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COMPLETION REPORT

on

Techniques for Evaluating the Effects of Water Resources Developmen on Estuarine Environments

TEXAS DEPARTMENT OF WATER RESOURCES
LP-75
1978

A COMPLETION REPORT ON

TECHNIQUES FOR EVALUATING THE EFFECTS

OF WATER RESOURCES DEVELOPMENT ON

ESTUARINE ENVIRONMENTS

Prepared by

Texas Water Development Board
August 1974

Texas Department of Water Resources

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ABSTRACT

TECHNIQUES FOR EVALUATING THE EFFECTS OF
WATER RESOURCES DEVELOPMENT ON ESTUARINE
ENVIRONMENTS

Texas Water Development Board, Austin, Texas

Office of Water Resources Research, Washington, D.C.

FILE RETRIEVAL DESCRIPTIONS

PLANNING : water resources, water allocation (policy), methodology, long-term, systems analysis, regional, operations research.

ENVIRONMENT: aquatic habitats, marsh habitats, alterations, ecology, simulation, modeling.

This research project was designed to provide a set of analytical techniques for use by water resources planners and decision-makers to assist in measuring and evaluating the effects of water resources development on estuarine environments. The techniques are designed to be sufficiently flexible to analyze many types of water development and management policies. This report describes: (1) the techniques developed by the Texas Water Development Board to measure the environmental impact of water resources development on estuarine environments, and (2) the application of these techniques to a prototype Texas River basin - estuarine system to demonstrate the methodology. At this time, results are not definitive but serve as valuable learning tool. Environmental effects of water development and management are examined by simulation models of stream, reservoir, and estuarine environments, and placed within a flexible analytical framework for evaluating a wide range of alternatives.

An estuarine ecological model (ESTECO) and an estuarine model (MOM) for migratory organisms (Gulf shrimp) were developed for use with existing Board models that were designed to simulate stream, reservoir, and river basin conditions as water use demands increase on projected scales. The test case was executed on the Guadalupe Estuary and its major contributing drainages, the San Antonio and Guadalupe River Basins. Year 2000 simulations indicate water use projections would increase frequency of low flow events with varying environmental effects.

Foreward

In 1967 the Texas Water Development Board initiated the Bays and Estuaries Program to collect more comprehensive data and develop analytical procedures for assessment of water resource systems. A specific objective was the development and implementation of computer models capable of environmental simulation for use in detailed planning, design, and management of water resource systems such as the Texas Water System (Texas Water Plan, 1968).

With the advice, encouragement, and financial assistance of the U.S. Department of Interior, Office of Water Resources Research (OWRR), the guidance of an eminent research advisory panel, and the engineering accomplishments of several consulting firms, the Texas Water Development Board has now completed its fifth research project relating to water resources planning programs.

This report volume summarizes the results of agency efforts to develop practical methodologies for evaluating the effects of water resources projects on the estuarine environments. The report has been prepared to inform resource planners and decision makers of the techniques developed for applying systems analysis procedures to the planning of water and related land resources projects.

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A COMPLETION REPORT

I. SUMMARY

The research described herein represents a systematic estuarine study in a State-supported research program which began in 1967. This research project has relied heavily upon the results of several previous research projects, supported in part by the Office of Water Resources Research, which have been conducted by the Texas Water Development Board, universities, and private firms (TWDB, 1969; 1971; 1974).

DESCRIPTION OF THE REPORT

This report discusses techniques developed and their application in a test case. The results of this test application and some conclusions are discussed.

Chapter II provides an introduction to the research project as well as background information on an aspect of the Texas water planning problem, especially with regard to the State's estuarine resources and the need for further research. Also Chapter II presents a discussion of the test case.

Chapter III described the overall analytical framework and each of the analytical techniques developed or applied in this research project.

Chapter IV illustrates the application of the methodology in the test case.

Chapter V is a summary of the study's limitations and suggestions future research.

RESEARCH ACCOMPLISHMENTS AND CONCLUSIONS

The basic objective of this research project was to develop an analytical framework for identifying and evaluating the interrelationships between estuarine ecosystems, fresh water and nutrient inflows, and the impact of alternative river basin water development, management, and operation plans on the associated estuarine ecosystems. The highly complex nature of a modern water resource development plan precludes a simple analysis and evaluation of the alternative implementation actions. It is essential that the myriad of hydrologic, physical, and environmental aspects of water resource development be considered in a comprehensive, systematic, and interactive manner so that important variables can be evaluated.

The objectives of this study were attained by (1) integration of existing techniques, with refinements, and new techniques developed as necessary from state-of-the-art concepts, into a framework for analyzing alternative water resources management policies under varying hydrologic conditions, (2) testing the capability of the techniques to describe "real world" processes, and (3) demonstration of the techniques on a prototype Texas river basin-estuarine system (San Antonio River Basin, Guadalupe River Basin, and Guadalupe Estuary. The framework is general, such that these new analytical techniques may be used in the analysis of a wide range of alternatives. The framework consists of conceptual models of a water resource system, a fresh water ecosystem, and an estuarine ecosystem with interconnecting links. An analysis using the framework is performed by postulating a water resource development plan, operating the system under projected future conditions of development and water use, and investigating the impacts with emphasis on fresh water inflow and the estuarine environments.

The techniques developed include an estuarine ecological simulation model and an estuarine migratory organism model. The estuarine ecological model was developed for the Guadalupe Estuary to analyze the interactions between environmental parameters and lower trophic level organisms. The migratory organisms model was developed to evaluate the response and interactions between "key" migratory estuarine species and environmental parameters.

Other techniques utilized in the project were adapted from previously developed modeling capabilities and refined as necessary. These included the stream and reservoir ecological simulation models. A previously-developed river basin and/or basins reservoir system simulation model was used to operate the postulated water resource system to meet projected water demands in the San Antonio and Guadalupe River Basins.

A thirty year time horizon was selected for analyzing projected future demands on the Guadalupe and San Antonio River Basins. Consumptive water uses and return flows over this planning period were derived from the projected water requirements for the years 1971 to 2000. Evaporation and natural runoff rates were derived from the historical hydrologic records covering the period 1941 to 1970. As a basis for comparison between historic and future conditions, the years 1970 and 2000 were selected.

In the analysis of projected future water demands on the San Antonio and Guadalupe River Basins, the major impact is the increase in low flow conditions for the Guadalupe Estuary although the seasonal distribution of inflows was virtually the same with development as the historic flow distribution. The depletion of fresh water inflows is due to the projected increase in consumptive use under future conditions.

Testing of the stream and reservoir ecological models proved satisfactory for most variables; however, initial testing revealed some weaknesses. Therefore, some refinements to these models were necessary before proceeding with the simulations. The greatest change in the stream environments was observed in the San Antonio River Basin since it is dominated by municipal return flows from the City of San Antonio. Proposed waste management policies in the form of more restrictive effluent standards had a positive impact on both river basins in terms of dissolved oxygen concentration. This was due to the reduced organic loadings and also to the reduction of ammonia by nitrification. However, an adverse stream impact indicated by these simulations was an increase in nutrients (nitrogen and phosphorus) due to the progressively larger volumes of treated effluent released to the river basins over time.

The stream environments of both basins were also affected by the construction of Cuero I and Cibolo Reservoirs. These impoundments changed the environments of a portion of their associated rivers from a free flowing stream (lotic) environment to a quiescent reservoir (lentic) environment. The reservoirs are subjected to high concentrations of nutrients which, when accompanied by typical Texas summer temperatures, stimulates the growth of excessive populations of phytoplankton. There were no significant changes in the environments of the existing reservoirs, Canyon and Medina, under future conditions. Canyon and Medina reservoirs are located in the upper reaches of the Guadalupe and San Antonio River Basins, respectively, and there is no signficant projected development above them.

Testing of the estuarine ecological model proved satisfactory for some variables, while the response of other remains questionable in a quantitative sense. However, it is encouraging that the proper qualitative response of these variables is apparent. Knowledge and experience gained through further application of the model can improve the quantitative results. The estuarine ecologic simulations indicate river inflows for the future conditions would be somewhat diminished, while the seasonal distribution of inflows remains virtually the same. The most significant impact on the estuarine system was due to the increased nutrient loadings which results from increased return flows under projected future conditions. This increase in biostimulants produced a substantial increase in phytoplankton production.

Results from application of the estuarine migratory organism model reflect an overall decrease in production of white shrimp under projected future conditions. Although these results appear to conflict with the increased biological production simulated by the estuarine ecological model, it should be noted that the models are focused on different production categories. Thus, it does not follow that an increase in phytoplankton production will be accompanied by increased white shrimp production in the future scenario (see Chapter IV).

In summary, the report describes a set of analytical techniques, built largely around the digital computer and a comprehensive data base, for analyzing the effects of water resources development and management policies on selected environmental aspects of a river basin and its associated estuarine system. The analytical techniques presented herein were developed for use by public agencies involved in water planning, development, and management activities, although their potential usefulness to others involved in this type of effort is apparent. The techniques are complicated and require a highly-trained, multi-disciplinary staff for proper application;

competence in hydrology, engineering, coastal processes, ecology, numerical analysis, and operations research is necessary for proper utilization of this methodology. Most public agencies involved in water planning on the scale which would make these techniques useful would have such staff capability.

A complete evaluation of the socio-economic responses to ecological changes in a river basin-estuarine system resulting from water resources development and management was beyond the scope of this project. However, the methodology developed in this research effort makes it possible to identify gross ecological changes resulting from the implementation of a particular plan. Furthermore, there is no pretense whatsoever that these techniques are all encompassing or a panacea; much more research needs to be done.

ORGANIZATION AND TECHNICAL STAFF

The Texas Water Development Board was responsible for over-all research project management, under the general direction of Mr. Lewis B. Seward, Principal Engineer - Project Development and Mr. Seth Burnitt, Director of the Operations Division. Mr. Jack C. Nelson of the Operations Division and Mr. William A. White, Director of the Systems Engineering Division, served as Principal Investigators and with Mr. Donald G. Rauschuber of Operation Division were responsible for the technical direction of the project and preparation of the final report. In addition, Messrs. Nelson and White were responsible for maintaining liaison with the Office of Water Resources Research and the Consulting Panel.

Assistance in all phases of the research and report preparation was received from the Consulting Panel: Dr. Gerald A. Rohlich, Chairman, University of Texas at Austin; Dr. B. J. Copeland, North Carolina State

University at Raleigh; Dr. Clark Hubbs, University of Texas at Austin; and Dr. Carl Oppenheimer, University of Texas Marine Science Institute, at Port Aransas. In addition to these individuals, Mr. B.D. King of the Texas Parks and Wildlife Department served as an ex-office member of the Panel. Throughout the project they reviewed progress and provided valuable guidance to the research staff.

The stream and reservoir ecologic models used in this research project were developed by Water Resources Engineers, Inc. Dr. Tommy R. Knowles and Mr. Curtis K. Carter of the Systems Engineering Division modified these models as appropriate for this project, developed an appropriate application procedure, and applied the models in the test case.

Dr. Quentin W. Martin and Mr. Phillip G. Savoy of the Systems Engineering Division conducted the multi-basin hydrologic simulations for the San Antonio and Guadalupe River Basin. Mr. Gordon L. Thorn, Jr. of the Systems Engineering Division conducted the tidal hydrodynamic model simulations for the Guadalupe Estuary.

Dr. Robert J. Brandes of Water Resources Engineers, Inc., (WRE) Austin, Texas, under the general direction of Dr. Frank D. March and Dr. Gerald T. Orlob, was responsible for the conceptual development, testing, and documentation of the estuarine ecologic model. Mr. Richard B. Wise of the Operations Division was instrumental in the application of this model in the test case.

Mr. Donald G. Rauschuber of the Operations Division coordinated and assisted in the development, testing, and documentation of the migratory organism model used in this research project. Dr. Carl Chen of Tetra Tech, Inc., Lafayette, California was responsible for the conceptual development of the migratory organism model.

The following technical and clerical staff of the Texas Water Development Board were instrumental in the completion of the project. Messrs.

Leonard W. (Nick) Carter, Glenn D. Merschbrock, Roger L. Wolff, Richard D. McWhorter, and Donald F. Schwartz provided technical assistance throughout the research project. Mrs. Glenda Leftwich was responsible for typing and assembly of the final report and administrative details throughout the research effort. Mesdames Nancy Hardin, Sue Niesner, and Starr Johnson also assisted in typing of the final report.

ACKNOWLEDGEMENTS

This research, as documented herein, would not have been possible without the enthusiastic support of many individuals and the agencies they represent. First, the research staff wishes to acknowledge the support given the project by the Texas Water Development Board, its members individually, and its Executive Director, Mr. Harry P. Burleigh.

Dr. E. Gus Fruh of the Environmental Health Engineering Department of the University of Texas at Austin generously gave of his knowledge, experience, and provided data which was extremely helpful in refining the reservoir ecological model.

Excellent coordination was available from the Texas Parks and Wildlife Department, the University of Texas Marine Science Institute at Port Aransas, and the U.S. Geological Survey. Their interest and assistance is sincerely appreciated by the research team.

Special acknowledgement is extended Dr. Lial F. Tischler, formerly Director of the Systems Engineering Division of the Texas Water Development Board, and presently the Manager of the Austin, Texas office of Engineering Science, Inc. Prior to his departure from the Board, Dr. Tischler directed the preparation of the research proposal to the Office of Water Resources Research which ultimately supported the research effort. Subsequent to leaving the Board, Dr. Tischler, as his schedule permitted, maintained close contact with the proceedings of the research effort and provided much valuable input.

II. INTRODUCTION

NEED FOR RESEARCH

Texas estuaries provide a vast potential for multipurpose utilization of their resources. The use of the bays and estuaries for navigation, commercial shell dredging, commercial and sport fisheries, oil and gas production, maintenance and propagation of marine life, and recreation is extensive. These often conflicting activities provide a major contribution to the viability of the State's economy. The goal of the State of Texas, with respect to its bays and estuaries, is to develop management plans that will assure continued use of these resources for the economic, recreation, aesthetic, and social benefit of the entire State and nation. There is presently insufficient or narrowly defined individual knowledge of the many and other conflicting factors that must be given equitable consideration in the development and ultimate implementation of comprehensive management plan for each important estuarine system. Therefore, additional studies are needed to accomplish this goal.

The efforts of Texas toward this objective are compartmentalized to effectively use the technical expertise of several state agencies with diverse responsibilities in estuarine studies and management. The Water Development Board, Parks and Wildlife Department, General Land Office, Water Quality Board, Water Rights Commission, Railroad Commission, Texas Coastal and Marine Council, and Governor's Office are primarily involved, with collateral duties also vested in other agencies including some river authorities, navigation districts, and local governments, as well as a multitude of Federal agencies.

A paramount concern of the State of Texas is the effect of upstream water resources development on fresh water inflows to the Texas bays and estuaries. The objective of the Water Development Board in the overall estuarine management concept is to assure that sufficient quantities of fresh water inflow of the necessary quality will be provided seasonally at optimum geographic locations for maintaining the estuarine environments and the health of their living resources.

The impact of altered fresh water inflows upon the environments of Texas estuaries must take into consideration the current and projected water requirements of the basins of origin. This includes municipal, industrial, agricultural, recreational, and fish and wildlife demands. Therefore, bay and estuary fresh water inflows are directly related to and not separable from river basin water resources management. Further, we must also realize that the increasing demand for water and increasing consumptive use in Texas is depleting the supply of fresh water available to maintain the beneficial production of the bays and estuaries. Ultimately, the natural resource policy issue and water resource management aspects must be clearly addressed by appropriate legislative actions at the State and/or federal level.

The Texas Water Development Board is the principal water resource planning agency of the State. Under Section 11.101 of the Texas Water Code, the Board is specifically charged with..."The preparation, development, and formulation of a comprehensive state water plan for this state, including a definition and designation of river basins and inter-watershed transfers..."Further, ..."Consideration shall be given in the plan to the effect of upstream development upon the bays, estuaries, and arms of the Gulf of Mexico and to the effect upon navigation..."

In carrying out its statutory directive, and in recognition of the fact that continued development of the surface water resources of the Texas is both necessary and inevitable to meet increasing demands for fresh water by an expanding population and to support state and national economic growth, the Board completed the Texas Water Plan in November 1968. The Plan, as formulated, is a flexible guide for the orderly development and management of Texas water resources to the year 2020. It is the first large-scale comprehensive water plan in the U.S. to recognize the need for allocation of a firm supply of fresh water for a vast estuarine system, consonant with progressive development and allocation of inland water supplies for other necessary and beneficial uses. Although the Plan tentatively provides a specific amount of water for estuarine inflow on an annual basis, it was, and is, clearly recognized that the amount specified is no more than a preliminary minimum estimate. Furthermore, the optimum seasonal and spatial distribution for these supplementary inflows could not be accurately determined in the planning studies because of insufficient knowledge of the estuarine ecosystems. The acute need for a reliable set of criteria and techniques for defining the response of estuarine ecosystems to varying amounts and regimens of fresh water and nutrient inflows is clearly obvious in order to solve this very complex "real world" problem.

THE BAYS AND ESTUARIES PROGRAM

Studies by the Board of past and present fresh water inflows to Texas bays and estuaries have used available sources of information on the physical, chemical, and biological characteristics of these estuarine systems in an effort to define the relationships among fresh water and nutrient inflows, and the estuarine environments. The Board realized during its planning activities that, with the exception of data from the Texas Water Quality Board's Galveston Bay Study, very little reliable data were available on the estuaries of Texas. Several limited study programs were underway; however, these were largely independent of one another. The data collected under any one program were not comprehensive, and since sampling and measurement of environmental and ecological parameters under different programs were not accomplished simultaneously, the resulting data could not be reliably correlated. In some estuaries, virtually no data had been collected.

A program was therefore initiated by the Board in 1967 to collect data considered essential for analysis of the physical and water quality characteristics of Texas bays and estuaries. To begin this program, the Board consulted with the U.S. Geological Survey and initiated a reconnaissance-level investigation program in September, 1967. Specifically, the initial objectives of the program were to define: (1) the occurrence, source and distribution of nutrients; (2) current patterns, directions, and rates of water movement; (3) physical, organic, and inorganic water quality characteristics; and, (4) the occurrence, quantity, and dispersion patterns of the water masses (fresh and Gulf) entering the estuarine system. To avoid duplication of work and to promote coordination, discussions were held with other state, federal, and local agencies having interests in Texas estuarine systems and their management.

Principally through this cooperative program with the U.S. Geological Survey, the Board is now collecting extensive data in all estuarine systems of the Texas Coast except Galveston Bay, which continues under study by the Texas Water Quality Board. An order of priority with respect to intensity of data collection in each principal estuary was established in coordination with the Texas Parks and Wildlife Department in early 1969 in order to develop data on a timely schedule for those areas which might be influenced by upstream development. This schedule, which coincides in many respects with on-going ecological and related studies in certain estuaries (Figure II-1) by the Parks and Wildlife Department, is indicated below:

1. Guadalupe Estuary (San Antonio Bay)
2. Lavaca-Tres Palacios Estuary (Matagorda Bay)
3. Nueces Estuary (Corpus Christi Bay)
4. Mission-Aransas Estuary (Aransas Bay)
5. Sabine-Neches Estuary (Sabine Lake)
6. Laguna Madre Estuary
7. Colorado Estuary
8. Brazos Estuary
9. East Matagorda Estuary

Data-collection activities are now concentrated in the San Antonio, Matagorda, Corpus Christi, and Aransas Bay systems.

Development and verification of two-dimensional mathematical hydrodynamic and conservative (salinity) transport models, considered basic to all aspects of estuarine studies, have been completed for the Lavaca-Tres Palacios, Guadalupe, Nueces, and Mission-Aransas Estuaries. The hydrodynamic models simulate spatial and temporal variations of tidal flows and amplitudes throughout the bay systems, thus defining the circulation patterns throughout the estuarine systems under varying conditions. The transport models are compatible with the hydrodynamic models and simulate transport, by convection and dispersion, of various conservative (non-biodegradable) particulate or dissolved constituents.

Ecological studies have been expanded in the Lavaca-Tres Palacios, Guadalupe, Nueces, and Mission-Arkansas Estuaries through contracts with private consultants, the City of Corpus Christi, the University of Texas Marine Science Institute at Port Aransas, the University of Texas School of Public Health at Houston,

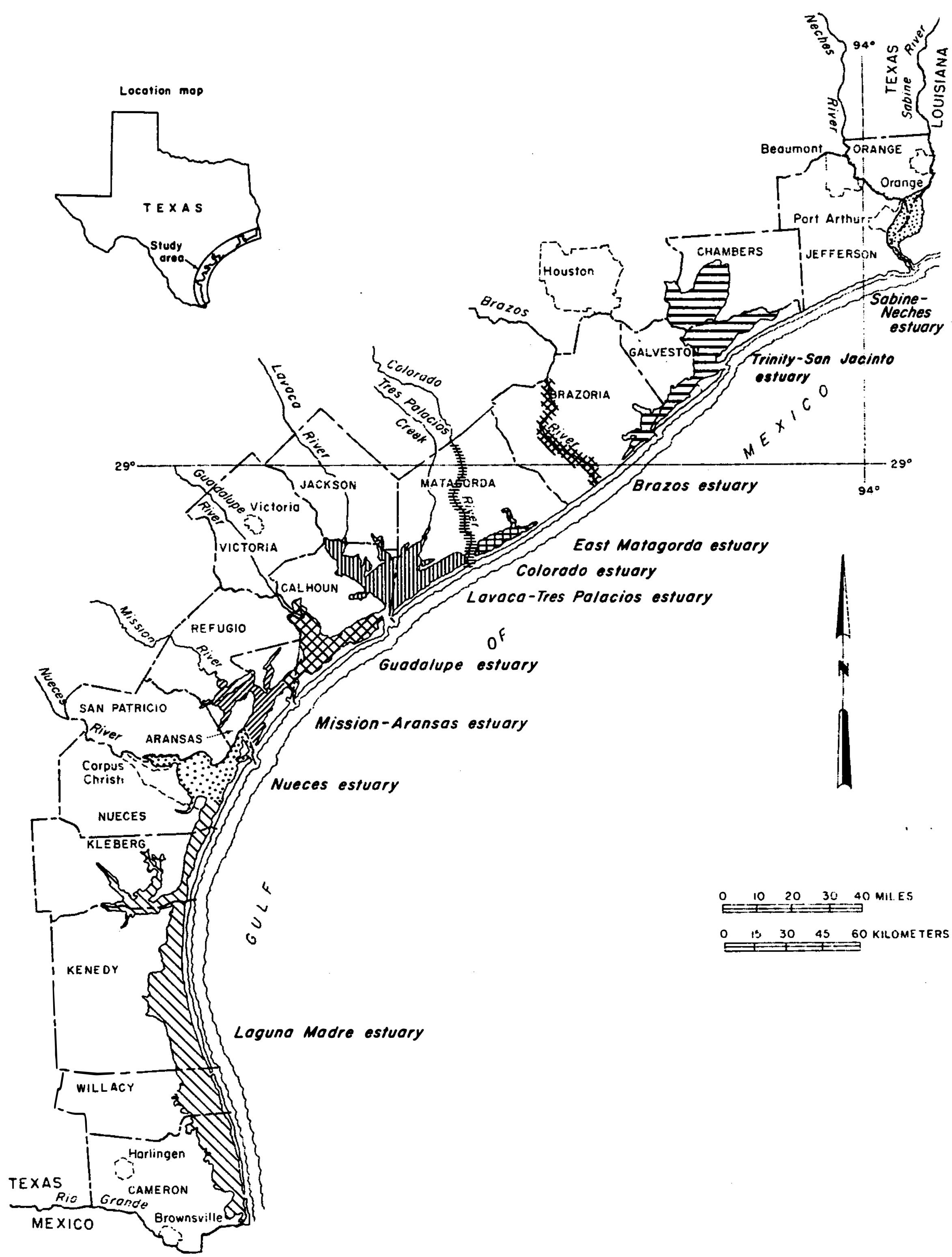

Figure II-1
Locations of the Estuaries

Base from Official State Highway Map of Texas, 1971 and interagency contracts with the Texas Parks and Wildlife Department. A data storage and retrieval system called Coastal Data System (CDS) has been developed and implemented by the Board for all state and federal data collected under these programs.

With the data being provided by the above-mentioned studies, and in response to the need to provide protection to the vital estuarine resources, the Board undertook the research described herein to develop a methodology for analyzing the effect of water resources development on an entire river basin and its associated estuarine system.

RESEARCH OBJECTIVES

The primary objectives of this study were to (1) define the interrelationships between estuarine ecosystems and fresh water and nutrient inflows, and (2) develop and test quantitative techniques (comprised of both manual and computerized methods) for simulating the interrelationships and to define and evaluate the impact of alternative river basin water development, management, and operation plans on the associated estuarine ecosystems. More specifically the objectives were:

1. To develop and test a methodology for utilizing an integrated set of water quantity/quality/ecological models for reservoirs, streams, and canals which can be used to operate a river basin or basins, water resources system under various stages of development and thus determine the quantity and quality of inflow to the associated estuary, or estuaries, over time.
2. To adapt and test the application of existing ecological modeling concepts to a shallow, nonstratified estuarine system. The ecological model should consider the inter-

relationships among the important indigenous organisms (bacteria, plankton, benthos, nekton, etc.) at various trophic levels, as well as their interaction with fresh water and nutrient inflows. The estuarine ecological model should interface directly with the estuarine hydrodynamic and mass transport models.

3. To develop and test a planning strategy for evaluating alternative river basin development and management policies* on the associated estuarine system, or systems, by interfacing the river basin and estuarine models.

TEXAS ESTUARINE ENVIRONMENTS

A Texas estuary may be defined as the region from the tidally-affected reaches of terrestial drainage inflow sources to the Gulf of Mexico. Shallow bays, mud flats, tidal marshes, and bodies of water behind barrier beaches are included under this definition. The estuarine systems are made up of subsystems, lesser but recognizable units with characteristic chemical, physical, and biological regimes. Major component parts include the primary, secondary and tertiary bays, which require separate treatment for proper understanding and management.

The physical characteristics of Texas' surface water resource systems present a unique opportunity to study and develop techniques for analyzing the extremely complex interrelationships between rivers and their associated estuaries. Texas has approximately 373 miles of open-ocean or Gulf shoreline

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* Herein, "development" is defined as the construction of physical facilities such as canals, pump stations, reservoirs, waste-water treatment plants, pipelines, etc., whose purpose is to enhance the quantity and quality of water available to satisfy multiple uses. "Management" is defined as the operation of these physical facilities and, for the purposes of this research project, excludes the institutional, political, and legal arrangements necessary for implementation of a plan.

and 1,419 miles of bay shoreline along which are located seven major estuarine systems and two smaller estuaries (Figure II-1) eleven major river basins, ten with headwaters originating within the boundaries of the State, have estuaries of major or secondary importance. These estuarine systems, with a total surface area of more than 1.3 million acres, include many large shallow bays behind the barrier islands. Additionally, thousands of acres of adjacent marsh and bayous provide habitat for juvenile forms of economically important marine species and also cycle and produce nutrients for the estuarine areas. The ecosystems which have evolved within these estuarine areas are vitally dependent upon the amount, seasonal, and spatial distribution of fresh water inflows and associated nutrients from the river. However, coastal tributary streams, marsh areas, and direct rainfall funoff within the adjacent coastal basins also play a key role in the ecological structure of the estuaries.

Texas estuarine esystems are shallow, irregularly shpaed, and generally well-mixed bodies of water. Critical environmental parameters vary, sometimes widely, between estuarine systems. For example, the Sabine-Neches Estuary in far East Texas has runoff contributions from watersheds which receive an average precipitation of 55 inches annually as compared to the Guadalupe Estuary drainage system with 35 inches annually, the Nueces Estuary drainage system with 25 inches annually, and the lower Laguna Madre drainage with about 20 inches annually (Figure II-2). The regional variance in gross evaporation rates is shown in Figure II-3.

The seasonal distribution of fresh water inflows (Figures II-4 and 5) to Texas estuarine systems has strongly influenced the biological-hydrological relationship which have evolved. Migratory nekton populations

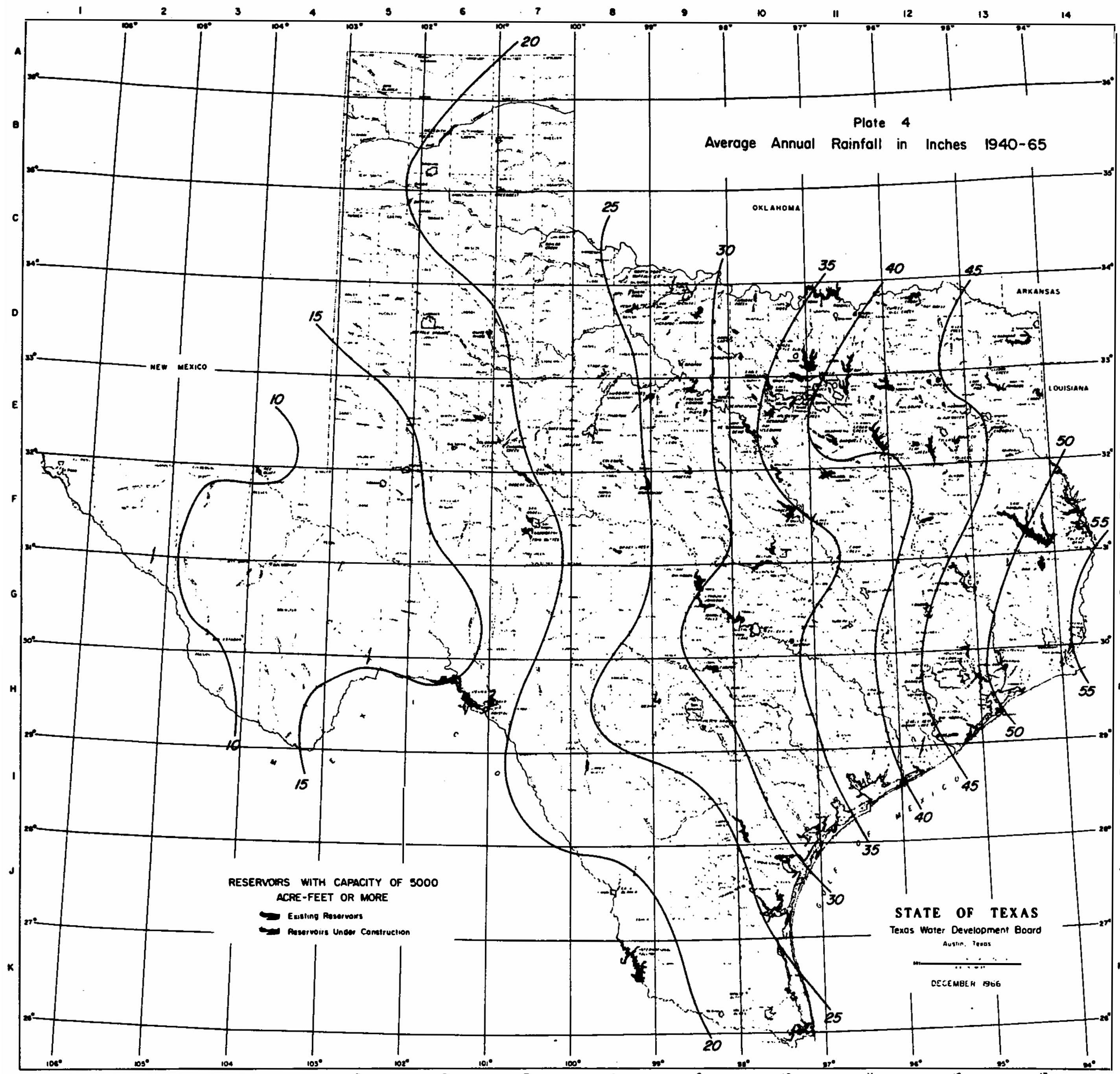

Figure II-2
Average Annual Rainfall, in Inches 1940-65

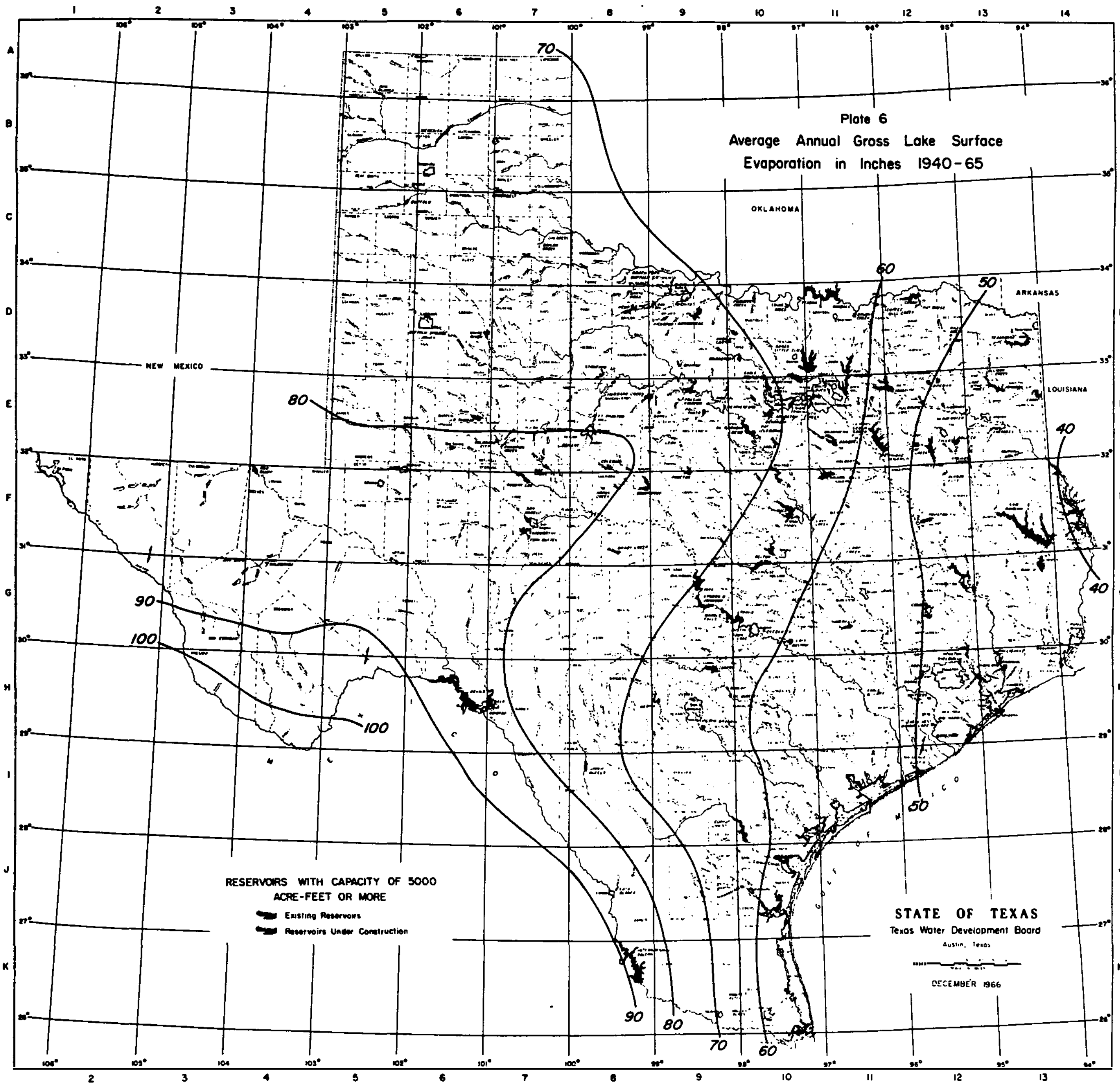

Figure II-3
Average Annual Gross Lake Surface
Evaporation, in Inches 1940-65

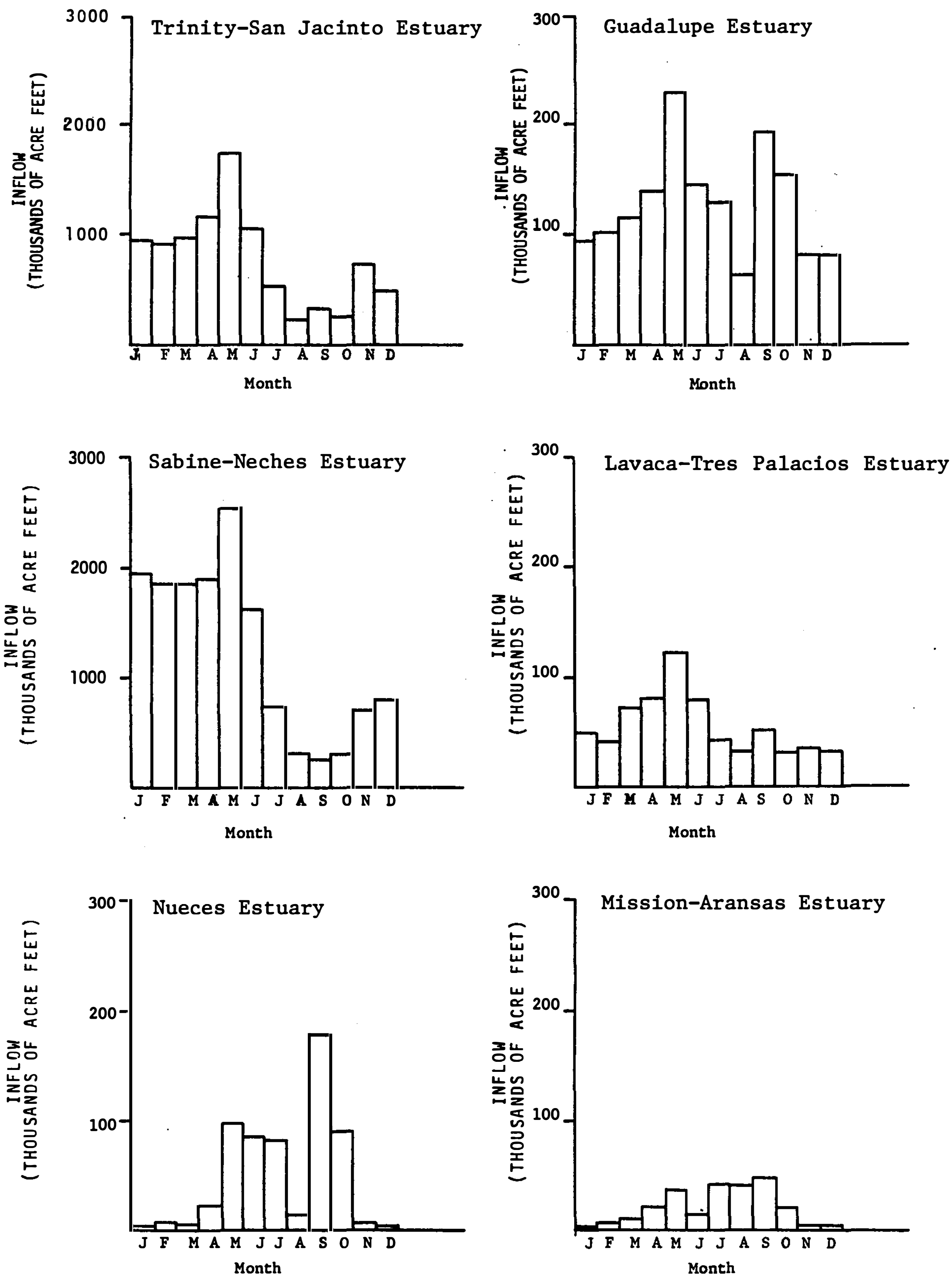

Figure II-4
Monthly Distribution of Fresh Water
Inflow to the Bays and Estuaries (1941-1965)

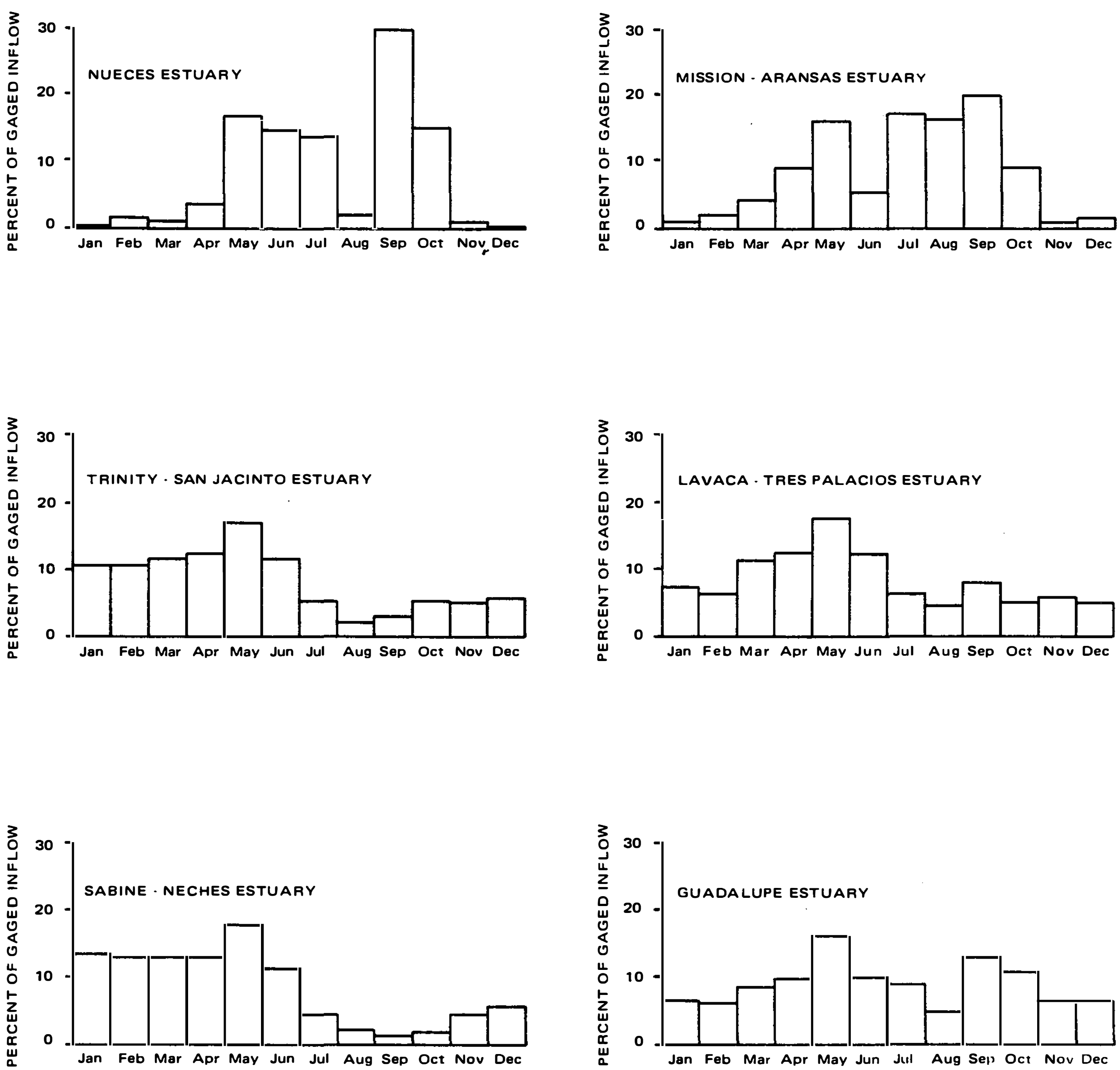

Figure II-5

Historic Monthly Distribution of Fresh Water Inflow to the Bays and Estuaries of Texas Based on Monthly Averages of the 1940-1946 and 1950-1956 Wet and Dry Periods, Respectively are acclimated to a varying range of seasonal fresh water inflows to the estuarine systems. The monthly average historical fresh water inflow distribution for the Guadalupe Estuary reflects a steady increase from January, peaks in May, declines in the summer months, peaks again September, and steadily declines during the remainder of the calendar year (Figure II-4).

In terms of energy input to the estuarine systems, the most productive and most dynamic of the estuarine habitats are tertiary bays. The tertiary bays are shallow areas where sunlight can effectively penetrate the water column and stimulate submerged vegetation. Substantial chemical energy is produced in these areas due to photosynthetic processes. Nutrient biostimulants are distributed throughout the estuarine system by tide and wave action.

Texas estuaries, due to their dynamic nature, are highly productive ecosystems. Severe droughts, floods, and hurricanes are the major climatic variables which exert control and influence over the estuarine ecosystems. The number of total species remain low, while numbers of organisms within a species fluctuates with the normal seasonal regime, as well as with climate drought and wet cycles. This type of regime provides for a continuing "shift" in dominant organisms, thereby preventing a single species from maintaining temporal dominance. By comparison a reservoir, through the process of eutrophication, becomes stagnant and often dominated by undesirable biological organisms.

Natural stresses encountered in an estuarine ecosystems are due, in part, to the fact that these areas represent the transition zone from fresh water to marine environments. In estuaries, biological community composition changes quantitively with respect to number of species and types of organism, as shown in Figure II-6. The number of species is lowest in the estuarine

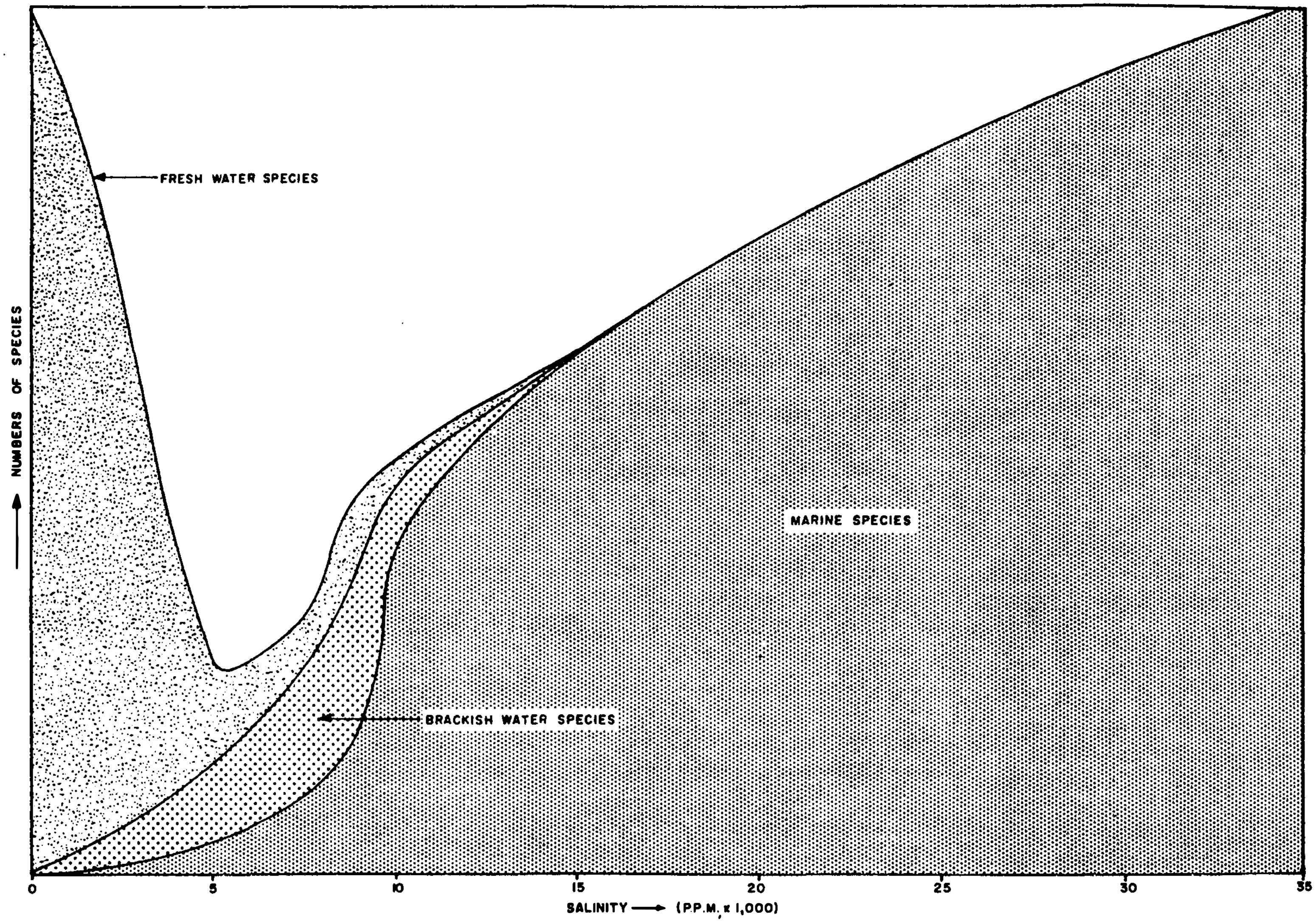

Figure II-6
Composition of Estuarine Environments

transition zone between fresh water and marine environments. The biological community which develops in a system depends to a great extent upon the relationships among environmental factors, species characteristics, and species functions in the ecosystem. The species composition of a community may vary taxonomically from one geographic locality to another, however, many species have wide distributions in Texas bays and estuaries.

A characteristic of Texas estuarine systems is that many of the organisms are not permanent residents, but spend only part of their life cycle in the estuary. Migration patterns constitute an integral part of the life history of many marine organisms. These migrations occur in seasonal cycles, many being for the purpose of reproduction. Larval and postlarval organisms immigrate into the estuary, because of food and physiological requirements and/or the need for low salinity waters to protect them against competing species, predators, and parasites which may elimate them in higher salinity waters. The juvenile forms use these highly productive nursery areas during early growth, and emigrate back to the Gulf of Mexico as adults.

Figure II-7, a hypothetical cross-section of a typical salt water marsh, illustrates the typical low channel banks which are inundated by high tides and/or river flows. In salt marsh areas, inorganic materials and organic detritus transported by river floods are cycled and assimilated through biological action and converted to organic tissue. This conversion is accomplished by the primary producers (phytoplankton and macrophytes) of the marsh ecosystem. The primary producers and organic materials produced in the marsh are transported to the bay system by an inundation-dewatering process. This process is controlled by the Gulf of Mexico tidal regime and river flood stages. The inundation-dewatering process is vitally important as a transport mechanisms for biostimulants.

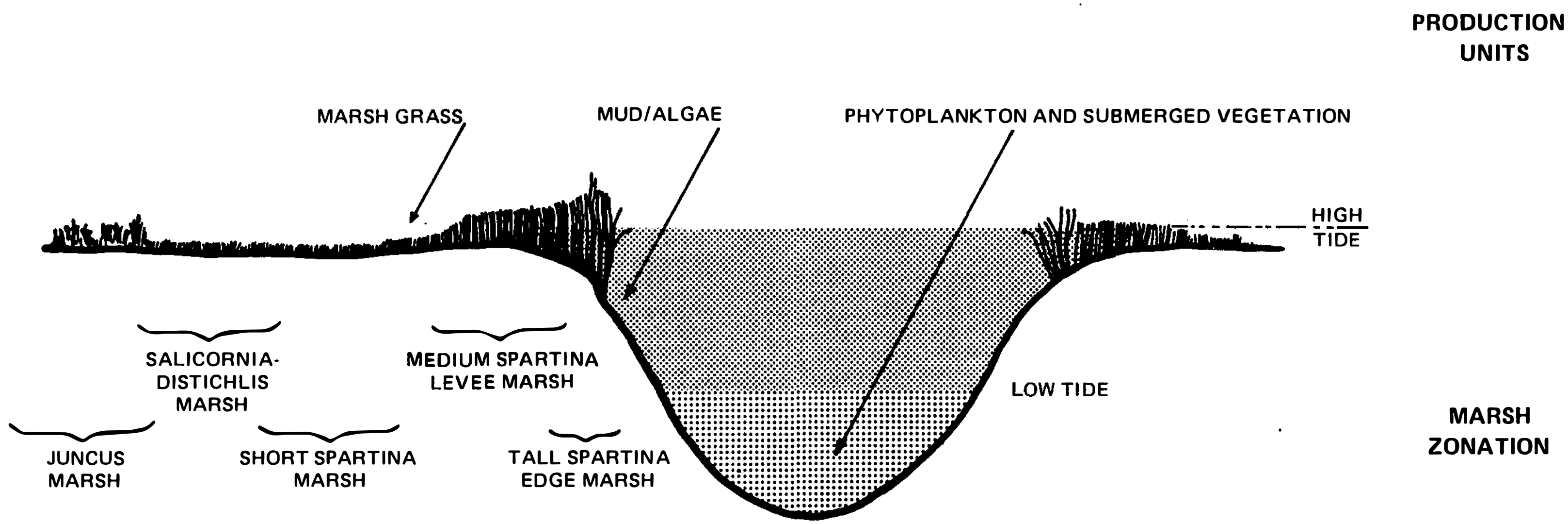

Figure II-7
Zonation in a Salt Marsh in Texas Estuary

It is important that the natural timing of fresh water inflows and high tidal action coincide with the migratory patterns of dominant estuarine species. If the natural timing of inundation does not correspond to the migratory patterns for certain economically important estuarine organisms, such as white shrimp estuarine conditions will not be conducive to optimal species growth. Coincidence of these events is made more complex by antecedent and ambient water temperature factors. For example, Guadalupe Estuary has an average water surface area of 143,000 acres and an average depth of about six (6) feet. Systems such as this tend to be highly sensitive and to air and associated water temperature changes. Growth and survival air and water temperature regimes. Consequently, inundation which supplies biostimulants to the estuarine system and the early stages of migratory patterns may coincide, but if the antecedent and ambient water temperatures are not optimum, the growth and survival of the species will be limited.

Many migratory organism species inhabit Texas estuarine systems at various stages of their life cycle. These organisms depend upon the estuarine system in their early development, generally during their postlarval and juvenile stages. Many finfish and shellfish species are dependent upon the estuarine system in their early life stages during different seasons. Penaeid shrimp species are primarily dependent on the estuarine system during the spring and summer. Finfish species, such as redfish, appear to be dependent upon the estuarine system during the fall months.

Not all nektonic organisms which utilize the estuarine system are migratory. Generally, about 25 percent of these animals can be classified as residents, that is, their complete life cycle occurs within the estuarine system.

Texas estuarine systems are extremely complex ecosystems. The complex interactions of hydrographic, chemical, physical, and biological parameters make it extremely difficult to completely define the intricate interrelationships of the estuarine ecosystem. However, major environmental factors and identifiable biological populations can be used as "key" indicators to understand and demonstrate the response (productivity) of higher food chain organisms to major changes in the ecosystem.

THE TEST CASE

To provide an example problem for use in the research described in this report, the Board selected one of its a current regional planning efforts, The San Antonio Regional Environmental Project, which is designed to provide alternative development and management plans for meeting the long-range water needs of a three river basin, semi-arid region of Texas. The focus of this study is to meet the urgent, short-term water supply problems of the San Antonio, Texas metropolitan complex, and the longer range water development and management problems of the Guadalupe, San Antonio, and Nueces River Basins and their associated estuaries Guadalupe Estuary and Nueces Estuary.

Description of Study Area

Figure II-8 shows the location and pertinent details of the study area. The area is composed principally of the Gulf Coastal Plains and includes a small but significant portion of the Edwards Plateau. Typical natural vegetation of the South Texas Plains that lie south of San Antonio between the Coast and the Rio Grande includes twenty (20) million acres of subtropical, dry land vegetation consisting of small trees, shrubs, cactus, weeds, and grasses. The Edwards Plateau consists of wooded rolling to locally deeply-disected topography within the study area.

There are two major areas of water use within the region. One is referred to as the Winter Garden Area, which consists of approximate 11,800 square miles and overlies the Carrizo Aquifer (See Figure II-8). The predominant use of water in this area is for irrigated agriculture which includes the production of grain sorghum, cotton, vegetables, pecans, peanuts, fruits and the feeding of livestock. The greatest water use within the region is the metropolitan and irrigated agricultural development along a strip about 180 miles long and five to 50 miles wide which overlies the Edwards and Associated Limestones, a major ground water aquifer of Texas (Figure II-8). This underground reservoir is a water supply source for many municipalities, for irrigation, and for military installations and industrial development in and around San Antonio. North of this strip, tributaries of the Nueces, Guadalupe, and San Antonio River flowing from the Edwards Plateau provide most of the recharge to the Edwards Aquifer as they flow across highly faulted areas where cavernous limestone crops out at the surface. The Edwards Aquifer is also the source of water for major springs in each of the three river basins, including Comal Spring in New Braunfels, one of the largest in the Southwestern part of the United States, and San Marcos Springs, in which there has developed an unusual and unique aquatic ecosystem. These spring discharges into the Guadalupe River Basin constitute a significant portion of the present downstream water supply. In addition, the springs and rivers provide a continuous flow which feed the Guadalupe Estuary.

The bay system, with about 143,000 surface acres, is the third largest inland bay system on the Texas Coast. It consists of Guadalupe, San Antonio, Espiritu-Santo, Hynes, and Mesquite Bays (Figure II-9). Rainfall in the area has averaged about 35 inches per year, and the mean annual temperature is about 69°F. Gross evaporation averages about 55 inches per year, resulting in an average net evaporation (gross evaporation-precipitation) of about 20 inches per year.

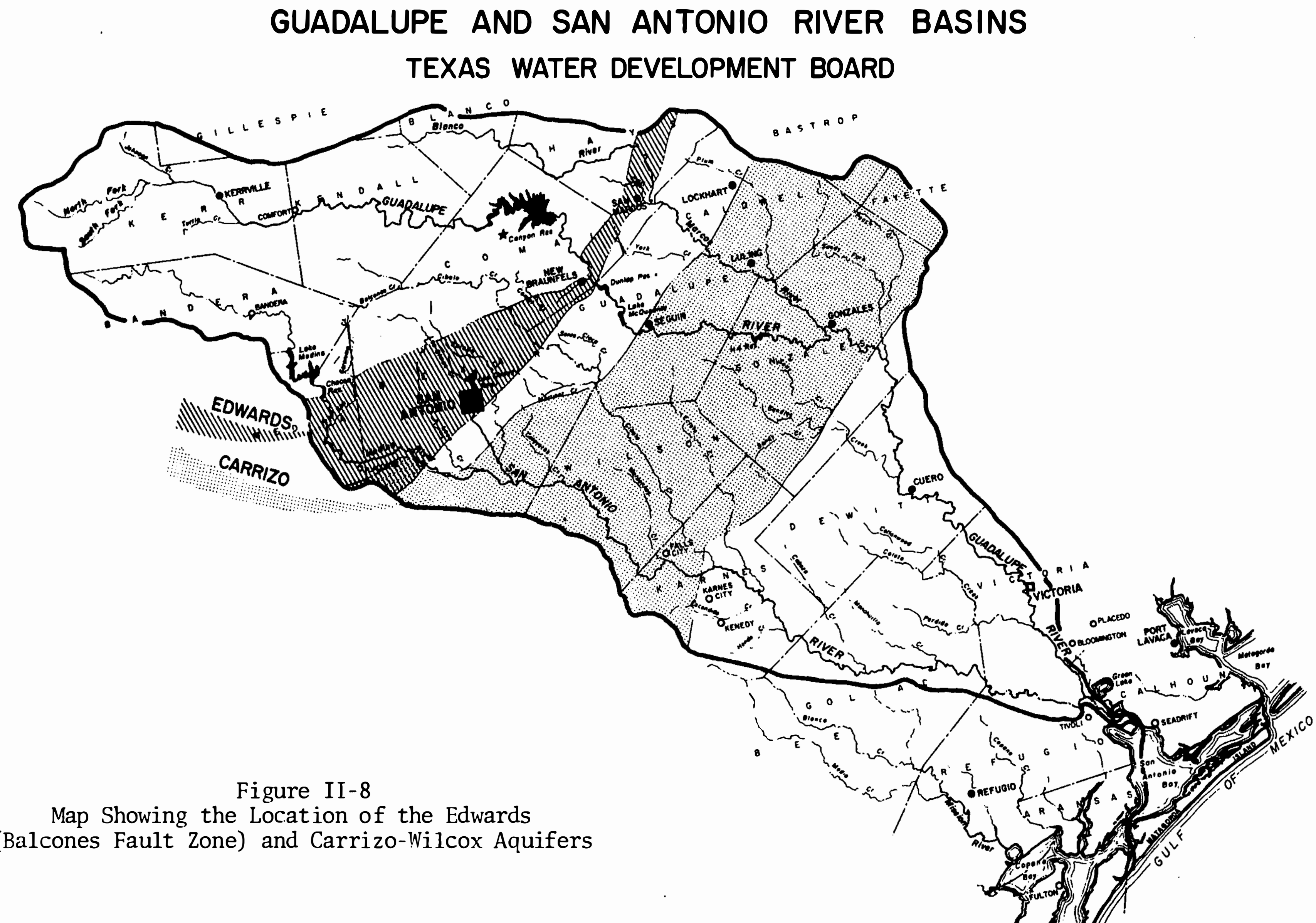

Figure II-8
Map Showing the Location of the Edwards
(Balcones Fault Zone) and Carrizo-Wilcox Aquifers

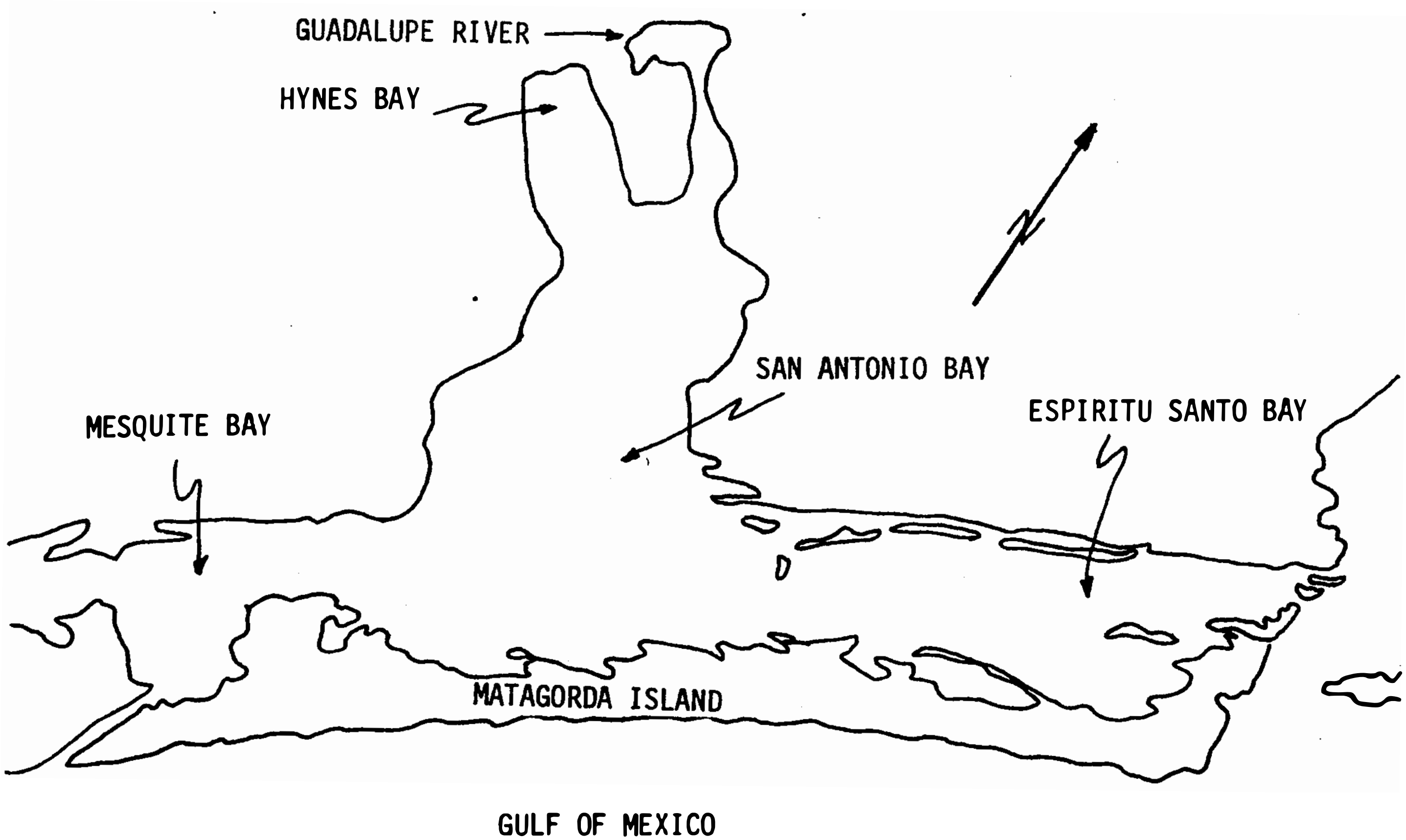

Figure II-9
Guadalupe Estuary

Presently, only two major industries are located in the Guadalupe Estuary area, and the bay ranks third in fishery resources on the Texas coast far exceeded by Matagorda and Galveston Bays. In terms of tourism, the Guadalupe Estuary is presently less developed than the Trinity-San Jacinto Estuary and the Nueces Estuary.

Inflows of fresh water to the Guadalupe Estuary historically averaged about 1.5 million acre-feet per year during the period 1941-1957. Approximately 0.2 million acre-feet of the total is derived from local coastal area runoff. An average of about 0.4 million acre-feet of precipitation is estimated to fall directly on the bay annually. Consequently, fresh water available to the bay historically has averaged about 1.9 million acre-feet per year.

Canyon Reservoir is the only existing major storage reservoir in the Guadalupe River Basin, providing both water supply and flood control storage. Supplies from the lower basin are presently diverted to the adjacent Lavaca-Guadalupe Coastal Basin under existing State permits. There are six small hydro-electric dams on the Guadalupe River downstream from New Braunfels. Although not a major reservoir, the existing salt water barrier below the confluence of the San Antonio and Guadalupe Rivers is important to basin development and operation. This collapsible fabric dam prevents salt water intrusion upstream.

Ingram, Cloptin Crossing, Lockhart, and Cuero 1 and 2 are reservoirs proposed for construction in the Guadalupe Basin in the Texas Water Plan (See Figure II-10). These together with Canyon Reservoir would provide flood control, water supply storage for both in-basin supply and interbasin transfer, and a potential recreational complex to supplement the present recreational development at Canyon Reservoir.

Major existing reservoirs in the San Antonio River Basin include Medina Lake on the Medina River, which provides water supply for irrigation in the

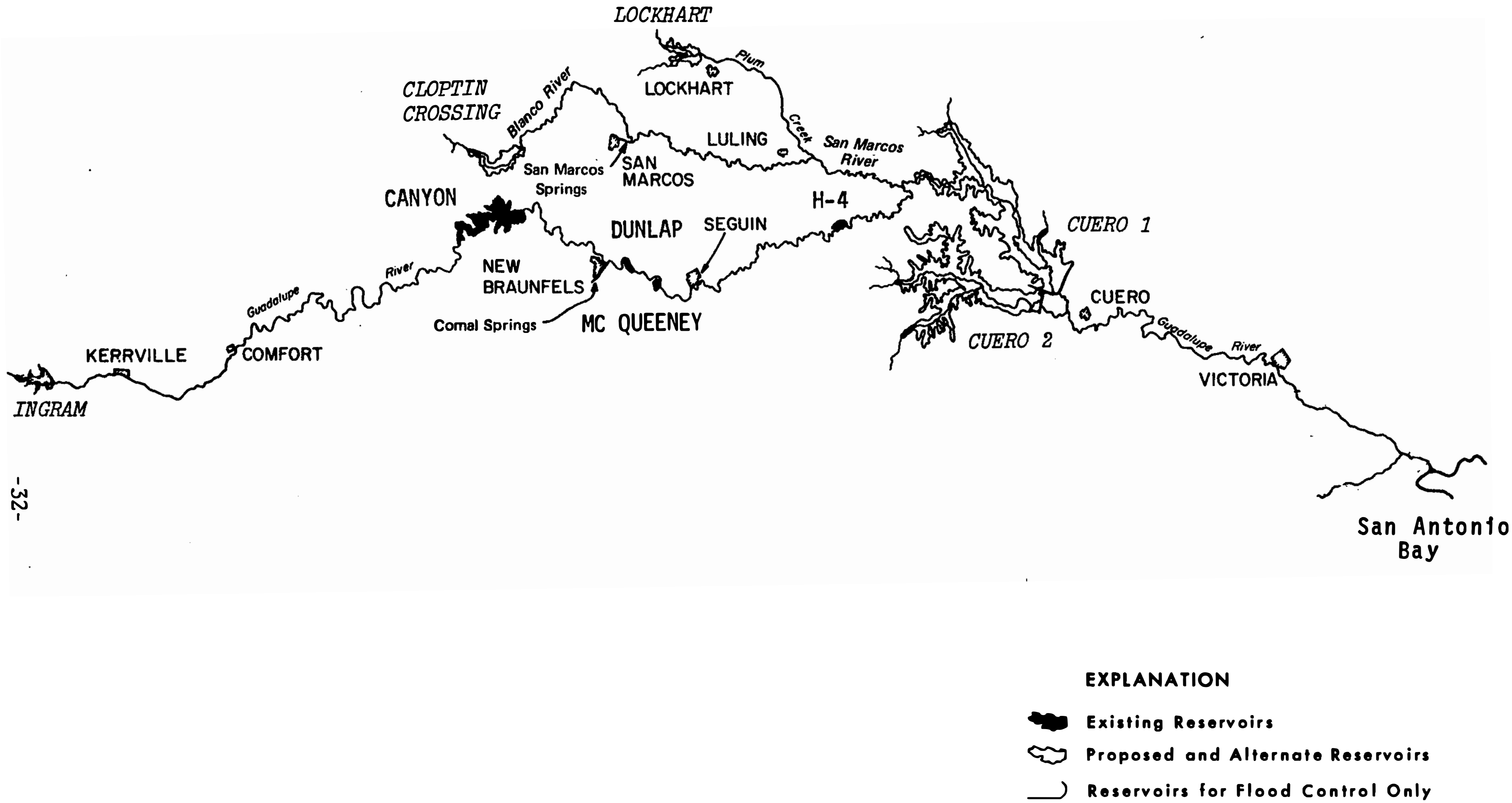

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Figure II-10
Guadalupe River Basin

San Antonio and adjoining Nueces River Basins under existing permits, and Olmos Reservoir, which provides flood control storage north of San Antonio. Supplies from Victor Braunig Lake and Calaveras Creek Reservoir are used for cooling water for steam-electric generation plants.

Cibolo and Goliad Reservoirs are proposed for additional development of the surface water resources of the basin under the Texas Water Plan (See Figure II-11). They would provide in-basin water supply needed flood control storage to mitigate flood hazards in the lower basin, and projected surpluses for potential export to other areas of water needs in the State.

The Edwards and Carrizo Aquifers hydrologically connect the upper parts of the three river basins; the Guadalupe, San Antonio, and Nueces. The three basins are similar in topography, geology, and hydrology. This hydrologic interconnection justifies the validity of regarding portions or all of these basins as a unit for developing means of meeting projected water requirements, while continuing to recognize the individuality of each river basin.

The Problem

The San Antonio region has, over the past twenty years, been experiencing one of the highest rates of population growth in the nation. The City of San Antonio, rich in history, the third largest city in the State, and the thirty-eight largest metropolitan area in the United States, is the hub of the region. San Antcnio is one of the nation's leading military centers and derives a large portion of its total revenues from federal spending. It also has a large tourist trade and serves the San Antonio region, as defined in this project, as the wholesale, retail, and distribution center. Recreational opportunities abound, especially for those interested in historic sites. In recent years the surrounding Texas hill country and nearby lakes have become

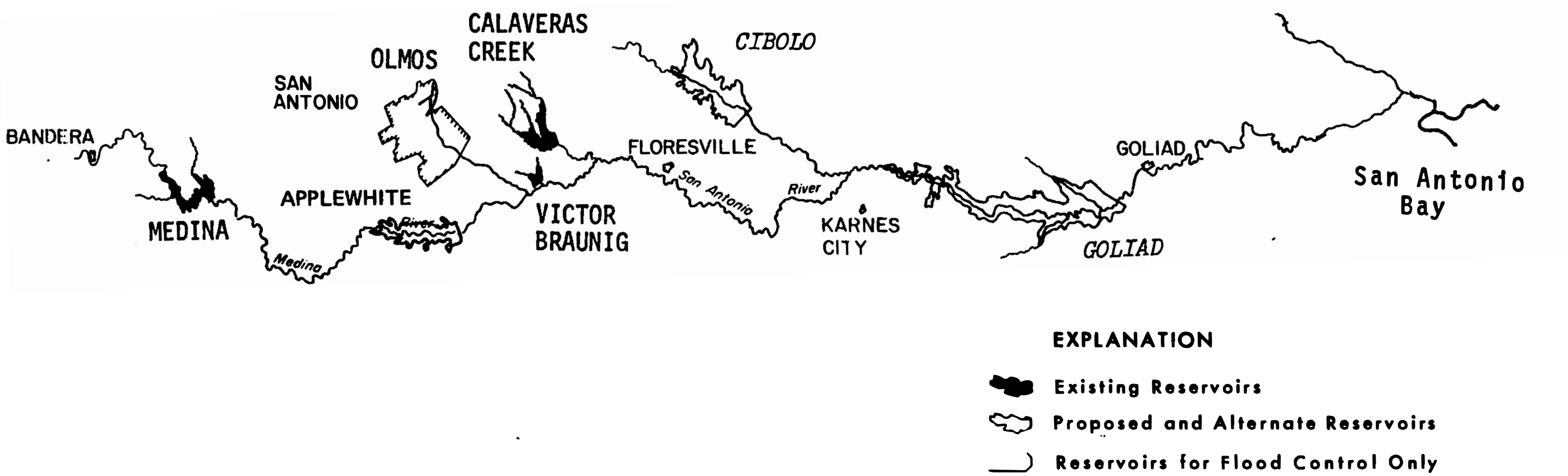


Figure II
San Antonio River Basin

extremely popular with visitors. This hill country is one of Texas' most popular area for vacation and retirement homes and growth along the Balcones Fault Zone is expanding rapidly. Other major cities in the region include Corpus Christi, New Braunfels. San Marcos, Seguin, Gonzales, and Victoria?

In the rural areas of the region irrigated agriculture, the production of minerals (principally oil and gas) and recreation provide the principal economic base. Below the Balcones Fault Zone, and particularly in the Winter Garden area, irrigated agriculture dominates the economy. There is also considerable amount of new irrigation of land overlying the Edwards Aquifer in the western parts of the region. The historic rate of irrigation development in the Carrizo and Edwards Aquifers if continued unconstrained and the increasing unrestrained municipal and industrial pumping from the Edwards Aquifer will result in: (1) marked variations in water levels in the underground reservoirs, (2) more frequent long periods of little or no spring flows, and (3) reduction in the dependable quantity of water available for all uses.

For this reason the Board has embarked on a multi-discipline planning effort to evaluate and recommend alternatives for meeting the future requirements of the area while maintaining the current high value of the natural environment of the region.

In summary, the Guadalupe and San Antonio River Basins and their associated estuarine system, the Guadalupe Estuary, provide an excellent test case with which to develop and verify the ecological modeling methodologies. The Guadalupe Estuary has been under intensive investigation by the Board, Texas Parks and Wildlife Department, U.S. Geological Survey, and various universities.

A large amount of physical, chemical, and biological data are available for use in this research project. The Guadalupe Estuary also is relatively free from man-made pollution and current upstream regulation of streamflow is minimal. Thus, the availability of data, the existence of relatively "natural" conditions in the study area, and the compatibility with the Board's current planning activities in the area were the determining factors in its selection as a test case for the research effort described in this report.

III. THE ANALYTICAL FRAMEWORK

The highly complex nature of a modern water resource development plan for a river basin and its associated estuary precludes a simple analysis and evaluation of alternative implementation actions. This analysis and evaluation must consider the total feasibility or each alternative from hydrologic, physical, environmental, economic, and social viewpoints. The social and economic aspects involved were beyond the scope of this research project; however, this chapter describes a methodology developed in this research which can be used to consider the hydrological, physical, and environmental aspects of water resources development in a comprehensive systematic, and interactive manner so that the important variables can be adequately evaluated and weighed at varying levels of detail. In general, the following discussions are intended to indicate:

- the approach followed,
- the procedures and analytical techniques that were used, and
- the parameters involved.

THE APPROACH

The basic approach followed during this research effort involved application of an integrated set of digital simulation models in an interactive manner as depicted in Figure III-1. Alternative water resource management policies are then analyzed on an individual basis under varying hydrologic conditions using a three-phase approach described below.

RIVER BASIN SIMULATION AND OPTIMIZATION

The hydrologic operation of a river basin for a selected management policy is performed on a monthly basis through the application of river basin simulation and optimization models. These models provide the hydrologic inputs to the stream, reservoir, and estuarine quality - ecological

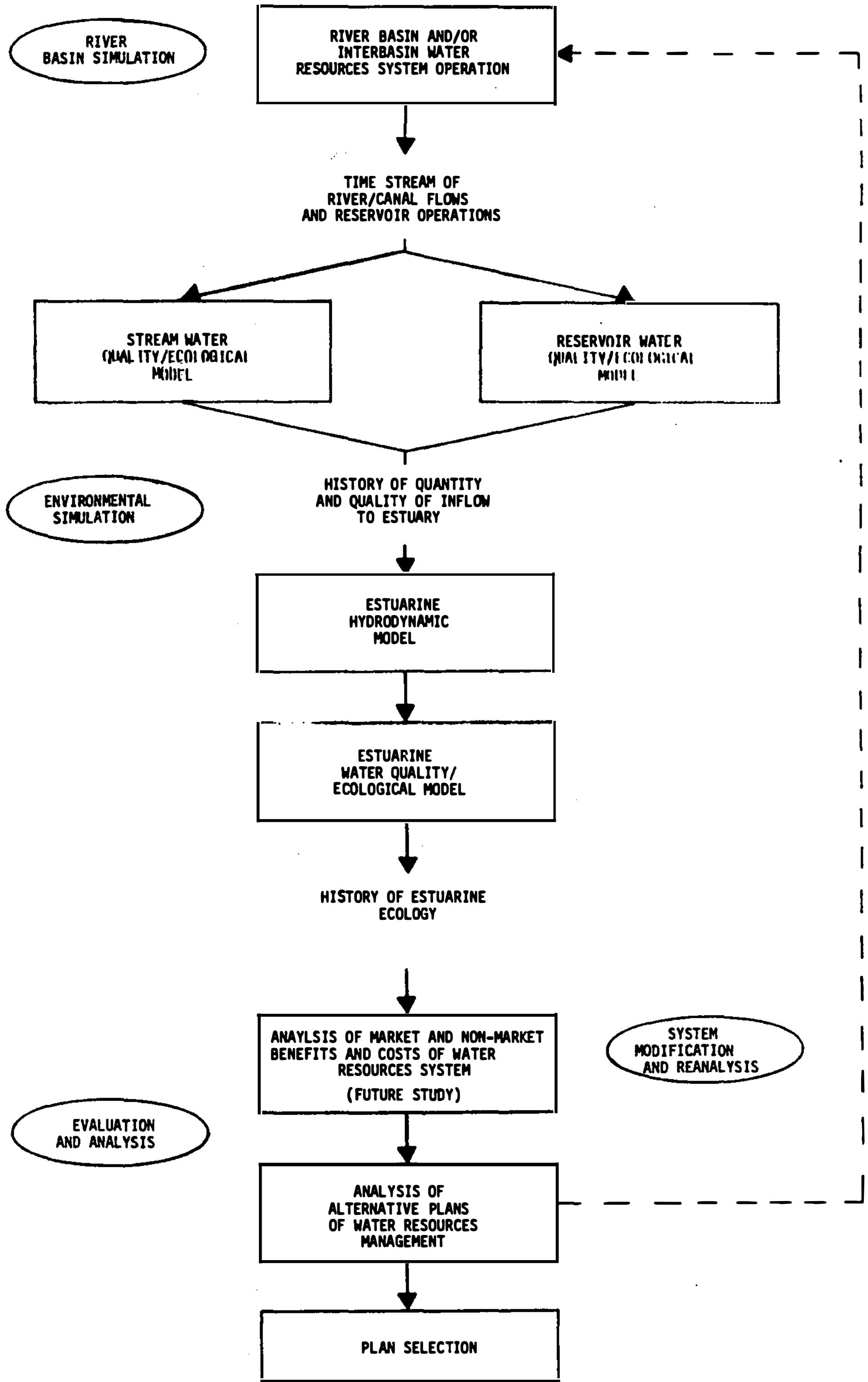


Figure III-1

Proposed Interactive Technique for Evaluating the Ecological Effects of Water Resources Development models. This phase of the methodology, which is discussed in detail in Report 131 (TWDB, 1971) and Appendix A of this report, involves selecting the sequence, size, timing of construction, and operation of an interconnected set of surface reservoirs, canals, and river reaches. The six steps involved in this phase are summarized as follows:

Step one - Identification of Objectives and Goals

Step One consists of identifying the goals to be met and the purposes to be served. This is perhaps the most difficult part of the planning process, but is the most important, and must be done before an optimal implementation plan can be selected. It is suggested that planners using the strategy should (1) specify an objective or goal including no action that serves the purposes defined as important in their orders of priority, (2) strive to find the resulting implementation plan to meet the goal, and (3) then decide, based upon the trade-offs present and risks involved, if the selected development plan or a modified version of it representing a lower or higher risk plan should be implemented. Meeting water demands at minimum expected cost, with minimum shortages, is one of the possible objectives that could be specified.

Step Two - Analysis and Development of Data Base

Step Two consists of developing a comprehensive data base for use in Steps Three through Six. This step requires two major types of data preparation activities. The first activity is that of developing, for use in the simulation and optimization models, a stochastic hydrologic data base comprised of

- refined runoff or reservoir inflow data,
- gross evaporation or climatic index data,
- net lake-surface evaporation data developed from rainfall data and gross evaporation data,

- irrigation water requirements developed by a consumptive use model, and
- municipal and industrial water requirements.

The second activity comprises the development of parameters which describe the system and the problem being studied, such as

- cost-capacity-elevation-area relationships for each reservoir and canal being considered in the analysis,
- the discount rate, repayment period, reservoir financing lag time, and pump-canal financing lag time used to calculate present value costs of capital investment and operation and maintenance costs, and
- data describing the physical and other characteristics of the system being analyzed.

To enhance the results of this step, trend analysis programs, data fill-in programs, stochastic data generation programs, and flow refinement and projection programs are used to help preserve the appropriate cross and serial correlations within each of the data sets, and thus develop a sound comprehensive data base at various levels of basin development for all subsequent steps in the planning and design process.

One of the unique characteristics of this methodology is the treatment of the stochastic element in both the runoff and the demands for water. Therefore, in addition to using a refined historical "filled-in" data set, a large number of stochastic sets of rainfall, runoff, and evaporation data, and unit demands for water can also be used.

The water supply also has a stochastic component. The variability of that component may be as great or greater than the demand variability, depending on the characteristics of the problem.

Step Three - Plan Development Based on Historical Data

Step Three consists of an initial analysis of the river basins and portions of river basins comprising the multibasin planning problem. The purposes of this analysis are to

- determine how to best control the available runoff,
- compute the amount of water that the system can be expected to yield,
- determine preliminarily how to develop the best set of storage and transfer facilities to move available supplies to use areas, and
- determine preliminarily the magnitude of the demands that can be met with the available supply.

From a water supply viewpoint, various locations and sizes of possible reservoirs are investigated in an attempt to find the storage arrangement that controls the runoff in each watershed at minimum unit storage cost (dollars per acre-foot of storage), yet makes sure that the major storage reservoirs, if possible, are near the major in-basin demand points.

To aid in this process, SIMYLD-II, a river basin simulation and optimization model, is utilized. SIMYLD-II computes the firm yield for any specified network of reservoirs and interconnecting river reaches and pump-canals with given maximum capacities and seasonal low-flow release constraints. The firm yields computed can and should be based upon numerous practicable assumptions about (1) seasonal distribution of the imposed demands and (2) spatial location of the demand within or external to the basin storage configuration. These computations are performed under various projected levels of watershed development (e.g., 1990, 2000, 2010, and 2020 conditions) using, as input, the refined historical and projected data base developed in Step Two.

Step Four - Plan Improvement Based on Historical Data

Step Four uses several simulation models, primarily SIM-IV and AL-IV, to help find "good" fixed plans at various demand levels (e.g., the 1990, 2000, 2010, and 2020 levels) using the refined historical data base projected to various future times on the demand buildup curve. This analysis is based on evaluating system performance of selected alternative sets of canals, reservoirs, and operation criteria over a specified economic life. A penalty cost is used to account for the economic impact of water shortages. This penalty cost, multiplied by the shortages (in acre-feet), results in the total penalty for failure to meet demands.

Based upon a series of initial simulations of the entire network, with each canal's maximum capacity set at a relatively high value, the models compute

- the amount of usage that each of the canals would get during a selected multi-year simulation period,
- the absolute maximum flow in each of the canals, and
- the ratios of maximum to mean flow in each of the canals.

Based upon these observations and the change in the economic response of the system (i.e., the total cost change) resulting from the iterative use of SIM-IV and AL-IV, certain canals of very low usage can be eliminated from further consideration. The maximum-capacity constraints of each of the canals left in the network can be successively reduced, from simulation to simulation, to levels that approached a minimum-cost solution. Here, the total cost response is the sum of (1) the construction costs multiplied by a present worth factor equal to unity, and (2) the sum of annual operation costs over a 100-year period.

Upon preliminary sizing of the ultimate ditch portion of the canal facility, the analysis is directed towards defining an optimal system (location, size, and operation criteria) for specified points on the demand buildup curve starting with the earlies point first.

Step Five - Plan Optimization Based on Historical and Stochastic Data

Step Five is designed to analyze and improve the "good" but sub-optimal plans derived in Step Four, using both the historical and selected stochastic sequences of hydrologic and corresponding demand data generated in Step Two. The SIM-IV model is used for the detailed analyses performed in Step Five. Step Five is also designed to

- quantify the impact that location of drought within the demand buildup period, in addition to magnitude, duration, and frequency of drought occurrence, has on selecting the optimal implementation plan,
- quantify changes in the "good" plans derived in Step Four which are required to secure more cost-effective (in terms of minimizing total costs) performance, and
- find the single implementation plan (the minimum-cost plan) which performs better against the historical and synthetic buildup in demand and project supply sequences than any other plan.

Step Six - Variability and Sensitivity Analysis

Step Six is the last step in the multibasin planning strategy discussed and consists of an extensive variability and sensitivity analysis. The purpose of this analysis is to subject the minimum-expected-cost plan found in Step Five to conditions other than the specified "best estimate" conditions assigned to many of the independent variables at the beginning of the analysis. Typical factors for which data are varied include the canal costs, the reservoir costs, the initial storage conditions, the buildup rate in the number of acres to be irrigated, the cropping pattern variables, the mean available water supply, the municipal and industrial demand levels, the amount and time at which import water is available, the mean of the evaporation variable, and the unit power cost.

ENVIRONMENTAL ANALYSIS

A water project, whether it involves the construction of a reservoir, pumping of ground water, desalinization of sea water or brackish inland waters, or the reuse of waste waters, has immediate and measurable impacts on the environment. The impacts may be both negative and positive, and the judgment of whether the overall project effect is negative or positive is often related to the attitudes of society. Therefore, it may be difficult to identify, at the inception of a project, whether or not potential environmental changes will ultimately be viewed as beneficial or adverse. Additionally, many environmental effects of water projects are subtle and do not manifest themselves until considerable periods of time after construction of the project. For these reasons, detailed analysis of the potential environmental changes is necessary for planning and management. To date, environmental assessments of this type for water resource projects have been largely qualitative or semiquantitative in nature; examples include estimates of acres of hardwood forest lost and miles of shoreline created.

Potential changes in aquatic and terrestrial ecosystems are usually based on professional estimates of the individual situations being studied. Frequently these estimates are guesses since basic data are often scarce and/or unreliable. Quantitative measures of potential biological changes are rare and usually unsatisfactory. In addition, these measures often fail to show adequately the interactions among the different trophic levels of the affected ecosystem. It is necessary to consider these interactions because the altered environmental conditions due to a project may not directly affect an organism in the upper trophic levels but rather may eliminate an organism in the food chain, which in turn could lead to reduction of an economically important higher trophic level organism. Other environmental effects might include the elimination or alteration of habitat, causing conditions unsuitable for the existing living resources of the estuarine ecosystem.

The factors which must be considered in an environmental analysis of a water resource project are discussed below along with the analytical techniques utilized to estimate these environmental changes. The emphasis is on determining aquatic environmental effects by the use of computerized simulation models; however, the potential exists for development of similar analytical models to analyze terrestrail environmental effects. This would complete the cycle of interaction between land and water environments.

Some Interrelationships of Water Use, Land Use, and the Environment

The interrelationship among water use, land use, and environmental quality are so pervasive that it is impossible to consider them all in a planning analysis of a water resources project. As previously discussed, every action which man takes in either the land, air, or water environment has an effect on the total environment although it may not be instantaneously measurable. The following discussion gives the major interactions known to be significant and which should be emphasized when a water project is planned.

Figure III-2 illustrates some of the major interconnections between aquatic and terrestrial ecosystems and land and water use. The terrestrial systems are considered to include the air environment and creatures inhabiting it. As shown in Figure III-2, land use affects water use; water use can affect water projects; water projects, water use, and land use all affect water quality and the aquatic and terrestrial ecosystems. The reverse linkages are equally important. An almost infinite number of physical loops and feedbacks functionally relate the construction of a water project and the subsequent use of the water to the terrestrial and aquatic environments. These relationships should be recognized during planning activities and evaluated when judged to be potentially significant.

Table III-1 exhibits the environmental effects of water use and development and divides the human activities related to water use and development into three major areas: water use related effects, land use related effects, and project development related effects. This classification is rather arbitrary but instructive. Only the most readily identifiable effects are shown and treated in this research project.

The environmental effects of water development and use in Table III-1 are divided into two major areas: (1) water quality effects direct changes in water quality and (2) physical effects on the aquatic environment. The physical effects include geomorphic changes, depletion of water by evaporation and mixing of unlike waters which may also result in water quality effects.

The water use related factors include effects resulting from agricultural, industrial (both for process and cooling), municipal and domestic, and recreational use of water. All of these types of uses can result in effects on water quality and potential changes in the physical environment of an aquatic ecosystem. For example, agricultural water use can result in return

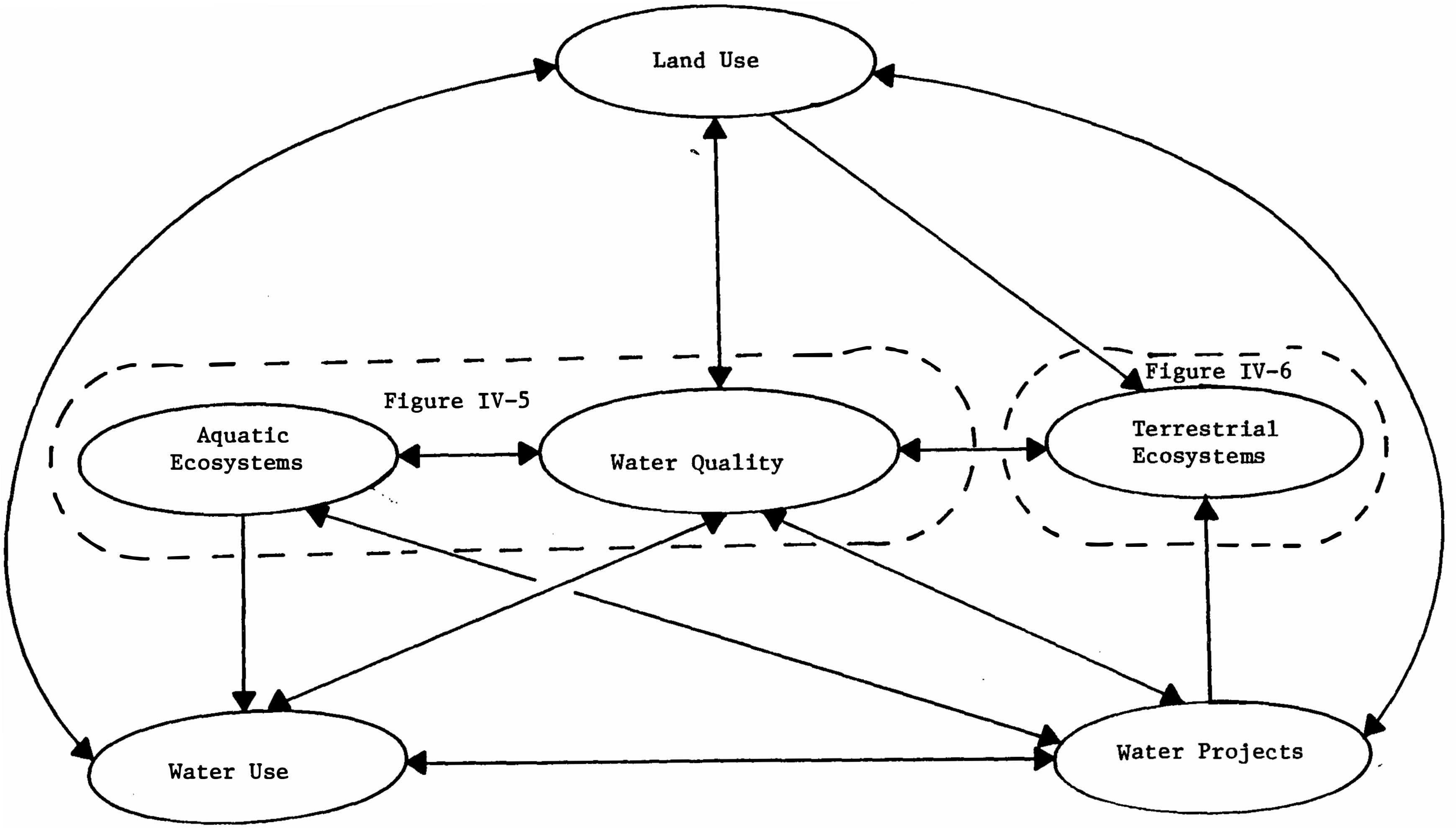


Figure III-2
Major Connections Between Aquatic and Terrestrial Ecosystems
and Land and Water Use

TABLE III-1

ENVIRONMENTAL EFFECTS OF WATER USE AND DEVELOPMENT

SPECIFIED HUMAN ACTIVITIES	WATER QUALITY EFFECTS	PHYSICAL EFFECTS
WATER USE RELATED		
Agricultural	N, S, T, Sa, O	De, Sed
Industrial		
Process	N, T, Sa, O	De
Cooling	T, H, Sa	De
Municipal	N, T, Sa, O, P	De, Sed
Recreational	O, N, P	
LAND USE RELATED		
Agricultural	N, S, T, Sa, O	De, Sed, Hy
Urban	N, T, S, O	De, Sed, Hy
PROJECT DEVELOPMENT RELATED		
Reservoirs	N, S, Sa, O, H	Hyd, Ch, Sed, De, Hy
Water Transfer Facilities	Sa, N	Re, Hyd, Ch, Sed, De
Flood Protection	S, N, O, Sa	Hyd, Ch, Sed, De, Hy
Groundwater Development	Sa, N, T, O	Su, De
Navigation	N, T, S, O	Hyd, Ch, Sed
Desalinization	Sa, N, T	
Wastewater Reuse	N, T, Sa, O, P	De
Phreatophyte Control	S, Sa, O, N	Ch, Sed, Hy
Soil Conservation	S, N, Sa	Sed, Ch, De, Hy
Weather Modification	Sa	De, Hy

Code of Water Quality and Physical Effects:

N	Nutrients
T	Toxicants
S	Sediment
Sa	Salts
O	Organics
H	Heat (temperature)
P	Pathogens
Hyd	Hydrodynamics
Ch	Channel Characteristics
Sed	Sedimentation Process
Re	Redistribution or Mixing of Waters of Different Origin
Su	Subsidence
De	Depletion of Water via Evaporation, Seepage, Mining Consumptive Use
Hy	Hydrologic Characteristics (Runoff, Flood Peaks, etc.)

flows and runoff containing materials such as plant nutrients, sediments, toxicants, salts, and organic materials. The related physical effects include depletion of the available water supply due to evaporation and transpiration by the crops, and channel modifications from sedimentation in the stream to which the agricultural return flows are discharged. These water quality and physical effects can cause changes in both aquatic and terrestrial ecosystems.

The water use effects discussed in the preceding paragraph are mainly a consequence of return flows or depletion of the water resource through evaporation and subsurface seepage. Land use activities may also have a direct effect on the aquatic environment irrespective of the water use relationship. For example, conversion of land from native vegetation to ridge and furrow agriculture may result in depletion of runoff from increased evapotranspiration and seepage into the subsurface. Additionally, surface runoff from these areas may contain organic and inorganic materials including nutrients, salts, and toxicants. The urbanization of land has a significant effect on surface water runoff originating in the area and also may affect underground waters. Urban runoff is generally greater in volume (per unit of surface area) and has a higher peak flow rate than does runoff originating in natural or agricultural areas because of the impermeable characteristics of the urban areas. Production of various pollutants, such as organic material and toxicants, is also generally higher from urbanized areas. Thus, changing land use patterns is an important factor to consider in regard to their effects on water quality and the environment.

An important consideration in the development of a water supply project is the potential for major land use changes in the project service area. Changes in the use of adjacent lands often follow reservoir construction.

A typical change is the transformation from a rural to a semi-urbanized or urbanized state. This may result in municipal and industrial return flows entering the reservoir with a subsequent change in water quality and, similarly, the urbanization of the area adjoining the waters of the reservoir will result in urban runoff entering the reservoir. Urban growth, if not controlled around fringes of a reservoir project, can result in substantial changes in the quality of water in the project and can severely affect the usability of the water for some purposes. This is a factor which should be considered in the project design and appropriate control measures could be implemented with the water project. A similar problem occurs when water is made available to agriculture in an area not previously irrigated. This change in land and water use can result in return flows and changes in the runoff patterns as discussed previously. These considerations must play an important part in the planning and design of any type of water resource project if the environmental and economic factors are accorded the importance they warrant.

A final major category in Table III-1 includes those environmental effects related directly to water project development. This category includes a number of different types of water resource projects. These could range from the construction of reservoirs for water supply to weather modification projects designed to enhance rainfall or minimize hail damage to crops. Each of these measures may have effects on water quality and on the physical characteristics of the water resource system being modified. These water quality-physical effects are numerous and varied and cannot be described in detail in this report. It suffices to indicate that each of the projects listed may result in the indicated changes which must be considered as the project is being planned and designed. The example problem provided in this research project illustrates how one might go about determining water quality and physical effects caused by a project, by changes in water use and by changes in land use.

Table III-2 is designed to illustrate some of the important water uses affected by water characteristics. The effects are some of the reverse linkages shown in Figure III-2. That is, the water use may affect the water quality and the water quality in turn may have an effect on the subsequent water uses. Many of these effects are inflicted on downstream users. In the case of a community or economy that recycles water, the effects would be more direct.

The Aquatic Environment

Figure III-2 and Tables III-1 and III-2 illustrate the interactions among land use, water use, water projects, and the environment. The effects on the aquatic environment due to changes in water quality or physical characteristics of the environment are particularly complex and interactive, and must be closely analyzed to appropriately anticipate the effects of a water project. It is mandatory, if environmental impact studies are to be useful, to provide detailed quantitative information on the ecosystems being disturbed by a water resource project. The simulation of natural ecosystems using numerical models and high speed digital computers appears to be a feasible and reliable means for performing these analyses.

Figure III-3 is a conceptual diagram of an aquatic ecosystem. This conceptualization is the basis for identifying relationships to be modeled for the purpose of the quantifying aquatic environmental changes due to project development. This diagram shows the relationships between natural and man-made inputs to the aquatic ecosystem and their important to the various biological components. As illustrated, water quality (as defined

TABLE III-2

PRINCIPAL WATER QUALITY AND AQUATIC ORGANISM EFFECTS ON WATER USE

Water Quality	Water Uses Affected
Sediment	M, I, R, E
Dissolved Salts (chlorides, sulfates, hardness, etc)	M, I, A, R, E
Pathogen's	M, I, R, E
Temperature	I, R, E
Organics (Non-living)	M, I, R, E
Toxicants (metals, pesticides, etc)	M, I, A, R, E
Dissolved Oxygen	M, I, R, E
Aquatic Organisms	
Phytoplankton	M, I, R, E
Zooplankton	R, E
Fish	R, E

Code of water uses affected:

M Municipal and Domestic

I Industrial Processing and Cooling

A Agricultural

R Recreational (hunting, fishing, swimming, etc)

E Environmental (ecosystem aspects)

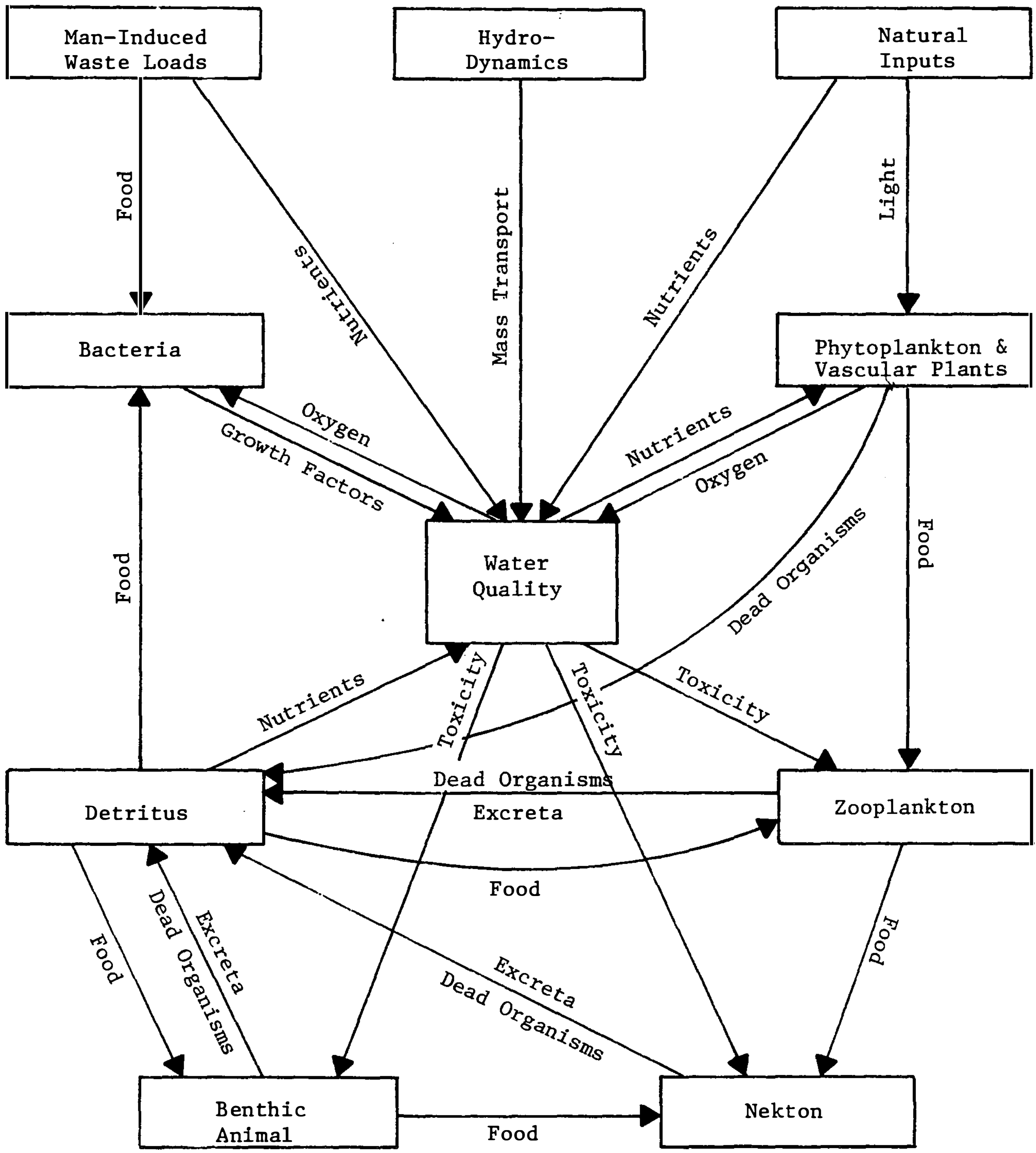


Figure III-3
Diagram of an Aquatic Ecosystem
(After Water Resources Engineers, Inc.)

by the chemical and physical properties of the water body) provides the interconnection between man's activities, external inputs to the aquatic ecosystem, and the organisms which inhabit it. Natural inputs to the aquatic ecosystem are sunlight, heat, salts, nutrients, sediment, and bacteria from adjacent lands. Other natural inputs include the hydrodynamic forces of the water body (velocity, circulation patterns) and the actual physical setting of the land which encloses the water e.g. pebble lined river channel, sand lined channel, rocky bottom reservoir, or muck bottom reservoir. Man's effects, especially development of a water project, are primarily introduced through the hydrodynamics and physical habitat inputs of the aquatic ecosystem. For example, the construction of a dam converts a free-flowing and possible high velocity stream (Lotic environment) into a standing impoundment with low velocities and minimized circulation (Lentic environment)

Another factor often not considered is the river downstream from a large dam site which may have its physical characteristics altered because of the controlled nature of the streamflow below the reservoir. The reduced frequency of floods may change the amount of vegetation in the stream channel area. The associated reduction in river sediment load (due to reservoir entrapment) may result in erosion of the existing downstream streambed and changes in the stream's bottom material. For example, the bottom material may change from gravel to fine sand or vice versa. These changes may be beneficial or detrimental. In Texas, for example, construction of several large, deep reservoirs have resulted in the creation of habitat suitable for cold water fisheries in the streams below the reservoirs because of the release of cool water from the lower layer (hypolimnion) of the reservoirs throughout the year.

Man-induced waste loads which enter the aquatic ecosystem can be of several types: municipal, industrial, and agricultural return flows. Each of these activities results in changes in the physical and chemical quality of the surface runoff. These three major inputs, as defined in Figure III-3, are causes of changes in the aquatic ecosystem. Perturbation in any of these three inputs can result in change of the aquatic ecosystem; the change may be beneficial or detrimental, and may be imperceptible using current measuring devices and techniques, but the change is inevitable.

Water quality is the principal common denominator controlling or effecting changes in the aquatic environment. Water quality constituents constitute part of the environment of all aquatic organisms. Components of the aquatic biota are linked to each other through the food web as shown in Figure III-3. These organisms. as they reproduce, grow, and die, contribute certain constituents to the water quality of their environment. They also serve as producers or consumers to sustain themselves and other organisms in the food chain. The relationships between the organisms and the aquatic environment are extremely complex and many are still unknown. However, the figure shows a number of relationships which could be represented mathematically in a simulation model of the aquatic ecosystem. More sophisticated models would include the addition of minor relationships and subdivision of each component to more accurately portray the environmental imapcts.

Terrestial Effects of Water Development Projects

The effects of water use and water project development on the terrestrial ecosystems is analogous to their effects on the aquatic ecosystem. However, with the major exception of actual destruction of terrestrial environments (e.g., the clearing of a reservoir site), the effects are usually less apparent and direct than the effects on the aquatic ecosystems.

Figure III-4 is highly simplified representation of the Major components of a terrestiral ecosystem and the related effects of man's activities. This figure is considerably more idealized than Figure III-3 for the aquatic ecosystem, although in actuality, the interactions may be equally numerous. Only basic impacts (land use, water quality, and water availability changes) on the biota of the terrestrial ecosystem are illustrated.

The effects of water quality changes on plants and animals are usually obvious and in many cases the relationships are well documented (Federal Water Pollution Control Administration, 1968). Selected water quality limits indicate the level of various constitutes at which the health of a particular plant of animal might become seriously degraded. Water quality factors are crucial in the use of water for irrigation purposes. As the salinity or dissolved solid content of water increases, its suitability for irrigation and for domestic, municipal, recreational, and industrial use decreases. In the example problem provided in this report some of these effects are shown and analyzed.

The changes in the terrestrial ecosystem due to changes in land use occur both in the location of the water project and in the locations where the projects water is used. For example, when a reservoir is constructed, river bottomland is converted to an aquatic environment, thus effectively eliminating all terrestrial organisms within the specific area inundated. The areas bordering the lake may change from an upland terrestrial environment to marsh areas which support a different type of terrestrial ecosystem than previously existed.

Additionally, urbanization near lakes may grow at a rapid rate which effectively eliminates many terrestrial species which cannot adapt to such activities. Similar changes occur in the service area where the water is

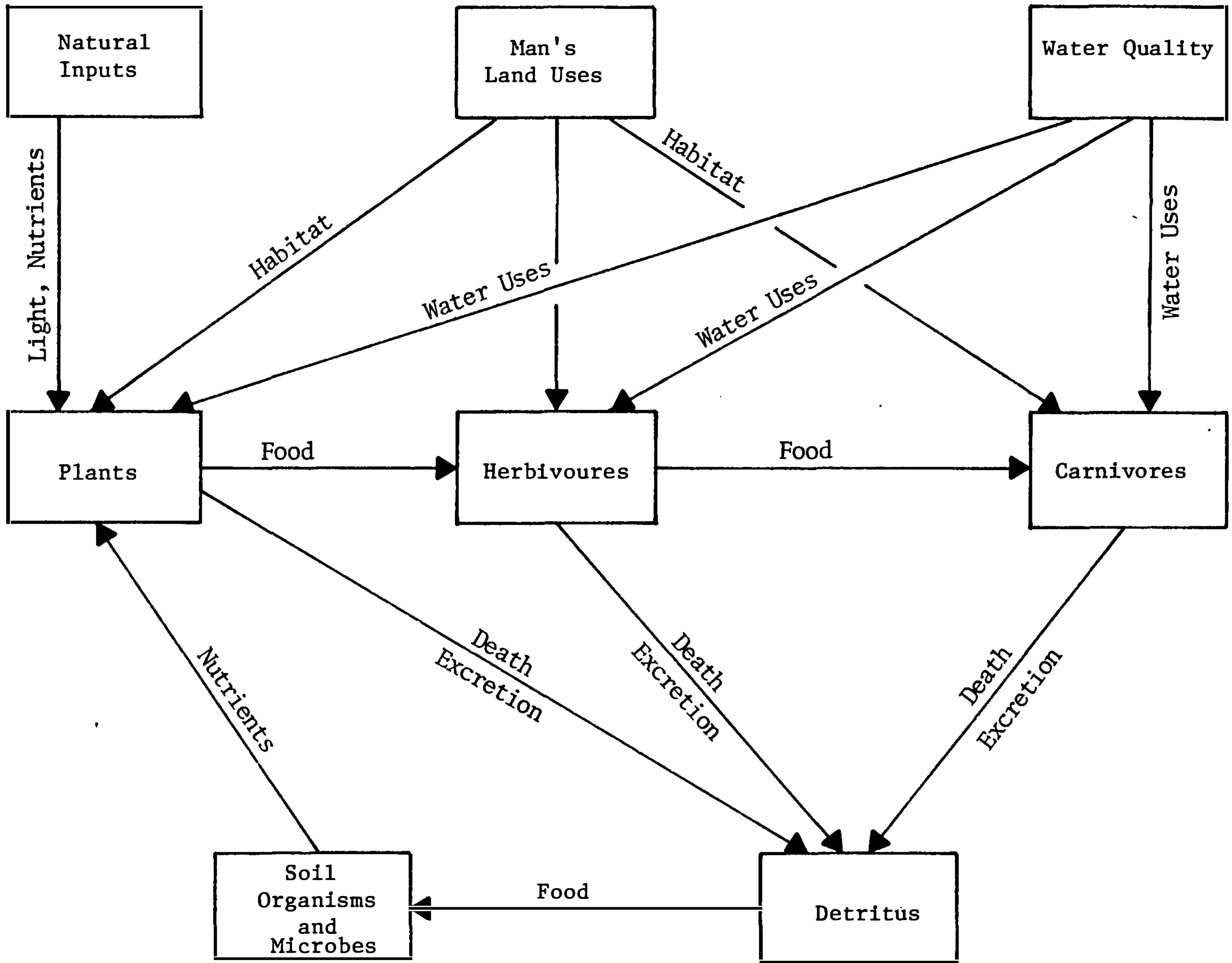


Figure III-4
Major Components of a Terrestrial Ecosystem

used. The introduction of an irrigation project to a natural environment commonly removes most native plants and animals from the areas being farmed and similarly, may eliminates species not directly affected but which are dependent upon environmental factors that are directly affected. Some other species, deer for example, may thrive if intensive urbanization does not occur. When water is used in an urban setting it may stimulate urban growth which further displaces the surrounding natural ecosystems. This type of change may be important and should also be considered.

Unfortunately, many of the interrelationships between the terrestrial biota and its environment are still unknown or there is insufficient knowledge to accurately quantify these. As a result, no attempt was made in this research project to develop a mathematical model for evaluating terrestrial impacts of water development projects.

Aquatic Ecological Models for Analyzing Water Quality and Selected Aquatic Life Impacts of Project Implementation

The environmental component of the methodology focuses primarily on the analysis of changes in the aquatic environment resulting from construction and operation of a water project. The emphasis is on the aquatic effects resulting from the construction of a reservoir and the associated uses of the water. The analytical tools developed for analyzing the impacts are designed to have sufficient flexibility so that other types of water resources projects such as wastewater reuse and improved watershed and land management practices can also be analyzed in relationship to their effects on the ecosystems existing in lakes and streams receiving effluent and/or runoff. The methods are based on the application of systems engineering or systems analysis techniques to the relationships among the aquatic environment and its biota.

Figure III-5 describes the conceptual analytical framework used to quantify aquatic environmental changes due to project development. The framework consists of a reservoir water quality-ecological model, which estimates the distribution of selected water quality-ecological variables in a reservoir; a stream water quality-ecological model, which estimates the distribution of these variables in a stream or river; and an estuarine water quality-ecological model which utilizes output from the reservoir and stream models to estimate the spatial distribution of these variables in an estuarine system.

The hydrologic data and information required for analysis of aquatic environmental changes are determined from a hydrologic simulation of the proposed project. The data required include (1) reservoir releases, (2) the quality and quantity of inflows during the period of analysis, and (3) the volume and surface area of the impoundment for each set project operating rules. As presently designed, these data are grouped into monthly time steps. It is also necessary to obtain, outside of the hydrologic simulation, monthly data on the meteorological and tidal conditions for the entire simulation period.

The aquatic ecosystem models are used to simulate water quality characteristics of existing streams and reservoirs in the study region under a number of alternative water management policies, and provide estimation of the resulting impact on the associated estuarine system. In addition to assessing the impact of future projects, the models are also used to estimate a time history of water quality characteristics (using monthly streamflow data) which might change due to changing economic conditions and corresponding waste loads imposed on streams in the contributing basin(s).

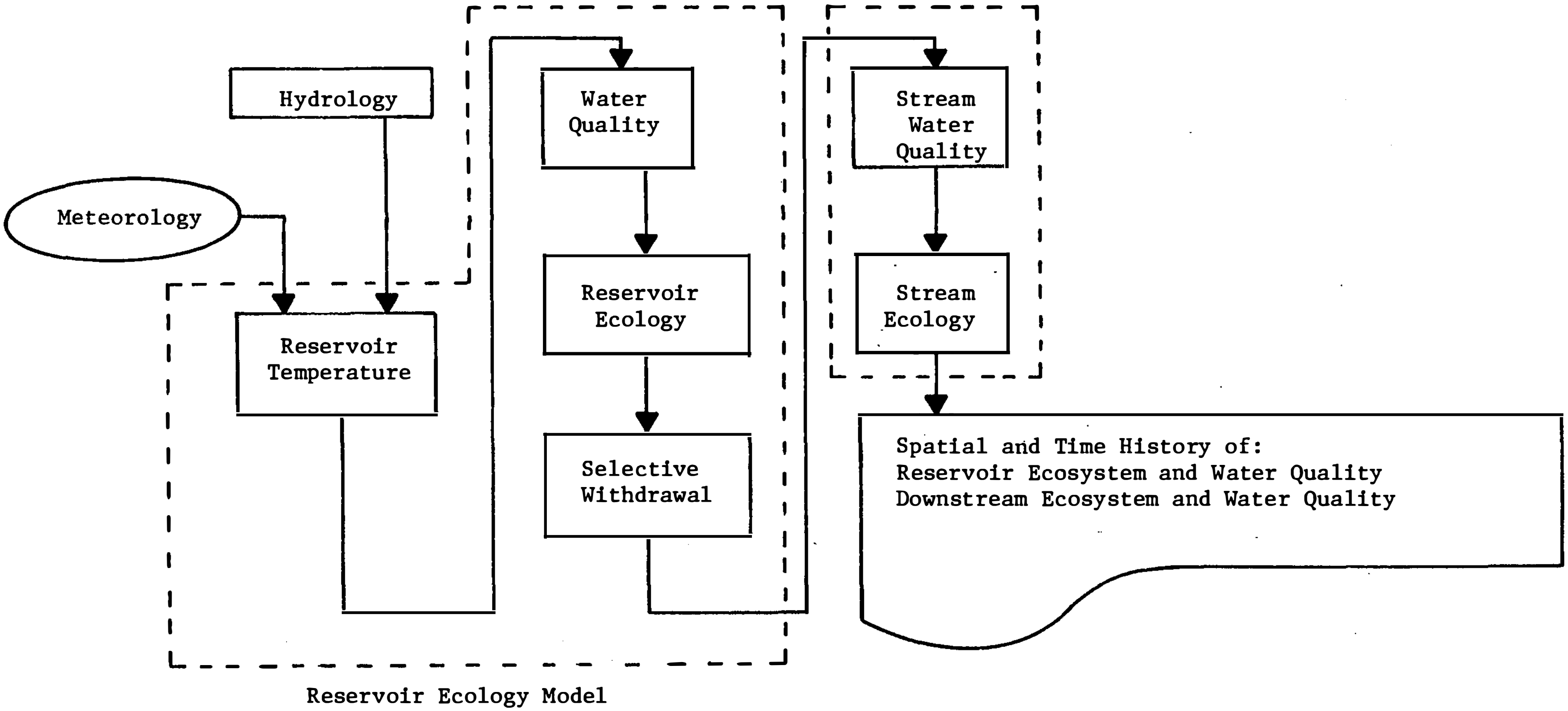


Figure III-5
Quantifying Aquatic Environmental Changes Due to Project Development

These factors would affect stream quality conditions regardless of whether reservoirs are constructed upstream. A variety of other possibilities may be investigated, including the possible reallocation of storage in existing reservoirs to provide for low-flow augmentation for downstream water quality management.

Operation of the interconnecting models illustrated in Figure III-5 applies to both streams with reservoirs and those without. In the case of the analysis of conditions in a stream which contains no reservoirs and in which none are proposed as policy alternatives, the stream quality model requires only hydrologic simulations and inflow water quality constitutents. In the case of alternative formulations of reservoir projects, all of the components are required.

The reservoir quality analysis involves the use of a water quality-ecologic simulation model which simulates changes in water quality characteristics within the reservoir under various inflow regimes. This modeling includes the capability of simulating both conservative and non-conservative water quality constituents.[1] The reservoir temperature model is also a reservoir hydrodynamic model because the hydrodynamic behavior of a thermally-stratified lake is directly related to the temperature profile within the impoundment. Knowledge of the reservoir hydrodynamics permits tracing of movement of selected water quality constituents in the reservoir inflow through the entire stratified pool. The major difference between modeling conservative

1 Conservative materials are defined as those which are relatively unaffected by chemical and biological interactions (chlorides and total dissolved solids). Non-conservative constituents, on the other hand, enter into one or more chemical or biological reactions which affect the concentration of these constituents in the body of water. These include dissolved oxygen, total organic carbon, and phosphorus.

constituents and non-conservative constituents is the inclusion of the appropriate source/sink terms for non-conservative materials. Information on the surface reaeration rates of the impoundment, biological reaction rates, and any chemical reaction rates which might affect non-conservative constituents is necessary.

The simulation of reservoir temperature, water quality, and aquatic biology is all performed by a single model. The model was developed by Water Resources Engineers, Inc. (Chen, C.W. and G.T. Orlob, 1972) and was applied to three Texas reservoirs by the research project staff. The model simulates the conceptual ecosystem shown in Figure III-3, and by coupling the water quality-ecosystem computations, the interactions which occur in nature may be simulated. The model simulates several "key" groups in each of the trophic levels of the aquatic ecosystem. The use of simulation techniques to determine aquatic ecological responses provides a projected time history of reservoir ecosystem responses to the reservoir or project operation. Table III-3 illustrates the input data required by the model and illustrates the output and nature of information available to the user.

Water quality characteristics of releases from the reservoir are used in the stream water quality analysis to develop spatial and temporal water quality characteristics of downstream flows. This set of streamflow water quality data are then used to develop information on changes in the stream's ecology, using a stream water quality-ecologic model similar to the reservoir ecological model. The output information required from the stream quality model, which serves as input to the estuarine (or reservoir) models, is similar to the data shown in Table III-3.

The estuarine quality analysis involves the use of a water quality-ecologic simulation model which uses the time sequence of water quality data developed by the stream and reservoir models. Estuarine hydrodynamics are

Table III-3
Variables for the Hydraulic and Ecologic Models

PARAMETERS	Lake System Hydraulic	Lake System Ecologic	River System Hydraulic	River System Ecologic
CLIMATE (ZONES)				
Latitude	I	-	I	-
Longitude	I	-	I	-
Atmospheric Pressure	I	-	I	-
Cloud Cover	I	-	I	-
Wind Speed	I	-	I	-
Dry Bulb Temperature	I	-	I	-
Wet Bulb Temperature	I	-	I	-
Wind Direction	I	-	I	-
Evaporation	O	C	C	C
Short Wave Radiation	O	C	C	C
Wet Solar Radiation	O	C	C	C
GEOMETRY				
Surface Area	I	C	-	-
Side Slope	I	I	-	-
Elevation	I	I	-	-
Volume	C	C	-	-
Channel				
Length	-	-	I	-
Width	-	-	I	-
Depth	-	-	I	-
Friction Factor	-	-	I	-
HYDROLOGY				
External Flow				
Rivers	I	I	I	I
Tide (1 point)	-	-	-	-
Waste Discahrges	-	-	-	-
Out flow	I	I	I	I
Internal Flow				
Channel Flows	-	-	O	O
Surface Overflow	O	C	-	-
*QUALITY CONSTITUENT**				
Temperature	O	O	-	O
Toxicity**	-	-	-	O
Total Dissolved Solid**	-	O	-	O
Coliform**	-	O	-	O
BOD**	-	O	-	O
Oxygen**	-	O	-	O
Total Carbon** (Inorganic)	-	O	-	C
PO_4 - P**	-	O	-	O
Alkalinity**	-	O	-	O
NH_3 - N**	-	O	-	O
NO_2 - N**	-	O	-	O
NO_3 - N**	-	O	-	O
Algae (2 Groups)	-	O	-	O
Zooplankton	-	O	-	O
Fish (2 Groups)	-	O	-	O
Benthic Animal	-	O	-	O
Detritus**	-	O	-	O
CO_2**	-	O	-	O
pH**	-	O	-	O

* Requires Initial Conditios

** Requires Steady-State Input Conditions

NOTES:

I Input
C Calculated
O Output
\- Not Applicable

PARAMETERS	Lake System Hydraulic	Lake System Ecologic	River System Hydraulic	River System Ecologic
SYSTEM COEFFICIENTS				
Light Extinction				
Background	-	I	-	I
Algal Suspension	-	I	-	I
Reacration				
Oxygen	-	I	-	I
CO_2 - C	-	I	-	I
Decay Rate				
BOD	-	I	-	I
Detritus	-	I	-	I
Coliform	-	I	-	I
NH_3 - N	-	I	-	I
NO_2 - N	-	I	-	I
Temperature Coefficient	-	I	-	I
Algae				
Respiration	-	I	-	I
Settling Velocity	-	I	-	I
Oxygenation Factor	-	I	-	I
Chemical Composition (C, N, p)	-	I	-	I
Maximum Specific Growth	-	I	-	I
Half-Saturation Constants (Light, Carbon, Nitrogrn, Phosphorus)	-	I	-	I
Zooplankton				
Respiration	-	I	-	I
Mortality Coefficients	-	I	-	I
Digestive Efficiency	-	I	-	I
Chemical Composition (C, N, P)	-	I	-	I
Preference for Algae	-	I	-	I
Maximum Specific Growth	-	I	-	I
Half-Saturation Constants (Algae, Detritus)	-	I	-	I
Fish (3 Groups)				
Respiration	-	I	-	I
Mortality Coefficients	-	I	-	I
Digestive Efficiency	-	I	-	I
Chemical Composition (C, N, P)	-	I	-	I
Maximum Specific Growth	-	I	-	I
Half-Saturation Constant	-	I	-	I
Benthic Animals				
Respiration	-	I	-	I
Mortality Coefficients	-	I	-	I
Digestive Efficiency	-	I	-	I
Chemical Composition (C, N, P)	-	I	-	I
Maximum Specific	-	I	-	I
Half-Saturation Constant	-	I	-	I
OTHERS				
Chemical Composition (C, N, P)				
Zooplankton Pellet	-	C	-	C
Fish Pellet	-	C	-	C
Benthic Pellet	-	C	-	C
Detritus	-	I	-	I

computed using the tidal hydrodynamics model, which provides a time series of water velocities and water surface elevations for the estuarine system. This information provides a basis for the water quality-ecologic simulations. In addition to the hydrodynamic data, the estuarine water quality-ecologic model (ESTECO) requires meterological data and specified physical "boundary" conditions in order to simulate the response of upstream on the estuarine ecosystem. The water quality-ecologic portion of the estuarine model is basically the same component used for the reservoir simulations; however, the solution of the water quality-ecologic constituents is accomplished spatially (x-y plane) for the estuarine system rather than vertically as in the reservoir model. Output from the estuarine water quality-ecologic model represents a spatial and temporal distribution of the various components of the estuarine system. The type of information provided is quite similar to that shown in Table III-3; a more detailed description is found in this report in a appendicular materials. In addition to the estuarine water quality-ecological model being an effective tool for evaluating the effects of various alternative water management policies on the estuarine environment, it also provides information for a migratory organism model which is used to assess the alternative impacts on estuarine migratory organisms. Migratory organisms are not permanent residents of the estuary, but spend only part of their life cycle in the estuarine environments.

Migratory Organism Model
for Evaluating "Key" Species'
Response to Environmental
Parameters

The estuarine ecological model simulates the interactions among environmental parameters and lower trophic level organisms, (i.e., planktonic and benthic organisms) within constraints of current accuracy of "calibration" of the model. However, the nektonic portion of the model was not considered by the research staff to be sufficiently refined to the poing of being capable of simulating the biomass dynamics marine nekton within an acceptable degree of accuracy.

The conceptual framework for describing the interactions between marine migratory organisms and the environmental parameters which control migratory patterns developed from detailed review of available literature, various statistical analyses, and admittadly, some "intuitive reasoning." Consequently, the migratory organisms model (MOM) was developed as an independent simulation tool which operates on a parallel basis with the estuarine ecological model.

The migratory organism model is used to simulate the response of key estuarine organisms to both seasonal and lone-term estuarine environmental regimes. The environmental parameters utilized to drive the migratory organism model are represented in the estuarine ecological model, thereby enabling the use of environmental response data interactively between the estuarine ecological model and migratory organism model for evaluating estuarine productivity.

The migratory organism model is basically an accounting program which computes numerical "scores" for three critical environmental parameters: freshwater inflow; salinity, and water temperature. The "scores" are used to evaluate estuarine environmental conditions as related to the growth and abundance of "key" estuarine organisms. Environmental limits and ranges for each variable are identified and "scores" are assigned to each range. The sources are accumulated in an accounting procedure to evaluate the effects of selected fresh water inflow regimes the migratory nekton (e.g., shrimp).

EVALUATION AND ANALYSIS

This phase of the methodology involves analysis and evaluation of two activities described above, the river basin hydrologic simulations and the environmental simulations. Analysis of selected water development and/or management plans defines both physical and hydrologic feasibility as well we resulting impacts on the ecology of the estuarine environment. This evaluation phase can be divided into three basis steps:

(1) analyzing the effects of a proposed water resources system on aquatic ecosystems in terms of changes in the productivity and/or life cycles of "key" species;

(2) estimating the social and economic costs and/or benefits of any ecological changes; and

(3) changing the development and/or management policies and re-analyzing the system response.

Output from the stream, reservoir, and estuarine ecological models consists of information on the spatial distribution, through time, of widely used water quality parameters as well as the growth, mortality, and relative abundance of selected "key" species of the estuarine biota. These data are interpreted by comparison of simulated water quality and species productivity in response to a postulated plan of water resource development with current known water-quality conditions and productivities. The estuarine migratory organism model (MOM) provides information on the response of "key" estuarine organisms to the seasonal and long-term estuarine environmental regimes represented by the estuarine ecological model. This information is used to evaluate the effects of water resource development projects and management plans on the productivities of some economically important estuarine organisms.

Complete evaluation of the significance of large-scale water resource projects must involve an estimate of the social and economic costs and benefits. This type of analysis was beyond the scope of this research project, although it is the next logical step. Some work that is currently underway and the results of several past investigations should be particularly useful in this type of analysis. For example, a research project, funded in part by the Office of Water Resources Research and recently completed by the Texas Water Development Board, involved the development of techniques for identifying and evaluating market and non-market benefits and costs generated by water resources projects. The results of this study are described in a report entitled "Techniques for Identifying and Evaluating Market and Non-Market Benefits and Costs of Water Resource Systems" (Texas Water Development Board, 1974). At a later date, the methodology described in report should provide an adequate basis for estimating the socio-economic effects of ecological changes in a river basin and its associated estuary.

The next step in the planning procedure, after an evaluation of the ecological effects of a particular water resources development/management regime has been made, is to modify proposed water resource development and management policies in an effort to increase the benefits and reduce the detrimental effects. This operation might involve changing the seasonal operating rules for certain reservoirs, importation of supplemental fresh water inflows, or other alternatives. The modified plan is then reanalyzed using the interactive modeling techniques to determine the changes it would have on the estuarine ecology. By comparing the simulation results of alternative plans, the "best" plan can be chosen. The "best" plan should meet demands for water, within tolerable shortages, at minimum cost while maintaining the associated aquatic ecosystems at levels of productivity consistent with state and national goals.

IV. THE TEST CASE

Consumptive water requirements within the San Antonio and Guadalupe River Basins are currently being met from a combination of surface and ground water sources. However, with the greatly increased water demands projected for these basins, it is evident that judicious water resources management will be essential in order to adequately supply future water needs. As a tool for analyzing alternative management schemes, the methodology and analytical framework described in Chapter III was applied to the San Antonio and Guadalupe River Basins and their associated estuary, the Guadalupe Estuary.

RIVER BASIN SIMULATION

Water resources management implies the most advantageous distribution of the available water resources among a variety of competing users consistent with physical, environmental, esthetic and economic constraints. In terms of water quantity, the management objective for the San Antonio and Guadalupe River Basins is to determine the "best" allocation of the available water resource (ground and surface waters) to the water use demand points through a network of existing and proposed reservoirs and conveyance facilities. Translating this objective into mathematical terms yields the problem of finding a "minimum cost" flow circulation within a "capacitated network" (See Appendix A). A capacitated network" is defined as a set of points (nodes) connected by line segments (arcs) where the permissible amount of flow transmitted along any line segment is bounded from above and below. For a water resources system, the nodes represent stream junctions, demand centers, or storage reservoirs, while the arcs correspond to stream channels or pump canals. In addition to giving a reasonable approximation of the physical system, the network approach leads to solution procedures which are highly efficient from a computational standpoint.

The capacitated network approach as applied to the Guadalupe and San Antonio River Basins is illustrated in Figure IV-1. Included in the system configuration are the major stream channels, water demand centers, and present and proposed reservoir and canal projects. The "central pool area" of the Edwards Aquifer and the San Marcos and Comal Springs are also represented.

The water resources system represented in Figure IV-1 includes major existing, proposed, and potential reservoirs and conveyance facilities in the Guadalupe and San Antonio River Basins. The system configuration illustrated in this schematic is designed to provide a flexible SIMYLD-II model for examining the operation of the various feasible combinations of future projects in the basins. In analyzing the operation of a particular system of projects, the reservoirs and canals not simulated are assigned maximum storage and pumpage capacities of zero. Thus, only minor data changes are necessary to simulate different system configurations.

Ground Water

The system simulation models described in Appendix A are intended only for surface water systems; however, the unique geologic and hydrologic characteristics of the Edwards Aquifer enables it to be analyzed as if it were a surface reservoir. Specifically, the highly permeable limestone comprising the Edwards formation allows unusually rapid transmission of water through the rock strata. This rapid equalization of hydraulic gradients causes the water level in the "central" artesian area to fluctuate in a nearly uniform manner with significant changes in storage volume. Thus, knowing the rate of recharge, pumping, and spring discharges, the change in volume and water level in the central pool of the aquifer can be readily determined.

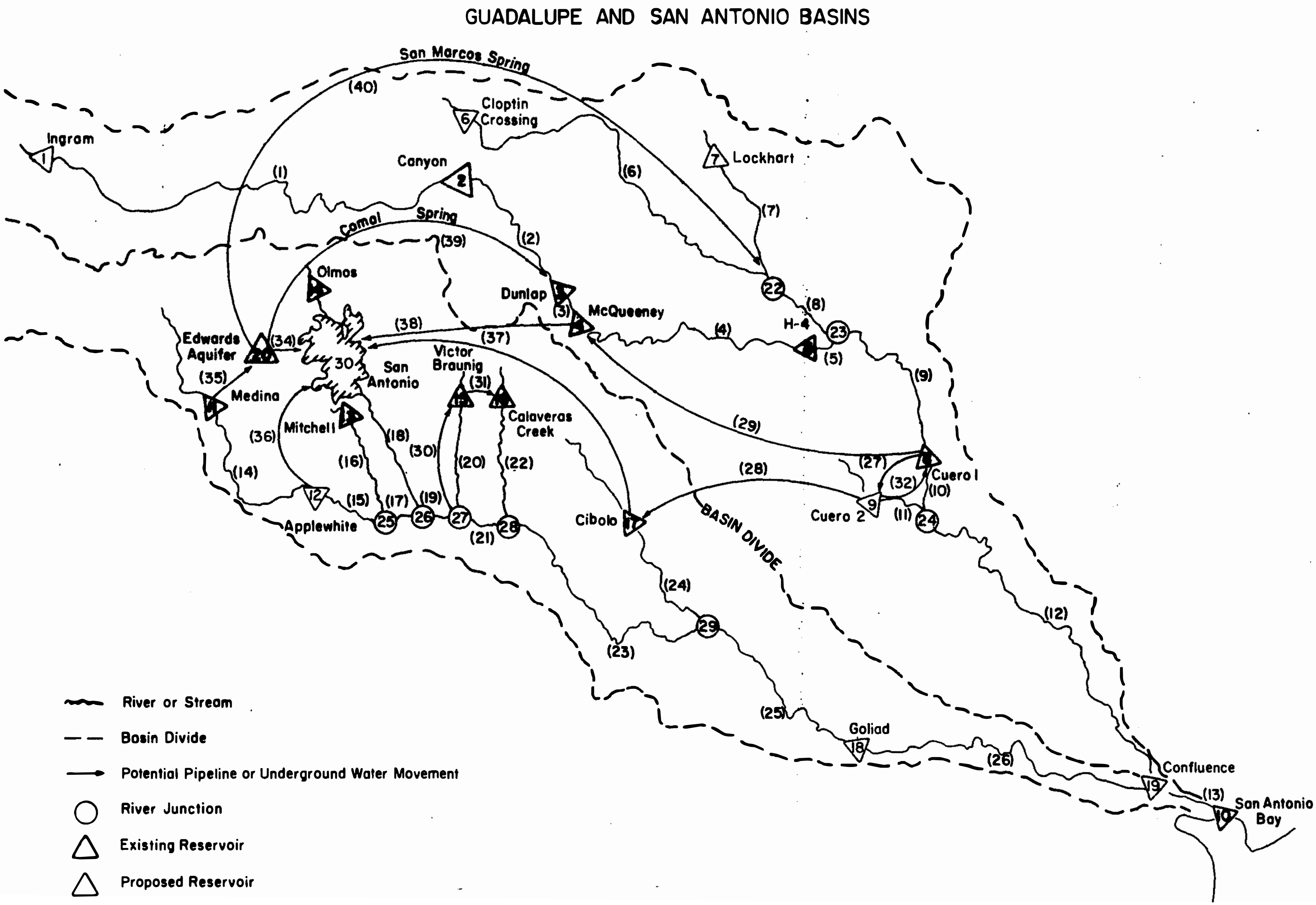


Figure IV-1
General Water Resources System

Recharge to the Edwards formation results from the percolation of surface water into the aquifer's limestone outcrops. Since the historic hydrology was used in this analysis, estimates of the historic annual recharge rates were given as inflows into the aquifer. Special provisions were required, however, for computing the recharge seeping from the Medina reservoir since this recharge rate is dependent upon the water depth within the reservoir. Figure IV-2 illustrates the depth-recharge approximations determined from observed monthly conditions (Freeze and Nichols, 1971). The higher recharge rates for a rising reservoir stage reflect bank storage effects.

Natural springs account for a large portion of the total outflow from the Edwards formation. Approximately 90% of these natural outflows are discharged from the Comal and San Marcos Springs. The flows from these two artesian springs depend upon the water level in the aquifer's central pool. For the Comal springs, this hydraulic interaction is a nearly linear relationship. The monthly water levels at San Antonio well 26 plotted against the average monthly discharge rates from Comal Springs for the years 1947 to 1959 clearly illustrates this linear dependence (Figure IV-3). Applying regression analysis yielded a linear predictive equation for springflow as a function of aquifer water level. This statistical model accounts for 98% of the variance in the observed data.

The San Marcos Springs are highly influenced by local recharge as well as by seepage from the central pool. Again using regression analysis, a mathematical model was derived for predicting the spring's average discharge rate using the annual aquifer recharge in the Blanco River Basin and the average annual water level in San Antonio well 26. This regression equation accounts for 89% of the variation in the data. Figure IV-4 compares the observed and predicted flow rates for the San Marcos Springs over the twenty-four year interval from 1941 to 1964.

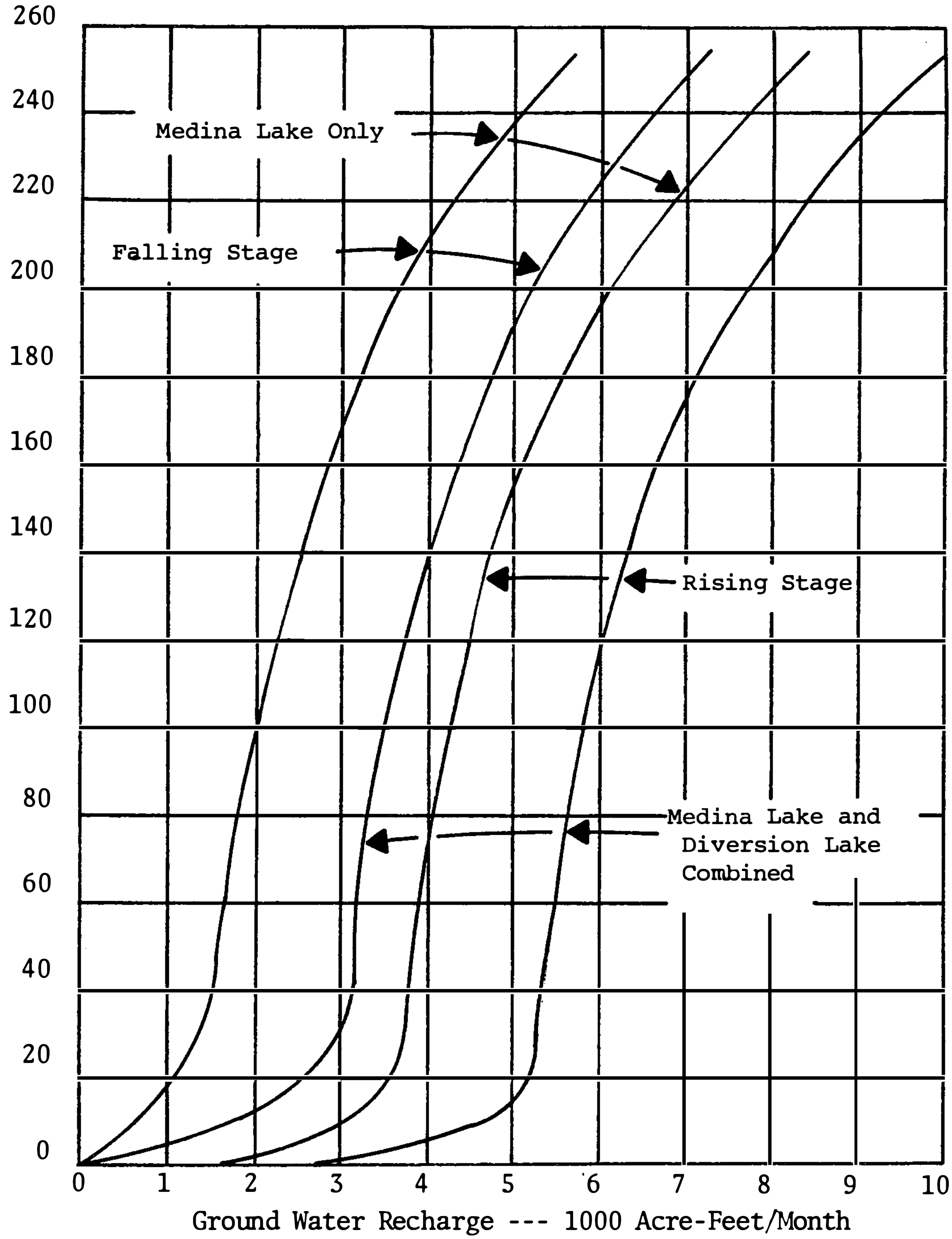


Figure IV-2
Medina Lake and Diversion Lake
Recharge Characteristics
(After Freese, Nichols and Endress 1971)

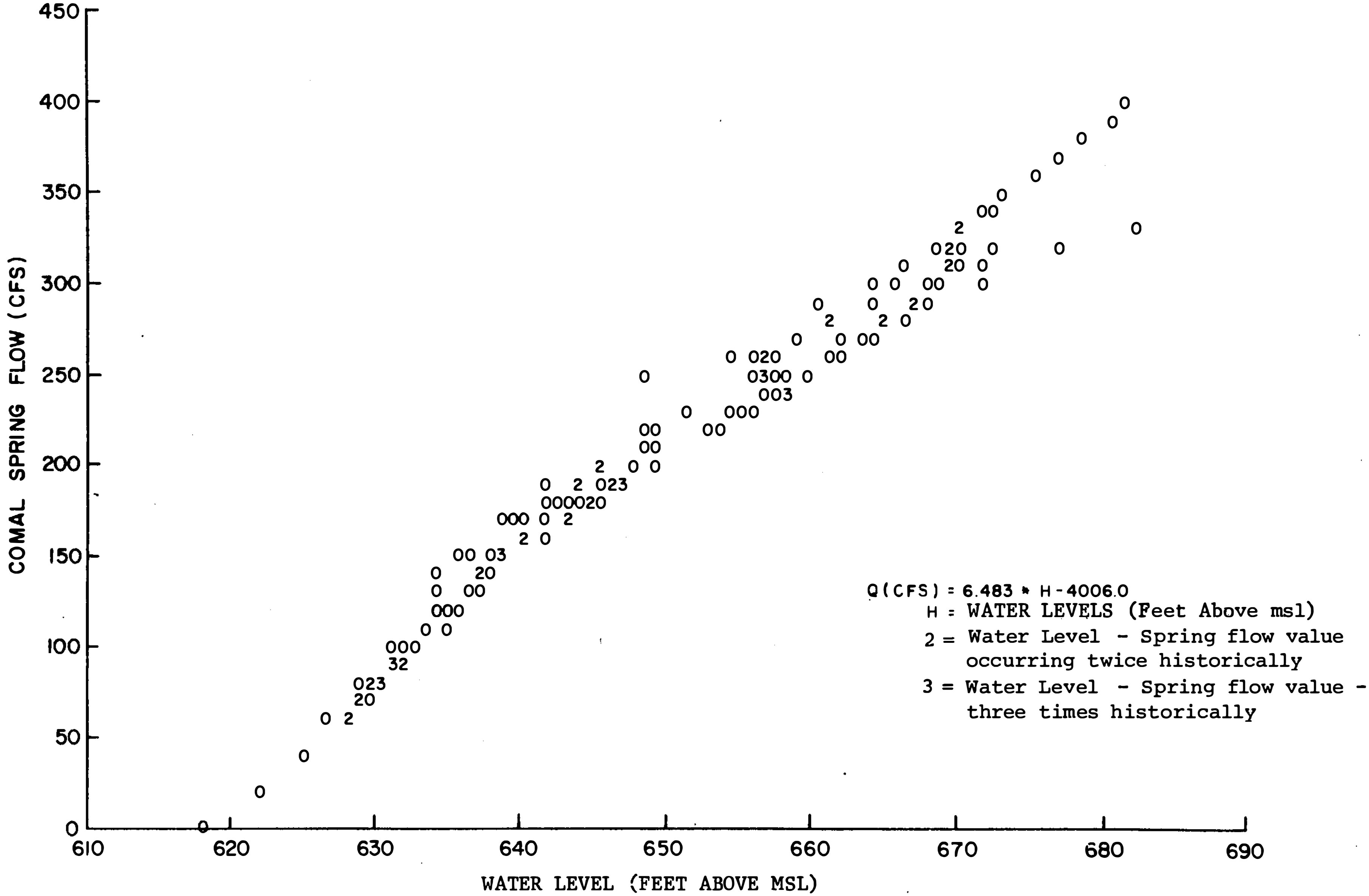


Figure IV-3
Correlation of Comal Spring Flow
and San Antonio Well #26

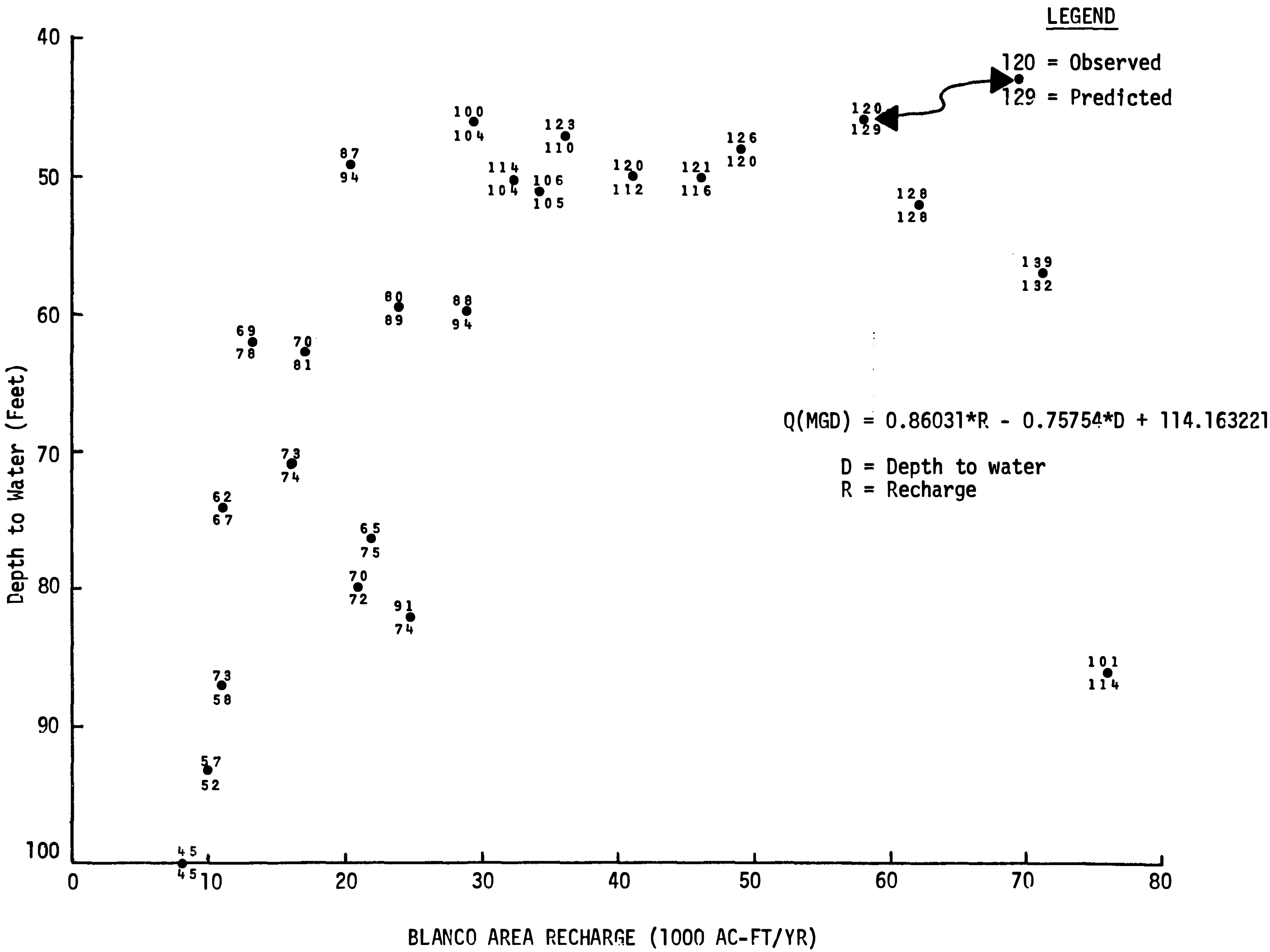


Figure IV-4
San Marcos Spring Discharge

System Simulation Model

The application of the network simulation programs to a given water resources system requires that the elements in the physical system be assigned to corresponding elements in the network model. For the Guadalupe and San Antonio River Basins, these associations are given in Table IV-1.

A thirty year time horizon was selected for this simulation analysis. The consumptive water needs and return flows over this planning period were derived from the projected water requirements for the years 1971 through 2000. (Tables IV-2, IV-3, and IV-4). The evaporation and natural runoff rates were taken from the adjusted historical hydrologic records covering the period 1941 through 1970.

Having specified a network model for the Guadalupe and San Antonio River Basins, it now remains to assign value or utility to the various water uses. The difficulties inherent in designating monetary values for water resources benefits tend to make purely economic measures of utility somewhat suspect. Therefore, a value measure based upon usage priority was thus selected for this analysis. All water needs (consumptive and storage) were ranked on an integer scale from 1 to 99. Highest priority demands were given a ranking of 1, with the least important water needs ranked 99. In operating a water resources system, the SIMYLD-II computer program meets higher priority uses before releasing water to meet lower priority requirements.

The water requirements in the Guadalupe and San Antonio River Basins may be classified as either consumptive or storage needs. The storage demands represent target levels of reservoir or aquifer storage, while consumptive needs consist of municipal and industrial requirements, and thermal reactor cooling water.

Table IV-1

Network Model for Guadalupe
- San Antonio Basins

Node Number*	Node Label	Demand at Node
1	Ingram Res.	-
2	Canyon Res.	Guad. Zone 1 Irrigation
3	Dunlap Res.	-
4	McQueeney Res.	Guadalupe Cty. M&I
5	H-4 Res.	Gonzales Cty. M&I
6	Cloptin Crossing Res.	-
7	Lockhart Res.	-
8	Cuero 1 Res.	Victoria Cty. M&I Victoria Cty. Cooling Water
9	Cuero 2 Res.	-
10	San Antonio Bay	-
11	Medina Res.	Medina Cty. W.I.D. Irr.
12	Applewhite	-
13	Mitchell Res.	S.A. Zone 1 Irrigation
14	Almos Res.	-
15	Victor Braunig Res.	Cooling Water
16	Calveras Creek Res.	Cooling Water
17	Cibolo Res.	-
18	Goliad Res.	S.A. Zone 2 Irrigation
19	Confluence	Coastal Canal Division
20	Edwards Aquifer	Balcones Escarpment Irrigation Uvalde, Medina & Comal Cty. M&I Bexar Cty. Cooling Water
21	Gulf of Mexico	-
22	-	Guad. Zone 2 Irrigation
23	-	-
24	-	Guad. Zone 3 Irrigation
25	-	-
26	-	-
27	-	Cooling Water
28	-	-
29	-	-
30	San Antonio	Bexar Cty. M&I

* See Figure IV-1

Table IV-2

Projected Intake Demands for Guadalupe
- San Antonio Basins

Demand Center (Node)**	Annual Demand (1000 AC-FT) 1970	1980	1990	2000	2010	2020	Priority
Guad. Zone 1 Irr. (2)	1.2	1.6	2.0	2.0	2.0	2.0	11
Comal Cty. M&I (20)	9.5	11.0	12.4	13.8	15.3	16.6	51
Guadalupe Cty. M&I (4)	4.7	6.2	7.9	9.7	12.1	14.6	2
Gonzales Cty. M&I (5)	3.2	3.3	3.3	3.2	3.2	3.1	3
Victoria Cty. M&I (8)[1]	0.0	7.4	17.1	29.7	44.6	62.0	4
Victoria Cty. Cooling Water (8)	12.0	20.0	62.0	102.0	140.0	184.0	4
Medina Cty. W.I.D. Irr. (11)	20.4*	20.4*	20.4*	20.4*	20.4*	20.4*	1
San Antonio Zone 1 Irr. (13)[2]	5.2*	5.2*	5.2*	5.2*	5.2*	5.2*	52
Victor D. Braunig Cooling Water (15)	24.0	24.0	24.0	24.0	24.0	24.0	47
Calaveras Cooling Water (16)	6.0	28.0	74.0	74.0	74.0	74.0	48
Cooling Water from Edwards (20)	11.4	11.4	11.4	11.4	11.4	11.4	51
San Antonio Zone 2 Irr. (18)	2.5	5.5	8.6	9.3	10.0	10.9	53
Coastal Canal Div. (19)[3]							
Lavaca-Guad. M&I	35.6	50.6	68.9	93.4	122.4	156.3	56
Lavaca-Guad. Irr.	8.1*	9.1*	10.2*	11.3*	12.3*	13.4*	56
Balcones Escarpment Irr. (20)[4]	57.1	79.1*	101.0*	123.0*	145.0*	166.9*	51
Guad. Zone 2 Irr. (22)	1.0	4.8	8.6	11.1	13.6	15.9	12
Guad. Zone 3 Irr. (24)	1.6	3.4	5.3	6.0	6.8	7.6	13
Bexar Cty. M&I (30)	188.4	243.9	305.5	378.1	459.6	547.7	40
Uvalde Cty. M&I (20)	3.6	4.4	5.3	6.1	7.0	8.0	51
Medina Cty. M&I (20	3.5	4.5	5.5	6.7	7.8	9.2	51
Bexar Cty. Cooling Water (27)	0.0	0.0	0.0	80.0	100.0	200.0	59

* Figures represent thousands of acres under irrigation
** See Figure IV-1
1 Figures represent total M&I demand minus 20,000 acre-feet supplied by ground water
2 Figures represent the surface-water irrigation around Mitchell Lake
3 Figures represent the export to Lavaca-Guadalupe Coastal Basin
4 Figures assumes that the acreage increases at the trend observed prior to 1970

Table IV-3

Return Flows for Guadalupe
San Antonio Basins

Return Point (Node)	Source (Node)
McQueeney Res. (4)	Comal Cty. (Guad) (20)
H-4 Res. (5)	Guadalupe Cty. (Guad) (4)
Node 22	Caldwell, Hays & Blanco Cty. (Guad) (-)
Node 23	Gonzales Cty. (Guad) M&I (5)
Node 24	Dewitt & Victoria Cty. (Guad) M&I (8)
	Victoria Cty. Cooling Water (8)
Mitchell Res. (13)	Leon Creek S.T.P. (Bexar City. M&I) (30)
Node 26	Rilling Road S.T.P. (Bexar Cty. M&I) (30)
	Cooling Water Pumped from Edwards (20)
Cibolo Res. (17)	Cibolo Creek S.T.P. (Bexar City.M&I) (30)
Confluence (19)	Goliad Cty. M&I (S.A.) (-)
Cibolo Res. (17)	Guadalupe Cty. M&I (S.A.) (4)
Medina Res. (11)	Bandera Cty. M&I (S.A.((-)
Cibolo Res. (17)	Comal & Kendall Cty. M&I (S.A.) (20)
Goliad Res. (18)	Wilson & Karnes M&I (S.A.) (-)
Node 27	V.D.B. Cooling Water (15)
	Bexar Cty. Cooling Water (27)
Node 28	Calaveras Cooling Water (16)

Table IV-4

Projected Return Flows for Guadalupe - San Antonio Basins

Source of Return Flow	Annual Return Flow (1000 AC-FT)					
	1970	1980	1990	2000	2010	2020
Comal Cty. M&I (Guad)	4.2	4.9	5.5	6.2	6.9	7.5
Guadalupe Cty. M&I (Guad)	2.6	3.3	4.5	5.9	7.7	9.5
Caldwell, Hays & Blanco Cty. M&I	3.3	6.0	8.3	10.3	14.9	20.0
Gonzales Cty. M&I (Guad)	1.3	1.4	1.6	1.6	1.7	1.7
Dewitt & Victoria Cty. M&I (Guad)	15.5	21.4	28.7	38.1	49.1	62.1
Victoria Cty. Cooling Water	6.0	10.0	31.0	51.0	70.0	92.0
Cooling Water From Edwards	3.4	3.4	3.4	3.4	3.4	3.4
V.D.B. Cooling Water	18.0	18.0	18.0	18.0	18.0	18.0
Calaveras Cooling Water	3.0	14.0	37.0	37.0	37.0	37.0
Bexar Cty. Cooling Water	0.0	0.0	0.0	57.0	48.0	116.0
Leon Cr. S.T.P. (Bexar Cty.)	11.4	11.8	13.3	14.7	16.3	18.1
Rilling Rd. S.T.P. (Bexar Cty.)	101.2	135.5	172.9	216.9	266.7	320.9
Cibolo Creek S.T.P. (Bexar Cty.)	1.2	1.7	2.3	2.9	3.6	4.4
Bexar Cty. Indust. (S.A.) (one third to each of node 13, 17, and 26)	4.5	6.6	7.2	8.4	9.6	10.8
Karnes & Wilson Cty. M&I (S.A.)	1.4	1.7	1.8	2.0	2.2	2.2
Kendall & Comal Cty. M&I (S.A.)	.4	.5	.6	.7	.8	1.0
Bandera Cty. M&I (S.A.)	.5	.7	.8	1.0	1.1	1.3
Guadalupe Cty. M&I (S.A.)	.7	1.0	1.4	1.8	2.4	2.9
Goliad Cty. M&I (S.A.)	.2	.3	.3	.3	.3	.3

Table IV-5

Network Model Priority Schedule for
Guadalupe - San Antonio Basins

Water Use	River Basin	
	Guadalupe	San Antonio
M&I	1-10	40-45
Cooling Water	4	46-50
Irrigation	11-20	51-55*
Export	56	56
Reservoir Storage	65-75	61-90***

*Irrigation demands on Medina Reservoir are given a priority rank of 1.

**Medina and Mitchell storage rankings are 2 and 1 respectively. These priorities reflect the special nature of these reservoirs.

A somewhat subjective approach was employed in matching rankings with demands; however, the following general guidelines established by the Texas Water Rights Commission were adopted in assigning usage priorities.

- Within a given river basin, municipal and industrial demands were given the highest priority, followed by thermal reactor cooling water needs, irrigation requirements and, finally, reservoir storage.
- Within a given water usage classification, upstream water needs were assigned higher priorities than downstream demands.
- The priority heirarchy was arranged to insure that all in-basin demands were satisfied before export from the basin was allowed.

Usage priorities for the Guadalupe and San Antonio River Basin were assigned according to specifications given in Table IV-5. Specific rankings for the individual demand centers are indicated in Table IV-2.

Results of the River Basins System Operation

The SIMYLD-II network model of the Guadalupe and San Antonio River Basins was used to simulate the operation of the two basins over the presiously specified thirity year (1971-2000) demand period. For this analysis, the proposed Cuero (Stage-1) and Cibolo reservoirs were assumed to have been constructed with maximum conservation storage capacities of 1,458,000 and 200,000 acre-feet, respectively. Closed conduits were assumed to link the Cuero impoundment to the Cibolo reservoir, as well as to connect the Cibolo impoundment with the City of San Antonio.[1] These closed conduits were maximum pumping capacity of 200 cfs. A schematic representation of this water resources system is illustrated in Figure IV-5.

1 Consideration of this specific configuration of reservoirs and conveyance facilities does not imply the superiority or inferiority of this developmental scheme over possible alternative plans, but is examined simply to illustrate the utility of the methodology developed in this project.

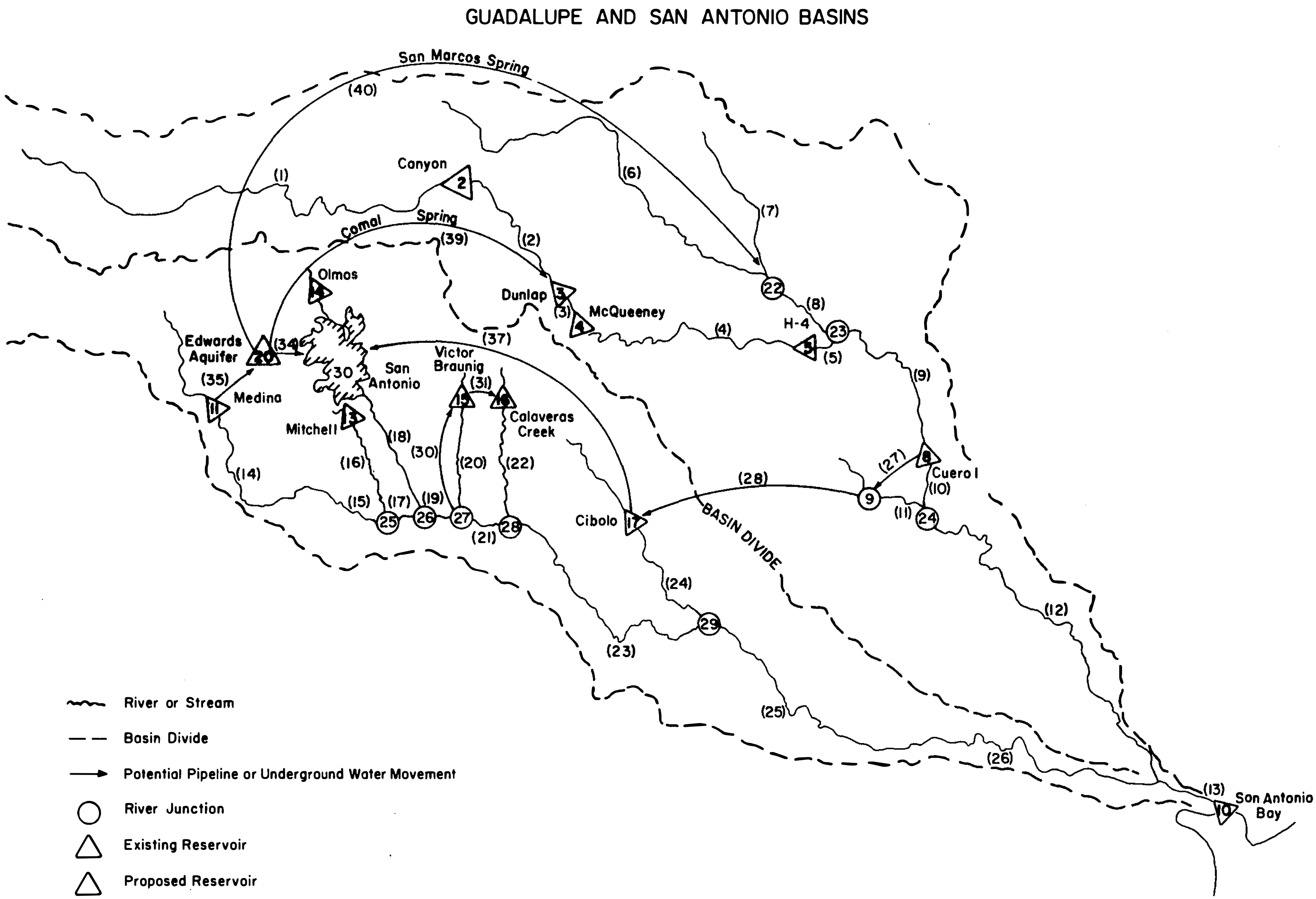


Figure IV-5
Test Case Water Resources System

As a ground water conservation measure, the water-supply pipeline from Cibolo to San Antonio was fully utilized to supply San Antonio water needs. The remaining San Antonio water requirements were satisfied by pumpage from the Edwards aquifer. All projected water requirements were satisfied in the thirty year simulation except for the irrigation needs supplied from Medina Reservoir. These demands could not be entirely satisfied because of the low Medina storage levels resulting from the reservoir's high seepage losses to the Edwards Aquifer. Historically, Medina Reservoir has been an unreliable source of irrigation water due to this leakage characteristic.

The simulated future stream flows in the San Antonio and Guadalupe Rivers and the fresh water inflows into the Guadalupe Estuary were generally lower than the flows during the actual historical periods. To illustrate this result of the simulation analysis, a number comparisons were made between the flows in 1970, a year of average runoff, and the simulated future flows in year 2000, the simulation year having year 1970 natural hydrology (runoff).

A comparison of the historic year 1970 and simulated year 2000 monthly flow rates in the Guadalupe River (Figure IV-6) indicates a significant decrease in the flows during the simulated future period. These reduced flow rates are due to the increased consumptive use in the Guadalupe River Basin and to the substantial interbasin export of water from the Cuero I Reservoir to the San Antonio River Basin. Additional factors responsible for the stream flow reductions are the water losses through reservoir evaporation (150,000 acre-feet in Cuero I alone) and the diminished spring flow at New Braunfels and San Marcos due to future increased ground water pumpage. Figures IV-7 and IV-8 indicate the decrease in the discharge rates at San Marcos and Comal Springs between the historical year 1970 and the simulated year 2000.

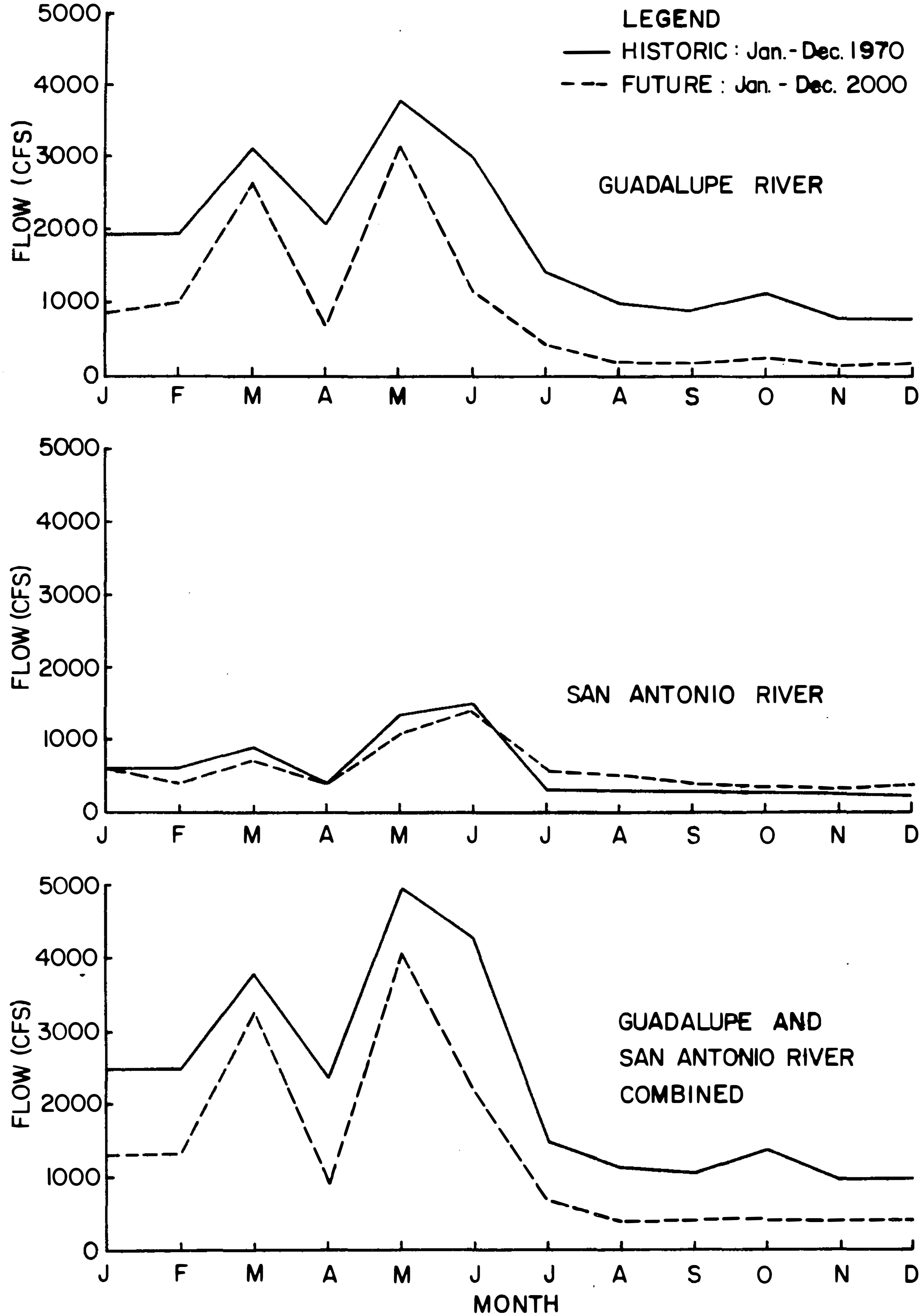


Figure IV-6
Historic and Future Inflows to
Guadalupe Estuary

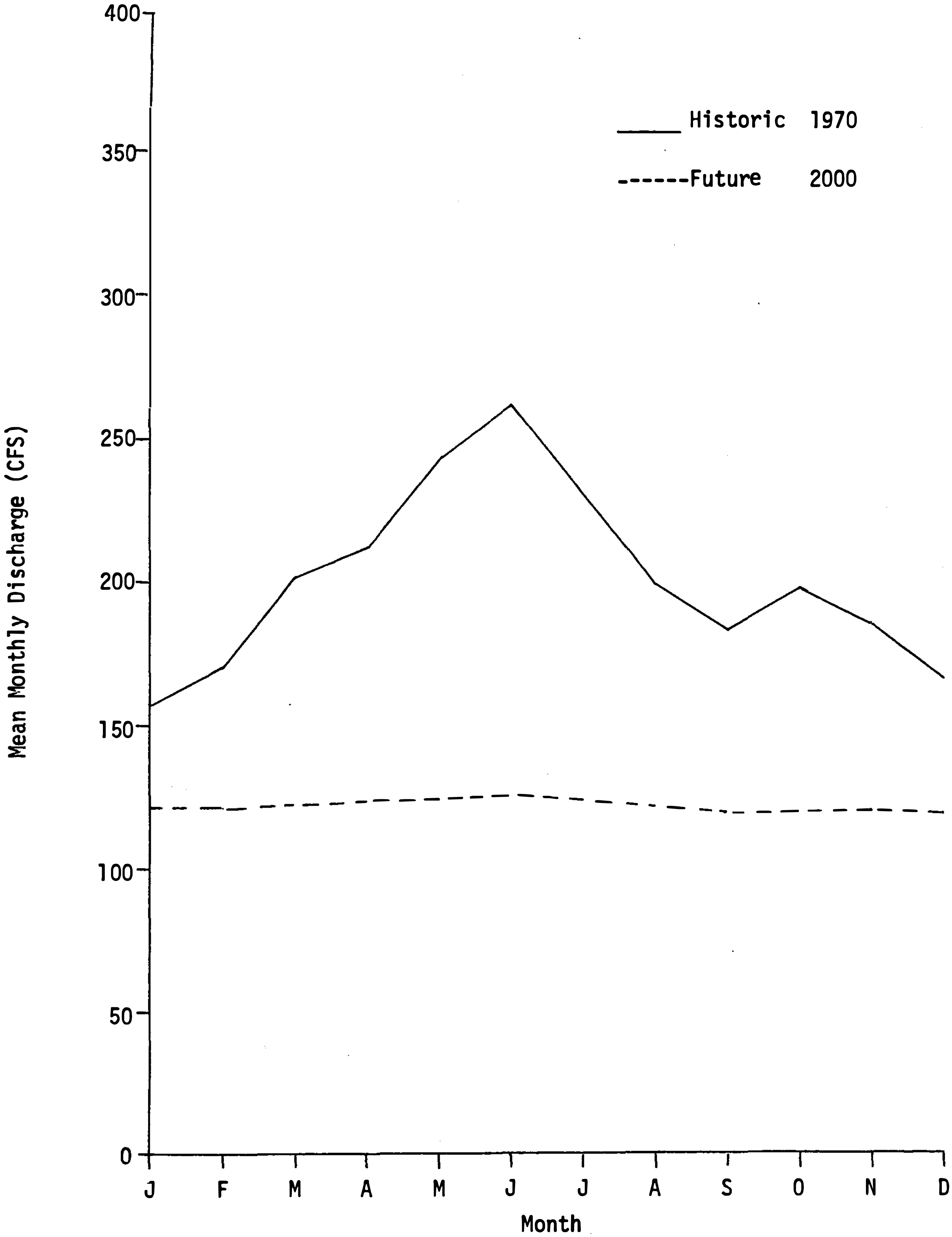


Figure IV-7
Historic and Future Conditions
San Marcos Springs

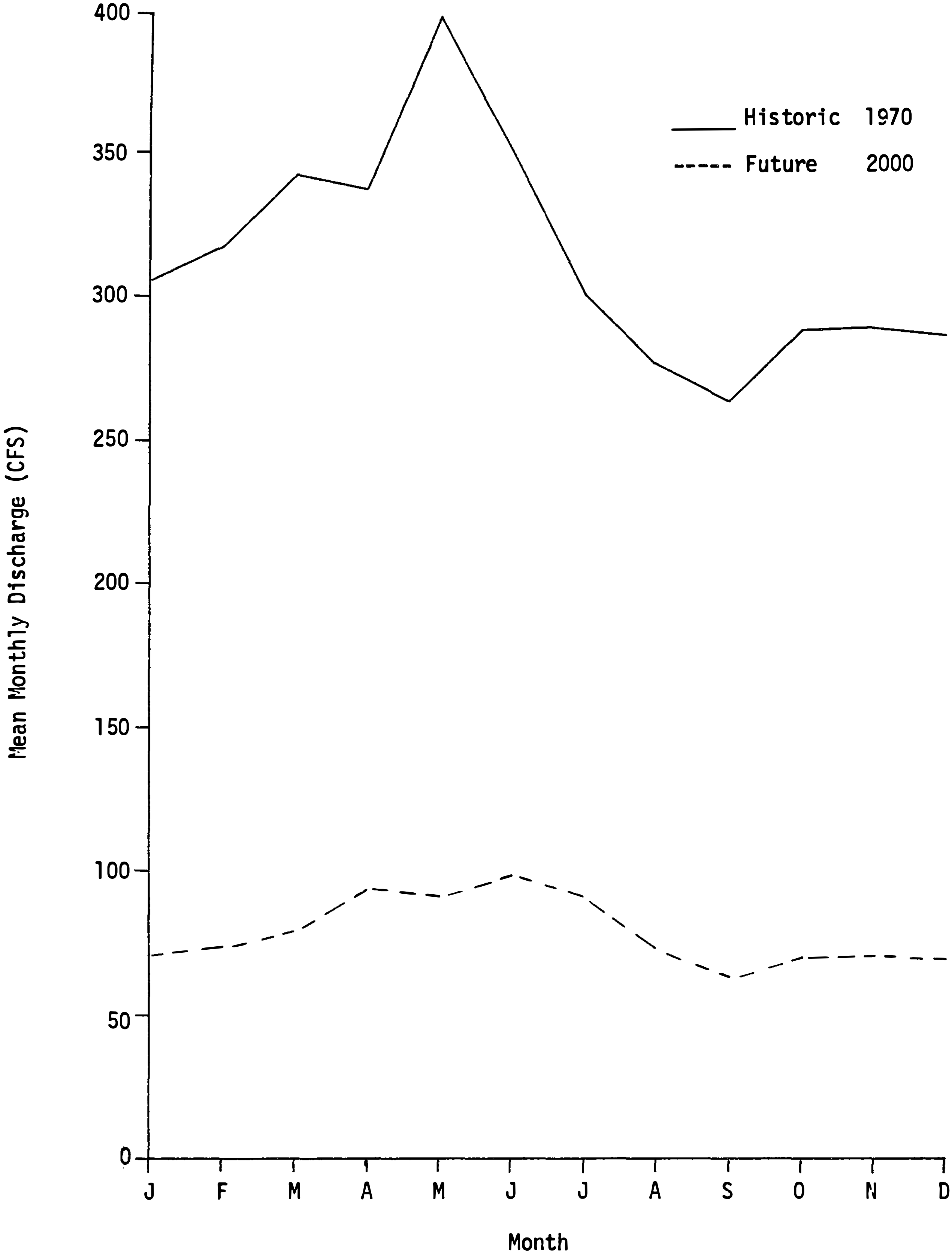


Figure IV-8
Historic and Future Conditions
Comal Springs

In Figure IV-6, the flow rates in the San Antonio River are compared for the same historical and simulated years noted in the previous discussion of the Guadalupe River. The simulated flows for the year 2000 appear to be more uniformly distributed and to have a slightly higher total annual discharge volume. This is due to the substantial interbasin transfer of water from the Guadalupe River Basin to the San Antonio area and to the increased future ground water pumpage, increased municipal and industrial return flows from the City of San Antonio in the simulated future period are expected to be only partially consumed to meet the projected demands for cooling water in electrical power generation plants in the San Antonio area. Consequently, total annual discharge volumes in the San Antonio River Basin could be expected to increase in the simulated future condition.

The final diagram in Figure IV-6 contrasts the historical 1970 inflows (1,639,770 acre-feet) and the simulated 2000 inflows (933,770 acre-feet) into San Antonio Bay. The Guadalupe River represents the most significant source of fresh water inflow into the bay and its reduced flows in the future simulation are directly reflected in the diminished estuarine inflows. Again, the most significant factors for this inflow reduction in the year 2000 are increased surface water demands, increased reservoir evaporation losses and diminished springflow rates in the Guadalupe River Basin.

To compare these variations in the historic and simulated flow regimes and to assess their effect on the various aquatic ecosystems, a detailed analysis was performed using the stream, reservoir, and estuary ecological models. The monthly stream and pipeline flows generated by the SIMYLD-II model were used as water quantity inputs for simulating future conditions in the various aquatic environments.

The results of each of these ecological simulations are discussed in detail in the following sections of this chapter.

ENVIRONMENTAL ANALYSIS

The environmental analysis was limited to treatment of the lake, stream, and estuarine environments in the test case. The initial phase of the analysis involved calibration of the lake, stream, and estuarine models to the extent possible with available data (see Appendices B and C). These simulations provided information relating to the capability for simulating the lake, stream, and estuarine environments. After the models were tested, they were used to evaluate future conditions in the selected aquatic environments using water qualtity inputs from flow information generated by the SIMYLD-II river basin operation model. It was also necessary to consider the quality of the future return flows as well as their magnitude. Table IV-6 lists target return flow qualities developed by the Texas Water Quality Board for Water Quality Segment 1901 of the San Antonio River Basin. The target implementation date for these levels of treatment is 1977 as established by Federal law. These specified levels of treatment were not yet available for the Guadalupe River Basin, therefore the qualities of the return flows in this basin were arbitrarily adjusted to future conditions to what appear to be reasonable and in line with those established for the San Antonio River Basin

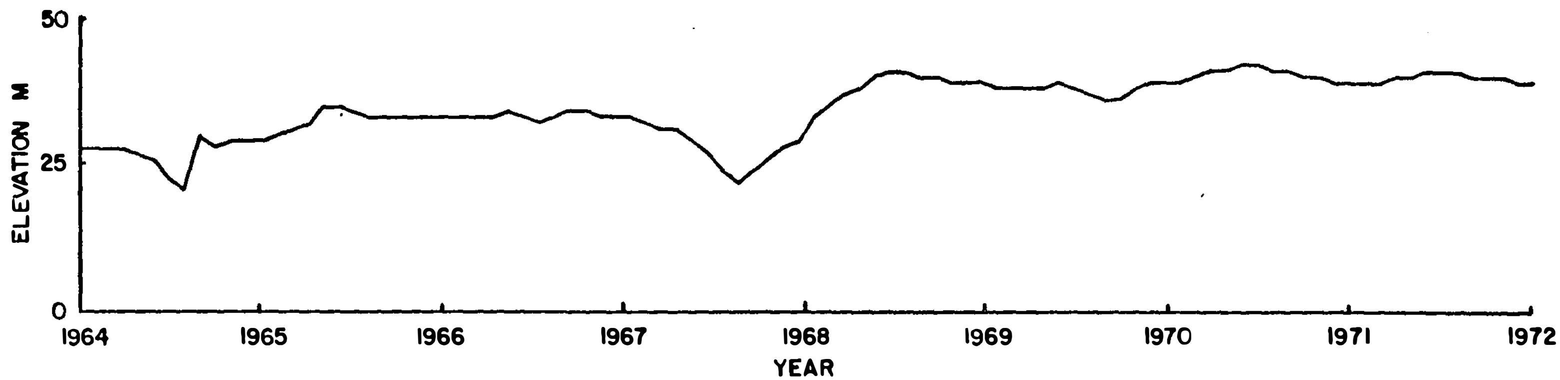
River Basin Environments

The lake and stream models were operated over a historical period from 1965 through 1971 and a future period from 1995 through 2000. The results of the reservoir ecological simulations are displayed in Figures IV-9 through IV-17. These figures exhibit selected water quality parameters

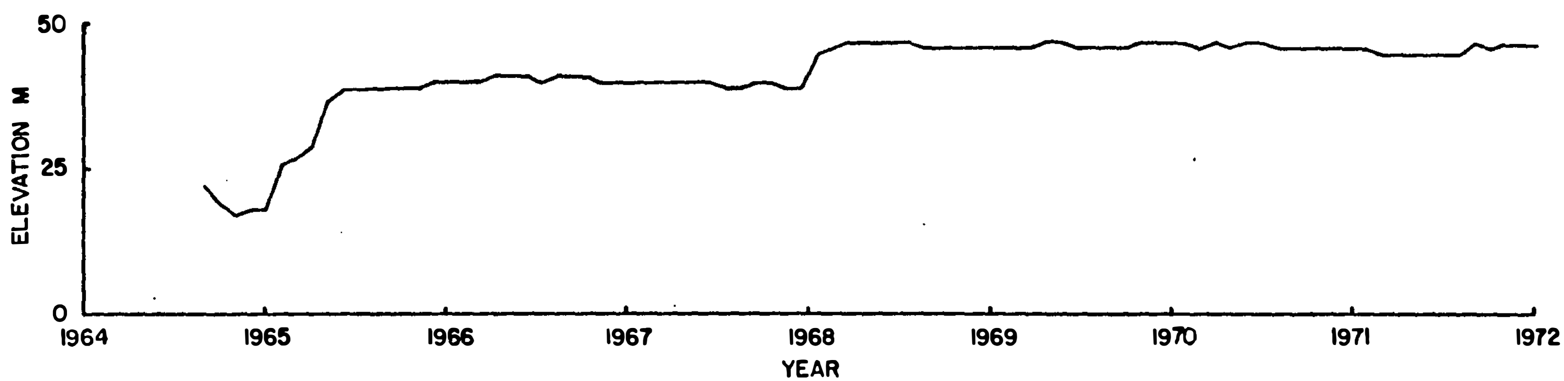
Table IV-6

Summary of Waste Load Allocation
for
The San Antonio River Basin

Waste Source	WCO No.	Recommended Parameter Concentrations BOD	NH_3
City of San Antonio-Rilling	10137-02	5	3
City of San Antonio-Salado	10137-08	5	3
City of San Antonio-Leon Creek	10137-03	5	3
Capitol Cement Co.	01510-01	15	
Capitol Cement Co.	01510-02	15	
Union Stockyards	00968-01	18	
Mission Road Power Plant	01513-01	5	
Mission Road Power Plant	01513-04	5	
Mission Road Power Plant	01513-05	5	
International Airport STP	10137-01	20	
W.B. Tuttle Power Plant	01516-01	5	
Lone Star Brewing Co.	00302-01	10	
Kaiser Cement and Gypsum Co.	01630-01	5	
Kaiser Cement and Gypsum Co.	01630-02	5	
W.S. Kickey Clay Mfg. Co.	01433-01	20	
Kirby, City of	10269	20	
Floresville, City of	10085	20	
Kenedy, City of	10746	20	
Karnes City, City of	10352-01	20	
Alcoholic Rehabilitation Ctr., Inc.	10193	20	
Goliad, City of	10458	20	
Community Treat (Rosillio Crk)	10827	20	
Mitchell Lake		5	3
Runge, City of	10266	20	



MEDINA



CANYON

Figure IV-9
Historic Reservoir Elevations

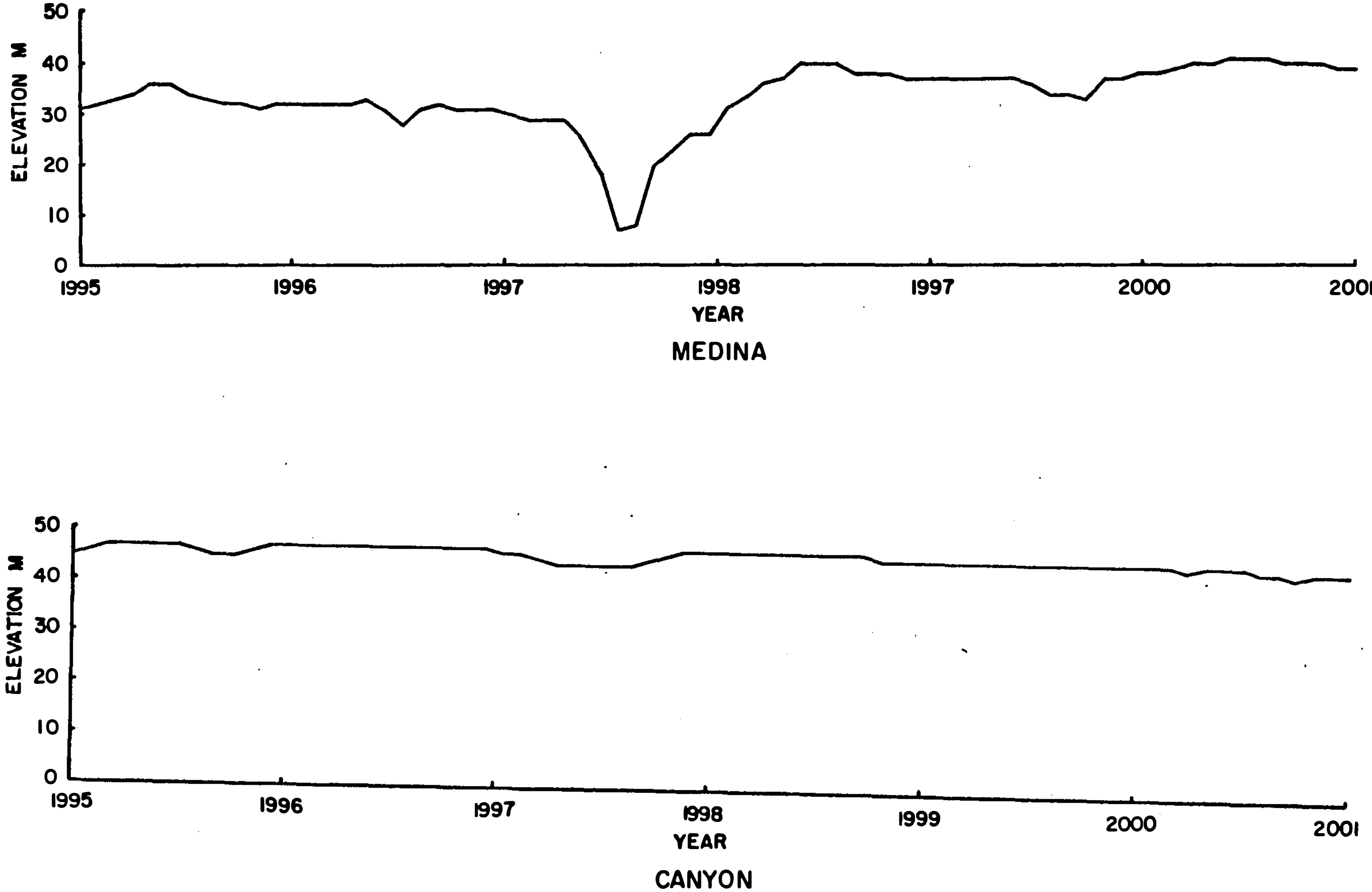


Figure IV-10
Future Reservoir Elevations

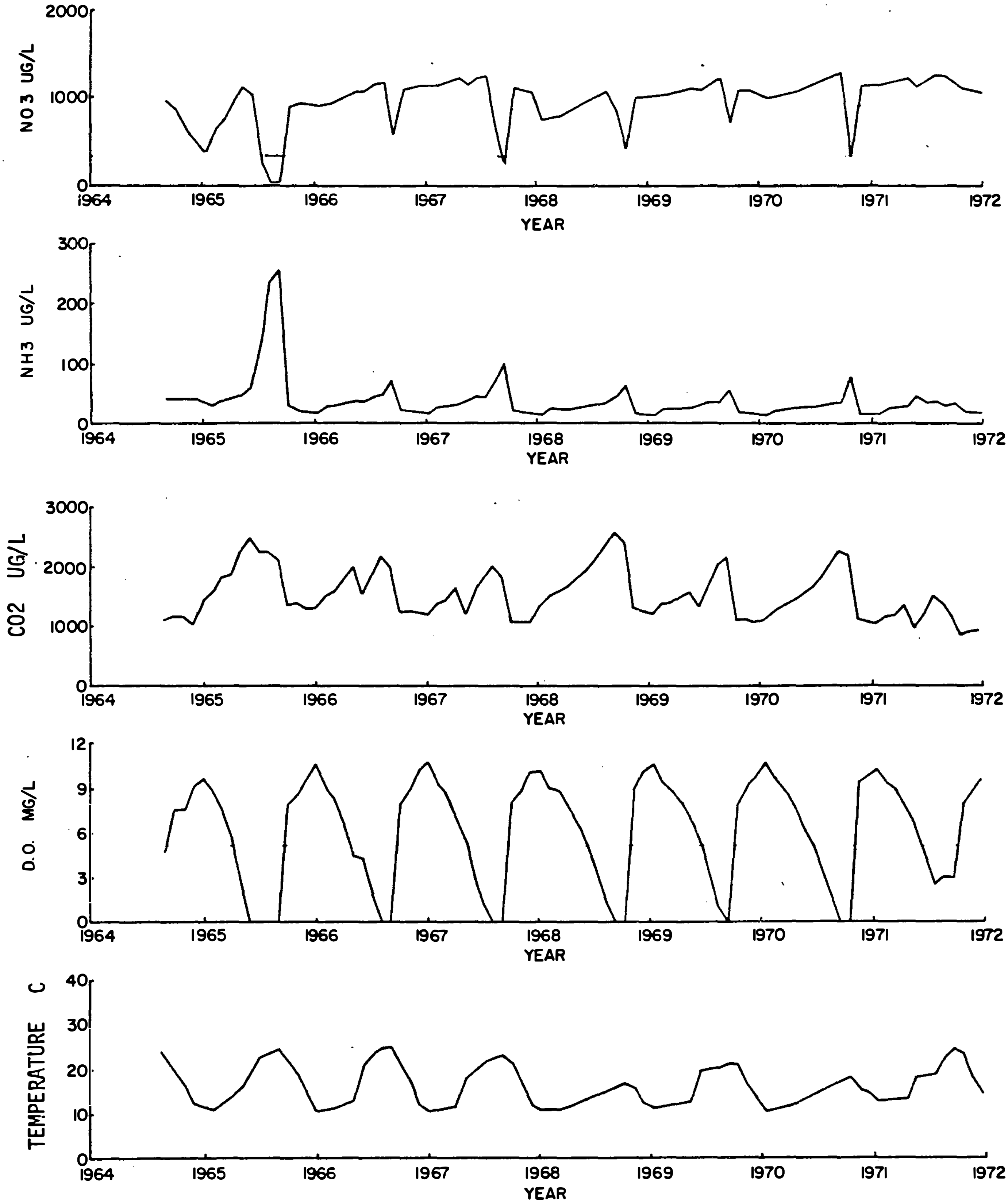


Figure IV-11
Canyon Reservoir - Historic Outlet Conditions

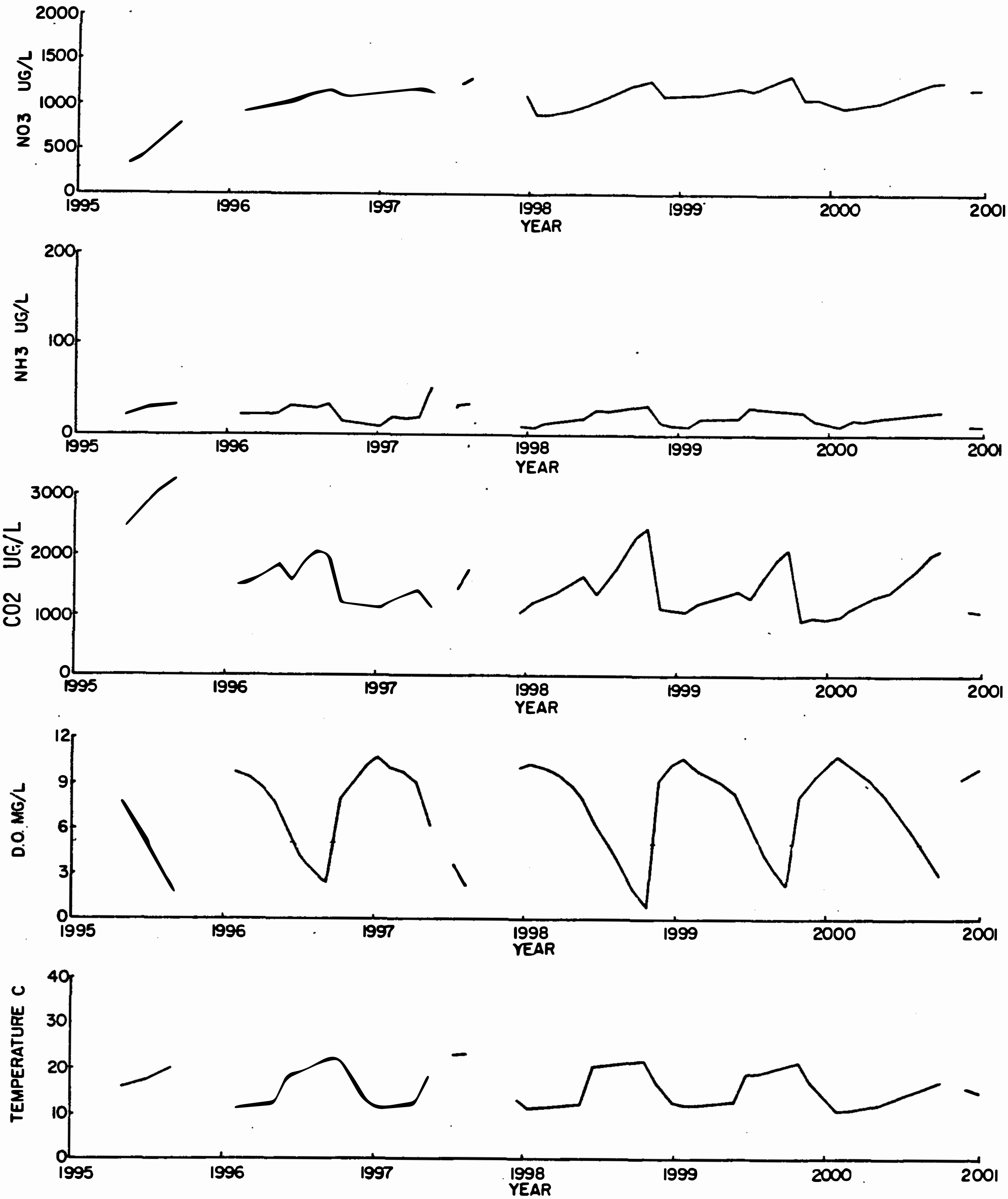


Figure IV-12
Canyon Reservoir
Future Outlet Conditions

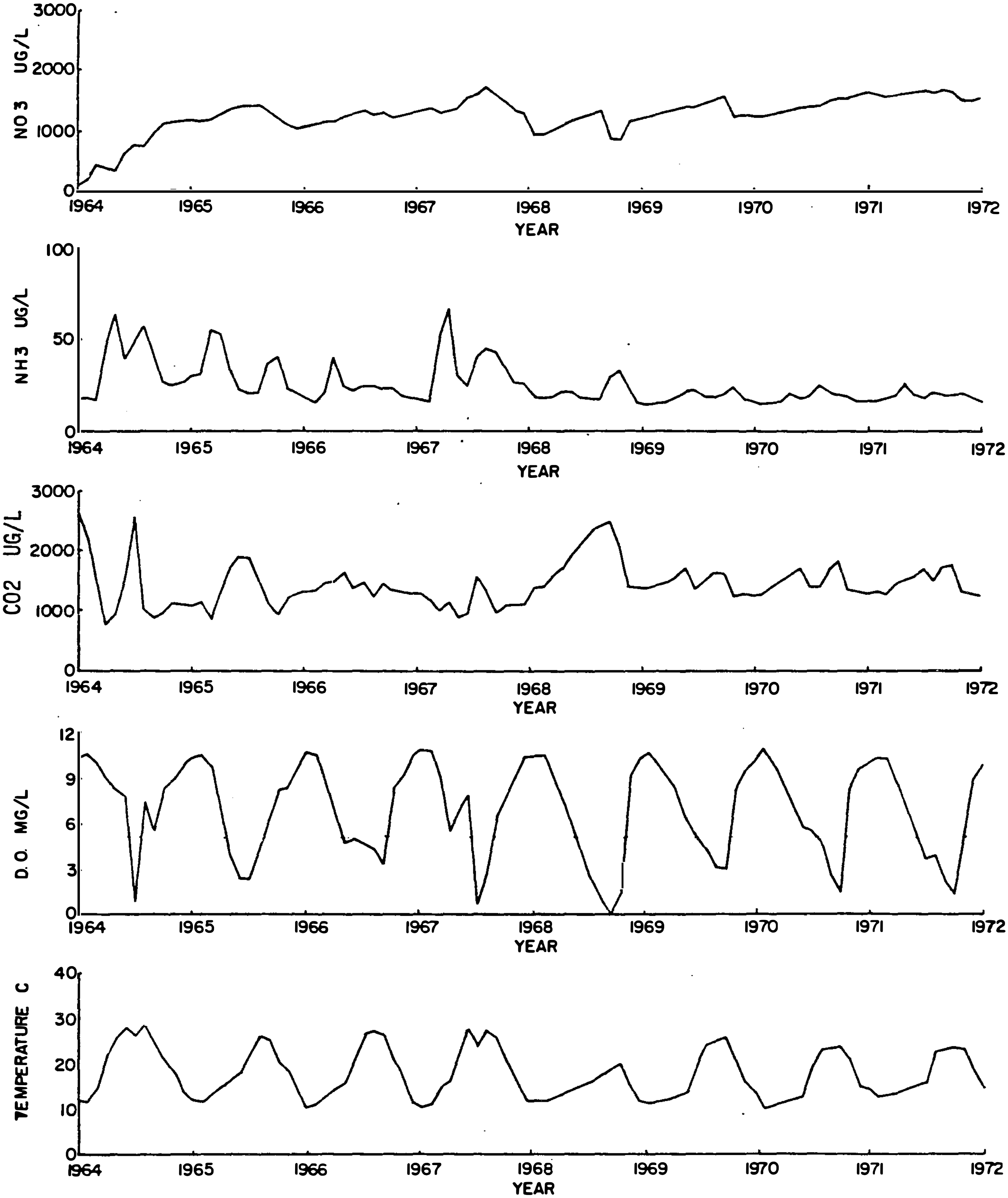


Figure IV-13
Medina Reservoir
Historic Outlet Conditions

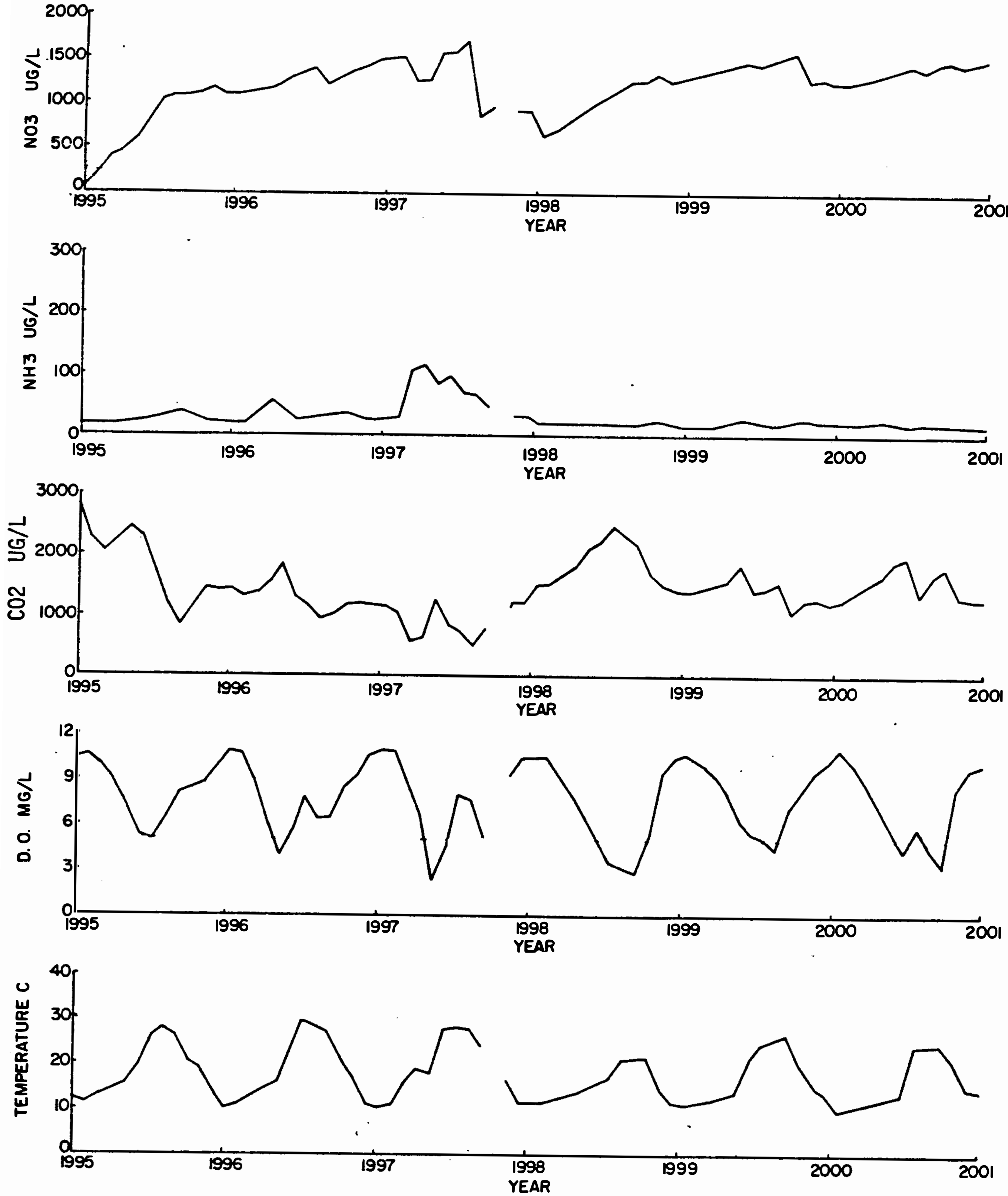
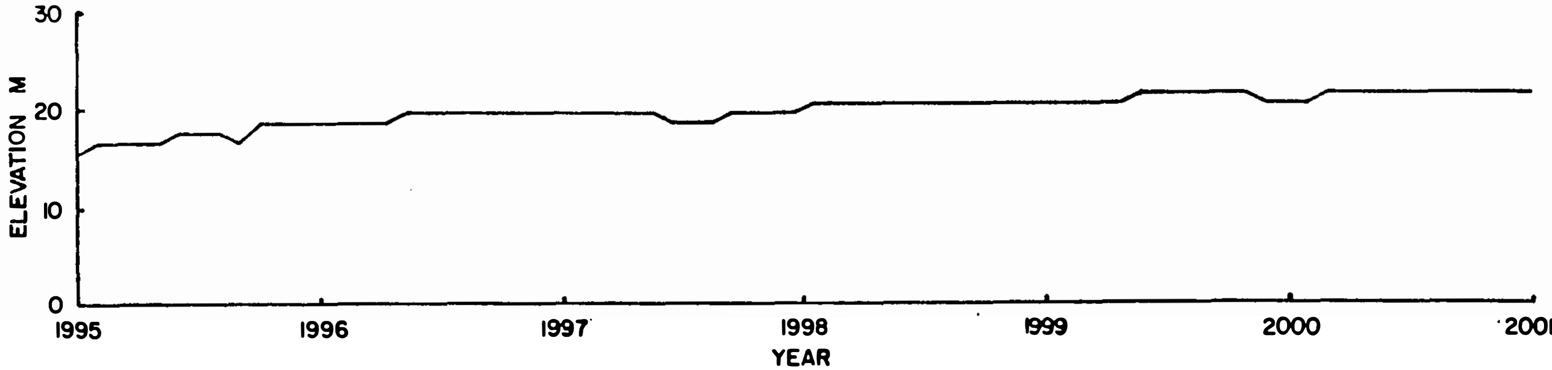
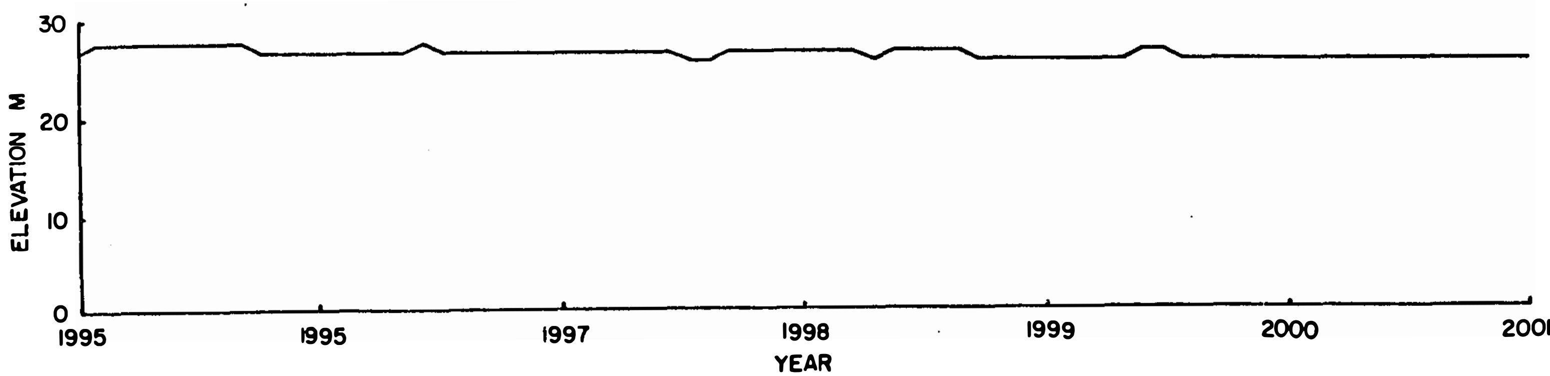


Figure IV-14
Medina Reservoir
Future Outlet Conditions



CIBOLO



CUERO I

Figure IV-15
Future Reservoir Elevations

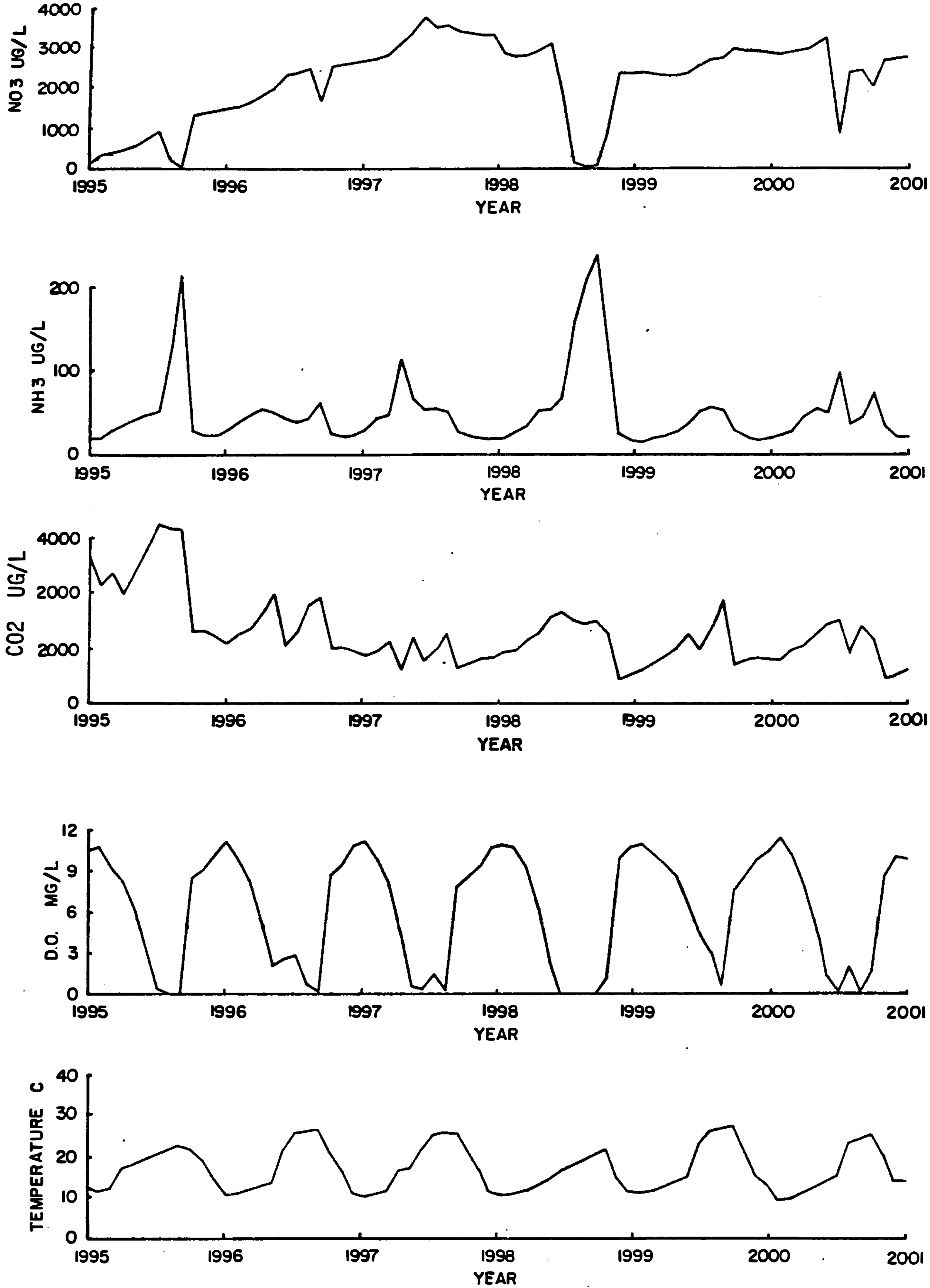


Figure IV-16
Cuero I Reservoir
Future Outlet Conditions

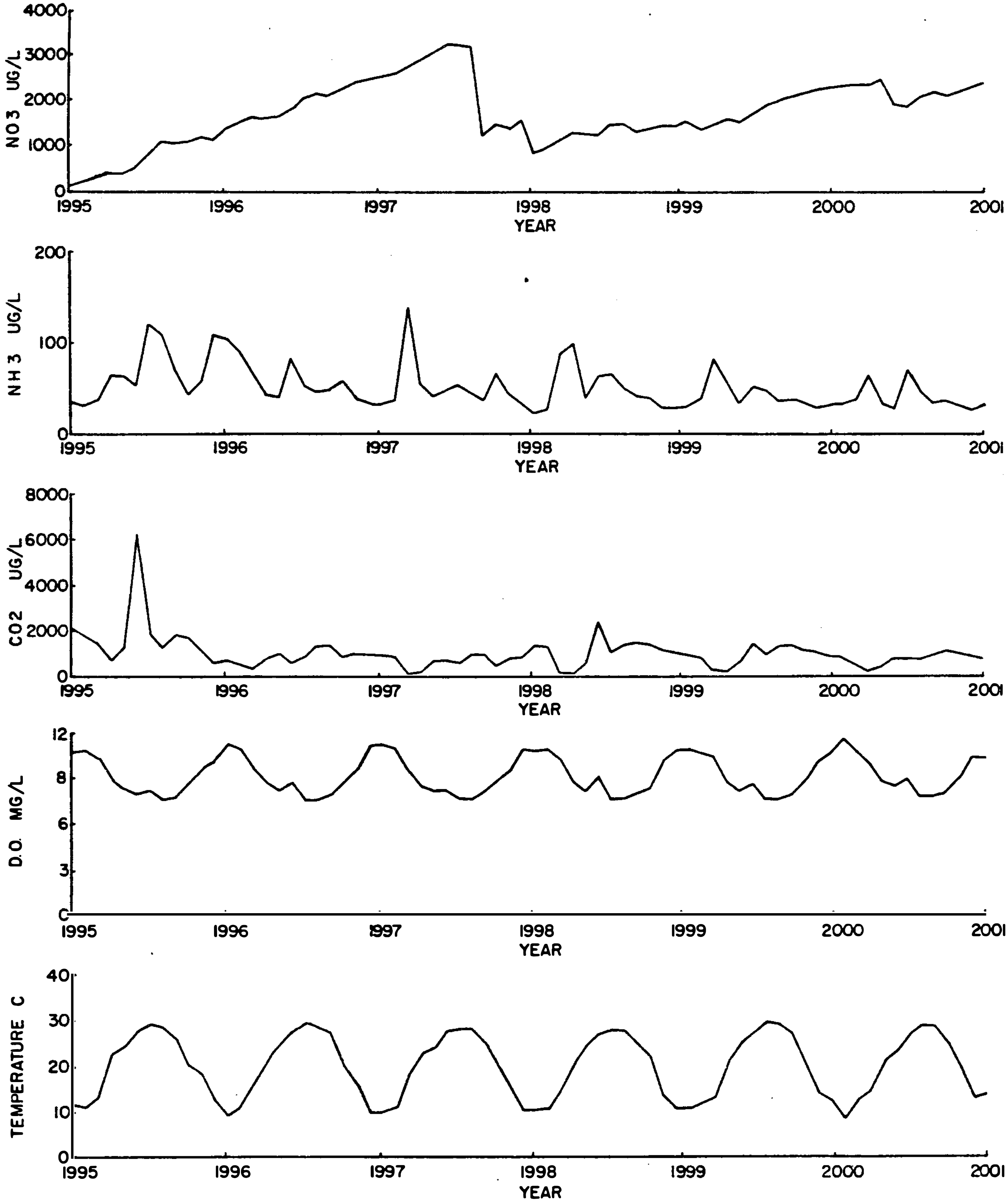


Figure IV-17
Cibolo Reservoir
Future Surface Conditions

of the releases and the water surface elevations for Canyon, Medina, and Cuero I reservoirs. Only the water surface elevation and the surface constituents concentrations are shown for Cibolo reservoir because the operation of Cibolo in the river basin system simulation described earlier was such that downstream releases occurred only when the reservoir spilled.

As indicated in Figures IV-11 and IV-14 little change in water quality is detectable between the historic and future simulations of the Canyon and Medina reservoirs. This is to be expected however, as both of these reservoirs are located in the upper reaches of their respective river basins where no significant growth in population or industrial development is projected.

Projected development below the Canyon and Medina reservoirs places larger future demands upon these reservoirs which frequently causes them to be drawn down to their target elevations which correspond to 90 and 100 percent of conservation storage respectively. Target elevation refers to a particular reservoir volume below which no further releases are made unless a demand exists that can only be met with releases from that reservoir; i.e., in the simulated future river basin operation, no provisions were made for minimum releases from these reservoirs. These periods of zero discharge are denoted by breaks in the temporal traces of the outflow constituents.

Table IV-7 lists recommended or acceptable limits for some selected water quality/biological parameters simulated by the ecological models. By comparing the limits shown in Table IV-7 with the simulation results, the desirability of the water for various uses can be ascertained.

Tɩ IV-7

Recommended or Acceptable Use Limits for Selected Water Quality Constituents Used in the Simulation Models

Constituent	Domestic And Industrial*	Agricultural: Irrigation	Agricultural: Livestock*	Recreational And Anesthetic	Biological (Aquatic) (Warm Water Species)
Dissolved Solids-mg/1	500[1], 1,000[2]	500[1], 5000[2]	10,000[3]	-------	---------
Dissolved Oxygen-mg/1	Saturation[1] 3[2]	----------	------	-------	5[1]
Temperature-°C	30	----------	-----	30	30[2]
Total Phosphorus-mg/1	0.1[4]	----------	-----	-------	.05
Carbon Dioxide-mg/1	-------	----------	-----	-------	25
Ammonia-mg/1 (as N)	0.01[1], 0.5[2]	----------	-----	-------	?
Nitrate-mg/1 (as N)	0[1], 10[2]	----------	-----	-------	0.3
Coliform Organisms No./100 ml	100[1,3] 10,000[2,3]	---------- 5,000[4]	----- -----	400[1,3] 2,000[2,3]	---------
Algae-mg/1 dry wt.	-------	----------	-----[5]	1.5	---------
pH	6.0 - 8.5	5.5 - 8.5	-----	6.5 - 8.3[1] 5.0 - 9.0[2]	6.0 - 9.0

Domestic and Industrial:
1. Desirable
2. Permissible
3. Monthly Averages
4. Phosphates

Agricultural:
1. No effect on most crops
2. Maximum for salt tolerant crops with careful management
3. Maximum depends on animal and ionic composition of water
4. For food or forage crops
5. No blooms of blue-green algae

Recreational and Anesthetic:
1. Primary Contact
2. Non-Contact
3. Fecal coliforms, not more than 10% of samples in 30 days

Biological:
1. Can go to 4 mg/1 for short periods
2. All warm water game species-not for spawning

For easy reference certain of these limits are shown directly on the figures. It is readily apparent that with the exception of low dissolved oxygen in the summer months, the releases from Canyon and Medina are of high quality.

The simulation results of the proposed reservoirs, Cuero I and Cibolo exhibited in Figures IV-15 through IV-17 indicate slightly higher concentrations of nutrients when compared to the future simulations of the Canyon and Medina reservoirs. This was the expected outcome as Cuero-I and Cibolo would be influenced by the return flows resulting from expansion in urban and industrial areas in these sections of the river basins. Overall, the major impact that Cuero-I and Cibolo would have in their immediate areas, would be the alteration of a free-flowing stream (lotic) environment to a quiescent reservoir (lentic) environment.

The results of the stream model simulations are displayed in Figures IV-18 through IV-24. Figures IV-18 through IV-20 exhibit selected water quality parameters in the Guadalupe River under historic and future conditions. For these simulations the Guadalupe River was modeled from just below Canyon Reservoir at river mile 303.0 to the confluence of the Guadalupe and San Antonio Rivers at river mile 10.0. The break (from river mile 160.0 to river mile 110.0) in the dashed line representing future conditions denotes the location of the proposed Cuero-I reservoir.

As can be seen from these figures the simulated future conditions do not vary greatly from the historical period, although some increase in nutrients is evident. One can readily see the impact that Canyon and the proposed Cuero I reservoir have on the Guadalupe River by looking at the traces of temperature and dissolved oxygen in Figures IV-18 and IV-19. The Canyon reservoir releases have in the past successfully supported at least for part of the year, a "put and take" cold water fishery in the

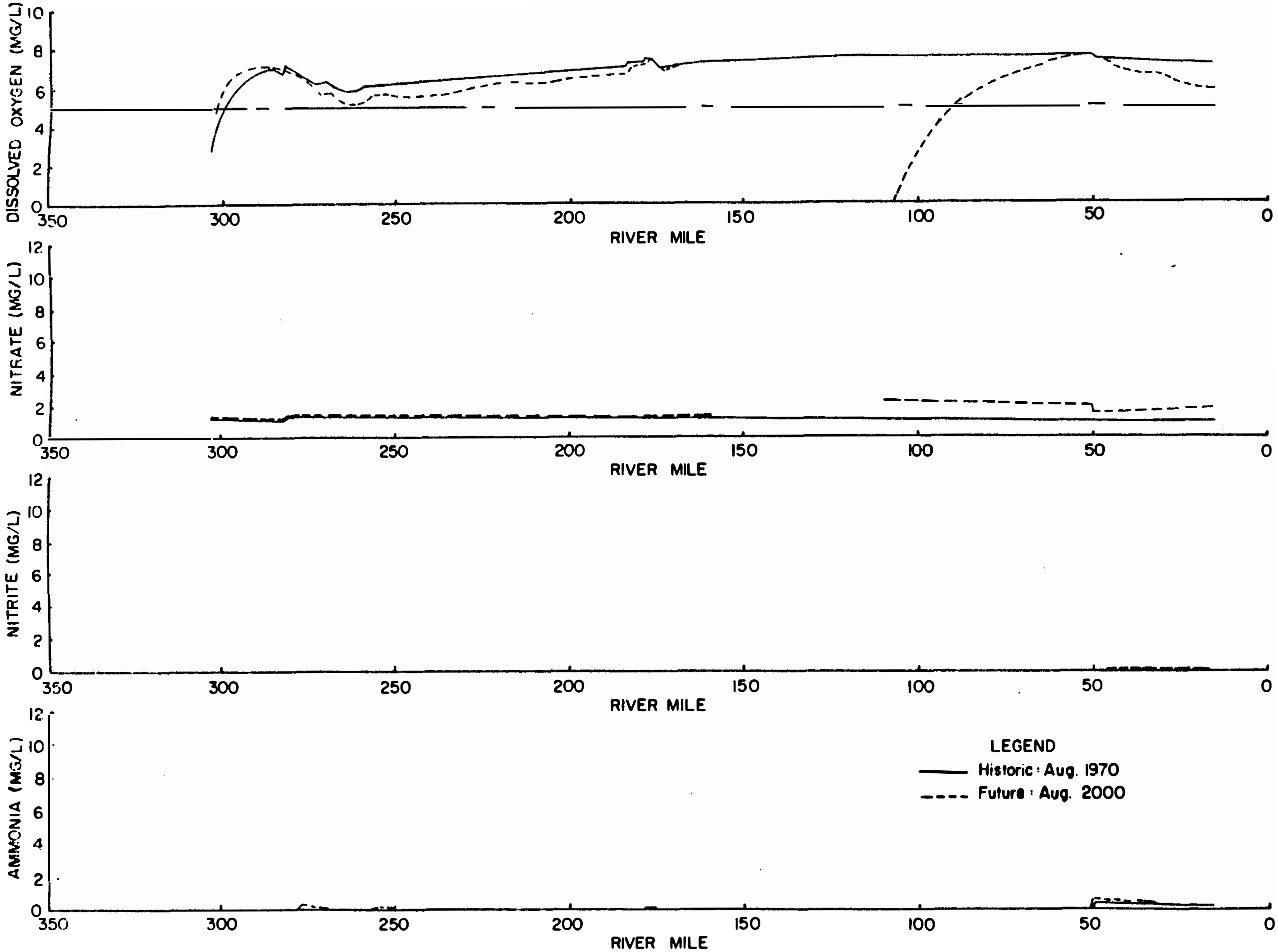


Figure IV-18
Historic and Future Conditions
Guadalupe River

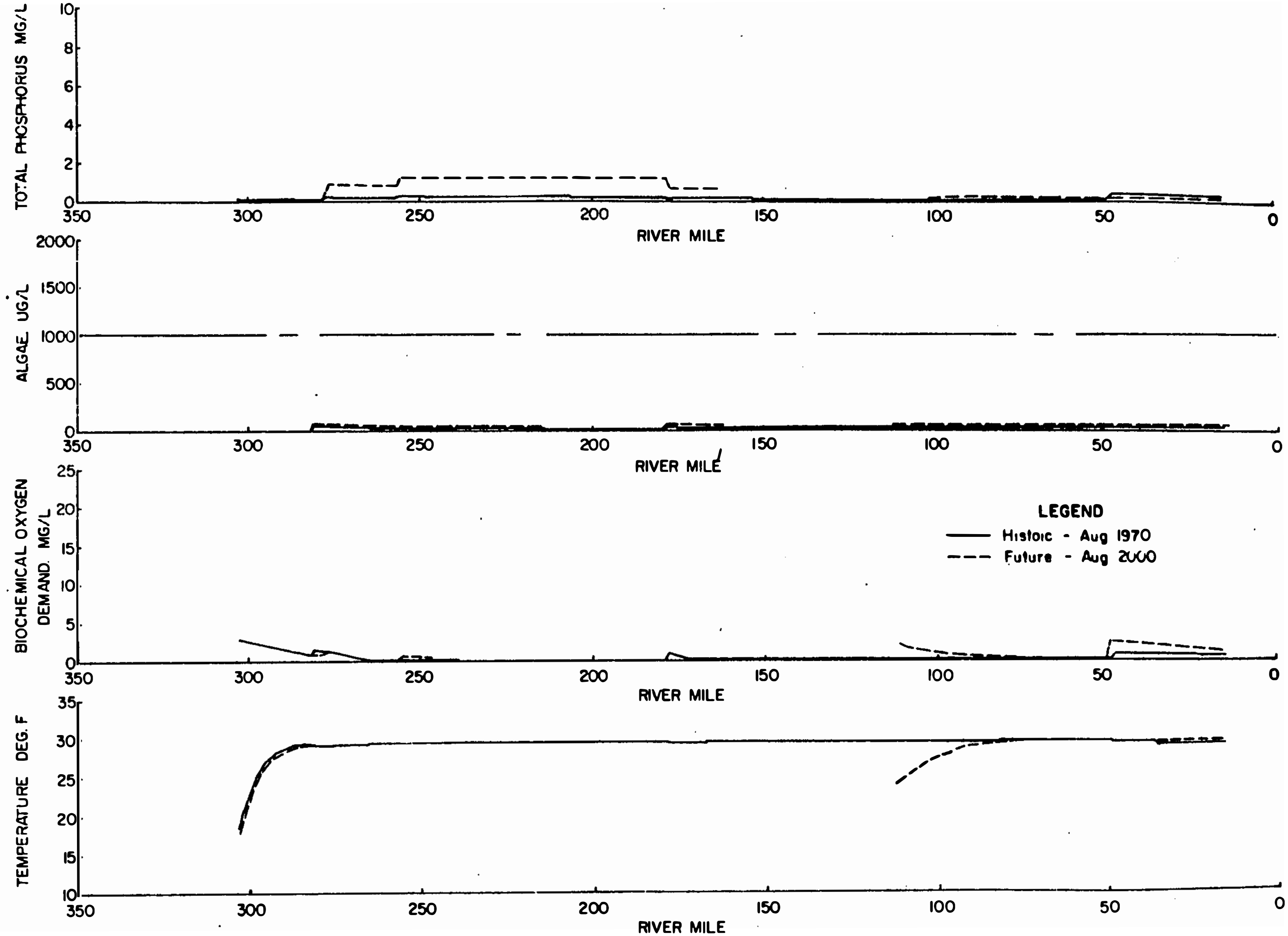


Figure IV-19
Historic and Future Conditions
Guadalupe River

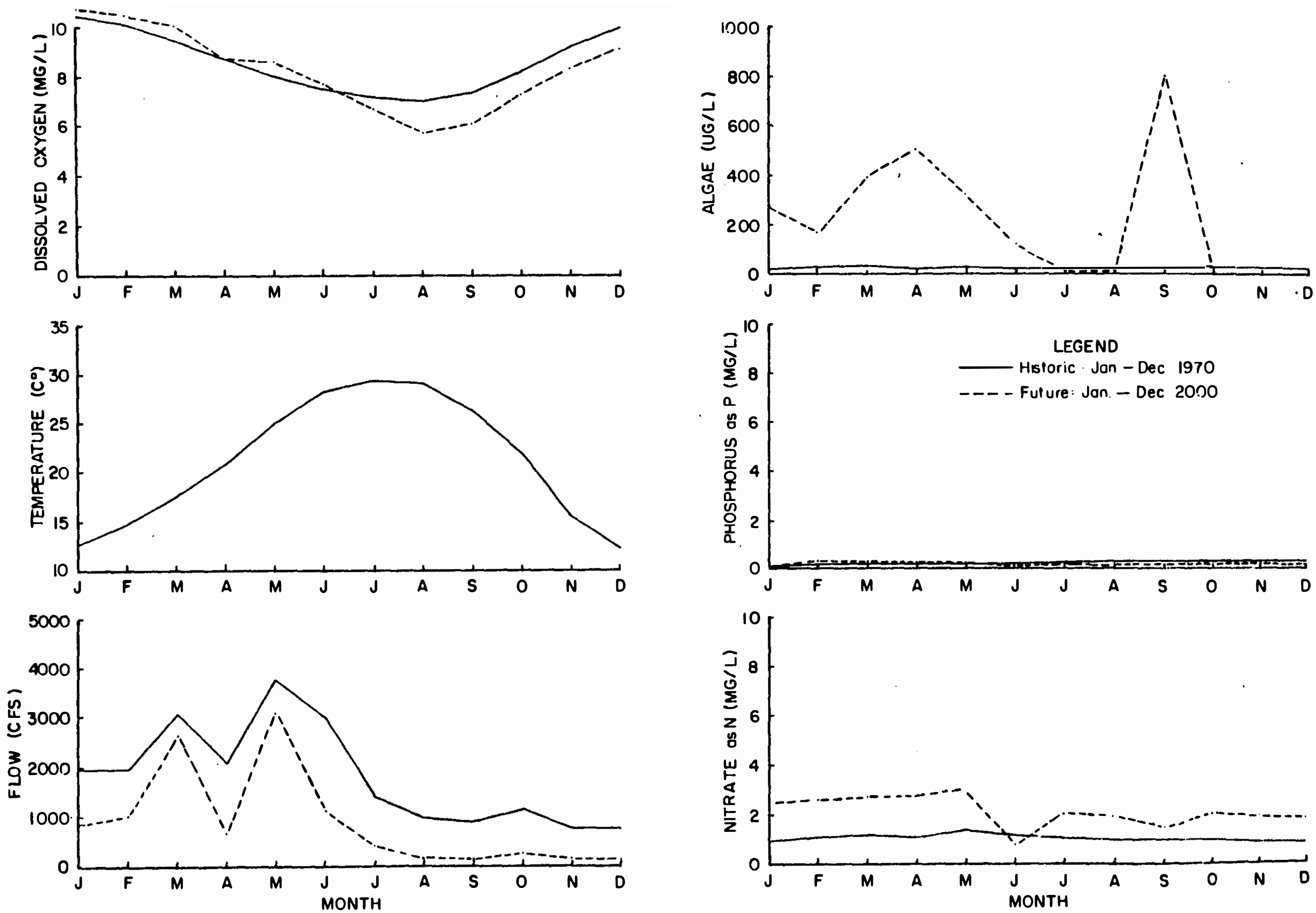


Figure IV-20
Historic and Future Inflows to
the Guadalupe Estuary
(Guadalupe River)

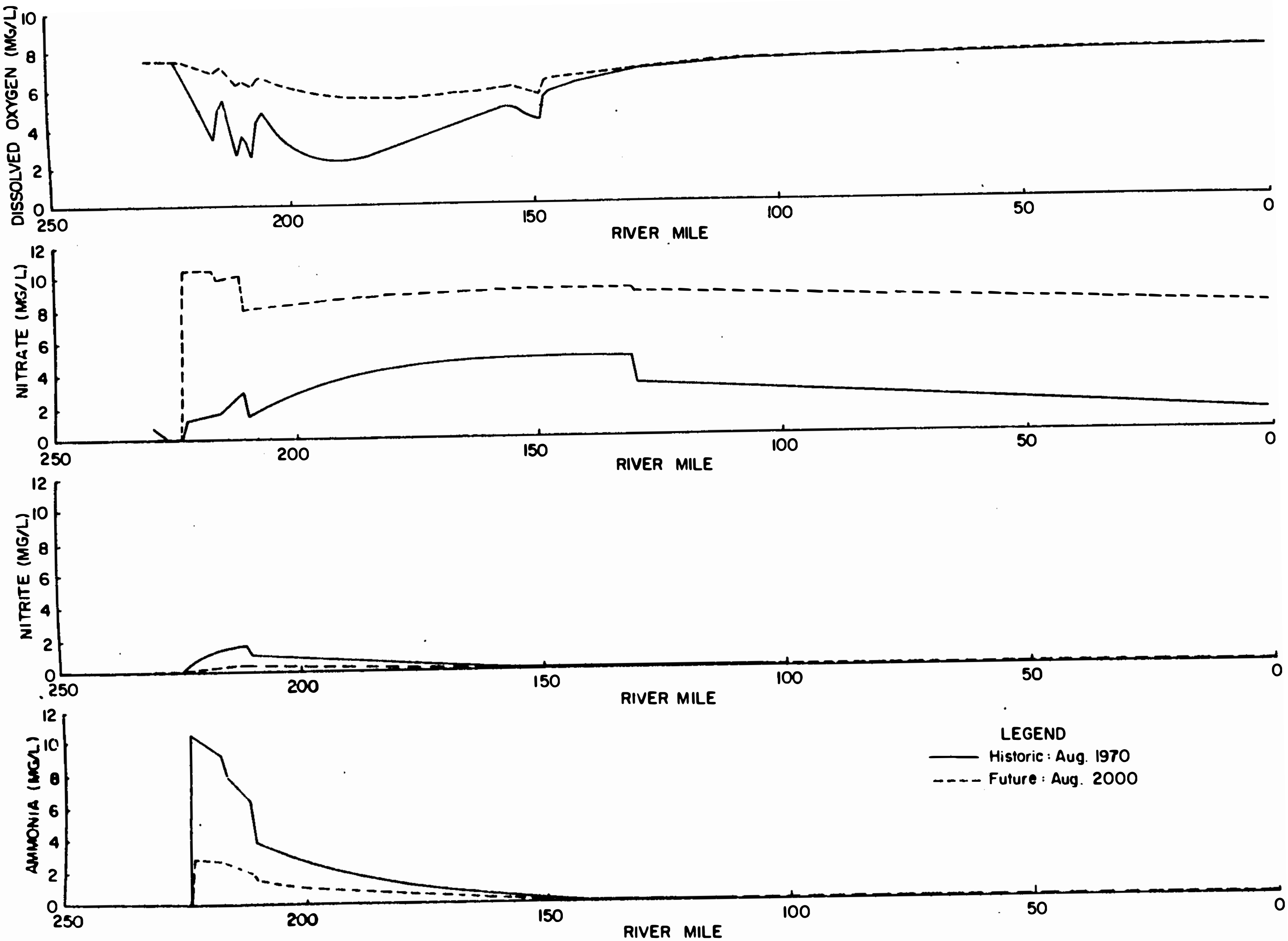


Figure IV-21
Historic and Future Conditions
San Antonio River

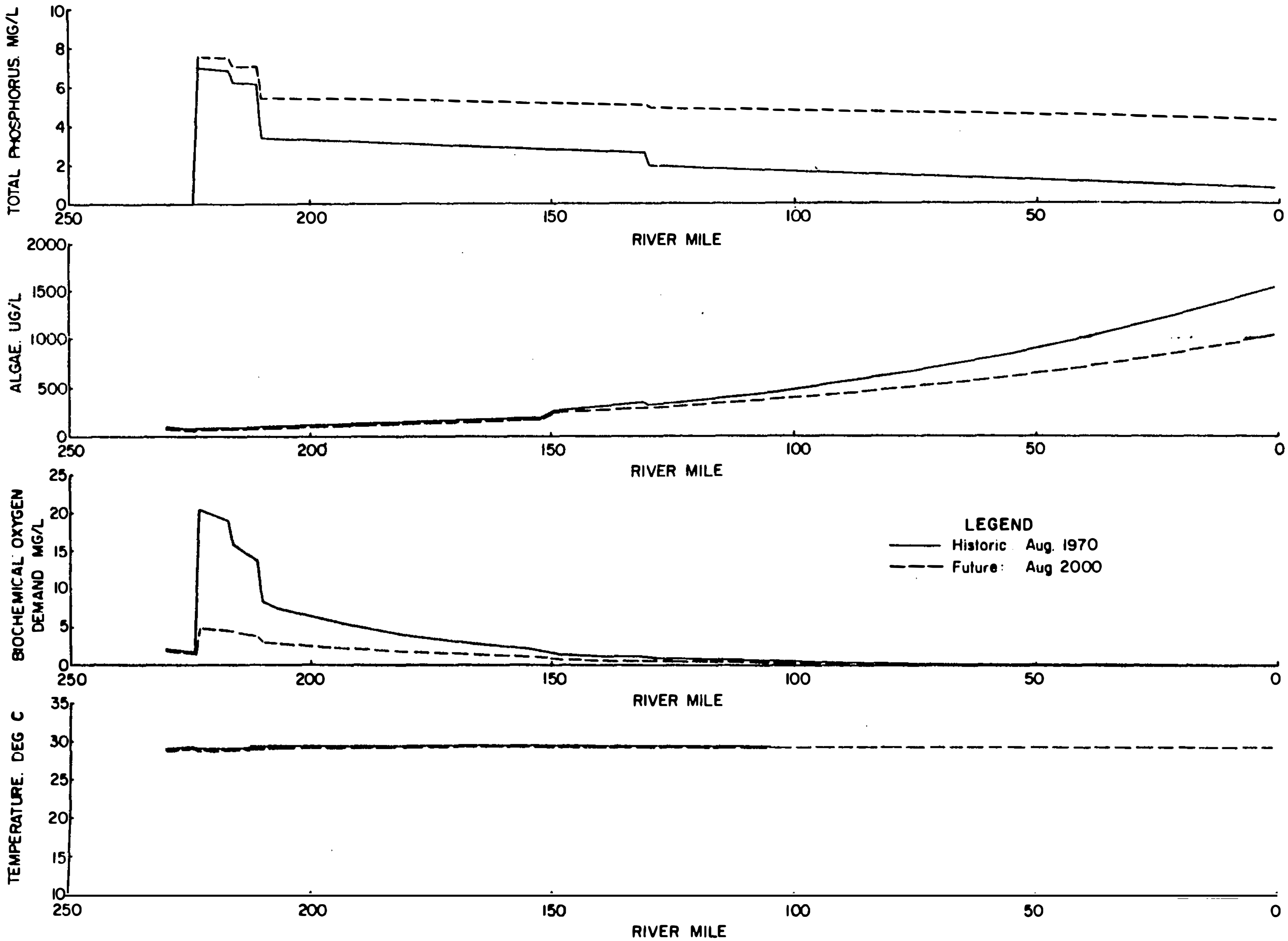


Figure IV-22
Historic and Future Conditions
San Antonio River

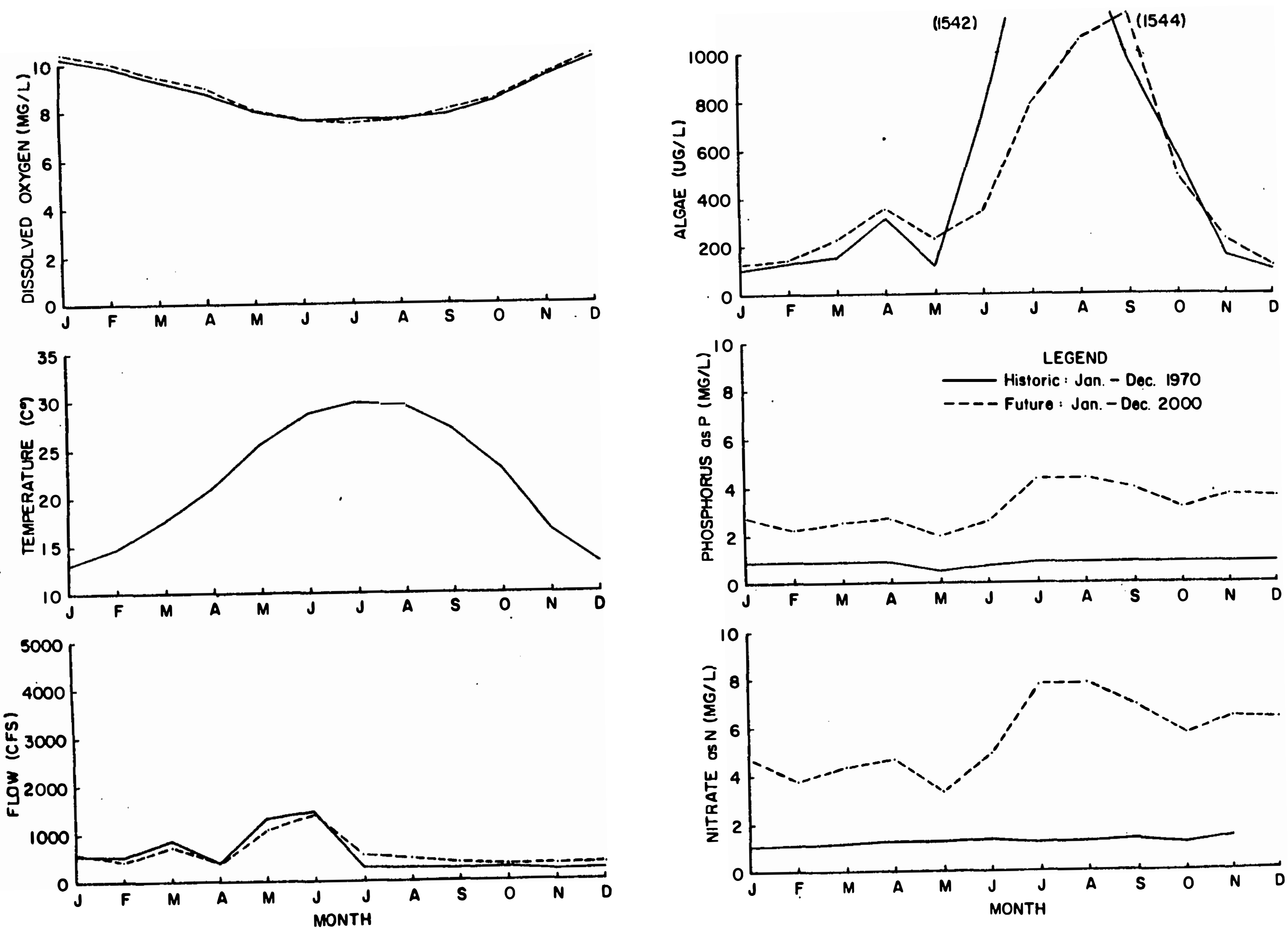


Figure IV-23
Historic and Future Inflows to
the Guadalupe Estuary
(Guadalupe River)

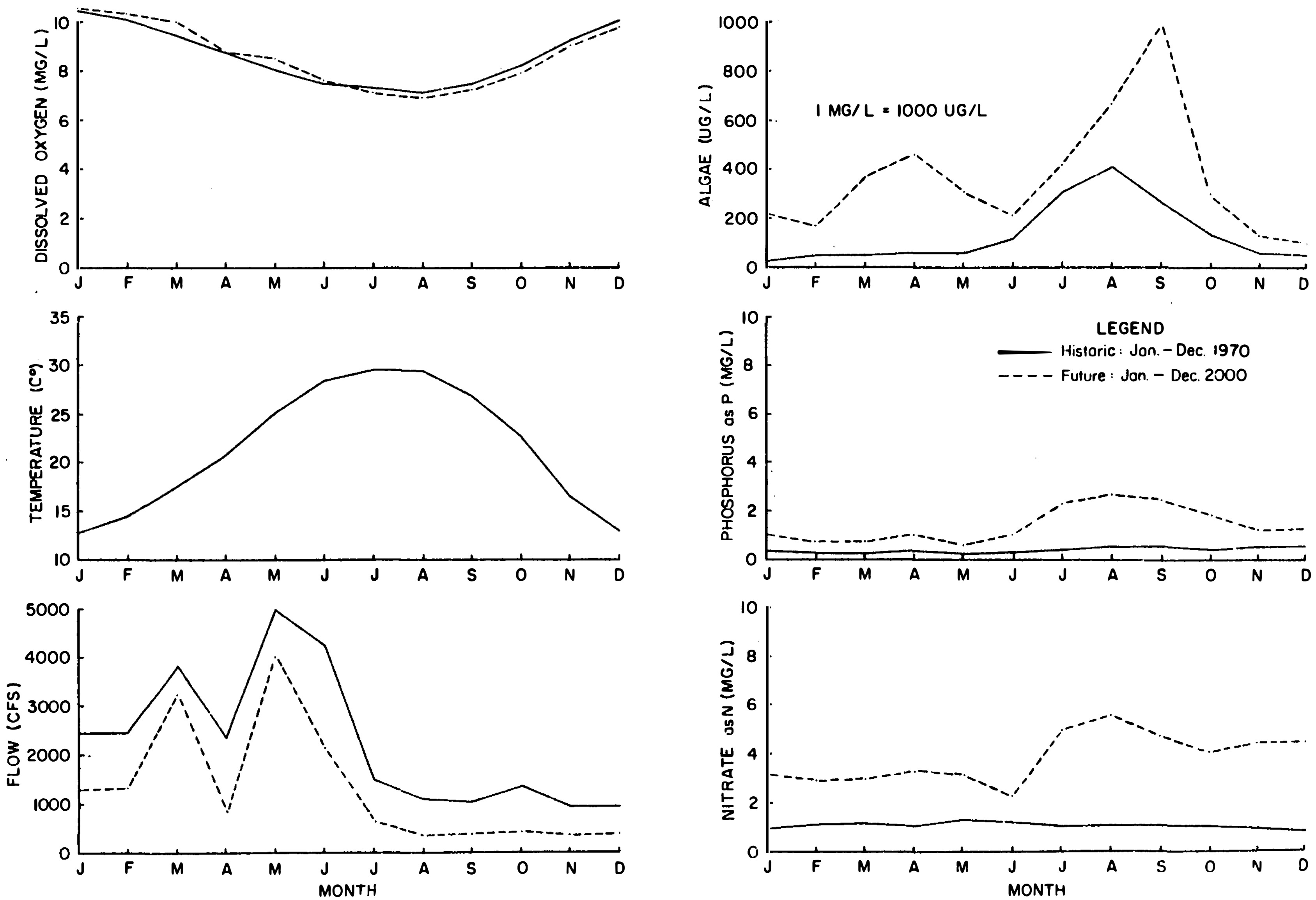


Figure IV-24
Historic and Future Inflows
to the Guadalupe Estuary
(San Antonio River and Guadalupe River)

first few miles below the reservoir. This points out a major drawback to the postulated river basin operation described earlier in this chapter, in that no provisions were made for minimum releases from the reservoir.

Figure IV-20 shows a monthly distribution of the simulated historic and future conditions in the Guadalupe River just above it is confluence with the San Antonio River and about ten river miles above the Guadalupe Estuary. Here it appears that algae are responding to the increase in nutrients.

Overall, water quality conditions in the Guadalupe River under both historic and future conditions are quite good. Organic and nutrient concentrations are low and no heavy growths of algae are evident.

The situation in the San Antonio River Basin is quite different from the Guadalupe River. Figures IV-21 through IV-23 exhibit selected water quality parameters in the San Antonio River under historic and future conditions. For these simulations the San Antonio River was modeled from its headwaters at river mile 232.0 to its confluence with the Guadalupe River at river mile 0.0. Also modeled was the reach of the Medina river below Lake Medina to the San Antonio River at river mile 210.0 and the reach of Cibolo Creek below the proposed Cibolo reservoir to the San Antonio River at river mile 130.0.

These figures indicate that the future water quality conditions will vary to a great extent from the historic. These illustrations also show the dominance of the return flows from the San Antonio metropolitan area on the water quality in the San Antonio River. Readily apparent is the impact of the 1977 target treatment levels given in Table IV-6. By reducing the ammonia with nitrification and reducing the organic load, the quality in the San Antonio River is improved significantly in terms of dissolved oxygen. Nitrification basically converts ammonia nitrogen to nitrate nitrogen and consequently total nitrogen is not affected by the reduction in ammonia. Nutrients (nitrogen and phosphorus) have increased under future conditions as indicated by Figures IV-21 through IV-23. Figure IV-22 indicates that these high nutrient concentrations have stimulated heavy algal growths in the past and most certainly will do so under future conditions. There was no algae data to calibrate the stream model, therefore these results should only be considered in a qualitative sense. The algae trace for future conditions in Figure IV-23 is lower than the historic for the months June through September in spite of the higher nutrient concentrations. This can be explained in part by the fact that the flows in the San Antonio River are higher under future conditions than under historic during this period. The larger flows reflect greater depths and consequently less light penetration.

Historically, water quality in Medina River and Cibolo Creek has been substantially better than the quality of the San Antonio River and these tributaries have had a dilution effect on the San Antonio River where they enter at river mile 210.0 and 130.0 respectively. This can be seen in Figures IV-21 and IV-22 and is expected to continue under future conditions although the dilution effect has been reduced in magnitude.

Overall, water quality in the San Antonio River Basin under the future conditions of river basin development and operation described earlier, could be improved from the standpoint of dissolved oxygen. However, nutrient will be increased and heavy algae growths should continue to depress oxygen valves.

Estuarine Environment

The estuarine ecologic model was developed in order to describe the response of the estuarine system under alternative plans of upstream development. This task was accomplished by extending the existing TWDB conservative mass transport model to account for the ecologic interactions which occur in the estuarine system. The formulations of these interactions are basically the same as those decribed for the reservoir ecologic model with appropriate modifications necessary to describe an estuary (See Appendix C). Initial model operations were performed using input data for June 1972 to simulate the July-September 1972 period. The main objectives for this task were to insure that the model was responding properly, and to adjust the biological rates and reaction coefficients for an estuarine system. The simulated results compared well with the observed data, however additional data packages which demonstrate seasonal trends will be required for further refinement and calibration of the model.

The historic period January through December 1970 and the corresponding future period January through December 2000 were selected as the test case. The model was operated for both periods using monthly average input data (i.e. hydrodynamics, meterological data, source concentrations). The future conditions were reflected in both the quantity and quality of the river inflows.

Figure IV-24 shows the historic versus future inflows to the Guadalupe Estuary. Depleted fresh water inflows under future conditions are the result of increased consumptive use in the San Antonio and Guadalupe River Basins. The distribution of future inflows to the estuary was not altered significantly. Inflows during the critical May-June period for white shrimp (See Appendix D) were adequate to reduce total dissolved solids at Turtle Reef below 10 ppt in the future simulation. This inflow period also provided for continued transport of "biostimulants" to the primary bay system.

Also illustrated in Figures IV-24 are the changes of inflow qualities for the historic versus future conditions. The future inflow quality is dominated by the increased return flows, which contribute the major portion of the streamflow during low flow periods. The concentration of total phosphates and the nitrogen series, therefore, have an inverse relationship with streamflow. The inflow concentration of algae, as illustrated in Figure IV-24, follows the concentrations of biostimulants; i.e., nutrients. Dissolved oxygen inflow concentrations for historic and future conditions adhere to the seasonal response of dissolved oxygen to the ambient water temperature regime.

The future inflow conditions to the Guadalupe Estuary, as simulated by the stream ecological model, show reduced salinities during the peak spring migrations economically of important estuarine organisms. Although future fresh water inflows were reduced in quantity, their transport of biostimulants, which are vital to the primary biological production of the estuary, were increased. Therefore, the future inflow regime provided increased concentrations of biostimulants per unit volume to excite the estuarine ecological model.

Typical responses of the estuarine ecological model to inflow concentrations of total dissolved solids and nutrients are shown in contour plots of total dissolved solids, nitrates, and phosphates (Figures IV-25 through IV-27). These figures are computed spatial distributions of selected constituents that illustrate the impact of the future conditions under three hydrodynamic regimes: (1) with January 1970 and 2000 representing an average inflow condition; (2) with May 1970 and 2000 representing a high inflow period; and (3) September 1970 and 2000 representing to a low inflow period. Comparison of the total dissolved solids plots demonstrate the estuarine model's response to different inflow conditions. The model's response indicates only minor changes in the distribution of total dissolved solids (TDS) for historic versus future conditions. Gulf tidal

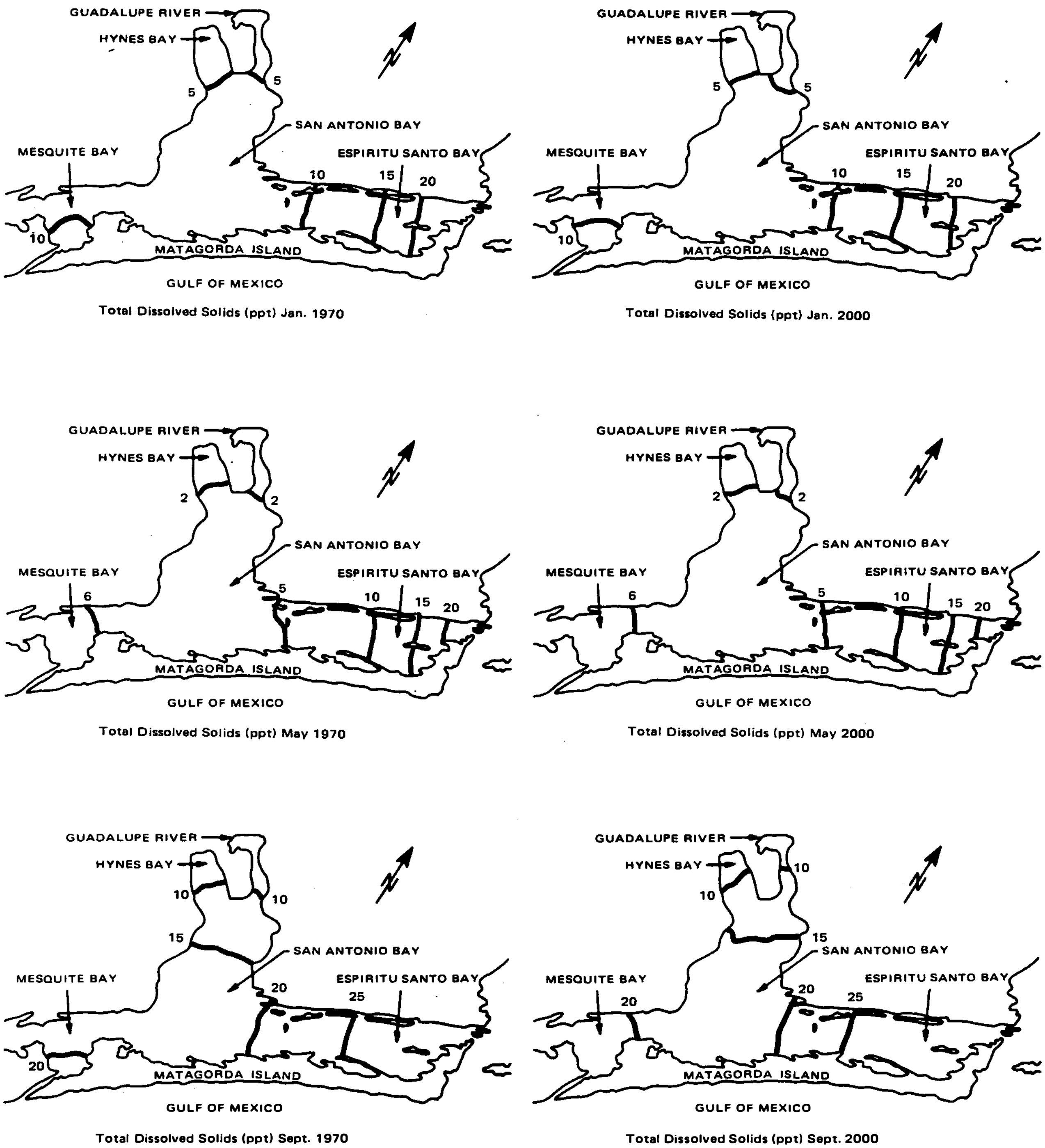


Figure IV-25
Historic and Future Total Dissolved Solids Distributions - Guadalupe Estuary

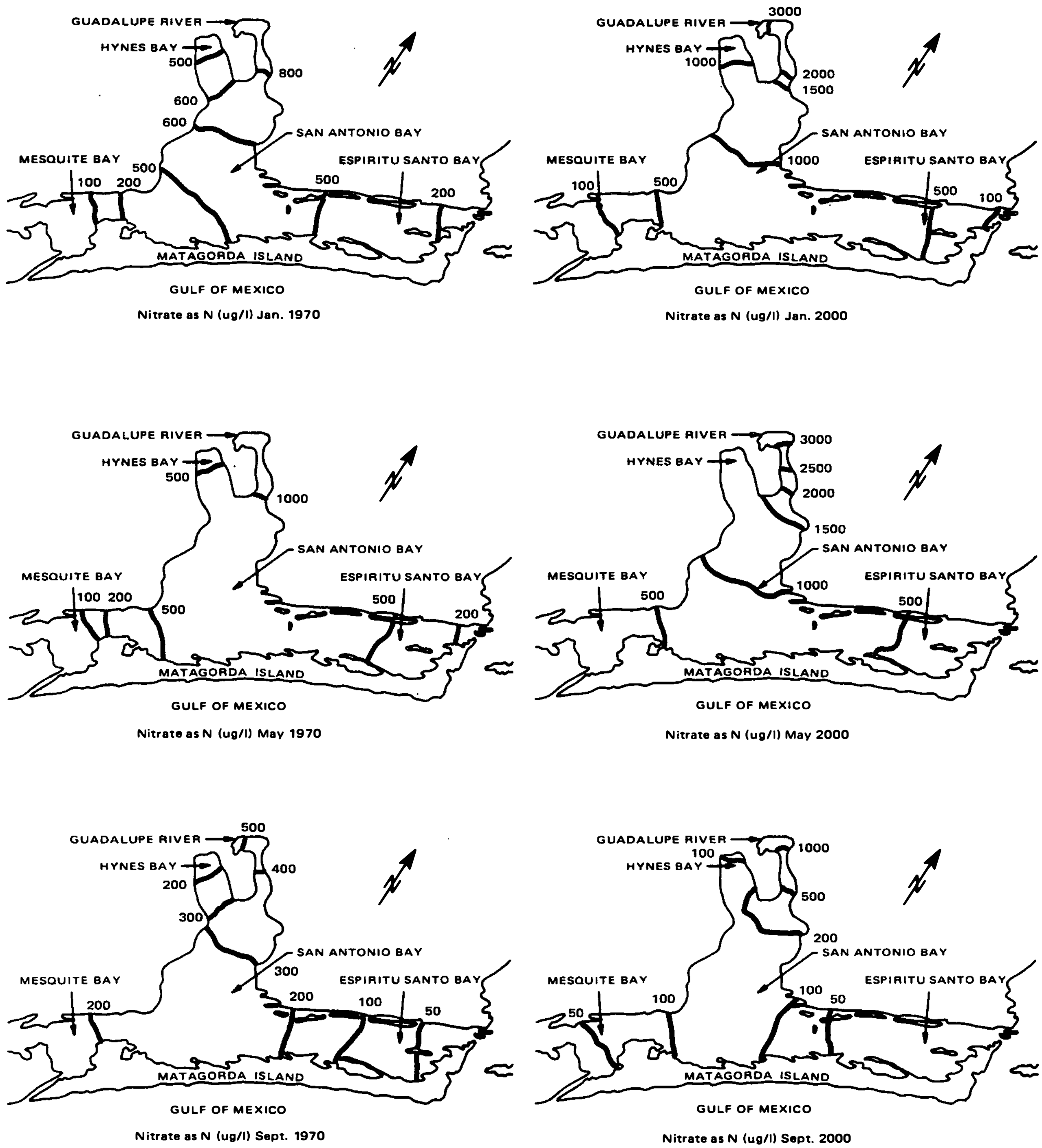


Figure IV-26
Historic and Future Nitrate Distributions - Guadalupe Estuary

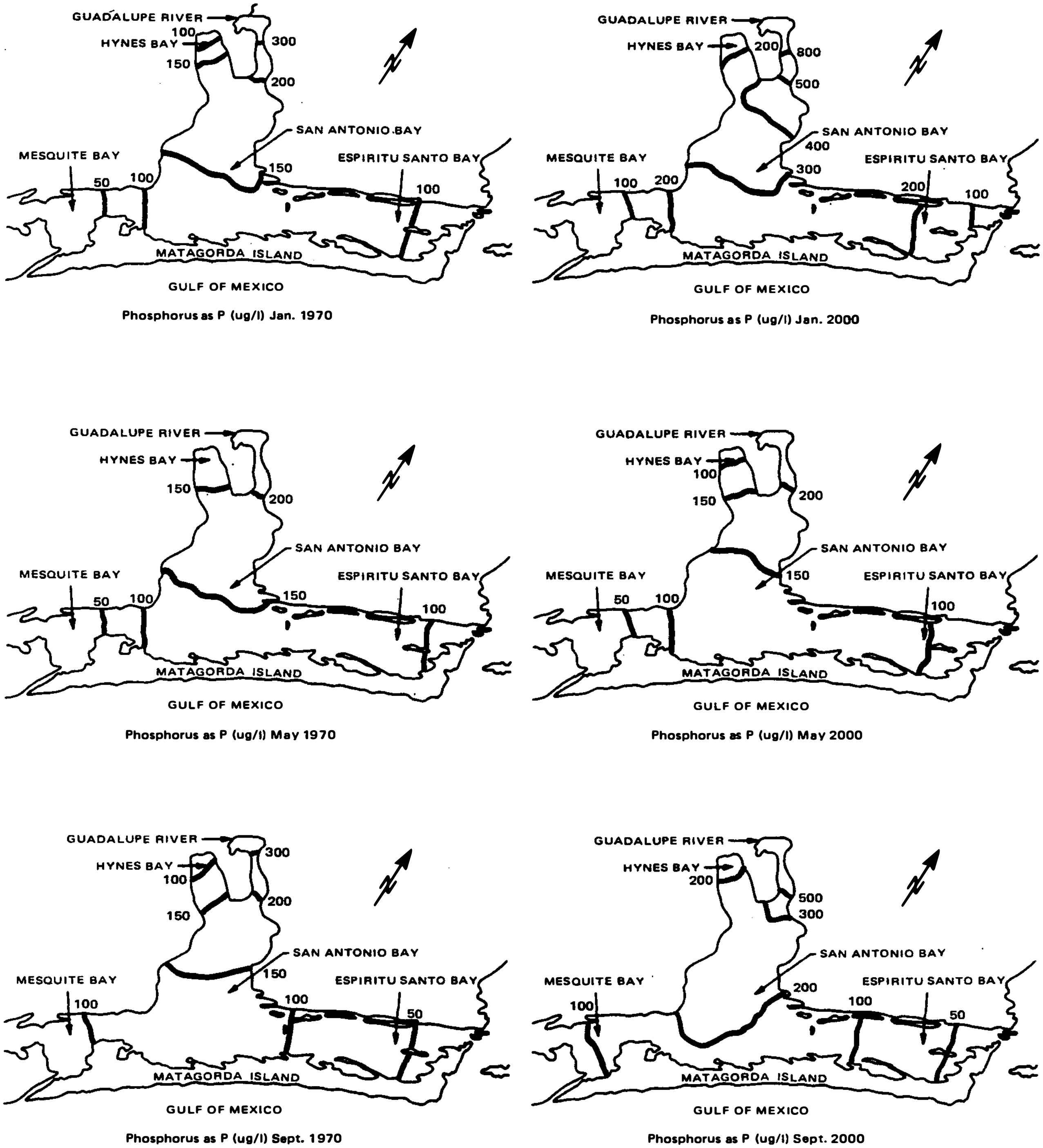


Figure IV-27
Historic and Future Phosphorus Distributions - Guadalupe Estuary

exchange and river inflow are the responsible parameters for developing the total dissolved solids patterns in the Guadalupe Estuary. River inflows dominate the distribution of TDS during high inflow conditions as illustrated in the January and May historic and future conditions. The Gulf tidal exchange impacts the system during low river flow, as demonstrated during September 1970 versus September 2000 where the increased demands on the future inflow conditions were of significant magnitude to slightly increase TDS in the upper bay regions.

The nutrient plots demonstrate the impact of the hydrodynamic transport of future nutrient loading from the river basin as compared with the historic period. The nitrate distributions illustrated in Figure IV-26 demonstrate increased concentrations throughout the estuary as a result of the hydrodynamic response of the system to the increased loadings under the future conditions, January 2000 and May 2000. Concentrations of nitrate in the September 2000 condition are decreased substantially compared to the historic condition in the open bay system. This is attributed to the algae population having sufficient contact time, under this low flow period, to reduce the concentration of this nutrient below historic levels. The distribution of phosphorus, Figure IV-27, again shows the hydrodynamic response of the system to the increased nutrient loadings under the future condition. This is apparent from the increased phosphorus concentrations throughout the system under all inflow regimes. The algae blooms during the September 2000 condition were not apparent in the distribution of phosphorus as only a very small fraction of the algal biomass is considered to be phosphorus dependent.

Figures IV-25 through IV-27 illustrate two aspects of the impact of the future conditions on the estuarine system. While the river inflows to the estuary were reduced in the future condition, the magnitude of this reduction was not sufficient to significantly alter the historic distributions of total dissolved solids. Further, the nutrient loadings under the future conditions provided increased nutrient concentrations which stimulate primary productivity. Additional results of the estuarine ecologic model are shown in Figures IV-28 and IV-29. These plots illustrate the temporal variation of selected constituents for the hydraulic element (I-15, J-14) which corresponds to the Turtle Reef area of the Guadalupe Estuary (see Appendix C). The model's response is demonstrated in the plot of total dissolved solids where the reduced inflows under future conditions produce uniformily increased total dissolved solids concentrations.

The nutrient concentrations at Turtle Reef, depict the ability of the bay system to assimilate nutrient materials by biotic and abiotic processes. The plot of ammonia nitrogen, shows reduced concentrations under future conditions, and is due in part to the more strigen effluent standards imposed on the future conditions. These standards were set in order to maintain stream dissolved oxygen concentrations above 5 mg/l. During the later part of the future simulation period May - November the ammonia nitrogen concentrations are further reduced below historic condition due to biotic assimilation. The biotic assimilation of nitrogen is further illustrated in the plot of nitrates, where the future concentrations are reduced below historic levels corresponding to a substantial increase in algae concentrations. The concentrations of phosphorus demonstrate the model's response to increased phosphorus loadings under future conditions. It is apparent from the comparison between river and bay concentrations of phosphorus that biological assimilation of this constituent is occuring in the estuarine system. The plot of inorganic carbon reflects the reduced inflows under future conditions, where biological assimilation and reduced hydrodynamic transport of this constituent is apparent when compared with the historic period.

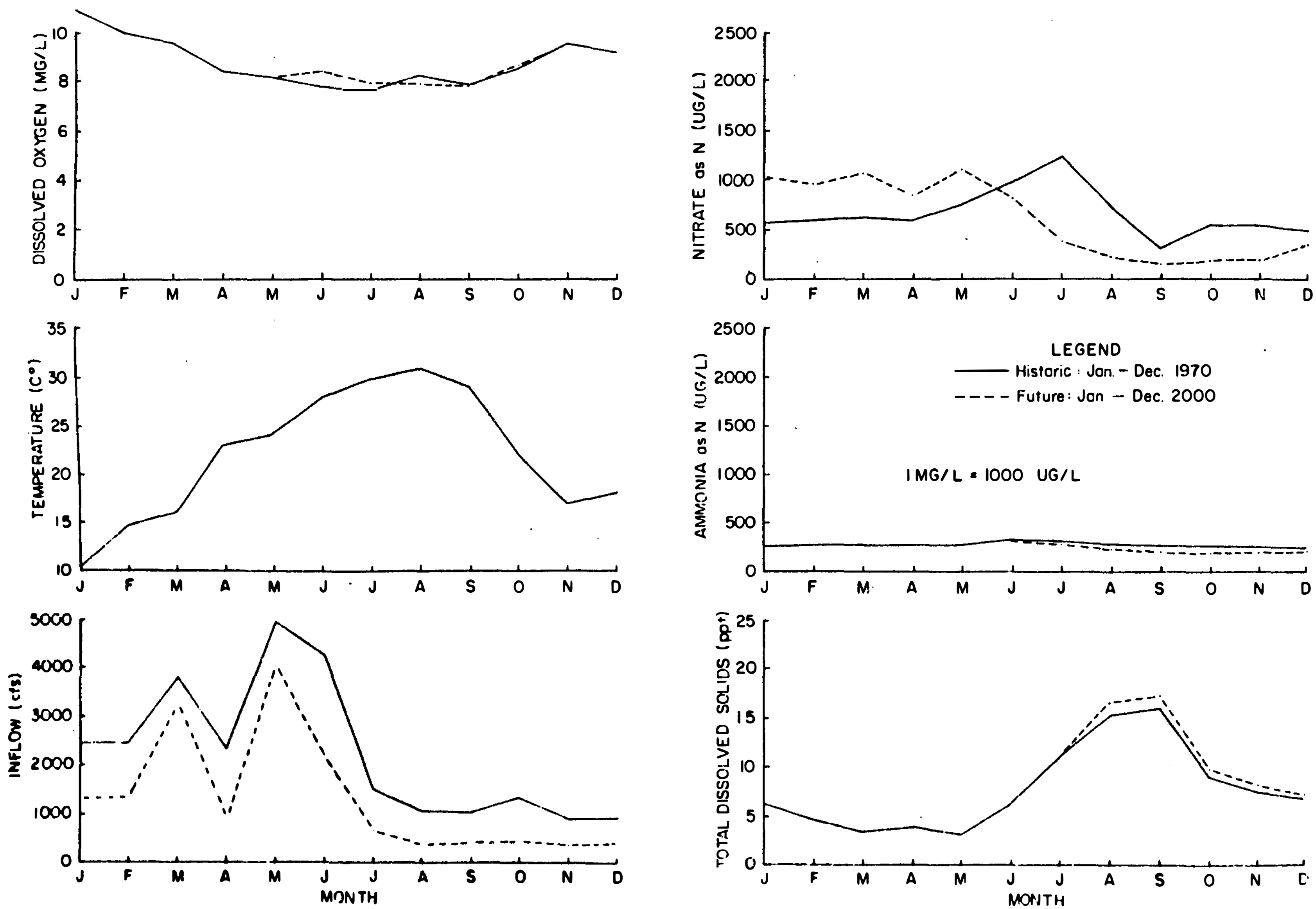


Figure IV-28
Historic and Future Conditions
for Turtle Reef Area
(Guadalupe Estuary)

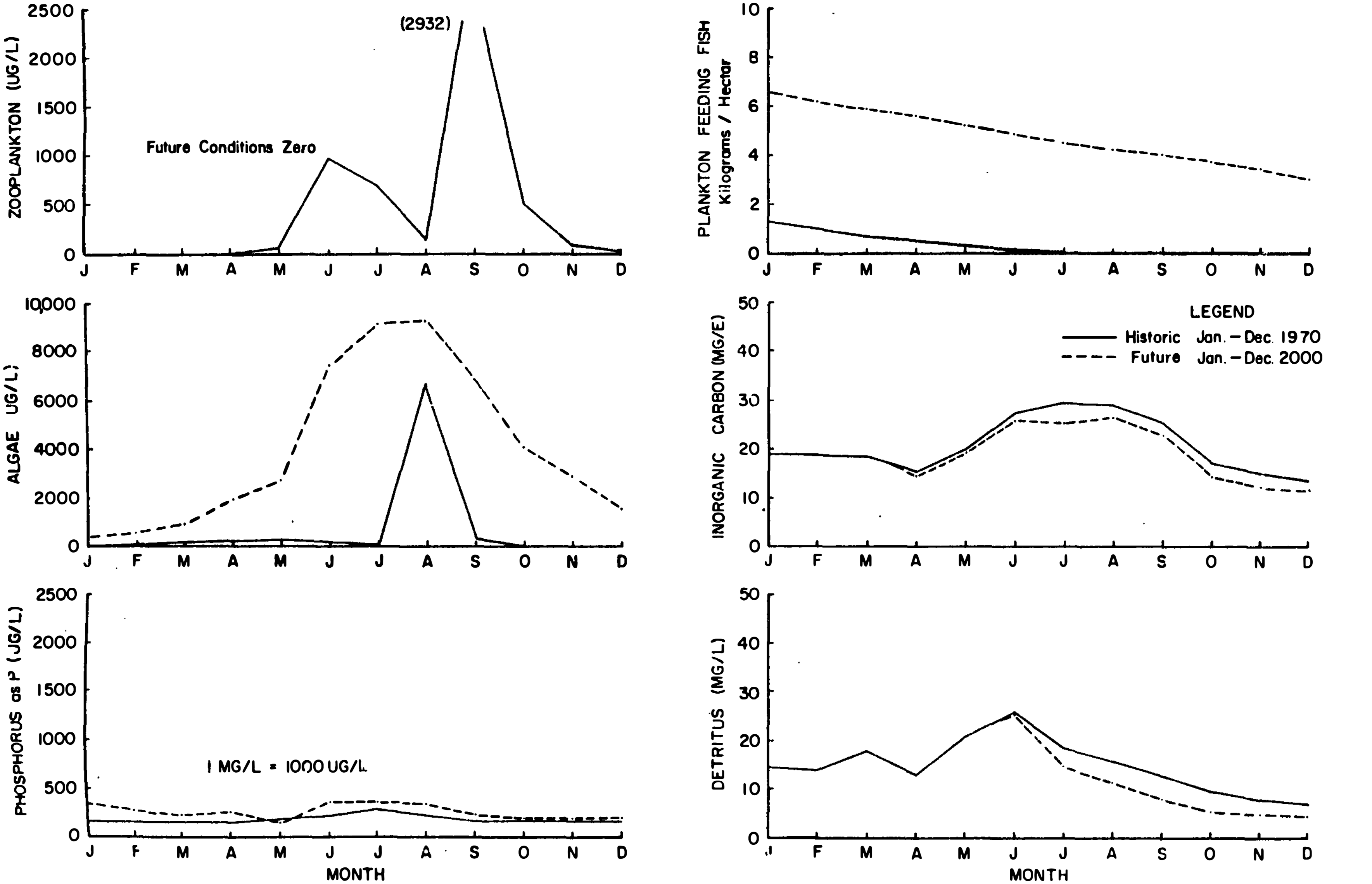


Figure IV-29
Historic and Future Conditions
for Turtle Reef Area
(Guadalupe Estuary)

The seasonal response of dissolved oxygen to the ambient temperature regime is also evident in the estuarine system. The concentrations shown are average daily values, not intended to depict the diurnal fluctuations of dissolved oxygen. It should be noted that these values approach saturation, which indicates that reaeration and temperature are the controlling factors for this constituent. This is consistent with previous research that has shown Texas estuaries in general to be wind dominated - temperature driven systems.

The detritus concentrations as simulated by the model are free floating organic materials carried by the river input and transported by the estuarine hydrodynamics. Volatile suspended solids information was used to estimate the detrital inputs to the estuarine ecologic model because of the scarcity of data on this constituent. Input concentrations were for both historic and future conditions were identical and the reduced mass influx is evident in the reduced detritus concentrations for the Turtle Reef area.

The plots of algae, zooplankton, and plankton feeding fish, while they lack quantitative accuracy, do indicate the proper response to the imposed constraints. This is illustrated in the historic period where both zooplankton and plankton feeding fish follow the concentrations of algae early in the simulation period. This situation does not occur in the future period towards the end of the mathematical simulation because the high standing crop of plankton feeding fish anticipated by the model has effectively removed the zooplankton from the system. The interactions of the biological and nutrient constituents are evident in the plots of nitrate and algae. Future algae concentrations shown are the result of increased nutrients supplied by the river. These interactions are further demonstrated towards the end of the future period where the algal populations have effectively reduced the nitrate concentrations below historic levels. While the biological results show less than acceptable numerical accuracy, the interactions of the biotic constituents are being reasonably simulated in a qualitative sense.

Migratory Organism Model

The migratory organism model (MOM) was developed and calibrated to simulate annual commercial white shrimp harvest for the 1962-1970 period. The composite simulated results obtained for this historical period are displayed in Figure IV-30. This graph is a representation of the total computed environmental scores for fresh water inflow (inundation), salinity, and water temperature versus annual white shrimp harvest. Similarily, MOM was operated to evaluate white shrimp harvest for teh test case years 1998, 1999, and 2000. These years correspond to the environmental conditions which occurred in 1968, 1969, and 1970, respectively. Consequently, the simulated white shrimp harvests are compariable between corresponding years.

For simulating white shrimp harvest for the test case years, monthly fresh water inflows to the Guadalupe Estuary were obtained from SIM-IV operational studies. These monthly inflows were distributed daily on the same daily percentage distribution which occurred in the corresponding historical monthly period. For example, the daily distribution of inflows for January, 1998 were distributed identically to the computed daily percentage distribution for January 1968. The daily salinities for the test case years were calculated from the Turtle Reef salinity equations shown in Table D-3 of Appendix D. Daily water temperature for corresponding days in the test case years and historical period were identical.

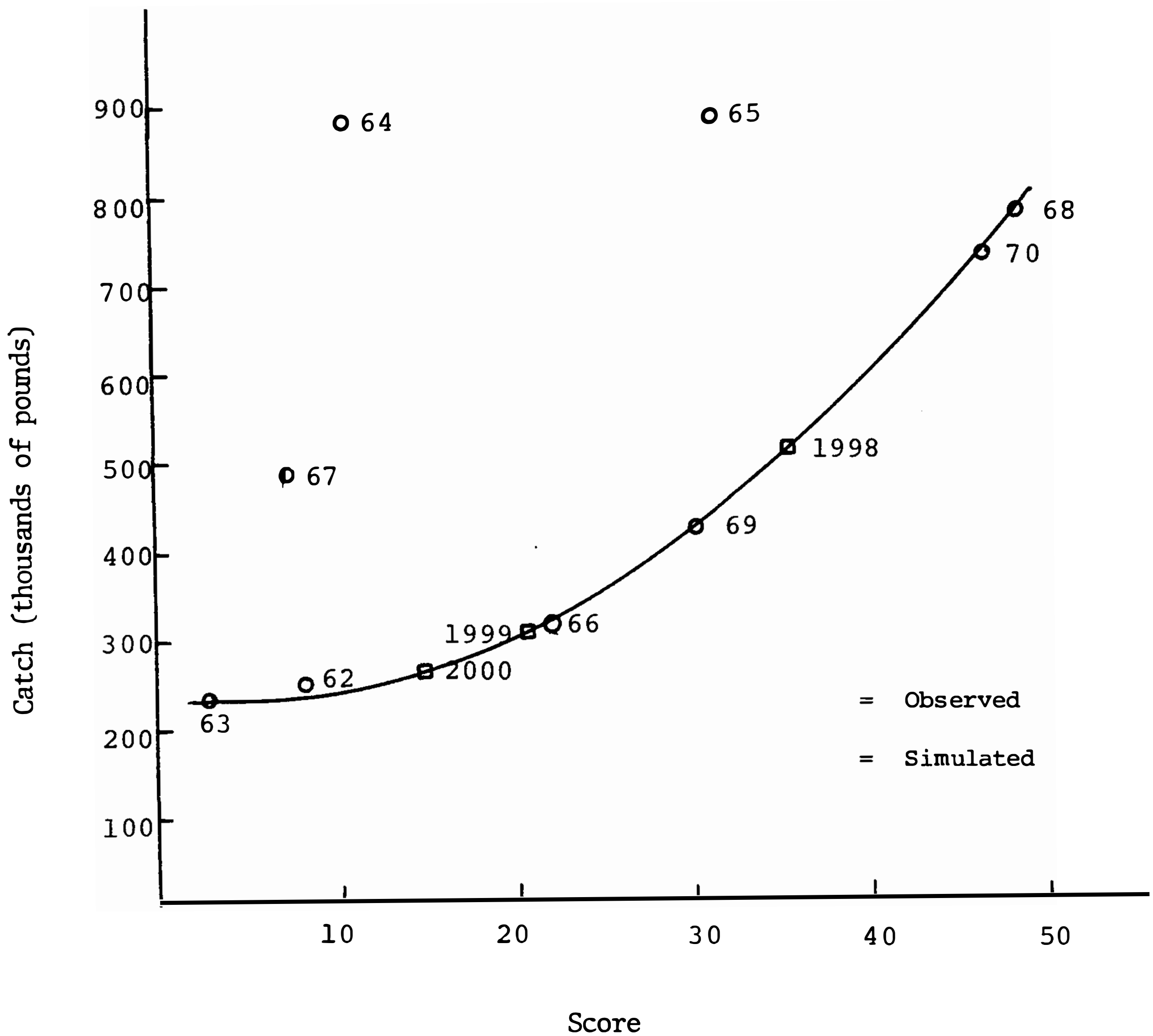


Figure IV-30
Flow and Salinity Environmental Score

Simulated white shrimp harvest for both compariable periods are as follows:

1968 - 777,000 pounds	1998 - 500,000 pounds
1969 - 413,000	1999 - 320,000
1970 - 720,000	2000 - 275,000

Historical total 1,910,000 pounds

Test case total 1,095,000

Difference 815,000 pounds (42.7% decline)

The decrease in harvest resulted from low scoring for fresh water inflow and salinity for the future condition. MOM evaluates environmental conditions for each 10 day interval from daily values of each environmental parameter. The environmental scores for these parameters were significantly lowered for the future years, as compared to the corresponding historical period, based on the evaluation of the "dynamic" ten-day intervals. The distribution and quantity of fresh water inflow was altered significantly enough for the future condition to lower the environmental score. Consequently, the salinity gradient distribution was significantly higher, also resulting in a lower environmental score. Therefore, the shrimp harvest was estimated about 42.7% lower for the future condition.

The largest decrease in annual white shrimp harvest occurred in the corresponding years 1970 and 2000. The annual fresh water inflow for these years was 1.55 million acre-feet and 0.93 million acre-feet, respectively. The inflow for 2000 might have been sufficient to maintain a viable shrimp harvest if the seasonal distribution had corresponded more to life cycle needs.

The white shrimp data analysis, which preceeded the development of MOM (i.e., total catch versus total runoff and monthly catch versus antecedent environmental conditions), showed that total annual runoff and total white shrimp catch are not directly related, but the seasonal distribution of fresh water inflow is extremely important (see development of MOM in Appendix D). This distribution of inflows has been shown to be critical to the estuarine system for maintaining salinity gradients and inundation regimes which are condusive to white shrimp survival and growth. Minimum flow supplies the basic transport mechanism for carrying biostimulants to the estuarine system. The annual inflow determined from this application of MOM for the Guadalupe Estuary was about 900,000 acre-feet. It must be emphasized, however, that this inflow quantity is subject to the limitation and assumptions of MOM and based on the historical period, 1962 through 1970.

Relationship of Results: MOM and ESTECO

As indicated in the previous section, MOM simulated for the test case years a loss of 815,000 pounds of commercial white shrimp harvest for the San Antonio Bay estuarine system. However, ESTECO simulated a significant increase in estuarine primary productivity for a portion of the test case period. These results reflect the importance of operating parallel models; i.e., a model for primary production (ESTECO) and a model for important consumer organisms (MOM).

The results can be explained in part due to the "dynamic" operation of MOM and the "steady-state" operation of ESTECO. MOM evaluates the effect of three environmental parameters on an indicator organism from daily computations. ESTECO is a food chain model which evaluates lower food chain responses from "steady-state" mean monthly conditions. Consequently, ESTECO evaluates monthly and seasonal trends of lower food chain organisms and MOM evaluates the effects of estuarine "dynamics" on a higher food chain organism. It is important that results from both models be examined carefully to explain the diverse effects of water resources development on estuarine environments.

V. LIMITATIONS AND RECOMMENDATIONS

As the remaining uncommitted supplies of water resources diminish and demands for this resource increase, the objectives of water resources planning broaden, the physical facilities and conveyance systems required become more complex, and the limitations under which they must be implemented become more stringent. Thus, development of ecological modeling techniques, such as described in this research project, can enhance the capability of the planners to make intelligent and comprehensive evaluations of the alternatives and their impact on aquatic ecosystems. Due to the tremendous complexity of aquatic ecosystems that must be considered in large-scale water resources planning problems, planners are turning to sophisticated mathematical techniques for assessments. The basis for these techniques is the representation of physical, chemical, and biological systems through sets of mathematical relationships which can be solved quickly and efficiently by high-speed digital computers. However, the limitations of these techniques must be understood to insure that the mathematical simulation is representative of those aspects of the planning problems which can be accurately quantified. At the same time, it is necessary that these methods are compatible for estimating factors which are not quantifiable under the present state-of-the-art.

This research project has been developed with experience and knowledge gained in laboratory and field investigations on the interactions between the chemical, physical, and biological parameters which are employed to describe the aquatic ecosystems.

Aquatic ecologic models have certain limitations, although they were found to be satisfactory in the test case simulation. The major limitations of the aquatic ecological models, as integrated into the analytical framework presented in this report, are due to the lack of both complete identification and quantification of areas of interface between the reservoir, stream and estuarine models. Although major areas of interface were identified, further quantification of the parameters is required. An interface limitation of the stream model is that it does not include fish, benthic organisms, zooplankton and detritus which are simulated in the lake and estuarine ecological models. Further, the aquatic ecological models do not have the capability to simulate changes in species composition due to environmental alterations.

A major limitation of the reservoir ecological model is nutrient removal from the reservoir. This includes the rates and driving forces for anaerobic mierobial metablism of nitrogen, phosphorus, and carbon in the water column, the transfer of nutrients across oxic-anoxic sediment interfaces, the formation of refractory compounds, fish harvesting as a function of season and fishing pressure, and the population dynamics of emergent benthic organisms. Additional experience with the reservoir ecologic model should result in the correction of these difficulties and improved simulation capabilities.

The greatest limiation encountered in the estuarine simulations was the inability of the models to accurately describe the production of estuarine dependent fisheries. Further development of the estuarine ecological model and the migratory organism model will result in better definition of the interactions of migratory organisms and improvement of trophic level interactions.

Considerable new research is needed to adequately quantify many of the above interrelationships. Detailed studies of (1) nutrient biogeochemical cycling in aquatic ecosystems, (2) biological response to nutrient concentration, and (3) fishery population dynamics are recommended to extend and refine the methodology developed in this research project. The methodology developed however, does provide the water resource planner with systematic techniques to evaluate the effects of water resources development on the estuarine environments. However, the mathematical models used to describe the aquatic environments of streams, reservoirs, and estuaries require further application and refinement to improve their capabilities. It is recommended that a series of carefully designed case studies of current water resource projects be conducted to further test the relationships developed in this study.

GLOSSARY OF TERMS

Abiotic	non-living; absence of life. Abiotic processes are those that result from chemical and/or physical factors.
Benthic	pertains to bottom or substratum of an aquatic environment. Benthic organisms or "Benthos" inhabit the bottom of waterways and may be sessile (attached or non-motile), creeping (snails), burrowing (clams, worms), or free-swimming (flounder).
Biomass	the amount of living matter.
Biota	the fauna and flora of a region.
Critical Period	used herein to denote the historical period of lowest natural flow for a drainage basin; also may refer to annual intervals or seasons of particular inflow dependency for estuarine fishery resources.
Ecology	the interrelationships between organisms and their environment.
Ecosystem	a complex of floral and faunal communities and their environment, forming a functional whole in nature.
Epilimnion	the water layer in a stratified acquatic environment extending from the surface to the "Thermocline" which is less dense than deeper waters (see "Hypolimnion"), generally wind-circulated, and essentially of uniform temperature (homothermous).
Estuary	an arm of the sea where fresh and marine waters mix.
(Fecal) Coliform Group	group of bacteria which comprise the aerobic and facultatively anaerobic, gram-negative, nonspore forming, rod-shapped bacteria that are frequently used as an indicator of pollution and the possible presence of pathogens.
Firm Yield	the maximum amount of water which can be guaranteed as a supply from a reservoir during the historical critical period.

Geomorphic	of or relating to the form of the earth and its surface features.
Hydrodynamics	a branch of the science of mechanics which relates to fluids and deals with the laws of motion and action of liquids.
Hydrology	a science dealing with the properties, distribution, and circulation of water on the surface of the land, in the soil and underlying rocks, and in the atmosphere.
Lentic	pertains to standing (non-flowing) waters such as reservoirs, lakes, ponds, swamps or bogs.
Lotic	pertains to flowing waters such as rivers, streams, and creeks.
Matrix	a rectangular array of numbers.
Migratory Organism	an organism which moves periodically from one region or climate to another for feeding and/or completing of the life cycle.
Nekton	free-swimming aquatic animals essentially indepdent of wave and current action.
Phytoplankton	the passively floating and/or weakly motile, microscopic plant life of an aquatic environment.
Piscavore	a carnivorous fish which feeds on other fishes.
Static	a term for a model which is based on observations in one time period.
Stochastic	random; variant with time.
Thermocline	the transition zone between the warm, upper layer (see "Epilimnion") and the colder, lower layer (see "Hypolimnion") in a stratified aquatic environment such as a lake or reservoir of sufficient depth.
Tide	the alternate rising and falling of the surface of the ocean and of water bodies such as bays and lagoons connected with the ocean. Generally occurs twice each lunar day as a result of unequal gravitational forces from the sun and moon in conjunction with the earth's rotational forces, but can be greatly altered by wind and storm phenomena.

Total Dissolved Solids (inorganic)	the total quantity of all dissolved mineral salts in water.
Trophic Level	in complex natural communities, organisms whose food is obtained from primary production (plants) by the same number of steps in the food chain belong to the same trophic level.
Yield	the amount of water which can be supplied from a reservoir in a specified interval of time.
Zooplankton	the passively floating and/or weakly motile, microscopic animal life of an aquatic environment.

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APPENDIX A

SURFACE WATER SYSTEM OPERATION MODELS

SIMYLD-II

To provide the water resources planner with a capability for analyzing the operation of a multireservoir system, the Texas Water Development Board has developed the SIMYLD-II network flow model. SIMYLD-II was designed to simulate the water storage and water transfer of a surface water resources system subject to a specified sequence of demands and hydrologic conditions. The model simulates catchment, storage, and transfer of water within a system of reservoirs, rivers, and conduits on a monthly basis with the object of meeting a set of specified demands in a given order of priority. It a shortage(s) occurs (i.e., not all demands can be met for a particular time period) during the operation, it is spatially located at the lowest priority demand points.

SIMYLD-II is also useful in determining the firm yield of a single reservoir within a multireservoir water resources system. Firm yield is defined as the maximum quantity of water a reservoir can be expected to deliver per unit time during the longest historical period of drought (period of lowest runoff of longest duration). By operating the storage facilities as an interconnected system, the firm yield of a given reservoir can be increased considerably over that realized by operating each reservoir independently, since spills from some reservoirs can be stored in other reservoirs. An iterative procedure is used to adjust the demands at each reservoir in order to converge on its maximum firm yield at a given storage capacity assuming total systems operation.

The model is designed for maximum flexibility in selecting operating ruled for each reservoir. The operating rules are formulated as the desired percentage of the reservoir capacity (either total or conservation) to be held in storage at the end of each month. A priority ranking can be assigned to each storage reservoir. This ranking is then used to determine the allocation of water between meeting demands and maintaining storage. The planner using the model has enough flexibility so that he may vary the desired monthly reservoir storage levels during the year and the priority of allocation of water between satisfying immediate demands and maintaining storage in the reservoirs by changing the operating rules.

SIMYLD-II can analyze either static or dynamic system operation, permitting use with either constant or time-variable demands. In addition, the planner can use the model to analyze the operation of the system under the expected ultimate demands for any selected hydrologic sequence.

The mathematical concept underlying SIMYLD-II is that the physical water resource system can be transformed into a capacitated network flow problem. In making this tranformation, the real system's physical elements are represented as a combination of two possible network components - nodes and links. Given the proper parametric description of these two network components, it becomes a straightforward task to develop the necessary capacitated network. Once developed, the network system can be analyzed as a direct analog of the real system.

As the nomenclature implies, a node is a connection and/or branching point within the network. Therefore, a node is analogous to either a reservoir or a non-storage junction (i.e., canal junctions, major river intersections, etc.) in the physical system. Additionally, a node is a network component which is considered to have the capacity to store a finite and bounded amount of the material moving in the network. In the case of SIMYLD-II, reservoirs are represented by nodes which have a storage capacity as well as the ability to serve as branching points. A non-storage capacitated junction is handled similarly to a capacitated junction (reservoir) except that its storage capacity is

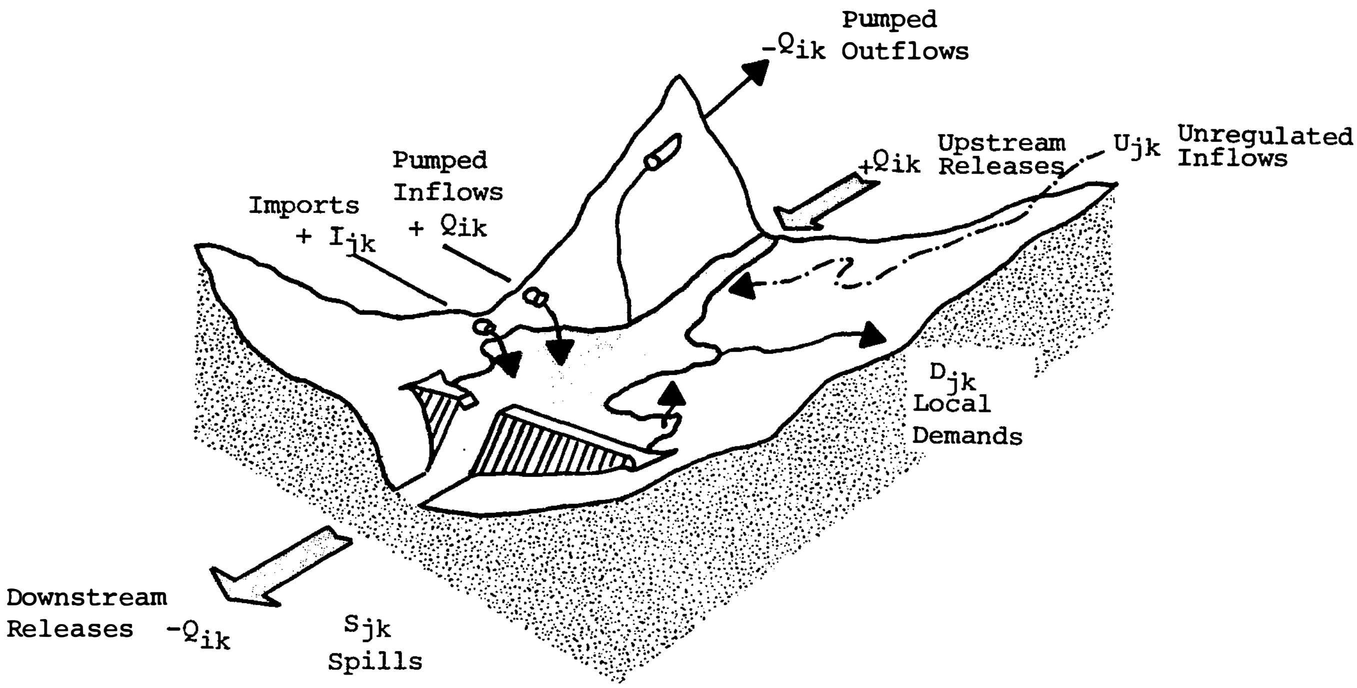


Figure A-1
Basic Terms in a Mass
Balance for a Reservoir

Also, any water entering the system, such as might occur naturally from runoff or artifically through import, must be introduced at a nodal point.

The SIMYLD-II network model is based upon the fundamental assumption that mass is conserved at all nodal points. The mathematical representation of the SIMYLD-II model insures material continuity by imposing mass balance equations on all storage and non-storage nodes over all time periods. Figure A-1 illustrates the basic terms that must be included in a mass balance equation for a typical reservoir. The general form of these continuity equations, as formulated for the jth reservoir of a system and time period k, would be:

$$\sum_{i=1}^{m} A_{ji} Q_{ik} - \frac{(S_{j,k+1} - S_{jk})}{\Delta t} = D_{jk} + E_{jk} - U_{jk} - I_{jk}$$

$j = 1,\ldots,n$

$k = 1,\ldots,L$

where

A_{ji} = +1 if flow in link i enters node j
-1 if flow in link i leaves node j
0 if link i is not connected to node j

Q_{ik} = Flow in link i during time period k (this can either be a pumped input/output or an upstream/downstream release)

$S_{j,k+1}$ = Storage contents of reservoir j at the end of time period k

S_{jk} = Storage contents of reservoir j at the start of time period k

Δt = Length of time period

D_{jk} = The local demand from reservoir j in time period k

E_{jk} = The evaporation loss from reservoir j during time period k

U_{jk} = Quantity imported directly into reservoir j during time period k (this can occur at only one node in the system)

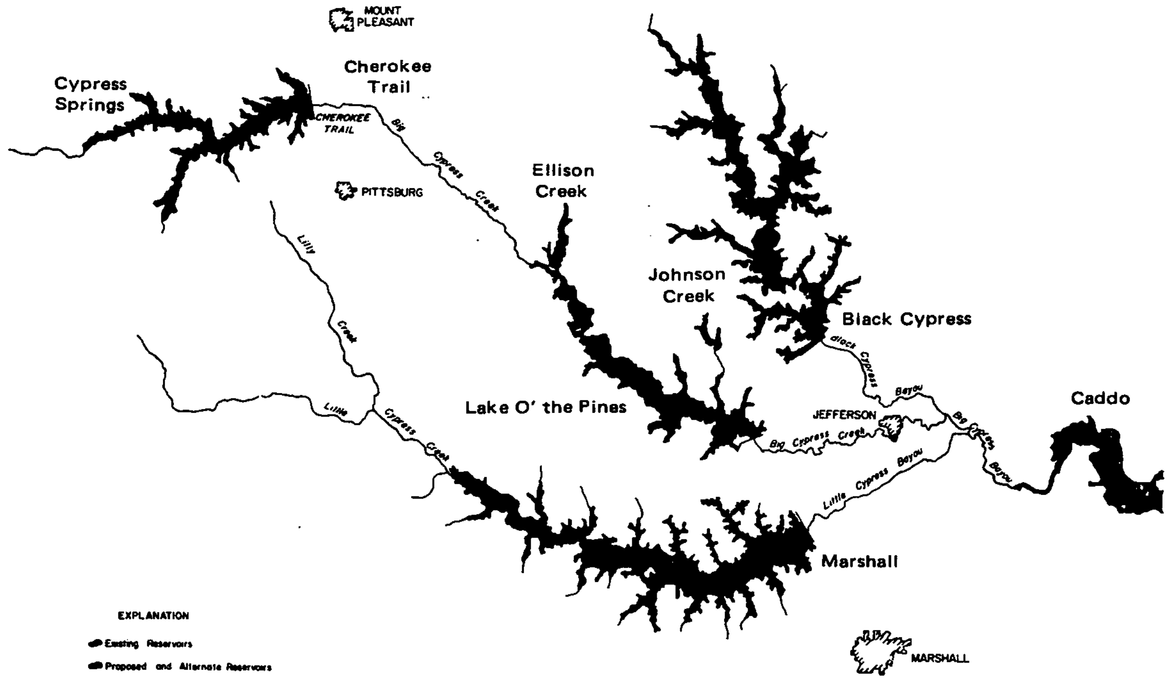


Figure A-2 Cypress Creek Basin

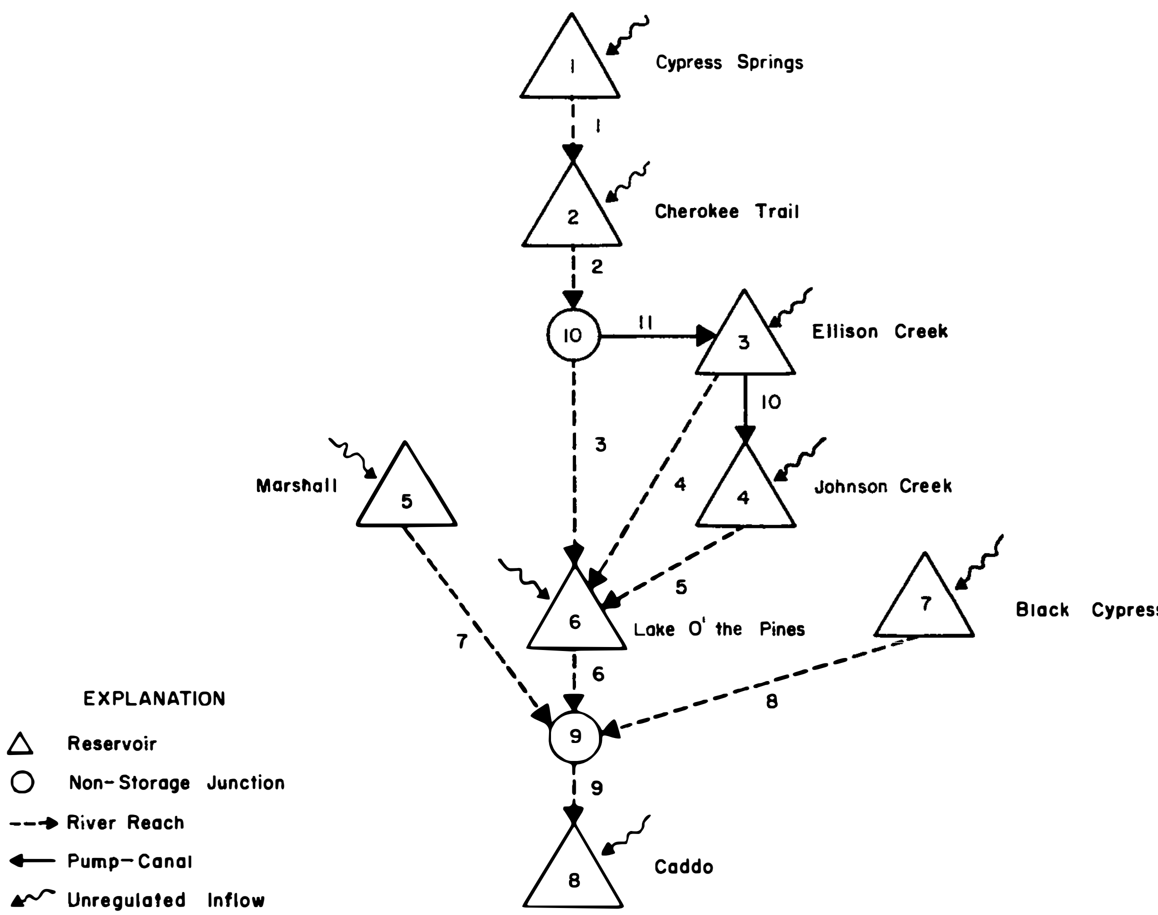


Figure A-3
Node-Link Configuration,
Cypress Creek Basin

I_{jk} = Quantity imported directly into reservoir j during time period k (this can occur at only one node in the system)

L = Number of time periods

m = Number of links, either pump-canals or rivers

n = Number of nodes, either reservoirs or non-storage junctions.

A similar equation can be written for all reservoirs and channel junctions in the system and for each time period to be considered.

The transfer of water among the various network nodes is accomplished by transfer components called links. Typically a link is a river segment, canal, or closed conduit with a specified direction of flow and a fixed maximum and minimum capacity. The physical system and its basic time-step operation, in this case a month, is formulated as the network flow problem . The set of solutions to this network flow problem provides the equential operation of the system with the set of monthly operations becoming the operation of the system over the length of a hydrologic sequence.

An initial step in the application of SIMYLD-II is the construction of the node-link diagram describing the physical system. Figures A-2 and A-3 illustrate a typical river basin and its node-link diagram. After the water resource system problem is represented as a network flow problem it is solved using a mathematical technique known as the out-of-kilter algorithm. This algorithm optimizes the transfer of water in the network, based on transfer costs. The algorithm operates by defining conditions which must be satisfied by an optimal "circulation" in a network - a flow which satisfies capacity restrictions on all arcs and also satisfies specified conservation of flow conditions at all nodes. When such a circulation is obtained, all arcs are said to be "in-kilter." If, at some point during the solution, such a circulation does not exist, some arcs are "out-of-kilter." An iterative procedure is used to bring the "out-of-kilter" arcs "in-kilter", if possible. The algorithm then proceeds to the next time step (Durbin and others, 1967). In the case of SIMYLD-II, the user-specified priorities for meeting demands for water and the priorities for storage of water in the reservoirs are used as the optimiization criteria. More detailed descriptions of these techniques are given in Texas Water Development Board Reports 118 and 131.

The SIMYLD-II model requires the following types of input data:

Basin Description

- reservoirs and demand points
- river reaches, canals, and pipelines

Reservoir Data

- initial capacities
- area-capacity curves
- upper and lower limits of conservation pools,

Input and Demand Information

- reservoir inflows
- evaporation rates
- monthly demand coefficients

An analysis with the SIMYLD-II model provides the following: (1) a time history of the optimal operation of the surface water system including reservoir storages, water transfers, and spills from the system, and (2) the demands met and shortages incurred during the simulation period.

SIM-IV

SIM-IV is a computerized procedure designed to simulate the operation of a large complex surface water sotrage and transfer system. The system can be either static or dynamic in nature, in that over time water storage and transfer facilities can be constant or can increase in size. The SIM-IV computer routine allows individual network system elements to be introduced at any point in the simulation time span. This capability provides the option of investigating various patterns of construction schedules in order that the least costly can be selected for implementation. These capabilities allow SIM-IV to be used either as a stand-alone procedure or as an extension of any staging analysis.

SIM-IV uses a representation of a surface water resource system exactly like that used by SIMYLD-II which was previously described. However, SIM-IV contains a procedure for minimizing the operational cost of fluid transfer within a capacitated network. A solution is produced for a finite time interval (one month), and the analysis moves forward in time in a stepwise fashion. Within the network. demands for the material in transport are made at any network junction and the amount of material in storage at each junction is constrained by specified limits. The assumption is made that the unit cost of transport is known at all points in time and space.

The network flow problem, as analyzed by SIM-IV, is stated in exactly the same manner as for the SIMYLD-II model. However, in SIM-IV, capital costs are entered individually for each system element (canal and reservoir) and system operating costs are computed by the model. In general, the movement of water via the transfer links will be done at a cost which is a known function of the quantity of water flowing and the pumping lift. It is the function of SIM-IV to meet system storage requirements and system demands while minimizing the cost of transporting water within the system. No water will be spilled from the system if storage capacity remains in the reservoir.

Conceptually, SIM-IV follows these steps in moving from a known set of state variables at the beginning of a time period to the solution for a required set of state variables at the end of the time period:

- The present status of the network is evaluated and all existing system elements are given an appropriate parametric description of numeric value(s). Non-existing but potential system elements are given zero values for all characteristics (storage, flow, etc.).
- All specified hydraulic and hydrologic inputs and demands are accounted for, and the mass blanace for the entire network system is determined. Bounds are placed on system demands, spills, and storage levels.
- The flows necessary to meet the levels required and at the same time minimize the system's total cost of water transport, are determined through the application of an optimization procedure.
- All necessary state variables have now been determined, and the status of the system at the conclusion of the current time period becomes the status at the beginning of the next time period.

This procedure is repeated in a stepwise fashion until a specified simulation interval has been spanned.

The SIM-IV model assumes that future hydrology is unknown, that is, it operates from month to month without any knowledge of coming events. It requires that the planner, based on his knowledge of the system, determine where he would like to store excess water in any given time interval. Since SIM-IV uses the out-of-kilter algorithm to solve the problem, the planner's preferences are translated into negative costs on the network arcs. This is explained in detail in Texas Water Development Board Report 118. These negative costs play no role in competing with meeting demands or selecting optimal paths in the network, but they allow the system to move water in advance of demands to selected storage sites. The pricing policy remains constant for the entire simulation period and is independent of the variations in yearly hydrology.

Demands for water can be specified prior to simulation, or, in the case of irrigation demands, can be expressed mathematically as a functional relationship in which the quantity of water demanded depends upon the quantity of water in the supply system. More detail about these functional relationships between the water supply and irrigation demand variables is provided in Texas Water Development Board Report 179.

Typically, the analysis of a surface water system using SIM-IV provides the following information: (1) the optimal capacities of all system elements (reservoirs, canals); (2) the optimal operation of this system to minimize cost and water deficits; and (3) the capital and operation and maintenance costs for each element for the period of analysis and the hydrologic and demand sequence used. The solution is a function of the hydrologic sequence used. Thus, in order to select a plan which would be expected to more nearly approximate an optimal solution it is necessary to analyze the response of the proposed (or existing) system using a number of different hydrologic sequences. The reason for analyzing multiple hydrologic sequences is that major droughts or floods, varying in magnitude and duration, may occur at varying points in time within different hydrologic sequences. Since most large system are designed to be staged with time and the demands are steadily increasing during the system construction-staging period, the temporal location of droughts in the hydrologic sequence determines the size of the water deficits experienced. Obviously, this has a significant effect on the benefits of the water system and should be analyzed in detail. The development of these hydrologic sequences and the choice of sequence to be used in the analysis is an important part of surface water resources analysis. The hydrologic sequence development has been discussed in detail in Texas Water Development Board Report 183.

AL- IV

The allocation model, AL- IV, is designed to analyze a multibasin water resource system to find:

- the minimum-cost operating plan for a system of reservoirs, canal junctions, canals, and river reaches;
- minimum-cost canal sizes; and
- reservoir operating rule coefficients for use in the SIM-IV model.

The AL-III model is essentially identical to the SIM-IV model in terms of the spatial representation of the water resource system and the use of the network flow solution technique. However, it is different in one important respect-the spatial representation is expanded to include time. The temporal dimension permits an optimal allocation of water based on the assumption that the planner has knowledge of the demands and available supplies in future time periods. This "look-ahead" feature allows maximum storage of water during wet periods so that it is available at the beginning of a drought.

For each time period in the problem, there is a corresponding node-link representation. The representations are connected by the rates at which reservoir storage contents are carried forward in time. These connections are referred to as "storage arcs" (arcs refer to all node connections in the problem, including canal and river links). Thus, the time-space representation of the problem can be envisioned as a layered network, each layer representing a time period with storage arcs connecting the layers. The example system illustrated in Figure A-4, expanded to include four time periods, is shown in Figure A-5.

The network thus established is solved, in the conventional manner, using the out-of-kilter algorithm. If monthly time increments are used and the problem contains a large number of nodes and links, the computer storage

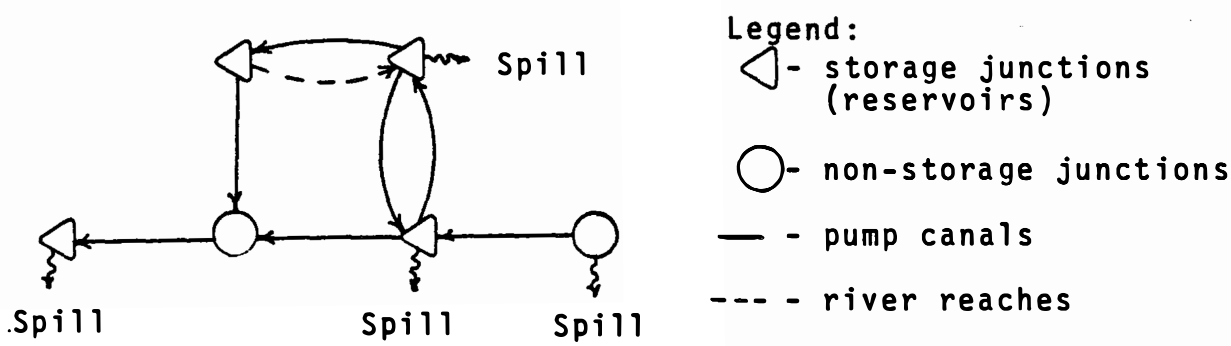


Figure A-4
Spatial Representation of the
System Configuration

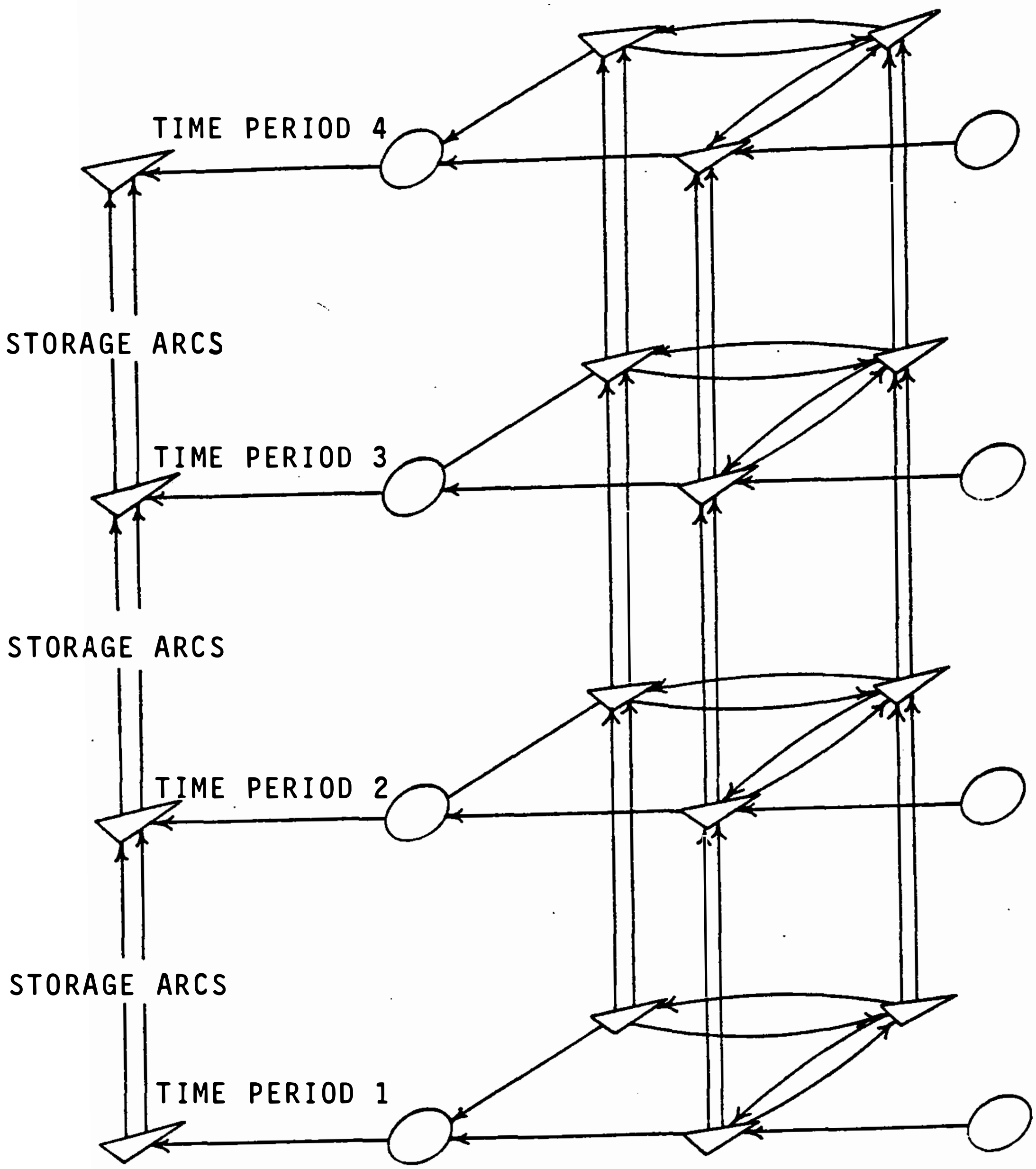


Figure A-5
Spatial Representation of the System Configuration Expanded to Include Four Time Periods

requirements are large. When this occurs, the allocation model can span only a few years at one time, in which case the number of years spanned is the number of years used in the network. Assuming the total problem involves a ten-year period and the maximum number of years the network can span is four, the procedure works as follows. The first problem solved would produce a solution for the first year. The first year is then deleted form the network and the fifth year added. A solution for the second year is obtained by solving this problem at which time the second year is deleted and the sixth year is added. This process of finding a solution for the first year of the series, removing that year from the series and adding the next year to the end of the series is repeated until the network problem formed by the last four years of the ten years has been solved. This example thus permits optimizing the system operation and configuration with a four year "look-ahead" at hydrology and demands.

With this concept of structuring the problem in terms of a network, one can obtain a solution that will minimize cost and simultaneously satify the inputs to and demands from the system.

The allocation model can be used to obtain reservoir operating rules for SIM-IV, to determine the minimum-cost system operation, and/or to determine canal sizes. These applications are described in detail in Texas Water Development Board Reports 118, 131, and 179 and their supporting computer program documentation volumes. However, the method used to develop operating rules for the SIM-IV model deserves a brief discussion here.

The allocation model spans a multi-year period and, as a result, it simulates the system operation with near perfect foresight of hydrology and demands. Thus, storage levels that result for each reservoir are consistent with the minimum-cost operational plan for the system. Since perfect knowledge of future hydrology is not possible this minimum-cost operational plan can never be achieved in practice. However, the total costs developed with such an allocation can be used as the cost objective to be achieved with the SIM-IV model which uses only monthly data which would be available to the operator.

The storage levels predicted by the allocation model are used to develop monthly "target" storages for each of the reservoirs in the water resource system. These "targets" are used in SIM-IV as monthly operating rules which tend to minimize spillage of water from the system and maximize the quantity of demands which can be met.

The time history of storage levels in each reservoir, as produced by AL-III, is used to develop storage plots for years in which surplus water was spilled from the system and for years in which deficits were incurred. If the reservoir storage could be maintained along the envelope of maximum storage levels that occurred during years of deficits, demands would have a high probability of being satisfied. In other words, this envelop describes a reservoir operational pattern that would minimize deficits. The envelope of minimum storage levels that occurred during years of system spillage describes the lowest levels at which a reservoir can be maintained without risking the chance of spilling surplus inflows. This envelope represents an operational pattern that would minimize system spillage.

Where the targets are set between these two envelopes, depends upon the inflows to and demands from the reservoirs since (1) the closer the targets are to the upper envelope the greater the risk of spillage, and (2) the closer they are to the lower envlope the greater the probability of deficits being incurred. The goal, of course, is to find targets that, when used in SIM-IV, will predict the same deficits and spills that were predicted by the allocation model. (It is possible that deficits could be reduced because SIM-IV predicts evaporation losses more accurately than the allocation model.)

In addition to providing information for setting targets, these plots indicate some general operational characteristics of the reservoirs. If the two envelopes are very far apart, this indicates that the reservoir is probably not too important in reducing either spills or deficits and the targets should be set primarily to minimize storage fluctuations. On the other hand, when the two envelopes are close to one another the reservoir is probably critical to the performance of the system and the targets should be set very carefully. If the condition occurs where the minimum storage envelope for spillage exceeds the maximum storage envelope for deficits, this means the reservoir is critical but that targets can be set anywhere within the range.

From the two envelopes on the storage plots, initial storage target levels are fetermined using the reservoir's demand-inflow ratio as a guide. If this ratio is high, targets are set initially along the envelope of maximum storage to minimize deficits. For reservoirs with a low ratio of demands to inflows, the initial targets are set along the minimum storage envelope to minimize spills. In the case of reservoirs whose inflows are about the same as their demands, initial targets are set about midway between the two envelopes with a smooth seasonal pattern.

APPENDIX B

STREAM AND RESERVOIR ECOLOGICAL MODELS

The ecological simulation techniques used in this project have been described previously by Chen (1970) and Chen and Orlob (1972). These authors discussed the techniques in terms of the fundamental concepts and the formalized translation of these concepts into functional prototype behavior. The following discussion generally summarizes the conceptual development and technical details of these ecologic simulation techniques as well as their application to two aquatic environments. The interested user is advised to consult these references for a more detailed description of the techniques.

THEORETICAL DEVELOPMENT

Figure B-1 presents a simplified conceptualization of an aquatic ecosystem which is comprised of water, chemical impurities, and various organisms. This figure also illustrates the interdependence or "coupling" of the water quality and biological relationships of an aquatic ecosystem, as well as the abiotic inputs to the system from various sources including air, soil, adjoining water, and the activities of man.

The formalized translation of this conceptualization to functionally represent prototype or "real-world" behavior is predicted by two fundamental principles:

1. That there is conservation of mass when a constituent is changed by reaction from one form to another (the Law of Conservation of Mass) and,
2. That the rate of change is equal to the product of a coefficient and one or more constituent concentrations that interact to cause the change (the Kinetic Principle).

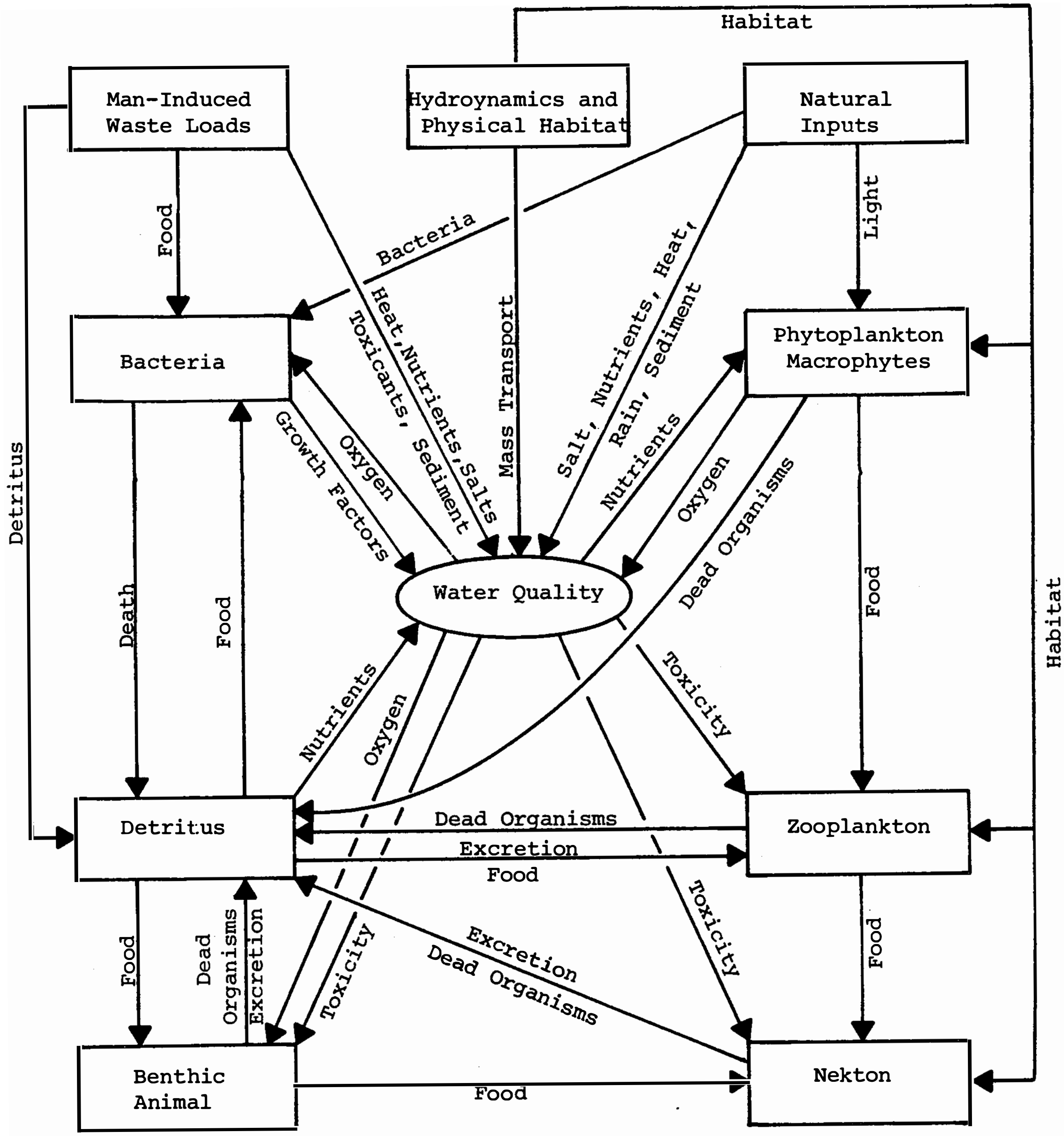


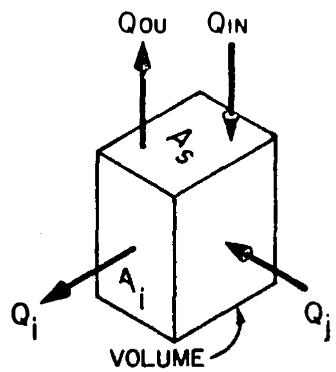
Figure B-1
Conceptual Representation of
an Aquatic Ecosystem

These two principles form therotical basis for the development of an ecological model. The basic functional relationships are represented by the mathematical formulations given in Table B-1.

Prerequisite to a rational solution of these equations is the physical description of the aquatic ecosystem. For simulation purposes, the geometry of an aquatic ecosystem is functionally represented by a set of contiguous hydraulic elements, each of which can be idealized as a completely mixed reactor for chemical and biological processes as illustrated in Figure B-2. A set of equations are written to describe the mass balance for all the pertinent ecologic transformations for each hydraulic element. These equations are solved with the help of a computer in a continuum over space and time to produce a simulation (a mathematical representation) of the behavior of the prototype. Output of the simulation includes temporal and spatial descriptions of fluid flows, quality parameters, and indigenous biota.

RESERVOIR ECOLOGIC MODEL

The hydrodynamic behavior of a sufficiently deep reservoir or lake is dominated by thermal stratification and resultant vertical density variation. Vertical water motions are inhibited by density layers and cold, low-oxygen outflows tend to be drawn from a layer (hypolimnion) of restricted depth near the outlet. Accordingly, the hydraulic elements which comprise the reservoir ecologic model are idealized as horizontal slices of uniform thickness as shown in Figure B-3. The bounding planes common between adjacent layers are uniquely determined from the reservoir's topography. Using the analogy illustrated by Figure B-3, the properties of the water within each slice are considered to be uniform. Hence, spatial differences in a horizontal plane are neglected in the model. The conceptualization above is a one-dimensional view of the water body along the vertical axis.



$$\begin{pmatrix} C_1 \\ C_2 \\ C_3 \\ \vdots \\ \vdots \end{pmatrix} = \begin{pmatrix} TDS \\ BOD \\ DO \\ TEMP \\ \vdots \\ ALGAE \\ ZOO \\ FISH \end{pmatrix}$$

1. *general mass balance equation for abiotic substances*

$$\frac{dVC_1}{dt} = \underbrace{\Sigma Q_i C_1}_{\text{ADVECTION}} + \underbrace{\Sigma EA\frac{dc_1}{dx}}_{\text{DIFFUSION}} + \underbrace{\Sigma QinCin}_{\text{INPUT}} - \underbrace{\Sigma Qou\,C_1}_{\text{OUTPUT}} \pm \underbrace{S_1 VC_1}_{\text{SETTLING}} \pm \underbrace{K_r A_s (C_1 - C_1^{*})}_{\text{REAERATION}} - \underbrace{K_{d,1} VC_1}_{\text{DECAY}}$$

$$\pm \underbrace{K_{d,2} VC_2}_{\substack{\text{TRANSFORMATION} \\ NH_3 \rightarrow NO_2 \rightarrow NO_3}} - \underbrace{\Sigma \mu_3 VC_3 F_{3,1}}_{\substack{\text{UPTAKE} \\ \text{BYPRODUCT}}} + \underbrace{\Sigma R_3 VC_3 F_{3,1}}_{\substack{\text{RESPIRATION} \\ \text{RELEASE}}}$$

2. *general mass balance equation for biota*

$$\frac{dVC_1}{dt} = \Sigma Q_i C_1 + \Sigma EA\frac{dc_1}{dx} + \Sigma QinCin - \Sigma QouC_1 + (\underbrace{\mu_1}_{\text{GROWTH}} - \underbrace{R_1}_{\text{RESPIRATION}} - \underbrace{S_1}_{\text{SETTLE}} - \underbrace{M}_{\text{DEATH}})\,VC_1 - \underbrace{\mu_2 VC_2 F_{2,1}}_{\text{GRAZING}}$$

3. *phytoplankton (algae)*

$$\mu_1 = \hat{\mu}\,\theta^{T-20}\frac{L}{K_l+L}\,\frac{C}{K_c+C}\,\frac{N}{K_n+N}\,\frac{P}{K_p+P} \qquad R_1 = r\theta^{T-20}$$

$$S_1 = \frac{S_t}{S_o} \qquad \mu_2, C_2 = \text{Zooplankton}$$

4. *zooplankton*

$$\mu_1 = \hat{\mu}\,\theta^{T-20}\frac{\text{Algae}}{K_a+\text{Algae}} \qquad R_1 = r\theta^{T-20}$$

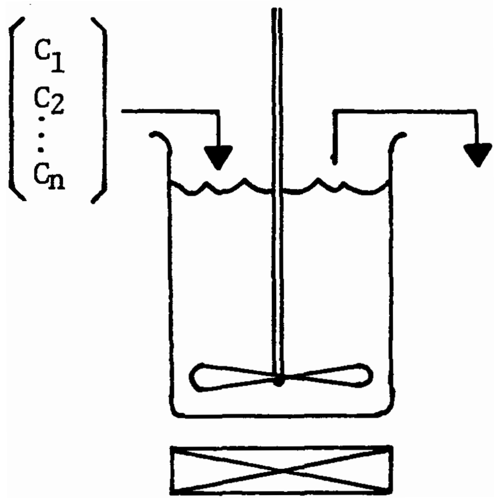
$$M_1 = \alpha + \beta \cdot \text{Toxicity} \qquad \mu_2, C_2 = \text{Fish}$$

5. *fish*

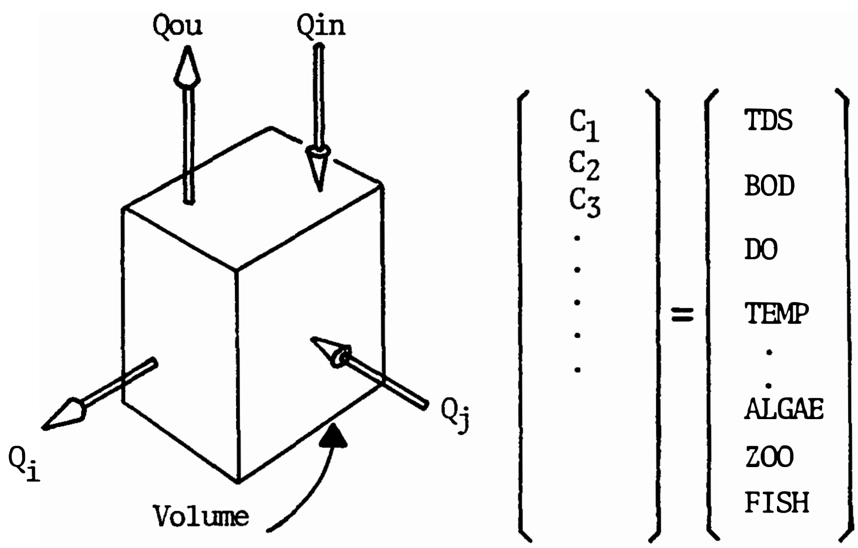
$$\mu_1 = \hat{\mu}\,\theta^{T-20}\frac{\text{Zoo}}{K_z+\text{Zoo}} \qquad R_1 = r\theta^{T-20}$$

$$M_1 = \alpha + \beta \cdot \text{Toxicity} \qquad \mu_2, C_2 = \text{Harvest}$$

Table B-1
Ecologic Model Formulations



A. a continuously stirred tank reactor, CSTR



B. an idealized hydraulic element

Figure B-2
A Continuously Stirred Tank Reactor
(CSTR) and an Idealized Hydraulic Element

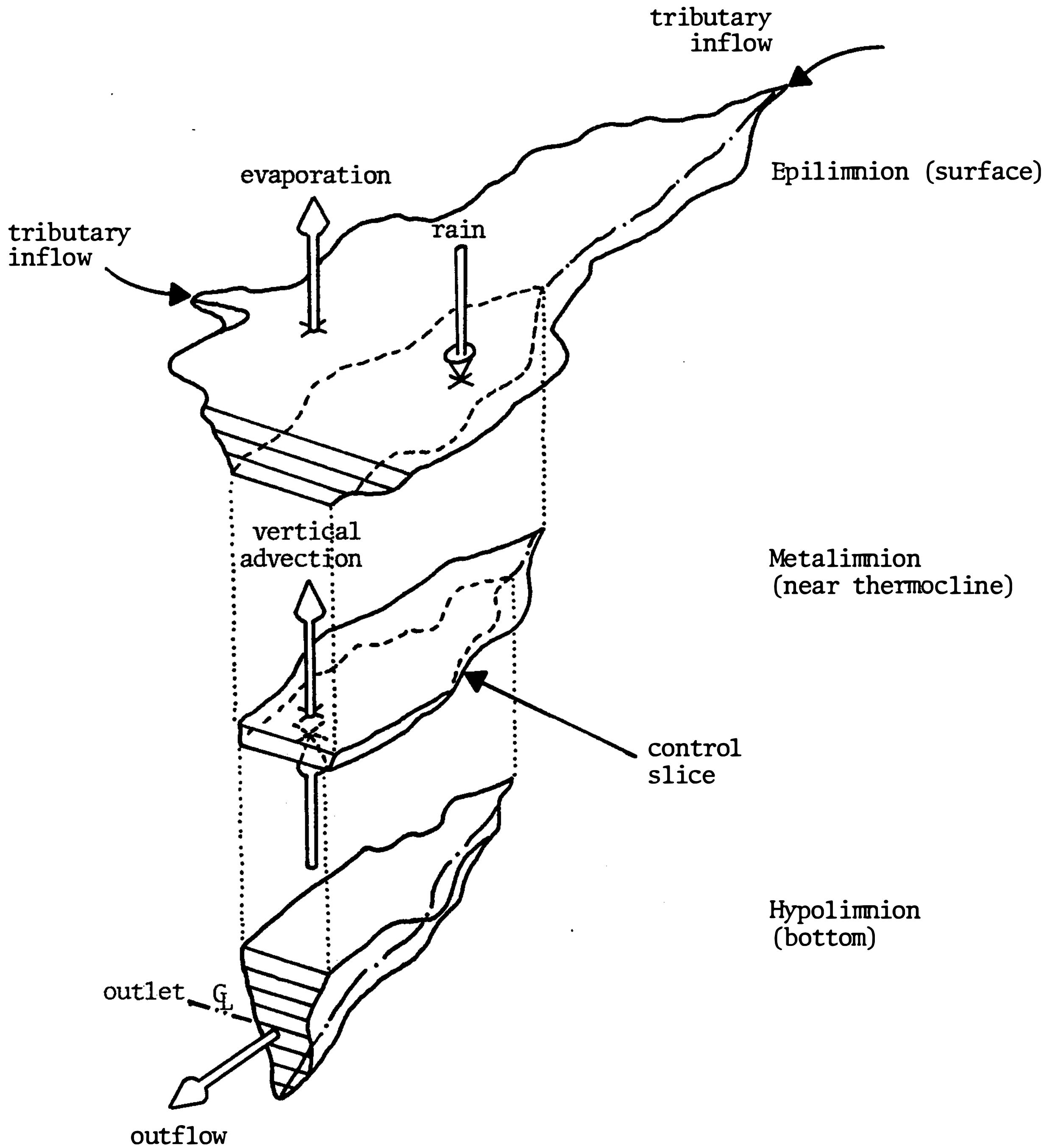


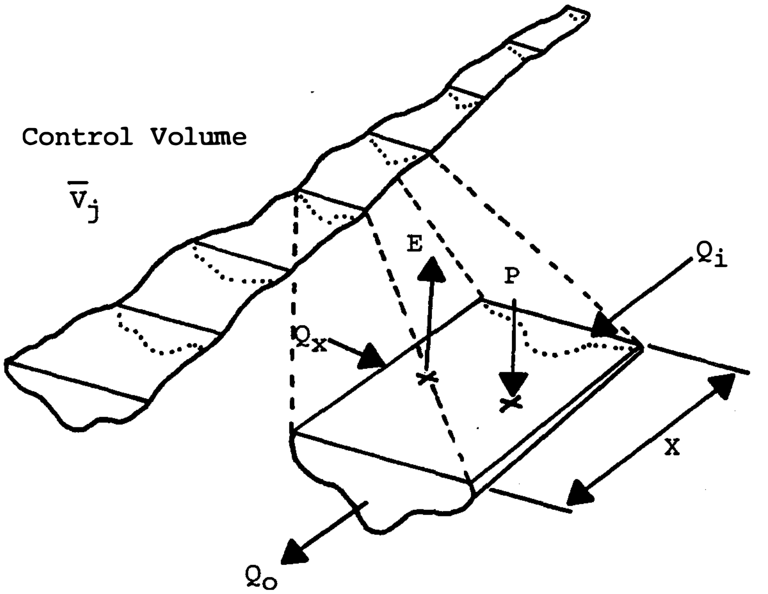
Figure B-3
Geometric Representation of a Stratified Reservoir

STEAM ECOLOGIC MODEL

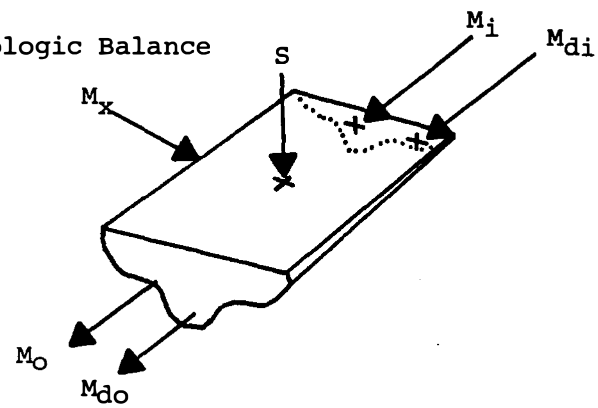
There is a fundamental difference between the stream ecosystem and the lake ecosystem. For the lake ecosystem, the hydrodynamic regime is considered temperature dependent and the physical geometry is represented by horizontal elements connected along a single vertical axis. The hydrodynamic behavior is treated as independent of temperature (density) in the stream model. Hence, for a stream or river, the water volume under consideration is most conveniently idealized as a system of prismatic volume increments, each having geometric characteristics unique to its location along the primary axis of flow (the longitudinal axis of the stream). Figure B-4 illustrates the manner of idealization of a natural stream channel as a system of incremental volumes. Using the same analogy that was applied to the reservoir model, the properties of the water within each incremental volume are considered to be completely uniform, the spatial differences in the vertical are neglected. This conceptualization results in a one-dimensional mathematical representation of the stream along the longitudinal axis.

SOLUTION TECHNIQUE

With the advent of large high speed digital computers, it has become economically feaible to solve very large systems of simultaneous linear equations. Along with the advances in computer hardware technology there has been a corresponding development of software capability resulting in more efficient solution techniques. Among these are variety of so-called "implicit" numerical methods, in which the variables and their derivations in time and space are considered unknowns and both are determined simultaneously. An implicit technique is used for both the lake and stream ecologic models.



Hydrologic Balance



Mass Balance

Hydrologic Balance

$$\frac{d\bar{V}_j}{dt} = Q_i - Q_o + P - E \pm Q_x$$

$\bar{V}_j$ = volume of control

Q_i = inflow rate along the x-axis

Q_o = outflow rate along the x-axis

P = precipitation rate on volume surface

E = evaporation rate from volume surface

Q_x = local inflow or withdrawal rate

Mass Balance

$$\frac{dM_j}{dt} = M_i + M_o + M_{di} - M_{do} + S + M_x$$

M_j = mass stored within the control volume

M_i = mass transfer associated with inflowing water

M_o = mass transfer associated with outflowing water

S = mass transfer by nonconservative processes

M_{di} = mass transfer by inward diffusional transfer

M_{do} = mass transfer by outward diffusional transfer

M_x = mass transfer by local inflow or withdrawal

t = time

$C_j = \frac{M_j}{V_j}$ = concentration of material in control volume

Figure B-4
Conceptual Representation
of a Stream System

The computational sequence proceeds according to the master flow chart diagram illustrated by Figure B-5 for the lake ecologic model. The computation sequence for the stream ecologic model is similar except that fish, benthic animals, zooplankton, and detritus are excluded.

LONG TERM ECOLOGIC SIMULATION

The lake ecologic model was originally designed to analyze relatively short-term changes in the aquatic environment. Because of the rapidity of certain of the biological reactions, short time steps (one day or less) are necessary to preserve the stability of the solution. Prior to this project, most simulations with the ecologic models covered the period of two years or less. Since one of the prime objectives of the analytical procedures developed in this research was to detect lone-term environmental effects, it was necessary to modify the models somewhat to permit long-term (greater than 10 years) simulations. These modifications are minimal and are described in the following paragraphs.

The principal model changes involved the three groups of fish and the benthic animal populations. All of these organisms have somewhat low growth rates (mass doubling times greater than 1 day) and exhibited some simulation deficiencies with the initial representations used. In general, the populations of these organisms tended to grow extremely large after extended simulation periods, resulting in unrealistic simulation results and numerical stability problems. The assumption of unrestricted exponential growth was obviously incorrect under long-term conditions. Two major causative factors identified were temperature and population biomass. These effects were corrected by using two rather well-established biological relationships.

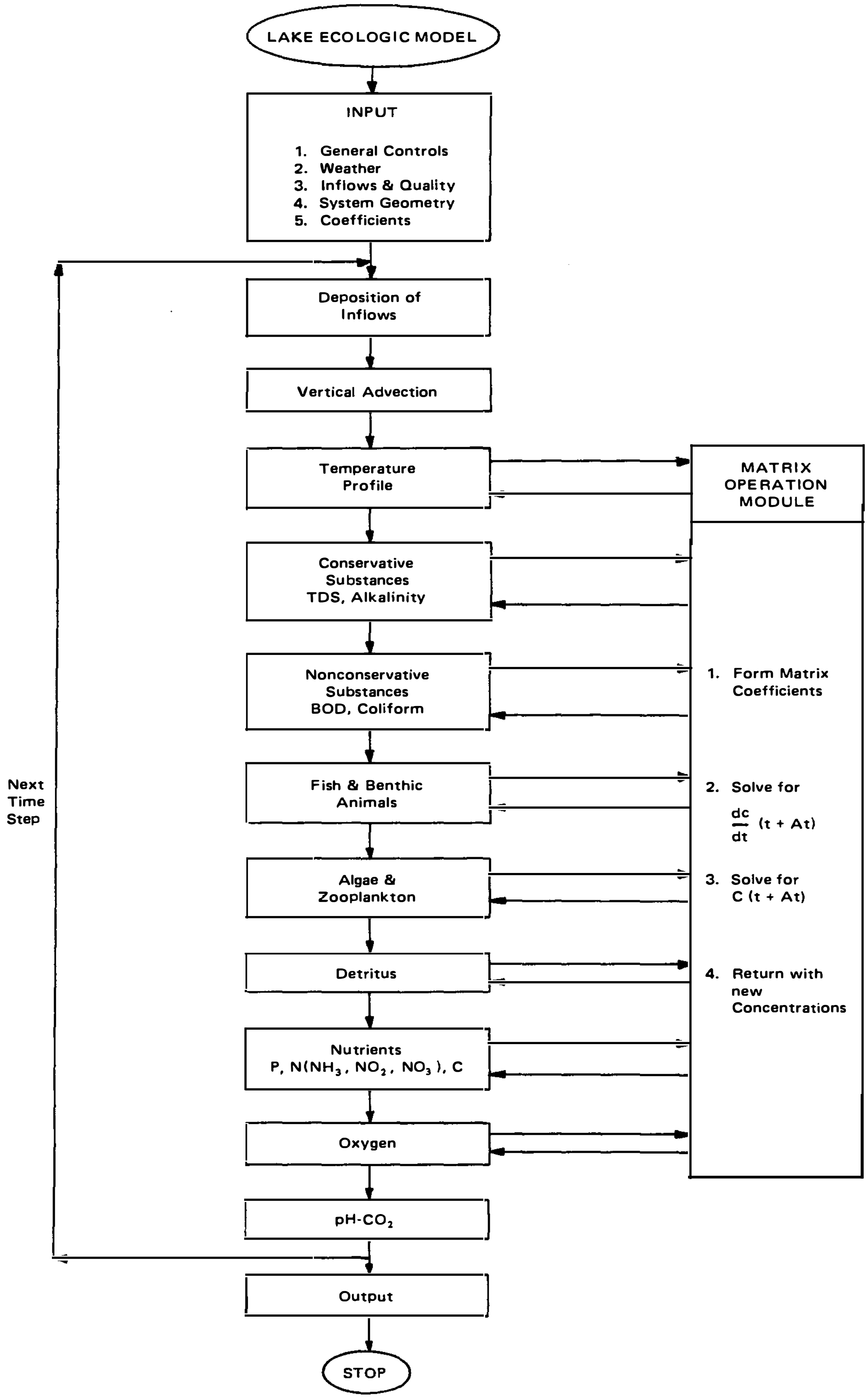


Figure B-5
Master Flow Chart for the Lake Ecologic Model

The temperature corrections to growth rate used in the original model were based on an approximate doubling of biological reaction rates (growth, death, respiration) with each 10°C increase in temperature with abrupt cut-offs at critical temperatures for each organism. This proved to be unsatisfactory because the elevated temperatures common in Texas water resulted in excessive growth rates. The growth rate - temperature relationships were modified to be more representative of actual conditions by fitting a second-roder polynomial to the growth rates and temperatures shown in the literature. A typical example of this type relationship is shown in Figure B-6. Figure B-7 illustrates the death rate - temperature relationship used in the model for this research project. This type of relationship has previously been used to model the growth and death of certain organisms due to abiotic factors (Lassiter, R.R. and Hayne, D.W., 1971). Using this type of function for the temperature dependency of growth resulted in significant improvement in the long-term simulation results. Further refinement of the fish and benthos calculations were affected by using a total biomass basis rather than the originally developed concentration basis in the computational matrix.

The affect of population biomass on the growth rate of a particular organism is ignored in the ecologic model. However, no problem is encountered in the long-term simulation of phytoplankton and zooplankton because their high growth and death rates and the predator-prey relationship used does not permit the biomass of a particular organism to overgrow the available food supply. The fish, with much slower rates, often lagged the available food supply such that the eventual occurence of exponential growth patterns of the organism deplete the food supply so rapdily that numerical stability problems occurred in the simulation. To rectify this situation a relationship previously used to model competition and crowding in higher trophic level ecosystems was applied (Lassiter, R.R. and Hayne, D.W., 1971). This runction is represented mathematically as:

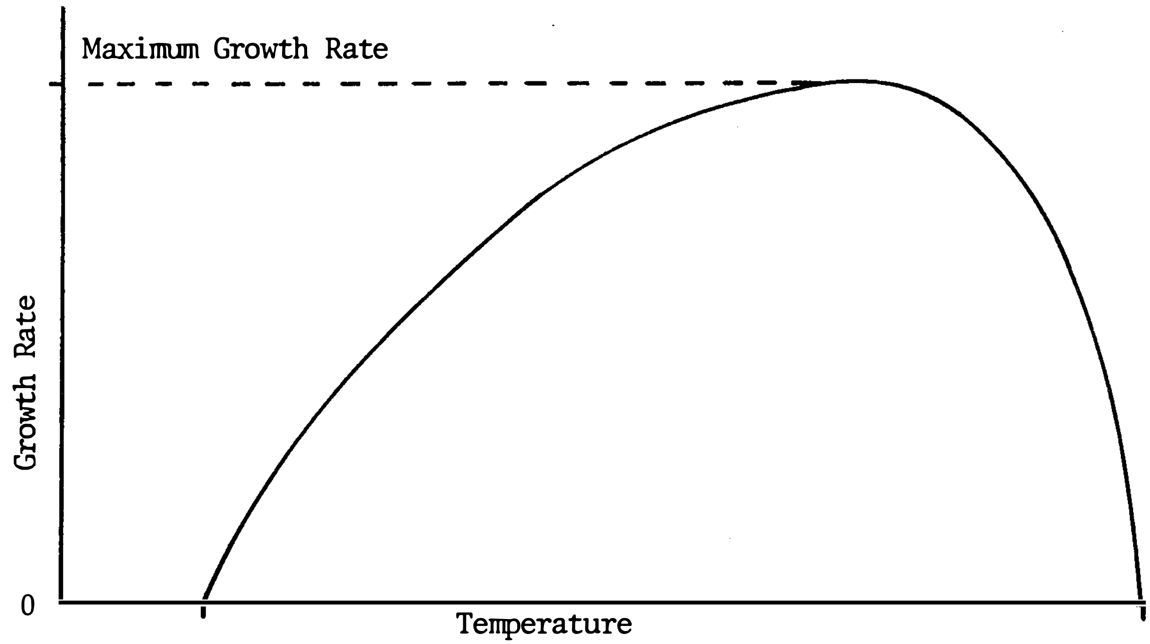


Figure B-6
Growth Rate - Temperature Relationship
Used for Fish in the Ecologic Model

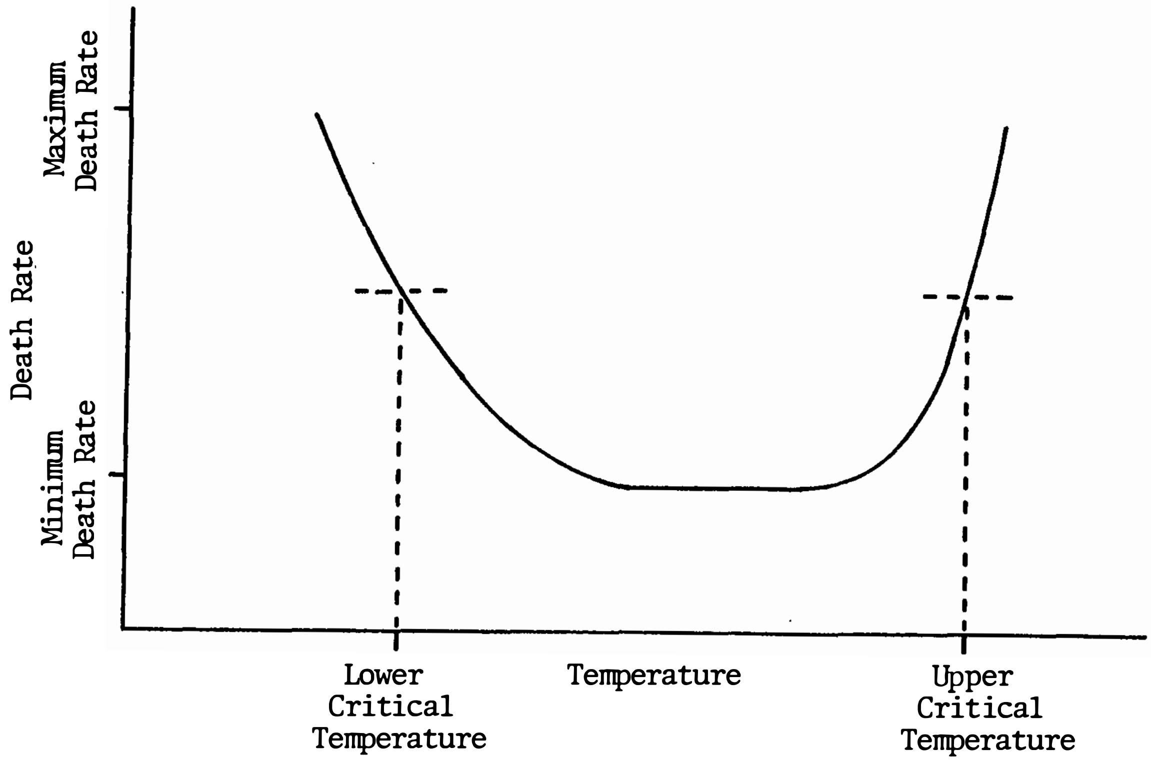


Figure B-7
Temperature - Death Rate
Relationship Used for Fish in the Ecologic Model

$$\frac{dN}{dt} = r^N(1-\frac{N}{K})$$

where: $\frac{dN}{dt}$ = rate of change of population size (biomass)

r = unit or intrinsic growth rate

N = population size (biomass)

K = maximum environmental carrying capacity (population biomass)

This relationship is depicted graphically in Figure B-8 and it can be readily seen that growth is directly regulated by the population size. The parameter K, as used in this project, is the largest possible standing crop for a specific "group" of organisms and is taken from field data for similar Texas resources. Inclusion of this relationship in the long-term model provided much-needed stability to the analytical solution.

Earlier simulations of Lakes Belton and Whitney (TWDB, 1974) indicated a need to establish the link between the sediment and water columns for the transfer of nutrients and oxygen across the sediment water interface. This was accomplished by quantifying the amounts of nitrogen, phosphorus, and carbon in the sediment as a weight percentage and assigning a temperature dependent decay rate for the sediment with an equivalent oxygen demand. This resulted in the production of an anaerobic hypolimnion during the summer which is confirmed by data from Canyon Reservoir.

The reservoir ecological model was originally developed and calibrated for a northwestern U.S. impoundment which did not experience anaerobic conditions. Southwestern impoundments are subjected to more elevated temperatures, higher organic loadings, and frequently undergo prolonged periods where the hypoliminion is devoid of oxygen. This requires that the anerobic mechanisms for chemical transformations be included in the model to reduce the amounts of nitrogen, phorphorus, and carbon in the water and sediment columns. In addition to anaerobic decomposition, nitrogen, phosphorus, and carbon are rendered

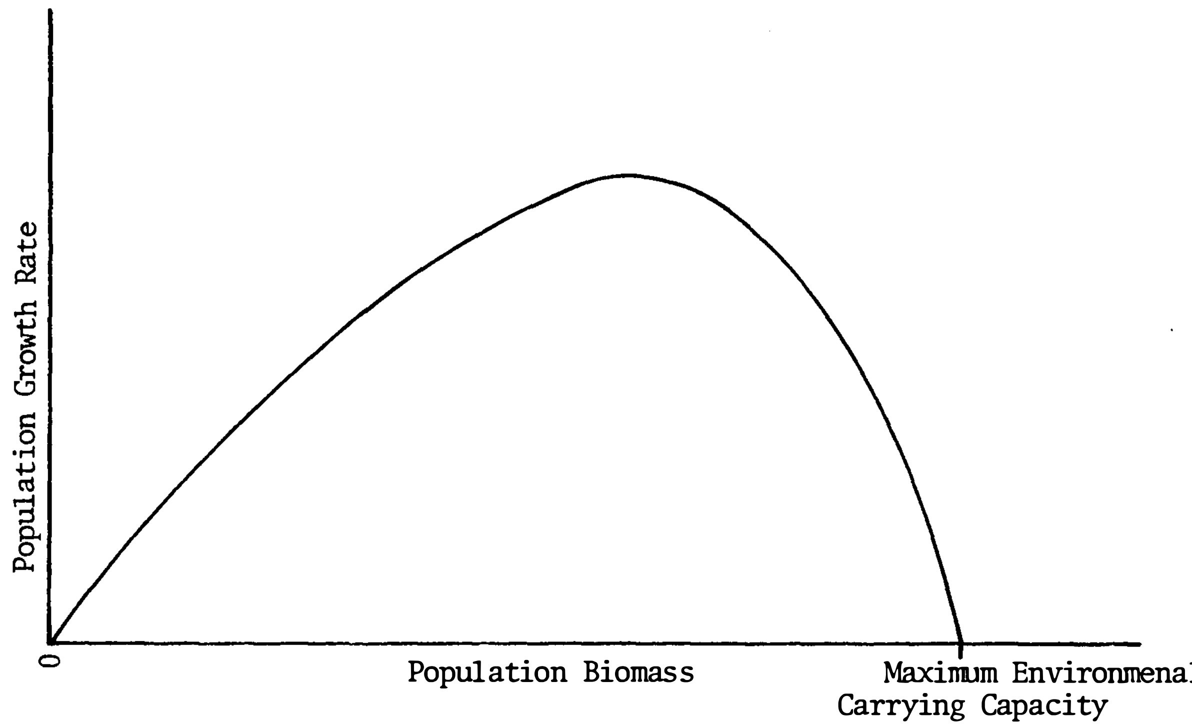


Figure B-8
Population Growth Rate as a
Function of Population Biomass

inaccessible to bacteria by the formation of refractory compounds that are ultimately buried deep in the sediment column. The above mentioned considerations improved the reservoir ecological model's ability to map the temporal, cyclic characteristics of nitrogen, phosphorus, and carbon in the reservoir environment.

Another factor to be considered in long-term reservoir operation with the lake ecologic model is the contribution of rainfall on the reservoir surface to the overall water balance. The model calculates evaporation using a heat balance technique and tributary streams provide most of the reservoir inflow. However, in a large reservoir precipitation adds significant quantities of inflow which must be accounted for in a continuous operation because the effect is cumulative. To correct for direct precipitation, an additional inflow source, entering the system at wet-bulb air temperature with saturated dissolved oxygen and equal to the mean monthly rainfall on the lake surface, was added to the model. Checking the results of this analysis against a reservoir operation study indicated that this change preserves the water balance.

The reservoir model also imperfectly simulated free CO_2. The equations used were based on temperature, pH, and alkalinity, and they generally yielded a value of CO_2 that was smaller than the actual amount present. After consultation with Dr. Bill Norton of Water Resources Engineering, this problem was rectified by decreasing the molecular diffusion coefficient of CO_2 which allowed the model to simulate saturated CO_2 conditions that exist in the highly alkaline, spring-fed reservoirs of the upper San Antonio and Guadalupe River basins.

Another modification to the reservoir model was made to account for the high seepage rate from Medina Reservoir. The seepage comes from the lower most layer of the reservoir and does not mix with the discharge of the remaining outlets.

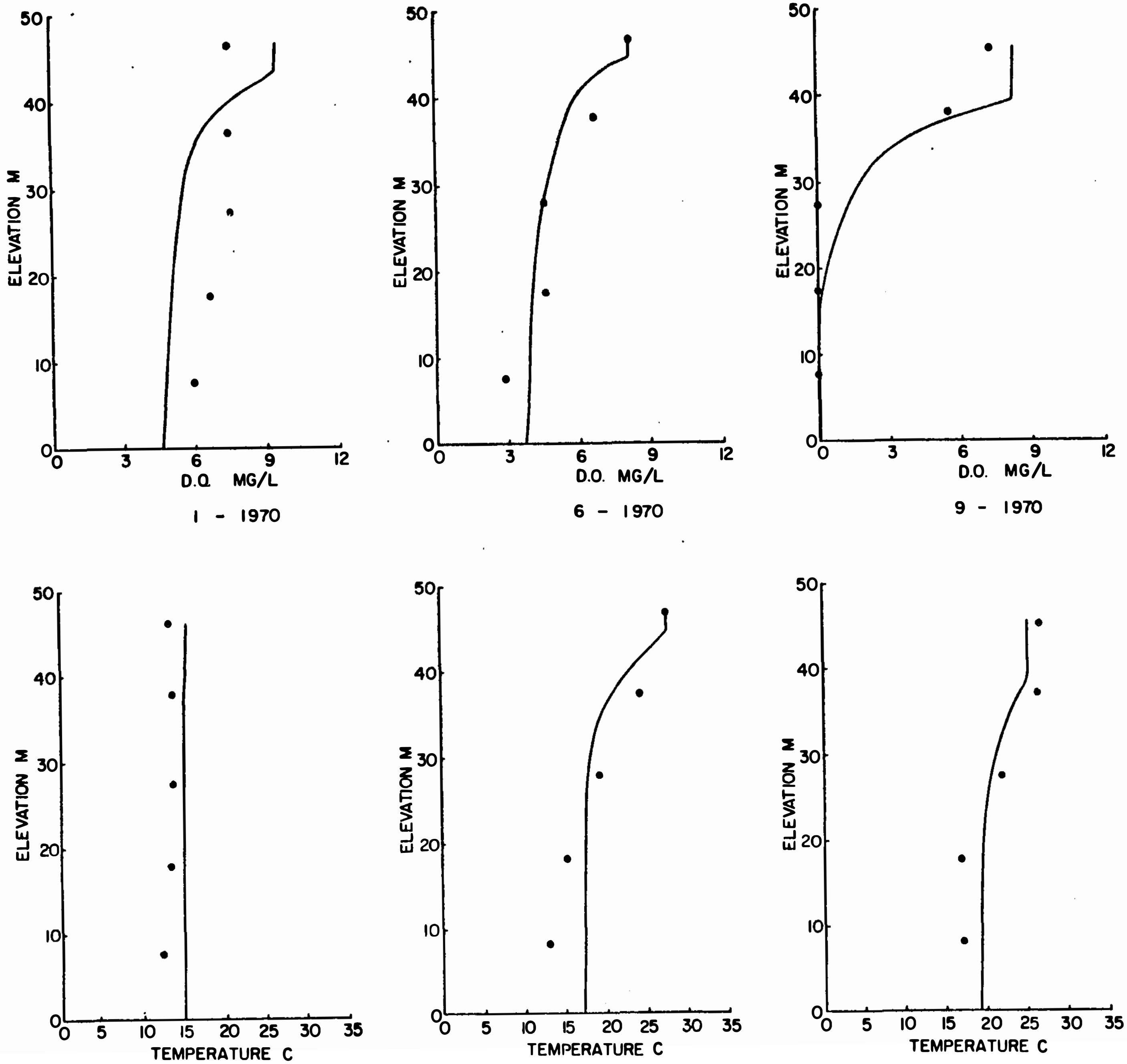


Figure B-9
Canyon Reservoir
Temperature and Dissolved Oxygen Profiles

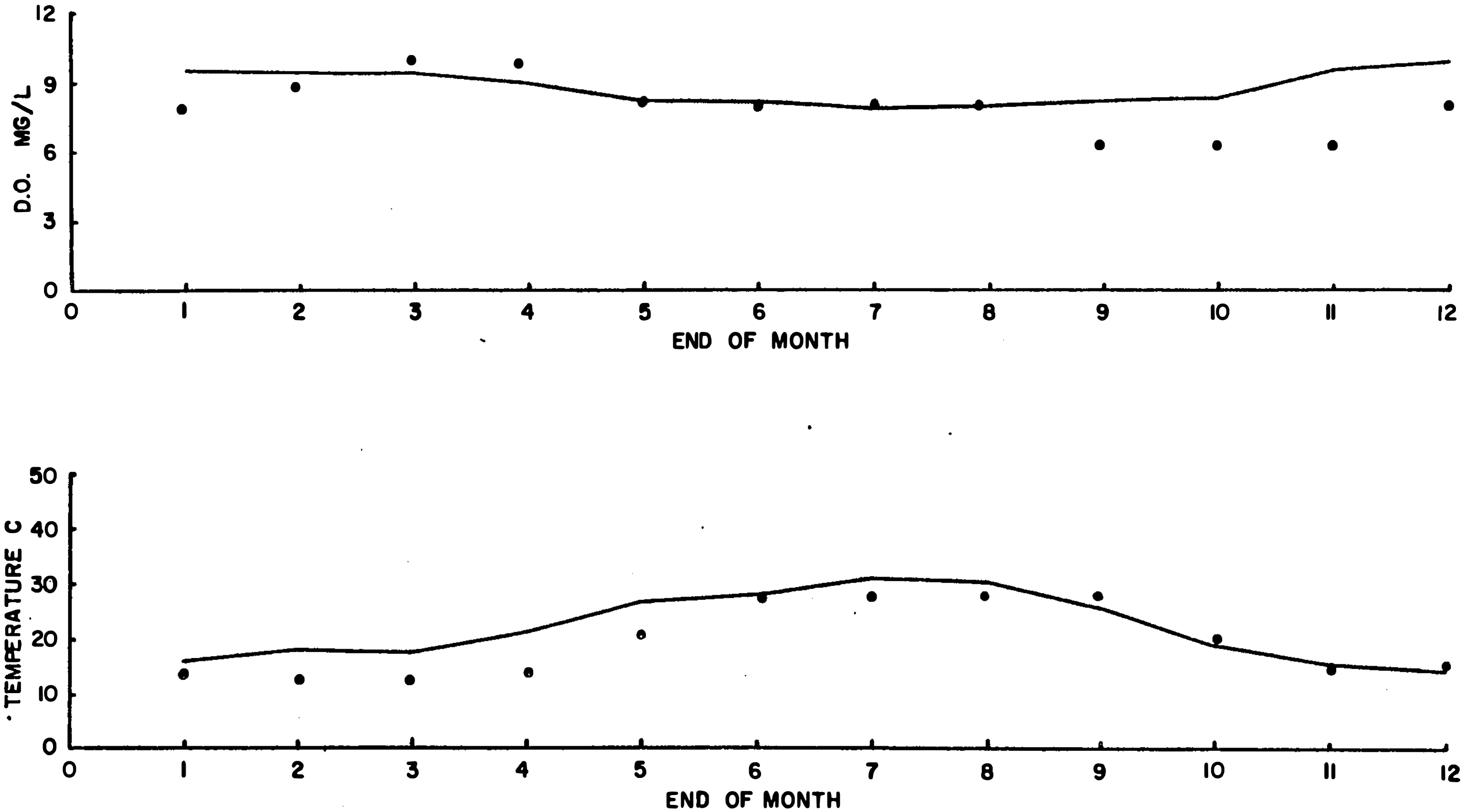


Figure B-10
Canyon Reservoir Top Element
Temperature and Dissolved Oxygen Concentrations

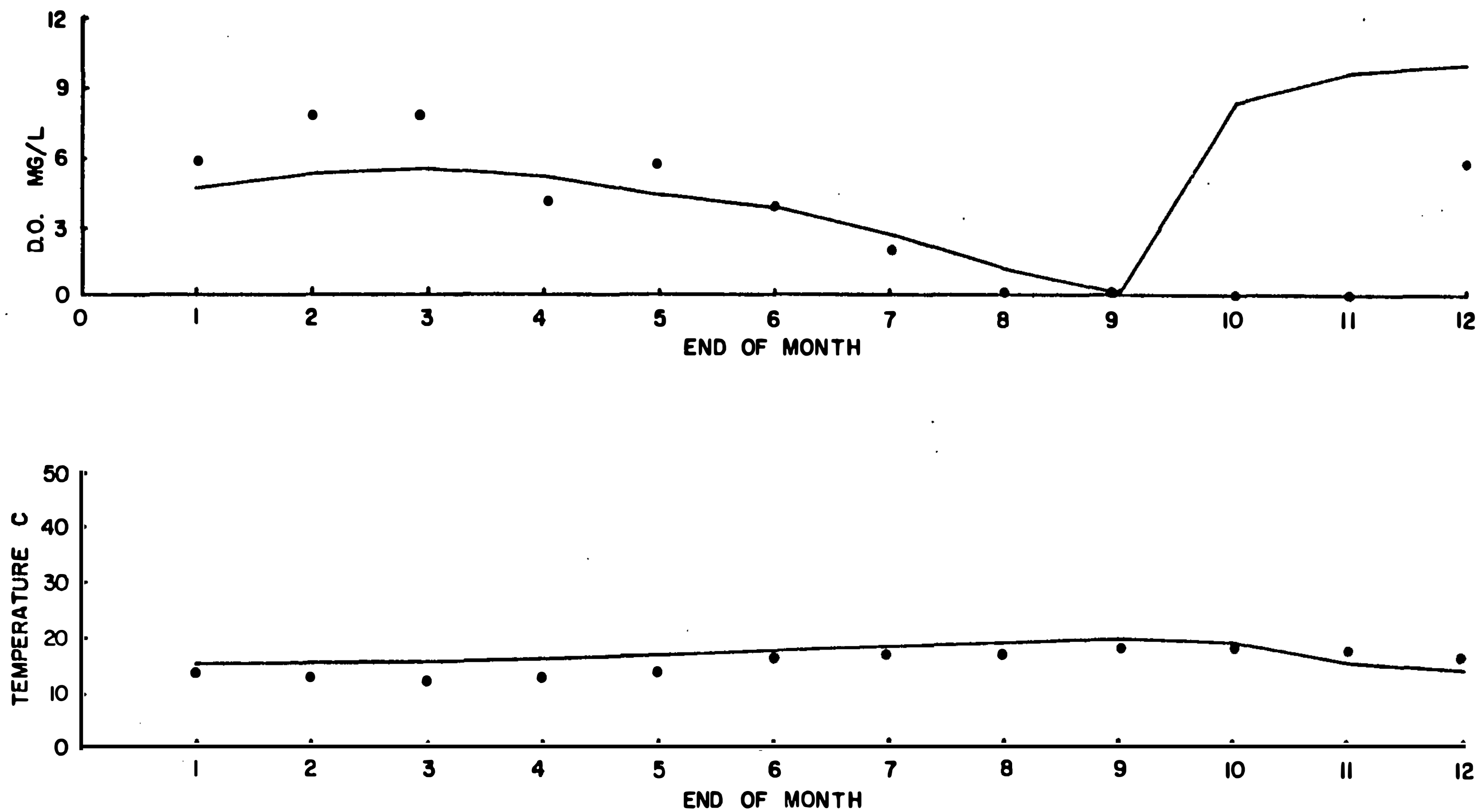


Figure B-11
Canyon Reservoir Bottom Element
Temperature and Dissolved Oxygen Concentrations

LIMITATIONS OF THE MODELS

Long-term operation of the lake ecologic model revealed certain limitations which could not be remedied during the course of this project. Predominant among these limitations was the inadequate long-term simulation of fish populations, even when the aforementioned improvements were added to the model. As more experience is gained in ecological modeling these deficiencies can be corrected providing that ecological research actively continue to make available better ecosystem definition.

Another problem encountered involves sedimentation in the reservoir over long time periods which results in decreased volume (sometimes substantially) and a higher surface area to volume ratio with concommittant increases in evaporation loss. These changes may be significant with regard to potential long-term changes in the aquatic environment and should be considered in future efforts.

The third limitation relates to the withdrawal from the reservoir of non-dissolved water quality parameters in the water discharged as seepage. To correct this problem requires a major alteration of the coding in the hydraulic mixing calculations for the quality constituent.

Rain is input to the surface of the reservoir, but no other quality parameters are included in this input source. A review should be made to determine the physical and chemical components of precipitation and the amounts in which they occur. Over long-term simulation, this should improve the model's computations.

Another major limitation is the question of nutrient cycling and removal from the reservoir. This includes the rates and controlling factors of anaerobic metoblism of nitrogen, phosphorus, and carbon in the water column, the transfer of nutrients across the oxic-anoxic sediment interface, the formation of refractory compounds, fish production as a function of season and mortality and also the population dynamics of emergent benthic organisms.

A major limitation of the stream model is that it does not include fish, benthic animals, zooplankton, and detritus which are simulated in the lake estuarine ecological models described in Appendix C. This is an important consideration when interfacing the stream model with the lake ecologic model or the estuarine ecologic model.

MODEL CALIBRATION

The reservoir ecological model was calibrated using data collected and published in a final report to the Guadalupe - Blanco River Authority and Upper Guadalupe River Authority entitled "The Influence of Canyon Reservoir on Water Quality of the Guadalupe River" (Hannan and Young, 1971). Data compilation began in November, 1969, and continued through December, 1970. Data were monitored at two points in the reservoir, one station in the trailrace of Canyon Dam, and one station on the Guadalupe River above flood control elevation of the reservoir. The data assembled included the following: water temperature, dissolved oxygen, planktonic chlorophyll a, bicarbonate alkalinity, pH, free carbon dioxide, specific conductance, turbidity, secchi disk transparency, total dissolved solids, dossolved inorganic solids, dissolved organic solids, nitrates, nitrites, ammonia, total Kjeldahl nitrogen, and phosphates.

Figures B-9 through B-11 exhibit the response of the reservoir model using December, 1969 data as initial conditions and monthly inflow quality constituent concentrations as input for the year 1970. The results displayed are reservoir profiles and time traces of dissolved oxygen and temperature. The continuous lines represent the model's performance and the circles correspond to measured data.

The stream model was calibrated for both the Guadalupe and San Antonio Rivers. The stream model was calibrated for the Guadalupe River from river mile 303.0 (just below Canyon Reservoir) to river mile 10.0 (confluence of the Guadalupe and San Antonio Rivers). This calibration was based on data collected in August, 1969 (Forrest and Cotton, Inc., 1970). Figures B-12 and B-13 illustrate the results of this calibration. Water quality in the Guadalupe River is quite good except for the low dissolved oxygen concentrations in the Canyon Reservoir releases during this period. Organic loadings and nutrient concentrations are low. There were no data to compare with the simulated algae concentrations; however, no heavy algal growth has ever been reported.

The stream model for the San Antonio River was calibrated from river mile 232.0 (headwaters of the San Antonio River) to river mile 0.0 (confluence of the San Antonio and Guadalupe Rivers). This calibration was based on data collected in August, 1970 (TWDB, 1972). Figures B-14 and B-15 illustrate the results of this calibration. These results show how the water quality in the San Antonio River is dominated by the return flows from the City of San Antonio. Organic loadings and nutrient concentrations are quite large resulting in severe dissolved oxygen deficits in the river. Again, there were no quantitative data available to compare with the simulate algae concentrations although heavy algal growths have been reported.

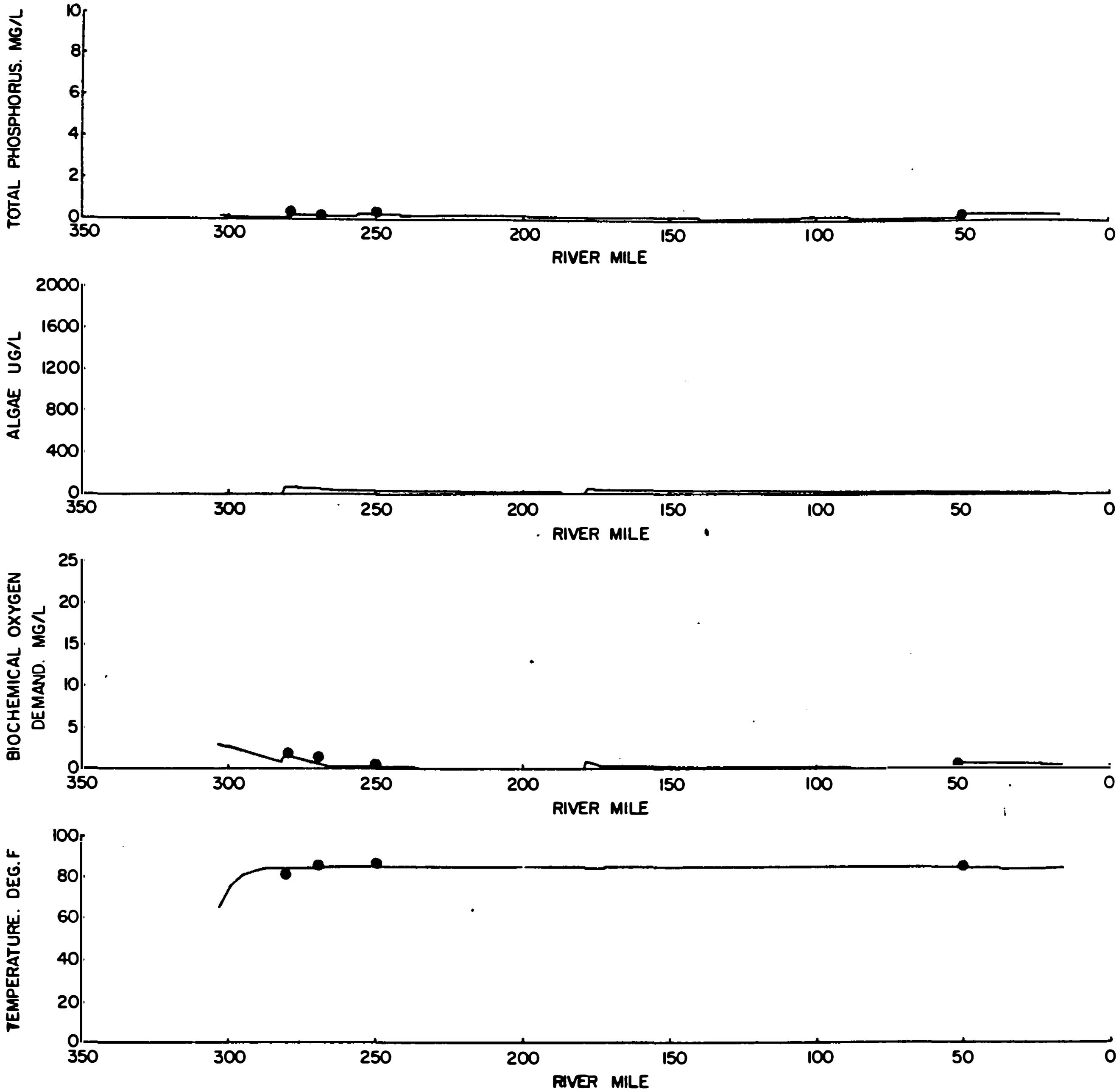


Figure B-12
Guadalupe River - August 1969

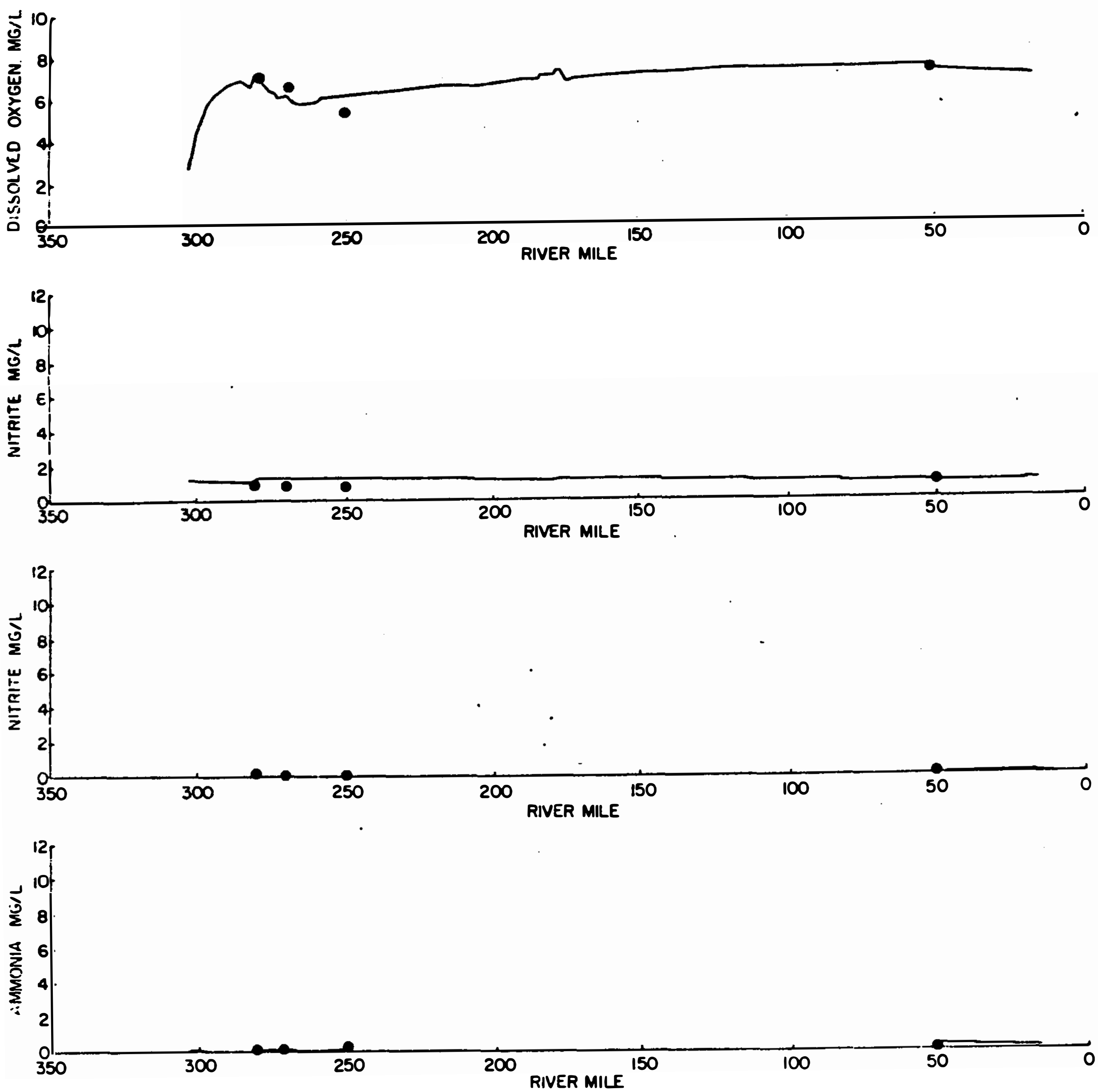


Figure B-13
Guadalupe River - Austin 1969

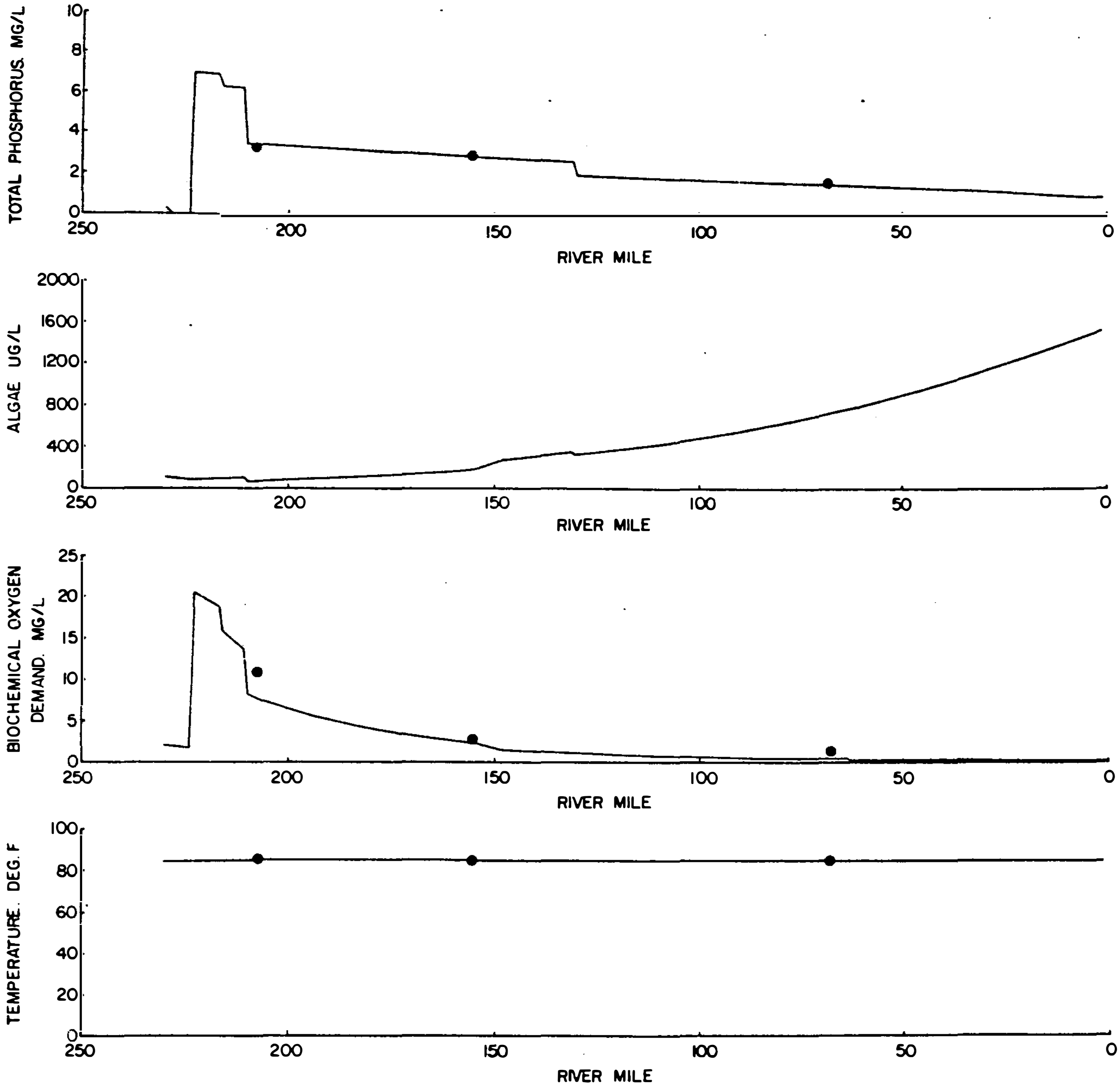


Figure B-14
San Antonio River - August 1970

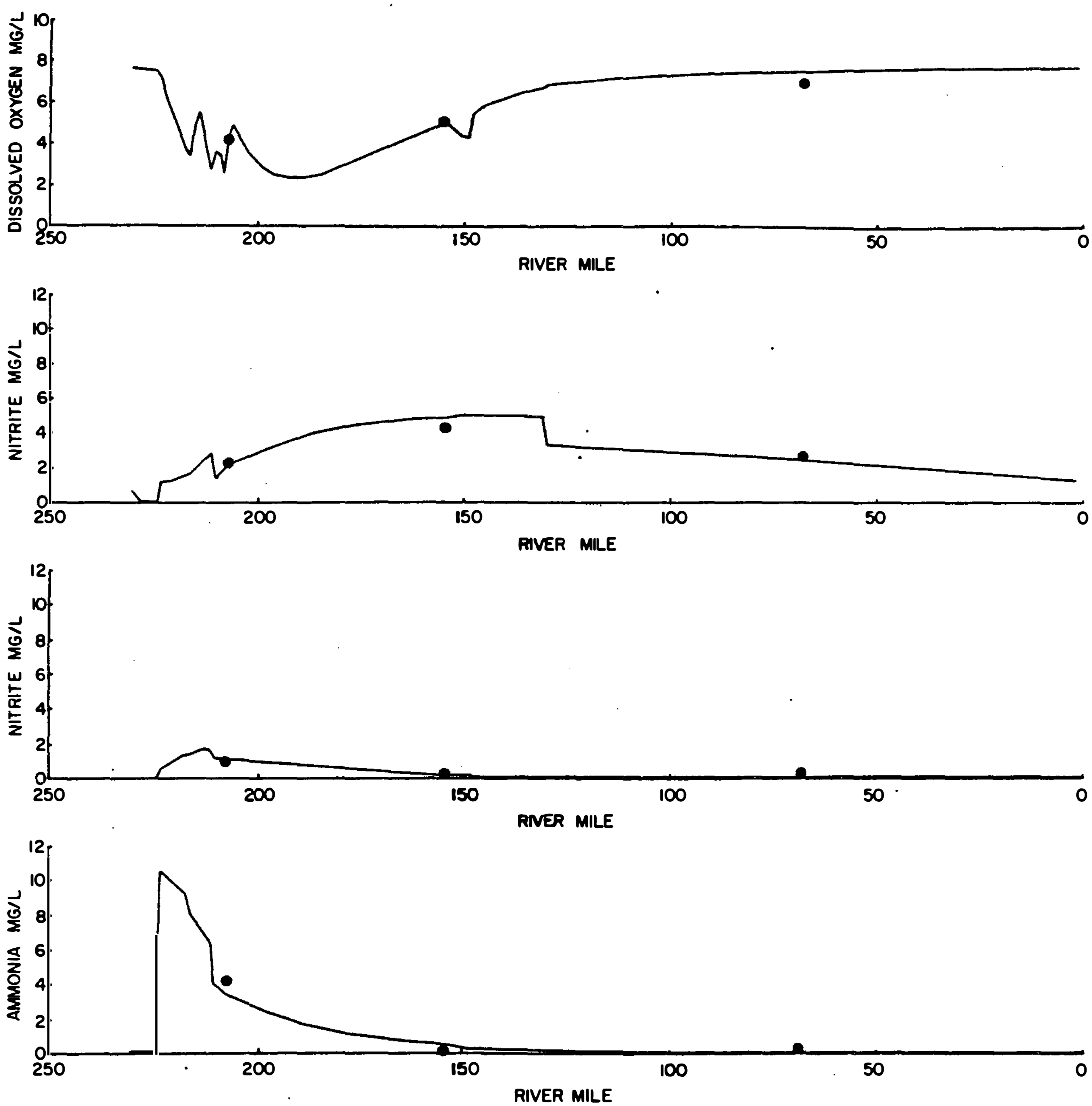


Figure B-15
San Antonio River - August 1970

APPENDIX C

ECOLOGIC MODEL AS APPLIED TO ESTUARIES

The prototype estuarine system is a waterbody subject to both hydrologic and tidal influences. Estuaries may have a wide variety of geometric configurations with one or several openings to the ocean. They receives fresh water from upstream rivers and may be defined to include portions of the rivers themselves, tidally influenced or otherwise. The prototype is considered, for the purposes of this study, to be well-mixed vertically; that is, not stratified.

The hydrodynamic behavior of the estuary is controlled primarily by tides at the mouth, although at times of high runoff the tributary inflows of fresh water may dominate. There are two to four tidal phases in tides of the Gulf Coast of the United States, one flood and one ebb or two flood and two ebb tides in each cycle of about 25 hours. During a flood tide, Gulf water moves into the system and estuarine water is pushed inland and mixed with fresh water entering through the landward boundary. The ebbing tide is characterized by a reversal of flow and a discharge of the estuarine water mixture through the seaward boundary to the Gulf. A fraction of estuarine water is considered to be "lost" to the Gulf and never returns. The remainder is assumed to mix with near shore Gulf water and to return to the estuary on the succeeding flood tide.

The transition between flood and ebb conditions ("slack water") occurs throughout the estuarine system at different times depending on the velocity of propagation of the tide wave from the mouth of the estuary. Since tidal motions are dominated by the moon, a complete tidal cycle has a period of approximately 25 hours, a lunar day. Variations in amplitude and phase of the tidal are associated with the combined effects of the sun and moon from month to month over the seasons of the year.

Estuarine water generally exhibits near seawater salinities at the estuary's mouth, virtually fresh water at the inland boundary, and brackish conditions in between. Where the river and the estuary meet, a delta is often formed by the deposition of sediment from upstream erosion. In this region the water may be rich in nutrients and conditions may be conducive to high planktonic productivity which, in turn, will encourage both indigenous and anadromous fisheries.

This project deals only with the vertically mixed estuary, one that is not stratified. While this is not true for all estuaries, it is a common condition of the coastal embayments and estuaries of the Texas coast. Good hydrodynamic models exist for this type of estuarine system, hence a solid base exists for development of a useful ecological model. The basic principles in the ecological model are essentially independent of the means by which hydrodynamic behavior is characterized. Therefore, the same ecological concepts that were applied to the stream and reservoir ecological models described in Appendix B can be used for the estuary as well.

GEOMETRIC REPRESENTATION

Mathematical abstration of estuarine geometry is accomplished by subdividing the waterbody into discrete volume units or "cells." Cells are characterized by surface area, depth, volume, and a friction factor. All water quality parameters that characterize the system are associated with cells; i.e., these volumes are treated as discrete CSTRs (see Figure B-2). Water is constrained to flow from one cell to another advecting and "diffusing" water quality constituents between cells until the functional behavior of the entire bay system is determined.

Figure C-1 shows a section of an estuarial grid network as it might be employed to represent a typical shallow estuary. This type of representation has been successfully employed in modeling a number of shallow estuarine system along the Texas Coast (Masch, et.al., 1971 and 1973). The grid network used in this study for the Guadalupe Estuary is illustrated in Figure C-2. It can be seen from the figure that the computational grid system can easily be adapted to any prototype geometry with a widely varying degree of detail. Experience has shown that systems thus formed are capable of reproducing prototype hydrodynamic behaviro with a high degree of reliability and provide an excellent base for quality characterization.

CONPUTATIONAL SEQUENCE

The computational sequence for the Estuary Ecologic Model can best be depicted by the master flow chart diagram shown in Figure C-3. As shown, the model is comprised of two modules, the *Tidal Hydrodynamics Program* and the *Ecologic (Quality) Program.* These modules are connected through the hydrodyanics program output, which serves as input to the ecologic program. Tidal hydrodynamics are furnished on a tape in a form suitable for subsequent quality and ecologic simulation.

HYDRODYNAMIC SIMULATION

Under the assumptions specified above, simultaneous solution of the dynamic equations of motion in each of the two coordinate directions in the horizontal plane and the two-dimensional unsteady continuity equation is required. The equations of motion neglect the Bernoulli terms, which have been shown to be small for the bays under consideration in this study (Masch, et. a., 1971 and 1973), but include wind stresses and the Coriolis acceleration and can be written as

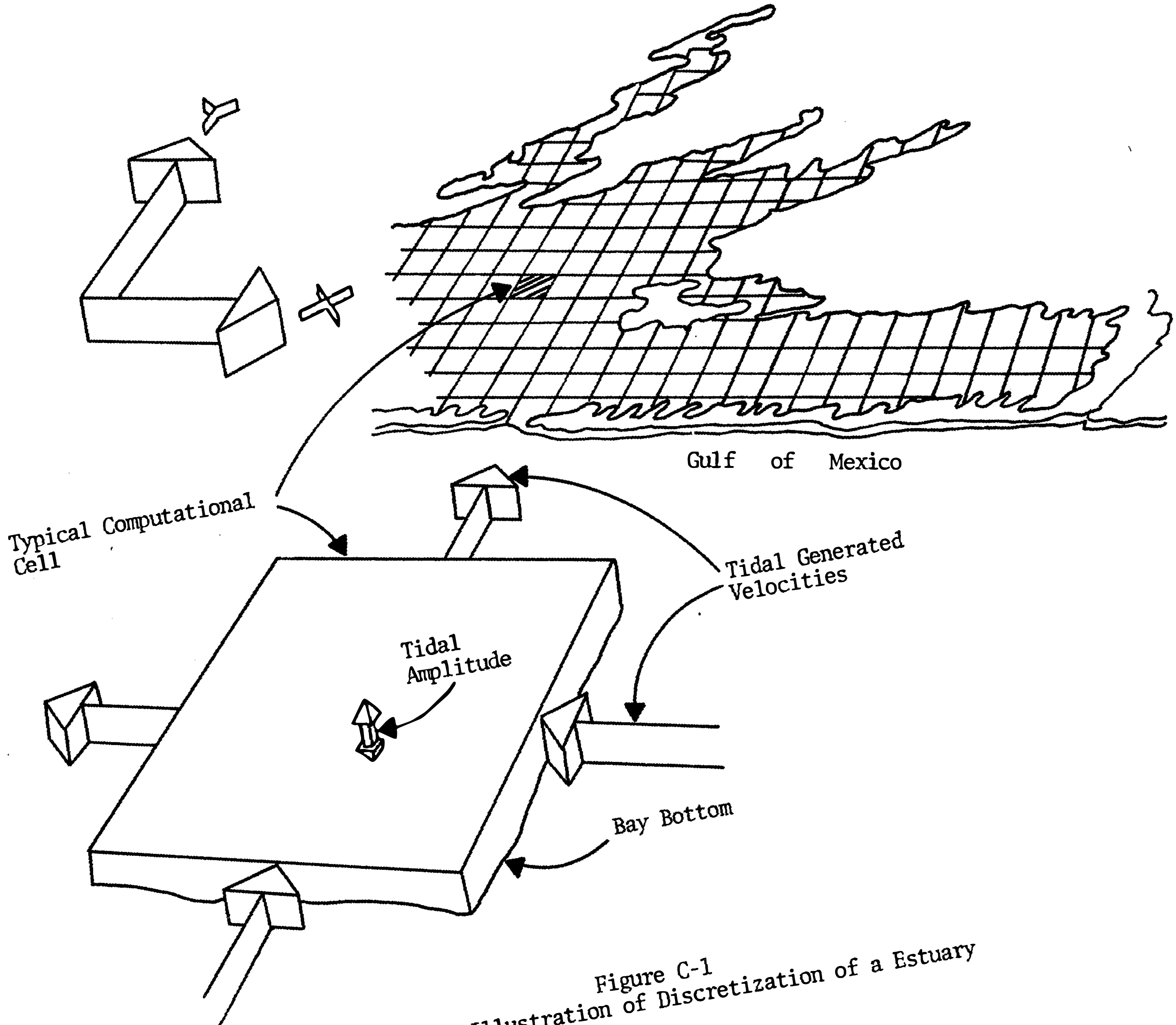


Figure C-1
Conceptual Illustration of Discretization of a Estuary

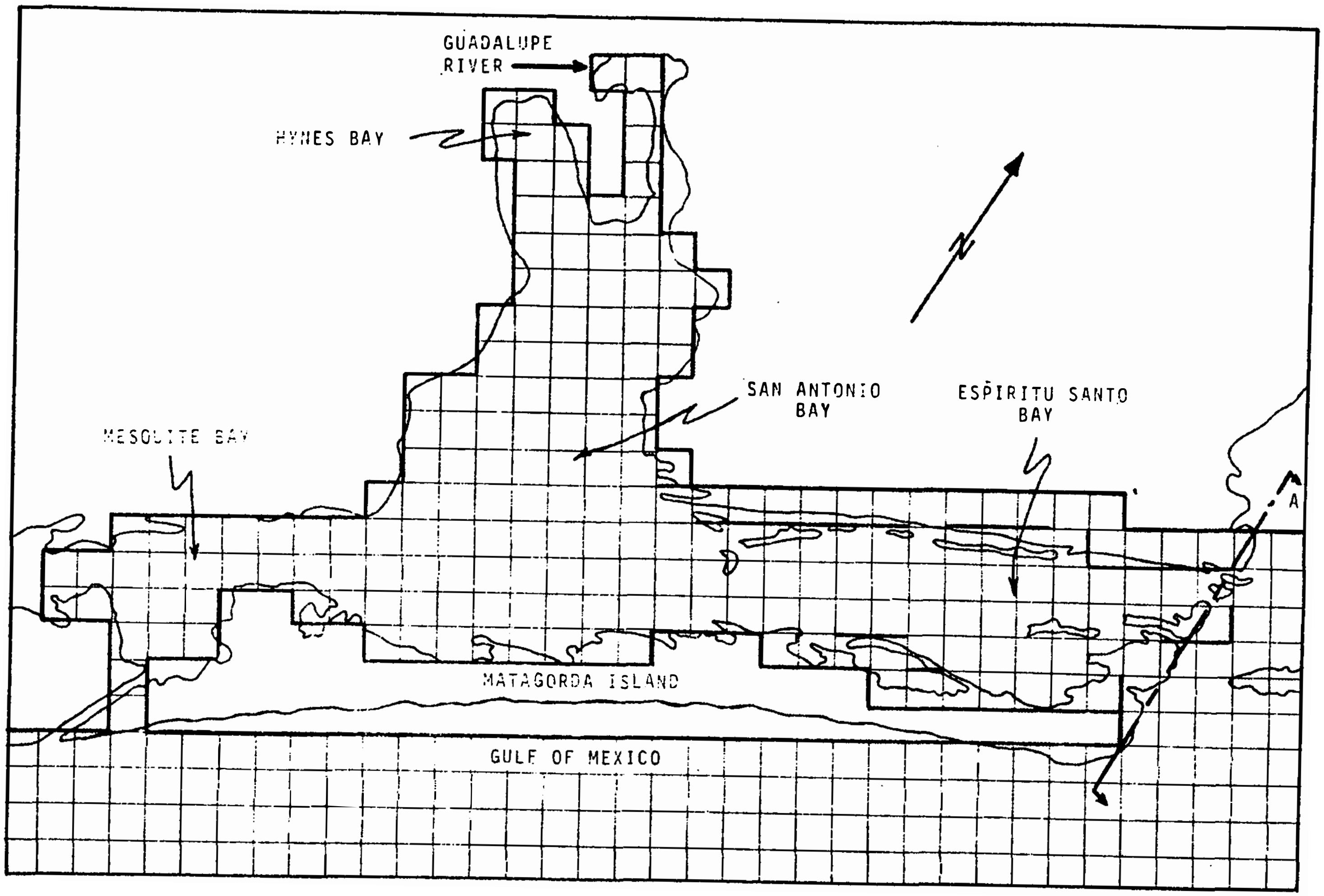


Figure C-2
Computational Grid Representation
of San Antonio Bay

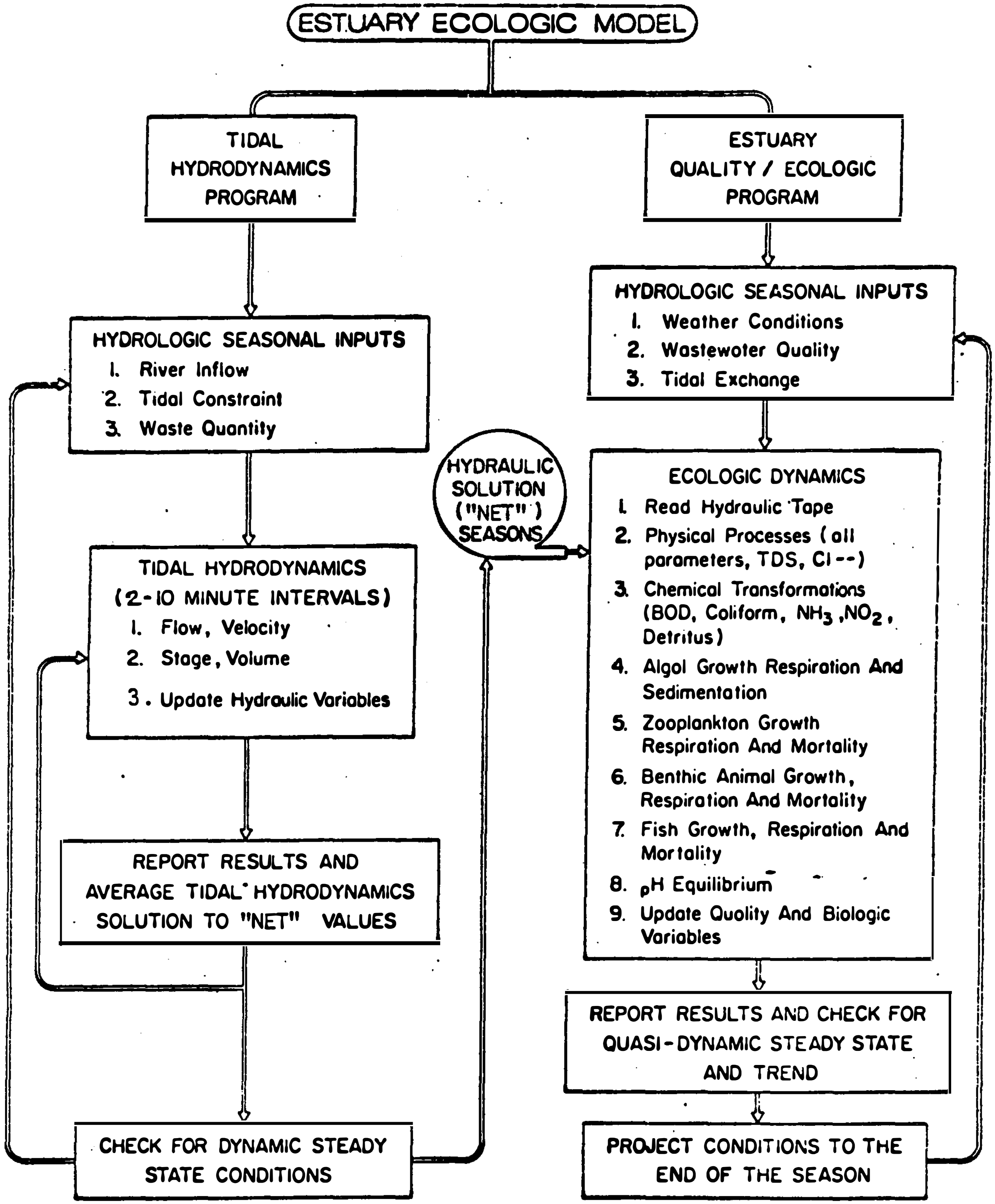


Figure C-3
Master Flow Chart Diagram for the
Estuary Ecologic Model

Solution Sequence:

1. Calculate flows, velocities, and water surface elevations in each cell at next level in time.
2. Average flows, velocities, and water surface elevations with their respective values at the previous time step to obtain "net" values.
3. Repeat

The solution results in spatial and temporal description of flows, velocities, and water surface elevations in each cell as well as the "net" tidal hydrodynamics during a tidal cycle.

A necessary condition for a stable solution using the explicit procedure outline above is that for all cells

$$\Delta t \leq \frac{\Delta s}{c} \qquad \text{(C-4)}$$

where

Δt = Maximum time step for stable solution

Δs = Width of grid cell

c = Celerity of shallow water wave disturbance = gd

In application of the model it is customary to impose a representative set of hydrologic and tidal conditions at the boundaries and run the model over several cycles, say two or three diurnal periods, until hydrodynamic equilibrium is reached. In the present instance, this procedure is followed for each of several sets of conditions corresponding to "seasons" of interest in the annual procession. Finally the resulting data for a complete cycle (i.e., velocities, discharges, tidal stages, water volumes, and depths) are written onto computer tape at intervals suitable for the ecologic simulation. Data are stored as averages over intervals of twenty-five (25) hours. No restrictions are placed on the number of hydrologic "seasons" that may be considered; this is discretionary with the user.

$$\frac{\partial q_x}{\partial t} - \Omega q_y = -gd \frac{\partial h}{\partial x} - gdS_{e_x} + X_w \quad \text{(C-1)}$$

$$\frac{\partial q_y}{\partial t} + \Omega q_x = -gd \frac{\partial h}{\partial y} - gdS_{e_y} + Y_w \quad \text{(C-2)}$$

The equation of continuity for unsteady flow can be expressed as

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial h}{\partial t} = r - e \qquad \text{(C-3)}$$

In eqs. (C-1), (C-2) and (C-3), q_x and q_y are vertically integrated flows per foot of width at time t in the x and y directions, respectively (x and y taken in the plane of the surface area); h is the water surface elevation with respect to mean sea level (msl) as datum; d is the depth of water at (x,y,t) and is equal to (h-x) where z is the bottom elevationwith respect to msl; go is the acceleration of gravity; Ω is the Coriolis parameter; S_{e_x} and S_{e_y} are the energy slopes in the s and y directions, respectively; X_w and Y_w are the wind stresses per unit density of the water; r is the rainfall intensity; and e is the evaporation rate.

The solution technique for the tidal hydrodynamics model is a step forward (in time) explicit procedure with the following steps:

Initialization:

1. Set inflow conditions for cells at landward boundaries,
   q = f(t)
2. Set water surface elevations or tidal conditions for nodes at seaward boundaries, h - f(t)
3. Set extraneous inflow - outflow conditions for all interior cells, including net flows from withdrawals, waste effluents, precipitation and evaporation.

that monitor the San Antonio Bay area. Ths information obtained from the hydrodynamic simulation in the form of steady state water surface elevations and two-dimensional flows reflects average 1972 summer conditions. Likewise, practical considerations dictated the use of average inflow qualities, as well as average initial and boundary conditions as input data for the ecologic simulation. Substantially all of the physical/chemical data used were collected by Texas Water Development Board and U.S. Geological Survey as part of their cooperative data collection program along the Texas coast. Information concerning the zooplankton, phytoplankton, and benthic populations was taken from data collected by Texas Parks and Wildlife Department under interagency contracts with the Texas Water Development Board. Additional data from studies by the University of Texas School of Public Health was used for the purpose of comparison and to compliment other data where needed.

The calibration process was an attempt to reproduce conditions in the prototype system (Guadalupe Estuary) by adjusting the numerous rates and coefficients that govern the mathematical description of the estuarine ecosystem. Table C-1 is a summary of the rates and coefficients obtained by this process. The simulation results using these values are shown in Figures C-4 and C-5 as spatial distributions of various constituents with the observed data superimposed. These figures show reasonably good agreement between observed and simulated values. The distribution of total dissolved solids shows observed values lower than simulated. This is the result of applying a net evaporation rate that was greater than actually occurred in the prototype system. The dissolved oxygen distribution also shows inaccuracies when compared with observed data. However, the discrepancies are reasonably

ECOLOGIC SIMULATION

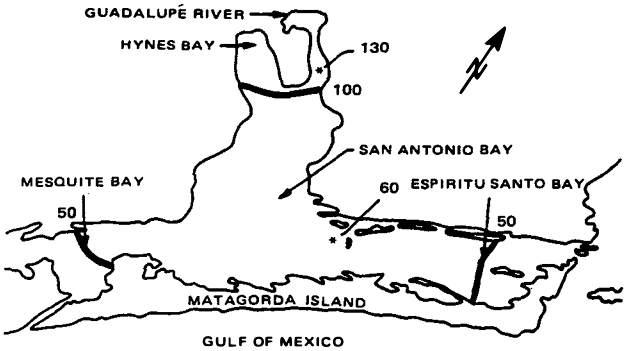
Like the numerical integration scheme used in the stream and reservoir ecologic simulations, the estuarine ecologic simulation is accomplished by evaluating the rate function (gradient) of a parameter at any given time and projecting forward at this rate for a short increment of time. In the solution procedure, computations must be made for all parameters (i.e., quality constituents, including biota) at all hydraulic elements, ("cells") in a grid system compatible with the tidal hydrodynamic model. The model is presently structured to solve one parameter for all hydraulic elements then proceed to the next parameter. Once all parameter for all hydraulic elements then proceed to the next parameter. Once all parameters have been evaluated, time is advanced rates and coefficients are updated and the procedure is repeated. The estuarine ecological model computes the biotic constituents first, followed by the non-conservative constituents, the conservative constituents, and finally an evaluation of pH is performed based on the dissociation constants for the carbonate-bicarbonate system in each hydraulic element.

MODEL CALIBRATION

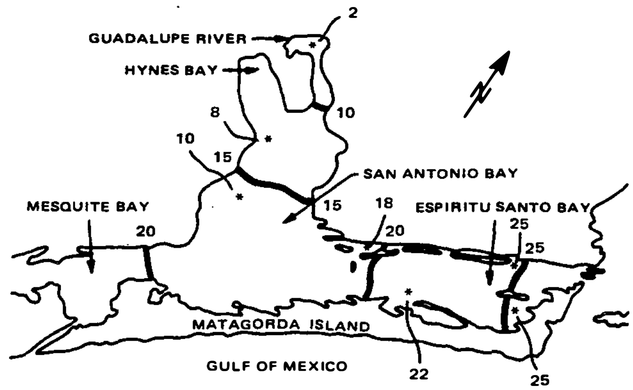
The estuarine ecological model was initially developed and calibrated for the Guadalupe Estuary using input data for June 1972 to simulate the summer period July through September 1972. The hydrodynamics used to describe this period were generated using the existing Texas Water Development Board tidal hydrodynamic model which had been previously calibrated and verified for this system. The inflow data, tidal regime, and meterologic conditions used were obtained from the USGS and the U.S. Weather Service stations

Table C-1
System Coefficients for the Guadalupe Estuary Simulation

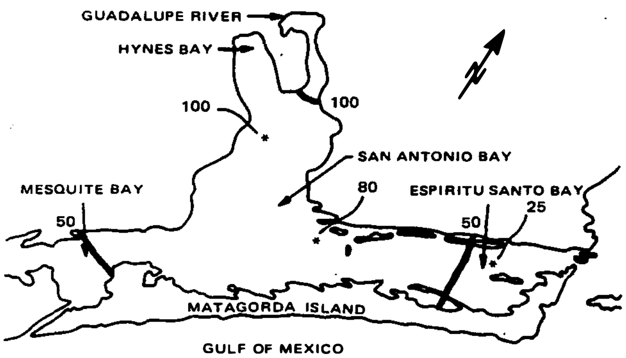
Parameter	Value	Parameter	Value
Decay Rate, per day		Half Saturation Constants	
BOD	0.2	Zoo on algae, mg/l	0.5
NH_3-N	0.09	Fish 2 on Zoo, mg/l	0.20
NO_2-N	0.27	Fish 3 on Benthos, mg/sq m	500.0
Detritus	0.002	Benthos on Sediment, mg/sq m	5000.0
Coliform	0.4	Algae 1	
Temperature Coefficient, Q_{10}		light, K Cal/sq m	0.003
		CO_2-C, mg/l	0.5
BOD	1.047	NO_3-N, mg/l	0.1
NH_3, NO_2, Detritus	1.02	PO_4-P, mg/l	0.03
Biologic	1.02		
		Respiration Rates, per day	
Maximum Specific Growth Rate, per day		Algae	.05
Algae 1	2.0	Zooplankton	0.02
Zooplankton	0.10	Fish	0.001
Fish 1	0.006	Benthos	0.001
Fish 2	0.012		
Fish 3	0.010	Settling Velocity, feet per day	
Benthos	0.01		
		Detritus	0.015
Stoicheometric Equivalence		Algae 1	0.05
		Mortality Rate, per day	
O_2/NH_3	3.5		
O_2/NO_2	1.2	Zooplankton	0.005
O_2/Detritus	1.3	Fish	0.001
O_2/Algae	1.6	Benthos	0.001
CO_2/BOD	0.2		



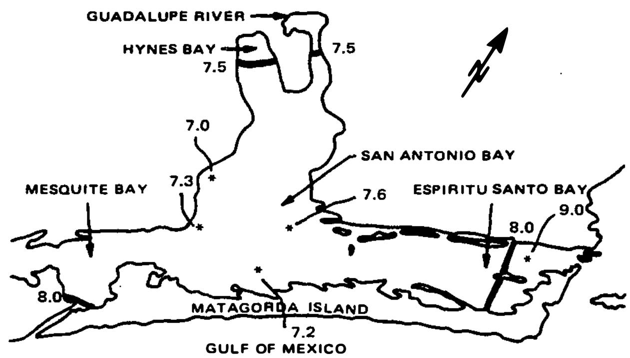
Ammonia as N (ug/l) Sept. 1972
*Observed



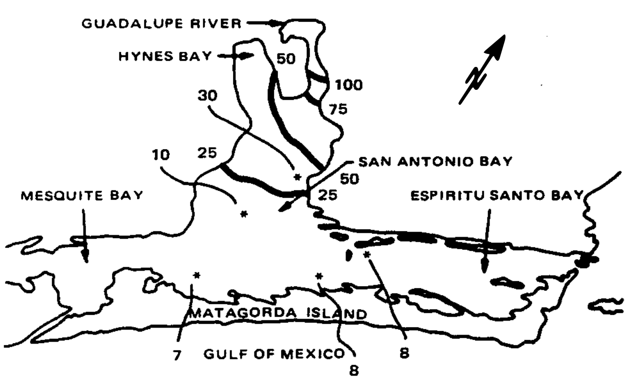
Total Dissolved Solids (ppt) Sept. 1972
*Observed



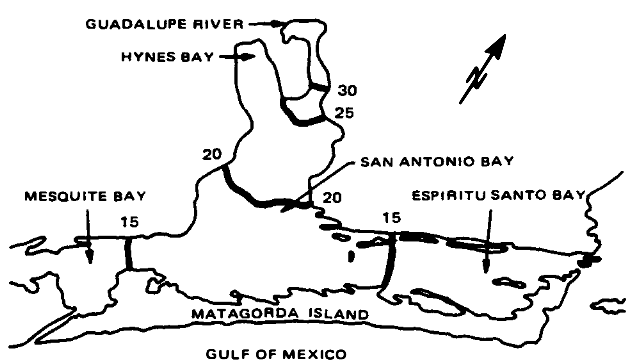
Phosphorus as P (mg/l) Sept. 1972
*Observed



Dissolved Oxygen (mg/l) Sept. 1972
*Observed

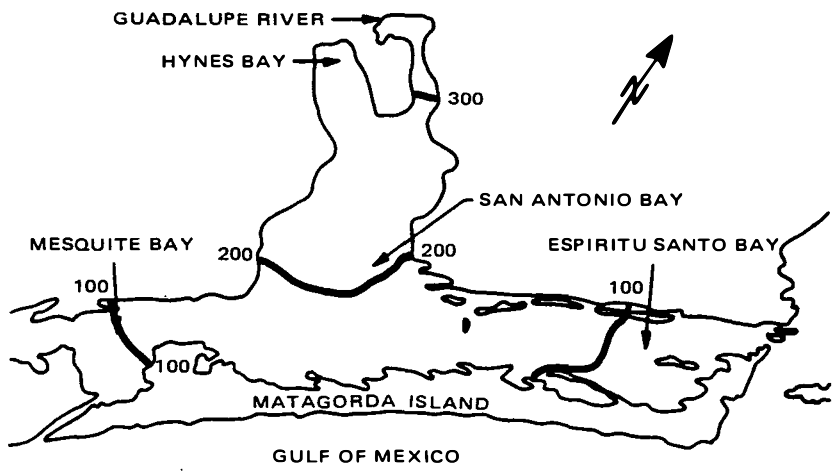


Zooplankton (ug/l) Sept. 1972
*Observed

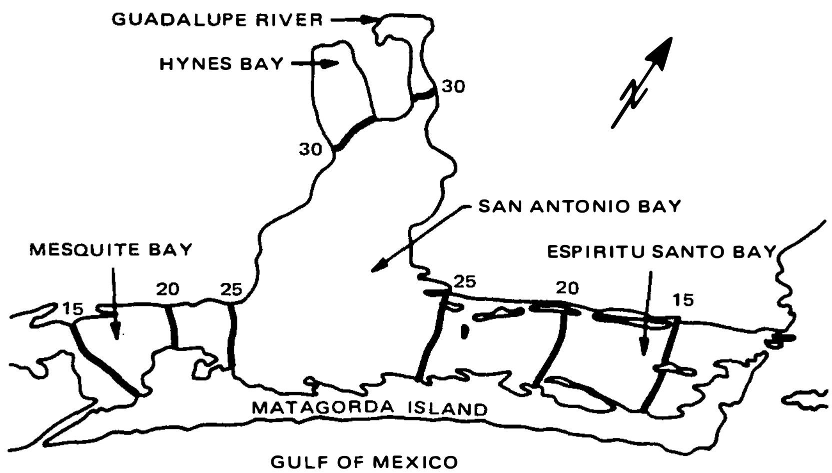


Detritus (mg/l) Sept. 1972

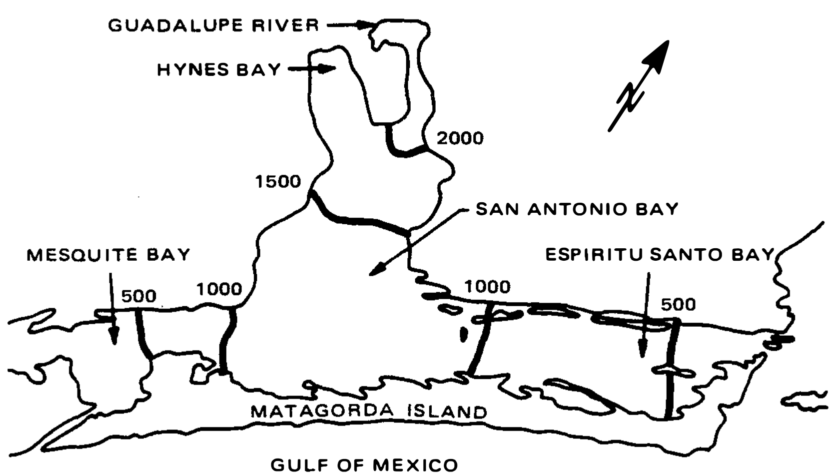
Figure C-4
Spatial Distributions of Selected Constituents - Guadalupe Estuary, September 1972



Nitrate as N (ug/l) Sept. 1972



Nitrite as N (ug/l) Sept. 1972



Algae (ug/l) Sept. 1972

Figure C-5
Spatial Distributions of Selected Constituents - Guadalupe Estuary, September 1972

small and could be the difference between a discrete observed value and the value produced by a six-hour time step simulation. The remaining distributions show good agreement with the observed data that were available for the simulated period.

MODEL LIMITATIONS

As presently structured, the estuarine ecologic model is capable of producing useful results over short time periods, but lacks the refinement necessary to describe the long-term phenomena which occur in the estuarine system. Modifications which were incorporated into the reservoir ecological model (Appendix B) have been applied to the estuarine ecologic model as well; however, the comprehensive data required to accurately calibrate the model to simulate periods in excess of a year are not yet available. Further refinement of the model is anticipated as these data becomes available. From the outset of the project it was apparent that the estuarine ecological model lacked the capability of describing the migratory phenomena of selected organisms which inhabit the estuary during a portion of their life cycles. In order to overcome this limitation, a migratory organism model was developed with the goal of providing a "migration factor" that could be used in the estuarine ecological model to account for this behavior. The present linkage between the models is through the evaluation of common parameters (fresh water inflow, temperature, and salinity). Future operation of the models should provide a direct linkage in the form of a set of verified equations which would evaluate input from the estuarine ecologic model, and calculate a migration factor that would be applied to the nekton organisms in the estuarine simulation. This interactive use of both models could provide better simulation of the estuarine ecosystem.

APPENDIX D

MIGRATORY ORGANISM MODEL

The evaluation of estuarine fish productivity was initiated to describe the effects of water resources development on higher trophic level organisms of particular economic interest to man. Mathematical models discussed in previous sections describe the physical, chemical, and biological interactions in aquatic environments. The estuarine ecological model's primary function is to evaluate specified interactions between environmental variables and lower trophic level production. The migratory organism model was developed to evaluate the response between "key" migratory estuarine species and physical environmental parameters.

The main objective in developing the migratory organism model was to relate the well-being or viability of migratory organisms to indicator environmental factors which describe the estuarine system. Well-being of the migratory organisms was measured in terms of monthly catch statistics. Catch statistics are a variable governed by mortality, growth, and catch effort. Environmental factors, as used here, are variables that impact on the liefe cycles of migratory organisms. Environmental factors selected for this analyses are in part subject to the influence of water resources development.

Monthly catch statistics are governed by catch effort and statutory fishing seasons. It is evident that the catch of a particular month is not necessarily related only to the environmental conditions of the same month. Environmental conditions for the period of spawning, migration, and growth are also important.

To develop a statistical model for migratory organisms on a rational basis, it was necessary to review the life cycles of selected migratory organisms. This review provided the theoretical basis for the selection of important environmental conditions at the proper seasons for inclusion in the statistical correlations. Biological principals, including intuitive processes, were used to dictate the relationships.

LIFE CYCLE REVIEW

Organism selected for this investigation include redfish, sea trout, white shrimp, and oysters. The species are predominant in the San Antonio Bay estuarine system and represent fisheries of major economic importance.

White Shrimp

The spawning of white shrimp in the Gulf of Mexico varies with time and depth over different coastal areas. Spawning generally begins in early April and continues until late September. It appears that a sudden warming trend, rather than an optimum temperature, initiates the spawn. The larvae, drift through a period of molts and soon migrate into the estuarine system on incoming tides.

The postlarvae reach the nursery grounds by the time they are 6-7 mm long. There is a trend for smaller juveniles to be located further up the estuary. Growth is continuous through the end of the summer. Immature shrimp must move out to Gulf waters to avoid mortality in the fall when temperatures often become too cold in shallow bay waters.

The availability of food is an important criteria for shrimp growth. White shrimp are omnivorous and food items include detritus, animal fragments, algal pieces and so forth. Fragments of bryozoa, sponges and corals as well as algae are known from their stomachs. Young shrimp under 10 mm may feed almost entirely on blue-green algae and diatoms. The high productivity of estuaries usually excludes food as a major limiting factor. Nevertheless, nutrient input is important to the overall food budget of the bay.

Given the availability of food, a primary growth factor is temperature. The maximum growth is found in the summer months, and minimum growth in the winter. It is reported that increased temperature raises the molting rate (Zein-Eldrin and Griffith, 1965). Also, varying degrees of activity have been observed by Aldrich and Wood (1968) to be associated with changes in temperature.

White shrimp can withstand higher temperatures than brown shrimp, but brown shrimp are more resistant to low temperatures (Zein-Eldrin, 1966). They both move to deeper water as the water temperature drops in winater (Lindner and Anderson, 1956). A sudden cold wave, however, can kill white shrimp while the brown shrimp will burrow in the mud for protection (Aldrich, Wood and Baxter, 1968). This would suggest that post-larval brown shrimp could overwinter in the bay or nearby shallow Gulf waters. Most white shrimp at the stage will either die or move out.

The effect of salinity of the white shrimp is ambiguous. It appears that the postlarvae do prefer lower salinities, but this preference may reflect more on the availability of food in the low salinity areas. Even at a young age, white shrimp are rather tolerant of salinity concentrations, having been found from 0.4 ppt (Gunter and Shell, 1958) to 47.96 ppt (Hildebrand 1958). It appears that temperatures below 15°C reduce the tolerance to low salinity. This is a natural occurrence, since low salinity waters are shallow and cool off rapidly when winter arrives.

Some reported growth rates of penaeid shrimp are shown in Table D-1. Rates for white shrimp are important for back-calculating the period of growth, time of spawning, and so forth.

Salinity is also an indirect limiting factor. Both high and low salinities cause death, while intermediate salinities are assumed to have little effect. High salinity can be caused by periods of drought or fresh water inflow depletion.

Table D-1
Shrimp Growth

Investigators	Method	Growth Rate
Brown Shrimp		
Pearson, 1939	Lab Growth	0.56 mm/day
Growth increase with temperature, °C, starts between		11°C and 18°C
Zein-Eldrin, 1965		1.4 mm/day at 32°C 1.1 mm/day at 25°C
Ringo, 1965	Catch Analysis	0.1 mm/day March to April Rose to average of 1.7 mm/day 3.3 mm/day in late May
Loesch, 1965	Young Shrimp Juvenile & Sub-Adult	1.6 mm/day in Spring .8 mm/day to 1.3mm/day in Summer
	Juvenile & Sub-Adult	.3 mm/day to 1.1 mm/day in Winter.
St. Amant	Catch Analysis (Trend)	$<$1 mm/day at $<$20°C $<$1.5 mm/day at $<$ 25°C
Klima	Tagging-Adult	1 mm/day in Summer

Enter nursery grounds at 8 - 14 mm total length, March, April; Max. May/June
Postlarval molt to juvenile 4 to 6 weeks after arriving.

Investigators	Method	Growth Rate
White Shrimp:		
Johnson, 1956		Total length 80 mm 2 months after hatch
Gunter, 1950	(28-100 mm Shrimp)	.8 - 1.3 mm/day
Viosca, 1920	(30-15 mm Shrimp)	.8 mm/day
Loesch, 1965		.3 - .9 mm/day in Winter .6 - 1.0 mm/day in Summer
	Very Young	2.1 mm/day in Summer
Lindner, 1956	100 mm Shrimp	.66 mm/day for two months
Klima, 1964	120 mm/Shrimp	.66 mm/day in Fall
Kutkuhn, 1962	Weight increase is maximum in middle of size range.	

Redfish (Red Drum)

Redfish (Sciaenops ocellata) are common in low to moderate salinities, but are known to survive in hypersaline water. It is not known what percentage of the adult population leaves the bay to spawn in the Gulf during fall and winter months. Adult diet is roughtly 40% shrimp, 40% crab, and 20% small fish.

Sea Trout

Spawning season of the spotted sea trout (Cynoscion nebulosus) runs from March to October. The sea trout live in the bay year around, but may move out into the Gulf during extreme bay conditions of salinity or temperature.

Oyster

The American Oyster (Crassostrea Virginica) is born in the spring as a result of the union of egg and sperm in the water column. The oyster in Gulf waters can grow to maturity in less than a year. Once spat are in the water column, they can move vertically but not horizontally to any extent. In less than a month the spat settle on preferably hard surfaces such as old oyster shells and growth begins immediately if water temperature is above 5°C.

The oyster growth rate depends on temperature, food availabilty, age and other environmental factors. High mortality in the summer months is commonly caused by direct high temperature and by the subsequent effects of increased salinity, low dissolved oxygen, and bacterial and fungal infections. The spawning cycle is nearly continuous throughout the year. Harvestable size is 3.0-3.5 inches in length, depending on the availability of oysters during the commercial season.

The oyster is a filter feeder, grazing on plankton, but there is some evidence that it can assimilate abiotic nutrients from the water. The filtering system is very thorough, as evidenced by accumulation of high bacterial counts and radioactivity in the body tissues. Attached at the bottom the oyster depends on the circulation of the system to bring it food.

Temperature is an important environmental factor. A minimum temperature of 20°C must be attained before spawning occurs (Morse, 1971). Oyster growth occurs at a minimum temperature of 5°C. In addition to its effects on growth and reproduction, temperature also has an effect on mortality. The greatest oyster mortality often occurs during the summer months (when oyster beds may be exposed to the hot sun or succumb to predators and disease associated with high salinities. Oyster mortality has been observed at temperatures greater than 37°C and salinities greater than 40 ppt, both of which are summer phenomena.

SELECTION OF INDICATOR ENVIRONMENTAL PARAMETERS

In order to evaluate the productivity of the Guadalupe Estuary system, an indicator organism or "key" species was selected for investigating overall correlations with important environmental parameters. The key species selected for this research project was the white shrimp. The life cycle and growth characteristics of this species has been described in detail previously. Criteria utilized in selection of the white shrimp are summarized as follows:

1. A migratory organism
2. Sensitive and responsive to ambient and antecedent temperature and salinity conditions

3. Life cycle in the estuary occurs within one year
4. Life cycle influenced by the hydrological regime
5. Availability of catch statistics.
6. Many other estuarine organisms have environmental requirements similar to the "key" species
7. "Key" species production is related to total estuarine productivity

Historical catch data for white shrimp in the San Antonio Bay estuarine system was obtained from two separate and independent sources. One set of data was compiled from the Gulf Coast Shrimp Data bulletin published monthly by U.S. Department of Commerce's National Oceanic and Stmospheric Administration, National Marine Fisheries Service. The data shown in Table D-2 for 1960-1971, reflect monthly commercial shrimp harvest as heads-off weight. The commercial shrimping industry in Texas is regulated by the Texas Parks and Wildlife Department. White shrimp are considered commercial size when 39 or less shrimp (heads-on) total one pound.

In 1964, the Texas Legislature established two regulatory shrimping seasons by statute. The first season runs from May 15 through July 15. This season is commonly referred to as the "brownie run." Mainly browh shrimp (Penaeus astecus) are commercially harvested during this period. Occasionally, large white shrimp, known as " overwintering whites" are caught during the first season, but the majority of the harvest is composed of brown shrimp. The second season starts on August 15 and ends on December 15. This season is known as the "white shrimping season" in that the majority of the harvest is comprised of white shrimp. Generally, peak brown immigration into the estuarine system is in February and the white shrimp in May. Consequently, split seasons were required to optimize the commercial harvest of both species.

Table D-2

Guadalupe Estuary Commercial
White Shrimp Harvest (pounds)

Year	August	September	October	November	December	Total
1960	0	43,888	155,570	120,582	24,137	344,177
1961	77,167	105,707	100,411	3,256	14,000	300,541
1962	0	134,429	73,785	32,988	2,927	244,129
1963	61,443	93,808	42,712	16,669	18,593	233,225
1964	158,694	365,635	234,345	102,093	515	861,282
1965	332,404	331,000	184,497	33,273	7,163	888,337
1966	95,288	115,788	56,871	38,019	0	305,966
1967	308,269	159,093	22,302	0	2,912	492,576
1968	142,988	282,100	241,200	110,600	0	776,888
1969	158,000	184,400	0	70,900	0	413,300
1970	239,100	248,900	162,500	72,300	0	722,800
1971	115,200	83,100	88,700	27,300	0	314,300

A second historical white shrimp data base was developed from the Texas Parks and Wildlife Department trawl sample data. The state agency began a routine biweekly trawl sampling program in the Guadalupe Estuary in 1958. TWDB staff, in cooperation with Texas Parks and Wildlife Department personnel, compiled and assimilated these data into a computer processable form for the 1960-1970 study interval. Seven historical sampling stations which had reliable and continuous data were selected. This data set is important in determining the relationship between white shrimp production and white shrimp commercial harvest in the Guadalupe Estuary. The Texas Parks and Wildlife Department data reflects the earliest occurrences and seasonal population dynamics in terms of shrimp abundance, whereas the commercial harvest data reflects the statutory seasonal harvest of the Guadalupe Estuary. Figure D-1 illustrates the relationship between the productivity of five Texas Parks and Wildlife Department historical sampling sites and historical commercial harvests (see Figure D-2 for sample locations). As can be seen in this figure, all historical trawl sampling sites, except Hynes Bay, generally follow the commercial white shrimp harvests.

Selection of meaningful and responsive environmental indicators for the Guadalupe Estuary was difficult because of the variable interactions within the ecosystem. Variables selected for this research project were salinity, water temperature, air temperature and fresh water inflow. They influence or are influenced by:

1. The effects of water resources development
2. Estuarine hydrodynamics
3. Spawning, food availability, and environmental conditions pertaining to growth, survival and harvest of white shrimp
4. More complex estuarine phenomena
5. Statistical variance through time

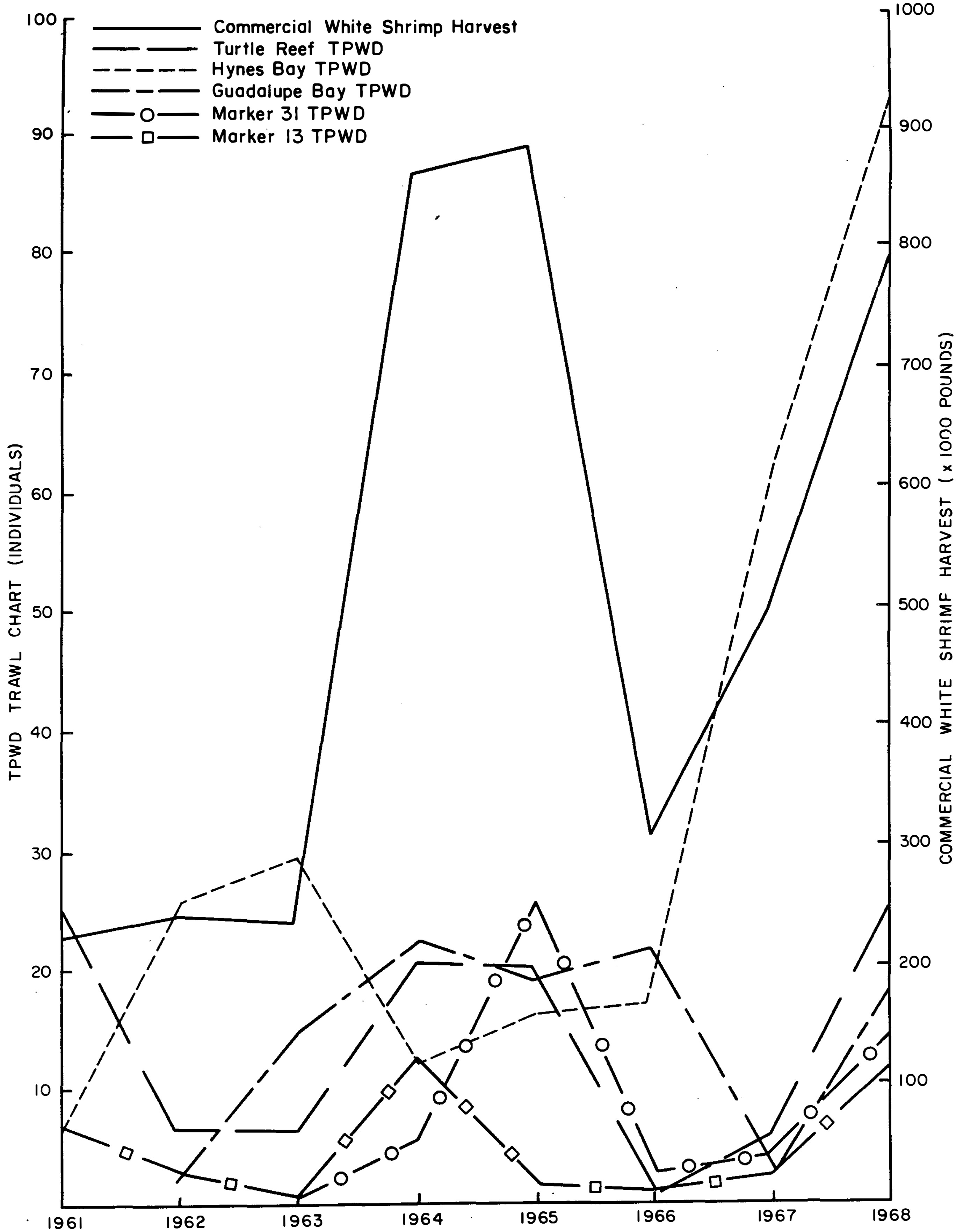


Figure D-1
Guadalupe Estuary System

The relationship of salinity and water temperature in the estuarine ecosystem to the growth and survival of white shrimp is quite complex. Laboratory studies report that the growth of postlarval white shrimp increases steadily betwene 18 and 25°C, with a rapid increase in growth for temperatures above 25°C and salinities of 5 to 15 ppt. Growth of postlarval white shrimp is more strongly affected by temperature changes at constant salinity. Thus, growth of this species appears more a function of temperature, within a relatively broad range of intermediate salinities. Optimal growth of postlarval white shrimp is about 32°C at low to moderate salinities, but the growth rate rapidly declines for temperatures above 33°C and becomes estremely limiting for temperatures at and above 35°C.

The peak population of postlarval white shrimp in the estuarine system is not exposed to long periods of low temperature in the estuarine system. Postlarval white shrimp do not generally become abundant in the Guadalupe Estuary until May when average water temperatures are above 25°C White shrimp in the estuarine system during this time of the year can be exposed to short periods of low temperatures caused by movement of cold fronts through the area. Low temperatures and sudden changes in temperatures can be detrimental to the growth and survival of white shrimp in the estuarine system. Water temperature in the shallow, marsh nursery areas of the Guadalupe Estuary during late spring and summer months can exceed 33°C. The principal growing period for white shrimp is also during the summer months. Thus, the inability of this species to withstand higher temperatures in the nursery areas could be more important to the growth and survival of the bay populations than their tolerance to temperatures below 25°C.

Water temperature and salinity data for the Guadalupe Estuary was compiled from the historical Texas Parks and Wildlife Department data base. In their trawl sample collection program, ambient salinity and water temperature data were collected and recorded. These data were compiled along with sample location and date into a computer processable form.

The salinity and water temperature data represent instantaneous values in space and time. Consequently, to obtain an understanding of these instantaneous values with respect to physical driving parameters, statistical regression analysis was performed on each data set. The regression equations developed from this analysis provide an understanding of the spatical and temporal responses of water temperature and salinity to selected environmental driving forces.

The Guadalupe Estuary is a shallow, wind-dominated body of estuarine water. Historical data show that differences in water temperature within the water column and between the upper and lower estuarine system were minor. Generally, the variation in water temperature between the upper and lower estuarine system is less than 2°C. Consequently, linear regression analysis was performed on the response of historical average water temperature and average regional air temperature.

For temperatures in degrees Farenheit, the following expression was developed:

$$T_w = 1.033\ T_a - 0.538$$

where T_w = water temperature and T_a = air temperature. This equation was developed under a previous contract with Water Resources Engineers, Austin, Texas. The average deviation between corresponding computed and measured values was 2.5°F.

The historical salinity data were compiled in chronological order with each sample location comprising a data set. The historical instantaneous salinity response to inflows varies with location because water circulation patterns (hydrodynamics) are governed by estuarine topography and geographical features such as reefs and spoil areas. Salinity sample locations are shows in Figure D-2. Regression equations developed from each of the data sets are shown in Table D-3. These equations relate the response of salinity to antecedent streamflow conditions. Three predominant antecedent inflow conditions could occur which will highly influence the instantaneous salinity response. One condition can best be described as a relatively constant inflow over an antecedent period. This condition would cause bay salinities to stablize with a slight periodic increase due to evaporation. A second condition coudl be described when a flood enters the estuarine system two or more weeks antecedent to a corresponding salinity value. And a third condition is noted when a flood occurs at the time the salinity is sampled. The latter two inflow conditions would cause bay salinities to fluctuate depending on sample location and magnitude of corresponding floods. Therefore the equations in Table D-3, which relate salinity response to fresh water inflow, have inflow terms describing recent and past antecedent inflow conditions.

Hynes Bay and Guadalupe Bay salinity sampling stations were the most responsive sites with respect to changes in fresh water inlfows. To a lesser degree, Dagger Point and Marker 31 sites were also responsive to fresh water inflow quantities. This is due in part to these stations being located in the general circulation patterns of the Guadalupe Estuary. The remaining stations, Swan Point, Turtle Reef, and Marker 13, were more responsive to the salinity changes in Hynes Bay than fresh water inflows because these sites lie away from the general circulation currents of the estuarine system. The response of salinity within various areas of the Guadalupe Estuary lead to the development of a "regional" area concept.

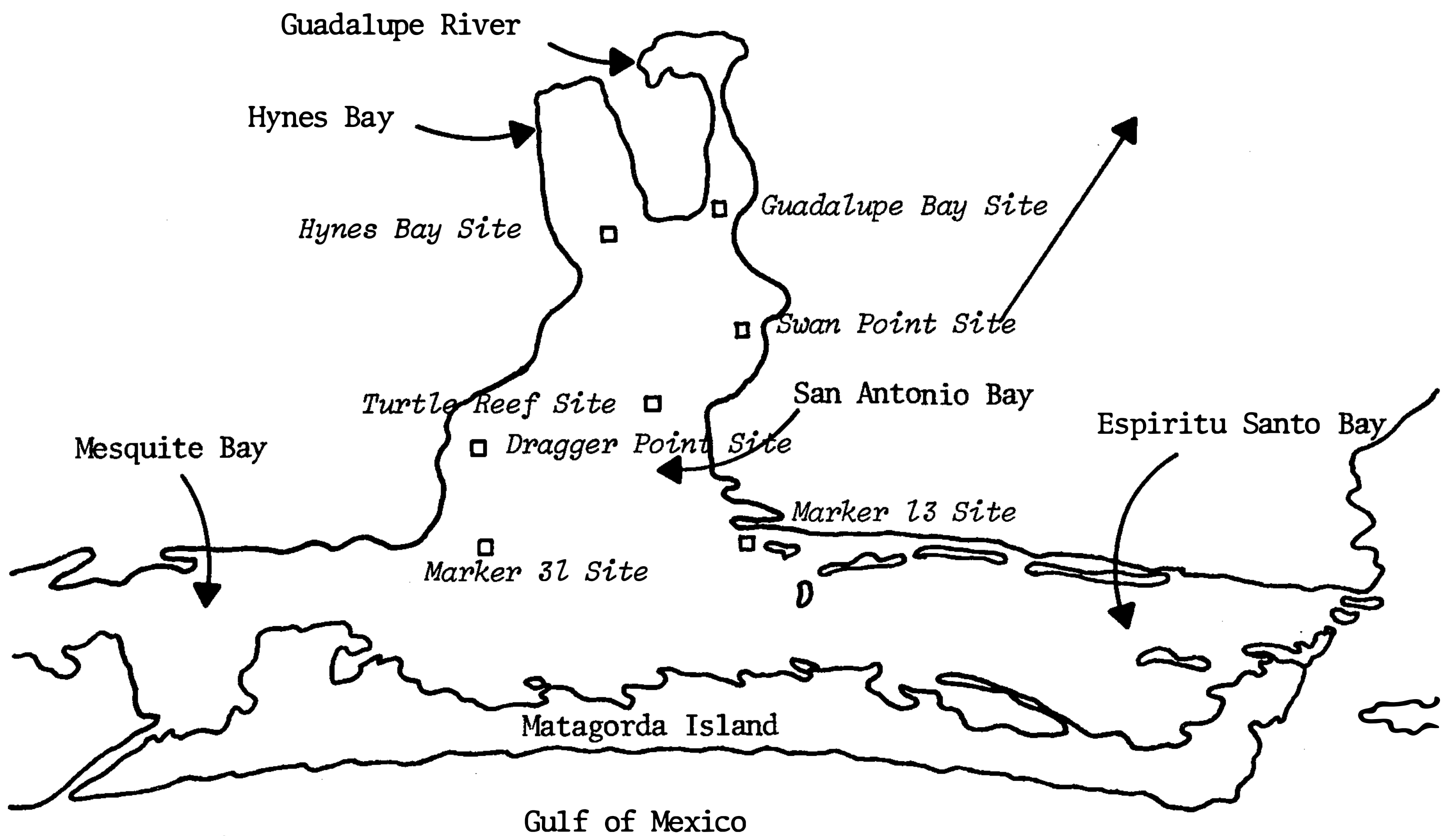


Figure D-2
Guadalupe Estuary
Texas Parks & Wildlife Department Historical
Sampling Locations

Table D-3

Salinity Equations Developed from TPWD Data

Hynes Bay Station 13

$$SAL13 = -12.5 + 11.1/\sqrt{Q_2} + 101.4/\sqrt{\sum_{i=3}^{29} Q_i} + 1.1/\sqrt{Q_4}$$

R = 0.90   Std. Error = 3.85

Swan Point Station 14

$$SAL14 = 1.31 + 0.28 * SAL13 + 4.06 * \sqrt{SAL13}$$

Turtle Reef Station 28

$$SAL28 = 1.36 + 0.25 * SAL13 + 4.36 * \sqrt{SAL13}$$

Marker 13 Station 32

$$SAL32 = 5.33 + 0.91 * SAL28$$

Guadalupe Bay Station 15

$$SAL15 = -2.34 + 7.71/\sqrt{Q_2} + 3.94/\sqrt{\sum_{i=4}^{19} Q_i}$$

R = 0.87   Std. Error = 2.72

Dagger Point Station 12

$$SAL12 = -1.67 + 262.0/\sqrt{\sum_{i=4}^{39} Q_i} - 23.2/\sqrt{Q_5}$$

R = 0.8   Std. Error = 4.11

Marker 31 Station 11

$$SAL11 = -6.3 + 18.3/\sqrt{Q_2} + 191.0/\sqrt{\sum_{i=4}^{39} Q_i} - 11.5/\sqrt{Q_6}$$

R = 0.90   Std. Error = 4.8

where Q_i is the antecedent daily fresh water inflow.

The Guadalupe Estuary can be sectionalized into regions of similar hydraulic and salinity characteristics. Consequently each region is similar in bottom substrate types and nutrient transport profiles. Figures D-3 illustrates the five regions of the Guadalupe Estuary employed in this analysis. Region 1 is comprised mainly of Hynes and Guadalupe Bays. Region 2 is in the center of the Guadalupe Estuary and is the primary transition zone from a fresh to marine environment. Region 3 lies on the lower western section of the estuarine system and encompasses Mesquite Bay and Cedar Bayou. Regions 4 and 5 are located in the lower eastern portion of the estuarine system and encompasses Espiritu Santa Bay. Regions 4 and 5 generally have higher salinities than the other regions because they are in proximity to the Gulf passes and their north and west perimeter is the Turtle Reef and Panther Point Reef systems. These oyster reef systems limit low flow circulation to regions 4 and 5.

The regional concept of the Guadalupe Estuary is important for evaluating the ecological responses of the estuarine system to changing environmental parameters. By identifying sections with similar characteristics, the estuarine system can be divided into subsets of the total system. Ecological responses and requirements can be established and investigated to each region. With the regional concept, requirements of each region can be examined and defined within the overall estuarine requirements.

Fresh water inflow is the last and probably one of the most important environmental parameters of the Guadalupe Estuary. Three vitally important estuarine functions served by fresh water inflows are:

1. Salinity gradient control
2. Transport of sedimentary and nutritive building blocks
3. Inundation of the deltaic marshes

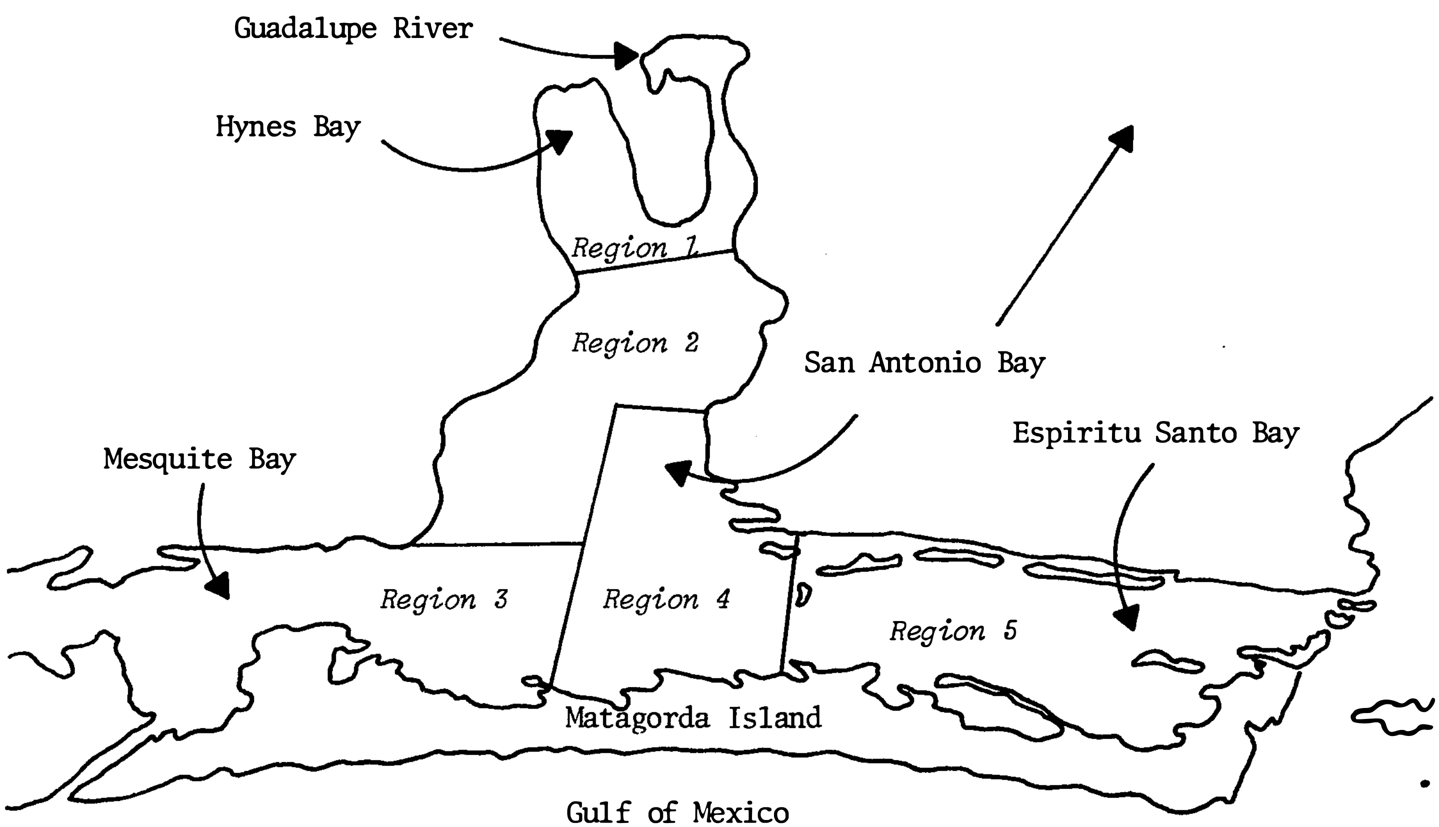
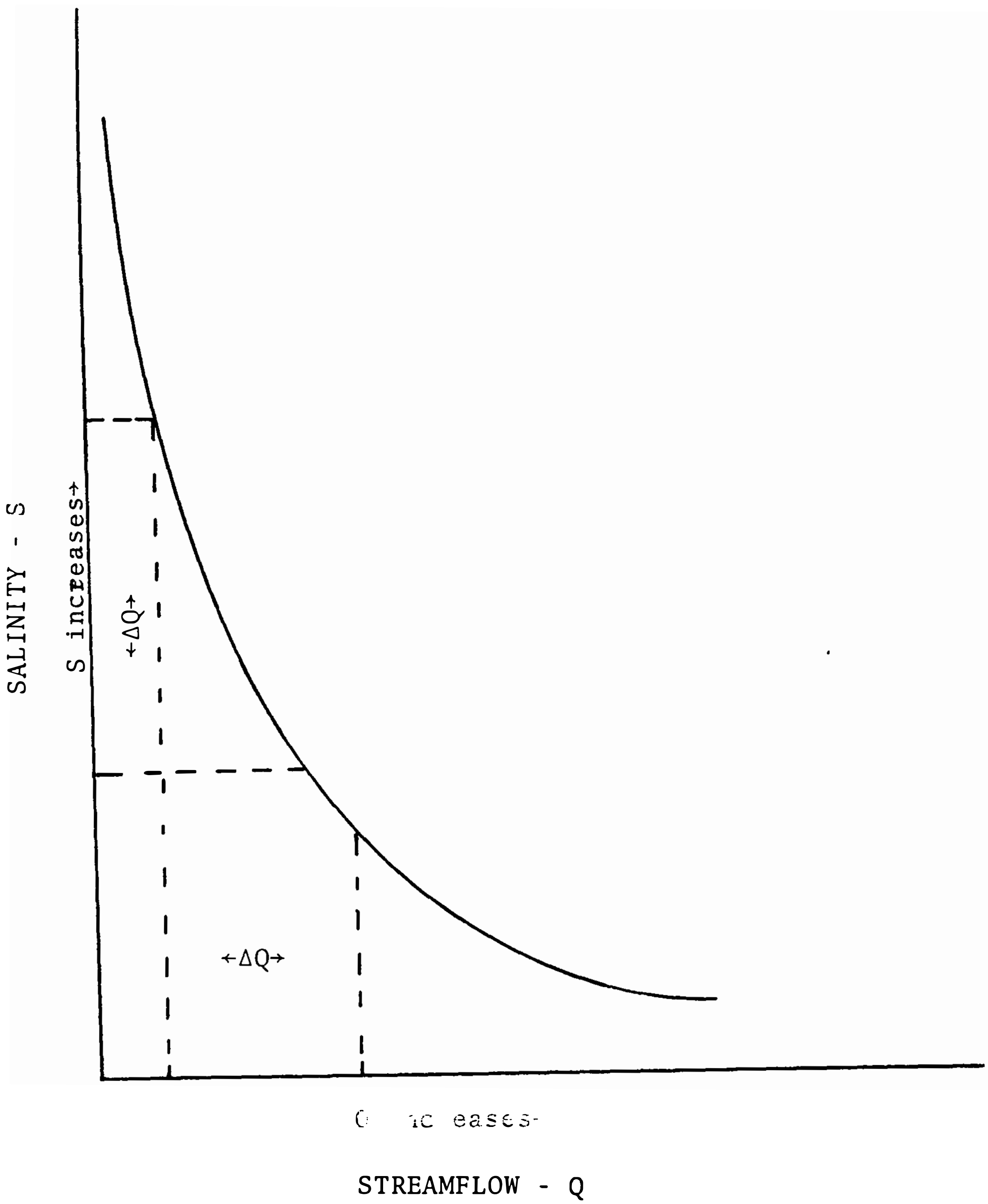


Figure D-3
Guadalupe Estuary System
Regions

The quantity, quality, and timing of fresh water inflow to the Guadalupe Estuary are important to maintain a healthy and viable ecosystem. As described above, inflow to the estuarine system and salinity are directly related. Obviously, higher inflows will result in lower estuarine salinities The salinity concentration in the estuarine system is constatnly changing with time due to fresh water inflow, Gulf tidal exchange, and evaporation. As expressed by the equations in Table D-3, salinity is not a linear function of inflow, but rather is a function of the reciprocal of the square root of inflow as illustrated in Figure D-4. Thus, a small change of inflow ΔQ in the lower flow ranges results in a large change of salinity ΔS. As the inflow rate rises above the low flow range the same change in ΔQ results in a much smaller change in ΔS. The configuration of this curve will vary slightly within the estuarine system depending on location, but the general shape does not change. To expand this point, Figures D-5 and D-6 are plots for antecedent inflow versus salinity graphs for the Hynes Bay and Turtle Reef stations, respectively. For Turtle Reef stations (Figure D-6), a flow rate of 500 cfs will maintain a salinity of about 25 ppt. An increase in flow rate from 500 to 1,300 cfs or a ΔQ of 800 crs causes a decrease in salinity from 25 ppt to 15 ppt, but a corresponding ΔQ increase from 1,300 to 2,100 cfs results in a ΔS decline from 15 to 9 ppt.

Fresh water inflows to the Guadalupe Estuary act as a transport mechanism carrying nutrients into the marsh and bay system. Fresh water inflows during flood stage inundate many square miles of marsh habitat. The inundation dewatering process acts as an exchange mechanism and brings organic nutrients from the marsh into the bay system. Inorganic nutrients deposited in the marsh are converted to an organic state by primary production and bacteriological


SALINITY - S
S increases→
←ΔQ→
←ΔQ→
STREAMFLOW - Q

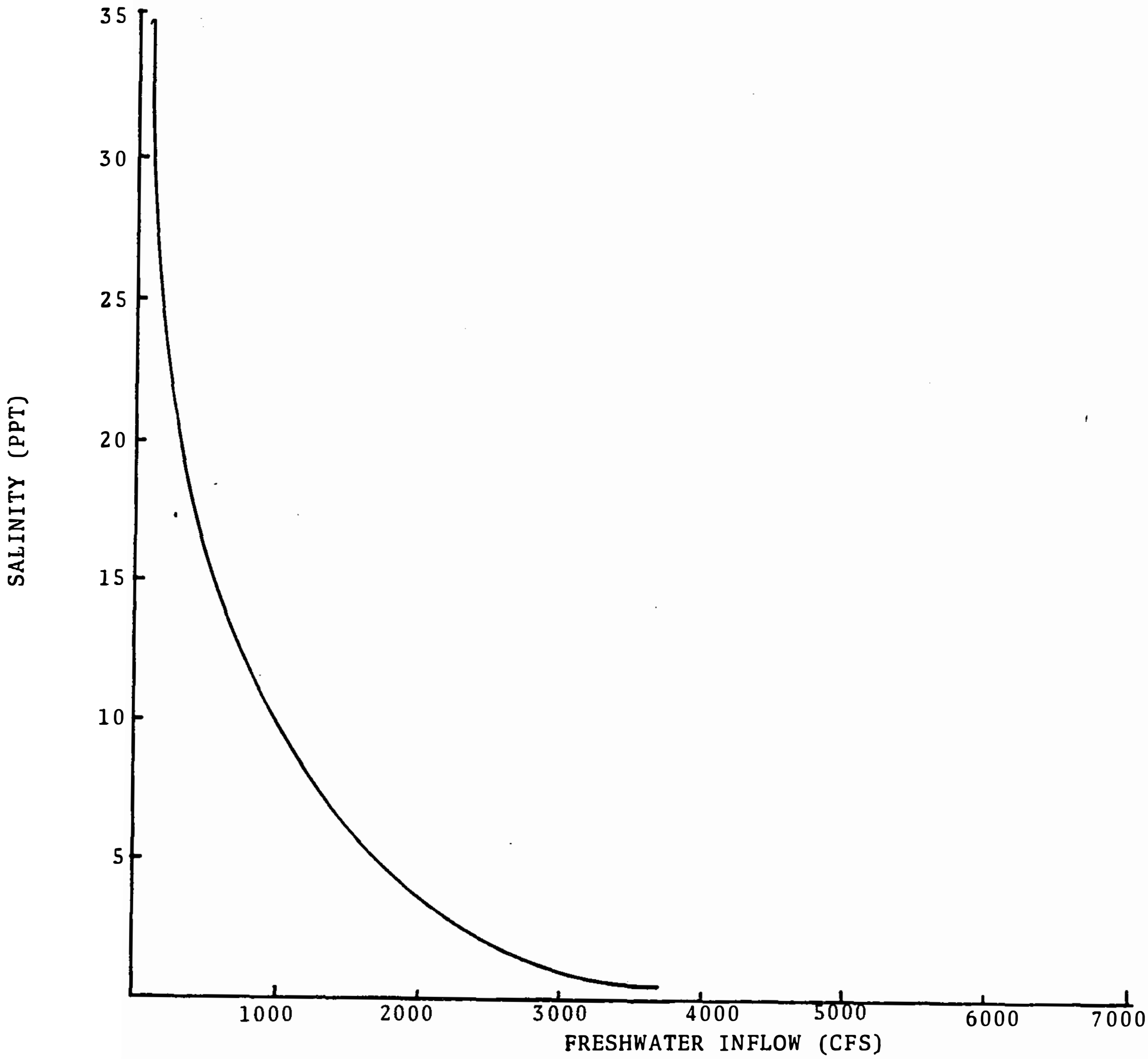


Figure D-5
Guadalupe Estuary - Hynes Bay
Salinity - Inflow

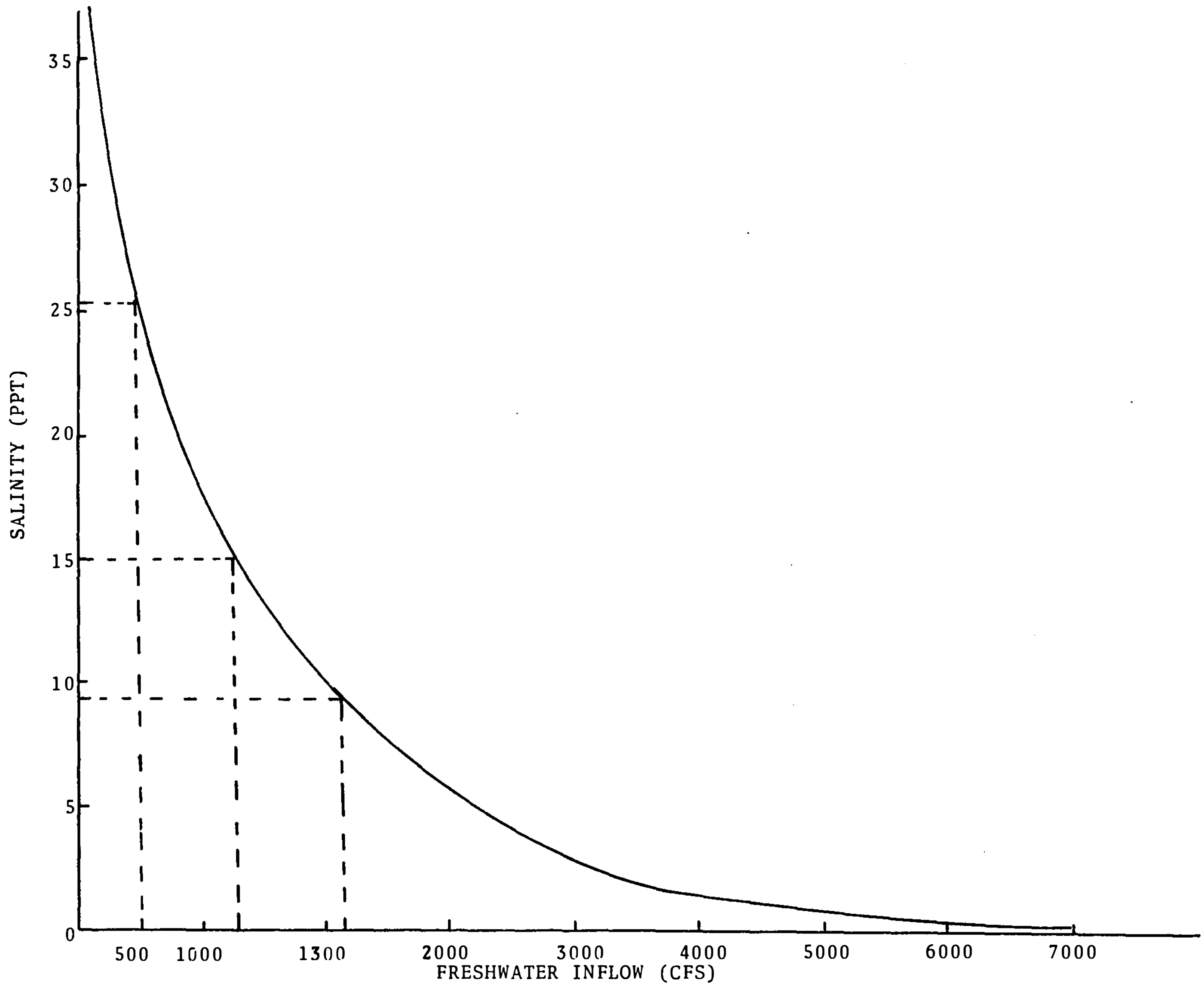


Figure D-6
Guadalupe Estuary - Turtle Reef
Salinity - Inflow

action. Nutrients transported to the Guadalupe Estuary by the Guadalupe River inflow supply the basic building blocks for the estuarine biological communities.

Large volumes of fresh water inflow can be detrimental to an estuary and may "blow-out" the estuarine system. They essentially flush the estuarine system, resuspend and transport sediements, and can cause rapid decreases in standing crop populations of phytoplankton, zooplankton, benthos, and nekton. A substantial "blow out" of the Guadalupe Estuary occurs on an average of once in every ten years. This is the recurrence interval of major hurricanes for this estuarine system. "Blow-outs" can also occur during heavy storm rainfall periods. A "blow-out" will occur in the estuarine system when fresh water inflow exceeds 600,000 acre-feet within a month, based on rainfall intensity, retention time, and Gulf tidal conditions. Recovery of the estuarine system after such an occurrence may be enhanced by the event but is governed by several environmental parameters such as season, temperature, food availability, and future inflows. "Blow-outs" may be considered beneficial over the long-term.

METHOD OF CORRELATION

Aggregation of environmental indicator parameters (inundation, salinity and water temperature) into the migratory organism model (MOM) was accomplished by graphical and statistical analyses of the Guadalupe Estuary. The background development for MOM was lengthly, involving theoretical considerations and statistical development of many parametric relationships. This section will not attempt to cover all areas of research in detail, but rather will discuss the general approaches and results which lead to the development of MOM.

Total Catch versus Total Runoff Analyses

As in many research projects, the initial step was to analyze pertinent data by means of graphical procedures. This analysis evaluated the relationship between annual fresh water inflow and annual commercial white shrimp production. Figure D-7 illustrates a plot of annual commercial white shrimp catch per acre versus annual volume displacement rate for the 1960 through 1971 period. As illustrated in this figure, little apparent correlation exists between these two variables. Similarily, a plot of annual Texas Parks and Wildlife Department trawl sample data for white shrimp and annual displacement rate shows little correlation between these two variables. It became obvious after examining numerous sets of graphs of white shrimp harvest versus air temperatures, water temperatures, and salinities (which are not presented in this text), that the overall relationship was more complex than a two dimensional space. However, the following trends were devevloped from this analysis:

1. Annual fresh water inflow could be quadratically related to white shrimp harvest, that is, there were low shrimp harvests for both "high" and "low" fresh water inlfow years.
2. The seasonal distribution of inflows appears to substantially influence white shrimp harvest.
3. Two distinct annual white shrimp populations are postulated to be a result of the seasonal temperature distribution.

The use of annual statistics does not adequately explain the complex "short term" environmental events which have a direct or indirect effect on white shrimp production. Seasonal temperatures, sudden changes in temperature, and fresh water inflow quantity and temporal distribution can influence white shrimp production. Consequently, a more detailed study was undertaken to relate the response of white shrimp to the antecedent environmental conditions.

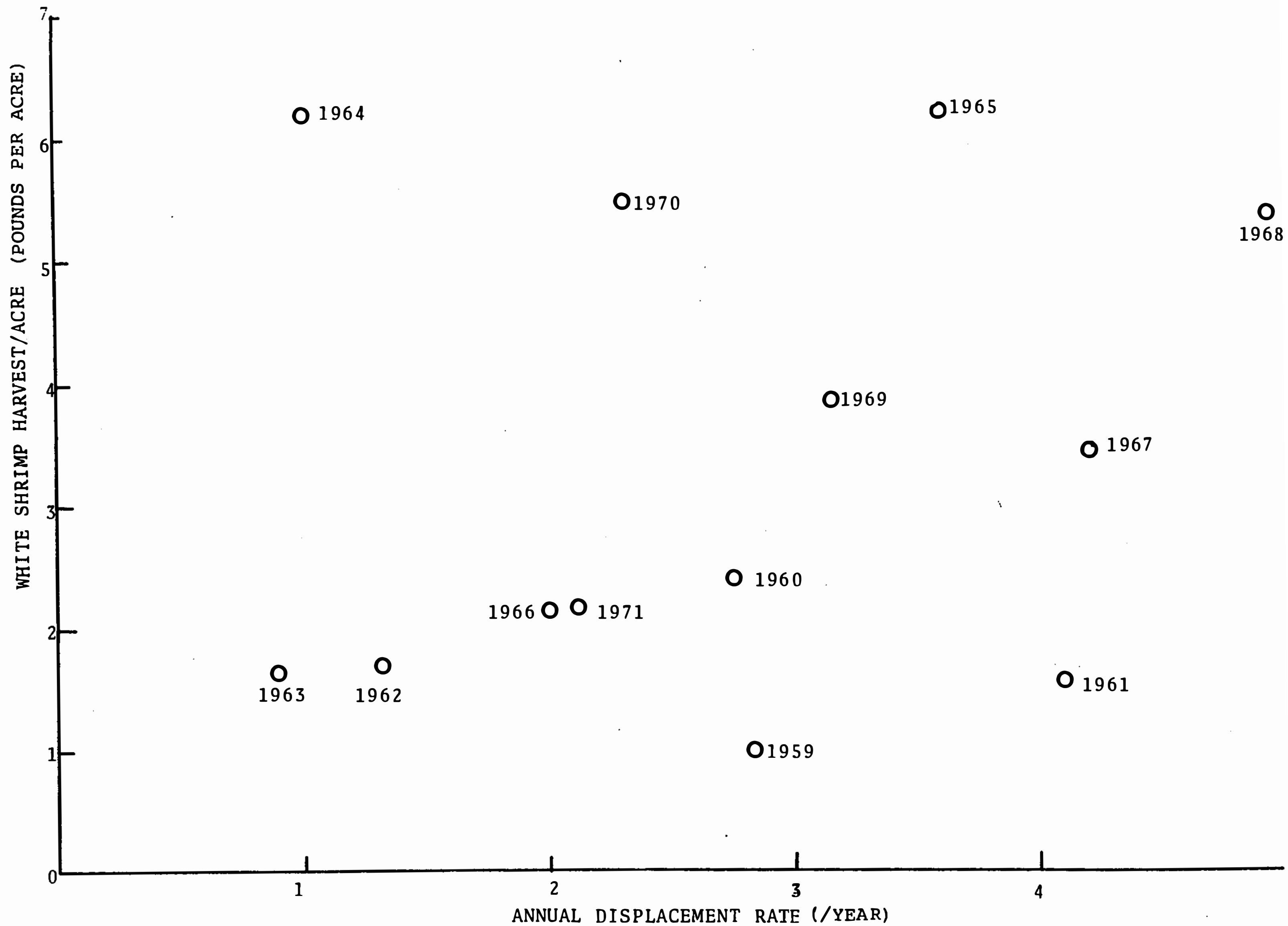


Figure D-7
Guadalupe Estuary
Shrimp Production/Acre vs. Displacement Rate

Monthly Catch versus Antecedent Environmental Condition Analysis

Annual commercial white shrimp harvest in the Guadalupe Estuary has fluctuated widely from a low of 213,000 pounds in 1962 to a high of 888,000 pounds in 1965 (1959-1970 study period). The largest percentage of white shrimp commercially harvested in the estuarine system are caught during the August 15 through December 15 shrimping season. During the 1959-1970 period, white shrimp harvest in September was predominant. Monthly white shrimp harvests for the 1960-1970 decade are shown in Table D-2.

The first step was to investigate the response of commercial white shrimp harvest levels to fresh water inflow quantities. Initially, the commercial white shrimp harvest for the month of September was used as the response variable dependent variable), since analysis of monthly catch statistics revealed that September's harvest was highly related to the total annual white shrimp harvest. Selection of one month's harvest allowed an in-depth study of the "lagging" effect of indicator environmental parameters on the white shrimp harvest.

For white shrimp to be commercially harvestable (39 or less shrimp per pound) in September, they must migrate into the Guadalupe Estuary in their postlarval stage during the previous May or June period. Consequently, the streamflow conditions which occurred during May and June could influence the survival and growth of September's white shrimp harvest. Stepwise regression analyses were performed relating combinations of antecedent monthly inflows to September's catch. A regression equation could not be defined which would explain a significant portion of the variance in the white shrimp harvest. However, the inflow for the months of May and June was related (correlated) to some degree to harvest.

The next process in the analysis was to relate other environmental indicator parameters to September's white shrimp harvest. A data base was developed which included monthly antecedent values for maximum and minimum air temperatures, water temperatures, and fresh water inflow. Due to the dimensional limitations of the stepwise regression computer program, an iterative procedure was initiated to examine these variables and their effect on September's commercial white shrimp harvest. After each iteration, the most significant variables remained in the regression program for the next step. Besides examining the independent variables listed above, over 10,000 linear and quadratic combinations of these variables were evaluated.

The following equation best describes the response of September's white shrimp harvest to indicator environmental parameters:

$$\text{SHRSEP} = -4{,}555{,}300 + 693 * \text{QJUN} - .85 * \text{QJUN}^2 + 33{,}469 * \text{WTNOV}_{-1} + 1{,}430 * (\text{MATJUN} * \text{MATAUG})$$

where SHRSEP = commercial shrimp harvest for September (pounds),

QJUN = gaged fresh water inflow for June (10^3 acre-feet),

WTNOV_{-1} = mean water temperature for November of the previous year (degrees Farenheit),

MATJUN = mean monthly minimum air temperature for June (degrees Farenheit) and

MATAUG = mean monthly minimum air temperature for August (degrees Farenheit).

This equation explained 75 percent of the white shrimp variance with a standard error of about 63,000 pounds.

Probably the most unexplainable or spurious independent variables in the above equation are the water temperature for the previous November and the product of the minimum air temperatures. A two-dimensional plot of these variables versus September's white shrimp harvest reflects a positive linear trend, see Figure D-8, and Figure D-9, respectively. In addition, November water temperatures and the minimum air temperature were the first variables to enter the regression equation; that is, they were initially the most statistically significant parameters. From this analysis, water temperature and air temperature appear to substantially influence commercial white shrimp harvests in the Guadalupe Estuary. This conclusion is logical since the estuarine system is a shallow, temperature responsive system and growth, survival, and migration of white shrimp are governed by temperature as well as fresh water inflow.

The regression equation developed in this phase of the analysis related montly harvests, of white shrimp to various environmental parameters. However, the equation does not fully explain the specific environmental conditions which influence growth, survival, and migration of white shrimp for use in the migratory organism model. In order to use white shrimp as a "key" species to describe the condition of the estuarine system, a different mathematical approach was developed. The regression analysis was valuable for discerning the "intra" and "inter" relationships of the selected environmental parameters and white shrimp harvests.

Conclusions and results developed from this phase of analysis are as follows:

1. White shrimp are sensitive and responsive to ambient and antecedent temperature conditions.

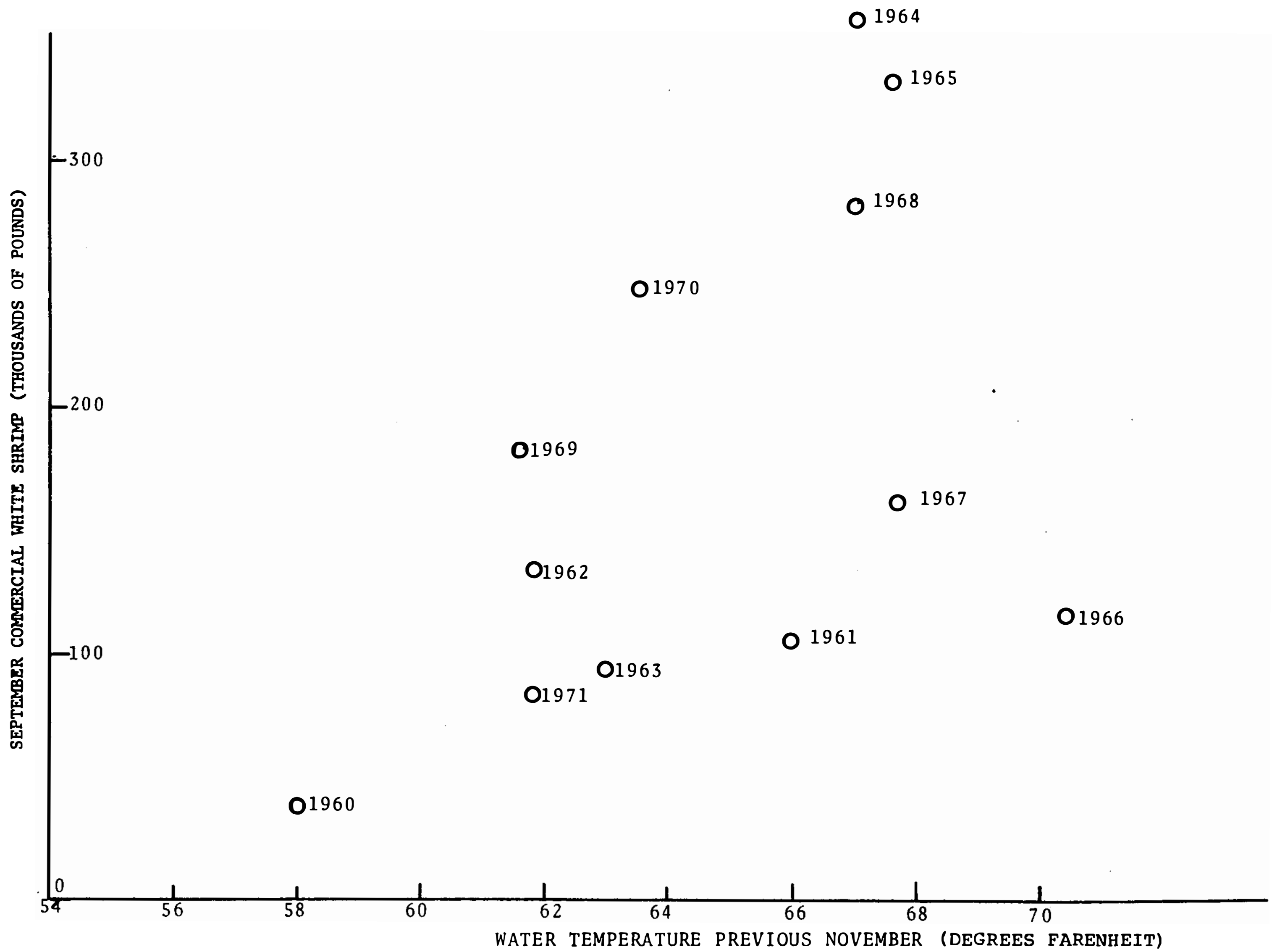


Figure D-8
Guadalupe Estuary
September Shrimp Production vs.
Water Temperature Previous November

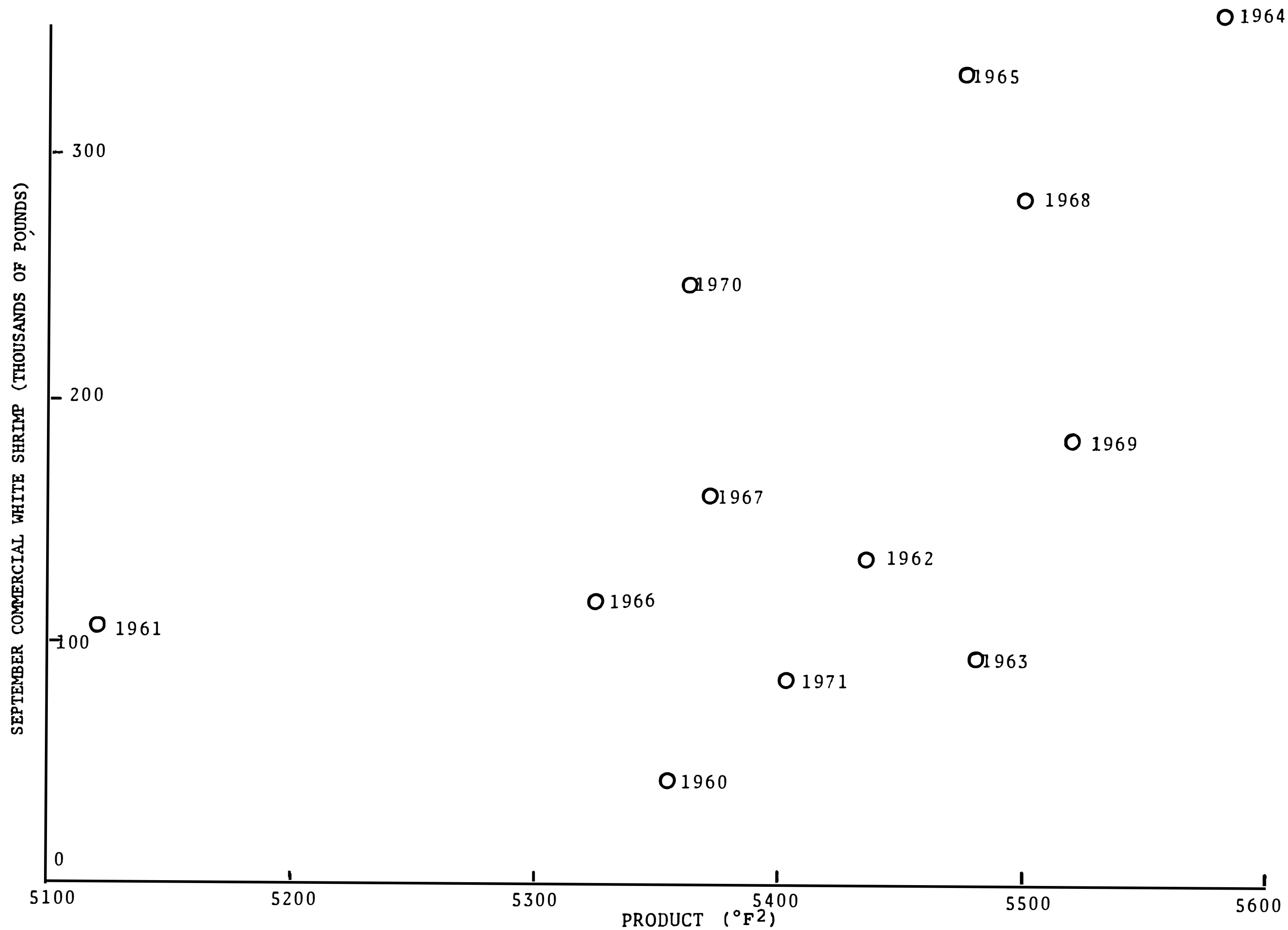


Figure D-9
Guadalupe Estuary
September White Shrimp Production vs.
Product Minimum Air Temperature
August x Minimum Air Temperature June

2. The environmental conditions prevalent in the estuarine system during periods of white shrimp immigration highly influences growth, survival, and eventual harvest of the organism.
3. Environmental parameters, such as temperature, salinity and fresh water inflow may be quadratically related to white shrimp harvest; that is, both extreme high and low levels can result in low production
4. The seasonal or temporal distribution of fresh water inflows, salinity gradients, and temperature regimes are a major determinent of white shrimp growth and survival.

MIGRATORY ORGANISM MODEL

The migratory organism model (MOM) was envisioned and developed from the preliminary data analyses described above and from existing knowledge of interactions of the environmental conditions such as inflows, hydrodynamics, and biological processes of the Guadalupe Estuary. MOM is not a statistical model but rather a "logic" model which evaluates the magnitude and seasonal distribution of important environmental parameters and shrimp physiology into an environmental accounting or scoring program. The environmental accounting procedure and environmental limits used in MOM are calibrated to annual commercial white shrimp harvest data. MOM could also be calibrated to other estuarine species such as red fish and sea trout, but due to time and data limitations for this project MOM was developed only for white shrimp. However, MOM is a mathematical tool which may be helpful in assessing the effects of water resources development projects on estuarine environments, particularly relating to migratory organisms such as the white shrimp.

Assumptions

The following is a list of basic assumptions employed in the initial development of MOM for the Guadalupe Estuary.

1. White shrimp harvests are representative of Penaeus setiferus biomass production.
2. Food is not a common limiting factor, but is regulated by inundation/dewatering process of the contributing wetlands and deltaic marshes.
3. Fresh water inflow serves three functions:
   a) derives the inundation/dewatering, process
   b) provides the transport mechanism for dissolved and particulate biostimulents,
   c) controls distribution of the salinity gradient.
4. Salinity has a physiological effect on white shrimp and is environmentally limiting.
5. Water temperature has a physilogical effect on white shrimp is environmentally limiting.
6. San Antonio Bay system can be regionalized into areas of similar environmental characteristics as illustrated in Figure D-3.
7. White shrimp harvest is substantially governed by the quantity, quality, and distirbution of fresh water inflows, salinity gradients, and water temperature regimes.

Methodology

Salinity and water temperature were compiled from the preliminary data analysis and liternature review to identify some environmental ranges (limits) for fresh water inflow. Environmental preferences of white shrimp vary depending on life stages. The environmental limits vary monthly and seasonally; however, growth and survival limitations of white shrimp caused by ambient conditions of the three selected environmental factors could occur in a shorter time period than a month. Consequently, the monthly environmental limits are evaluated based on responses of the environmental factors over three, 10-day increments per month.

Environmental ranges are assigned to each environmental parameter and distributed monthly from a graphical representation of the 10-day increment data. Figures D-10, 11, and 12 are graphs of 10-day values versus time (months) for fresh water inflow, salinity and water temperatures, respectively. "Good" and "poor" shrimping years are indicated by different symbols. As illustrated in these graphs and except for water temperature, good and poor historical shrimping years exhibit separations or clusters from one another over time. This separation suggests that an environmental difference exists between the good and poor shrimping years. Consequently, lines drawn between the groupings reflect a monthly distribution of corresponding environmental limits or ranges. Months which don't exhibit a defined separation between good and poor shrimping years suggests the corresponding environmental factor does not limit white shrimp growth or survival during these months.

The migratory organism model is an environmental accounting program which computes a "score" for three important environmental factors; fresh water inflow (inundation), salinity, and water temperature. The accounting procedure is used to evaluate the effect of the magnitude and seasonal distribution of the environmental factors on annual commercial white shrimp harvest. A score is computed based on a range of optimal monthly conditions for the three environmental parameters. Each environmental parameter is assigned a set of rante limits and a score for each range. The optimum monthly range for each environmental parameter (as related to white shrimp production) will have the highest assigned score with corresponding lower scores for adjacent ranges.

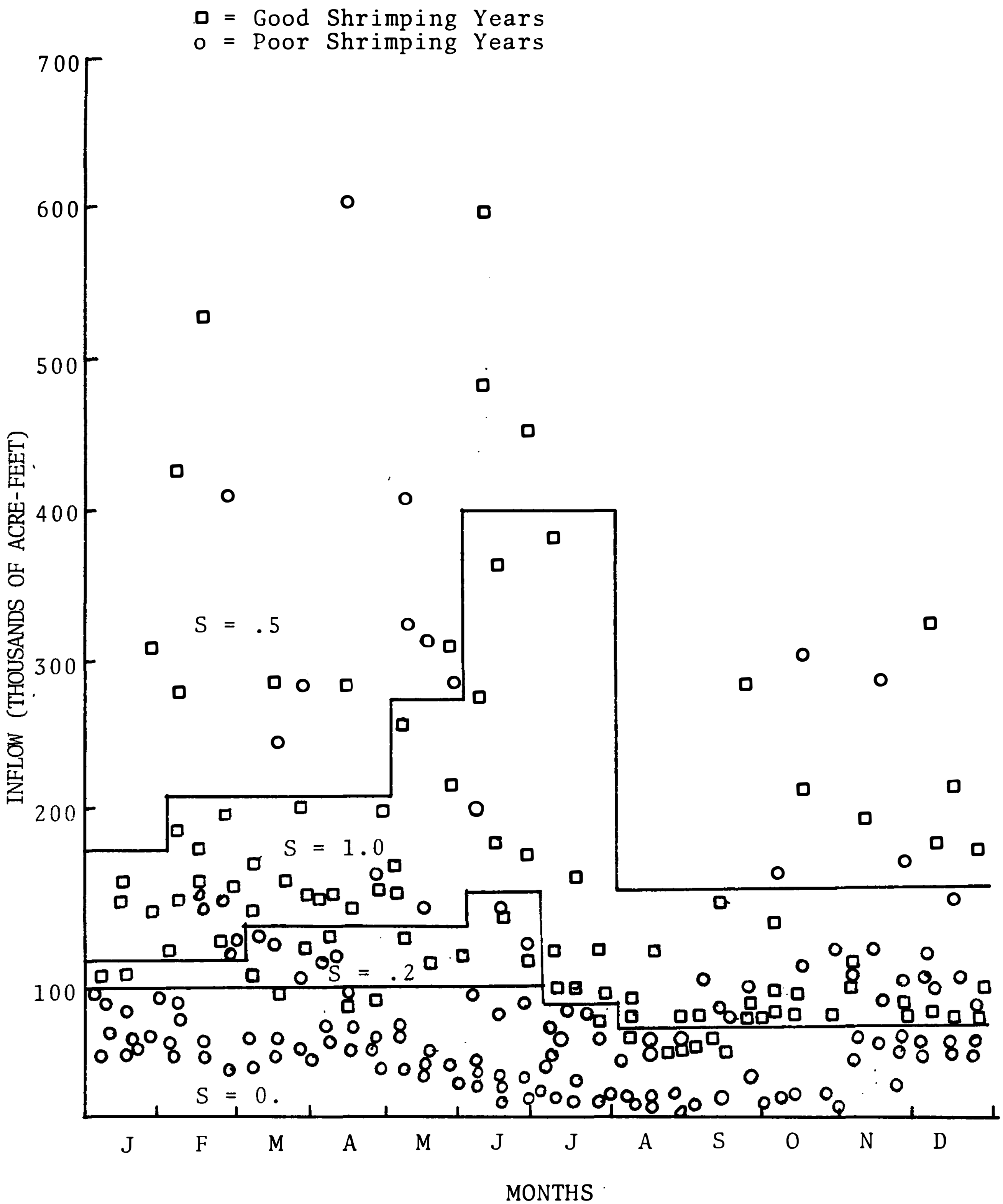


Figure D-10
Fresh Water Inflow
Environmental Limits

□ = Good Shrimping Years
o = Poor Shrimping Years

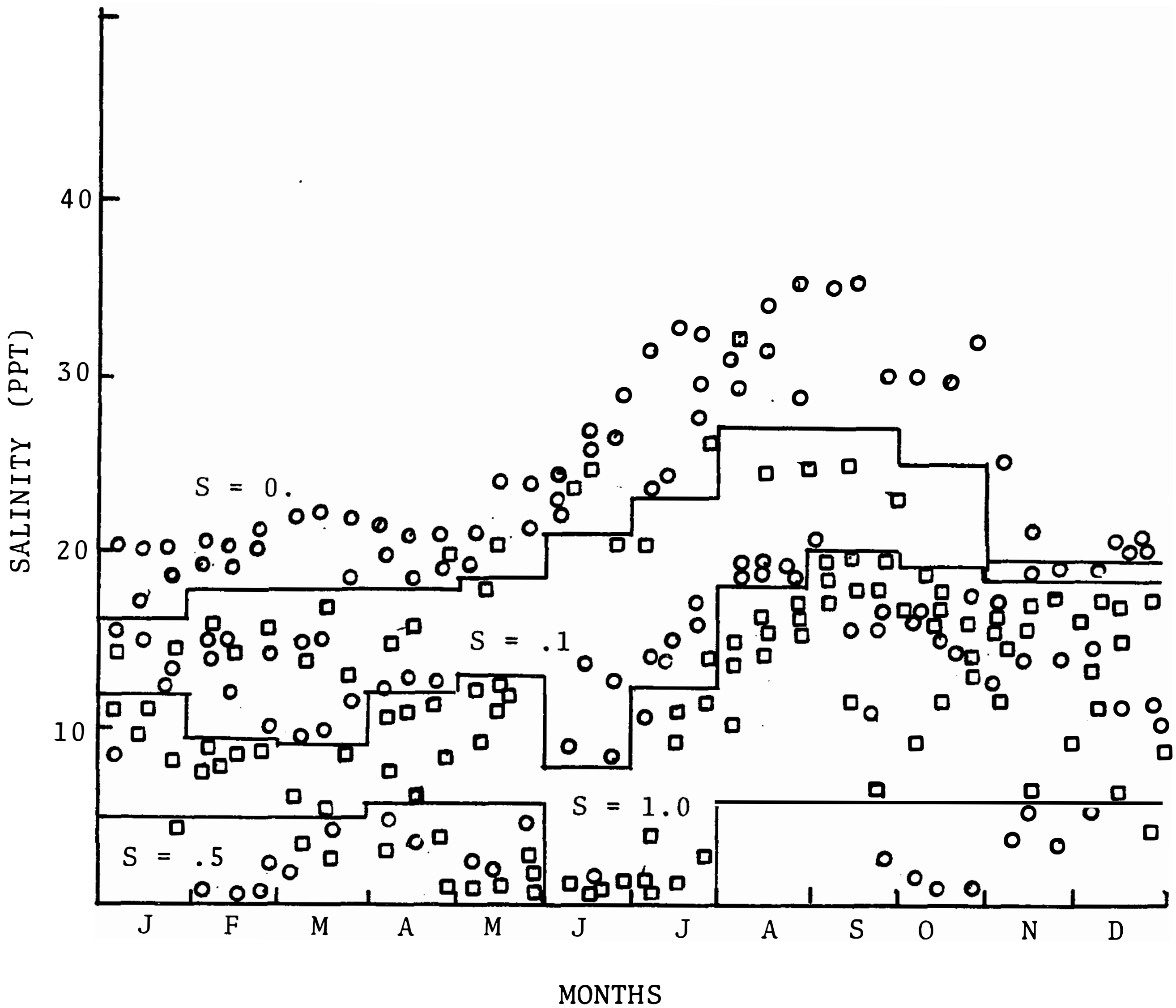


Figure D-11
Salinity
Environmental Limits

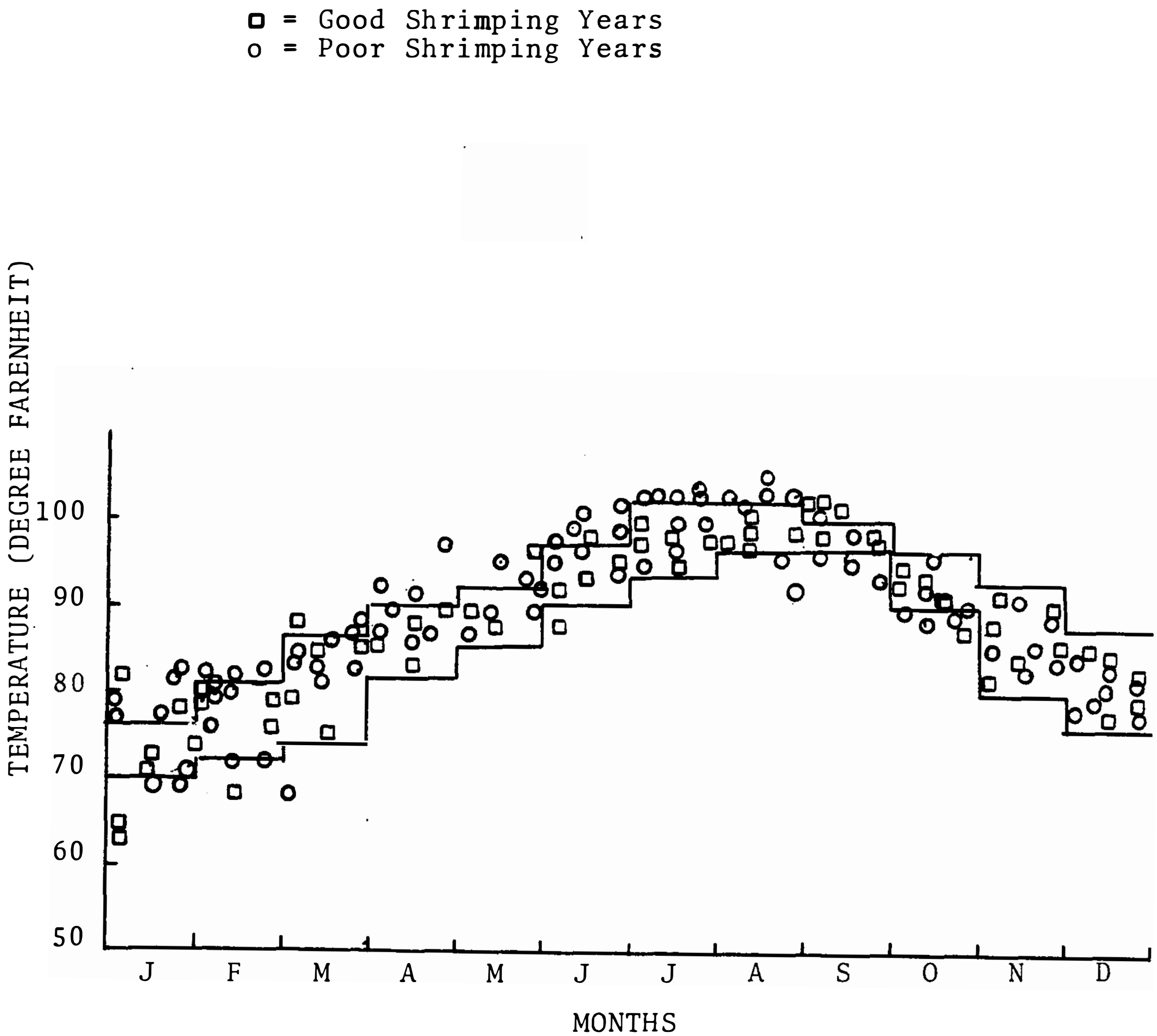


Figure D-12
Temperature
Environmental Limits

MOM is operated daily with a score assigned for each 10-day increment. The score for three consecutive 10-day periods are totaled to yield a monthly score for each environmental parmeter.

MOM operates on a 360 day year, since each defined month has 30 days. The monthly score for each environmental parameter is summed in three ways for evaluation. First, the three monthly environmental parameter scores are added among themselves for each month, to yield a total monthly response score for each parameter. Finally, the monthly response scores are added through time to yield a total yearly response score for the combined three environmental parameters. Consequently, for a given set of conditions for the three environmental parameters a set of response scores can be computed. Higher scores would indicate higher white shrimp production and lower scores would indicate lower white shrimp production. A typical output for MOM is shown in Table D-4.

Scores are assigned to the environmental ranges for each factor through the concept of biological responses. Figure D-13 illustrates this concept. Each factor is assumed to be related to white shrimp harvest as a quadratic function. Extreme low values and high values of a factor can result in reduced shrimp production, whereas, an intermediate factor value may contribute to good white shrimp production. Scores can be assigned to each environmental range for corresponding factors. A score of 1.0 was assigned to "optimal" environmental range. Scores less than 1.0 were assigned to lower ranges. Each corresponding score is multiplied by a weighting factor between 0.1 and 1.0. For months which do not exhibit a defined separation between good and poor shrimping years, (i.e., non-limiting environmental conditions), the score was multiplied by a low weighting factor. However, for months which do have apparent limiting conditions, the weighting factor is assigned a high value of 1.0.

Table D-4
Migratory Organism Model
Output

1962

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEARLY SCORE
INUNDATION	.0000	.0000	.0000	.2000	.2000	1.0000	.0000	.0000	.2000	.2000	.2000	.6000	2.6000
SALINITY	.3000	.3000	.3000	.3000	.3000	.3000	.3000	.3000	1.2000	1.0500	.0000	1.6000	6.1500
WATER TEMP	.1800	1.4000	3.0000	2.2000	2.5000	2.5000	2.5000	.9000	.6000	2.5000	.5000	.1800	18.9600
TOTAL SCORE	.4800	1.7000	3.3000	2.7000	3.0000	3.8000	2.8000	1.2000	2.0000	3.7500	.7000	2.2800	27.7100

1963

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEARLY SCORE
INUNDATION	.0000	1.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.4000	.0000	1.4000
SALINITY	.0000	.1000	.2000	.1000	.0000	.0000	.0000	.0000	.0000	.0000	.5000	.5000	1.4000
WATER TEMP	.1200	2.2000	2.2000	.6000	1.7000	2.5000	2.5000	1.4000	2.2000	1.7000	.6000	.2800	18.0000
TOTAL SCORE	.1200	3.3000	2.4000	.7000	1.7000	2.5000	2.5000	1.4000	2.2000	1.7000	1.5000	.7800	20.8000

1964

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEARLY SCORE
INUNDATION	.0000	1.0000	1.2000	.0000	.0000	1.0000	.0000	1.0000	.2000	.2000	.5000	.0000	5.1000
SALINITY	.0000	.2000	.3000	.2000	.0000	.1000	.1000	.2000	.3000	1.5000	1.5000	1.0000	5.4000
WATER TEMP	.2800	1.7000	3.0000	1.4000	.6000	2.2000	.6000	.6000	.6000	.6000	.6000	.3400	12.5200
TOTAL SCORE	.2800	2.9000	4.5000	1.6000	.6000	3.3000	.7000	1.8000	1.1000	2.3000	2.6000	1.3400	23.0200

1965

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEARLY SCORE
INUNDATION	.5000	2.0000	.4000	.4000	1.5000	2.5000	2.0000	1.0000	.0000	.5000	.5000	.4000	11.7000
SALINITY	.1000	2.0000	1.1000	1.2000	1.6000	3.0000	2.1000	2.1000	2.1000	1.5000	1.5000	1.2500	19.5500
WATER TEMP	.1800	3.0000	2.5000	3.0000	3.0000	2.5000	2.2000	2.5000	2.2000	.6000	.5000	.1800	22.3600
TOTAL SCORE	.7800	7.0000	4.0000	4.6000	6.1000	8.0000	6.3000	5.6000	4.3000	2.6000	2.5000	1.8300	53.6100

1966

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEARLY SCORE
INUNDATION	.6000	2.0000	1.4000	.7000	.9000	2.0000	1.0000	.0000	.4000	.6000	.0000	.0000	9.6000
SALINITY	2.1000	.3000	.3000	2.1000	1.5000	.3000	.3000	1.2000	3.0000	1.5000	.6000	.0000	13.2000
WATER TEMP	.1800	1.4000	3.0000	2.2000	1.7000	3.0000	1.7000	2.2000	.6000	2.2000	.6000	.6000	19.3800
TOTAL SCORE	2.8800	3.7000	4.7000	5.0000	4.1000	5.3000	3.0000	3.4000	4.0000	4.3000	1.2000	.6000	42.1800

1967

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEARLY SCORE
INUNDATION	.0000	.0000	.0000	.0000	.0000	.0000	.0000	1.0000	.2000	.3000	.4000	.6000	2.5000
SALINITY	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	1.6000	.7500	1.0000	1.5000	4.8500
WATER TEMP	.1200	1.4000	2.5000	1.7000	1.4000	2.5000	3.0000	1.4000	.9000	.6000	.6000	.4400	16.5600
TOTAL SCORE	.1200	1.4000	2.5000	1.7000	1.4000	2.5000	3.0000	2.4000	2.7000	1.6500	2.0000	2.5400	23.9100

1968

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEARLY SCORE
INUNDATION	1.5000	2.5000	3.0000	2.5000	2.5000	2.5000	3.0000	3.0000	.5000	.6000	.6000	.4000	22.6000
SALINITY	1.6000	1.5000	2.5000	2.0000	1.5000	3.0000	3.0000	3.0000	3.0000	1.5000	1.5000	1.5000	25.6000
WATER TEMP	.1800	2.2000	3.0000	3.0000	2.2000	2.0000	1.2000	.6000	.6000	1.7000	.6000	.3400	17.6200
TOTAL SCORE	3.2800	6.2000	8.5000	7.5000	6.2000	7.5000	7.2000	6.6000	4.1000	3.8000	2.7000	2.2400	65.8200

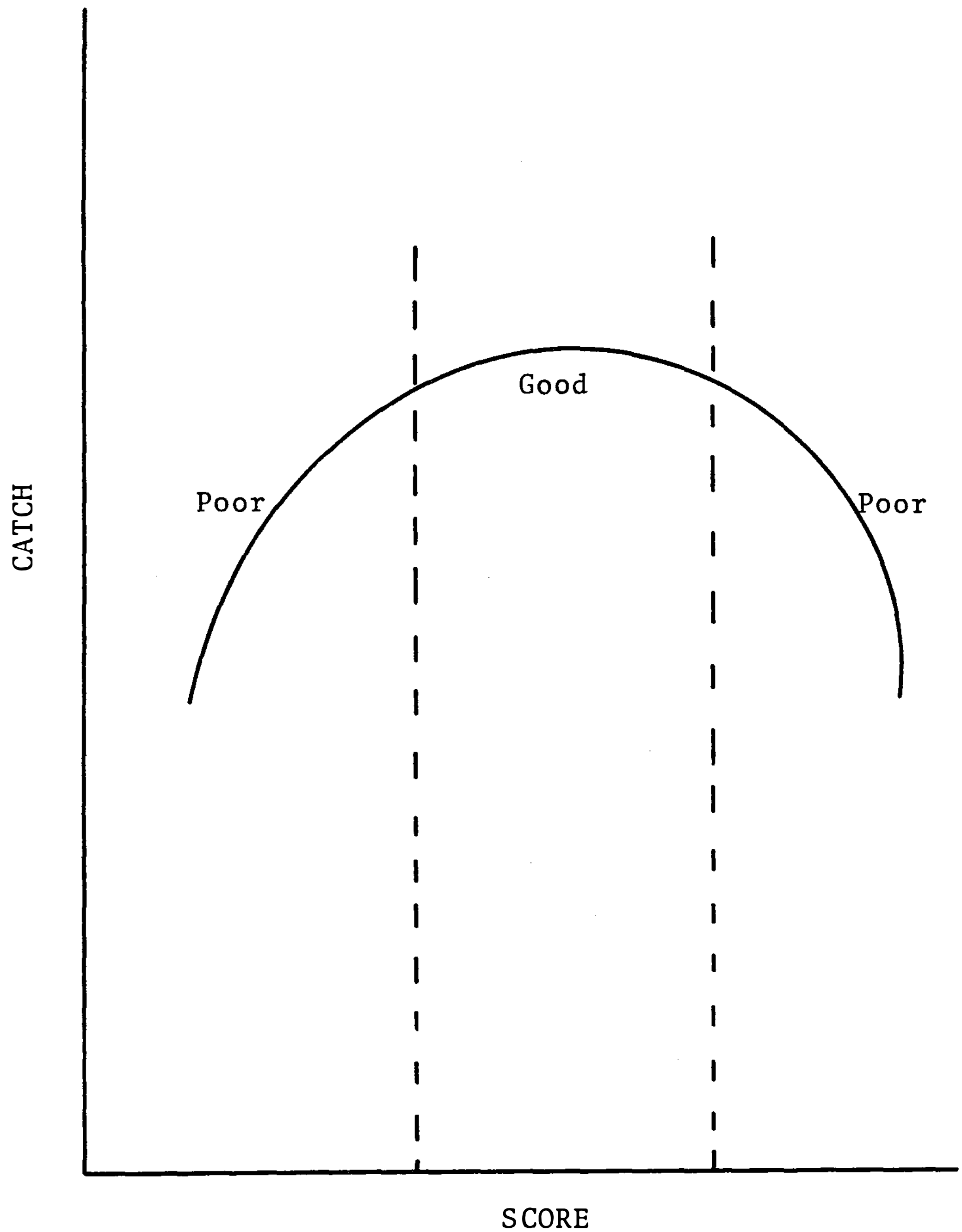


Figure D-13
Concept of Biological Response

Model Calibration

The adjustment of environmental limits, scores, and weighting factors, (i.e., model coefficients), were performed manually through a trial and error procedures. Iterative computer runs of MOM were performed. After each iteration invividual yearly and total yearly environmental factor scores were plotted against corresponding white shrimp harvest. This procedure was repeated until the "best-fit" curve could be obtained by adjusting the model coefficients.

The calibration of MOM was performed for the 1962-1970 period. The calibrated results obtained for this period are shown in Figure D-14, 15, and 16 for fresh water inflow, salinity, and water temperature, respectively. The figures show a graph of corresponding annual scores versus white shrimp harvest. As illustrated in these figures, 1962, 1963, 1966, 1967, 1968, 1969, and 1970 scores lie on a smooth curve, whereas, 1964, 1965, and 1967 do not relate to the curve. The years of 1964 and 1965 were probably the most unexplainable non-fit years, having a high white shrimp harvest but relatively low environmental scores. This may be due in part to environmental influences which MOM does not presently evaluate such as food availability, economics, or source data inaccuracies. The good white shrimp harvest and low environmental score for 1967 may be related to Hurricane Beuliah which hit the San Antonio Bay system on September 18-23, 1967. Extremely flooding and high fresh water inflows resulted in poor inflow and salinity conditions, significantly lowering the environmental score computed by MOM for the later months of 1967 and causing this point lie off of curve. Such catestrophic events are apparently not handled adequately by the Model.

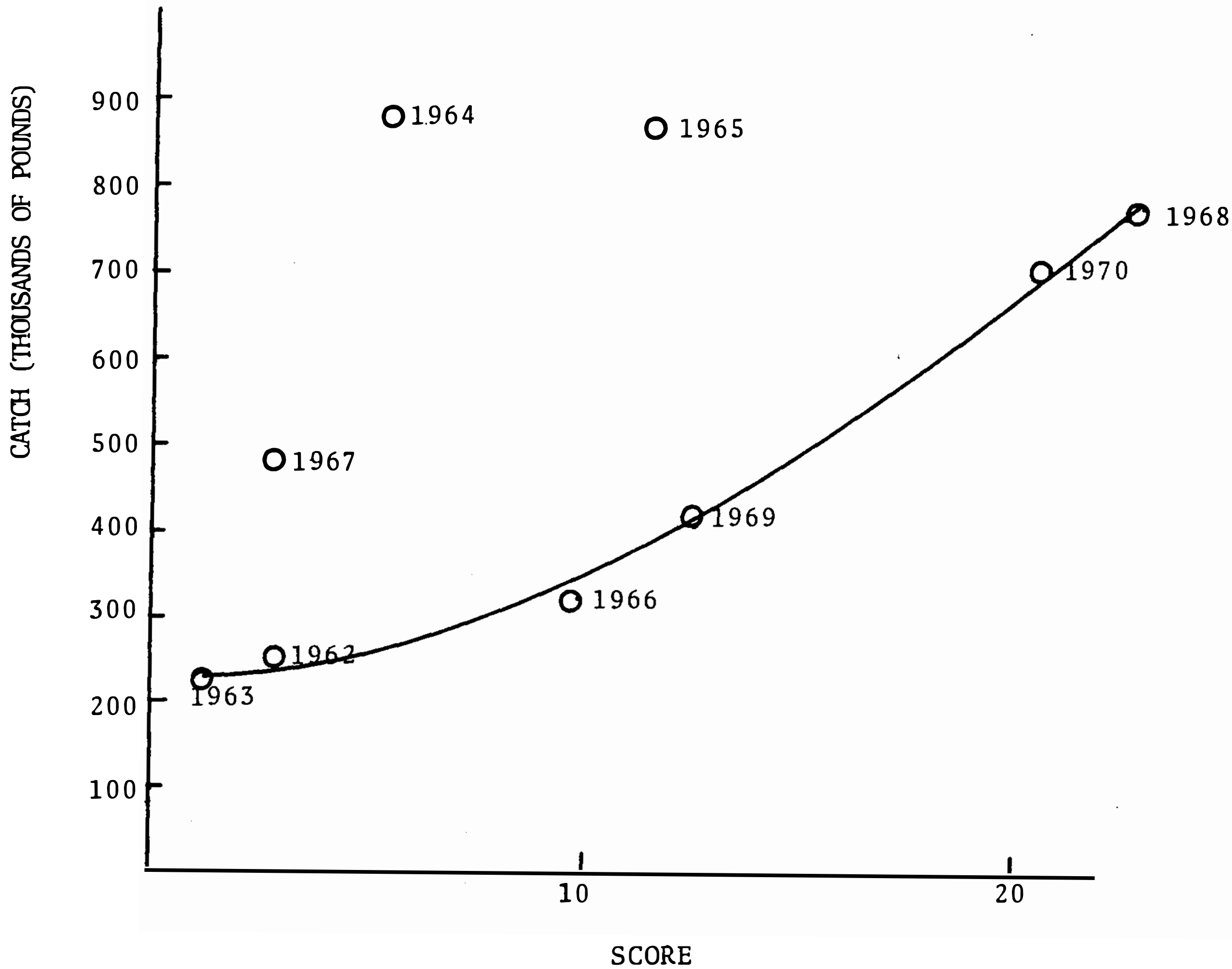


Figure D-14
Fresh Water Inflow
Environmental Score

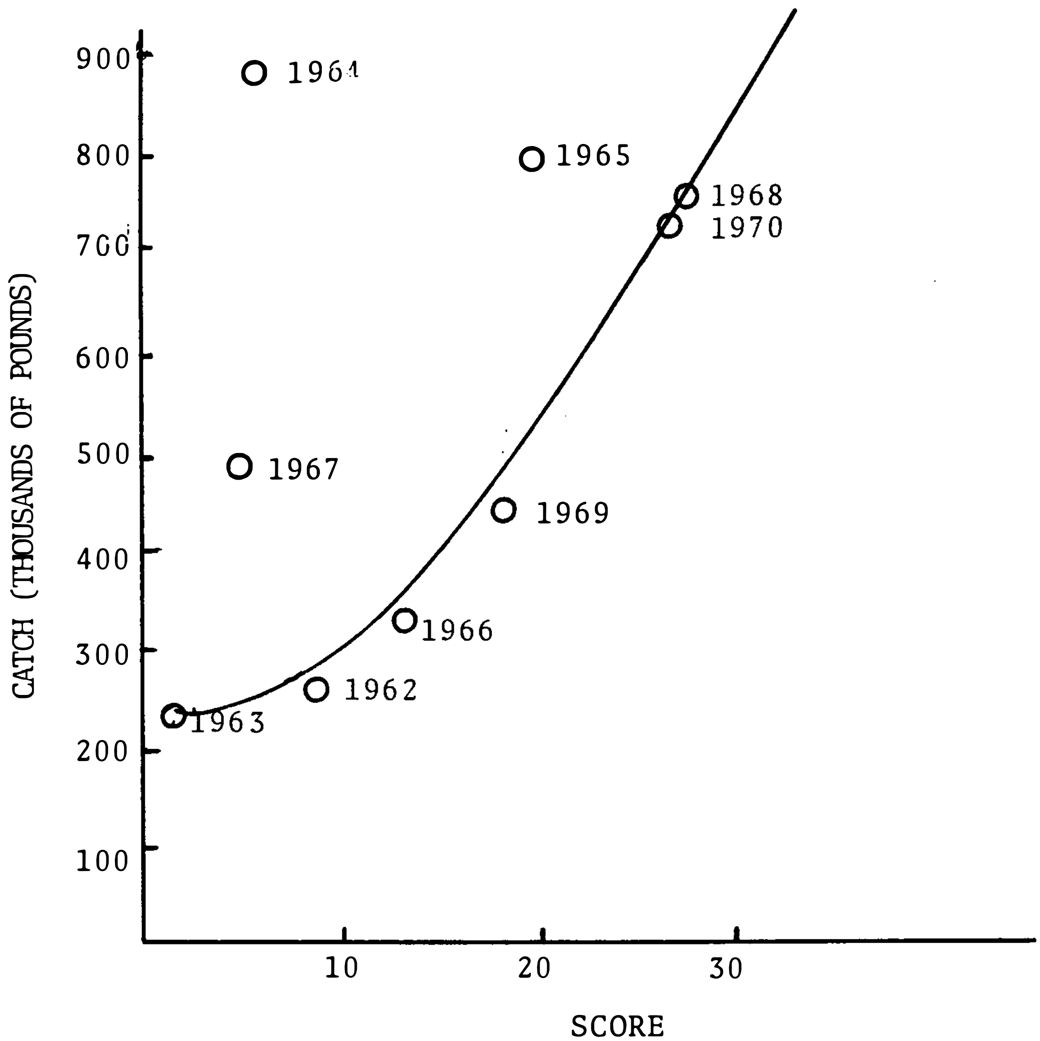


Figure D-15
Salinity
Environmental Score

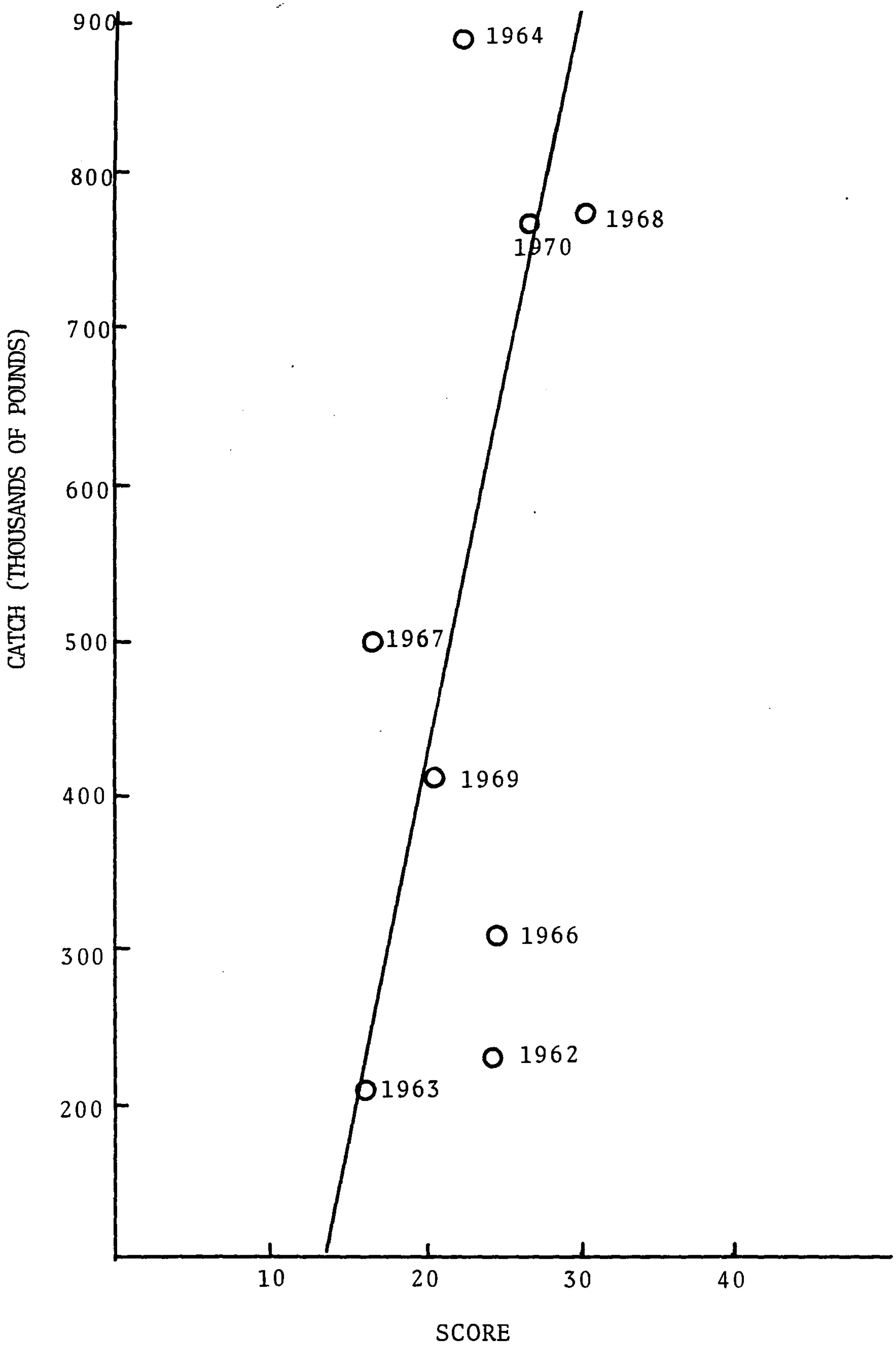


Figure D-16
Maximum Temperature
Environmental Score

Calibration of MOM in the manner generally describes historical white shrimp harvests in relationship to selected environmental parameters. The individual environmental score curves shown in Figure D-14 through 16 are similar in shape and form. Consequently, these environmental factors appear to have a reasonably balanced influence and response in MOM; that is, one parameter is not over weighted as compared to another.

Relationship of MOM to ESTECO

The migratory organism model (MOM) was developed to evaluate the response of estuarine white shrimp production to selected environmental parameters. The estuarine ecological model (ESTECO) primarily evaluates the interactions between environmental parameters and lower trophic level organisms, such as plankton and benthic organisms. The nekton portion of the estuarine ecological model classifies all estuarine fish species into three groups; one group feeds on planktonic organisms, another on benthic organisms and the last ground feeds on other fish. The estuarine model estimates the immigration and emigration of the total estuarine nekton population by externally adjusting the fish harvest coefficients for each appropriate season. MOM is an independent model which operates parallel to ESTECO for simulating the production of migratory organisms. Environmental parameters which are used in MOM are also common to the estuarine ecological model. Environmental responses obtained from the estuarine ecological model and MOM can be used interactively between both models to evaluate the effect of environmental responses on immigration and emigration cycles, fish harvests, and estuarine production. Linkage between ESTECO and MOM is presently external. Responses inturpreted from MOM under a given set of environmental conditions can be externally adjusted for input into ESTECO. It is a research goal of the Board to "hard-link" both models together by using a set of mathematical equations. With future operation of both models under common conditions, knowledge of the interactions between both models will increase and may allow for confident mathematical linkages.

Mathematical linkage between MOM and ESTECO could possibly be accomplished through the use of common factors (e.g., an environmental factor and a food factor). An environmental factor of salinity (total dissolved solids) is presently common to both models and equations have been developed for each region of the Guadalupe Estuary which can be used as a common link. It will be considerably more difficult to develop a "hard-link" for the food factor (e.g., carbon) due to the lack of a long-term, historical nutrient data base for the estuarine system. However, recent estuarine sampling programs have collected nutrient data. Consequently, the near future offers the possibility of sufficient nutrient data for developing a food factor linkage. In the meantime, further development of the models and refinement of response accuracy will be necessary before full scale utilization for planning and and management purposes can be realized.