates over the entire sampling period gave total respiration values that could be interpreted on a gm/m^2/day basis.

Total reef community

Total reef metabolism was the sum of the exposed value (low tide) and the underwater value (high tide), based on the assumption that each tidal stage was twelve hours per day.

Development of Models, Simulations, and Energy Calculations

Two models of the oyster reef system were developed. A larger model was used for conceptualization (Fig. 7), and a smaller model for simulation using data from field measurements (Fig. 8).

Three basic groups of symbols used in the oyster reef diagrams were forcing funtions (circles), storages (tanks), and flows (lines). A description and equation for each symbol used in the diagrams is given in Fig. 9. Reference to the model diagram shows the outside energy sources (forcing functions) considered important to be larvae, salinity variation, food, current, tide, and heat. Transfers of energy between forcing functions and storages occur along the connecting pathways. Stored properties are larvae biomass, oyster biomass, reef structure, biomass of all organisms other than oysters, and diversity

The effect of temperature, both natural and man-induced, was diagramed to operate on two pathways simultaneously; pulling on the respiration pathways and pushing on the food uptake pathways.

Energy values of the forcing functions, storages, and flows of a discharge bay model and a control area model were calculated and put on diagrams. Model simulation was done on two EAI analog computers slaved to function as one unit.

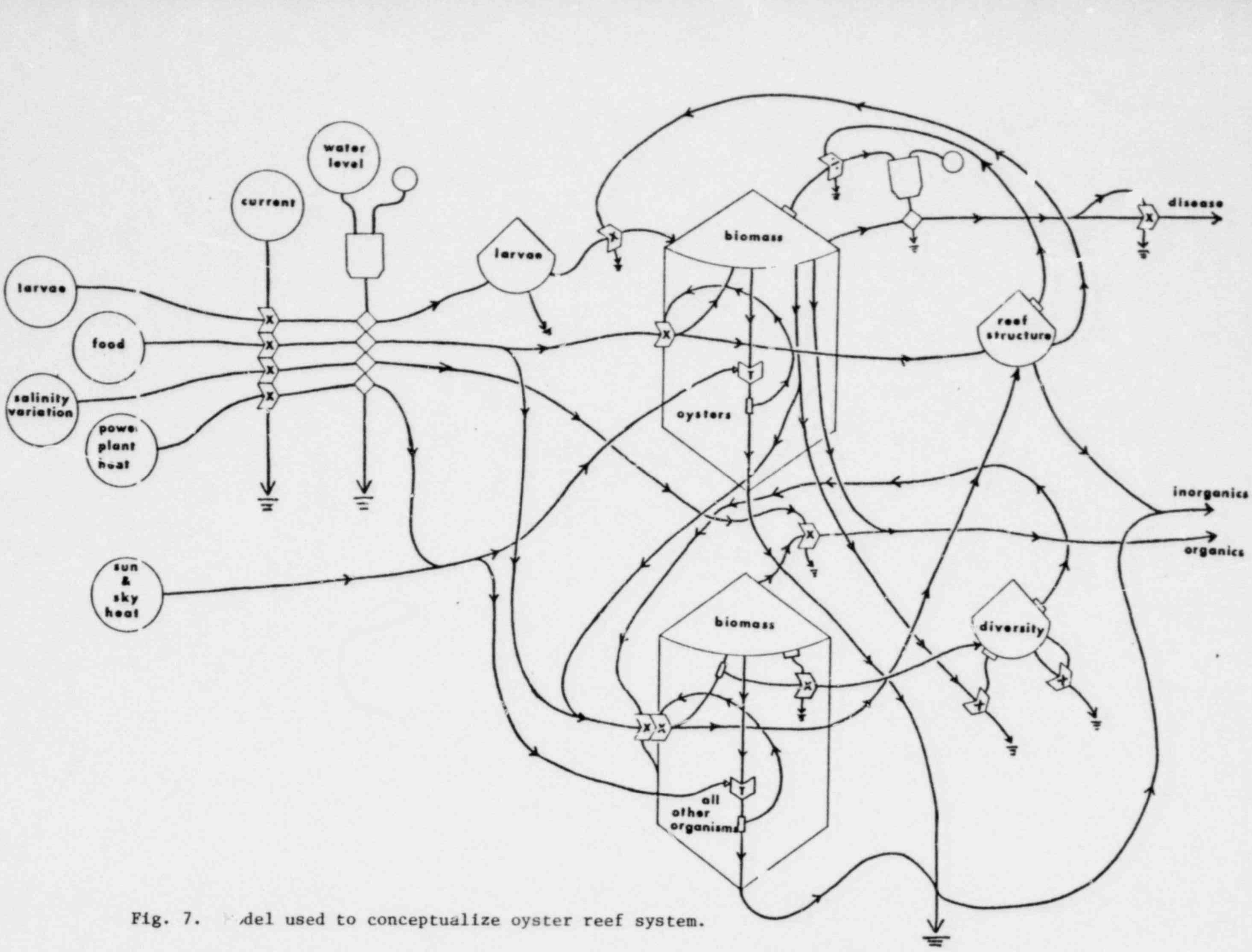


Fig. 7. Model used to conceptualize oyster reef system.

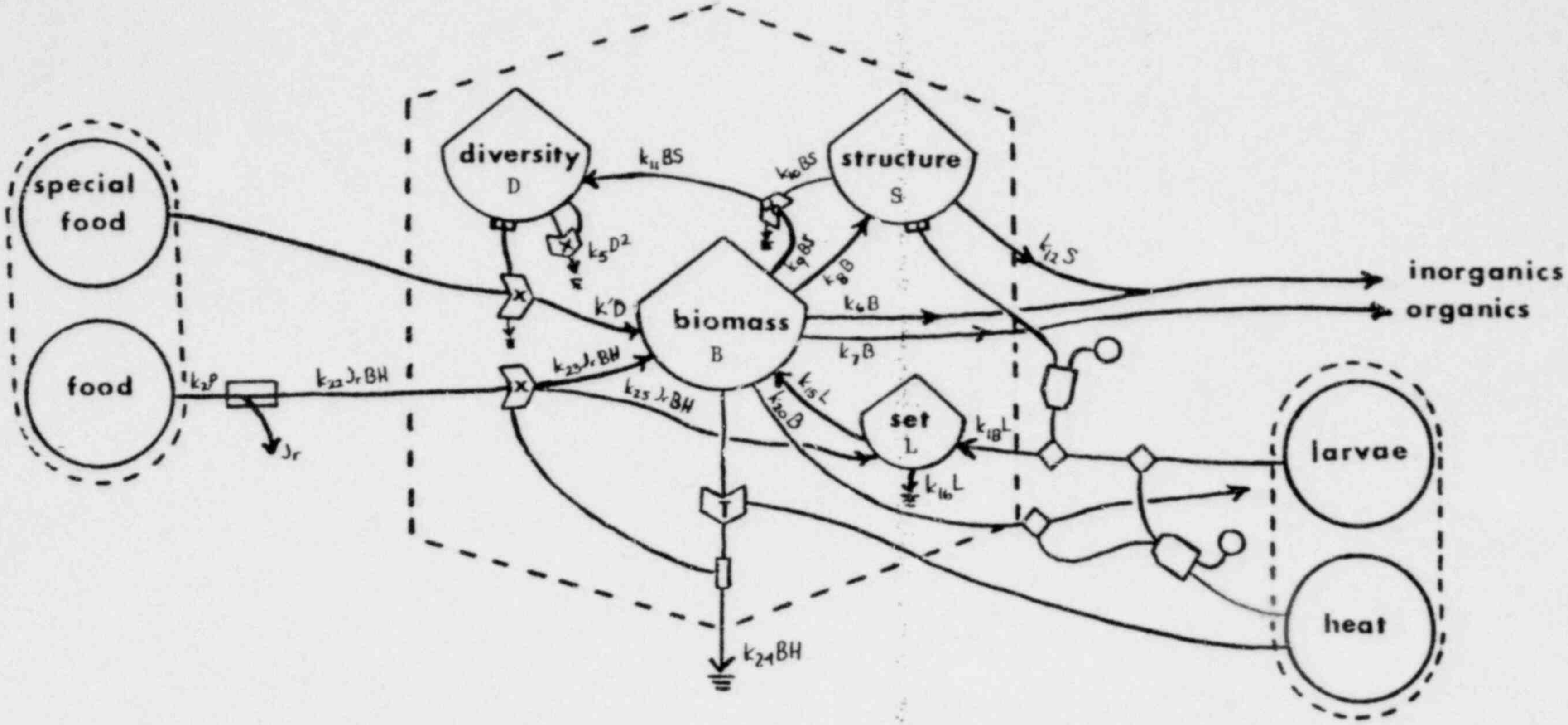


Fig. 8. Oyster reef model evaluated with field data and used for simulation. Equations are:

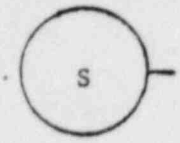
$$\dot{B} = k'D + k_{23}JrBH + k_{15}L - k_8B - k_7B - k_6B - k_{20}B - k_{24}BH - k_9BS$$

$$\dot{D} = k_{11}BS - k_5D^2$$

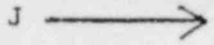
$$\dot{S} = k_8B - k_{12}S - k_{10}BS$$

$$\dot{L} = k_{18}L + k_{25}JrBH - k_{16}L - k_{15}L$$

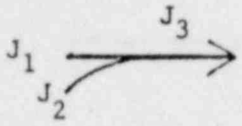
$$Jr = k_2P \; /(1+k_{21}BH)$$



Forcing Function. Outside source of energy or materials: such as sun, fossil fuel, heat, tide, water, or food.

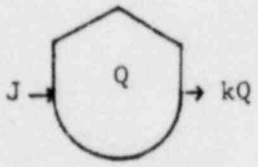


Pathway of energy or materials. Arrow designates flow in either direction or flow against a backforce. Flow, J, is proportional to population of active forces, N.



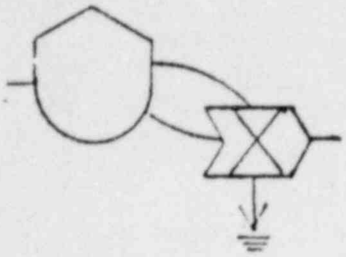
Adding Junction. Intersection of two flows capable of adding. $J_1 + J_2 = J_3$

Heat Sink by which potential energies entering the system leave is degraded form according to the second law of thermodynamics. Outflow is -kS.

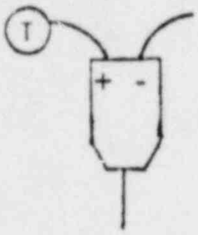


Passive Storage of energy or materials in which no new potential energy is generated. work must be done in moving the potential energy in and out of the storage. This is called a state variable with the sum of the inputs and outputs being dQ/dT= J-kQ.

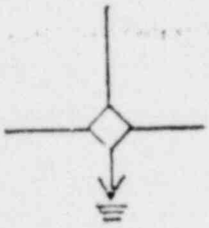
Fig. 9. Symbols used in model diagrams.



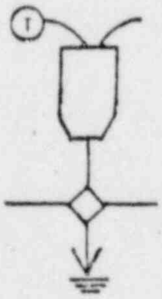
Flow a Squared Function from a passive storage. Represents loss of potential energy:eg, stress function such as disease, or high energy cost of information storage.



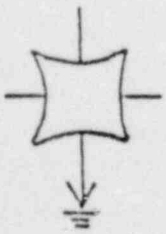
Logic Comparator with a critical threshold, T. logic on or off control depends on which input (+ or -) is larger.



On-Off Switch to a flow.

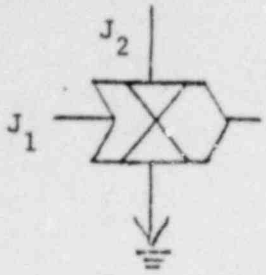


Comparator-Switch Mechanism combines above two components for switching action of flows that control other flows: eg, switching off flows of food, larvae, and salinity when tide is out, on when it is in.

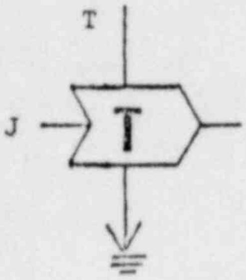


General Symbol for switching function.

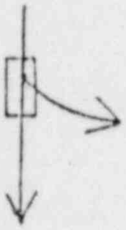
Fig. 9. Continued.



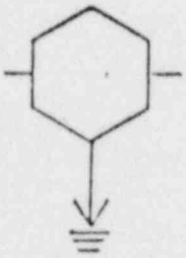
Workgate. Intersection at which one flow makes possible another. In this case one flow affects the conductivity of the other to produce a multiplier output, kJ_1J_2.



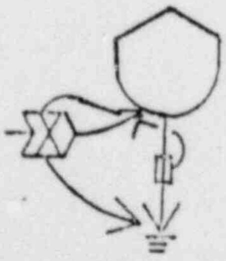
Workgate. specia; case of the above where temperature is used as a linear input. Output is kJT.



Rate Sensor monitors flow rate and controls input of another flow in proportion to monitored flow.



Self-Maintaining Consumer uses its own stored potential energy to do work on the processing and work of the unit. An auto-catalytic response through combination of passive storage, workgate, and rate sensor: can symbolize an animal, city industry, oyster reef system, ect.



Special Case of self-maintenance that adjusts inflow to depreciation.

Fig. 9. Continued.

RESULTS

Biomass and Numbers

Biomass data are given in Tables 1 and 2, and numbers data are in Tables 3 and 4, for the Discharge Bay and Control Area respectively. T-tests for differences in mean values of biomass and numbers between the discharge and control areas gave the following results at the 95% confidence levels (1) no dignificant biomass differences were found for oysters, reef structure or larval set(spat), (2) significantly larger biomass was found for all other organisms in the control area, (3) oyster numbers were not significantly different, but (4) numbers of spat were larger in warmer waters, (5) other organisms were less numerous in the discharge area.

Seasonal differences in the discharge bay oyster biomass proved significant. T-tests at the 95% confidence level showed no significant seasonal fluctuations in other stocks such as reef structure, other organism biomass and larval set. Significant seasonal differences were found for other organisms, but trends indicated essentially no changes in oyster biomass in the control area. A sharp seasonal change in larval stocks might be inferred from control data in Table 4.

Height-frequency distribution curves of oysters are given in Fig.10 for both areas. The peaks of the curves are similar, but large oysters were missing in the discharge area.

Relationship of whole blotted wet weight to shell height for oysters in the discharge and control areas was determined for two biomass samples (Fig. 11 and Fig. 12). The curves were similar. One curve of (wet) meat

Table 1.

Dry Weights of Oyster Reef Organisms and Structure per Quarter Meter Square.
Crystal River, Florida - Discharge Bay

Reef Number	Date Sampled	Total Reef Weight incl. all organisms[b] g	Total Reef Structure[b] g	Whole Weight of Oysters[a] g	Meat Weight of Oysters g
1	July 19, 1973	25053.2	23331.9	2120.7	25.3
6	July 30, 1973	39137.1	35167.6	4764.8	65.1
2a	July 31, 1973	7494.0	6699.1	837.8	6.8
2b	July 31, 1973	8542.6	7873.3	950.3	6.9
2a	Dec. 07, 1973	9668.0	8719.7	2030.6	26.6
2b	Dec. 07, 1973	9339.2	8765.0	2115.6	25.1
$\bar{x}$[e]		32095.2[c] 8761.0[d]	29249.8[c] 8014.3[d]	2136.6	26.0
S. E.				577.7	8.7

a Blotted wet weight in this column only

b T-tests indicate significant difference at 95% confidence level in data in these columns taken at different sample depths. Reefs 1 and 6 sampled to 20 cm. Reefs 3 and 4 sampled to 10 cm

c Mean of values from reefs 1 and 6

d Mean of values from reefs 2a and 2b

e $\bar{x}$ = mean

f S. E. = one standard error about the mean, $\bar{x}$

Table 1 (continued)

Dry Weight of Oyster Reef Organisms per Quarter Meter Square
Crystal River, Florida - Discharge Bay

Reef Number	Date Sampled	Whole Weight of Crabs g	Whole Weight of Barnacles g	Whole Weight of Mussels g	Whole Weight of Spat g
1	July 19, 1973	13.8	-	-	-
6	July 30, 1973	38.7	-	7.2	250.8
2a	July 31, 1973	9.6	6.7	-	25.1
2b	July 31, 1973	15.7	9.5	0.2	102.2
2a	Dec. 07, 1973	7.0	0.4	-	9.6
2b	Dec. 07, 1973	3.7	10.3	-	31.6
$\bar{x}$		14.8	6.7	3.7	83.9
S. E.		5.1	2.2	-	44.7

Table 2.

Dry Weights of Oyster Reef Organisms and Structure per Quarter Meter Square.
Crystal River, Florida - Control Area

Reef Number	Date Sampled	Total Reef Weight incl. all organisms[b] g	Total Reef Structure[b] g	Whole Weight of Oysters g	Meat Weight of Oysters g
1	July 20, 1973	23826.0	17826.9	3196.7	32.5
5	Aug. 06, 1973	38010.9	33486.2	2891.0	39.2
3	Aug. 06, 1973	12480.4	10605.5	1647.3	21.6
4	Aug. 06, 1973	8552.2	6448.9	2139.5	20.6
4	Jan. 10, 1974	11259.6	9014.4	1346.5	20.1
4fringe[e]	Jan. 10, 1974	4830.0	2869.4	284.8	4.0
x (does not include fringe sample)		30918.4[c] 10516.3[d]	25656.6[c] 8527.2[d]	2244.2	26.8
S. E.		-	-	353.4	3.9

---

a Blotted wet weight in this column only.

b T-tests indicate significant differences at 95% confidence level in data in these columns taken at different sample depths. Reefs 1 and 5 sampled to 20 cm. Reefs 3 and 4 sampled to 10 cm.

c Mean of values from reefs 1 and 5

d Mean of values from reefs 3 and 4

e Fringe regers to sample collected in low organism density area on oyster reef

Table 2 (continued)

Dry Weight of Oyster Reef Organisms per Quarter Meter Square.
Crystal River, Florida - Control Area

Reef Number	Date Sampled	Whole Weight of Crabs g	Whole Weight of Barnacles g	Whole Weight of Mussels g	Whole Weight of Spat g	Whole Weight of Drills g
1	July 20, 1973	33.2	-	38.7	-	-
5	Aug. 06, 1973	27.7	239.4	141.4	82.2	232.8
3	Aug. 06, 1973	11.4	-	23.7	39.4	-
4	Aug. 06, 1973	20.7	30.9	38.4	75.2	30.3
4	Jan. 10, 1974	35.0	45.6	59.4	128.1	-
4fringe	Jan. 10, 1974	3.2	16.6	28.1	70.6	-
x (does not include fringe sample)		25.6	105.3	55.0	81.2	-
S. E.		4.3	67.2	19.7	18.2	

Table 3.

Numbers of Organisms per 0.25 m^2 - Discharge Area

Organism	July 19, 1973 Reef	July 30, 1973 Reef	July 31, 1973 Reef		Dec. 7, 1973 Reef		$\bar{x}$, Numbers/ 0.25 m^2	S. E.
	1	6	2a	2b	2a	2b		
Oysters	110	132	150	237	207	207	174	20
Spat	198	425	22	106	39	94	147	61
Crabs	63	179	182	208	111	89	139	24
Mussels	-	77	2	3	-	-	27	25
Barnacles	-	-	51	154	6	33	61	32
Worms	-	98	-	1	-	-	-	-
Amphipods	-	20	-	-	-	-	-	-
Anemones	-	59	-	-	-	-	-	-

Table 4.

Numbers of Organisms per 0.25 m^2 - Control Area

Organism	July 20, 1973	Aug. 6, 1973			Jan. 10, 1973		$\bar{x}$, Numbers/ 0.25 m^2	S. E.
	Reef	Reef			Reef			
	1	5	3	4	4	4 Fringe		
Oyster	411	61	342	228	199	49	248	60
Spat	450	646	360	978	1037	626	696	135
Crabs	136	439	210	281	939	204	401	144
Mussels	391	1025	480	555	1010	410	692	135
Barnacles	-	-	6	477	695	159	393	203
Worms	17	42	103	-	-	-	54	26
Starfish	-	-	-	-	-	1	-	-
Amphipods	36	93	-	-	-	-	-	-
Anemones	1	367	-	-	-	-	-	-
Conches	-	2	-	1	-	-	-	-
Clams	-	22	-	-	-	-	-	-

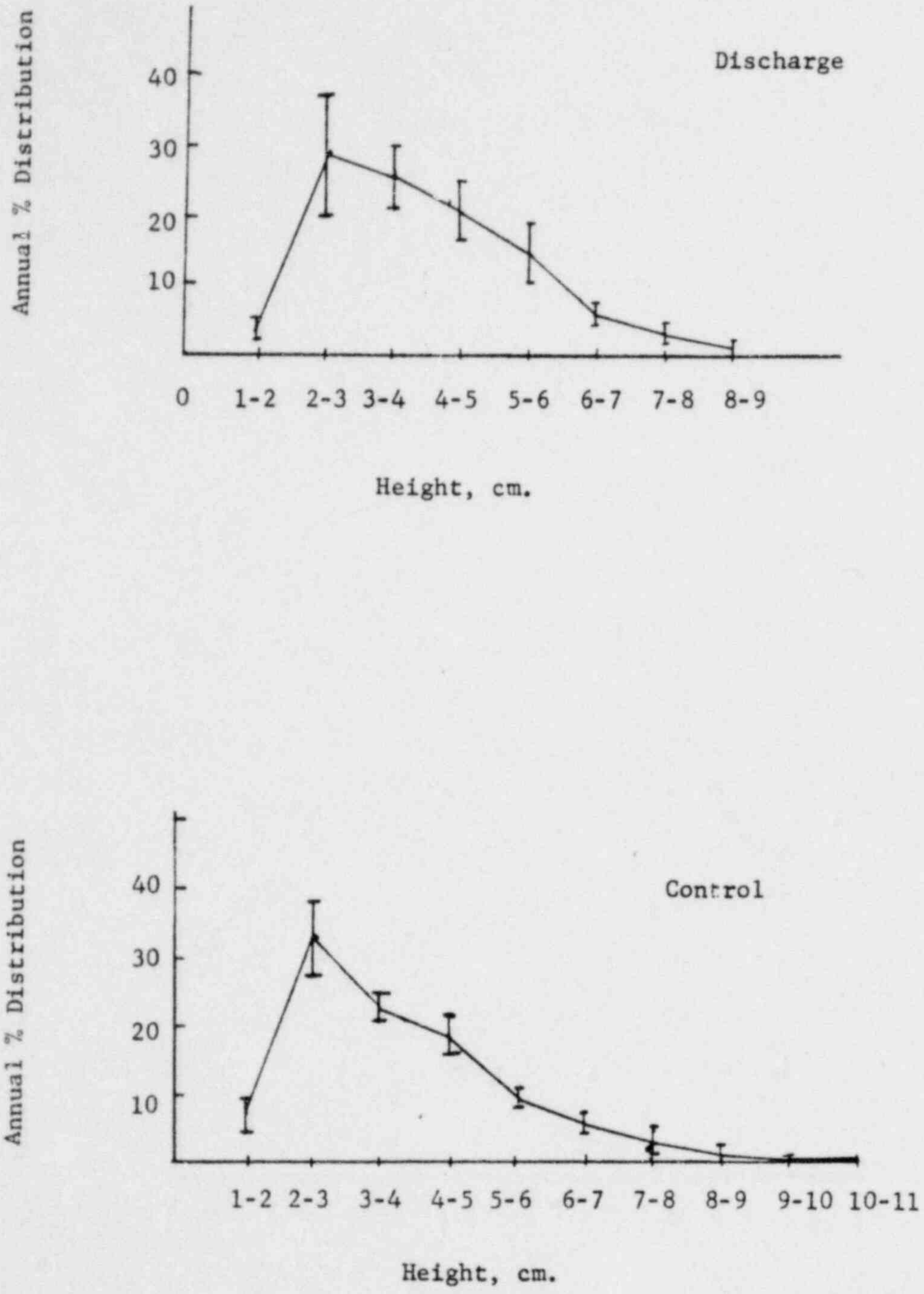


Fig. 10. Height frequency distribution curves of oysters. a. Discharge bay. b. Control bay.

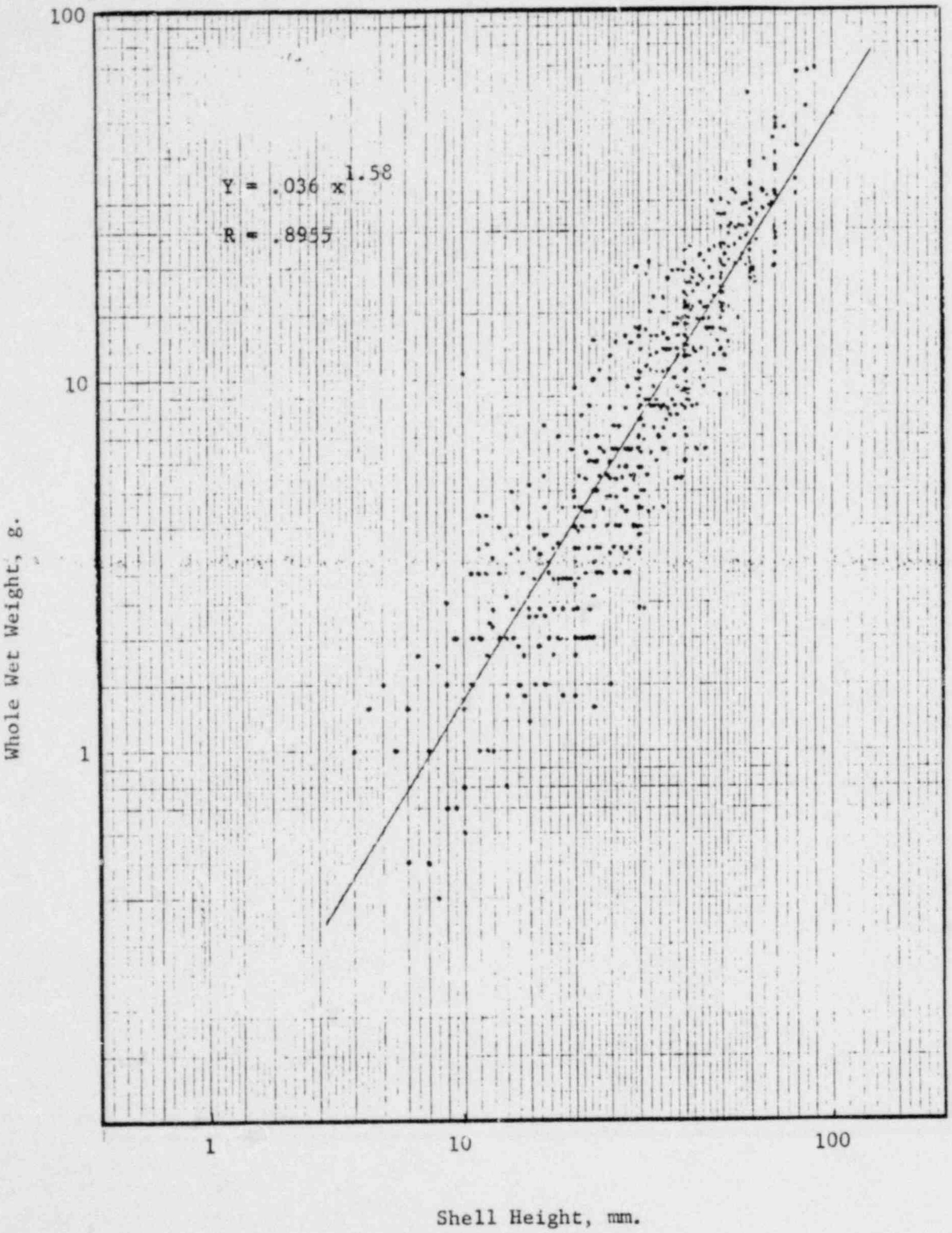


Fig. 11. Relationship of whole (blotted) wet weight to shell for Crassostrea virginica in discharge bay, July 30, 1973, reef 6.

POOR ORIGINAL

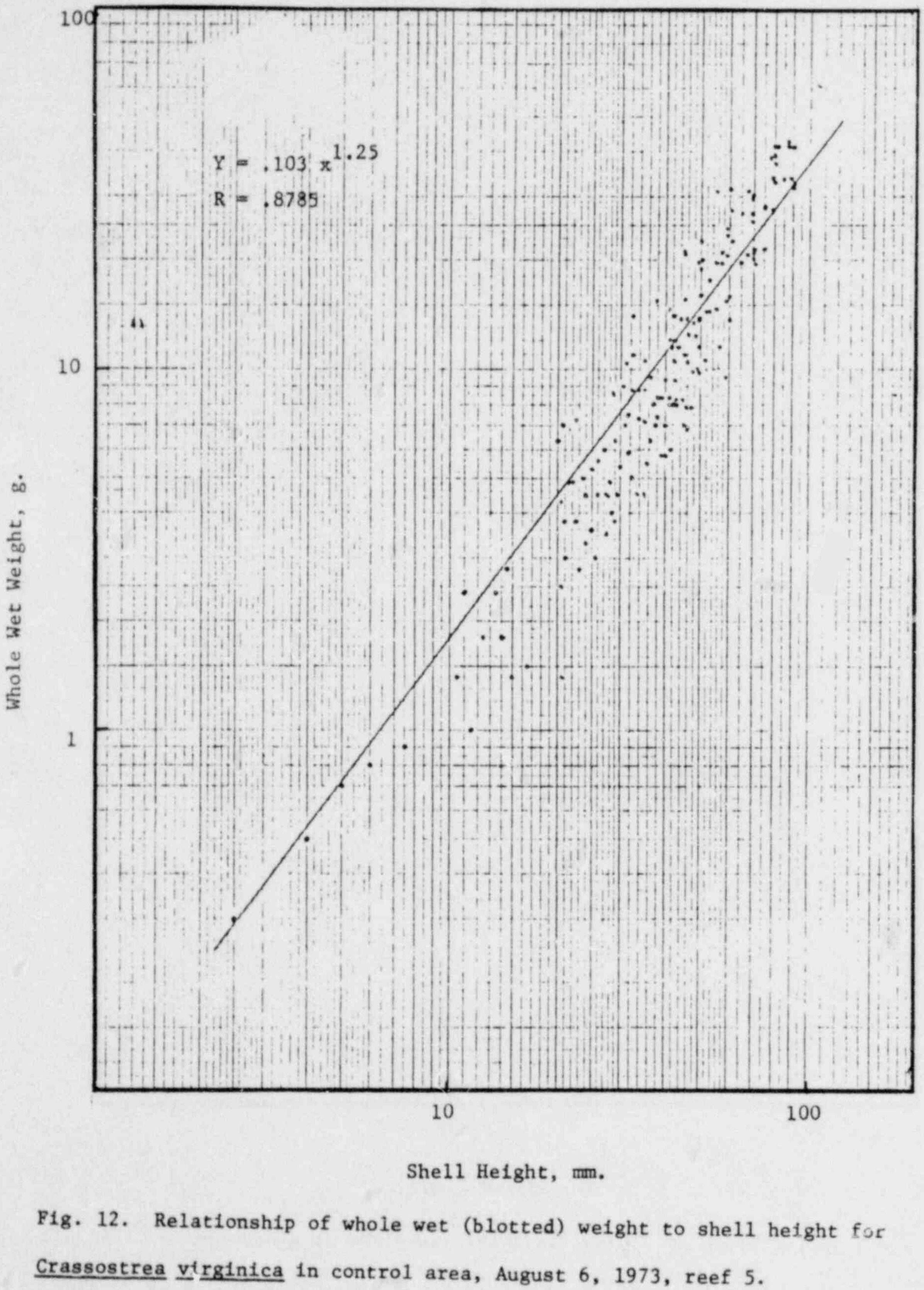


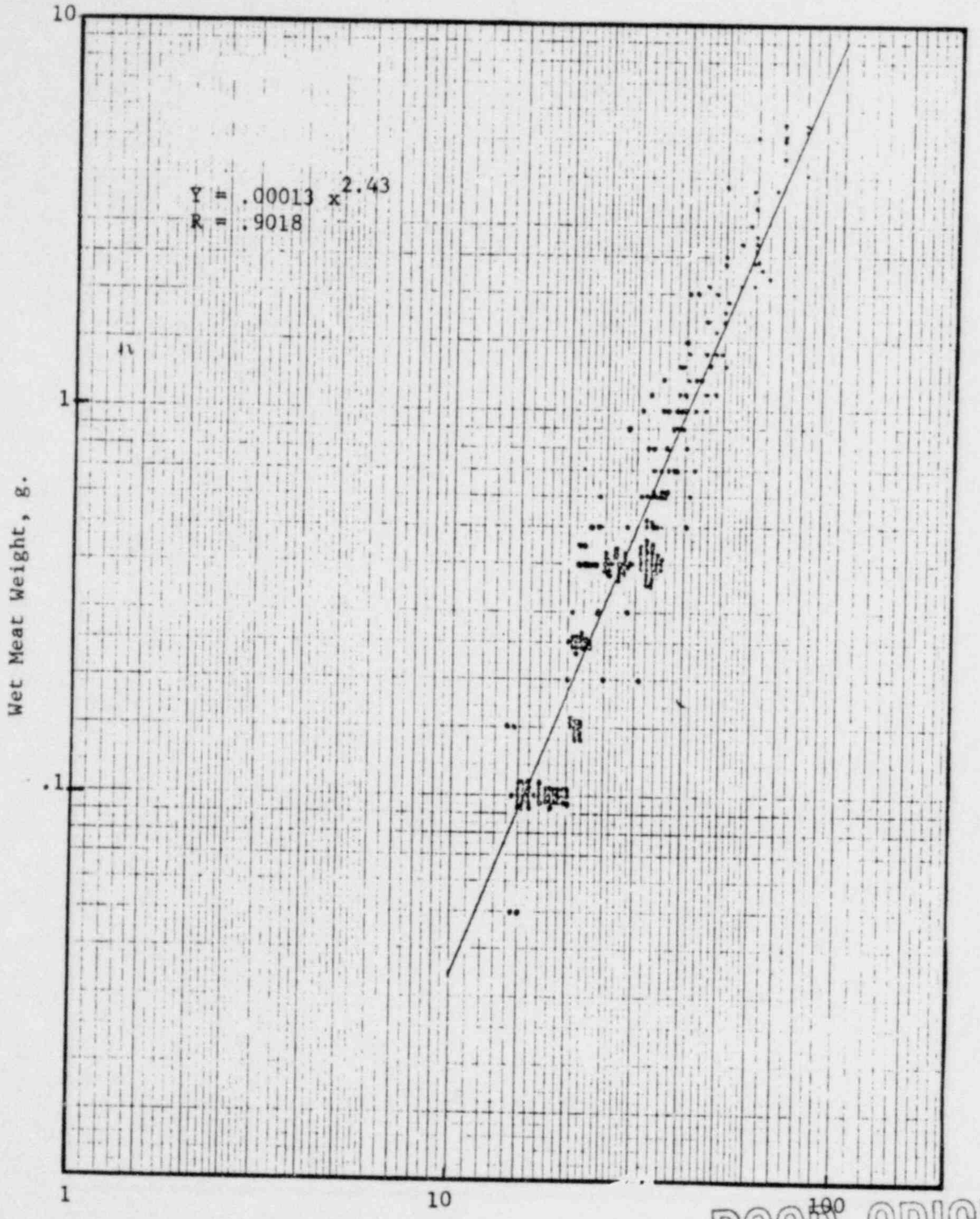
Fig. 12. Relationship of whole wet (blotted) weight to shell height for <u>Crassostrea virginica</u> in control area, August 6, 1973, reef 5.

POOR ORIGINAL

weight and shell length was made for a control area sample. (Fig. 13).

Ratios of dry weight to wet weight are given in Table 5 .Those for the discharge bay were slightly higher for oysters, set, and crabs.

Area-weighted estimates of biomass based on distribution of mass relative to each reef and each reef as a percentage of the total reef system are given in Table 6 . The area-weighted values indicated a higher oyster biomass in the discharge bay. The biomass of all other organisms was higher in the control area.



POOR ORIGINAL

Fig. 13. Relationship of wet (blotted) meat weight to shell height for Crassostrea virginica in control area, January 10, 1973, reef 4.

Table 5

Ratios of dry weight to wet weight as percentages for selected organisms in Discharge and Control areas.

Area	Percent of total weight equal to dry weight						
	oyster meat	set incl. shell	crabs incl. shell	barnacles incl. shell	mussels incl. shell	drills incl. shell	starfish
Discharge	13.4 %	72.7 %	35.6 %	62.9 %	-----	-----	-----
Control	11.4 %	70.9 %	27.2 %	64.3 %	63.6 %	77.8 %	37.0 %

Table 6

Area-weighted Estimates of Biomass[a]

Organism	Discharge Bay		Control Area	
	Structure (all shell) g/m^2	Dry meat weight g/m^2	Structure (all shell) g/m^2	Dry meat weight g/m^2
Oysters	49,979.2	196.4	35,449.1	119.5
Set[b]	694.2	36.8	274.9	14.5
Other organisms	106.2	56.8	748.7	135.1
Total	50,779.8	290.0	36,472.7	269.1

[a] Area-weighted estimates based on distribution of mass relative to each reef and each reef as a percentage of the total reef system.

[b] Spat and juveniles

Larval Setting

Spat cage setting rates were similar in both areas (Table 7 and 8) T-tests showed the June setting rate peak in the control area to be significantly higher (95% confidence level) than the March and September rates. No significant differences were found among rates in the discharge bay. Annual mean setting rates of 4.6 spat/.25 m^2/day for the discharge area and 5.3 spat/.25m^2/day were not significantly different.

The mean level of 317 spat/.25m^2 in the discharge area did not test significantly different from the 380 spat/.25 m^2 in the control. Larval numbers appeared higher at certain periods of the year (Table 9), however, no significant difference could be found between high and low variations. Differences at the 95% confidence level did exist between individual discharge and control areas. Numbers of larvae on reefs 5 and 6 differed from those on reef 2 in the discharge, while reef 1 differed from reef 5 in the control (Fig. 14).

Diversity

Results of species per thousand counts are given in Tables 10 and 11. Species per thousand data was translated into various other diversities indices of interest. Mean values of species/thousand were significantly different between discharge and control areas. Seasonal values were significantly different in the thermally-affected area but not in the control area.

Marine organisms collected and identified from oyster reefs are listed in Table 12.

Table 7

Oyster reef set count data - set cage count
Number spat per .25 m^2.
Discharge Bay.

Reef Number	Date Sampled	Number Counted	Time period	Rate, #/.25 m^2/day
2	May 12, 1973	49	Int. count	
5	" " "	564	" "	
6	" " "	312	" "	
2	June 20, 1973	119	41 days	2.9
5	" " "	709	" "	17.3
6	" " "	493	" "	12.0
2	Dec. 18, 1973	110	181 days	0.6
5	" " "	749	" "	4.1
6	" " "	339	" "	1.9
$\overline{x}$		317		4.6
S.E.		64		2.0

Table 8

Oyster reef set count data - set cage count
Number spat per .25m^2.
Control Area

Reef Number	Date Sampled	Number Counted	Time Period	Rate, #/.25m^2/day
1	May 13, 1973	560	Initial count	
3	" " "	159	" "	
4	" " "	243	" "	
5	" " "	298	" "	
1	June 22, "	597	42 days	14.2
3	" " "	519	" "	12.4
4	" " "	516	" "	12.3
5	" " "	347	" "	8.3
1	Dec. 17, "	812	180 days	4.5
3	" " "	472	" "	2.6
4	" " "	388	" "	2.2
5	" " "	170	" "	0.9
$\overline{x}$		380		5.3
S.E.		47		1.5

Table 9

Spat Count Data from Biomass Samples- Discharge Bay

Reef Number	Date Sampled	Number	Dry Weight gms.	Weight/Individual, gms. (whole)
1	July 19, 1973	198	----	----
6	" 30, "	425	250.8	0.59
2a	" 31, "	22	11.0	0.50
2b	" " "	106	102.2	1.0
2a	Dec. 7, "	39	9.6	0.2
2b	" " "	94	31.6	0.3
$\overline{x}$		147	83.9	0.64
S.E.		66	44.7	0.18

Spat Count Data from Biomass Samples- Control Area

Reef Number	Date Sampled	Number	Dry Weight gms.	Weight/Individual, gms. (whole)
1	July 20 1973	460	----	----
5	Aug. 6, "	646	82.2	0.13
3	" " "	359	39.4	0.08
4	" " "	987	75.2	0.08
4	Jan. 10, 1974	1037	128.1	0.12
4 fringe	" " "	619	70.6	0.11
$\overline{x}$		698	79.1	0.10
S.E.		136	21.3	0.02

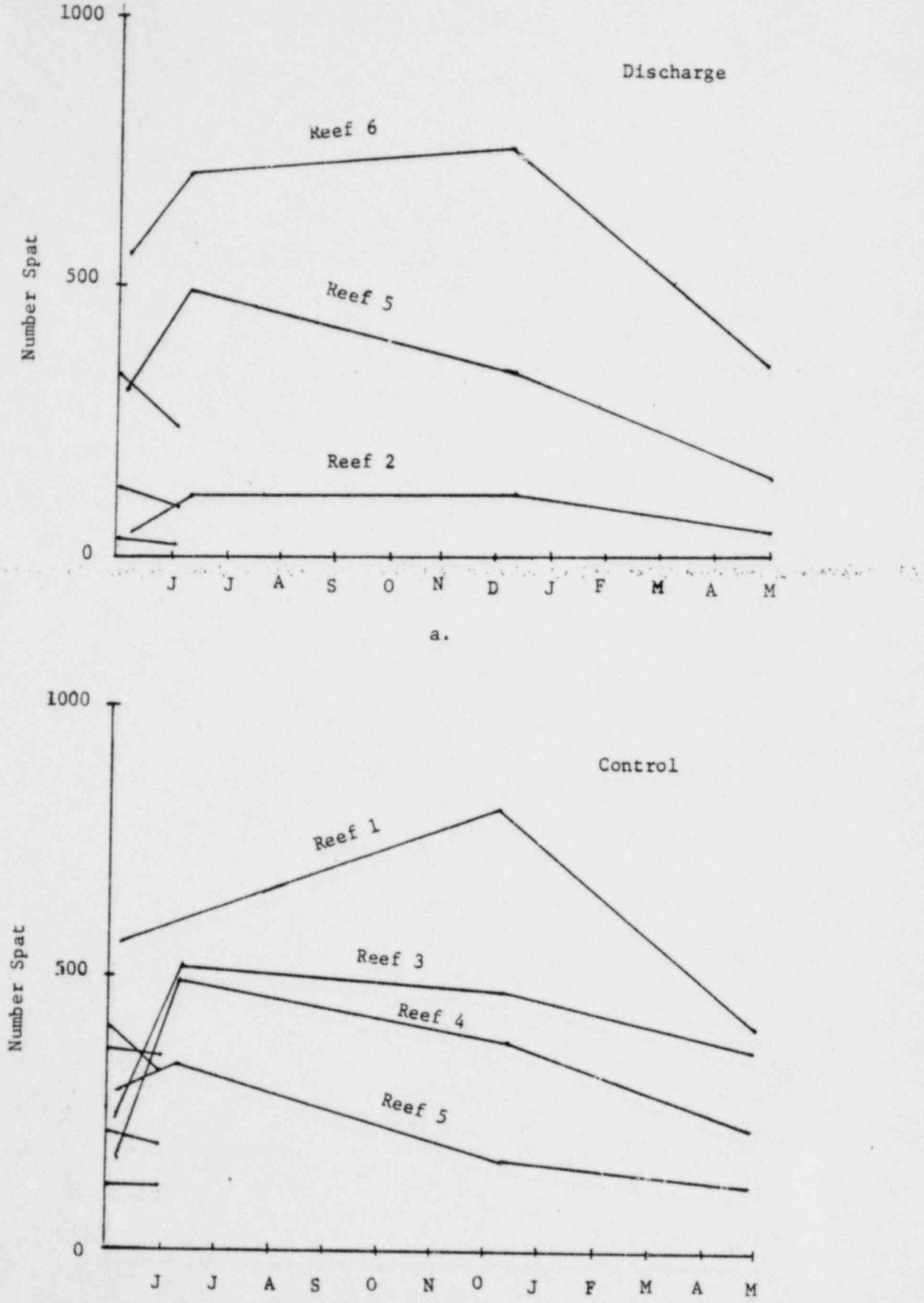


Fig. 14. Seasonal larval setting rates. a. Three reefs in discharge bay. b. Four reefs in control area.

Table 10

Diversity Indices - Discharge Bay

Date	Reef Number	Number Individuals	Number Species	Species/ 1,000[a]	Margalef[b]	Menhinick[c]	Pielou[d]	Shannon-Weaver[e]	Simpson[f] Dominance
March:	1	404	8	11	0.81	0.40	0.12	1.03	0.68
	2	1057	13	13	1.19	0.40	0.15	1.53	0.43
	3	1000	14	14	1.30	0.44	0.21	2.06	0.36
	4	1005	13	13	1.20	0.41	0.19	1.93	0.51
	5	1004	16	16	1.50	0.50	0.18	1.83	0.48
	6	1013	13	13	1.20	0.41	0.17	1.73	0.49
S. E. Mean				13.3 ± 0.7	1.20 ± .09	.43 ± .02	.17 ± .01	1.68 ± .15	.49 ± .04
June	1	1166	11	11	0.99	0.33	0.20	1.99	0.36
	2	1102	11	11	0.99	0.33	0.17	1.72	0.43
	3	1163	12	12	0.98	0.34	0.15	1.46	0.56
	4	1175	13	13	1.17	0.38	0.19	1.94	0.36
	5	1166	12	12	1.03	0.34	0.16	1.71	0.44
	6	1134	13	13	1.19	0.37	0.20	2.02	0.35
S. E. Mean				11.8 ± 0.3	1.06 ± .03	.34 ± .01	.18 ± .01	1.81 ± .09	.42 ± .03

Footnotes to Table 10

a) Odum, Cantlon and Kornicker: number species/1000 individuals

b) Margalef: number species -1 / $\log_2$ number of individuals

c) Menhinick: number species / N; N = number of individuals

d) Pielou: Shannon-Weaver / $\log_2$ number of species

e) Shannon-Weaver: ni/N) $\log_2$ni/N ; N = number of individuals, ni = number of individuals/species

f) Simpson: $(ni/N)^2$

Table 11

Diversity Indices - Control Area

Date	Reef Number	Number Individuals	Number Species	Species/ 1,000[a]	Margalef[b]	Menhinick[c]	Pielow[d]	Shannon-Weaver[e]	Simpson[f]
Feb.:	1	1060	12	12	1.09	0.37	0.22	2.20	0.32
	2	513	10	12	1.00	0.44	0.18	1.63	0.47
	3	1061	15	15	1.39	0.46	0.24	2.36	0.30
	4	1043	19	19	1.80	0.59	0.23	2.29	0.31
	5	1106	13	13	1.19	0.39	0.24	2.33	0.29
S. E. Mean				14.2 ± 1.3	1.29 ± .14	.45 ± .04	.22 ± .01	2.18 ± .14	.34 ± .03
June:	1	1160	16	15	1.42	0.46	0.19	1.94	0.41
	2	1132	14	14	1.28	0.42	0.18	1.78	0.47
	3	1158	14	14	1.23	0.40	0.18	1.90	0.44
	4	1228	17	17	1.56	0.48	0.20	2.06	0.38
	5	1194	14	14	1.22	0.39	0.20	2.04	0.37
S. E. Mean				14.7 ± 0.5	1.34 ± .05	.43 ± .01	.17 ± .02	1.94 ± .06	.41 ± .02

a Odum, Cantlon, and Kronicker: number species / 1000 individuals

b Margalef: number species - 1 / $\log_2$ number of individuals

c Menhinkck: number species / N ; N = number of individuals

d Pielou: Shannon-Weaver / $\log_2$ number of species

e Shannon-Weaver: $(ni/N) \log_2 ni/N$;

f Simpson: $(ni/N)^2$

TABLE 12

List of marine animals collected and identified from oyster reefs at Crystal River, Florida, 1973-1974.

Phylum	Common Name	Scientific Name	Discharge Bay	Control Area
Anthropoda				
Class Crustacea				
	Fiddler crab	*Uca pugilator*	+	
	Fiddler crab, juvenile	*Uca sp.*	+	
	Flat mud crab	*Eurypanopeus depressus*	+	+
	Porcelain crab	*Petrolisthes armatus*	+	+
	Mud fiddler crab	*Uca minax*	+	
	Little Xanthid crab	*Eurypanopeus abbreviatus*	+	+
	Common mud crab	*Panopeus herbstii*	+	+
	Blue crab	*Callinectes sapidus*	+	+
	Spider crab	*Libinia dubia*		+
	Hermit crab	*Paguras annulipes*	+	
	Stone crab	*Menippe mercenaria*	+	+
	Burrowing shrimp	*Upogebia affinis*	+	
	Snapping shrimp	*Alpheus armalatus*	+	
Class Insecta				
	Springtail	*Anurida martima*	+	+
Mollusca				
Class Gastropoda				
	Small snail	*Bittium sp.*	+	
	Oyster drill	*Polinices duplicata*	+	+
	Snail	*Nassarius vibex*	+	+
	Banded Tulip shell	*Fasciolaria distans*		+
	Crown conch	*Melongena corona*	+	+
	Ark shell	*Arca reticulata*	+	+
Class Pelecpoda				
	Cross-barred venus	*Chione cancellata*	?	?
	Calico scallop	*Pecten gibbus*		+
	Small clam	*Tellina lineata*		+
	Mussel	*Brachiodontus sp.*	+	+
	American oyster	*Crassostrea virginica*	+	+

TABLE 12 CONTINUED

Phylum	Common Name	Scientific Name	Discharge Bay	Control Area
Echinodermata				
Class Asteroidea				
	Common starfish	*Echinaster sp.*		+
Chelicerata				
Family Micryphantidae				
	Dwarf spider	*Erigone teniupalpus*	+	+
Marine Fishes				
	Scrawled cowfish	*Lactophyrys quadricornis*		+
	Skillet fish	*Gobiesox strumosus*	+	
	Toad fish	*Opsanus beta*		+

---

a Observed once or twice only.

Metabolism

Underwater with artificial channels

Fig. 15 shows one hourly rate of change of oxygen in a tidal cycle. Rate of change of oxygen over three tidal cycles is shown in Fig. 16 for the thermally-affected bay. Total observed change was 39.1 g $O_2/m^2/23$ hrs. At an average rate of 1.70 g $O_2/m^2/hr$, and assumed tidal inundation of 12 hours, the underwater community metabolism rate was calculated to be 20.4 g $O_2/m^2/day$. Correlated with biomass data, this gave a rate of

$$\frac{0.123 \text{ g } O_2}{\text{g dry wt.}} \text{ / day.}$$

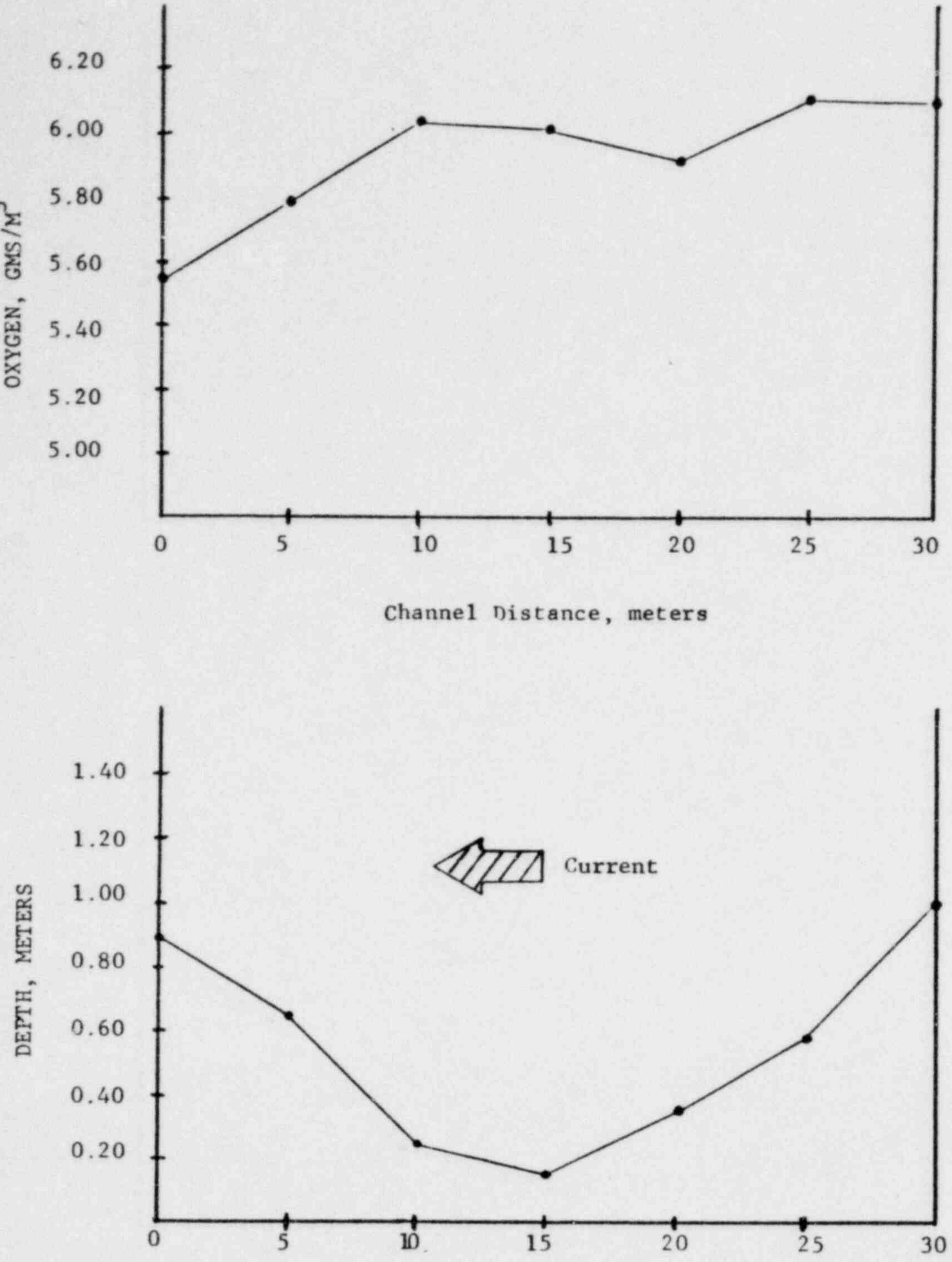
For the unaffected bay, total observed change shown in Fig. 17 was 17.4 g $O_2/m^2/24$ hrs. This gave an average rate of 0.73 g $O_2/m^2/hr.$, calculated to be 8.8 g $O_2/m^2/day$ underwater. On a gram per gram basis this was

$$\frac{0.083 \text{ g } O_2}{\text{g dry wt}} \text{ / day.}$$

Apparent differences in slopes of plots of respiration and current (Fig. 18) indicated higher respiration in the Discharge Bay for any given current speed.

Exposed reefs with CO_2 gas exchange

CO_2 gas metabolism results are given in Fig. 19, 20, 21 and 22 with corresponding light and tide data. Exposed reef metabolism was 3.1 g $C/m^2/day$ (6.2 g $O_2/m^2/day$) in the control area. The gram per gram body weight rates were $\frac{0.035 \text{ g } O_2}{\text{g dry wt}}$ / day in the control area and $\frac{0.039 \text{ g } O_2}{\text{g dry wt}}$ / day in the Discharge bay.



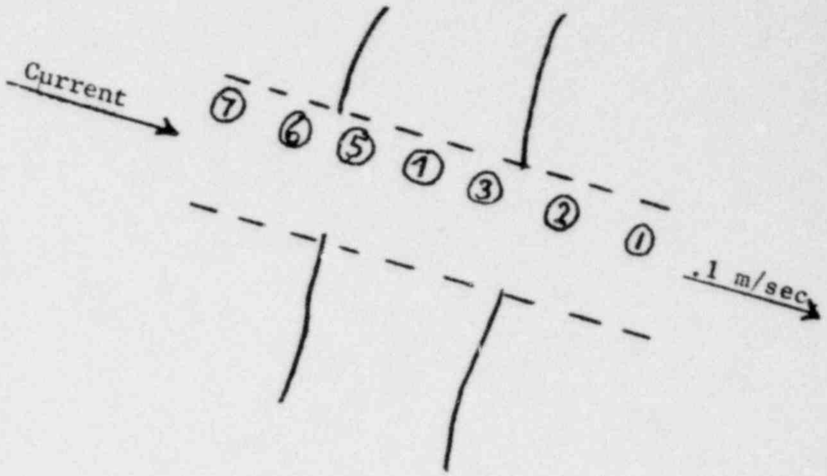
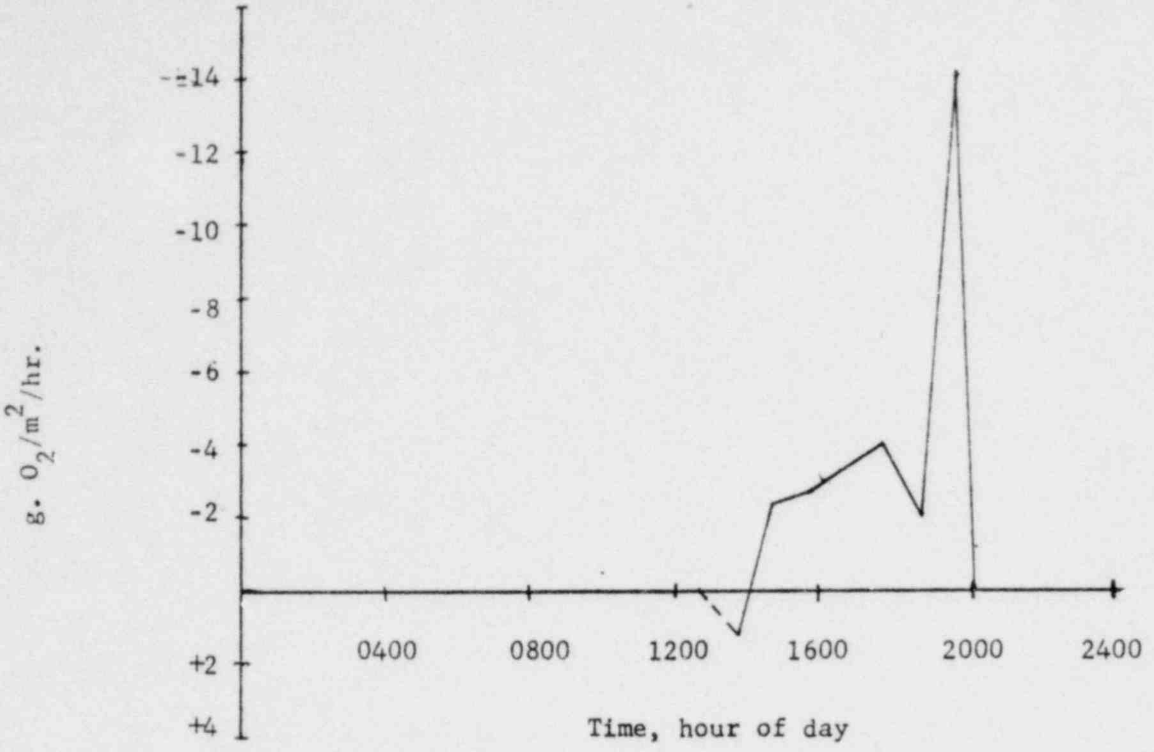


Fig. 15. Upstream-downstream data using plastic channels, one hourly sample, October 8, 1973, in discharge bay, reef 6.



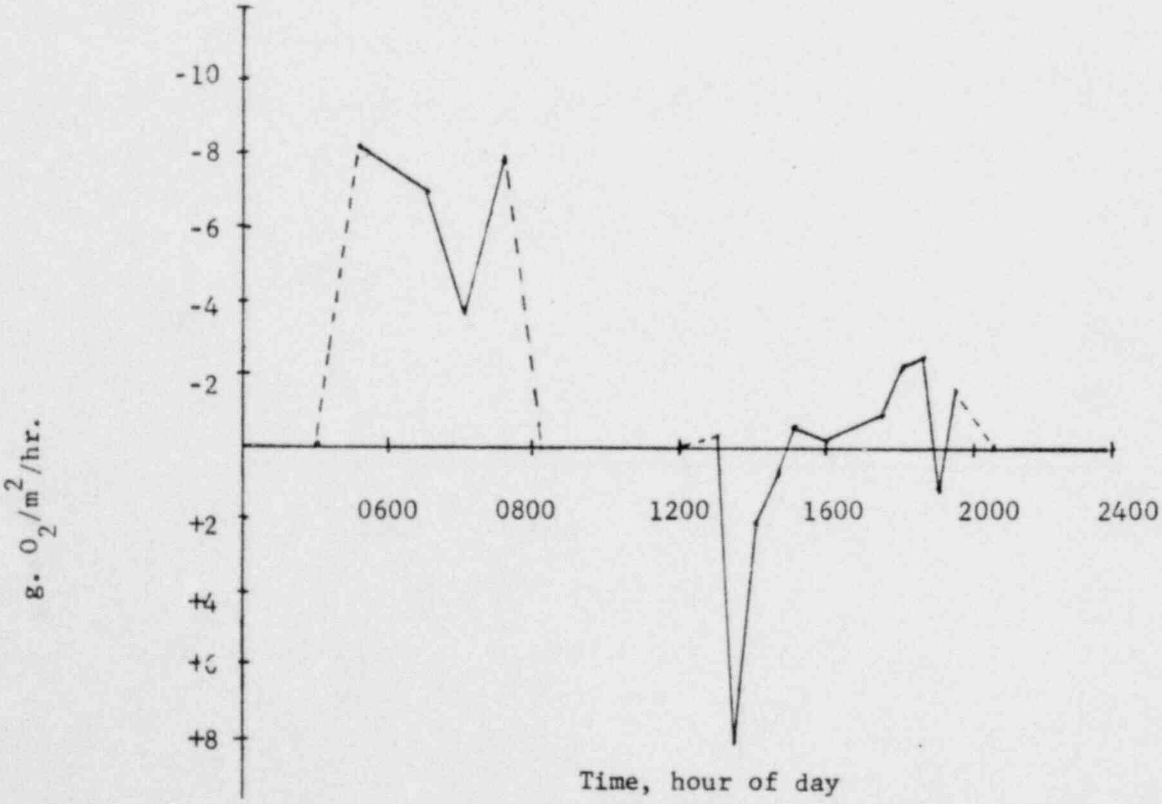


Fig. 16. Composite of upstream-downstream oxygen changes in plastic channels in discharge bay over three tidal cycles, reef 5. Each point is based on quadruplicate samples.

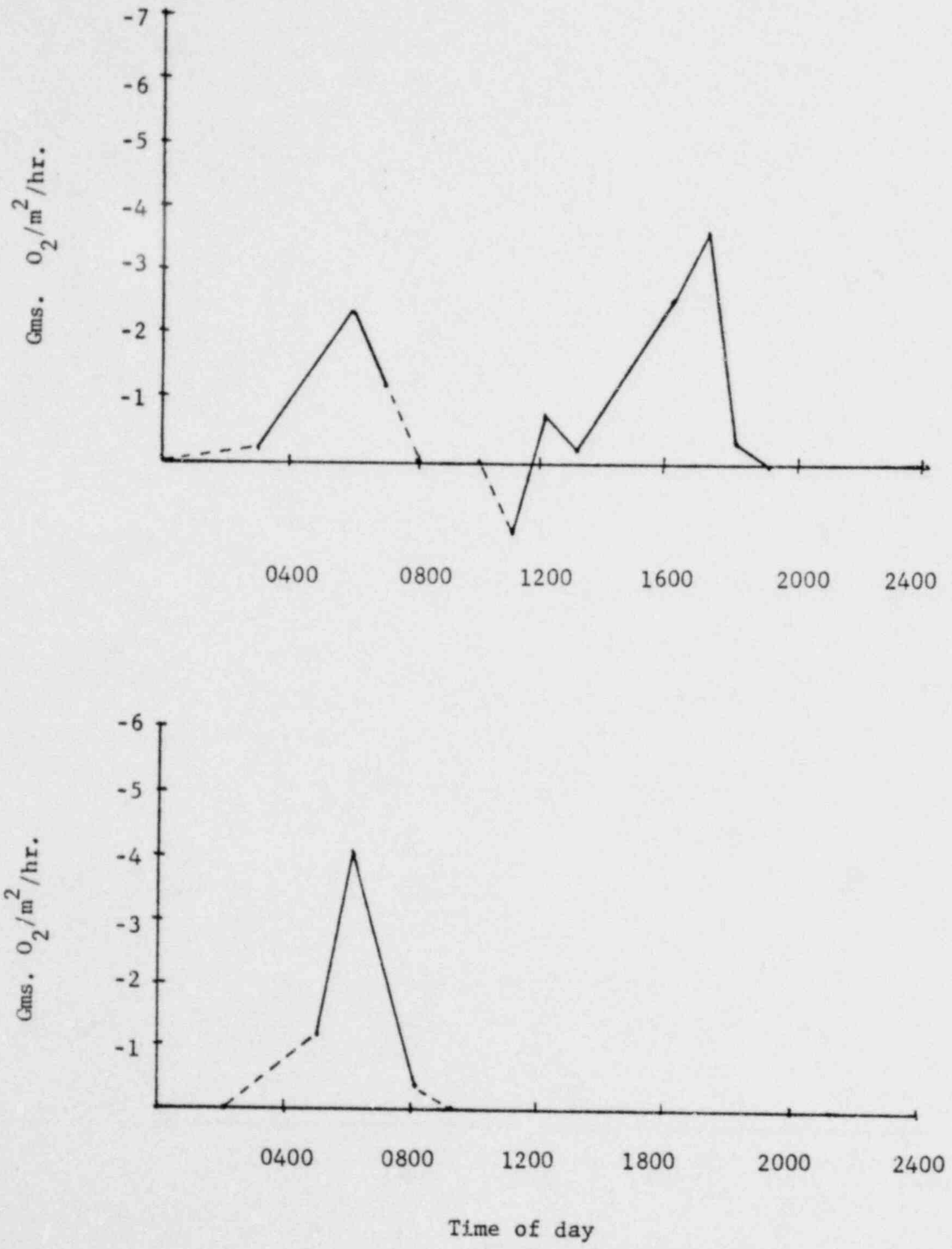


Fig. 17. Composite of upstream-downstream oxygen changes in plastic channels in control area over three tidal cycles, reef 1. Each point is based on quadruplicate samples.

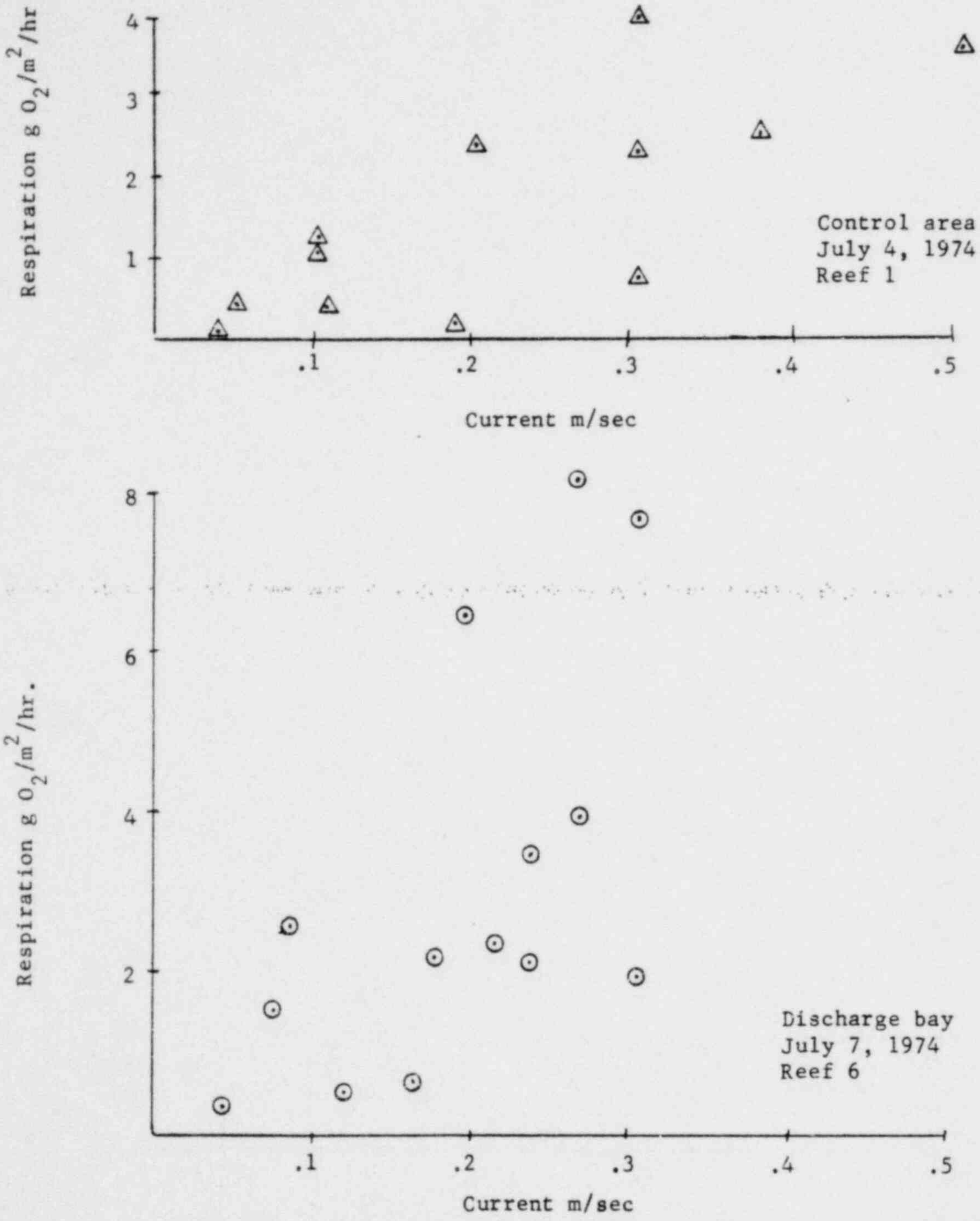


Fig. 18. Respiration and current.

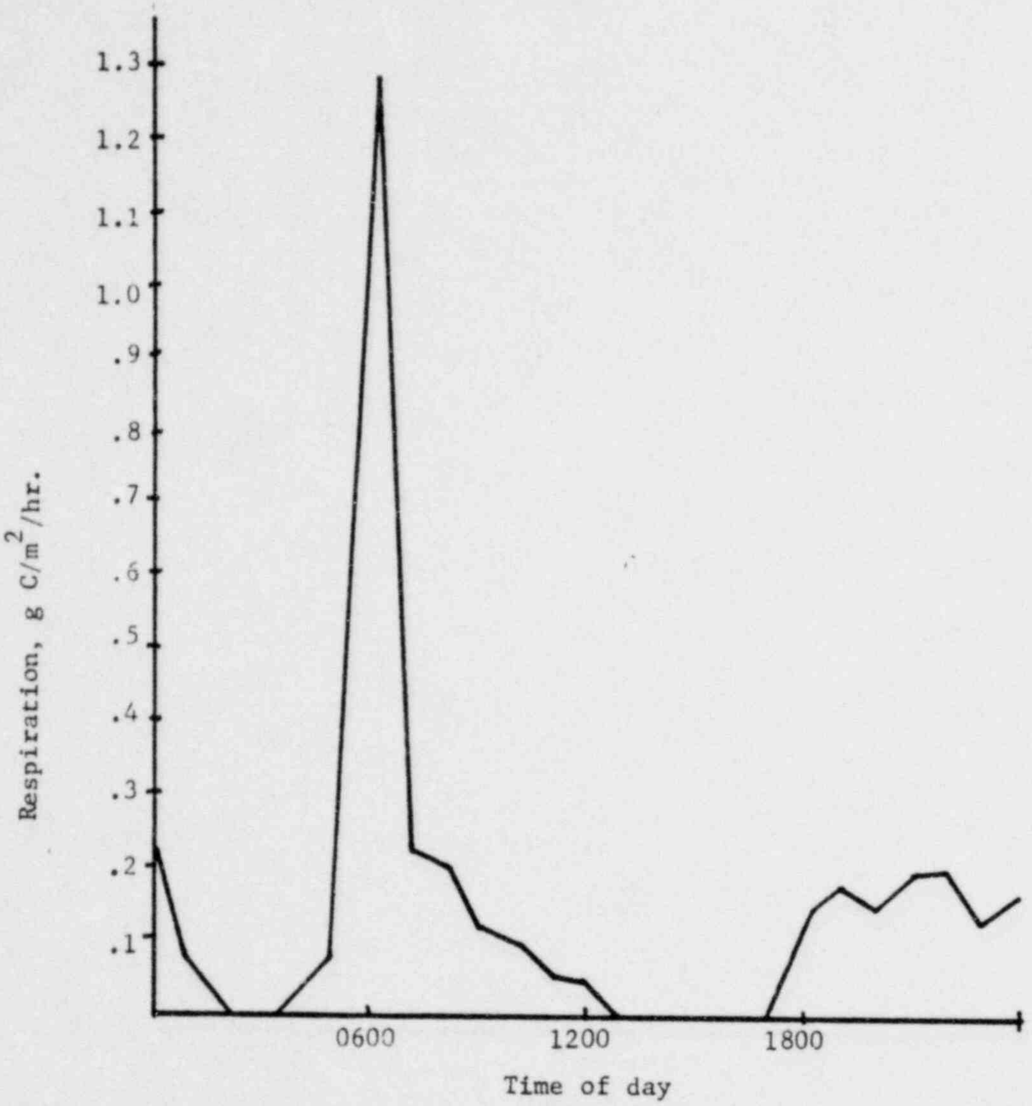


Fig. 19 . Respiration rates of exposed oyster reef assemblage, July 30, 1973, in discharge bay, reef 2a.

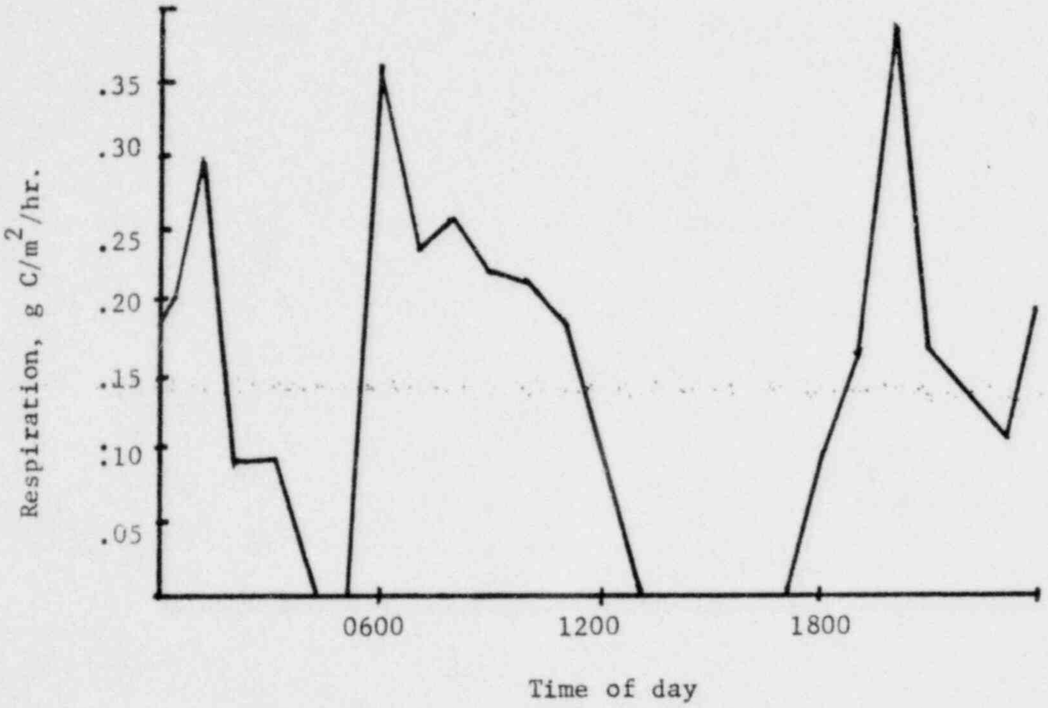


Fig. 20. Respiration rates of exposed oyster reef assemblages, July 30, 1973 in discharge bay, reef 2b.

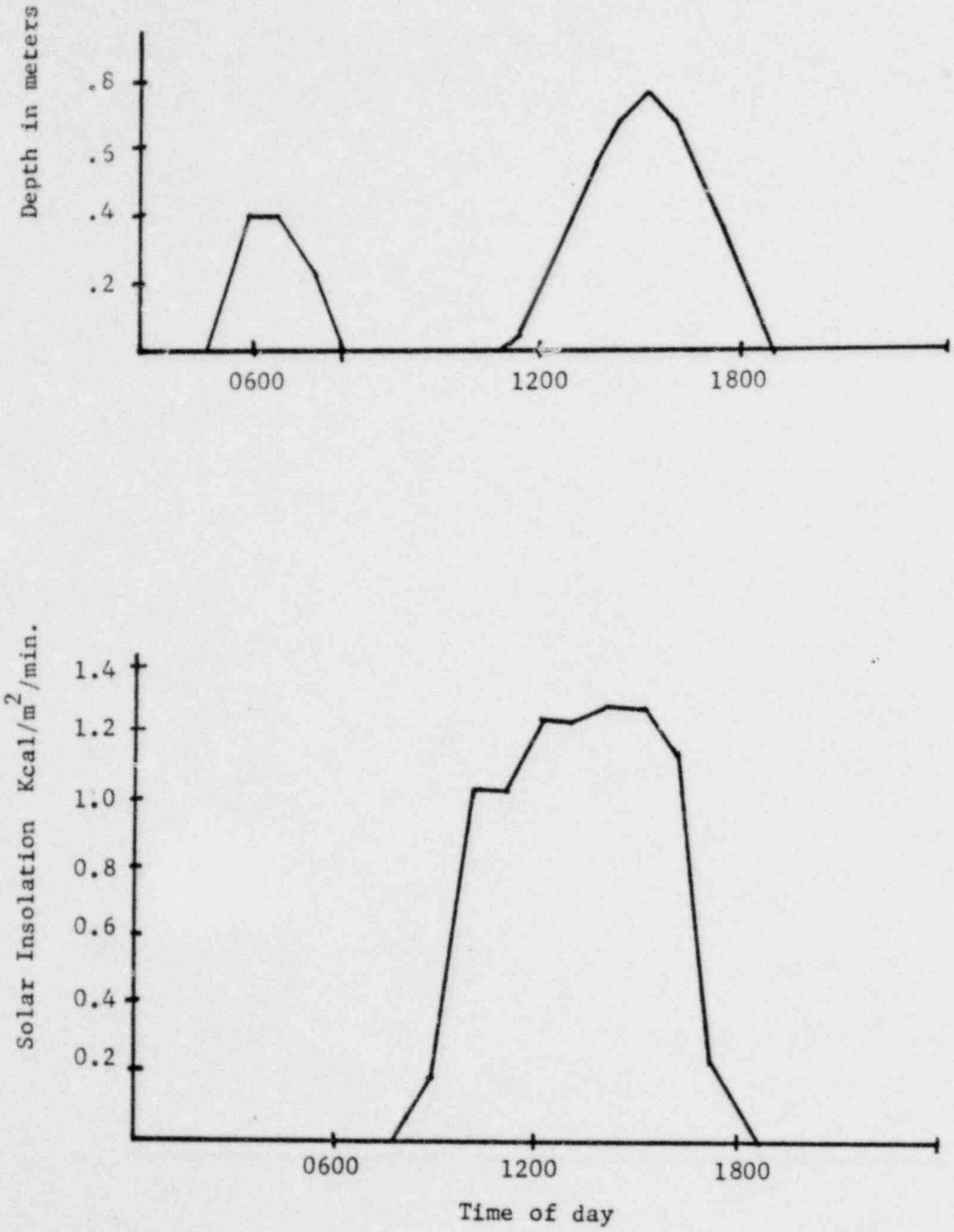


Fig. 21. Tide and solar insolation data, July 30, 1973 in discharge bay, reef 2.

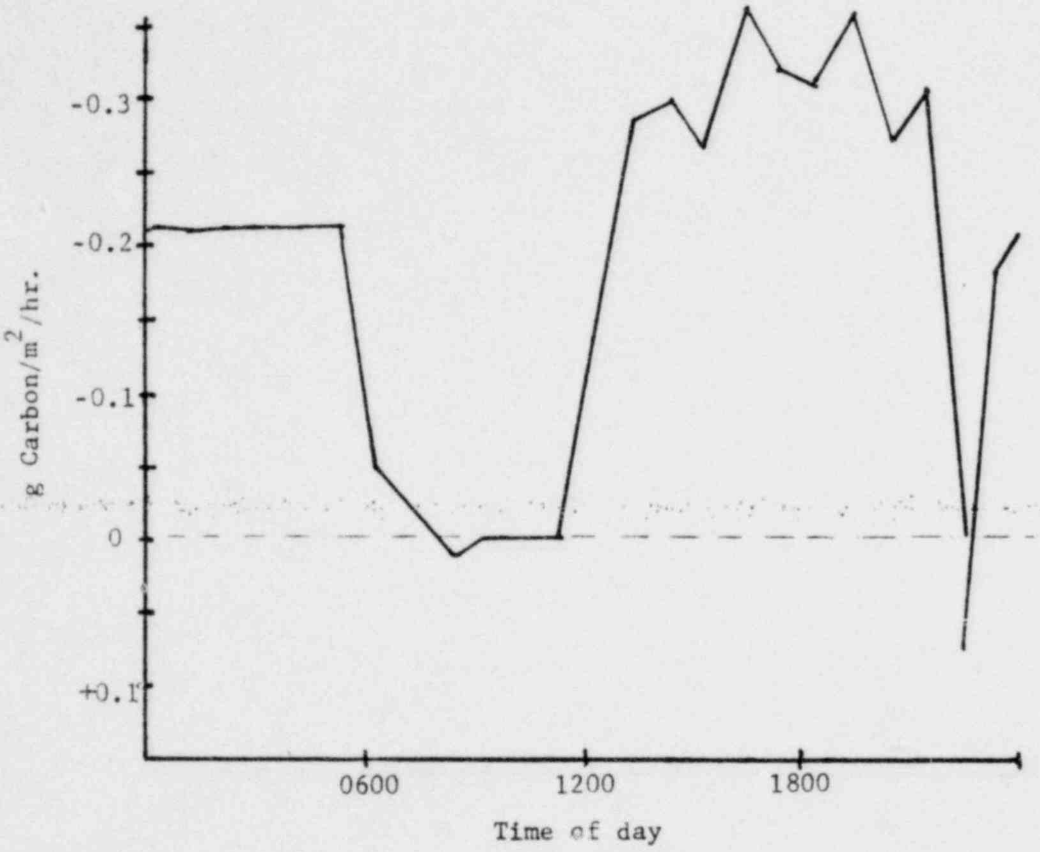


Fig. 22a. Respiration rates of exposed oyster reef assemblage, August 7, 1973 in control area, reef 4.

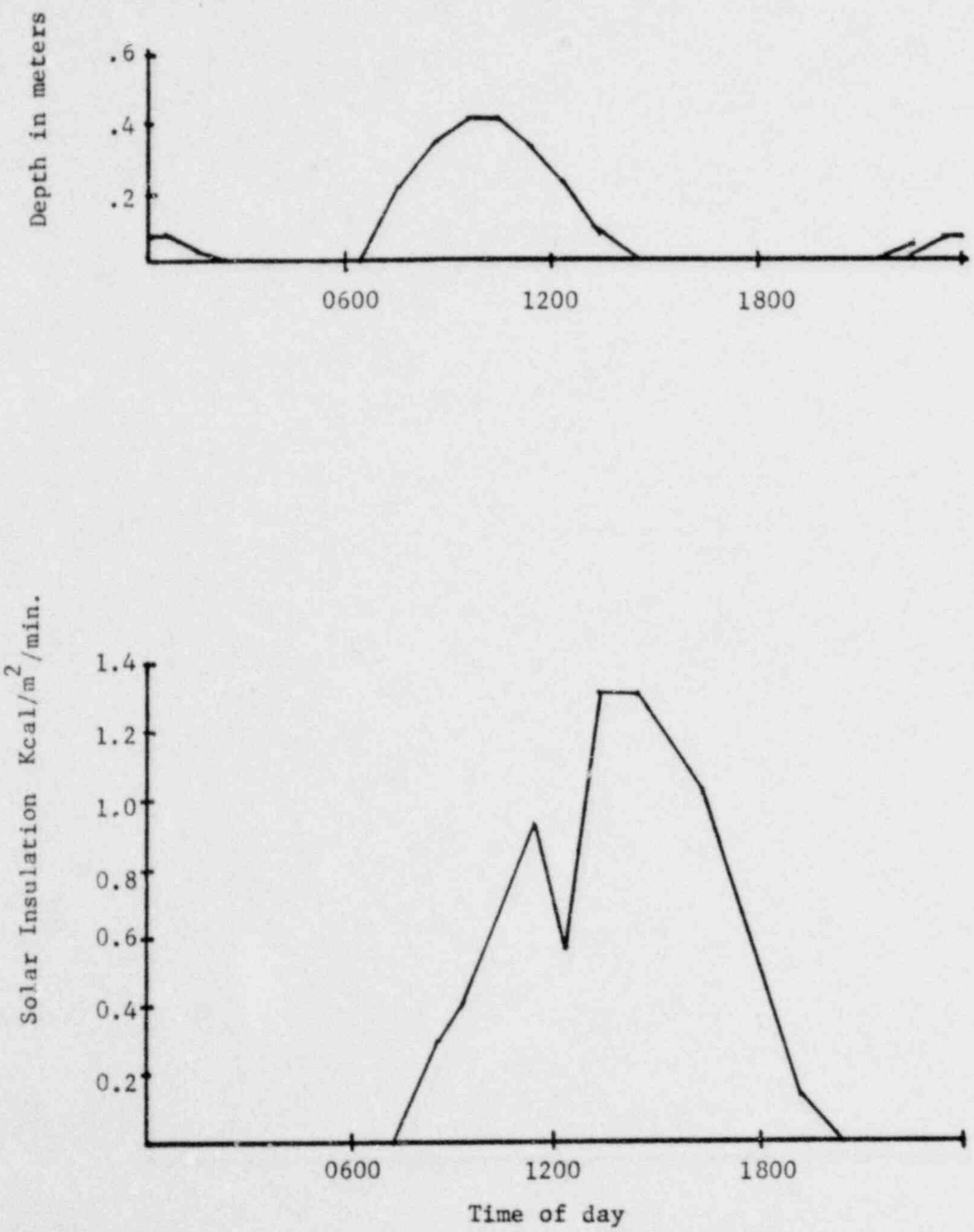


Fig. 22b. Tide and solar insolation data, August 7, 1973, in control area, reef 4.

Total reef metabolism

Total metabolism of the oyster reef community determined on the basis of a half day at each rate (exposed and submerged) was 20.94 g O_2/m^2/day in the thermally-affected bay and 15.67 g O_2/m^2/day in the unaffected bay. This represents a difference of about 27%. Based on area-weighted values of biomass for each area, gram per gram weights used for modeling purposes were $\frac{.072 \text{ g } O_2}{\text{g dry wt}}$ / day for the Discharge reefs and $\frac{.058 \text{ g } O_2}{\text{g dry wt.}}$ / day for the control reefs.

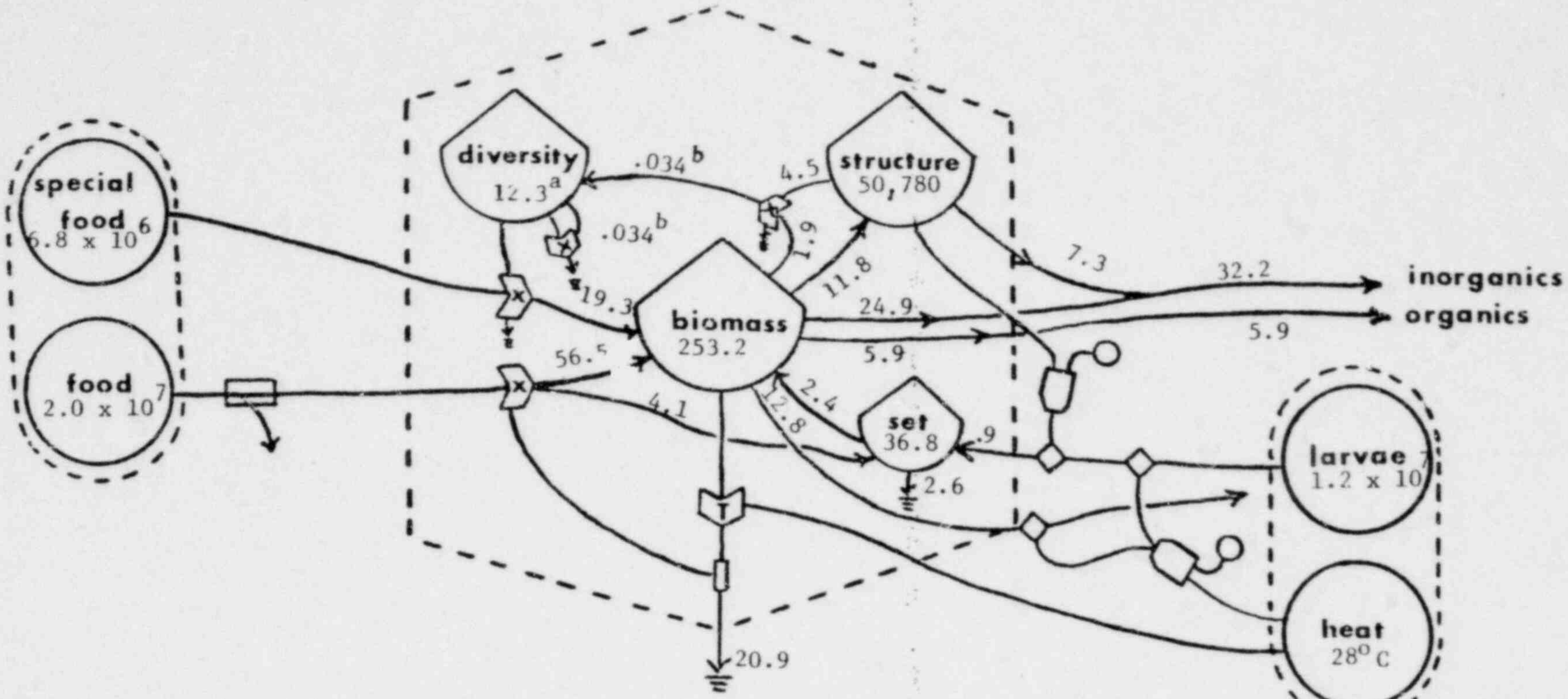
Simulation of Seasonal and Temperature Effects

Evaluated oyster reef diagrams for the thermally-affected and unaffected areas are given in Fig. 23 and 31. Each number on the diagrams represents an estimate of mass or materials for that component. Calculations of model component values are described in Tables 13 and 15. A simulation of each model was made using the values in the diagrams. Model response to changes in temperature, food conditions, respiration rates, and reef standing stocks was investigated. Comparison of responses was made between the control area and the discharge bay simulations.

Simulation of Thermally-affected Bay Model

Results of the simulation of the plume-influenced model (Fig. 23) are summarized in Table 14. Figure 24 compares simulated data and field data. Simulation graphs referenced in the Table are given in Fig. 25 through 30. Each graph represents approximately four years of simulated data after the model reached steady-state conditions. In cases where no steady-state was reached, the initial four years of simulated data was offered.

Some general responses of the thermally-affected reef model were: (1) increasing temperature decreased reef stocks; increased temperature did not wipe out reef stocks even at high temperatures. (2) Changes in respiration had a significant effect on the reef system model. Large reductions in respiration rates shifted the model from steady-state to growth conditions. (3) Over-harvest effects, whether by man or nature, changed reef storages; in the extreme case (80% reduction), biomass and diversity decayed completely. (4) Flow of food appeared to be a limiting factor in the model. The push effect of temperature on respiration possibly exceeded the pull capability



Flows are g/m^2/day

Stocks are g/m^2 (except where stated)

a Species/thousand (stock)

b Species/thousand/day (flow)

Fig. 23 . Evaluated oyster diagram of thermally-affected discharge bay.

Table 13

Thermally Affected Oyster Reef System Value Calculations - Storages

Model Component	Value	Description	Calculations	Reference
B	253.2 g/m^2	A. All reef organisms (except spat)	A. 253.2 g/m^2 area weighted dry meat weight	A. Lehman, Crystal River Field Data, 1973
D	12.3 species/ thousand	B. Diversity	B. 12.3 species/thousand	B. "
S	50,779.8 g/m^2	C. Reef structure (oyster shell, etc.)	C. 49,979.2 g/m^2 area-weighted	C. "
L	36.8 g/m^2	D. Oyster set (attached larvae)	D. 36.8 g/m^2 area-weight dry meat weight	D. "
F	6.8 x 10^6g	E. Special food	E. Based on rate of special food uptake to food uptake = 34%. (2 x 10^7g)(.34) = .68 x 10^7	E.
I	2.0 x 10^7	F. Food	F. a) Detritus (.0072 mg/m^2) = .01 mg/ m^2); b) Phytoplankton (1.59g/m^2) c) Bacteria (0.1g/m^2)	F. a)Krey, 1967 b)McKellar, Cry. Riv. Field Data, 1973 c)Rayment, 1967
T	1.23 x 10^7 g	G. Larvae	G. (62.1/m^3)(1.55 x 10^{-2}g/ind.091.28 x 10^7m^3) = 123.2 x 10^5 = 1.23 x 10^7g	G. Maturo, Cry. Riv. Field Data, 1973
H	28°C	H. Heat	H. a) Power plant heat = 4°C; b) Sun and sky heat: (1) incoming radiation: 3900 kcal.m^2/day = (3900)(1.28 x 10^7 m^2) = 4.99 x 10^{10} kcal. (2) Mean temp. Crystal River 24°C	H. a)Grimes, 1971 b)(1) Odum,1971 (2) Odum,1971

Table 13. **Continued**

Thermally Affected Oyster Reef System Value Calculations - Flows

Model Component	Value	Description	Calculations	Reference
$k_{23}BH$	56.5 g/m^2/ day	1. Reef organisms food uptake	1. a)filtering rate = 144 1/12 day for adult oyster at 50% efficiency; b)Sestion in water = 1.13 x 10^{-3}g/1 (1.70g/m^2) ÷ (1.5m) = 1.13 x 10^{-3}g/1 (144 1/oyster/da)(695 oysters/m^2) = 1 x 10^5 1/m^2/da	1. a)Collier, 1959 b)See calculation of model component I_2
k'D	19.3 g/m^2/da	2. Reef organisms special food uptake	2. Food uptake by increased predation = increased efficiency nutrient recycling etc.: Using steady state assumption by method of diff. See calc. of JB_9 JB_2 = 19.3 g/m^2/day	2. Lehman, Cry. Riv. Field data, 1973
$k_{24}BH$	20.9 g/m^2/da	3. Reef organisms respiration	3. Sum of underwater and exposed rates = 20.9 $g/O_2/m^2$/day	3. Lehman, Cry. Riv. field data, 1973-1974
k_8B	11.8 g/m^2/da	4. Organisms loss to reef structure	4. a)assume oyster growth period approx. 180 days per year; b)(2116.g shell/m^2 of living oyster biomass) c) assume year longevity $\frac{2116g/m^2}{180\ day}$ = 11.8g/m^2/day	4. a) b)Lehman, Cry. Riv. field data c)Field observations & height-frequency curves indicate oysters in discharge area approx. 1 yr. life span

Table 13. Continued

Model Component	Value	Description	Calculations	Reference
k_6B	24.9 g/m^2/day	5. Inorganic loss from reef organisms a)Oyster pseudo-feces deposition b)Oyster feces deposition	5. a)8% of dry body wt. per day (196.4 g/m^2/da)(.08) = 15.71; b)5.6% dry body wt. per day (196.4 g/m^2/da)(.056) = 11.00 g/m^2/da; c)84% total deposition of oysters is inorganic, (15.71 + 11.00 g/m^2/da)(.84) = 23.28 g/m^2/da inorganic from oysters; d)inorganic deposition from other organisms, 5.6% dry body wt. per day (56.8 g/m^2 x .056) = 3.18 g/m^2/da. Assume 50% feces inorganic (3.18 g/m^2/da x .5) = 1.6 g/m^2/day. Total loss = 23.3 + 1.6 g/m^2/da = 24.9 g/m /da	5. a)Day et al., 1973 b)Day et al., 1973 c)Day et al., 1973 Haven & Morales-alamo, 1966 d)Day etal., 1973
k_7B	5.9 g/m^2/da	6. Organic loss from reef organisms	6. a)organic deposition from oysters = 4.3 g/m^2/day; b)organic deposition from other organisms = 1.6 g/m^2/da Total loss = 4.3 + 1.6 g/m^2/da = 5.9 g/m^2/da.	6.a)see calc. for inorganic deposition b)see calc. for inorganic deposition
$k_{20}B$	12.8 g/m^2/da	7. Reef organisms loss due to spawning	7.a)one female can have 50 x 10^6 eggs/yr. b)104 oysters/m^2 adult, assume 30% oysters adult, (assume 50% fertility) = 5.2 x 10^9 eggs/m^2/yr. Assume egg = .1 mass larvae c)larvae biomass = .9 x 10^{-5} g/larvae (.9 x 10^{-5} g/larvae)(.1)(5.2 x 10^9) = = .468 x 10^4 g/m^2/yr. = .00128 x 10^4 g/m^2/year.	7.a)Day wtal., 1973 c)Carriker, 1951

Table 13. Continued

Model Component	Value	Description	Calculations	Reference
$k_{15}L$	2.4 g/m^2/da	8. Rate of set growth	8. a)5mm per week; b) 0.5 gm per week; .004 g/larvae/day (558 larvae/m^2)(.004 g/larvae/da) = 2.4 g/m^2/da.	8. a)Ingle & Dawson, 1952 b)Copeland & Hoese, 1966
k_9BS	1.9 g/m^2/da	9. Reef loss to diversity	9. Steady state assumption by method of diff.: input = output x + (58.9) = .1 x + (76.3) x - .1x = 76.3 - 58.9 .9x = 17.4 x = 19.3 .1x = 1.93 g/m^2/day	
$k_{18}L$	.9 g/m^2/da	10. Larvae setting rate	10. 18 larvae per m^2/da (18 larvae/m^2/da x .05 g/larvae) = .9 g/m^2/da	10.Lehman, Cry. Riv. field data
$k_{25}JrBH$	4.1 g/m^2/da	11. Food uptake of set	11. Steady state assumption by method of diff.:Input = .9 g/m^2/da output = 5 g/m^2/da 5 - .9 g/m^2/da = 4.1 g/m^2/da	
$k_{16}L$	2.6 g/m^2/da	12. Set respiration	12. 14.4% of dry wt. per da for adult oysters (36.8 g/m^2/da)(.072) = 2.6 g/m^2/da	12.Lehman, Cry. Riv. field data, 1974
$k_{12}S$	7.3 g/m^2/da	13. Reef structure lost due to chemical physical weathering & biological weathering	13. a)chemical & physical weathering at 1% of stock per yr. (50780 g/m^2) (.01) = 507.8/365 = 1.39 g/m^2/da b) biological weather est. at 50% of input = 5.9 g/m^2/da Total = 7.3 g/m^2/da	
$k_{10}BS$	4.5 g/m^2/da	14. Reef structure export to diversity	14. Steady state assumption input - output = 11.8 - 7.3 g/m^2/da = 4.5 g/m^2/da	
$k_{11}BS$	.034 species/ 1000/da	15.Input to diversity	15. Steady state information assump.: input = output : 12.3 species/yr. = .034 species.1000/da	

Table 13. Continued

Model Component	Value	Description	Calculations	References
$k_{11}BS$	.034 species/ 1000/da	16. Cost of maintaining diversity	16. Steady state assump.: input = output	
k_5D^2	60.6 $g/m^2/da$	17. Food available to reef system w/out diversity	17. Sum of food uptake by reef organisms = 56.5 + 4.1 = 60.6 $g/m^2/da$	
$k_{22}JrBH$	60.6 $g/m^2/da$	18. Food available for other bay systems (J remainder)	18. Assume 50:50 reef system to other systems = 60.6 $g/m^2/da$	
k_2P	121.2 $g/m^2/da$	19. Total food input to bay (not incl. special food)	19. 60.6 + 60.6 $g/m^2/da$ = 121.2 $g/m^2/da$	

TABLE 14 .

Simulation Data-Thermally-affected Model

Simulation Conditions	Figure Number	Biomass g/m^2/year	Set g/m^2/year	Diversity species/1000/year	Structure g/m^2/year
Normal: 16-30°C	25b	76.0	45.3	13.3	5×10^4
2°C below: 14-28°C	25c	96.5	45.3	14.8	5×10^4
2°C above: 18-32°C	25d	62.5	46.0	11.8	5×10^4
4°C above: 20-34°C	26a	53.5	46.3	11.5	5×10^4
6°C above: 22-36°C	26b	42.0	44.4	9.9	5×10^4
10°C above: 26-40°C	26c	36.5	45.0	9.3	5×10^4
Respiration reduced 50%	27a	115.5	43.9	16.7	5×10^4
Respiration increased 50%	27b	42.5	40.2	10.2	5×10^4
Respiration reduced 85%	27c	178.0	54.5	24.6	5×10^4
Food increased 50%	28a	93.5	58.2	14.5	5×10^4
Food reduced 100%	28b	53.0	53.4	12.4	5×10^4
Special food reduced 50%	28c	19.0	48.8	6.4	5×10^4
Special food reduced 100%	28d	0.0[a]	48.5	0.0[b]	5×10^4
All stocks reduced 50%	29a	47.0	53.2	7.2	2.5×10^4
All stocks reduced 80%	29b	3.0	47.1	0.0[c]	1.25×10^4

TABLE 14. **Continued**

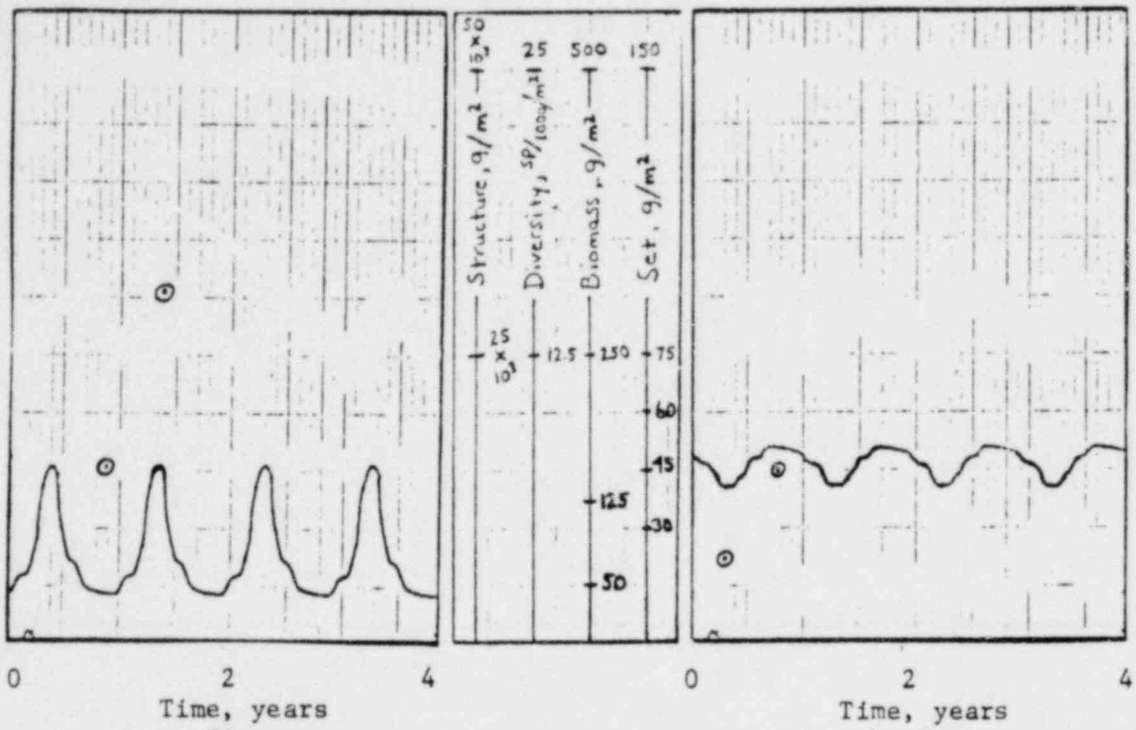
Simulation Conditions	Figure Number	Biomass g/m^2/year	Set g/m^2/year	Diversity species/1000/year	Structure g/m^2/year
Spawning temperature 18°C	30a	68.0	55.3	12.3	5 X 10^4
Spawning temperature 23°C	30b	78.5	58.6	13.8	5 X 10^4

---

[a] Within less than one year

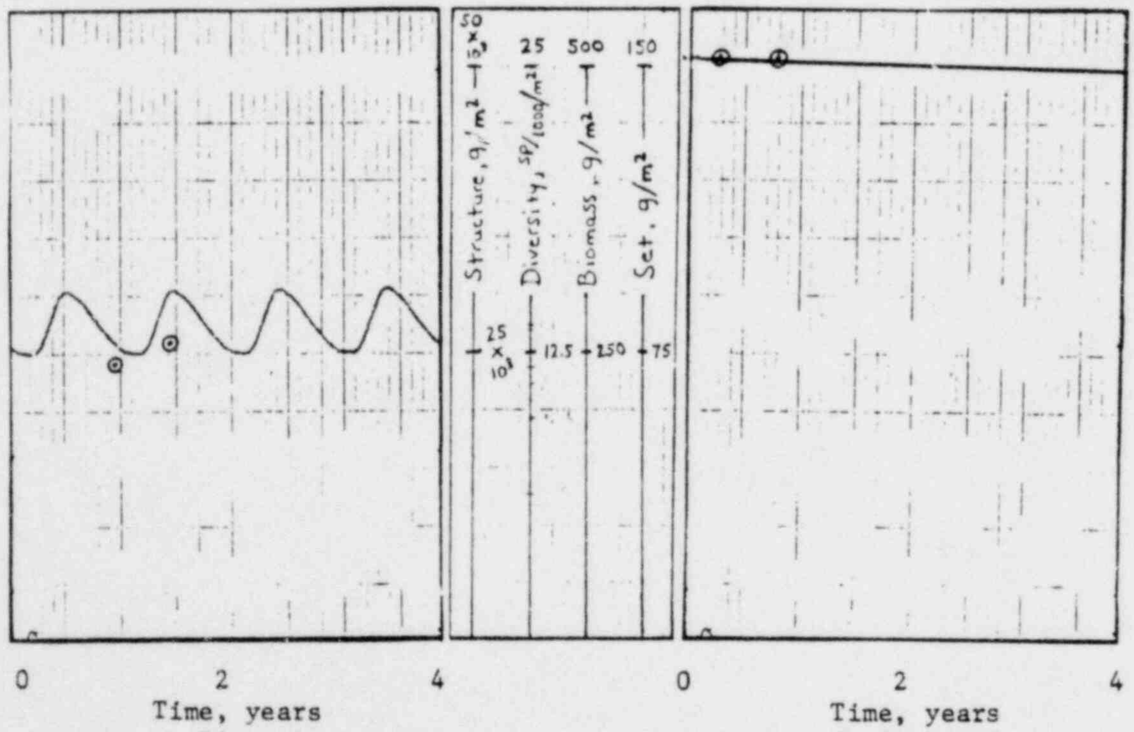
[b] In approximately 5 years

[c] In approximately 10 years



a. Biomass

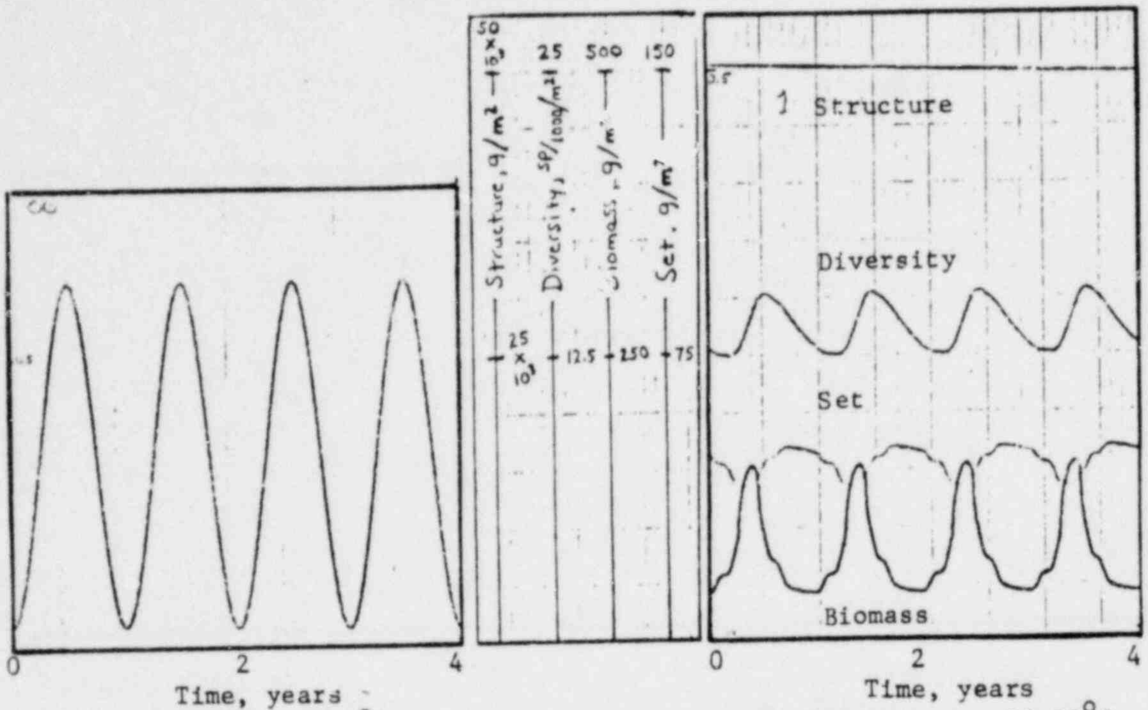
b. Set



c. Diversity

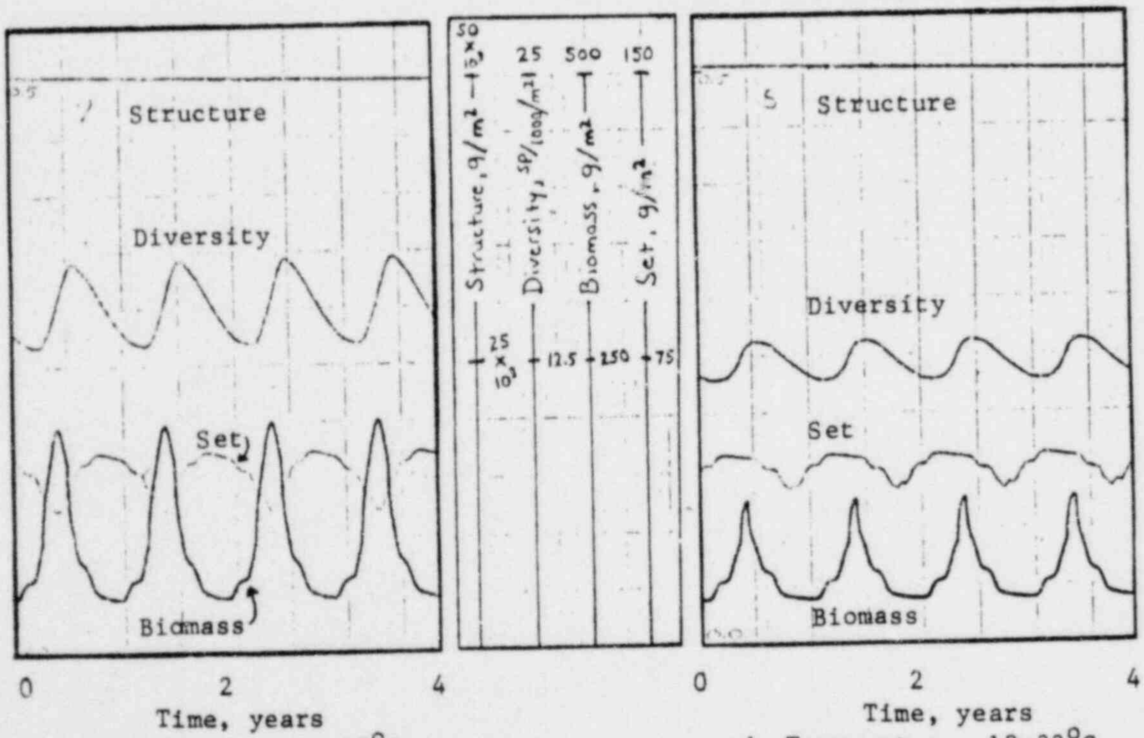
d. Structure

Fig. 24. Field data (discharge bay) plotted with simulated data from thermally-affected model, (a) biomass, (b) set, (c) diversity, (d) structure.



a. Heat, T=14°C

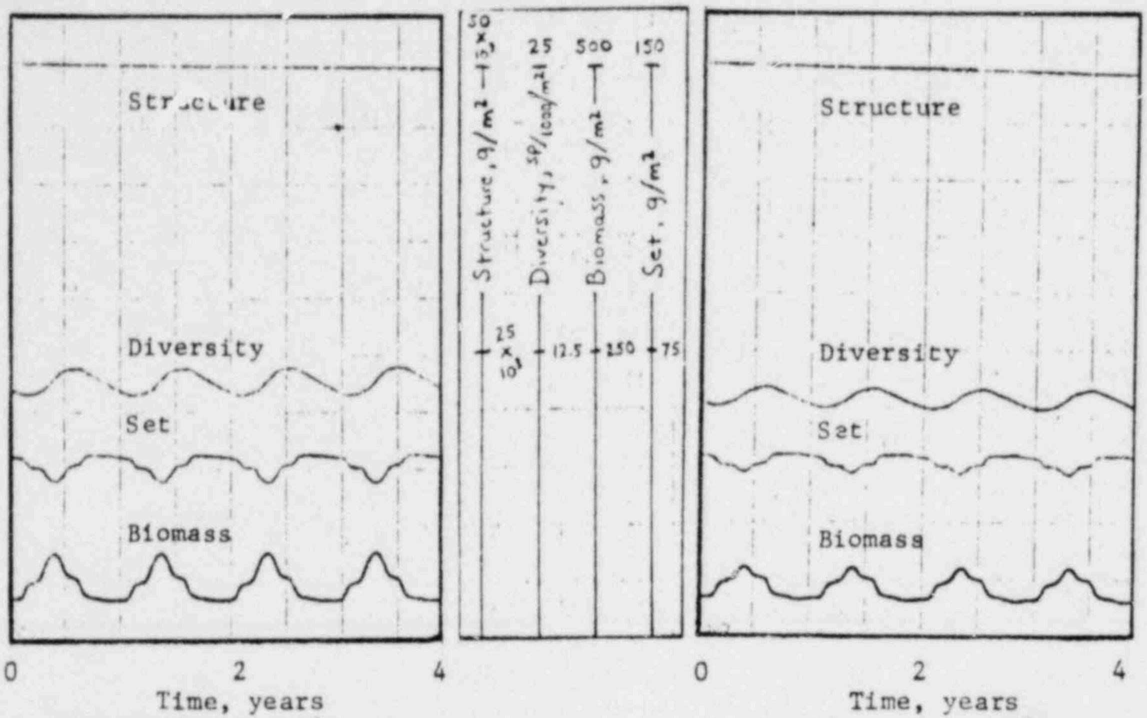
b. Temperature, 16-30°C



c. Temperature, 14-28°C

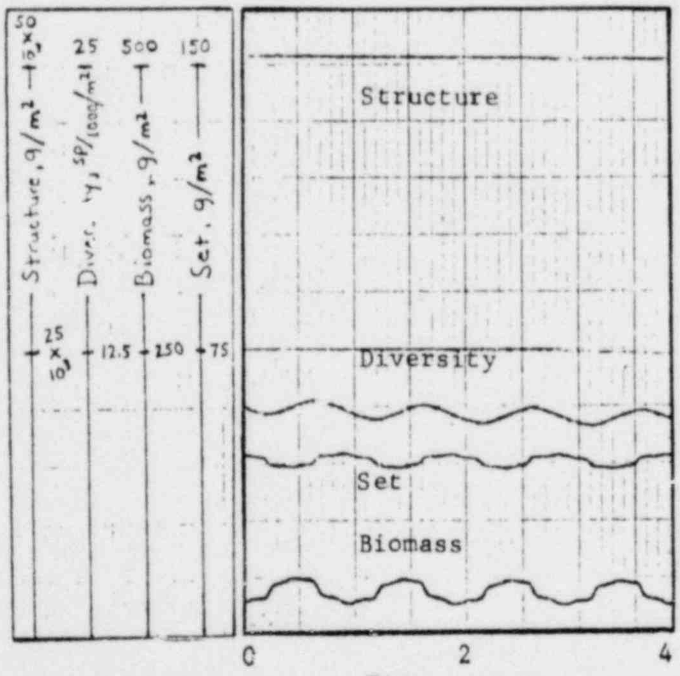
d. Temperature, 18-32°C

Fig. 25. Response of thermally-affected model to temperature, (a) heat (b) normal temperature range (c) 2°C below normal (d) 2°C above normal



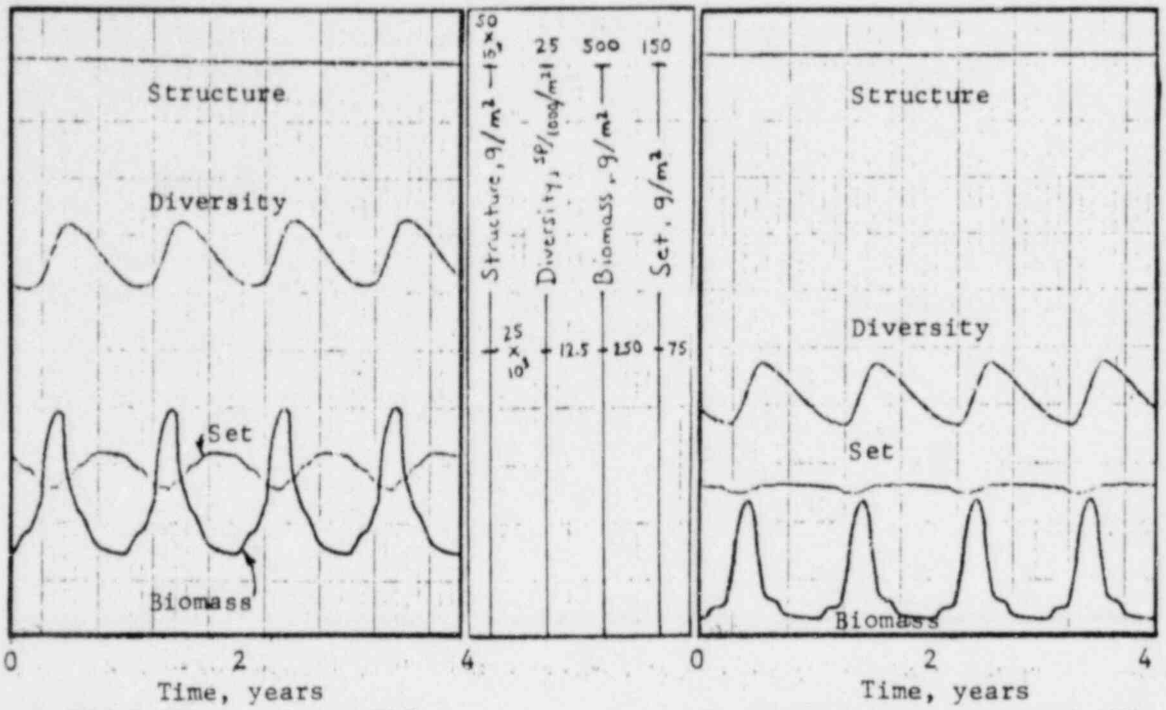
a. Temperature 20-34°C

b. Temperature 22-36°C



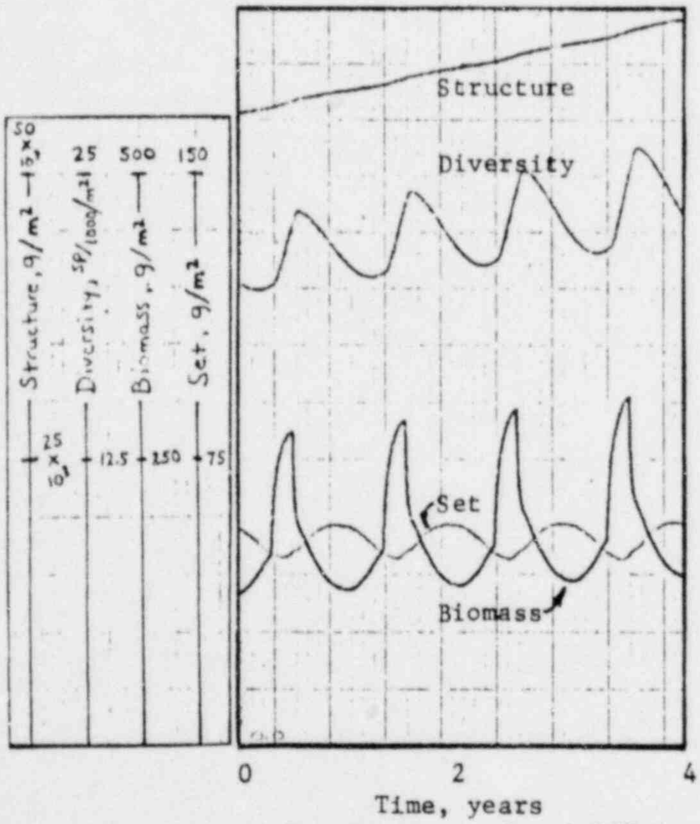
c. Temperature 26-40°C

Fig. 26. Response of thermally-affected model to temperature (a) 4°C above normal, (b) 6°C above normal, (c) 10°C above normal



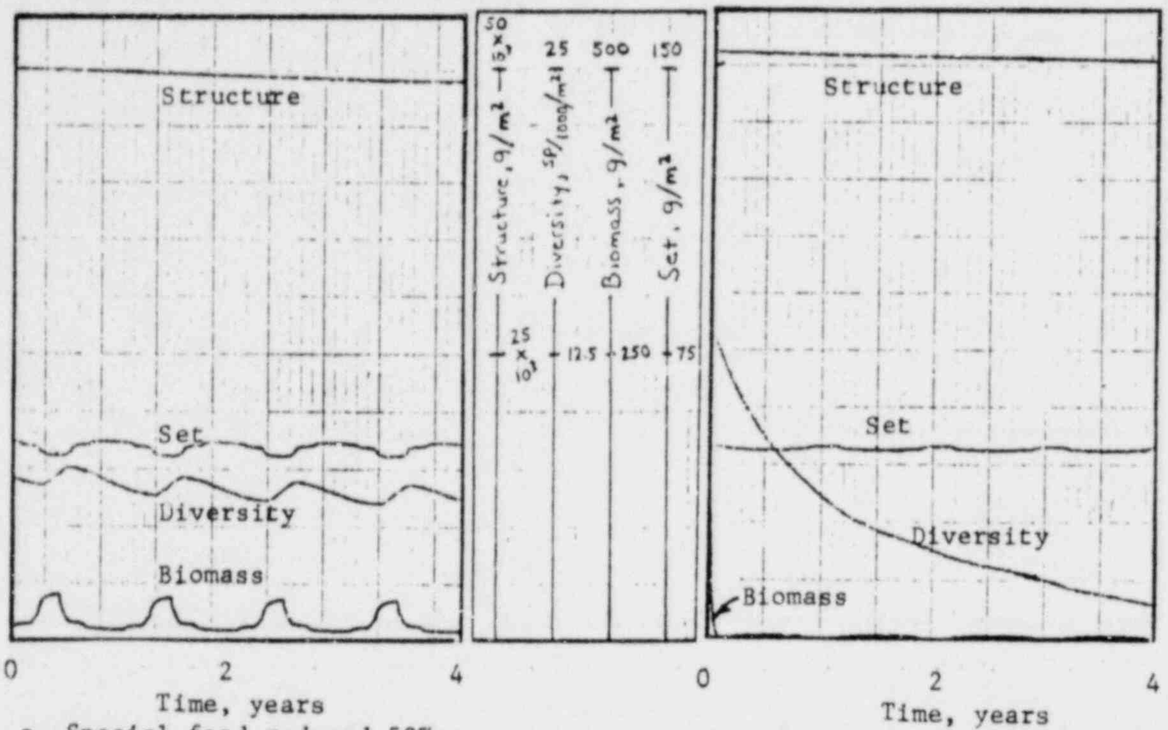
a. Respiration reduced 50%

b. Respiration increased 50%



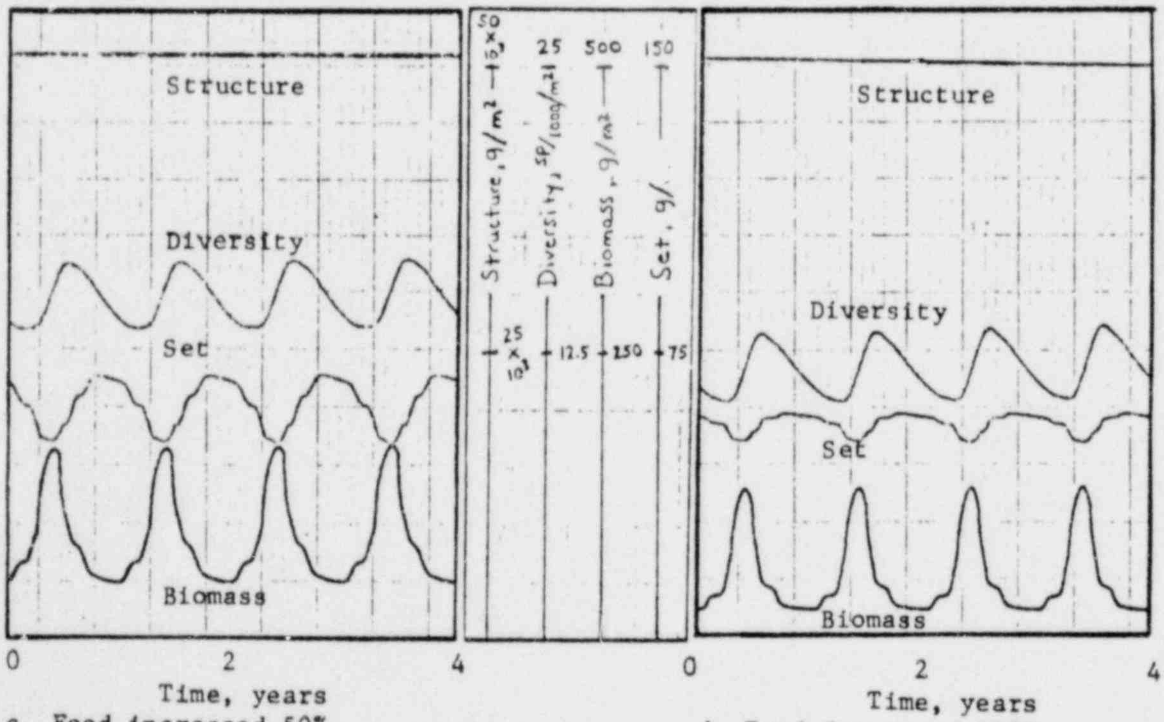
c. Respiration reduced 85%

Fig. 27. Simulation curves of respiration changes in thermally-affected model, (a) respiration reduced 50% (b) respiration increased 50% (c) respiration reduced 85%.



a. Special food reduced 50%

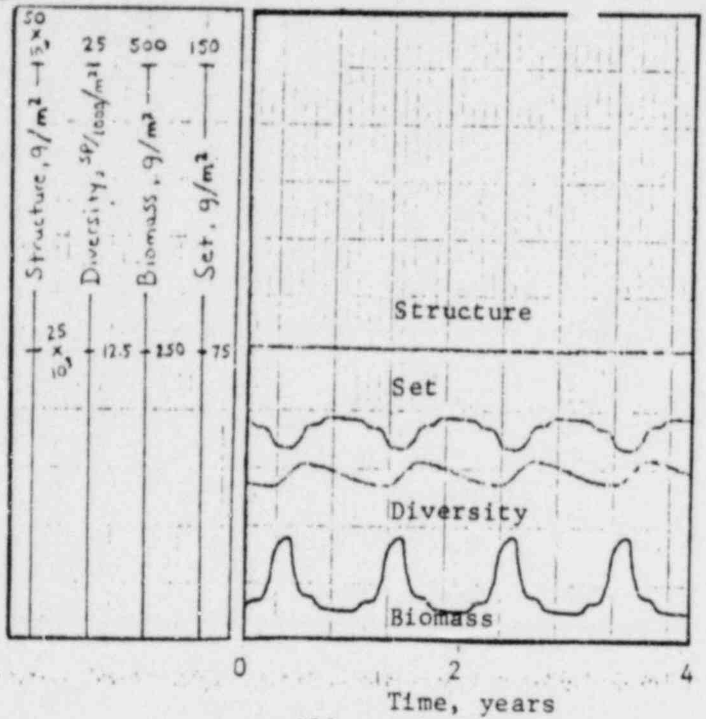
b. Special food reduced 100%



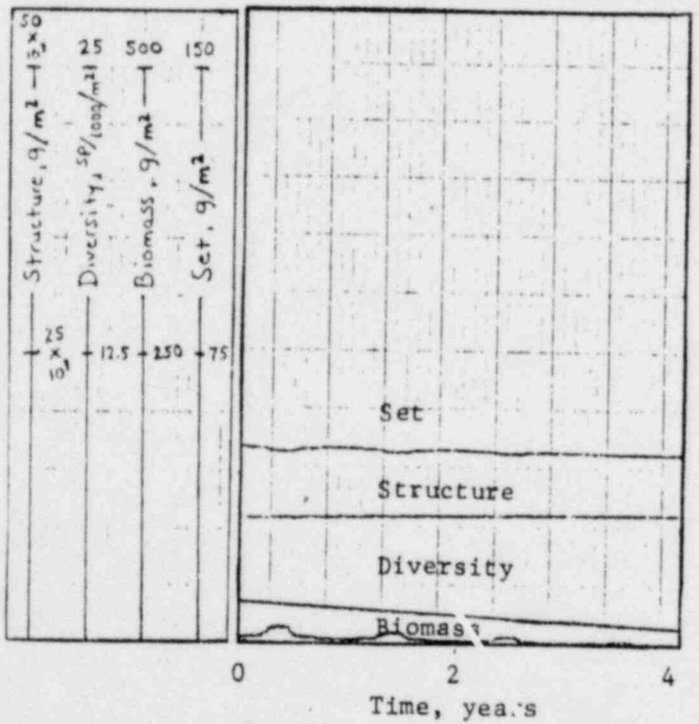
c. Food increased 50%

d. Food decreased 100%

Fig. 28. Response of thermally-affected model to changes in food conditions, (a) special food reduced 50% (b) special food reduced 100% (c) food increased 50% (d) food decreased 100%.

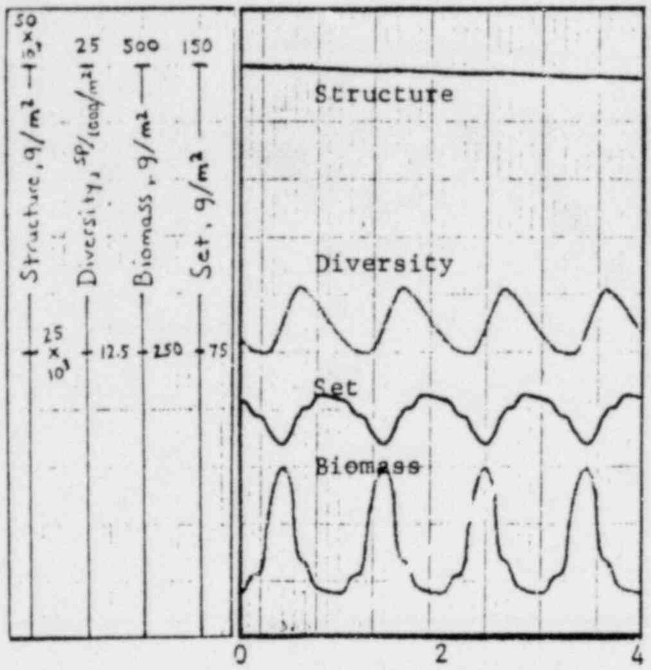


a. All stocks reduced 50%

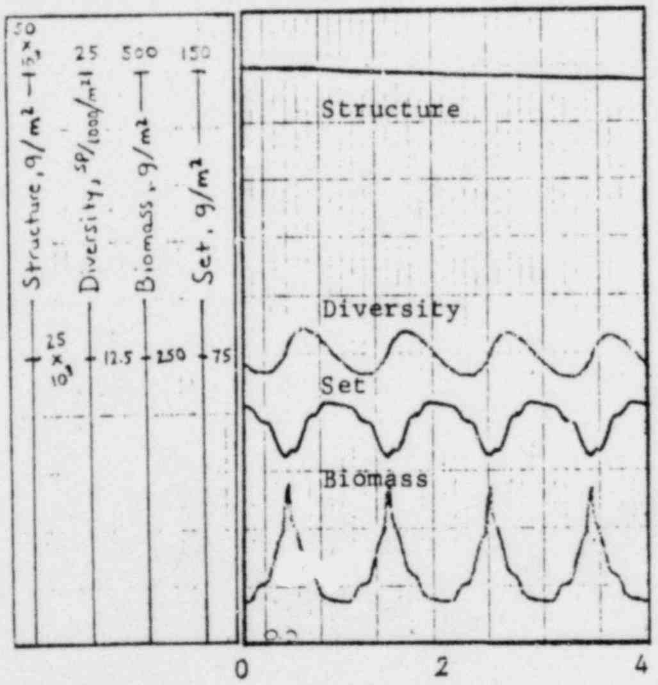


b. All stocks reduced 80%

Fig. 29. Simulation graphs of thermally-affected model (a) all stocks reduced 50%, (b) all stocks reduced 80%.



Spawning temp. 23°C



Spawning temp. 18°C

Fig. 30. Response of thermally-affected model to changes in spawning temperature (a) spawning temperature 3°C above normal (b) spawning temperature 2°C below normal.

of the model to bring in more food. (5) Changes in spawning temperature influenced levels of storages somewhat, but total effect on levels other than set was not too pronounced.

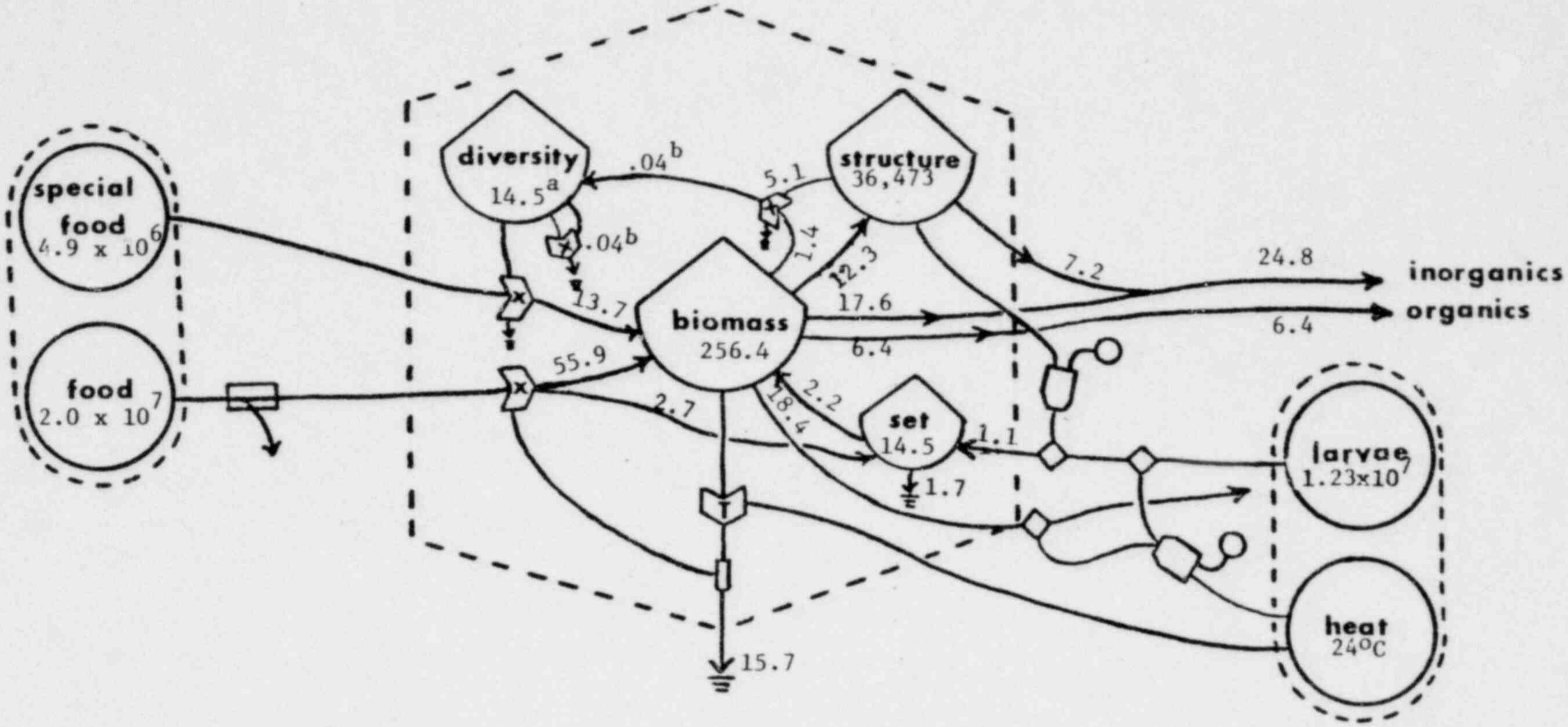
Simulation of Control Area Model

Normal range of temperature in the control area was simulated as 12-26°C (Fig. 32); a mean temperature 4°C less than the thermally-affected bay. Field data and simulateddata under normal conditions (12-26°C) were plotted together (Fig. 32). Simulation results are summarized in Table 16. Figure 33 through 38 are simulation graphs referred to in Table 16.

A summary of the responses of the control area model showed: (1) increased temperature reduced model stocks, but nover completely destroyed them, (2) changes in respiration varied model response. Initial reductions increased stodks; further reductions decreased them. Increasing respiration up to 50% simulated stocks but introduced extreme seasonal fluctuations, (3) response of the push-pull temerature mechanism indicated flow of food was not totally limiting, (4) over-harvesting as simulated in the model reduced reef storages, but severe over-harvesting (80% reduction) did not completely wipe out standing stocks, (5) colder and warmer spawning temperatures stimulated increased biomass in both cases.

Comparison of Simulation Results between Discharge and Control Areas

Simulations of conditions defined as normal for each area (Fig. 23, discharge and Fig. 31, control) gave similar biomass levels. Set was higher in the control area, but structure was less. Diversity was lower in the discharge bay. Seasonal variation in stored properties was less in the thermally-influenced model; oscillations tended to be smoother.



Flows are g/m^2/day

Stocks are g/m^2 (except where stated)

a Species/thousand (stock)

b Species/thousand/day (flow)

Fig. 31. Evaluated oyster reef diagram of control area.

Table 15.

Control Area Oyster Reef System Value Calculations - Forcing Functions

Model Component	Value	Description	Calculations	Reference
F	4.9×10^6	A. Special food	A. $(2.0 \times 10^7 g)(.245) = 4.9 \times 10^6$ See Table	A. Special food
I	$2.0 \times 10^7 g$	B. Food		B. See Table
T	$1.23 \times 10^7 g$	C. Larvae		C. See Table
H	24°C	D. Heat	D. Mean annual temp. from sun & sky heat	D. Grimes, 1971
B	$254.6 g/m^2$	E. All reef organisms (except spat)	E. Area-weighted dry meat wt = $254.6 g/m^2$	E. Lehman, Cry. Riv. field data, 1973
D	14.5 species/ thousand	F. Diversity	F. Annual average = 14.5 species/ thousand	F. Lehman, Cry. Riv. field data, 1973
S	$36,472.7 g/m^2$	G. Reef structure (oyster shell, etc.)	G. Area-weighted mass = $36,472.7 g/m^2$	G. Lehman, Cry. Riv. field data, 1973
L	$14.5 g/m^2$	H. Oyster set (attached larvae)	H. Area-weighted dry meat weight = $14.5 g/m^2$	H. Lehman, Cry. Riv. field data, 1973

Table 15. **Continued**

Control Area Oyster Reef System Value Calculations - Flows

Model Component	Value	Description	Calculations	References
$k_{23}JrBH$	55.9 $g/m^2/da$	1. Reef organisms food uptake	1. a)filtering rate = 144 1.12 hr. day for adult oyster at 50% efficiency = 100 1/12 hr. day based on respiration ratios between the two bays; b) Sestion in waters = 1.13 x 10^{-3} g/1 (1.70 g/m^2)/(1.5m) = 1.13 x 10^{-3} g/1 11 $1/m^2$/day x 990 oysters/m^2 = 9.90 x 10^4 $1/m^2$/day 9.90 x 10^4 $1/m^2$/day x 1.13 x 10^{-3} g/1 = 11.19 x 10^2 g/m^2/day at 50% efficiency = 55.9 g/m^2	1. a) Collier,1959 b) See calc. of model component I_2, Table
k'D	13.7 $g/m^2/da$	2. Reef organisms special food uptake	2. Steady state assumption by method of diff.; see calc. of J_{B9}, this table	2. See calc. of model component J_{B2},Table
$k_{24}BH$	15.7 $g/m^2/da$	3. Reef organism respiration	3. Sum of underwater and exposed rates = 15.7 g/m^2/da	3. Lehman, Cry. Riv. field data, 1973-74
k_8B	12.3 $g/m^2/da$	4. Organism loss to reef structure	4. a)assume oyster growth approx. 180 days/yr.; b) (2217 g shell /m^2 of living oyster biomass) c)assume one year longevity 2217/m^2/180 days = 12.3 g/m^2/da	4. a) b)Lehman, Cry. Riv. field data,1973 c)See calc. of model component J_{B4}, Table

Table 15. Continued

Model Component	Value	Description	Calculations	Reference
k_6B	17.6 $g/m^2/da$	5. Inorganic loss from reef organisms a)oyster pseudofeces deposition b)oyster feces deposition c)total oyster deposition d)other organism deposition	5. a) 8% dry body wt./day (119.5 g/m^2) (.08) = 9.56 g/m^2/day b) 5.6% dry body wt./day (119.5 g/m^2)(.056) = 6.69 g/m^2/day c) 84% total deposition of oysters is inorganic. (9.56 + 6.69 g/m^2/day) (16.3 g/m^2/day)(.84) = 13.7 g/m^2/day d) 5.6% dry body wt./day (135.1 g/m^2)(.056 = 7.56 g/m^2/day Assume 50% feces inorganic:(7.56 g/m^2/day)(.5) = 3.78 g/m^2/day Total loss = 13.7 + 3.9 g/m^2/day = 17.6 g/m^2/day	5. a)Day et al, 1973 b)Day et al, 1973 c)Day et al, 1973 Haven & Morales-Alamo, 1966
k_7B	6.4 $g/m^2/da$	6. Organic loss from reef organisms	6.a) organic deposition from oysters = 2.6 g/m^2/day; b) organic deposition from other organisms = 3.8 g/m^2/day Total loss = 2.6 + 3.8 g/m^2/day = 6.4 g/m^2/day	6.See calc. of J_{B_5}, this table
$k_{20}B$	18.4 g/m^2/day	7. Reef organism loss due to spawning	7. 297 oysters/m^2 w/ 50% fertility = 149 oysters/m^2 (149 oysters/m^2)(50 x 10^6eggs/yr) = 7.45 x 10^9 eggs/m^2/yr. (.9 x 10^{-5} g/larvae)(.1)(7.45 x 10^9) = .671 x 10^4 g/m^2/yr = .001838 x 10^4 g/m^2/day	7.See calc. J_{B_7}, Table

Table 15. **Continued**

Model Component	Value	Description	Calculations	Reference
$k_{15}L$	2.2 $g/m^2/da$	8. Rate of set growth	8. (2792 $larvae/m^2$)(.0008 g/larvae/day) = 2.2 $g/m^2/day$ (Based on $\bar{x}$ wt/larvae 80% less in control	8.See calc. J_{B_8}, Table
k_9BS	1.4 $g/m^2/day$	9. Reef loss to diversity	9. Steady state assumption by method of difference: $x + (58.1) = .1x + (70.4)$ $x - .1x = 70.4 - 58.1$ $.9x = 12.3$ $x = 13.67$ $.1x = 1.37$ $g/m^2/day$	
$k_{18}L$	1.1 $g/m^2/day$	10. Larvae setting rate	10. 21 $larvae/m^2/day$ (21 $larvae/m^2/day$ x .05 g/larvae) = 1.05 $g/m^2/day$	10.Lehman, Cry. Riv. field data, 1973
$k_{25}JrBH$	2.74 $g/m^2/day$	11. Food uptake of set	11. Steady state assumption by method of diff.: output = 3.84 $g/m^2/day$ input = 1.1 $g/m^2/day$ 3.84 - 1.1 = 2.74 $g/m^2/day$	
$k_{16}L$	1.7 $g/m^2/da$	12. Set respiration	12. 11.6% dry body wt. per day (as measured for adult oysters) (14.5 g/m^2)(.116) = 1.68 $g/m^2/day$	12.Lehman, Cry. Riv. field data, 1974
$k_{12}S$	7.2 $g/m^2/day$	13. Reef structure lost to chemical, physical & biological weathering	13. a) (36473 g/m^2)(.01) = 364.7 364.7/365 = 1.00 $g/m^2/day$ b) (12.3 $g/m^2/day$)(.5) = 6.2 $g/m^2/day$ Total = 6.2 + 1.0 = 7.2 $g/m^2/day$	13.a)See calc. J_{S_1}, Table b)See calc. J_{S_1}, Table
$k_{10}BS$	5.1 $g/m^2/da$	14. Reef structure export to diversity	14. Steady state assumption; Input = 12.3 $g/m^2/day$ Output = 7.2 $g/m^2/day$ 12.3 - 7.2 = 5.1 $g/m^2/day$	

Table 15. Continued

Model Component	Value	Description	Calculations	Reference
$k_{11}BS$	.040 species/ 1000/day	15. Input to diversity	15. 14.5 species/thousand 14.5/365 days = .040 species/1000/da	
k_5D^2	.040 species/ 1000/day	16. Cost of maintaining diversity	16. Steady state assumption Input = .040 species/1000/day Output = 0 .040 - 0 = .040 species/1000/day	
$k_{22}JrBH$	58.7 $g/m^2/da$	17. Food available to reef system without diversity	17. Sum of food uptake by reef organisms 2.8 $g/m^2/day$ + 55.9 $g/m^2/day$ = 58.7 $g/m^2/day$	
k_2P	117.4 $g/m^2/da$	18. Total food input to bay (not incl. special food)	18. 58.7 + 58.7 $g/m^2/day$ = 117.4 $g/m^2/da$	

TABLE 16 .

Simulation Data-Control Area Model

Simulation Conditions	Figure Number	Biomass g/m^2/year	Set g/m^2/year	Diversity species/1000/year	Structure g/m^2/year
Normal: 12-26°C	33 b	75.0	81.9	15.6	3 X 10^4
2°C below: 10-24°C	33 c	110.5	78.3	17.4	3 X 10^4
2°C above: 14-28°C	33 d	65.0	76.7	12.8	3 X 10^4
4°C above: 16-30°C	34 a	45.0	83.0	11.7	3 X 10^4
6°C above: 18-32°C	34 b	34.5	75.3	9.5	3 X 10^4
10°C above: 20-34°C	34 c	18.5	84.6	6.7	3 X 10^4
12°C above: 24-38°C	34 d	16.0	80.7	6.4	3 X 10^4
Respiration reduced 50%	35 a	101.5	77.2	17.0	3 X 10^4
Respiration increased 50%	35 b	84.0	74.7	16.1	3 X 10^4
Respiration reduced 75%	35 c	154.0	71.2	21.1	3 X 10^4
Respiration reduced 85%	35 d	135.5	71.9	21.4	3 X 10^4
Food increased 50%	36 a	92.5	77.9	18.1	3 X 10^4
Food reduced 100%	36 b	103.5	72.4	17.9	3 X 10^4
Special food reduced 50%	36 c	20.5	75.8	6.9	3 X 10^4
Special food reduced 100%	36 d	0.0[a]	78.0	0.0[b]	3 X 10^4
All stocks reduced 50%	37 a	59.5	77.8	10.3	1.5 X 10^4
All stocks reduced 80%	37 b	13.5	77.7	0.0[c]	0.6 X 10^4

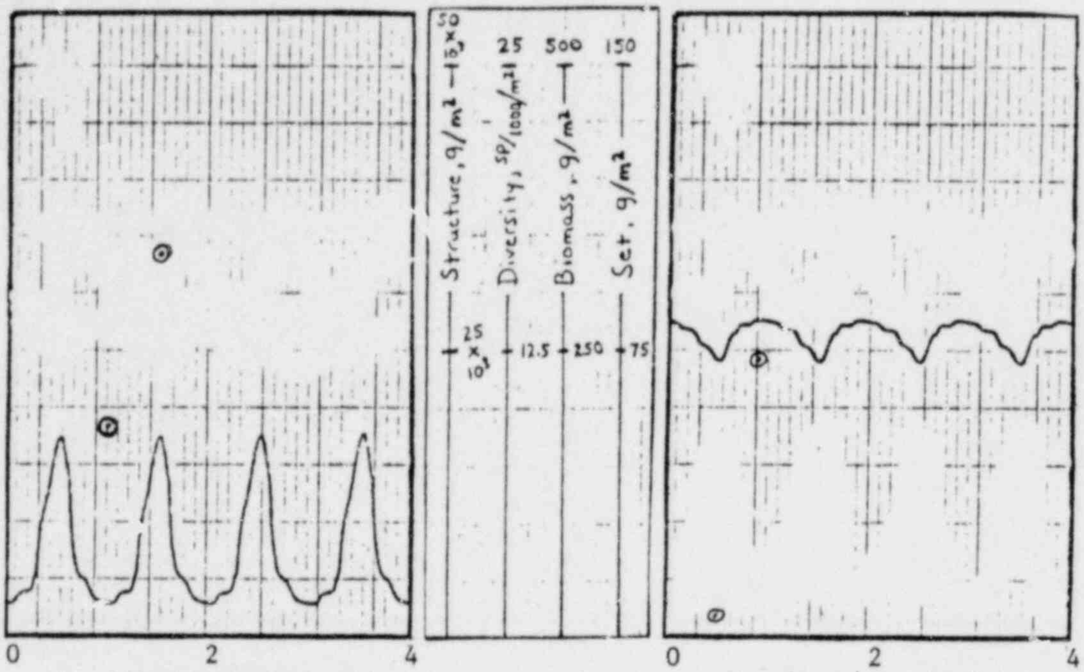
TABLE 16. Continued

Simulation Conditions	Figure Number	Biomass $g/m^2/year$	Set $g/m^2/year$	Diversity species/1000/year	Structure $g/m^2/year$
Spawning temperature 18°C	38 b	84.5	75.1	15.8	3×10^4
Spawning temperature 23°C	38 a	100.0	85.0	17.3	3×10^4

[a] Within less than one year

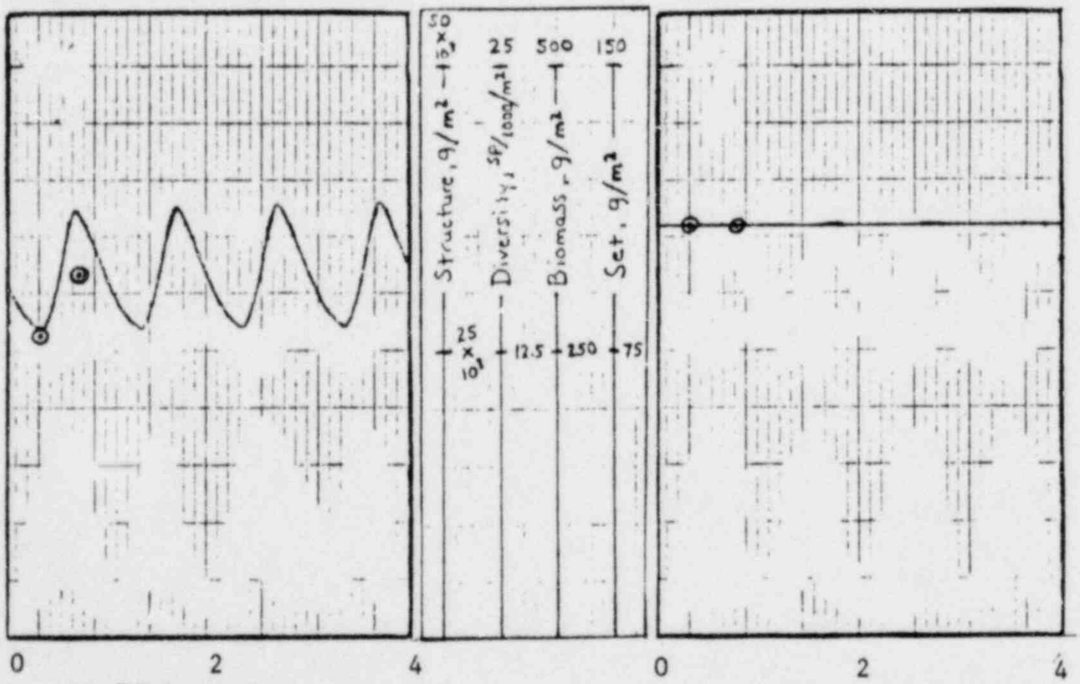
[b] Within less than eight years

[c] In approximately 20 years



a. Biomass

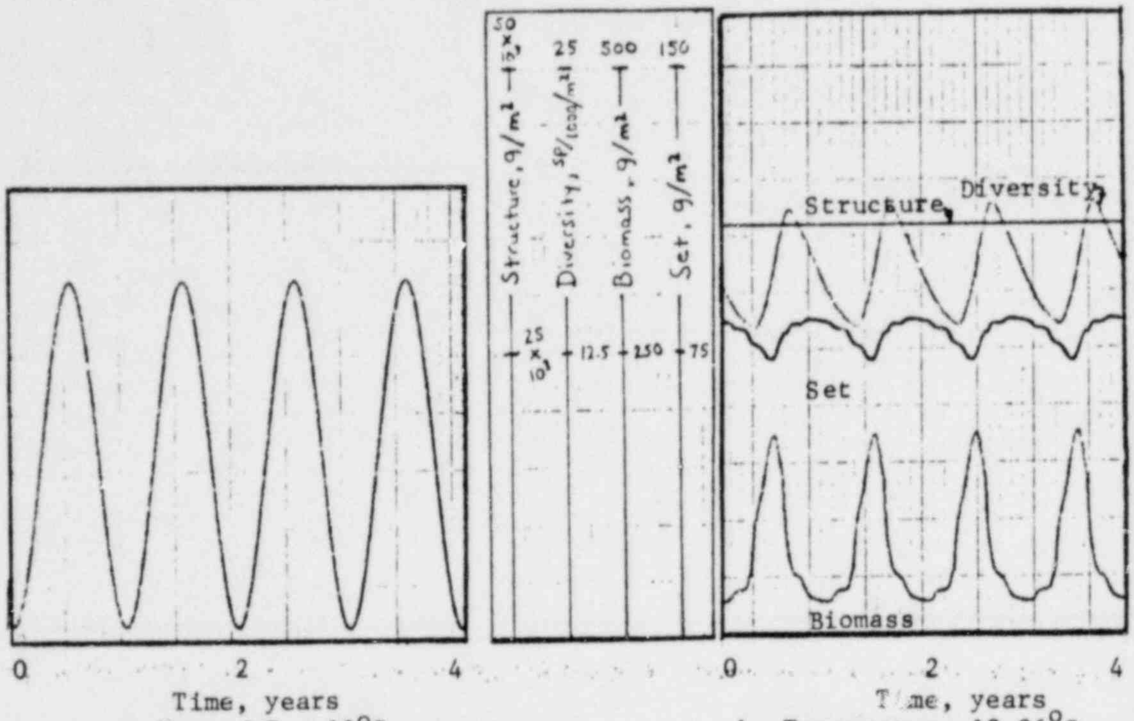
b. Set



c. Diversity

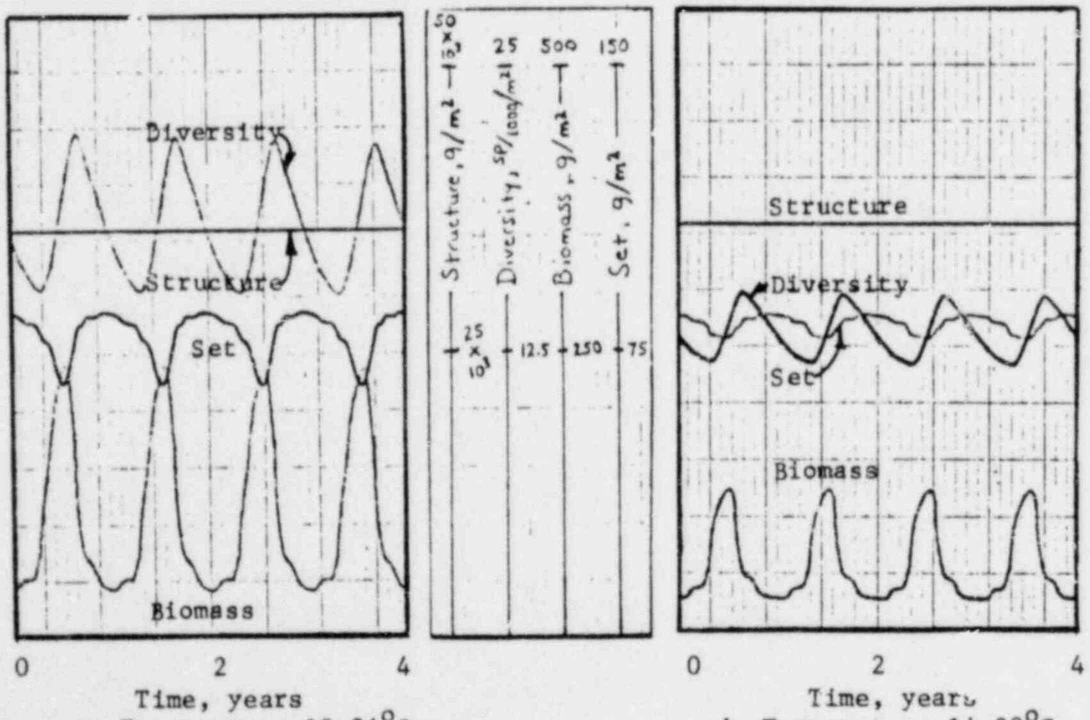
d. Structure

Fig. 32. Field data (control area) plotted with simulated data from control area model, (a) biomass, (b) set, (c) diversity, (d) structure.



a. Heat, ΔT = 12°C

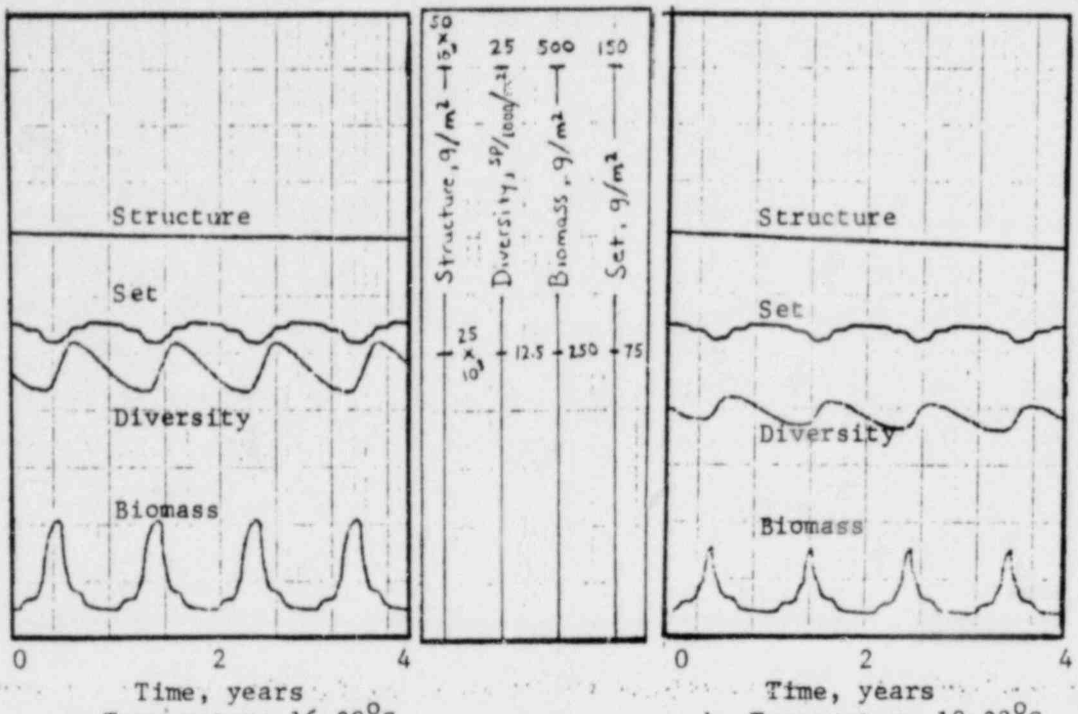
b. Temperature 12-26°C



c. Temperature 10-24°C

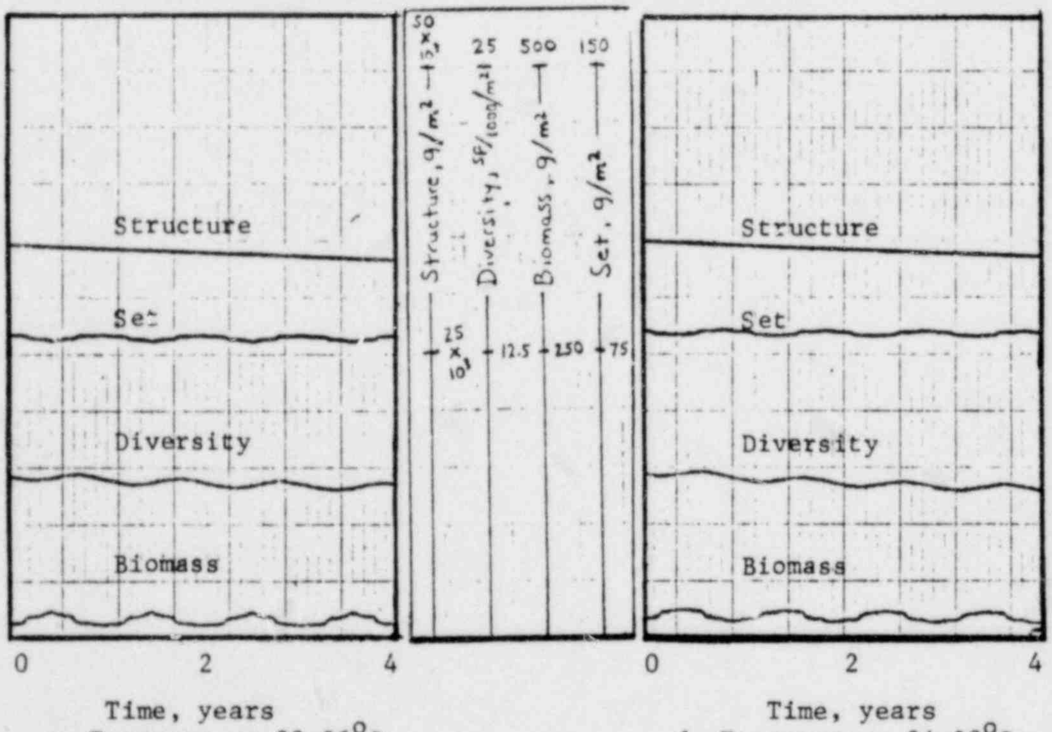
d. Temperature 14-28°C

Fig. 33. Response of control area model to temperature, (a) heat, (b) normal temperature range, (c) 2°C below normal, (d) 2°C above normal



a. Temperature 16-30°C

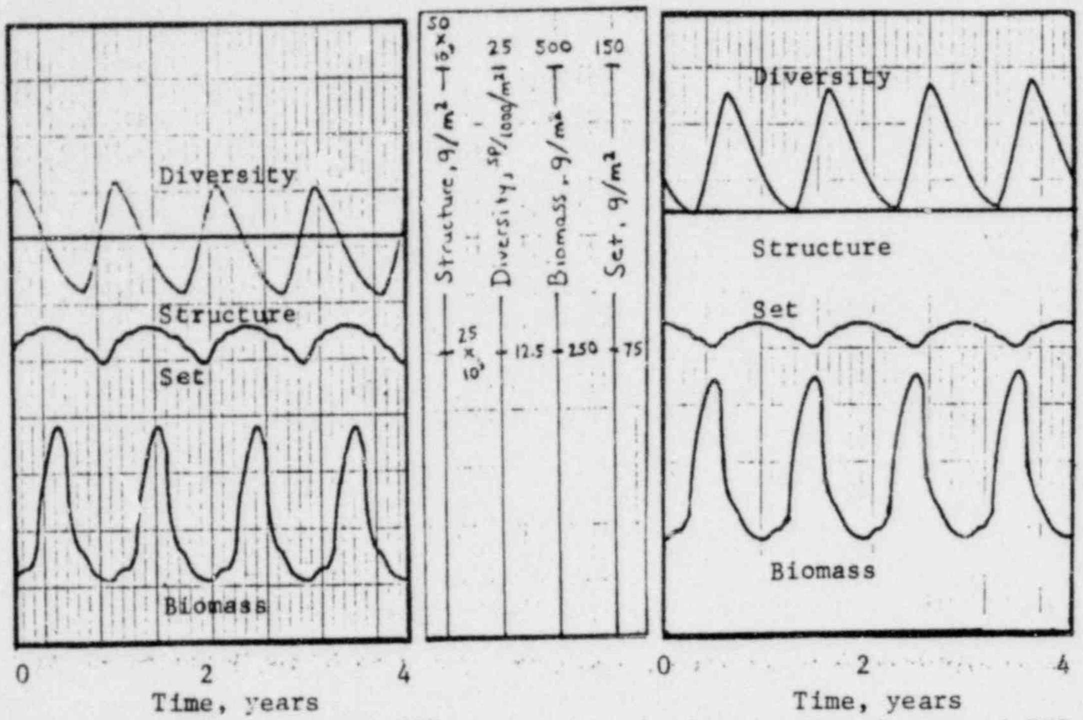
b. Temperature 18-32°C



c. Temperature 22-36°C

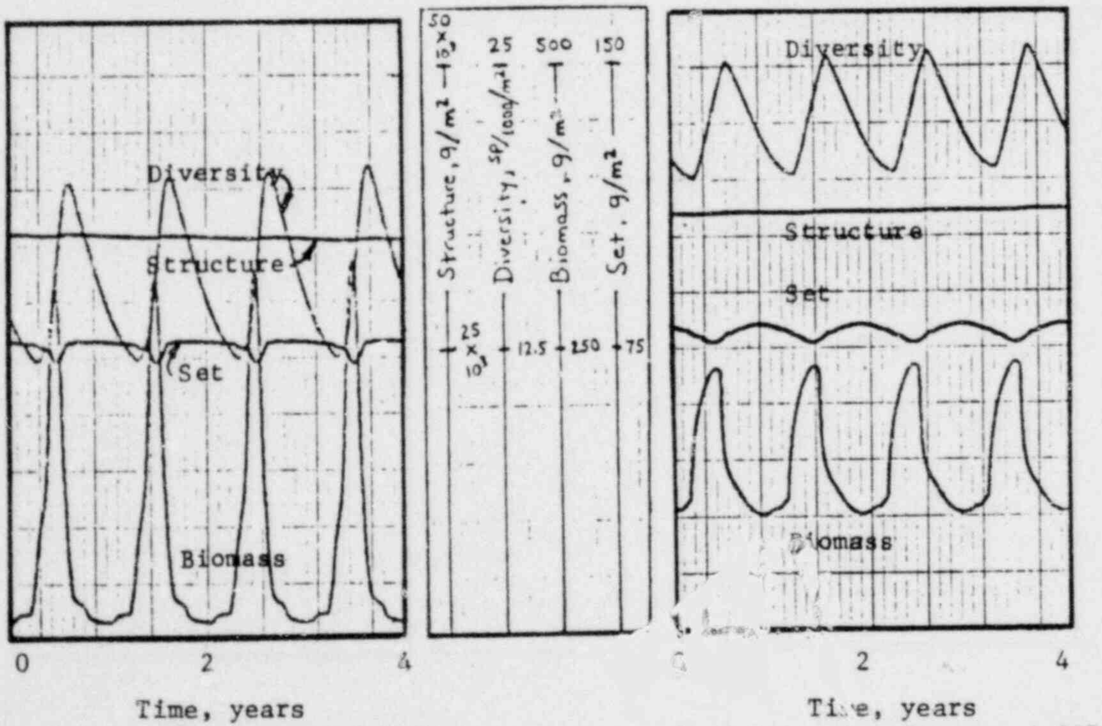
d. Temperature 24-38°C

Fig. 34. Response of control area model to temperature, (a) 4°C above normal, (b) 6°C above normal, (c) 10°C above normal (d) 12°C above normal



a. Respiration decreased 50%

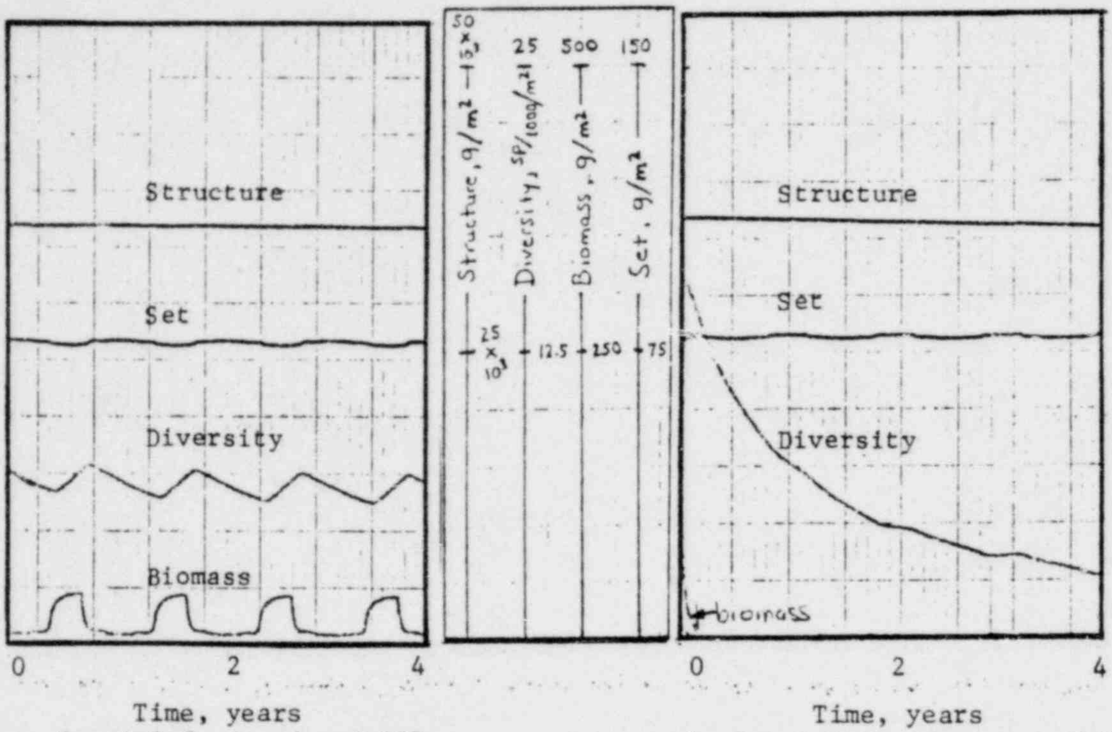
b. Respiration decreased 75%



c. Respiration increased 50%

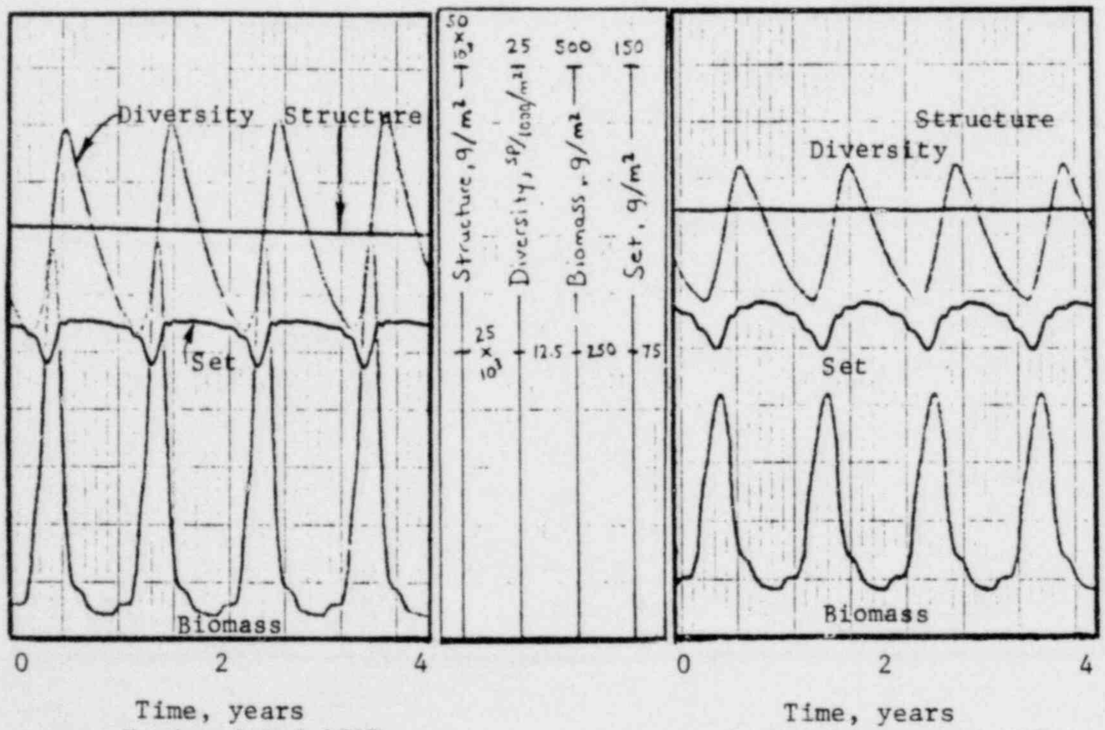
d. Respiration decreased 85%

Fig. 35. Simulation curves of respiration changes in control area model (a) respiration decreased 50%, (b) respiration decreased 75% (c) respiration increased 50%, (b) respiration decreased 85%.



a. Special food reduced 50%

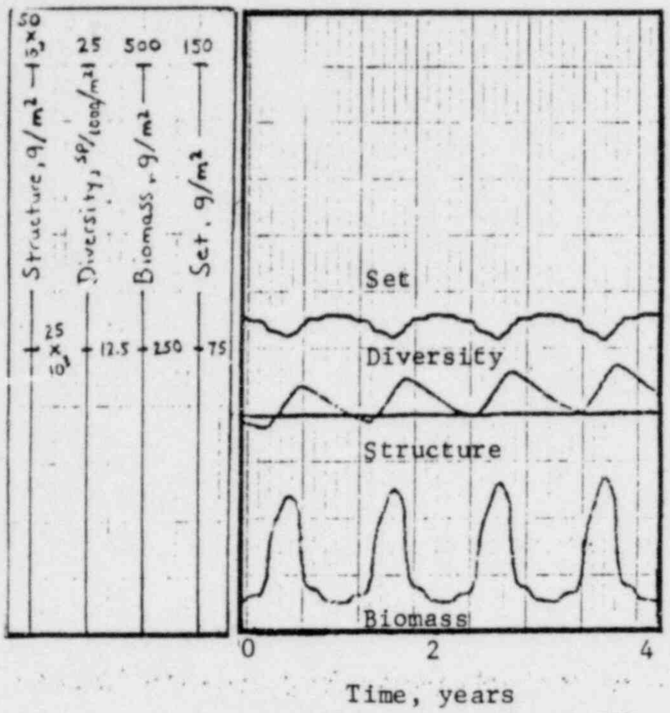
b. Special food reduced 100%



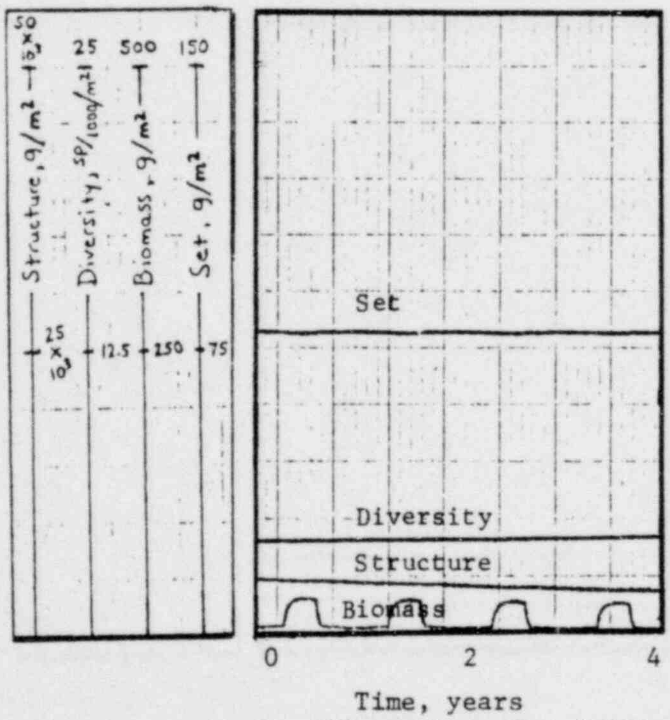
c. Food reduced 100%

d. Food increased 50%

Fig. 36. Response of control area model to changes in food conditions, (a) special food reduced 50%, (b) special food reduced 100%, (c) food reduced 100% (d) food increased 50%.

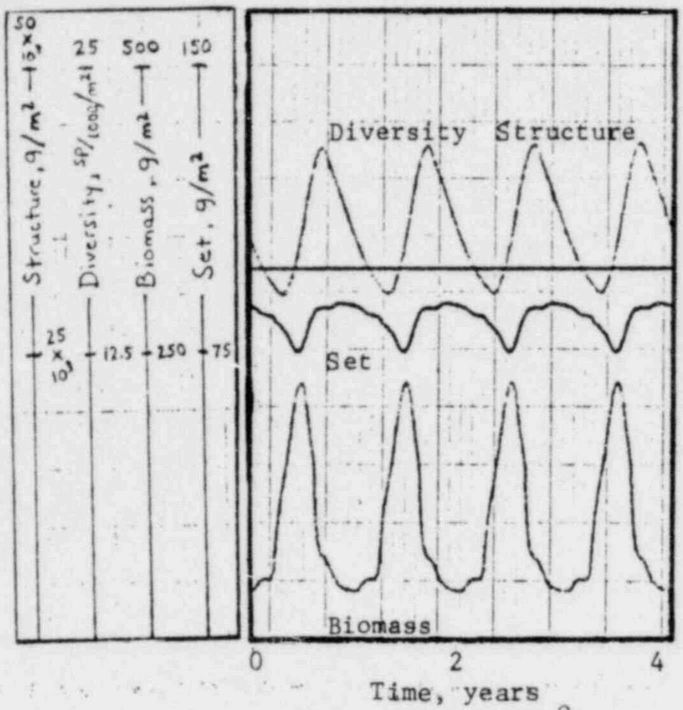


a. All stocks reduced 50%

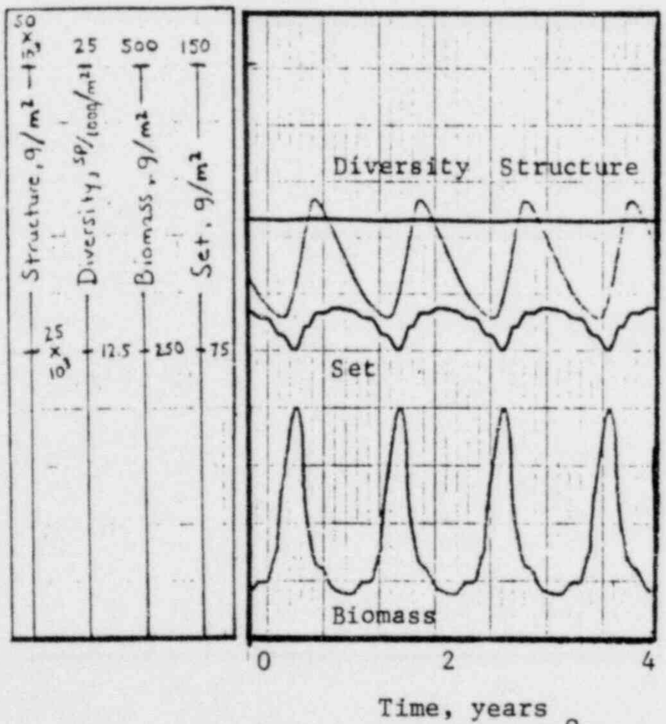


b. All stocks reduced 80%

Fig. 37. Simulation graphs of control area model, (a) all stocks reduced 50%, (b) all stocks reduced 80%.



a. Spawning temp. 23°C



b. Spawning temp. 18°C

Fig. 38. Response of control area model to changes in spawning temperature (a) spawning temperature 3°C above normal, (b) spawning temperature 2°C below normal.

Increased temperature effects on biomass were similar between the two models with biomass depressed slightly more in the control area. Reduction in diversity with respect to temperature was greater in the discharge bay.

Changes in respiration were different. The discarge bay model increased stocks with decreased respiration and decreased stocks with increased respiration. This indicated that the push-pull mechanism could no longer compensate for additional losses due to increased respiration. In the control area model, decreasing respiration first increased stocks, and then further decreases resulted in stocks being reduced. Increased respiration stimulated levels of state variables but induced stronger seasonal variation. This indicated the stimulus-effect of push-pull to increase food to the reef. Overall response of models to changing food flows were similar; one exception in the control simulation, stocks increased when food to oysters was off. Although trends were similar, the reactions of the thermal model to changing food conditions were greater on a percentage basis.

Different responses to spawning was noted for each area. In the control area, any change (increase or decrease) in spawning temperature stimulated reef stocks. In the discharge bay, raising spawning temperature increased biomass and set; decreasing temperature of spawning reduced biomass, but increased set.

LITERATURE CITED

Carriker, M.R. 1951. Ecological observations of the distribution of oyster larvae in New Jersey estuaries. Ecol Mono. vol. 21 no. 1, p. 19-38

Collier, A. 1959. Some observations on the respiration of the American oyster *Crassostrea virginica* (Gmelin). Pub. Inst. Mar Sci. Univ. Tex. Vol. 6, p. 92-108

Copeland, B.J. and H.D. Hoese. 1966. Growth and mortality of the American Oyster, *Crassostrea virginica*, in high salinity shallow bays in central Texas. Pub. Inst. of Mar. Sci. Vol II, p. 149-158

Copeland, B.J. and W.R. Duffer. 1964. The use of a clear plastic dome to measure gaseous diffusion rates in natural waters. Limnol. Oceanogr. 9:494-499

Day, J.W., 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. Pub. Center Wetland Resources, Louisiana State Univ., Pub. no. LSU-SG-72-04

Grimes, C.B. 1971. Thermal addtion studies of the Crystal River steam electric station. Fla. Dept. Nat. Res. St. Petersburg, Fla. Prof. Paper Series No. 11

Haven, D.S. and R. Morales-Alamo 1966. Aspects of biodeposition by oysters and other invertebrate filter feeders. Limnol. Odeanogr. 11(4): p. 487-498

Hall, Charles A.S. 1971. Migration and metabolism in a stream ecosystem. Ph.D. dissertation. Dept. of Zoology. Univ. of North Carolina, Chapel Hill

Ingle, R.M. and C.E. Dawson. 1952. Growth of the American oyster, Crassostrea virginica (Gmelin) in Florida waters. Bull. Mar. Sci. Gulf & Carib. 2(2): 393-404.

Krey, J. 1961. Der Detritur in Meere. J. Cons. Int. Explor. Mer., 26: 263-280

Lugo, A.E. 1969. Energy, water and carbon budgets of a granite outcrop community. 1969. Ph.D. Dissertation, Dept. of Botany, Univ. North Carolina, Chapel Hill

Margalef, R. 1959. Information theory in ecology. Gen. Syst. 3:36-71

Maturo, F.J., J.W. Caldwell, W. Ingram. 1973-74. Studies of zooplankton populations in thermally affected and control waters near the Crystal River power plants. 1973-74

McKellar, H.N. 1974. Metabolism and models of outer bay ecosystems affected by a coastal power plant. Ph.D. dissertation. Dept. Environ. Eng. Sci. Univ. Florida, Gainesville

Menhinick, E.F. 1964. A comparison of some species diversity indices applied to samples of field insects. Ecology. 45: 859-861

Nixon, S.W. and C.A. Oviatt, C. Rodgers, and K. Taylor 1971. Mass and metabolism of a mussel bed. Oecologia (Berl) 8, p. 21-30

Odum, E.P. 1971. Fundamentals of Ecology. W.B. Saunders Co. Philadelphia, 3rd Edition

Odum, H.T. 1956. Primary production in flowing waters. Limnol. and Oceanogr. 1:102-117

Odum, H.T. 1957. Trophic structure and productivity of Silver Springs, Florida Ecol. Monogr. 27:55-112

Odum H.T. and R.F. Pigeon, Eds. 1970. A tropical rain forest. Technical Information Dept. (TID) - 24270 (PRNC-138)

Odum, H.T., J. Cantlon, and L.S. Kornicker. 1960. An organizational hierarchy postulate for the interpretation of species-individual distributions, species entrophy, ecosystem evolution, and the meaning of a species variety index. Ecol. 41: 395-399

Odum, H.T., H.N. McKellar, W.B. Smith, M. Lehman, D. Young, M. Kemp, M. Homer, and T. Gayle 1974. Simulation of models of estuarine ecosystems at Crystal River. Dept. Environ. Eng. Sci., Univ. Florida, Gainesville

Pielou, E.C. 1966. The measurement of diversity in different types of biological collections. J. Theoret. Biol., 13:131-144

Raymont, J.E.G. 1963. Plankton and Productivity in the Oceans. Permagan Press, New York

Shannon, C.E. and W. Weaver. 1963. The mathematical theory of communication. Univ. of Illinois Press, Urbana. 117 pp.

Simpson, E.H. 1949. Measurement of diversity. Nature, 163:688

Young, D.L. 1974a. Salt marsh and the effect of thermal plumes. Ph.D. dissertation (in progress), Dept. Environ. Eng. Sci. Univ. Florida Gainesville

Young, D.L. 1974b. Studies of Florida Gulf coast salt marshes receiving thermal discharge. <u>In</u> Thermal Ecology., J. W. Gibbons and R.R. Sharitz, eds. U.S. Atomic Energy Commission, CONF-730505

4D. ECOSYSTEMS OF THE INTAKE AND DISCHARGE CANALS

W. M. Kemp

Department of Environmental Engineering Sciences
University of Florida
Gainesville, Florida 32611

INTRODUCTION

Connecting the Crystal River steam electric generating system with the adjacent estuarine waters are the intake and discharge canals. The intake canal which was built for the dual purpose of channeling both cooler offshore water and fuel barges to the power plant, extends some 13 kilometers west of the plant. The canal is laterally confined with double-heading for the first five km. The mean depth of the intake canal waters is about 6.5 meters compared to the 1-2 meter depths in surrounding bays, and the width at mean low water (MLW) varies from 90-110 meters. The double-bulkheaded portion of the discharge canal extends less than 2 km, and the total length of dredged channel is about 4 km. The discharge canal was designed with a smaller cross-sectional area (4.5 m deep, 60 m wide) so as to maintain a higher velocity and assure adequate lateral flow entrainment upon discharge to the shallow bay receiving waters.

Fig. 1 shows the location of sampling areas for this study. Notice that all stations are within the double bulkheaded portion of the canals. The community metabolism stations were selected so as to allow 1-4 hour flow times between stations. Stations 1, 4 and 7 were used only in the

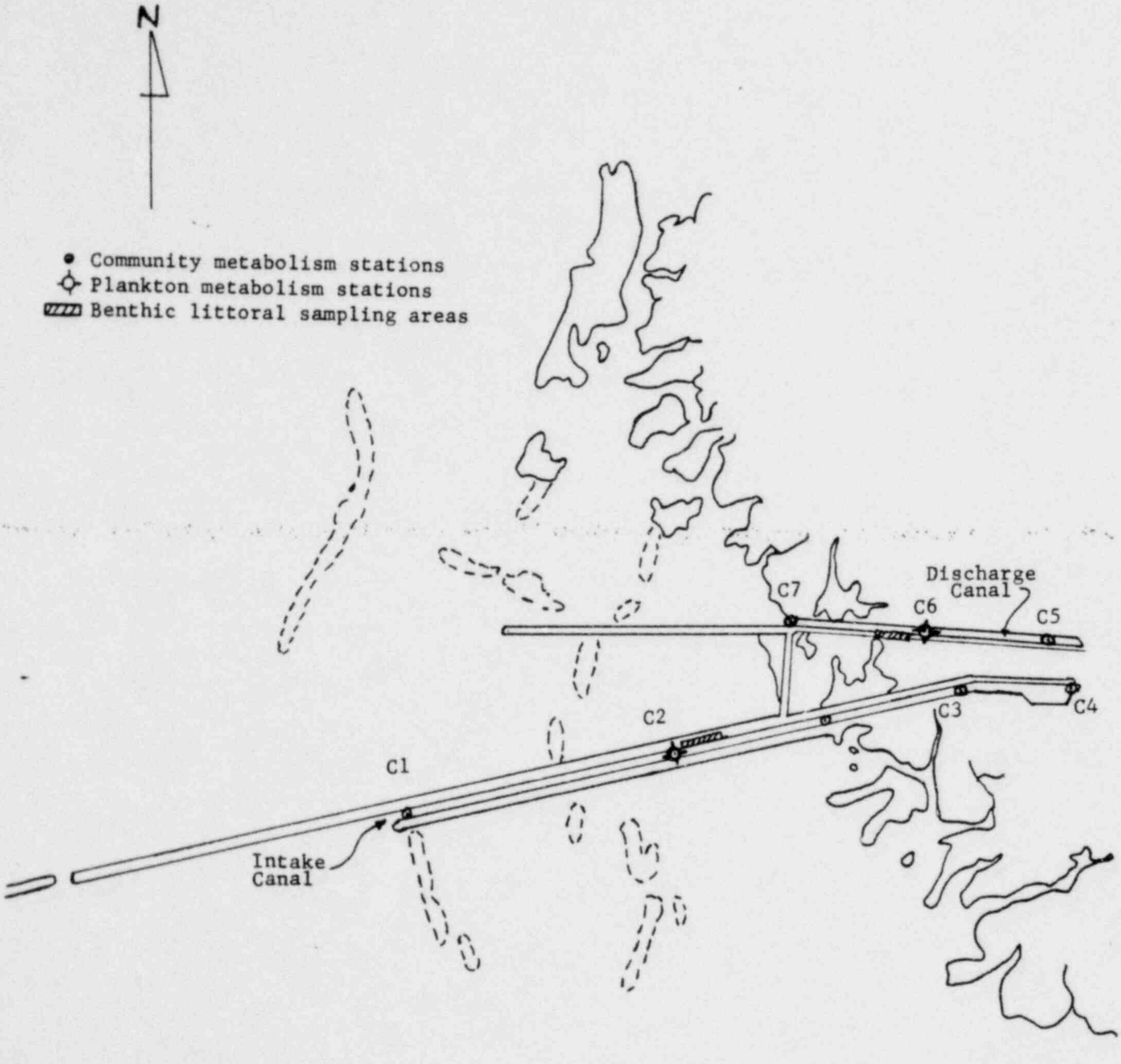


Fig. 1. Location of Sampling Stations for Intake and Discharge Canal Ecosystems

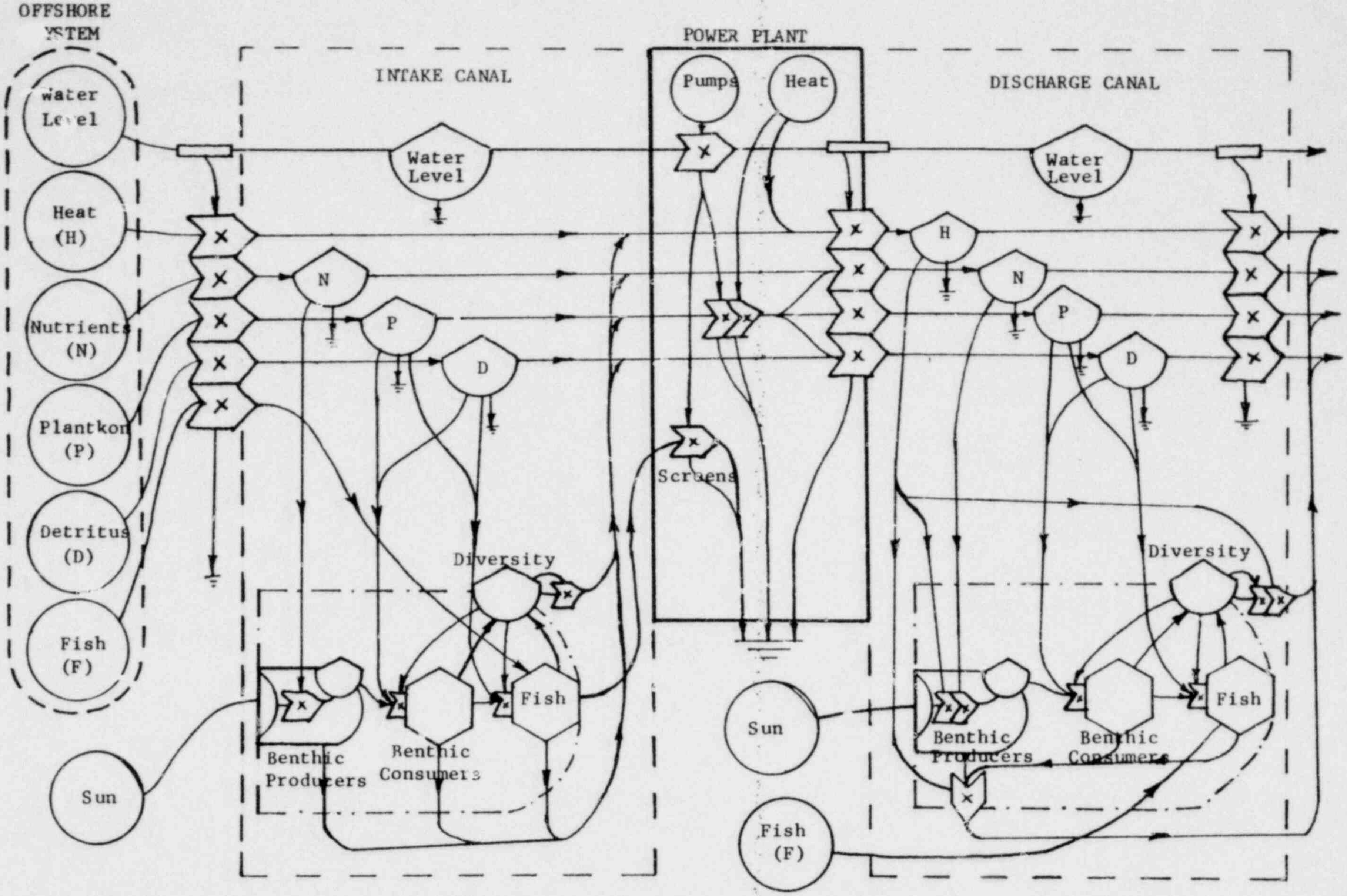
early stages of this study. The plankton metabolism sampling and incubation stations were selected for convenience and central location in canals. The intertidal benthic sampling quadrats were established in relatively uniform areas which appear to be representative and typical for the entire canal intertidal areas.

In an analogous sense the canals are like the incurrent and excurrent siphons of a giant filter-feeding oyster or clam (the power plant). They are dominated by the large flows of water pumped by the power plant, by the steady stream of barges that move in and out, by the large ratio of intertidal area to cross-section, and by the discharge of heat and chlorine. Large consumer animals add additional connections to offshore and adjacent coastal systems by apparently continual migration flows. Fig. 2 provides a diagrammatic representation of the major energy flows in the intake and discharge canal systems. Because of their proximity to the power plant and since they are strongly influenced by plant activities, the intake and discharge canals offer a reasonable point at which to monitor the effects of power plant operation on the estuary.

METHODS

The magnitude of metabolic work in the canals was studied by measuring the primary production and respiration of the total community and of the plankton component. Community metabolism was measured using a modified version of the two-station diurnal oxygen method developed by Sargent and Austin (1949), Odum and Odum (1955), Odum (1956) and Owens and Edwards (1965). This technique considers the changes in oxygen content of water as it flows

Fig. 2. Energy Diagram for Intake and Discharge Canal Ecosystems Dominated by Power Plant Circulating Water Flows



from an upstream station to a downstream station during a consecutive 24 hour period. The method used in this study provides corrections for tide-induced changes in depth, diffusion, flow time between stations, and vertical stratification, and has general applicability for river portions of any estuary. Dissolved oxygen concentrations were measured using the azide modification of the Winkler method. Duplicate or triplicate samples were taken at each time and station. Diffusion was measured by the dome method of Copeland and Duffer (1964). Plankton metabolism was measured using the light and dark oxygen bottle method. Two to four replicate light and dark bottles were incubated at 0.3 m , 3.0 m and occasionally 1.5 m at each station for 24 hours. In order to estimate the depth extent of light transmission, water transparency was measured routinely with secchi disk, and on one occassion with submarine photometer.

The littoral benthic animal community structure was studied by measuring the numbers and biomass of component organisms and the species diversity of the overall community. Relatively homogeneous sampling areas were established for both canal ecosystems, and were marked off with stakes at 5 m intervals for 40-50 m along the MLW mark. To insure randomness of sampling each of the 5 quadrats (m^2) between stakes was assigned a number, and the quadrat to be sampled on a given date was determined by a random number generator. Within the square meter quadrat a 0.25 m^2 frame was placed so as to obtain a representative sample of that quadrat. All organisms, rocks and soil were collected in buckets to a depth of about 15 cm below the soil surface (or to the zone of black anaerobic sediment), and returned to the laboratory for sorting. Numbers of all dominant animals were recorded and organisms were blotted, weighed and then dried at 90°F to constant weight. Blotted wet and dry weights were recorded along with the total number of macroscopic animal species encountered.

RESULTS AND DISCUSSION

Statistical tests have yet to be performed on summer field data; however general discussion is provided. Table 1 provides the results of community metabolism measurements for the summer of 1972. The mean value for total gross primary production is 35% greater for the intake canal than for the discharge canal ecosystem. This may be attributable to the greater depth of euphotic zone (mean secchi disc: intake - 2m, discharge - 1.6m) or to inhibitism of primary production with thermal and chlorine discharge. P/R ratios are slightly higher (17%) for intake canal during the summer; however they are 3 times greater than for the discharge canal during the period from August 18 to September 2. Fig. 3 shows the trends over the three month period. Discharge canal production is rather constant throughout the summer, whereas intake canal production peaks in early July and again in early September.

Table 2 lists the levels of plankton metabolism measured between August 1973 and September 1974. Gross plankton productivity is about 2.5 times greater in the intake canal than the discharge. Plankton production accounts for about 36% of the total production for the intake canal ecosystem but only 21% for the discharge canal. The time graph of plankton metabolism given in Fig. 4 tends to indicate a later summer bloom phenomenon. On one occasion in early September, plankton production accounted for 95% of the total production in the intake canal.

The detailed results of the littoral benthic sampling are provided in Table 3. The swifter flowing discharge canal waters have developed a littoral community dominated by oysters, barnacles and crabs. Its total

Table 1. Community Metabolism for Crystal River Power Plant Intake and Discharge Canals, Measured by Two Station Diurnals

Date 1974	Location	Station Pairs	Day Net Production P	Night Respiration R	P/R Ratio	Gross Production P + R
June 26-27	Intake Canal	3-2*	0.2	6.8	.03	7.0
		3-4*	1.4	4.6	.30	6.0
	Discharge Canal	5-6*	0.1	10.7	.01	10.8
		6-7*	0	15.3	0	15.3
July 1- 2	Intake Canal	2-3*	7.7	14.5	0.53	22.2
	Discharge Canal	5-6*	2.9	5.3	0.55	9.2
July 10-11	Intake Canal	2-3	4.7	5.6	0.84	10.3
		2-3*	4.0	5.9	0.68	9.9
	Discharge Canal	5-6	4.2	5.1	0.82	9.3
		5-6*	2.6	8.5	0.31	11.1
July 17-18	Intake Canal	2-3	3.3	5.5	0.60	8.8
		2-3*	3.6	6.2	0.58	9.8
	Discharge Canal	5-6	3.4	7.8	0.44	11.2
		5-6*	4.7	6.8	0.69	11.5
Aug 12-13	Intake Canal	2-2A	3.0	7.4	0.41	10.4
		2A-3	1.6	10.3	0.16	11.9
	Discharge Canal	5-6	1.7	4.8	0.34	6.5
Aug 18-19	Intake Canal	2-2A	6.7	9.2	0.73	15.9
		2A-3	4.7	8.0	0.59	12.7
	Discharge Canal	5.6	3.0	8.4	0.12	11.4
Aug 25-26	Intake Canal	2-2A	6.6	4.7	1.40	11.3
		2A-3	7.3	6.2	1.18	13.5
	Discharge Canal	5-6	3.8	7.2	0.53	11.0
Sept 1-2	Intake Canal	2-2A	7.7	8.7	0.89	16.4
		2A-3	6.5	11.3	0.58	17.8
	Discharge Canal	5-6	2.5	8.5	0.29	11.0
Sept 10-11	Intake Canal	2-2A-3	6.8	8.4	0.81	15.2
	Discharge Canal	5-6	517	2.9	1.97	8.6
Mean	Intake	---	5.1	8.0	0.65	13.2
	Discharge	---	3.0	6.7	0.45	9.8

* sampled by wading in shallow (1m) water. Others sampled in middle of canal by boat.

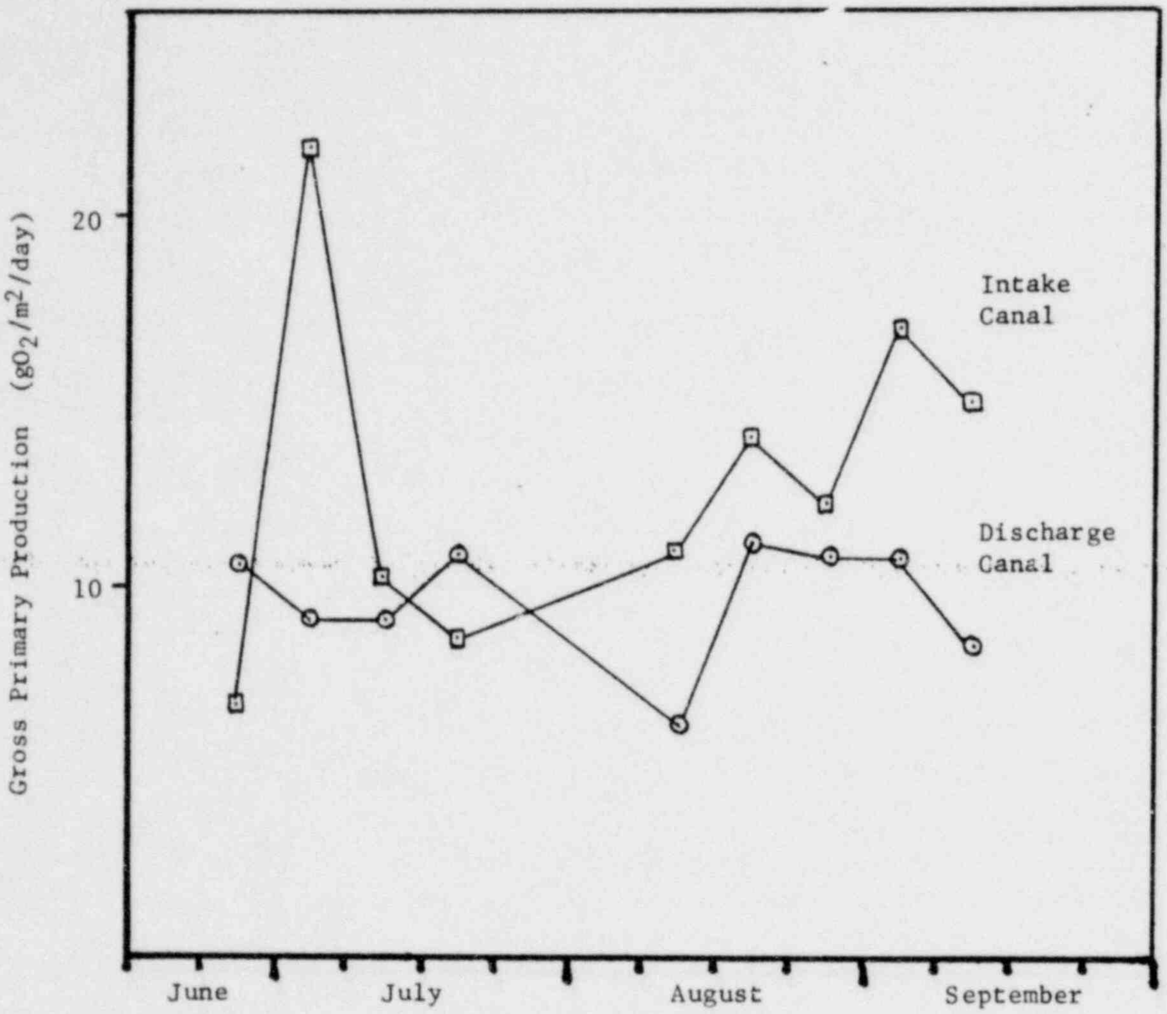


Fig. 3. Gross Primary Production for Crystal River Power Plant Intake and Discharge Canals during Summer 1974

Table 2. Plankton Metabolism as Measured by Light and Dark Oxygen Bottles in Intake and Discharge Canals.

Date of Sample	Intake (I) or Discharge (D)	Change in surface light bottles (gO_2/m^3/day)	Change in surface dark bottles (gO_2/m^3/day)	GPP Gross primary production (g$O_2$$m^2$/day)	T R Total plankton respiration (g$O_2$$m^2$/day)	Ratio GPP/TR
June 26-27	I	+0.12	-0.62	1.76	3.52	0.50
1974	D	-0.04	-0.82	1.35	3.04	0.45
July 1-2	I	+0.57	-0.88	4.48	5.09	0.88
1974	D	+0.16	-0.72	1.98	2.94	0.67
July 10-11	I	+0.47	-0.45	2.79	2.99	0.93
1974	D	+0.69	-0.37	2.76	1.44	1.92
July 17-18	I	_0.25	-0.41	2.12	3.07	0.69
1974	D	-0.31	-0.56	0.50	2.52	0.20
Aug 12-13	I	+0.44	-0.58	2.68	4.09	0.65
1974	D	-1.17	-1.22	0.17	5.67	0.03
Aug 18-19	I	+0.13	-0.69	2.80	4.76	0.59
1974	D	-0.40	-0.77	1.11	3.59	0.31
Aug 24-25	I	+0.36	-0.89	3.96	5.85	0.68
1974	D	-0.31	-0.80	1.32	3.60	0.36
Sept 1-2	I	+4.75	-1.41	16.89	9.17	1.84
1974	D	=1.46	-1.55	0.44	6.20	0.07
Sept 10-11	I	+2.32	-0.90	7.28	5.85	1.25
1974	D	+3.98	-1.11	9.54	5.00	1.91
Aug 23-24 1973	D	-0.50	=1.05	1.08	4.63	0.23
Aug 28-29	I	+0.79	-0.65	3.98	3.62	1.10
1973	D	-0.20	-0.62	0.87	2.79	0.31
Nov 16-17	I	+0.92	-0.11	3.10	1.36	2.28
1973	D	+1.09	-0.41	3.28	0.84	3.91
Jan 11-12 1974	I*	-0.28	-0.41	0.52	3.66	0.14
Mean	I			4.71	4.49	1.05
	D			2.09	3.52	0.59

* Sampled and incubated in intake canal turn-around basin.

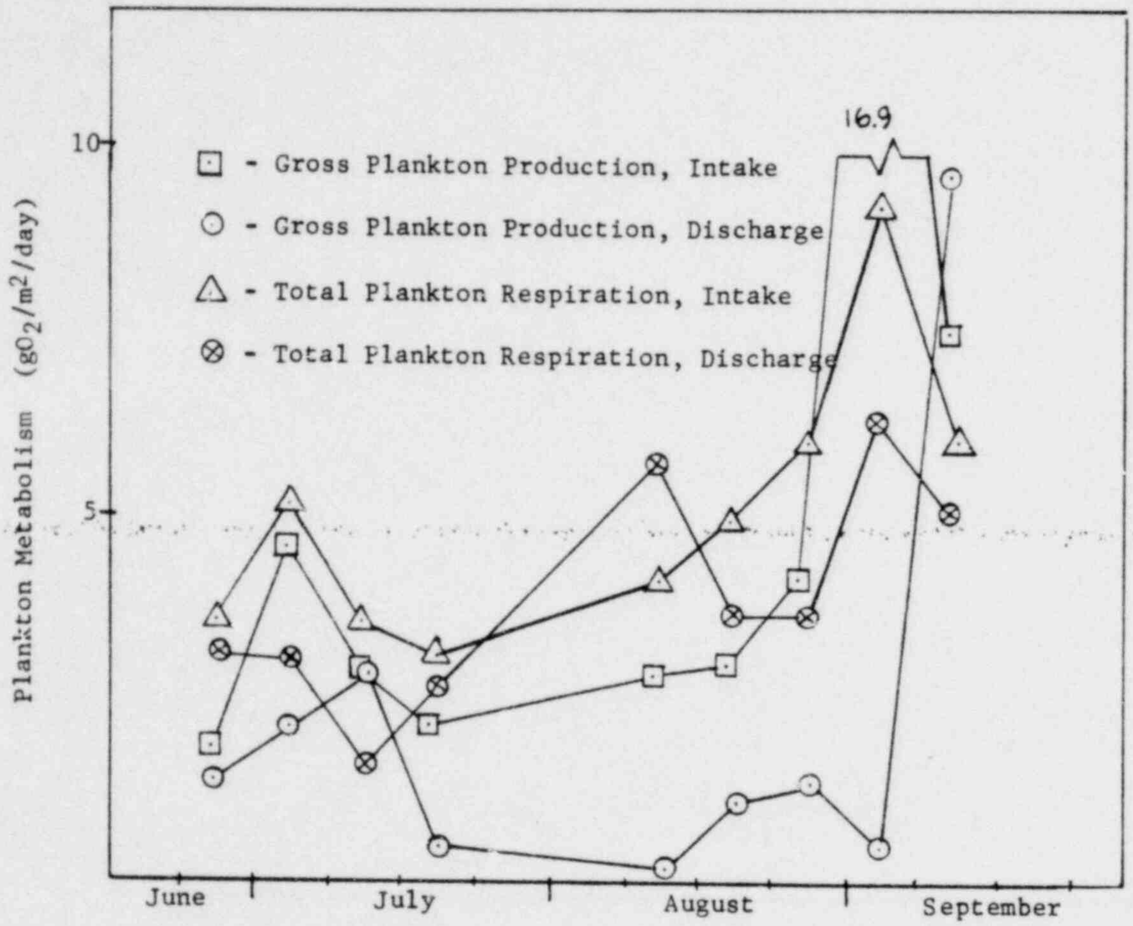


Fig. 4. Plankton Metabolism for Crystal River Power Plant Intake and Discharge Canals during Summer 1974

Table 3. Numbers, Biomass and Species Diversity for Benthic Animals Inhabiting the Intertidal Zone of Intake and Discharge Canal Ecosystems. (gm organic matter/0.25 m^2)

Date of Sample	Intake (I) or Discharge (D)	Oysters			Mud & Stone Crabs		Porcelain Crabs		Barnacles		Mussels		Surpulidae	Total Biomass	Diversity SPP/ 0.25m^2
		Adults		Spat											
		No.	Wt.	No.	No.	Wt.^{a}	No.	Wt.^{a}	No.	Wt.^{b}	No.	Wt.^{b}	No.		
1974 June 30	I	0	0	11	10	0.1	23	0.2	44	1.3	35	.6	16	2.1	21
	D	12	2.4	0	106^c	1.3^c	--	--	13	0.3	0	0	40	4.0	12
July 17	D	40	6.3	0	149	3.7	28	0.3	48	0.7	4	0.04	100	11.0	13
	D	29	4.9	0	126	3.2	30	0.2	71	0.6	3	0.08	130	9.0	13
July 30	I	34	1.6	114	7	0.5	113	0.8	21	0.2	51	0.24	60	3.3	19
	I	21	0.7	138	18	2.0	324	2.0	15	0.1	27	0.12	80	4.9	15
Aug. 13	I	17	2.2	381	17	1.4	211	2.3	20	0.9	45	0.7	105	7.5	15
	I	9	1.1	622	24	5.7	191	2.6	23	0.7	17	0.08	225	10.2	17
"	D	8	0.3	0	195	5.7^c	3	0	133	3.6	6	0	135	9.6	13
	D	43	2.9	4	189	3.4^c	1	0	25	0.6	2	0	120	6.9	12
1973 Sept. 13	D	50	3.0	0	79^c	1.5^c	---	---	167	9.5	0	0	---	14.0	12
Sept. 14	I	55	6.5	174	---	---	402^c	7.1^c	0	0	128	0.5	200	14.1	18
Sept. 15	D	53	(6.5)	0	134^c	7.5^c	---	---	220	15.1	0	0	---	29.1	11
Sept. 17	D	71	2.1	---	168	1.8	0	0	272	12.8	0	0	190	16.7	12
Mean value for summer	I	22.5	2.1	311	14	2.0	253	2.9	16	0.6	51	0.35	128	7.5	17.8
	D	33.0	3.2	1	147	3.9	9	0.1	122	5.6	2	0.05	117	12.8	12.2

a Assumes that mass of organic matter = (.3) mass whole animal.

b Assumes that mass of organic matter = (.2) mass whole animal.

c Includes both porcelain and mud crabs and listed under species which is dominated by > 95%.

animal biomass is about 70% greater than for the intake canal system. The intake canal intertidal animal community is dominated by the small porcelain crab, Petrolisthes sp. with mud and stone crabs contributing substantially to the overall biomass. Oysters are also important in the intake; however, whereas virtually no spat were found in the discharge, great numbers were recorded in the intake (mean, 311). It appears that in the discharge canal, due either to entrainment mortality or shock, very few spat will set. However, for those that do set, the survival rate to adulthood is relatively large. The intake canal benthic intertidal animal community is 46% more diverse than the discharge canal. This may be attributable to thermal stress or other factors.

Simulation of Intake Canal Model

Evidence provided by various project investigators indicates that within the confines of the Crystal River Power plant intake canal there has developed a highly metabolic ecosystem. This system is continuously seeded - alternately by offshore water during flood tides and nearshore water on the tidal ebb. Large consumer animals (fish, crabs, etc.) act to connect this system with external marine ecosystems by migrating in and out of the canal. Becuase of the constant water movement through the canal, the relatively deep water (5-6M) and the steep rocky shores, this canal ecosystem exhibits many characteristics similar to an offshore reef system.

Fig. 5. which was given in a previous report, illustrates some major characteristics of this ecosystem, with emphasis on the consumer components. The fish populations are divided into two categories migratory and resident, according to their life-histories. Under steady-state conditions there is

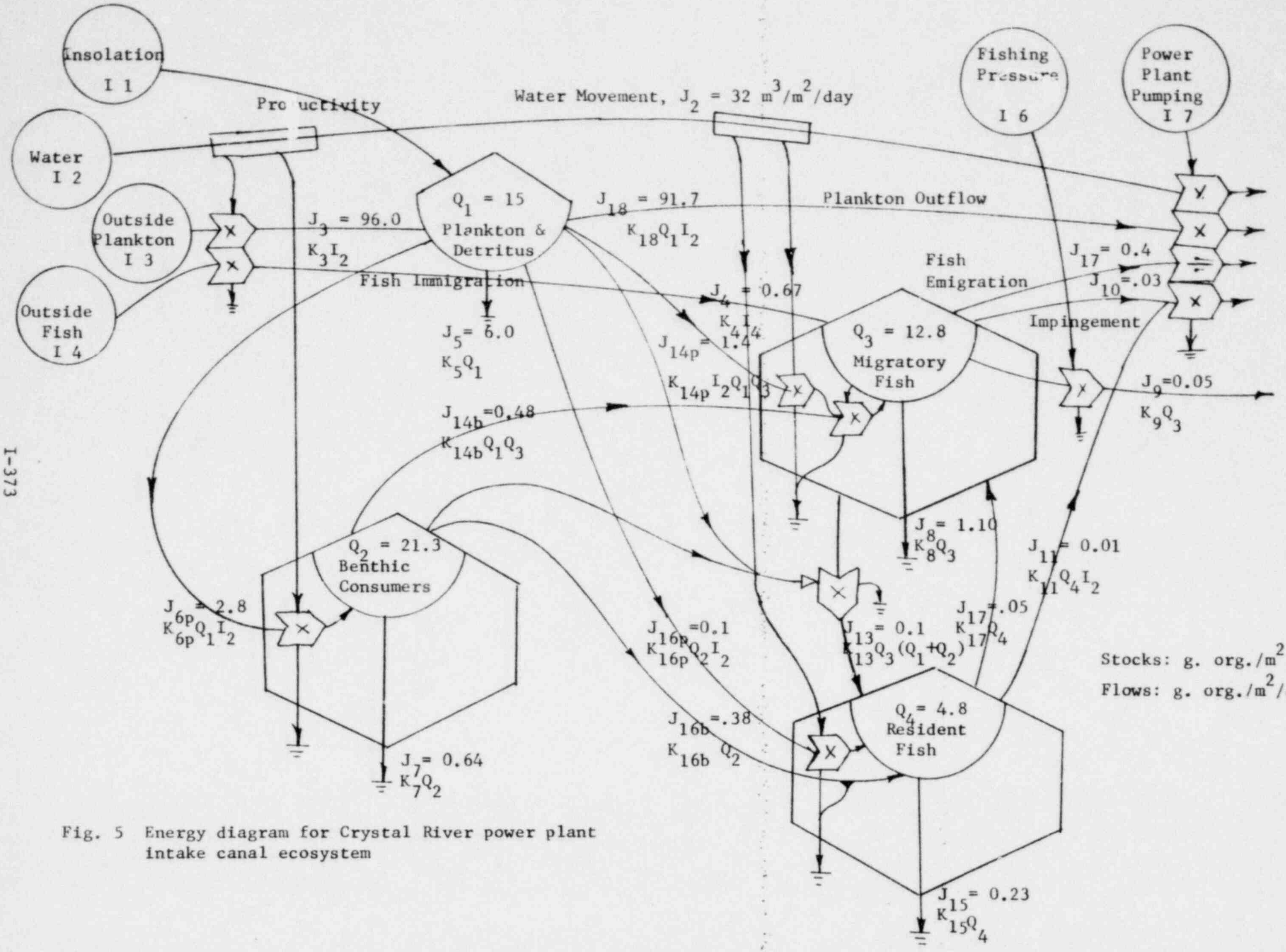


Fig. 5 Energy diagram for Crystal River power plant intake canal ecosystem

a balance between fish migration, in situ growth, fishing harvest, and mortality due to impingement onto the intake screens. An important question has been raised as to the nature of this balance. Specifically, are the energy losses due to screen mortality offset by growth and development of a resident canal population which is subsidized by power plant water pumping? A cursory comparison of flows J16, J14, J8, J15, J13, J17, and J11 in the diagram indicates that screen mortality is probably offset by growth in the canal. However, any conclusions should be made with caution because of the tentative nature of these numbers.

Based on the relationships expressed in this diagram and the numerical values as explained in Table 4, an analog model simulation has been run to elucidate certain system dynamic characteristics and to predict the general trends expected with any changes in forcing functions. It is also hoped that the model will provide a better understanding of the power plant's effect in subsidizing, stabilizing, and stressing the intake canal ecosystem. Corresponding to the diagram configuration a set of differential equations is used to mathematically describe the ecosystem. They are as follows:

(1) <u>Plankton and Suspended Detritus, Q1</u>

$$Q1 = k3I2 + k1\ S - k5\ Q1 - k18\ Q1\ 12 - k14p\ Q1\ Q3\ I2$$
$$- k16p\ Q1\ 12 - k6\ Q1\ 12$$

(2) <u>Benthic Animals, Q2</u>

$$Q2 = k6\ ke\ Q1\ 12 - k7\ Q2 - k14b\ Q2\ Q3 - k16b\ Q2$$

(3) <u>Migratory Fish, Q3</u>

$$Q3 = k14b\ ke\ Q2\ Q3 + k14p\ ke\ Q1\ Q3\ 12 + k4\ 12 + k17\ Q4$$
$$- k13(Q1\ Q3 + Q2\ Q3) - k8\ Q3 - k9\ Q3 - k10\ Q3\ 12 - k12\ Q3(1/12)$$

(4) <u>Resident Fish, Q4</u>

$$Q4 = k16p\ ke\ Q1\ 12 + k16b\ ke\ Q2 + k13\ ks\ (Q1\ Q3 + Q2\ Q3)$$
$$- k17\ ks\ Q4 - k11\ Q4\ 12 - k15\ Q4$$

Eight different computer simulation runs are presented in Fig. 6 . The first run employs pathway coefficients as calculated based on data in Table 4 , and it represents the general system character under average present conditions. It is seen that system requires about four months to reach a steady-state after being initially set at some other levels. The resident fish population which is initially at zero goes through an early peak after one month, while the benthic consumers first dip to a minimum at two months. The migratory fish follow a trend parallel to the resident population with out the initial peak. The concentration of plankton and suspended detritus exhibits a strikingly stable character, as it dives immediately to its steady-state value.

In the second computer run the input plankton concentration is increased two-fold from the initial (run #1) settings, and while the steady-state concentration increases proportionately, its steadfast stability is maintained. This simulation represents the response of the system to changes in source water as with tidal fluctuations. Under these conditions both fish populations increase markedly, with the predominantly planktivorous resident fish being most affected (x7). In a somewhat counterintuitive manner the benthic consumer populations which feed on the benthics are affected to an even greater extent. The system takes a week or two to achieve steady-state, and it is unlikely that either the high or low steady-level would ever be reached within the six hour interval between tidal extremes.

The stability of this plankton component is apparently attributable to the strong influence that water advective transport imparts to the system. In the third model run, the consumption rate of benthic animals (which feed exclusively on plankton and suspended detritus) is doubled, and while the benthic biomass also doubles, the level of plankton mass is virtually unaffected. Thus, the plankton and suspended detrital biomass is controlled principally by outside concentrations and not internal flows. The rate of water flow into the canal does not, however, affect the plankton level, as is seen in fifth and sixth simulation results.

The sensitivity of the model to increased fish immigration rates is investigated in the fourth computer run. A five-fold increase in immigration leads to an even greater rise in fish stocks, with the resident and migratory populations expanding by factors of 7 and 18, respectively. This, however, occurs partly at the expense of benthic animals, which decline to one-fourth of their original value in run #1. This sensitivity is particularly significant in that migration rates used to evaluate the model are only rough estimates, and Dr. Snedaker's ongoing work will hopefully tighten these numbers. In a similar sensitivity analysis, shown as run #8, it is seen that fish populations are much less responsive to a major change (5x) in fishing pressure.

The effect of changes in water flow rate is presented in runs #5, 6, and 7. Both fish populations are extremely sensitive to either an increase or decrease in water flow. An 80 percent rise in water flow rate causes a full order-of-magnitude increase in fish stocks, and nearly a year is required to achieve steady-state. This run is an attempt to simulate effects of the addition of the third generating unit. It is quite probably that an 80 percent increase in water flows and velocities may cause a far greater increase in screen wash fish mortalities. This would be because a "threshold" velocity from which fish are able to escape might be exceeded for numerous species (especially juveniles). Therefore, run #7 was done assuming a five-fold increase in impingement rate as a result of the same water flow increase (80%) as in run #5. The result is that some of the growth subsidy afforded by the water flow is negated by increased fish mortality. In the sixth simulation run the water rate is decreased by 90 percent. This represents a situation where the power plant might go to a closed circulating-water-system (e.g., cooling tower), which would use only one-tenth of its total flow for make-up water. Under such conditions the fish populations are essentiially removed from the system, a residual plankton and benthic community would remain at reduced levels.

Table 4. Sources of Data for Simulation of Intake Canal Model

Source	Description	Calculation	Reference
I_1	Insolation	Avg. Insolation $\approx$ 3900 Kcal/m^2/day	Odum, 1971
I_2	Kinetic Energy of Water	K.E. $1/2\ mv^2 = 1/2(\frac{10^3 kg}{m^3})(10\ cm/sec)^2$	________
I_3	Particulate Organics	$(5gC/m^3)(2\ g\ org/gC) = 10\ g\ org/m^3$	Kemp, 1973
I_4	Fish	Assume mean offshore density = 30 g/m^2	Weatherly, 1972
I_5	Larval stocks	Avg. spat set = 50/m^2/day	Lehman, 1973
I_6	Fishing	Estimater 10 fishermen per day	Fla. Power Corp, 1972, Vol. 5
I_7	Plant Pumps	$(1420\ \frac{ft^3}{sec})(\frac{m^3}{35.6\ ft^3})(3600 \cdot 24\ \frac{set}{day}) =$ $3.4 X 10^6\ m^3$/day	Fla. Power Corp, 1972, EIS

Table 4. Continued

Flow	Description	Calculation	Reference
J_1	Plankton Productivity	$(1\ gmC/m^3/day)(3\ m$ euphotic zone) (2 g org/gm C) $J_1 = 6\ gm\ org/m^2/day$	Kemp, 1973, Mckellar, 1973
J_2	Water plow	$J_2 = 1420\ ft^3/sec = 3.5 \text{ X } 10^6\ m^3/day$ $J_2' = (3.5 \text{ X } 10^6 m^3/day)/(1.1 \text{ X } 10^5 m^2)=$ 32 m/day	Fla. Power Corp., 1972
J_3	Part. organics flow	$J_3 = (32\ m/day)X(3\ g/m^3) = 96\ g/m^2/day$	Kemp & Boynton
J_4	Fish immigration	Assume population replaced every 4 weeks J_4=18.8 g/m^2/28day = .67 g/m^2/day	Estimate by
J_5	Plankton resp.	Prod. and resp. balanced on avg: J_5= $J_1 = 6\ g/m^2/day$	Kemp, 1973, McKellar, 1973
J_6	Benthic animal assim.	Assume avg. consump. turn-over time= 20 days J_6=(21.3 g/m^2)/15 days = 1.4 g/m^2/day	Day et al., 1972
J_7	Benthic Animal resp.	By difference, see J_6, J_{14B}, J_{16B} $J_7 = (1.4 - 48 - .28)= .64;$ $\tau = \frac{21.3}{.64} = 33$ days	
J_8	Migratory fish resp.	Avg. resp. rate = 0.25 mgO_2/g fish/hr $J_8=(.25)(24\frac{hr}{da})(2\frac{org}{O_2})(10^3 g/mg)(18.8g/m^2)$ $(5\frac{g\ wet}{g\ dry}) = 1.1\ g/m^2/day$	Nicol, 1967
J_9	Fishing Harvest	$(10\ \frac{fishermen}{day})(0.5\ kg\ fish/man)/$ $(1.1 \text{ X } 10^5 m^2)= 0.05\ g/m^2/day$	Florida Power Corp. 1972 Vol. V.
J_{10}	Resident fish impinge	$J_{10} = (956\ kg)(.25\frac{dry}{wet})(1.13\frac{screen}{factor})/$ $(365\ days \text{ X } 1.1 \text{ X } 10^5 m^2)=.0075\ g/m^2/da$	Snedaker, 1973

Table 4. Continued

Storage	Description	Calculation	Reference
Q_1	Particulate organics in water	$(e\ gm\ org/m^3)\ X\ 5m = 15\ gm\ org/m^2$ of which $(6\ gm\ org/m^2/day)\ X\ 1\ day =$ $6\ gm/m^2$ is phytoplankton	Boynton, 1973 Kemp, 1973
Q_2	Benthic animals	Avg. biomass on canal bottom assumed same as avg. in bays = $8.3\ gm/m^2$ Avg. biomass on canal banks = $60\ gm/m^2$. Prorated avg. for canal $Q_2 = \frac{(\overset{3000}{50ft.\ X\ 60gm/m^2}) + (\overset{1250}{150ft.\ X\ 8.3m/m^2})}{200\ ft.} = 21.3\ \overset{dry}{gm}/m^2$	Snedaker, et al, 1973 Kemp, 1973
Q_3	MIgratory fish	Based on screen wash ratio $\frac{3500\ migratory}{900\ resident} = 3.9$ $Q_3 = 3.9\ X\ (4.8\ gm/m^2) = 18.8\ gm/m^2$	Snedaker, et al, 1973 summer
Q_4	Resident fish	Avg. biomass estimated at same as maximum biomass found in bays (based on deeper water, trapping effect) $Q_4 = (\frac{387\ gms\ wet}{16\ m^2})(0.20\ \frac{dry}{wet}) = 4.8\ \frac{gm\ dry}{m^2}$	Snedaker, et al, 1973, summer

Table 4. Continued

Flow	Description	Calculation	Reference
J_{11}	Migratory Fish Impinge	$J_{11} = (3300 \text{ kg})(.25)(1.13)/(365 \cdot 1.1 \times 10^5) = 0.026 \text{ g/m}^2\text{/day}$	Snedaker, 1973
J_{6P}	Part. consump. by benthics	$J_{6P} + 2 J_6$	Nicol, 1967
J_{12}	Emmigration	By difference, $J_{12}=(\overset{J_4}{.67}+\overset{J_{14}}{.94}+\overset{J_{17}}{.05}-\overset{J_8}{1.1}-\overset{J_{13}}{0.1}-\overset{J_9}{0.5}-\overset{J_{10}}{.01})= 1.66-1.26 = 0.40$	
J_{13}	Resident recruitment	Assume $J_{13}=2.8 \text{ g/m}^2\text{/day}$	complete exchange between pops. every 6 days
J_{17}	Migrant Recruitment	Assume $J_{17} = 0.75 \text{ g/m}^2\text{/day}$	
J_{15}	Resid. Fish resp.	Avg. resp. rate = 0.2 mgO_2/gm fresh/hr $J_{15}=(.2 \text{ mgO}_2\text{/gm/hr})(24\text{hr/day})(2\frac{\text{mg org}}{\text{mgO}_2})(\frac{1 \text{ gm}}{10^3\text{mg}})(4.8 \text{ g/m}^2)(5\frac{\text{g wet}}{\text{g dry}})$ $= 0.23 \text{ g/m}^2\text{/day}$	Nicol, 1967
J_{16}	Resident fish assim.	By difference (.29 - .10) = 0.19 $\text{g/m}^2\text{/day}$ $\tau = (4.8 \text{ g/m}^2)/(.19 \text{ g/m}^2\text{/day})$ $= 25$ days	Day et al, 1972
J_{14}	Migrant fish assim.	Assume 20 day turn-over time $J_{14}= (18.8\text{gm/m}^2)/(25 \text{ day})=0.94 \text{ g/m}^2\text{/day}$	Day et al, 1972
J_{16B}	Benthic consumption by res. fish	$J_{16B} = (.75)(0.19)(2\frac{\text{foods consumed}}{\text{foods assimilated}}) = .28 \text{ g/m}^2\text{/day}$	Adams, 1971

Table 4. Continued

Flow	Description	Calculations	Reference
J_{16P}	Part. consumption by reg. fish	$J_{16P} + (.25)(0.19)(2) = .10\ g/m^2/day$	Weatherly, 1972
J_{14B}	Benthic consumption by mig. fish	$J_{14B} + (.25)(.94)(2\frac{\text{foods consumed}}{\text{foods assimilated}}) = 0.48\ g/m^2/day$	Weatherly, 1972
J_{14P}	Part. consumption by mig. fish	$J_{14P} = (.75)(.94)(2) = 1.40\ g/m^2/day$	Weatherly, 1972
J_{18}	Particulate outflow	By difference: $J_{18} = (96 + 6 - 1.4 - .10 - 28) = 91.7\ g/m^2/day$	Weatherly, 1972

Fig. 6. Simulation Results for Intake Canal Consumer Model.

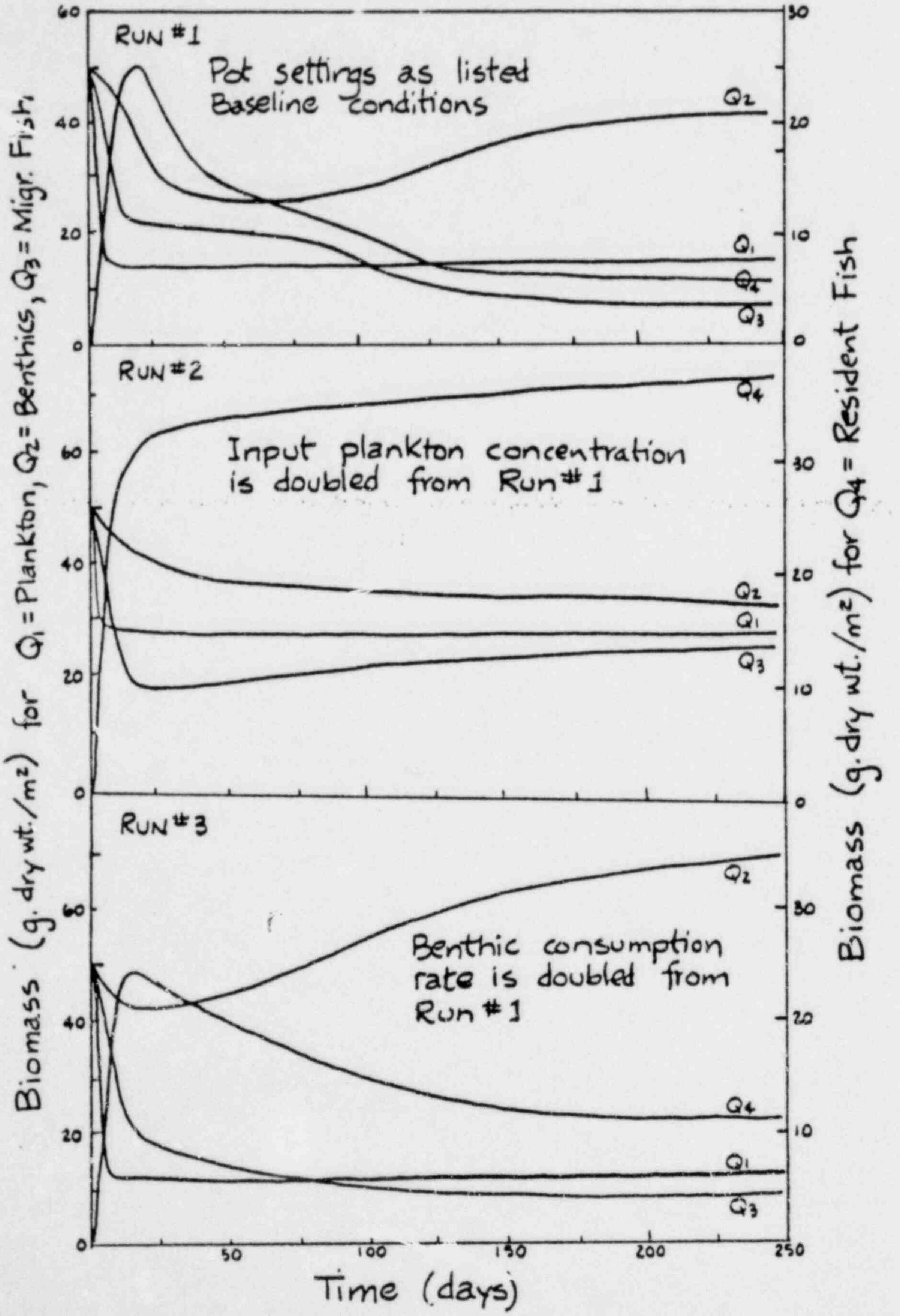


Fig. 6. continued

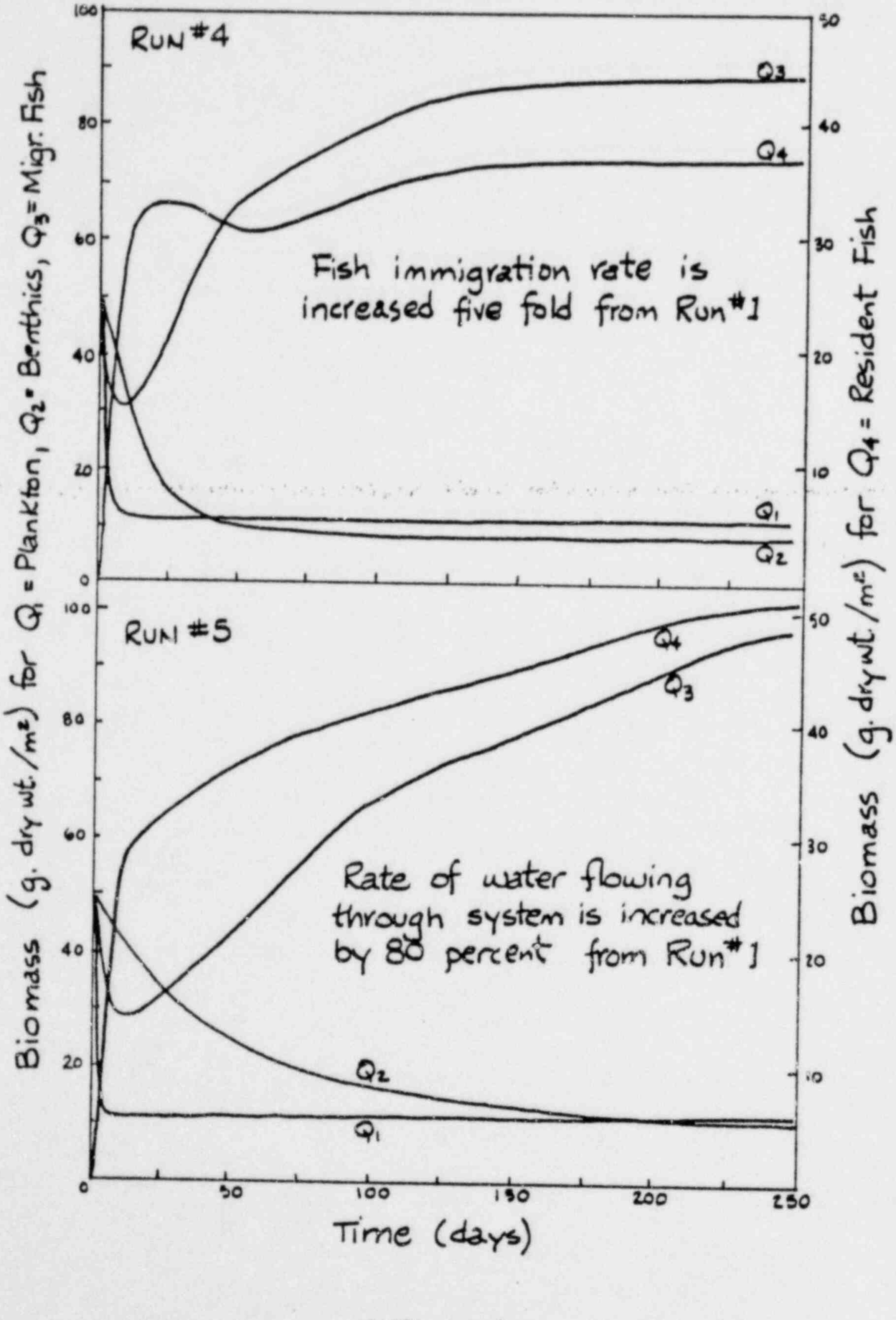
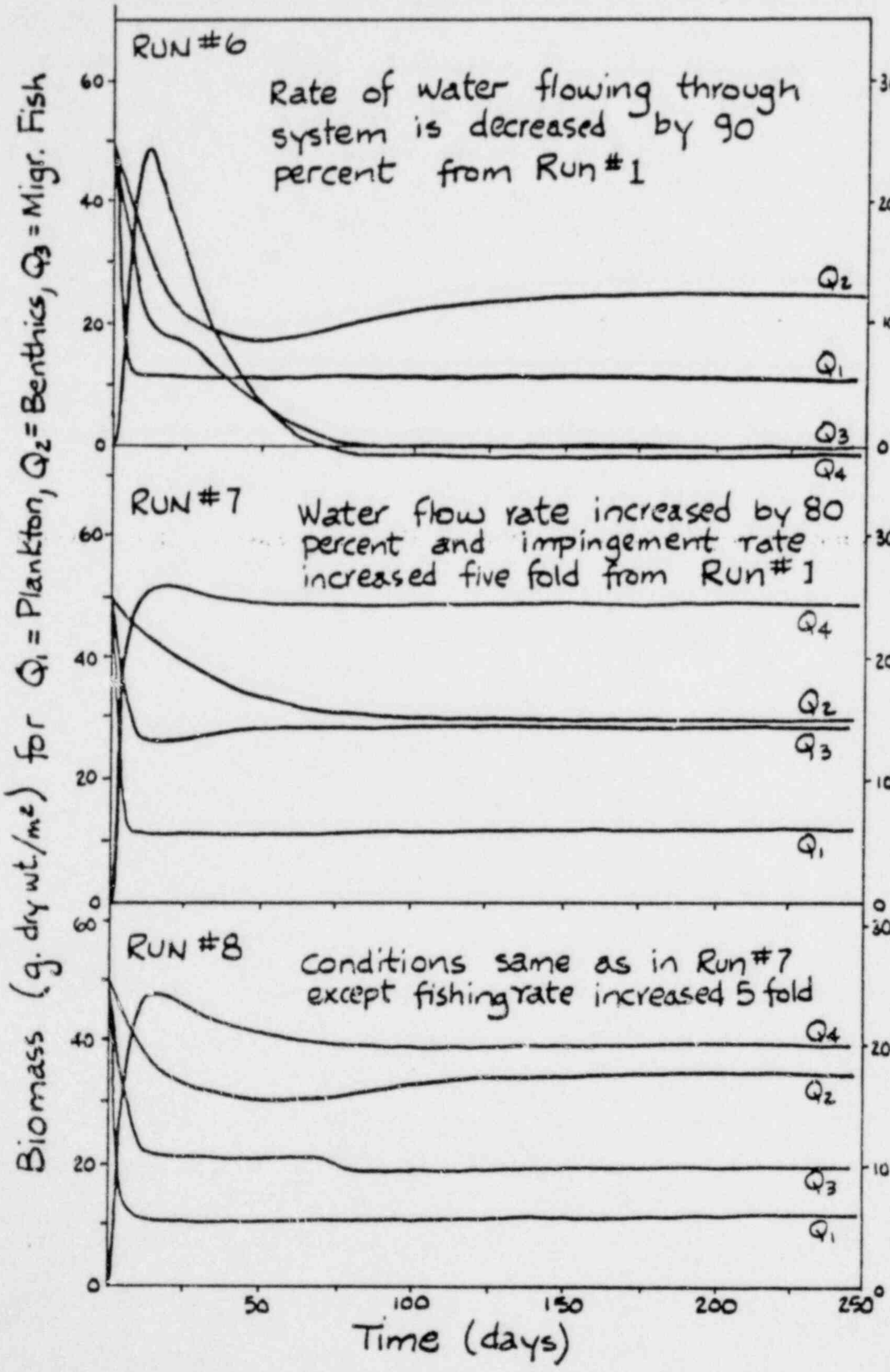


Fig. 6. continued



LITERATURE CITED

Copeland, B.J., and W.R. Duffer. 1964. The use of a clear plastic dome to measure gaseous diffusion rates in natural waters. Limnol. Oceanog. 9:494-499

Day, J.W., W.G. Smith, P.R. Ragner, and W.C. Stowe. 1973. Community structure and carbon budget of a salt marsh and shallow bay estuarine system in Louisiana. Publ. No. LSU-SG-72-04. Center for Wetland Resources. Louisiana State University. Baton Rouge, La. 70803

Edwards, R.W. and M. Owens. 1965. The oxygen balance of streams. In: G.T. Goodman, R.N. Edwards, and J.M. Lambert (eds). Ecology and the Industrial Society. J. Wiley and Sons, N.Y.

Nicol, J.A. 1967. The Biology of Marine Animals. John Wiley and Sons, Inc. N.Y.

Odum, H.T. 1956. Primary production in flowing waters. Limnol. Oceanogr. 1:102-117

Odum, N.T. 1957. Trophic structure and productivity of Silver Springs, Florida. Ecol. Mono. 27(1):55-112

Odum, H.T. and E.P. Odum. 1955. Trophic structure and productivity of a windward coral reef community on Eniwetok Atoll. Ecol. Mono 25:292-320

Sargent, M.C. and T.S. Austin. 1949. Organic productivity of an atoll. Amer. Geophys. Union Trans. 30(2):245-249

4E. CHARACTERISTICS OF TIDAL CREEKS RECEIVING THERMAL DISCHARGE

Mark Homer

Department of Zoology and
Department of Environmental Engineering Sciences
University of Florida
Gainesville, Fla. 32611

INTRODUCTION

The intertidal zone of a salt marsh serves as an important transition zone between aquatic and terrestrial ecosystems. Dominated by tidal creeks which alternately flood and drain with the tidal cycle, the creeks serve as conduits from the marsh to the estuary and vice versa. Organic materials, important to the marsh and estuarine systems, are transported through these tidal creeks. Most of this organic material is recycled into nutrients used by the various plant communities. However, some of this material is quickly upgraded by fish into protein which may then be transferred up a food chain. Tidal creeks adjacent to the discharge canal of a power plant at Crystal River, Florida, have been found to be inundated by the plant's thermal discharge (Fig. 1). The purpose of this study is to examine the characteristics and functions of tidal creeks and to quantify any differences found to be associated with the thermal plume.

The present study began in May of 1974, and this preliminary report includes data on creek fauna, temperature and metabolism measurements. The fish collection work extends earlier studies by Adams, et al (1973) and their results are included in this report with permission of the senior author.

METHODS

Temperature

In order to determine the area of salt marsh affected by the thermal plume, temperature and salinity measurements were taken in three tidal creeks adjacent to the discharge canal. (Fig. 1). In addition to this mapping, thermographic buoys have been placed in creeks near the discharge area (Fig. 1) and in a control area (Fig. 2) by workers from the University of South Florida. Temperature measurements have also been taken with each fish collection. (Fig. 3)

Macroinvertebrate Collections

Core samples, for small crabs and other invertebrates, were taken along with each fish collection beginning in August, 1974. The core was taken using a 30 cm inside diameter ($0.071m^2$) metal drum, which was pressed into the sediment at high tide to a depth of about 1/2 meter. These samples were taken halfway up the berm of the creek. At low tide, the sediment was removed from the core and frozen.

Fish and Swimming Invertebrates

The methods of fish collecting are basically the same as Adams, et al (1973). Nets were hung on stakes across the mouth of a creek at peak flood tide, and as the tide ebbed and the creek dewatered, fish, crabs and shrimp were left stranded in shallow pools or lying on the sediment. The animals were then collected by hand or dipnet and preserved in 10% formalin. Collections were made monthly in two creeks, quarterly in two others. The net used is a 20 meter long drop net with a 1.6 mm bar mesh and extra heavy lead line. 1 1/2" bar mesh gill nets were used in the deeper channels of the creeks.

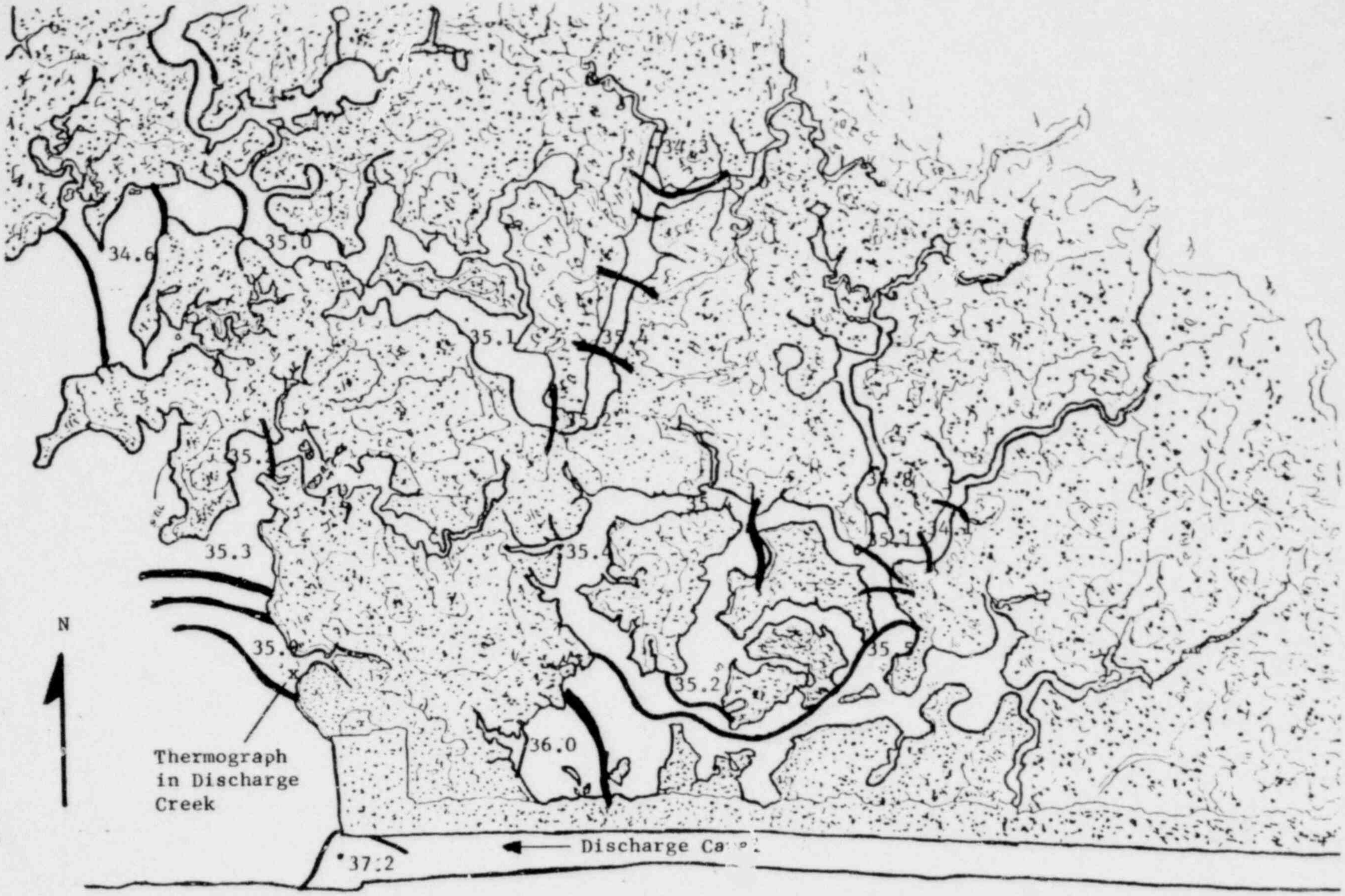


Figure 1. Temperature measurements in creeks of thermally effected marsh. Isotherm intervals = 0.2°C

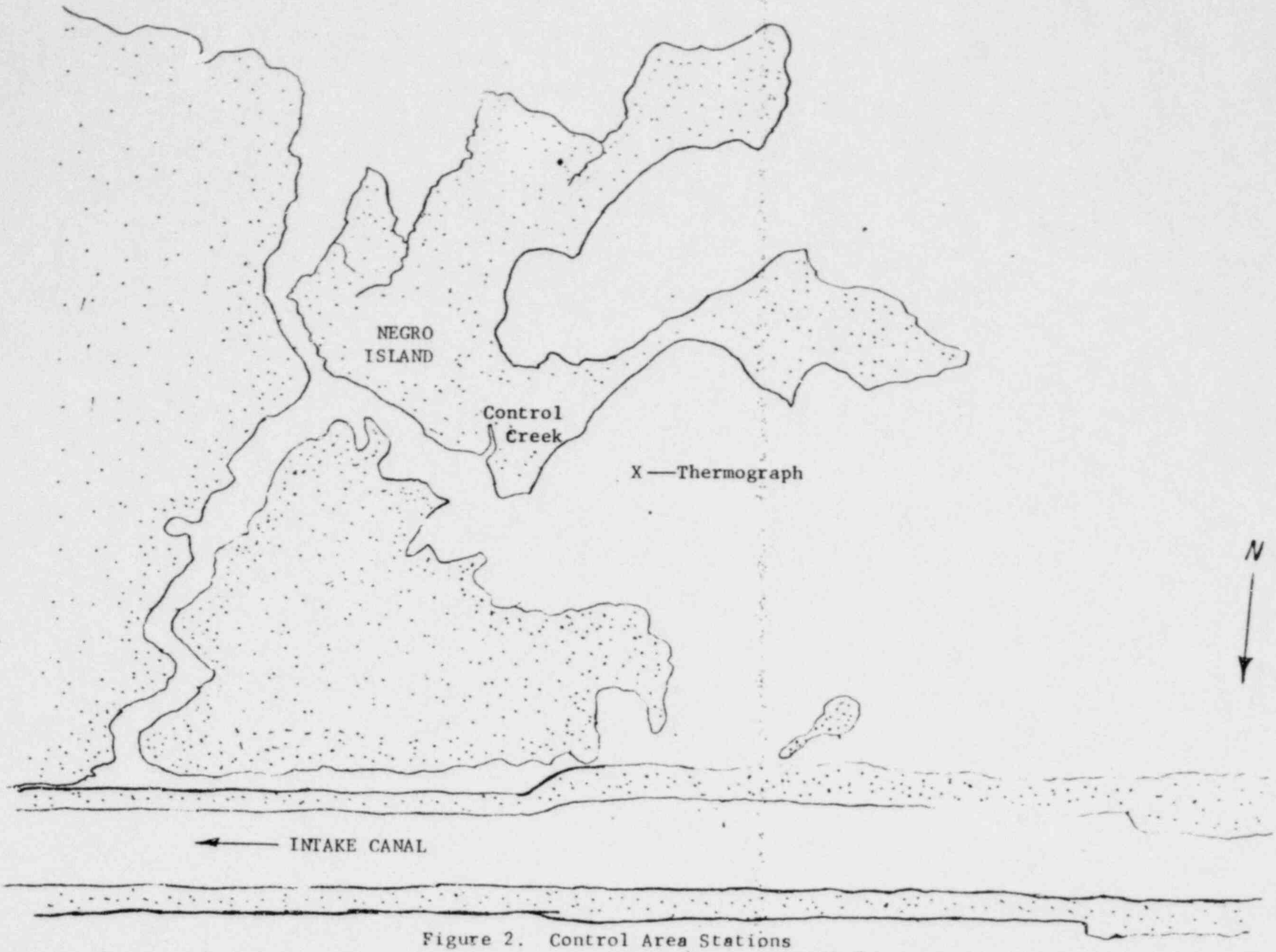


Figure 2. Control Area Stations

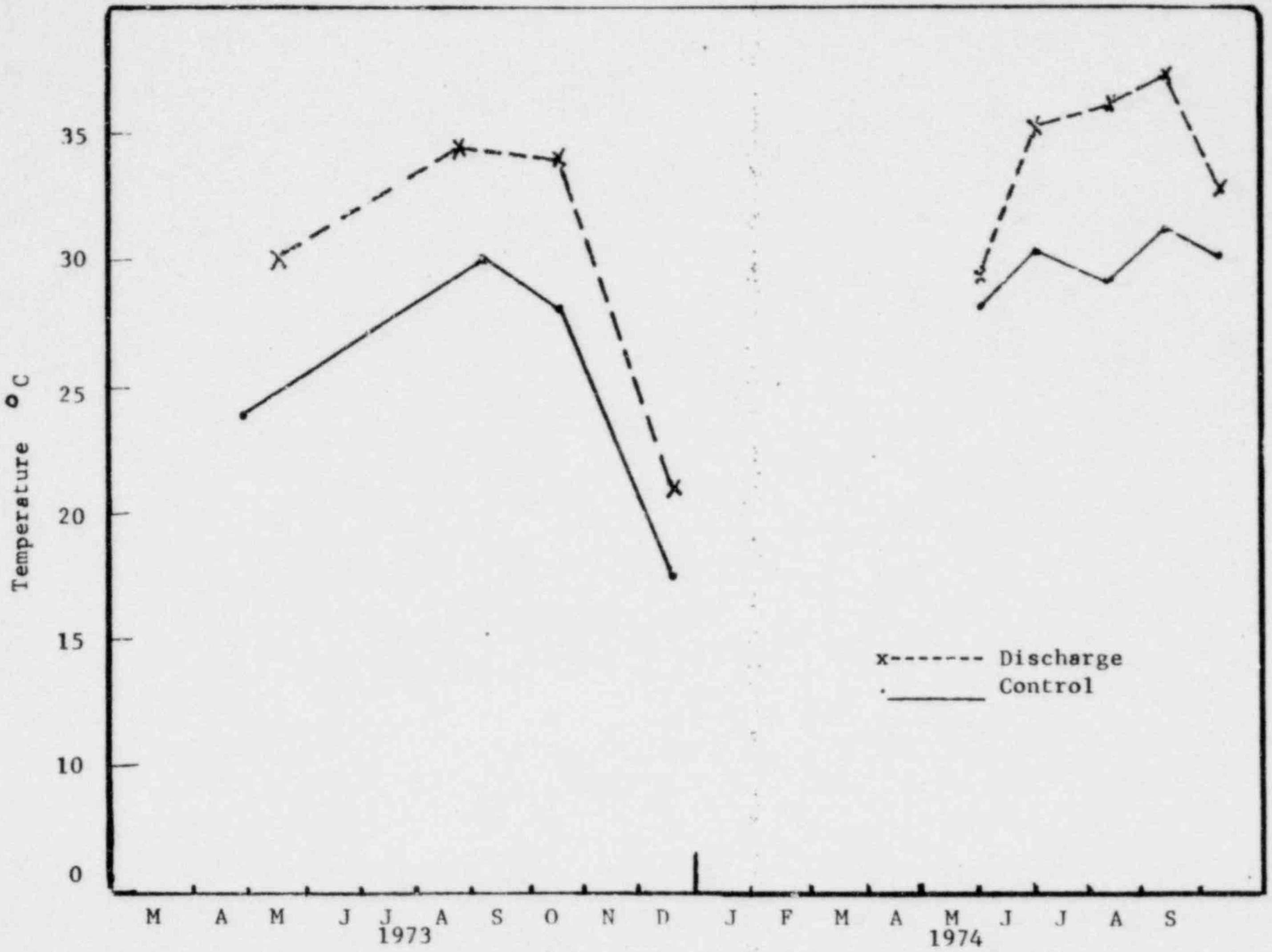


Figure 3. Creek temperature on sampling dates
1973 data from Adams, 1974.

Crab burrows were counted in each core quadrate, and these numbers will later be correlated with counts made by Young (this report) in the salt marsh.

Diversity

Diversity of fish for each sample was reported as species found in counting 1000 individuals. This was determined by plotting data points on the graph representing total species as a function of the log of total individuals. A straight line was drawn from the point representing one individual and one specie to each data point. The point at which the resultant curve or its extension crossed the 1000 individual line was used to determine species per 1000.

Growth and Production

For the purposes of calculating growth rates and tertiary creek production, length and weight measurements to the nearest mm and .1 gm respectively were made for a large percentage of the total sample. This data was then used to construct length-weight curves and length frequency histograms (Figs. 4a-e) which were used to calculate growth rates.

In this preliminary report, two methods for calculating growth and production were used. Ricker's (1973) method assumes exponential growth

$$G = \frac{\ln \bar{W}_2 - \ln \bar{W}_1}{\Delta t} \qquad (1)$$

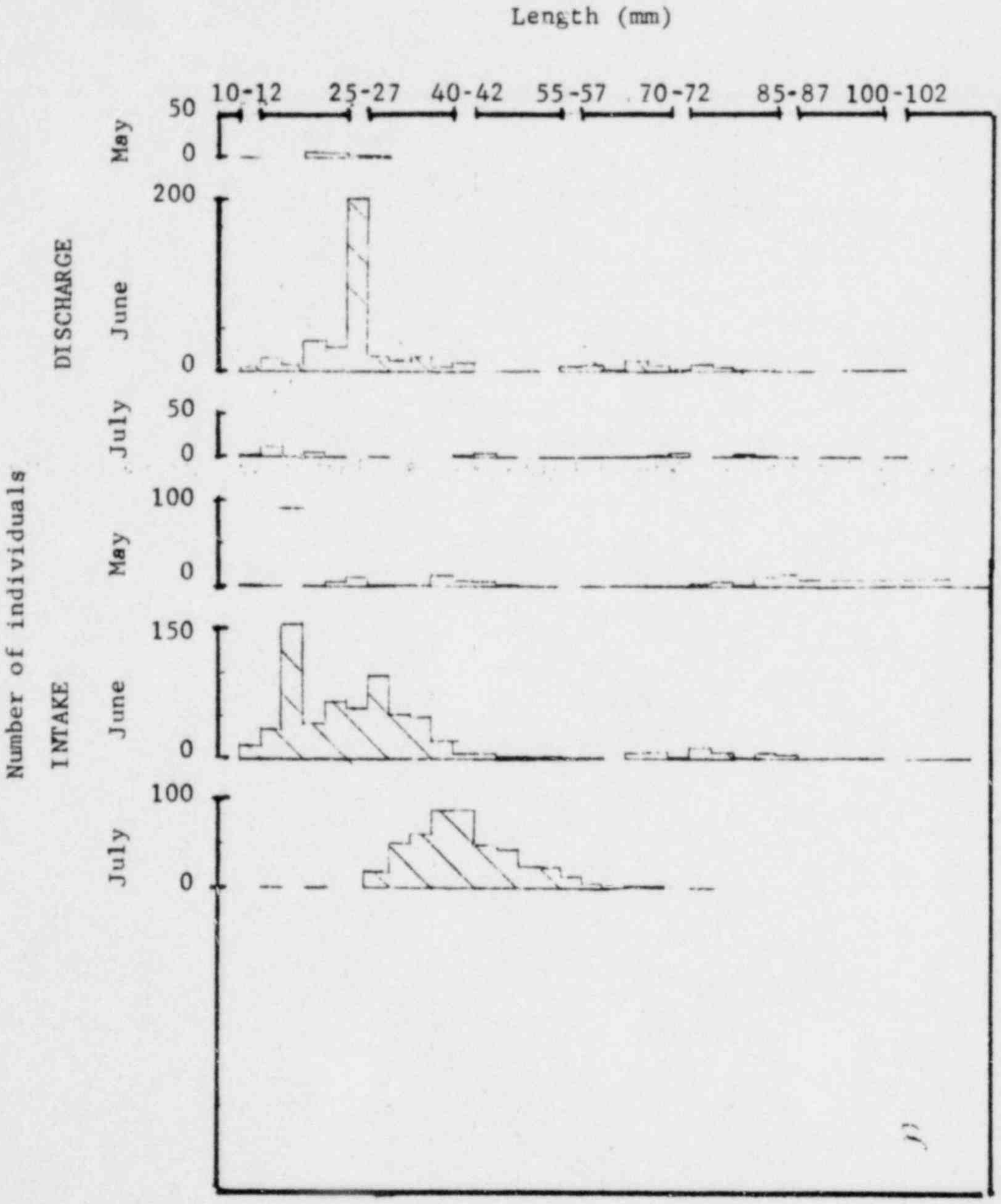


Figure 4a. Length frequency histograph for <u>Fundulus similis</u>.

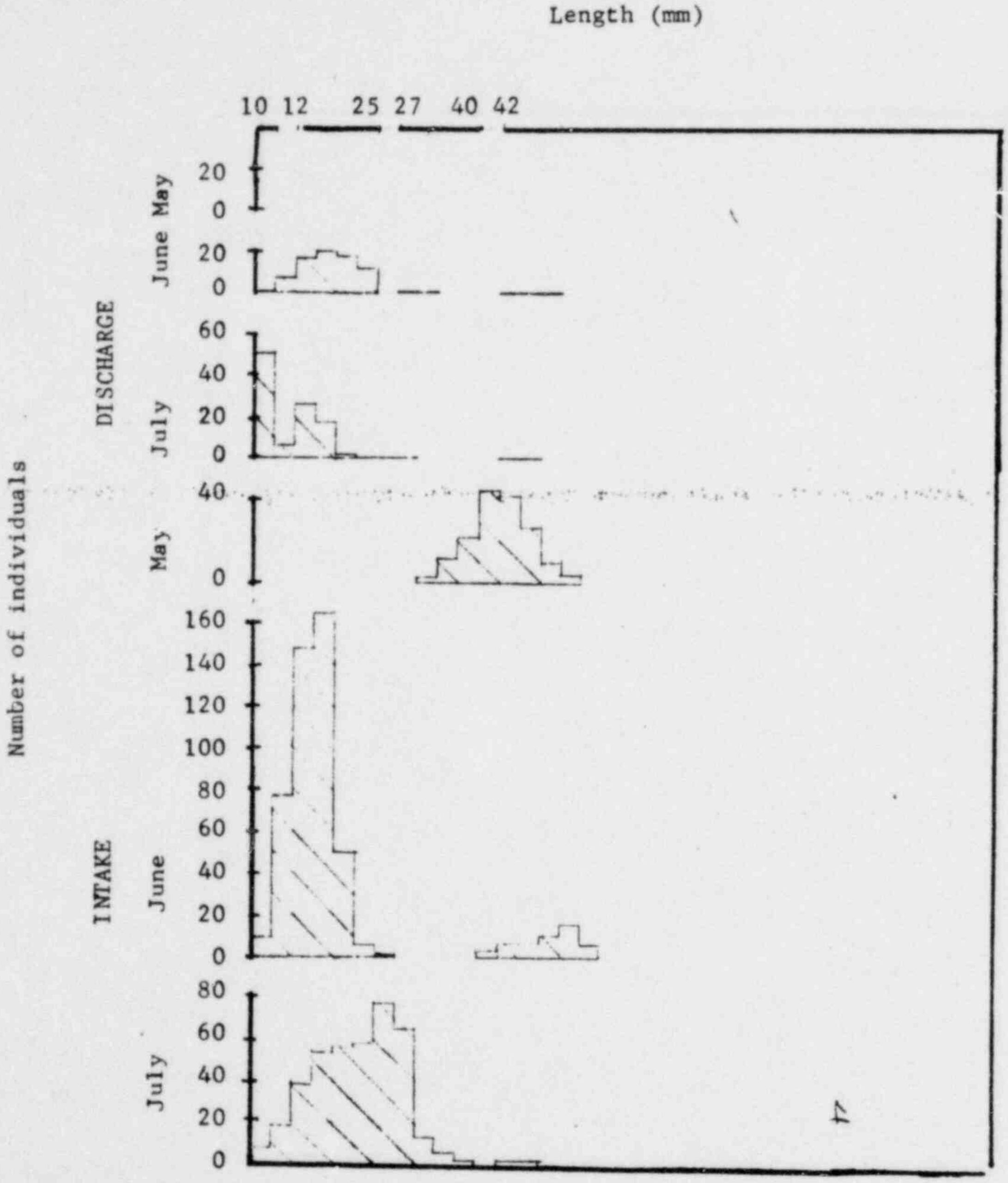


Figure 4b. Length frequency histograph for *Floridicthys carpio*.

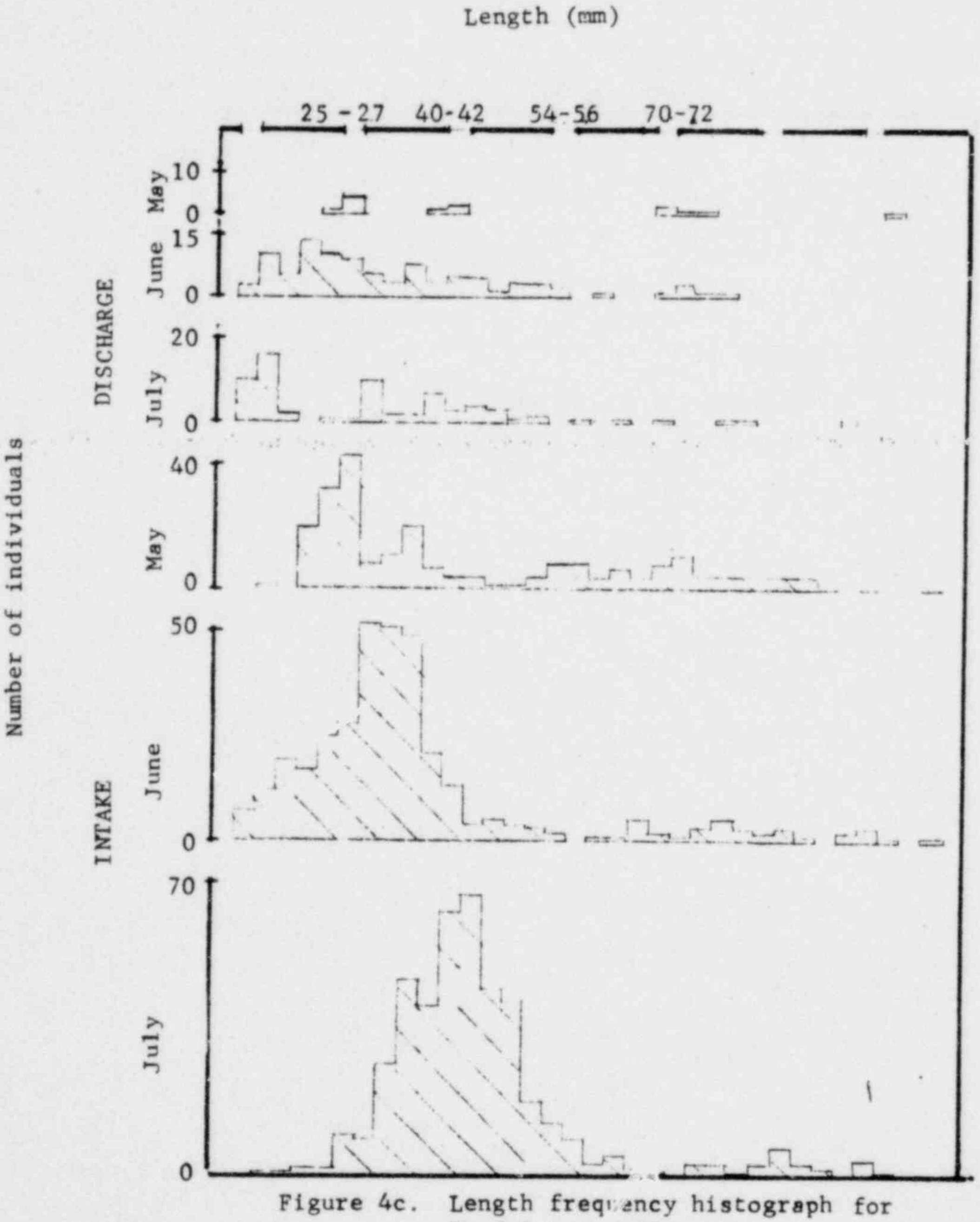


Figure 4c. Length frequency histograph for Fundulus grandis.

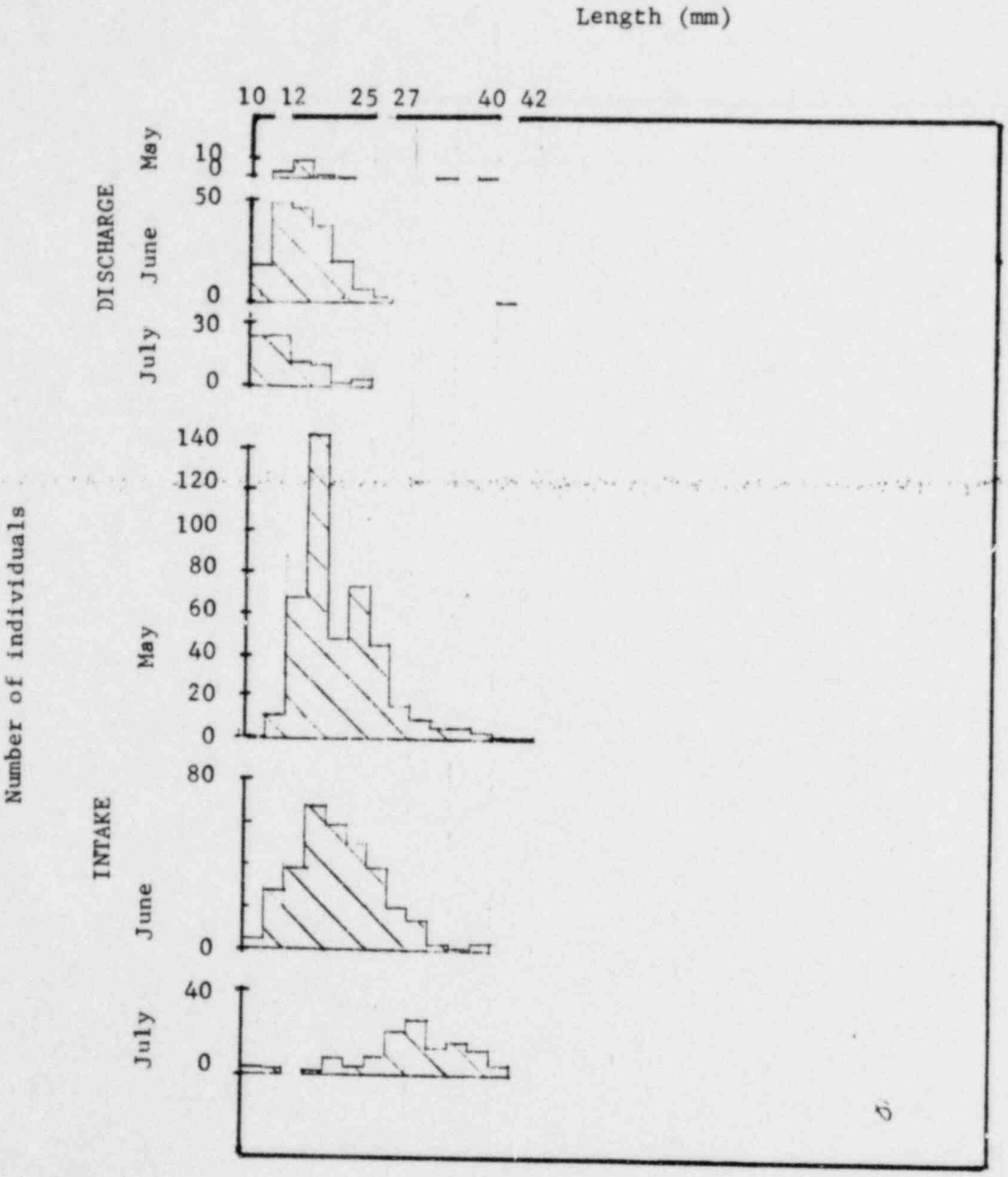


Figure 4d. Length frequency histograph for *Cyprinodon variegatus*.

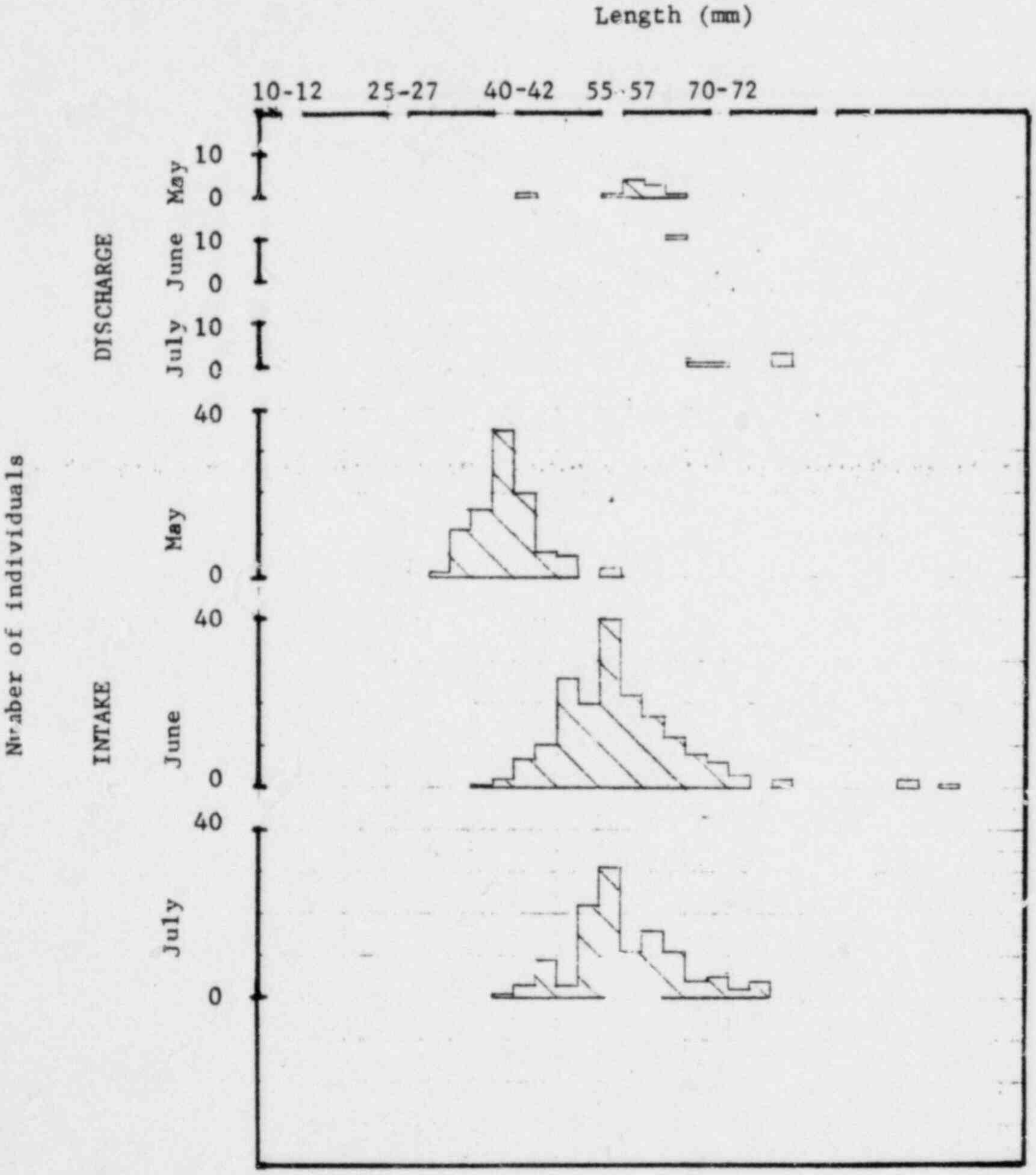


Figure 4e Length frequency histograph for <u>Lagodon rhomboides</u>.

where $\overline{W}_2$ and $\overline{W}_1$ are the mean weights of an age class at times 1 and 2. This growth rate is then multiplied times the mean biomass of the two samples $\frac{B_1 + B_2}{2}$, to give production.

$$P = G\,\overline{B} \tag{2}$$

Allen's (1950) method assumes linear growth (Eq. 3).

$$G = \frac{W_2 - W_1}{2} \tag{3}$$

where $W_2 - W_1$ are the total weights for fish of an age class. This total growth is then multiplied times the mean numbers of the two samples (Eq. 4) to give production.

$$P = G\,\overline{N} \tag{4}$$

Metabolism

Fish metabolism was measured using a flow through respirometer after Hoss (1967). Two species of killifish, <u>Fundulus grandis</u> and <u>F. similis</u>, were used in this study. Fish were collected from two tidal creeks, discharge and control. After a 6-8 hour acclimation period, respiration was measured by monitoring oxygen levels of inflowing water, outflowing water, and the volume of water that passed through the chamber. These measurements were run at ambient temperature (30°C) and at a lower (24°C) temperature after allowing a 24 hour acclimation period.

Planktonic and sediment metabolism measurements were started in August, 1974 using the light and dark bottle method. Four racks containing six bottles (3 light and 3 dark) were placed in a discharge creek and in a control creek two in each creek. The bottles were hung about 1 foot below the surface and left in the creek for two hours. Methods used were the same as in McKellar (this report).

Sediment metabolism was measured by using a modified light and dark bottle technique. Short (1.2 m) pieces of poly vinyl chloride tubing (3-5 cm inside diameter) were pressed into the sediment to a depth of approximately 5 cm. Water was then introduced in to the bottles, sealed and incubated in situ for 24 hours. These were then handled in the same manner as the plankton bottles.

RESULTS

Temperature mapping results (Fig. 1) showed the plume effects reaching far back into the adjacent marsh at flood tide. There was a gradual temperature drop moving northeast into the marsh, with the largest temperature difference between canal temperature and creek temperature at about 4.5°C. Salinity measurements were useful in tracing the plume. Canal salinity at that time of the year is about 27%-28% while ambient creek salinity is about 18% - 20%.

Temperatures taken on the fish collection dates are shown in Fig. 3. The temperature difference between the two creeks averages about 5°C except for the May, 1974, samples when unit #1 was down, and the September, 1974, sample which was taken at night when the power plant's load was down. The thermograph measurements have not as yet been worked up.

Fish and Swimming Invertebrates

Nine collections (22 samples) have been made to date (four by Adams, et al 1973) and 18 of the samples are presented in this report in Tables

1 and 2 and Fig.5 and 6. 54 species of fish have been caught in the four creeks with five additional species - Lutjanus griseus (Gray snapper), Orthropristes chrysoptera (Pigfish), Bairdiella chrysura (Silver perch), Lepisosteus oculatus (Spotted gar) and Sphyrna tiburo (Bonnethead shark) - caught in various other creeks using other methods. The tidal creeks have been surveyed and biomass is presented on a g/m^2 of watershed basis. Rough approximations of watershed area (3500 m^2 for both creeks) are used for this report, with a more detailed calculation to be made at a later date.

Fig. 4, which represents seasonal abundance (g/m^2) of fish, shows marked differences in temporal abundance between the two creeks. The control creek's biomass peaks out in August or September with high values during the warmer months. The discharge creek's biomass starts to increase to the control creek's summer level in August or September and eventually surpasses the control area's biomass during the fall months. This implies a temporal shift in the discharge system of about 2-3 months.

Fig. 5, which represents seasonal abundance in numbers of individuals/m^2, shows a different effect. In this case, the numbers of fish in the control area always excedes (except for Nov. 1974 when a cold front moved in during the control sampling time) the discharge areas numbers.

Fig. 7, which shows biomass levels of blue crabs (Callinectes sapidus), indicates a trend similar to that shown in Fig. 4. Blue crab biomass in the discharge creed started to increase in August and surpassed the control area's level in September.

Table 1

Seasonal biomass of creek fishes - grams/m^2

Species	Common Name	April 13, '73 Discharge	March 30,'73 Control	July 25,'73 Discharge	August 8,'73 Control	Sept. 20, '73 Discharge	Sept. 22, '73 Control	Nov. 17,'73 Discharge	Dec. 1, '73 Control	May 4, '74 Discharge	May 4, '74 Control	June 1, '74 Discharge	June 2, '74 Control	July 17, '74 Discharge	July 16, '74 Control	August 16,'74 Discharge	August 14,'74 Control	September 17,'74 Discharge	September 16,'74 Control
Carcharhinus limbatus	Blacktip shark					5198.0													
Dasyatis sabina	Atlantic stingray				468.5		929.5				3883.7						152.4		
Elops saurus	Ladyfish						169.5												
Myrophis punctatus	Speckled worm eel								1.5								6.7		10.4
Brevoortia sp.c.f.patronus	Gulf menhaden																7.8		
Harengula pensacolae	Scaled sardine									8.8	0.8		0.5		0.6		5.7		
Opisthonema oglinum	Atlantic thread herring														2.4		29.8		
Anchoa hepsetus	Striped anchovy				6.7										60.2		394.7		
Anchoa mitchilli	Bay anchovy						0.7			98,160.0			1275.5		146.6		106.5	106.5	28.4
Synodus foetens	Inshore lizardfish										3.1		26.4						
Arius felis	Sea catfish																	1036.2	
Opsanus beta	Gulf toadfish			27.8		13.4													
Hyporhamphus unifasciatus	Halfbeak									7.0									5.9
Strongylura marina	Atlantic needlefish			25.8													771.7	129.8	461.1
Strongylura notata	Redfin needlefish	25.0	17.9	2.3	24.7	16.5	1086.4	64.5			27.0		86.0		32.9		180.0	63.0	
Strongylura sp.	Unidentified juveniles									19.5	0.4			13.6			0.6		
Adinia xenica	Diamond killifish				4.5	3.9	0.7	2.2	13.2							0.1		1.0	2.8
Cyprinodon variegatus	Sheepshead killifish	7.8	147.1	5.6	64.9	1.5	118.3	605.9	25.1	7.1	240.3	31.2	161.0	6.8	232.0	0.8	15.4	1.9	16.6
Floridicthys carpio	Goldspotted killifish	8.6	1176.5		25.9	0.2	66.4	8.4	3.0		673.5	33.9	378.8	21.8	249.6	35.4	416.8	139.0	235.4
Fundulus grandis	Gulf killifish	1058.6	3805.9	1433.0	1086.6	359.7	786.7	1590.0	143.4	94.1	858.4	194.0	1022.5	148.3	1646.5	371.8	890.7	'220.5	
Fundulus similis	Longnose killifish	114.9	1991.1	348.5	1221.1	193.3	853.3	418.5	71.8	94.5	2207.3	793.3	365.8	306.9	846.2	446.8	847.5	796.9	

Table 1

Species	Common Name	April 13, '73 Discharge	March 30, '73 Control	July 25, '73 Discharge	August 8, '73 Control	Sept. 20, '73 Discharge	Sept. 22, '73 Control	Nov. 17, '73 Discharge	Dec. 1, '73 Control	May 4, '74 Discharge	May 4, '74 Control	June 1, '74 Discharge	June 2, '74 Control	July 17, '74 Discharge	July 16, '74 Control	August 16, '74 Discharge	August 14, '74 Control	Sept. 17, '74 Discharge	Sept. 16, '74 Control
Lucania parva	Rainwater killifish								0.3			0.3	2.4		0.2				0.1
Gambusia affinis	Mosquitofish								4.3										
Poecilia latipinna	Sailfin molly	15.0	8.8	179.0	0.5	13.9	4.9	623.3	2.2			34.7	1.9	14.1	2.5	53.7	1.0	9.6	9.7
Menidia beryllina	Tidewater silverside	121.4	62.0	115.0	3011.9	37.5	1294.7	833.2	60.3	513.0	4412.2	2.9	4525.6	19.6	7832.3	1.6	3774.6	197.8	857.3
Syngnathus floridae	Dusky pipefish												0.2						
Caranx hippos	Crevelle jack																4.5		
Oligoplites saurus	Leatherjacket			4.4	49.8	16.9	26.7	2.1							32.8		32.7	13.6	3.1
Selene vomer	Lookdown						1.9												
Trachinotus falcatus	Permit																0.8		
Eucinostomus argenteus	Spotfin mojarra	295.9		224.2	2989.7	69.6	2366.7	302.9	7.8	398.3	6.2				1716.2	87.4	3868.7	769.3	428.3
Eucinostomus gula	Silver jenny	46.4			82.6		939.5	75.1	1.7						86.8		104.4		
Eucinostomus letroyi	Mottled mojarra					5.6	20.5	11.4		69.4									
Eucinostomus sp.	Juveniles < 35mm			41.3	277.8	59.1	459.5	97.4	8.5			12.3	345.3	0.8	580.3	46.4	390.6	17.9	131.5
Archosargus probatocephalus	Sheepshead				1238.7														
Lagodon rhomboides	Pinfish	106.9	2958.8	1557.9	3400.6	401.2	8311.2	704.1		78.8	277.0	9.6	1300.0	77.2	847.2	110.6	958.0	586.6	377.8
Cynoscion nebulosus	Spotted sea trout					9.4											6.0		
Leiostomus xanthurus	Spot	2346.6	63.2	1373.6		11.0				27.4									
Pogonias cromis	Blackdrum										0.6				87.0	3880.8		1917.6	199.1
Sciaenops ocellata	Red drum			53.4		114.0												419.2	
Chaetodipterus faber	Spadefish				0.5	4.6	10.6								3.1		11.0	30.0	15.5
Mugil cephalus	Striped mullet	30.6	4047.9	208.7	819.2	7877.6	2132.8	8529.9		334.4	1343.0		4450.2		1314.5	434.6	448.5	5367.4	5265.0
Mugil curema	White mullet			44.0		1836.7	1121.2	445.1		150.9		220.1			56.4		161.6	715.0	969.1
Mugil trichodon	Fantail mullet			809.9	752.2	249.4	258.1	3512.6		0.7	68.0	26.2	284.6	0.6	494.0		1770.4	475.3	809.3
Mugil sp.	Juvenile mullet < 25mm					1.1	3.3	1.1	1.6								0.4		0.2

Table 1

Species	Common Name	April 13,'73 Discharge	March 30,'73 Control	July 25,'73 Discharge	August 8,'73 Control	Sept. 20,'73 Discharge	Sept. 22,'73 Control	Nov. 17,'73 Discharge	Dec. 1,'73 Control	May 4,'74 Discharge	May 4,'74 Control	June 1,'74 Discharge	June 2,'74 Control	July 17,'74 Discharge	July 16,'74 Control	August 16,'74 Discharge	August 14,'74 Control	Sept. 17,'74 Discharge	Sept. 16,'74 Control
Polydactylus octonemus	Atlantic threadfin		653.7																
Bathygobius soporator	Frillfin goby			28.1		4.1													
Gobiosoma robustum	Code goby															0.2		0.3	
Microgobius gulosus	Clown goby		1.3			.1	1.5		14.2		6.3	1.2	5.4		7.9	0.2	0.3		16.0
Scomberomorus maculatus	Spanish mackeral														0.8		0.3		
Prionotus tribulus	Bighead searobin												0.2		5.2				0.1
Paralicthys albigutta	Gulf flounder		4.8				76.8			9.1	81.8		60.7				101.7		
Archirus lineatus	Lined sole			0.2	2.3		0.8								9.7		10.6		5.7
Symphurus plagiusa	Blackcheek tonguefish														1.1				
Sphoerides nephelus	Southern putter				0.2						4.8		3.5						
Chilomycterus schoepfi	Stripped burrfish												0.8						0.2
Uncollected juveniles, est.	Probably Cyprinodontidaes					50.0	25.0												
Total Weight		4177.6	14,947.0	6482.4	15,872.6	16,609.9	21,236.0	17,840.2	358.9	99,973.0	14,227.9	1359.7	14,715.4	696.7	16,056.6	5465.9	15,365.9	12,908.6	10,766.6

Table 2

Seasonal abundance of creek fishes- numbers/m²

Species	Common Name	April 13,'73 Discharge	March 30,'73 Control	July 25,'73 Discharge	August 8,'73 Control	Sept. 20,'73 Discharge	Sept. 22,'73 Control	Nov. 17,'73 Discharge	Dec. 1,'73 Control	May 4,'74 Discharge	May 4,'74 Control	June 1,'74 Discharge	June 2,'74 Control	July 17,'74 Discharge	July 16,'74 Control	August 16,'74 Discharge	August 14,'74 Control	Sept. 17,'74 Discharge	Sept. 16,'74 Control
Carcharhinus limbatus	Blacktip shark					1													
Dasyatis sabina	Atlantic stingray				2		4				12						2		
Elops suarus	Ladyfish						1												
Myrophis punctatus	Speckled worm eel																3		2
Brevoortia sp.c.f.patronus	Gulf menhaden																1		
Harengula pensacolae	Scaled sardine									29	2		1		1		9		
Opisthonema oglinum	Atlantic thread herring														1		9		
Anchoa hepsetus	Striped anchovy				3										23		108		
Anchoa mitchilli	Bay anchovy						1			250,000			4602		299		659		151
Synodus foetens	Inshore lizardfish										1		2						
Arius felis	Sea catfish																	4	
Opsanus beta	Gulf toadfish			4		2													
Hyporhamphus unifasciatus	Halfbeak									3									1
Strongylura marina	Atlantic needlefish			8	15	5	6	1			4		124		42		40	13	13
Strongylura notata	Redfin needlefish	2	2	2	10	3	30	9			1		26		17		25	4	
Strongylura sp.	Unidentified juveniles									11	1			3			2		
Adinia xenica	Diamond killifish				64	56	6	1	46							1		11	1
Cyprinodon variegatus	Sheepshead killifish	1	22	2	30	18	257	113	49	17	432	180	329	72	125	11	21	38	221
Floridicthys carpio	Goldspotted killifish	2	236			5	131	12	9		165	80	508	108	402	87	245	80	300
Fundulus grandis	Gulf killifish	89	188	396	130	96	211	253	58	13	161	99	346	74	436	73	110	40	16
Fundulus similis	Longnose killifish	20	285	49	168	134	181	104	45	29	237	428	606	60	488	202	106	244	209

Table 2

Species	Common Name	April 13, '73 Discharge	March 30, '73 Control	July 25, '73 Discharge	August 8, '73 Control	Sept. 20, '73 Discharge	Sept. 22, '73 Control	Nov. 17, '73 Discharge	Dec. 1, '73 Control	May 4, '74 Discharge	May 4, '74 Control	June 1, '74 Discharge	June 2, '74 Control	July 17, '74 Discharge	July 16, '74 Control	August 16, '74 Discharge	August 14, '74 Control	Sept. 17, '74 Discharge	Sept. 16, '74 Control
Lucania parva	Rainwater killifish								1			1	5		1				1
Gambusia affinis	Mosquitofish								48										
Poecilia latipinna	Sailfin molly	5	2	80	4	12	10	212	2			71	14	116	10	41	17	15	30
Menidia beryllina	Tidewater silverside	55	380	123	3477	20	1074	281	48	1106	8650	29	8715	159	9738	163	4021	122	796
Syngnathus floridae	Dusky pipefish												1						
Caranx hippos	Crevelle jack																1		
Oligoplites saurus	Leatherjacket			5	24	12	15	1							22		20	8	2
Selene vomer	Lookdown						1												
Trachinotus falcatus	Permit																1		
Eucinostomus argenteus	Spotfin mojarra	78		84	1081	36	552	136	5	56	1				512	38	788	178	173
Eucinostomus gula	Silver jenny	12			49		204	30	1						42		42		
Eucinostomus lefroyi	Mottled mojarra					4	14	8		12									
Eucinostomus sp.	Juveniles < 35mm			41	424	135	1290	154	21			113	2218	1	1481	109	696	35	211
Archosargus probatocephalus	Sheepshead				1														
Lagodon rhomboides	Pinfish	68	136	152	301	25	769	45	10	96		1	179	5	122	6	138	25	27
Cynoscion nebulosus	Spotted sea trout					1											1		
Leiostomus xanthurus	Spot	1500	29	186		1				3									
Pogonias cromis	Blackdrum										4			2		90		16	4
Sciaenops ocellata	Red drum			1		1												1	
Chaetodipterus faber	Spadefish				1	1	1								2		8	2	2
Mugil cephalus	Striped mullet	72	39	6	6	87	10	100		8	24		62		13	1	4	20	32
Mugil curema	White mullet			2		84	54	8		35		47			8		6	12	2
Mugil trichodon	Fantail mullet			173	240	8	7	109		7	655	59	825	1	196		215	21	40

Table 2

Species	Common Name	April 13, '73 Discharge	March 30, '73 Control	July 25, '73 Discharge	August 8, '73 Control	Sept. 20, '73 Discharge	Sept. 22, '73 Control	Nov. 17, '73 Discharge	Dec. 1, '73 Control	May 4, '74 Discharge	May 4, '74 Control	June 1, '74 Discharge	June 2, '74 Control	July 17, '74 Discharge	July 16, '74 Control	August 16, '74 Discharge	August 14, '74 Control	Sept. 17, '74 Discharge	Sept. 16, '74 Control
Polydactylus octonemus	Atlantic threadfin		146																
Bathygobius soporator	Frillfin goby			5		2													
Gobiosoma robustum	Code goby															1			1
Microgobius gulosus	Clown goby		2			1	9		30		6	2	21		15	1	1		51
Scomberomorus maculatus	Spanish mackeral														1		1		
Prionotus tribulus	Bighead scarobin												1		1				1
Paralicthys albigutta	Gulf flounder		2				1			3	3		4			2			
Archirus lineatus	Lined sole			1	16		6								37		24		17
Symphurus plagiusa	Blackcheek tonguefish														2				
Sphoerides nephelus	Southern putter				1						2		3						
Chilomycterus schoepti	Stripped burrfish												1						1
Uncollected juveniles, est.	Probably Cyprinodontidaes																		
Total Weight		1902	1469	1320	6046	760	4869	1582	370	251,340	10,457	1110	18,593	601	14,036	809	7309	890	2327

Macroinvertebrates

Two collections (4 samples) of macroinvertebrates are shown in Table 3. As of now, not enough samples have been taken to make any judgements concerning these measurements. In August, the discharge collection was about 33% (60.5 g/m^2 - 40.9 g/m^2) higher than the control sample. In September, the control collection was about 27%. (69.0 g/m^2 - 50.6 g/m^2 higher than the discharge sample.

Diversity

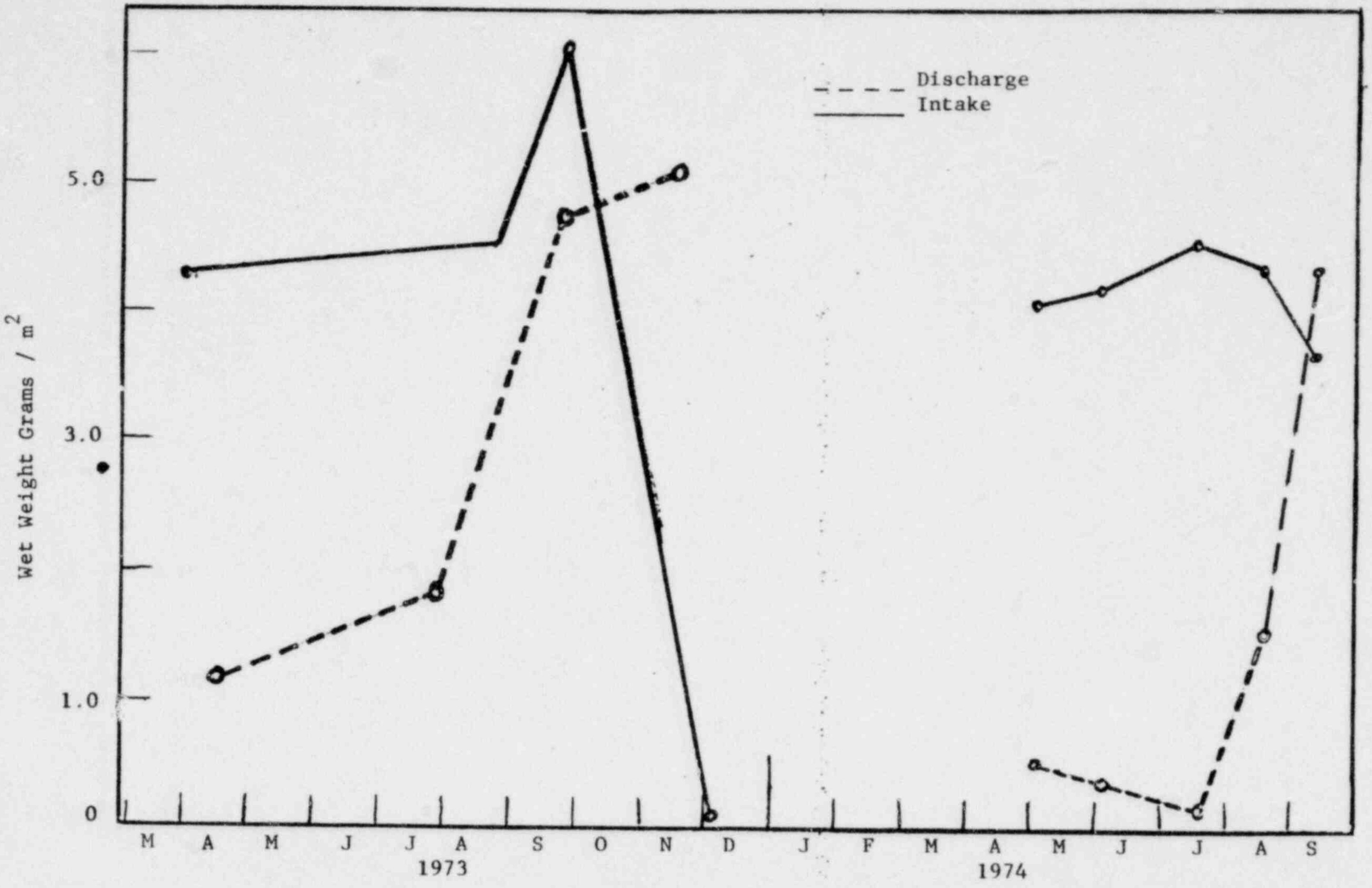
During 1974, diversity, as represented by species/1000, was higher in the control area (Fig. 8 and Table 4) then in the discharge area, although still relatively high for estuarine areas. This is quite different from the diversity levels in 1973, where diversity was either higher in the discharge area or at about the same level as the control creek.

Growth and Production

Growth and production rates were calculated for 1 age class of two species of resident killifish, Fundulus grandis and F. similis, The results of the two methods are shown in Table 5. The calculations are at too early a stage for comparison purposes, but the two methods were found to be in close agreement with one another. The negative values shown for F. grandis in the control area during May were due to heavy recruitment of age class 0 juveniles.

Table 3. Macroinvertebrate Collections

Date and Location	Species	Wet Weight (g/m^2)	Dry Weight (g/m^2)	Individuals/ m^2
August, 1974 Discharge	*Uca pugnax*	43.2	10.5	211
	Sesarma sp.	16.9	4.3	28
	Total weight	60.1	14.8	239
August, 1974 Control	*Uca pugnax*	35.6	8.0	296
	Panopeus sp.	5.6	1.5	14
	Total Weight	41.2	9.5	310
September, 1974 Discharge	*Uca pugnax*	17.7	3.2	84
	Panopeus sp.	37.2	11.4	14
	Total Weight	54.9	14.6	98
September, 1974 Control	*Uca pugnax*	66.4	13.0	422
	Panopeus sp.	2.4	0.5	28
	Total weight	68.8	13.5	450



.Figure 5. Seasonal trends of fish biomass in discharge and control areas 1973 data from Adams (1974)

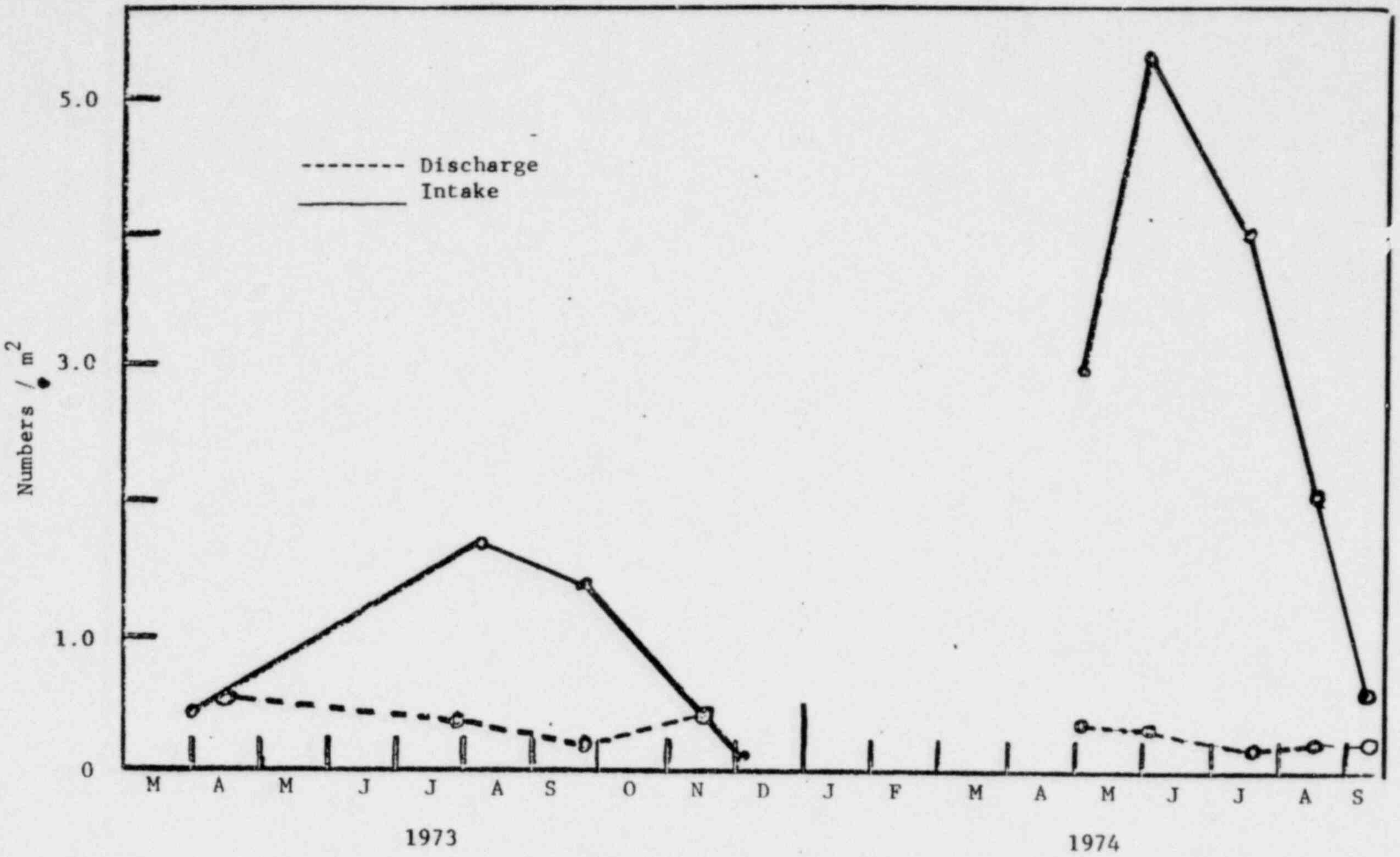


Figure 6. Seasonal trends of fish numbers in control and discharge creeks
1973 data from Adams (1974)

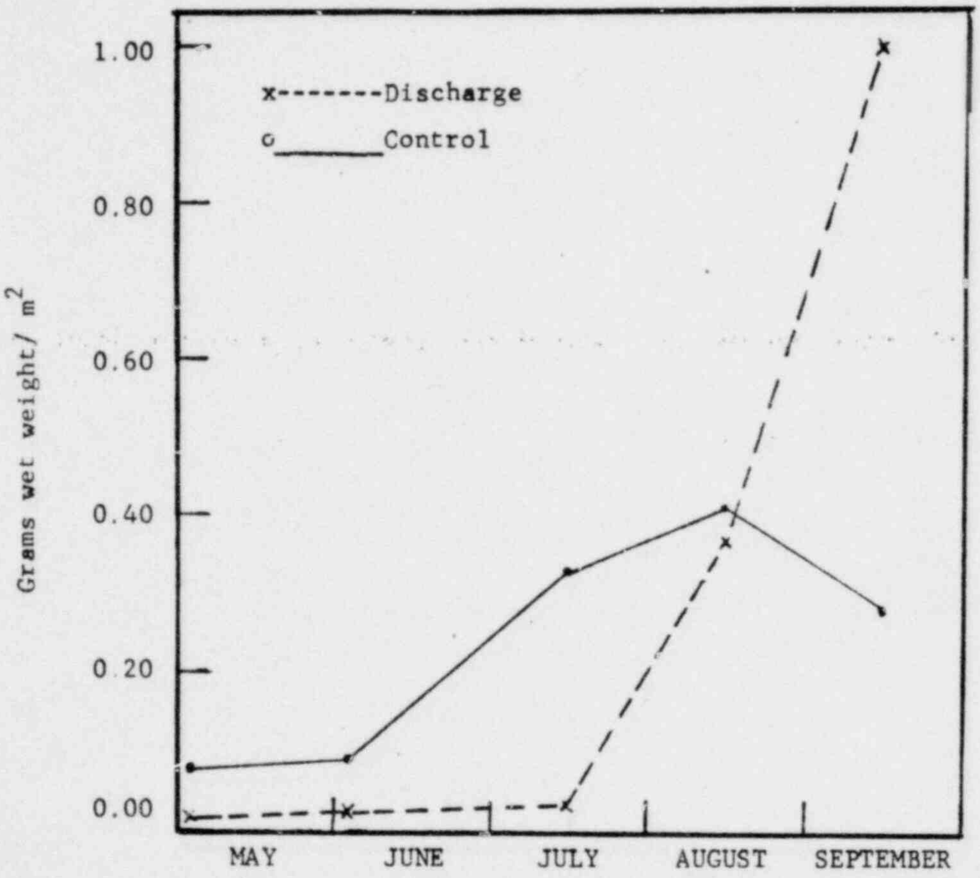


Figure 7. Biomass of *Callinectes sapidus* in two tidal creeks.

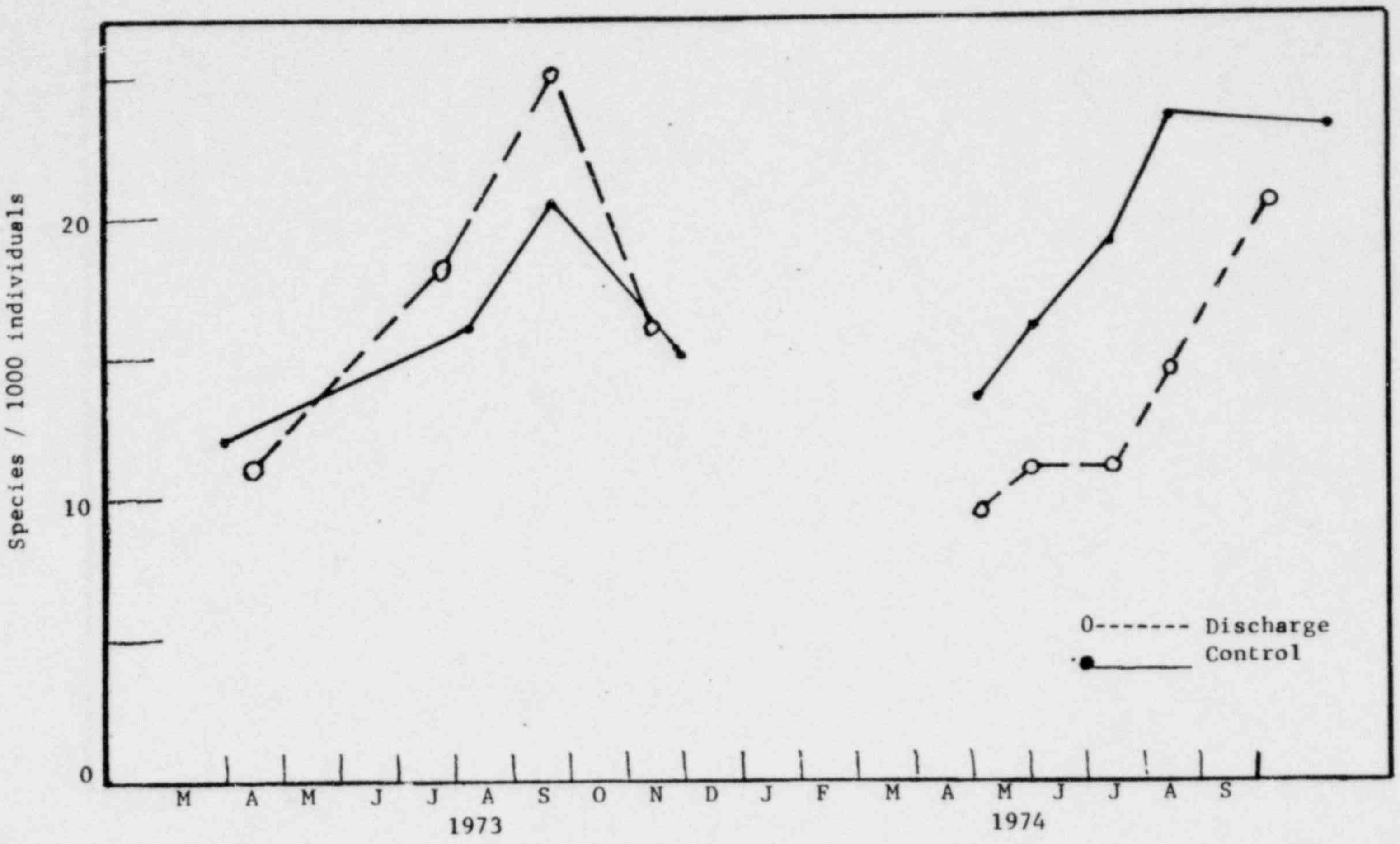


Figure 8. Species / 1000 individuals. 1973 data from Adams, 1974.

Table 4. Species Diversity of Tidal Creek Fish

Date	Location	Species/1000
April, 1974	Discharge	11
March, 1973	Control	12
July, 1973	Discharge	18
August, 1973	Control	16
Sept., 1973	Discharge	25
Sept., 1973	Control	20.5
Nov., 1973	Discharge	16
Dec., 1973	Control	15
May, 1974	Discharge	9.5*
May, 1974	Control	13.5
June, 1974	Discharge	11
June, 1974	Control	16
July, 1974	Discharge	11
July, 1974	Control	19
August, 1974	Discharge	14.5
August, 1974	Control	23.5
Sept., 1974	Discharge	20.5
Sept., 1974	Control	22.5

* without _Anchoa mitchilli_, species/1000 = 14

Table 5. Fish Production at Two Tidal Creek Resident Killifish, *Fundulus grandis* and *F. similis*

Species	Age Class	Location	Date	Production, 10^{-2}gms wet weight/m^2/mo	
				Ricker's method	Allen's method
Fundulus grandis	0	Discharge	May-June, 1974	0.21	0.20
F. grandis	0	Control	May-June, 1974	-0.22	-0.22
F. grandis	0	Discharge	June-July, 1974	1.78	1.25
F. grandis	0	Control	June-July, 1974	20.38	17.40
F. similis	0	Discharge	May-June, 1974	-0.05	-0.05
F. similis	0	Control	May-June, 1974	1.44	1.25
F. similis	0	Discharge	June-July, 1974	13.31	13.82
F. similis	0	Control	June-July, 1974	22.45	20.23

Metabolism

Results of the fish respiration study, showed that the discharge fish may have utilized an adaptive mechanism to lower their metabolic rate at elevated temperatures. This may be due to an acclimation adjustment which would entail higher turnover rates.

Table 6 shows results of light and dark bottle measurements during August and September, 1974. Again it is too early to indicate trends, but the values for plankton metabolism gross production, total respiration and P/R ratios are slightly higher than values reported for the adjacent shallow bays (Smith, this report).

Discussion

Trends indicated by this preliminary report show a possible seasonal displacement of fish in the discharge area. The occurrences of large fish in the discharge creeks indicates possible osmotic stress. This stress may occur at high temperature and salinity levels. Because of a lower surface area to volume ratio, large fish may be better equipped to handle this stress.

The difference in discharge creek diversity between the 1973 and 1974 collections may be due to sediment scouring in the discharge creek. This scouring may be caused by the blockage of marsh drainage patterns due to interference from the spoil banks of the canal. Becuase of this scouring, another discharge creek is being looked at.

Table 6. Light and Dark Bottle Metabolism in Two Tidal Creeks

Location	Date	Gross Production gms $0_2/m^3$/day	Total Respiration gms $0_2/m^3$/day	$\frac{\text{Gross Production}}{\text{Total Respiration}}$ (P/R)
Discharge	August, 1974	1.83	1.95	0.94
Control	August, 1974	1.29	2.21	0.58
Discharge	August, 1974	2.29	2.16	1.06
Control	August, 1974	2.01	1.27	1.58
Discharge	September, 1974	1.95	1.34	1.46
Control	September, 1974	2.82	1.24	2.29
Sediment Metabolism Light and Dark Bottles				
Discharge	August, 1974	none	0.86 gms.$0_2/m^2$	
Control	August, 1974	none	0.73 gms.$0_2/m^2$	

LITERATURE CITED

Adams, C.A. 1974. Fish abundance and biomass in Tidal Creeks (Crystal River). In Florida Power Corporation 2nd Crystal River Environmental Progress Report to the Federal Interagency Research Advisory Committee.

Allen, K.R. 1950. The computation of production in fish populations. N.Z. Sci. Rev. 8:39.

Hoss, D.E. 1967. Rates of Respiration of estuarine fish. Proceedings of the 21st Annual Conference of the Southeastern Association of Game and Fish Commissioners.

Ricker, W.E. (ed.), 1968. Methods for Assessment of Fish Production in Fresh Waters. IBP Handbook No. 3. Blackwell, London.