SEMINAR PROCEEDINGS:

FRESHWATER AND THE FLORIDA COAST:

SOUTHWEST FLORIDA

Editors:

William Seaman, Jr.
Richard McLean

OCTOBER 1977

SWFWMD
REPORT NUMBER 1977-1

Sea Grant
REPORT NUMBER 22

FRESHWATER AND THE FLORIDA COAST:

SOUTHWEST FLORIDA

Proceedings of a Seminar for the

SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT

May 26-27, 1977

Tampa, Florida

Report Number 1977-1

Coordinated by the

STATE UNIVERSITY SYSTEM OF FLORIDA

Sea Grant College Program

Report Number 22

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Background

Florida's population of 8.5 million is expected to reach 13.5 million by the year 2000. As the nation's fastest growing major state, Florida offers amenities that lure three-fourths of its new residents to the coastal zone, with just 16 of the state's 38 coastal counties supporting 70% of the population. In addition, nearly 30,000,000 tourists visit annually, with prime attractions including beaches and sports opportunities ringing the state's 1300-mile coastline.

In this setting, a variety of water uses have felt increased pressures--all the way from drinking water supplies in the uplands down to the production of fisheries in the coastal salt marshes and lagoons. In an attempt to reconcile the many water uses essential to different sectors concerned with economic, engineering, biological and other points of view, the seminar "Freshwater and the Florida Coast" was conducted. Specifically, it was organized to address questions that water management authorities face on both a daily and a long-term basis. Questions such as "What is the role of freshwater in estuaries?, Is freshwater 'lost' if it runs to sea?, How much water can be removed upstream and still sustain estuarine systems?".

Seminar participants also had a variety of secondary questions that reflected their diversity of backgrounds from consulting firms, planning and regulatory agencies, research laboratories, and the general public. They were interested, for example, in both past research findings and future planning and research needs in the Southwest Florida Water Management District. A seminar evaluation mid-way through the program helped to identify some of these points and allowed panelists the opportunity to address them.

Specific concerns of the District that motivated the seminar, and which were expressed in a charge to the participants, included the need for fiscally sound guidelines and assurances that scientific research expenditures would lead to constructive recommendations (that are not content to solely call for more study of the problem). Nor was a simple or generalized characterization of basin water needs and problems desired. Rather, guidelines and recommendations -- "tools to do the job" -- were sought.

Proceedings Format

This volume contains the formal presentations made. The remarks of the panel chairmen and summary speaker are not given verbatim, but highlights are integrated into one summary.

Workshops

After all presentations, participants assembled in three workshop groups to devise guidelines for water flow in the Anclote and Peace River drainages. As a reference point, participants were given three conditions to meet in establishing levels of freshwater flow into estuaries of the central west Florida coast. The conditions were to (1) maintain current "environmental productivity" of the estuaries, as exemplified by present commercial and sport fisheries; (2) stop saltwater intrusion, with primary emphasis on surface water; and (3) achieve the freshwater flows at minimal cost to citizens in the District over the next 50 years. Consequently, it was necessary to consider volume of water flow to sustain the fisheries, consequences of over-consumption of water upstream, and alternatives if goals would not be met.

Highlights of Presentations

The Southwest Florida Water Management District extends south from the Withlacoochee River Basin to the Peace River Basin, thereby including parts of Levy through Charlotte Counties along the Gulf of Mexico coastline (Figure 1, page 5). It includes the Tampa Bay metropolis as well as vast agricultural acreage inland, plus major phosphate, industrial, and other urbanized areas. Present demands for freshwater within District boundaries include domestic use, 300 million gallons per day (MGD); agricultural, 485 MGD; and industrial 400 MGD, the latter figure reflecting recent technological improvements and recycling. Potential demands for the year 2020 are projected at 980 MGD domestic; 860 MGD agriculture; and 220 MGD industrial. Population will more than double in the next 45 years, increasing from 2.3 to 4.9 million.

Urbanized and developed areas now cover about 7.5% of the District's approximately 10,000 square miles, whereas cropland and pasture cover 23%; rangelands, 20%; wetlands, 18.5%; forest, 15%; water, 3%; and mines, 2%.

The District, administratively, has five priorities: flood control; flood plain delineation (descriptive, not regulatory); regulation of consumptive water use and well construction; conservation; and water management planning. It has a three-phase estuarine project underway, the first phase being a literature search and analysis that is published separately and concurrently with this report.* The second phase is the seminar herein reported, to assemble some of the tools needed to decide on quantities of freshwater that might be diverted from an estuary. Based on the seminar, a third phase is the implementation of water plans that will sustain certail goals for estuarine productivity. By law the District addresses water quantity, whereas water quality is addressed by the Florida Department of Environmental Regulation through such authorities as the U.S. Environmental Protection Agency and section 208 of the 1972 National Water Quality Act. The District is one of five in the state.

*Snedaker, S.G., and D. de Sylva et al. 1977. Role of Freshwater in Estuarine Ecosystems. Volume 1--Summary; Volume 2--Abstracts, University of Miami; prepared for the SWFWMD, SWFWMD Planning Report 1977-2.

The subtropical climate of the District is characterized by a summer rainy season that contributes over half of the annual rainfall, which exceeds 50 inches. Evapotranspiration averages 39 inches per year, while runoff ranges from zero to 20 inches annually. Runoff is less in the northern part of the District, which geologically is a simple layering of surface sands, underlying clay, and a thick limestone formation that contains the Floridan Aquifer. South of the Hillsborough River the valuable Aquifer is a more complex assemblage of clay lenses and limestone.

Leaving the Central Highlands, surface drainage flows from elevations of 300 feet through a series of marine terraces and Coastal Lowlands and into a series of shallow coastal marshes and lagoons that are increasingly characterized by mangrove trees in the southerly parts of the District. Salinity of the estuaries varies not only with wide seasonal fluctuations in river flow, but also it may be influenced locally by large groundwater discharges (i.e., coastal springs and seepage).

As generally well-documented for estuaries, the fertile coastal bays, marshes, and grassflats of the District also sustain a high level of fisheries production that is estimated at levels of $5 million commercially (dockside) and perhaps as much as $270 million for sport fisheries. Freshwater runoff dilutes salt water and creates a variety of habitats along salinity gradients, while introducing nutrients into the food web that produces up to 85% of the economically important marine species. Thus, habitat, protection, and fuel for both the plankton-grazing and the detritus-based food chains are provided through runoff.

Runoff patterns altered by development and drainage accelerate flows and increase their amplitude, whereas decreased flows are caused by some well withdrawals. These altered patterns affect estuarine circulation, stratification, mixing, dissolved oxygen and other factors, thereby controlling fish distribution and transport, predation, and food supply, Besides direct use of estuarine habitat for purposes such as spawning or nursery grounds, fisheries may less directly "use" estuaries as in the case of wide-ranging oceanic stocks such as king and Spanish mackerel that feed on estuarine dependent fishes such as menhaden once they move offshore.

Other estuarine functions important to man include the buffering of hurricane and storm effects, and assimilation of some wastes. Other consequences of low flow include: saltwater intrusion in coastal groundwater and surface water; possible release of heavy metals when benthic substrates become anaerobic; salt tolerant mosquito populations may increase; schistosomiasis may develop; erosion of downstream shoals as renourishment of sand or silt ceases; and possible changes of coastal circulation. (See reference footnoted on p.2.) Each consequence may carry a cost to coastal citizens and communities, such as artificial renourishment of eroded coastal barrier island beaches. Conversely, increased freshwater discharge has resulted in localized sediment deposits that interfere with harbor traffic.

In partially mixed estuaries on the East coast of the United States one unit of freshwater inflow commonly induces about nine units of seawater to circulate through the estuary. The magnitude of estuarine circulation is therefore very sensitive to any change in freshwater inflow caused by retention, diversion or consumptive water use. A variety of mathematical procedures now exist to describe, explain, and predict such events.

For example, analytical and numerical models are used in predicting responses of groundwater, surface water, and biological systems to natural and urban influences. They are applied practically to such situation as design of seepage ponds to enhance groundwater recharge, or to predict the flow of groundwater seaward to maintain a salt-freshwater interface in coastal groundwater supplies. For surface waters, a variety of models for urban and nonurban basins, and rivers and estuaries have been evaluated and verified and are available at low cost. They are employed to estimate peak flows, design storage facilities, and even to establish flow augmentation for purposes of maintaining dissolved oxygen levels.

Similarly, the performance of economic and biological systems can be predicted but in all these situations there should be clear procedural guidelines. To an extent, the natural systems can be categorized either according to the degree to which they may be stratified, partially mixed, or vertically homogeneous water bodies, or in terms of plant life and bases of the food web which may include salt marsh, phytoplankton and mangrove forest in areas of the District. Indeed, such classification is viewed as a first step in putting scientific analysis to work in water management. In this way, a basic feeling for the sensitivity of the system is developed. Then, attention can be focused on specific aspects of an estuarine drainage as might be done in identifying input and removal points for water prior to stating the biological consequences of changed salinity gradients.

The social and institutional framework in which the techniques discussed in the seminar papers are applied must be understood so that the causes of possible water use conflicts, and not the symptoms, are ultimately addressed. Part of this framework includes a clear statement of management goals, and the recognition that in some situations management responsibilities may be too fragmented. Scientists can generate numbers and procedures for meeting the goals, and contribute to their formulation, but the decision-making authority is responsible for setting priorities.

In the case of the estuarine drainages of Southwest Florida, substantial information exists. Although much of it is unpublished, it is available through several organizations and individuals. These sources should be consulted, possibly in a small workshop format, prior to major new estuarine research on flow by the District. Although the approach might be on an estuary-by-estuary basis, possible generalizations might be useful for District-wide planning.

Indeed, various overviews and generalizations are possible, for instance in characterizing the ways water is valuable as a transport medium, a chemical reactant or physical component, or perhaps as an information bearer. Working at the level of the whole system, we see that individual parts may change while overall characters do not. For example, a shift in fisheries species while total poundages remain constant.

With an understanding of the economic, hydrodynamic, and biological systems, scientists will contribute to water management not just through recommendations on timing, sources and consequences of flow regimes, but also through innovative ways to alter those demands. Technology for water recycling and storage is just part of an approach to environmental engineering that portends the design of new systems. In the accelerated pace of urbanization in the District, those privy to such technological skills are more inclined to contribute their knowledge even when the confidence levels do not approach the 99 percent desired. The papers in this volume provide a basis for some of those contributions.

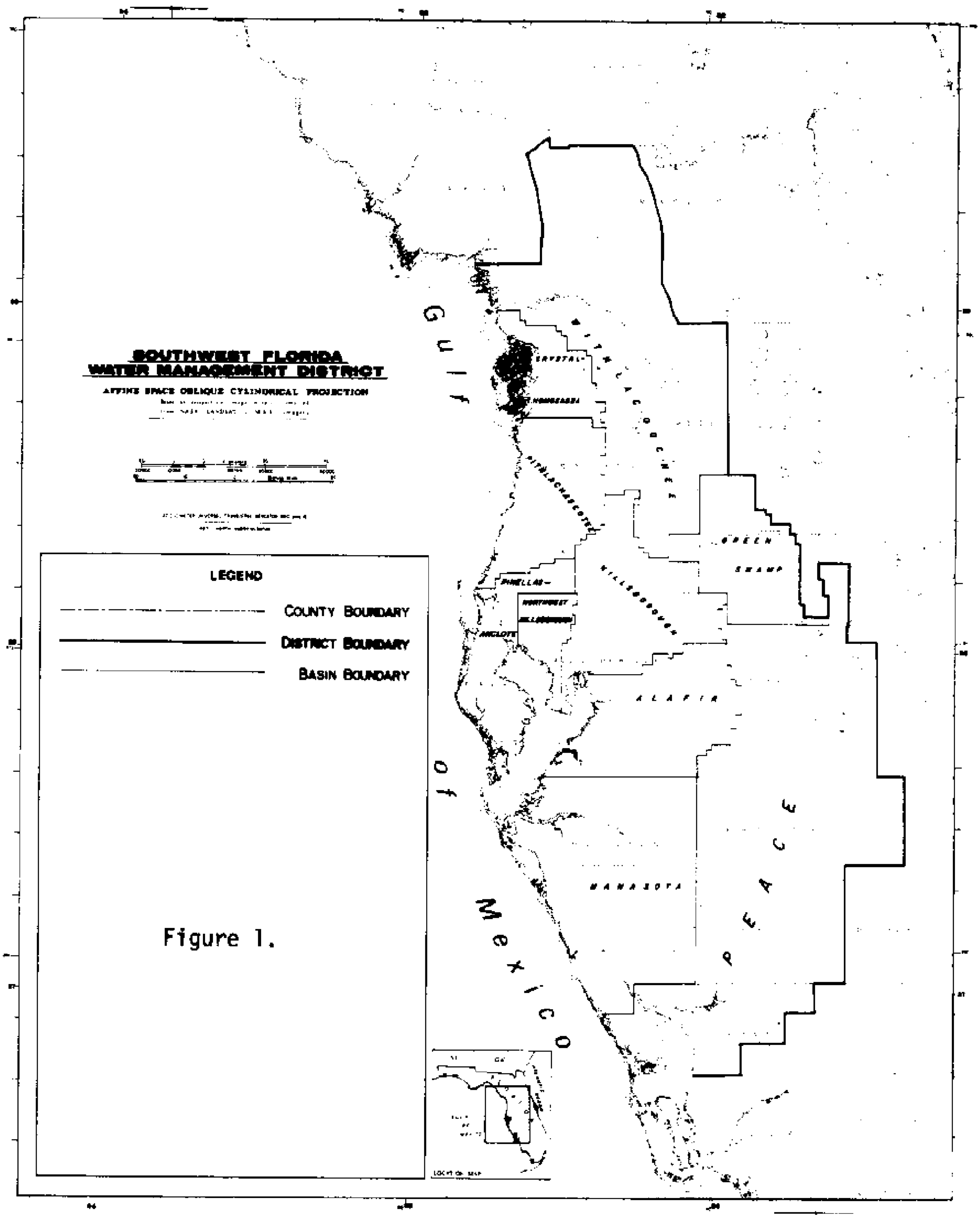

Figure 1.

GENERAL DESCRIPTION AND WATER REQUIREMENTS OF SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT

by

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John R. Wehle[2]

1. INTRODUCTION

The SWFWMD encompasses nearly 10,000 square miles on the west coast of penisular Florida. It extends from the Withlacoochee River Basin on the north to the Peace River Basin on the south, and westward to the Gulf between these two major river systems. The District covers all or part of 16 counties and includes the Tampa-St. Petersburg-Clearwater metropolitan area, the Sarasota-Bradenton, Punta Gorda-Port Charlotte, and Lakeland-Winter Haven urban complexes, and numerous smaller communities. These communities, as well as agriculture, mining, recreation, and industry and the desire to preserve and maintain natural habitats, place heavy demands on the District's water resources.

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NOTE: Much of the information in this paper has been adapted from Draft II - Southwest Florida Water Management District Water Use Plan. The authors wish to express our appreciation to our colleagues on the District Planning Staff who originally developed much of this material. Special recognition is extended to John Thompson, John Rickerson, Nick Nichols, Rich McLean, Fred Hafer, and John Bowers.

As a result of widespread flooding in 1960 which had caused numerous deaths, injury to hundreds of people and damages totalling nearly $220 million throughout the State, the Florida Legislature established the SWFWMD the following year (1961 - Chapter 61-691, Florida Statutes). The District's purpose at that time was to serve as local sponsor for the "Four River Basins, Florida" project -- a flood control project designed by the Corps of Engineers and authorized by Congress in 1962.

For several years, flood control remained the District's major objective. Nevertheless, it became apparent that flood control was not the only water-related concern in southwest Florida. Several years of below-average rainfall, coupled with continually increasing water demands for industrial, agricultural, and domestic uses, eventually set the stage for potential water-supply problems.

In response to the increasingly serious situation, the Governing Board expanded the District's water-management role in 1968 by establishing the Southwest Florida Water Management District (Regulatory) (SWFWMD(R)). This action enabled the Board to more effectively deal with the growing need to regulate the use of the water resource and at the same time to eliminate its abuse.

Today, water is an even more critical factor in maintaining our increasingly complex lifestyles. While water has not yet become a constraint on growth, it does have the potential of doing so. Whether or not it will in the future depends on public policy and careful application of planning concepts. Should traditional policies and patterns of water use continue, serious water problems could occur which would affect future development and environmental quality.

Recognizing this as a potential, state-wide problem, the Florida Legislature passed the Florida Water Resources Act of 1972 (Chapter 373, Florida Statutes). Included in this Act was the requirement to develop the Florida State Water Use Plan (SWUP). Each of the five water management districts in the state was given the responsibility for developing that portion of the SWUP for its own area. We expect that the results of this symposium will make an important contribution to SWFWMD's Water Management Plan.

The first two papers in this symposium will set the stage for the remainder. This first paper will describe the general setting of the area, and briefly discuss the competition for water, including estuarine freshwater requirements. The following paper, by Messrs. Courser and McLean, will describe the District's estuarine systems in greater detail and discuss the associated informational needs as we presently understand them.

2. THE GEOGRAPHIC SETTING

Climate

The SWFWMD is located in the transition zone between the tropical climate of southern-most Florida and the humid subtropical climate that characterizes the remainder of southeastern United States. The three climatic characteristics of greatest significance to water management are temperature, rainfall, and evapotranspiration.

Temperature There is little temperature difference from one section of the District to another during the summer. Mean temperatures range between 80^{o} and 82^{o}F at almost all points during the June to September period. In winter, mean temperatures range from nearly 60°F in the northern sections of the District to 65°F in the southern portion.

Temperature affects water management in many ways. The fact that people find the climate attractive contributes to the increasing municipal/domestic water demand by both the permanent population and the number of tourists that come to the state. A long growing season which permits multiple cropping is a major reason Florida uses more water for irrigation than any other eastern state. The natural vegetation, much of which is adapted to year-round growth, promotes high annual evapotranspiration losses.

Rainfall While some rainfall normally occurs every month of the year in the District, there is a distinct rainy season extending from late May through September, and a low rainfall season from October through April. About 60-65 percent of the annual rainfall occurs during the rainy season. The modest winter rainfall is the result of the cyclonic storms that characterize all of the eastern United States. Since Florida represents the normal southern limit of these storms, rainfall is relatively light. Summer rainfall is derived principally from convectional storms which usually occur in the afternoon and early evening. Rainfall tends to be intense, but of short duration (1-2 hours), and highly localized. Geographically, summer rainfall is highly variable. Areas only a few miles apart often receive widely differing amounts of rain. At irregular and infrequent intervals hurricanes, tropical storms, and tropical depressions produce copious rainfall. Median annual rainfall varies from 50" to 53" throughout most of the District.

Evapotranspiration Evapotranspiration (Et) is a term used to describe the combined loss of water by plant transpiration and evaporation. There have been several estimates of evapotranspiration in Florida; estimates made within the past twenty-five years range from 28 inches per year to over 45 inches per year. The evapotranspiration within the District has been determined to be approximately 39 inches per year and close to 60% of this total occurs in the six-month period from May to October. The greatest evapotranspiration usually occurs in May and June and in some years these two months can account for nearly 25% of the annual total.

Geomorphology

The District is located within two of Florida's major topographic regions - the Coastal Lowlands and the Central Highlands. The area is made up of low, nearly level plains and gently undulating to rolling areas with numerous intermittent ponds, swamps and marshes, as well as many lakes and perennial streams. Elevations in the area range from sea level along the coast to approximately 300 feet above sea level in the highlands. More than 300 square miles of the District are covered by freshwater.

The land forms and the characteristics of the materials in Florida had a marked effect upon the formation of surface water bodies, such as streams, lakes, and springs. These characteristics influence the direction of both overland and underground flow and the varying amounts of recharge to the Floridan Aquifer.

Hydrogeology

In that portion of the District north of the Hillsborough River, the geology is characterized by a simple arrangement of three basic components.

At the surface, a layer of sand occurs which varies from a few inches to several hundred feet in thickness. Below the sand, in most of this northern area, a clay layer of varying thickness is present. Beneath the clay and sand lie several thousand feet of limestone laid on the floor of ancient oceans between 10 and 50 million years ago.

South of the Hillsborough River, the geologic arrangement begins to become much more complex. Although the sand/clay relationship is much the same as previously described, the limestone formations are often divided into separate smaller units by the presence of clay or denser limestone lenses.

Due to these geological differences, the hydrology of the two areas differs greatly. In the northern area, hydrology, like the geology, is relatively simple. The upper sands receive and store a portion of the rainfall and where sufficient thickness is available, can be called the upper or surficial aquifer. Separated from the sands by the relatively impermeable clay layer, the limestones form the very prolific and productive Floridan Aquifer. South of the Hillsborough River the surficial aquifer is similar to that of the northern area. Beneath the water table aquifer, however, the clay lenses and denser limestones divide the Floridan Aquifer into as many as five separate zones, each having different water pressures and qualities.

The variation in the effectiveness of the confining beds is one of the factors that causes the runoff rate to vary from place to place in the District. The average annual runoff rate over the southern part of the District is generally from 8 to 16 inches in contrast to the 0 to 8 inches, generally, over the northern part. However, along the Big Coastal Springs area, the runoff rate is greater than 20 inches per year.

Biological Communities

In general, the elevation of the soils of the District usually determine how much water is available for plant growth. The higher elevations are usually the driest and support flora and fauna acclimated to the droughty conditions. As one proceeds down grade, water becomes more abundant (since the water table is closer to the surface) and plant types change to more water dependent species.

The culmination of the terrestrial topographic drop is the open freshwater system. This includes the District's rivers, streams, lakes and ponds. It is necessary for the plants and animals of these systems to be flooded in order to survive.

The freshwaters of the rivers and streams eventually wind their way to the Gulf where they mix with the marine waters to form the extremely productive brackish water estuaries. They, with their associated salt marshes, mangrove swamps, submerged vegetation, and freshwater inflow, are responsible for the tremendous marine fish and shrimp productivity enjoyed by the people of the State.

Land-Use

The use of land within the District is an indicator of ultimate water needs. The most extensive land use in the District is cropland and pasture occupying over 23% (2,240 square miles) of the area. Following pasturelands, rangelands use 20% (1,910 square miles), wetlands cover 18.5% (1,800 square miles), and over 15% (1,460 square miles) of the land is forested. Urban uses such as residential, commercial, and highways, altogether consume approximately 7.5% (730 square miles) of the total land area in the District. Strip mines take up almost 2% (200 square miles) and water, 3% (300 square miles).

3. PRESENT AND FUTURE WATER DEMANDS

Arranged in descending order of magnitude, the major freshwater uses are agricultural, industrial (including mining and food processing), domestic (public supply and rural), and power.

Population and Domestic Use

The population of the District was approximately 2,313,000 as of mid-1976 and had a raw water demand of approximately 300 mgd. On the average, 1,260 new citizens have located in the District each week since it was established in 1961. Over 1,750,000 people now live within 40 miles of Tampa; this represents nearly 80% of the District's total. The Tampa-St. Petersburg Standard Metropolitan Statistical Area (SMSA) is the most densely populated region in the District and the second most in the state. Projections indicate that the Tampa-St. Petersburg SMSA will continue to be the primary population growth area in the District, but that Sarasota, Port Charlotte, and the coastal regions of Citrus and Hernando Counties will become increasingly important centers during the next 25 years.

It is likely that retirement will continue to be the main inducement for migration to areas of the District and that the major urban land use will be residential. The population of the District was approximately 1,227,000 in 1961 when the District was established. It is expected to have increased 300% by the year 2020, to nearly 4,900,000 people with an expected water demand of approximately 890 mgd. The share of the District population living within 40 miles of Tampa is likely to have decreased to approximately 70% or an increase in population to 3,430,000.

Agriculture

Agricultural water demand in the District during 1975 was estimated to be 485 million gallons per day (mgd). Of this amount, citrus irrigation was the highest followed by truck crops and pasture. As the demand on food producers increases, the amount of intensively farmed acreage will increase. The future trend in the District appears to be for an expansion of irrigated acreage while the total amount of farmed acreage will show little or no increase. The resulting water use is difficult to predict due to the development of new conservative irrigation techniques, but may increase to 860 mgd by 2020. In the future, as in the present, approximately 90% of the irrigation should occur from Pasco County southward.

Industrial

The Southwest Florida Water Managment District is not usually considered to be a heavily industrialized region. However, nearly 15% (110,000) of the District's employed residents derive their income directly from industries, both large and small. Most of the District's approximately 2,300 industrial establishments are light manufacturing, chemical processing, food and beverage processing, and service-related industries. These smaller industrial endeavors are dwarfed by several large, dominant industries, of which phosphate mining, limerock mining, and citrus processing are the largest.

Polk County has historically been the dominant contributor to Florida's phosphate industry by producing nearly 80% of the state's total production. However, the future location of the center of phosphate production is expected to shift into DeSoto, Hardee, and Manatee Counties as new mines begin operation. Further expansion of this industry is also expected to occur in the Southeastern Hillsborough County area.

The phosphate mining industry, which required approximately 317 mgd in 1970, had decreased its demand to approximately 243 mgd by 1975. Much of this decline is due to extensive recycling of process water by the industry.

At current and anticipated rates of production, phosphate reserves are expected to last for only another 30 to 40 years. However, the actual date of the end of phosphate mining depends greatly on worldwide fertilizer use trends and production from other areas. Whenever phosphate mining ends, a large percentage of the current industrial demand will no longer be required and industrial water use figures will decline dramatically.

Limerock mining requires the second largest amount of water in the industrial water-use category with a 1975 water demand of approximately 86 mgd. In the District, limerock mining is centered in Hernando and Sumter Counties, which have approximately 90% of the associated water demand. However, limerock mining should become more important in Citrus, Levy, and Pasco Counties. Limerock mining water requirements are expected to reach a level of approximately 110 mgd in the mid-1980's and should remain at approximately this level into the twenty-first century.

Citrus processing operations used nearly 37 mgd in 1975, which represents a 60% decrease from the 1970 figure of 62.5 mgd. Much of this decline can be attributed to increased operating efficiencies and greater reuse of water by citrus processing plants. Water requirements for this industry are expected to total approximately 43 mgd in 1985, and 50 mgd in the year 2020.

Various other industries require water within the District to bring the 1975 total industrial water demand to approximately 400 mgd. This demand should rise to approximately 468 mgd by 1985 and then decrease to approximately 220 mgd by the year 2020.

Power

While power plants in the District withdrew approximately 643 mgd of fresh and salt water for cooling purposes in 1975, only 18 mgd of freshwater was consumptively used. This consumptive demand may total 250 mgd by 2020.

4. HISTORY OF ESTUARINE CONSIDERATION

Thus far in this paper, we have considered only water for withdrawal uses with little consideration of instream requirements. During the early phases of the development of the District Water Management Plan, little thought was given to the effects of major freshwater withdrawals to estuaries.

When the Florida Legislature enacted the Water Resources Act of 1972 (Chapter 373, Florida Statutes), they made it clear that the natural environment was to be considered in the development of a water management program.

373.016(2) (e) - Declaration of Policy states:

"(2) It is further declared to be the policy of the Legislature:

(e) to preserve natural resources, fish and wildlife;"

This obviously includes estuarine environments.

Chapter 373.036 - State Water Use Plan further states:

> "(1) The department shall proceed as rapidly as possible to study existing water resources in the state; means and methods of conserving and augmenting such waters; existing and contemplated needs and uses of water for protection and procreation of fish and wildlife, irrigation, mining, power development, and domestic, municipal, and industrial uses; and all other related subjects, including drainage, reclamation, floodplain or floodhazard area zoning, and selection of reservoir sites. The department shall cooperate with the division of state planning of the department of administration, or its successor agency, progressively to formulate, as a functional element of a comprehensive state plan, an integrated, coordinated plan for the use and development of the waters of the state, based on the above studies."

and further:

> "(7) The department shall give careful consideration to the requirements of public recreation and to the protection and procreation of fish and wildlife. The department may prohibit or restrict other future uses on certain designated bodies of water which may be inconsistent with these objectives."

It is therefore clear that the information developed in this symposium, and further studies based on these results, are not only sanctioned by, but in a sense mandated by the law.

In December, 1974, two staff members, Bill Courser and John Wehle, were discussing overall effects of water withdrawals on the environment. As they discussed each item, the concern for the estuaries naturally fell into place. Through the next few months several discussions took place as to what some of the problems might be and possible solutions for them.

As a result of these discussions, a memo was written to the Executive Director, Donald R. Feaster, in March of 1976, which outlined the problem and a possible method of analysis and solution. In February, 1976, the District had hired Mr. Rich McLean in the State Water Use Plan Section to coordinate environmental input to the Plan. Rich was charged with undertaking the estuarine project and he has played the key role in its development since that time.

It will be through efforts such as this symposium to determine what water will be required for instream uses. The Southwest Florida Water Management District will utilize these results in developing a comprehensive water management plan that addresses <u>all</u> needs.

AN OVERVIEW OF THE ESTUARIES WITHIN THE SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT

by

William D. Courser[1]

Richard V. McLean[2]

1. Introduction

The preceeding paper indicated the present predicted demands for water within the District. Diversions of overland flow, as well as groundwater withdrawals that affect river flow, have and will continue to create conditions of diminished runoff to the estuaries. This seminar is being held expressly for the Southwest Florida Water Management District to address the problem of keeping the estuaries healthy and productive while meeting the increasing demand for freshwater.

This paper will include a general discussion of the importance of estuaries as well as some specific factors that influence the estuaries of the central Florida Gulf coast. A brief description of each major estuary within the District is also given.

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2. The Importance of Estuaries

Estuaries are defined here as coastal water bodies with a free connection to the sea, that are affected by tidal action, and within which seawater is measurably diluted by freshwater from overland runoff. The overland runoff is important to an estuary for many reasons. Of the most important are its load of suspended growth factors and the fact that it dilutes seawater.

The suspended growth factors, nutrients and vitamins, are in essence "fertilizer" for the estuaries. The continuous input of fertilizer is partially responsible for the tremendous plant growth that occurs there.

Phytoplankton and macro-vegetation in concert with bacteria and fungi are the base of the food web. Small pieces broken from the larger plants, called detritus, are decomposed by bacteria and fungi. Microscopic animals ingest the phytoplankton and the detritus with its coat of decomposers as food. These small animals are in turn fed upon by larger animals and so the food web grows. The products of the web that directly benefit man are the abundant fish, shellfish, and shrimp it produces.

From this simplified description it can be seen that one of the reasons the estuaries are important is the quantity of fin and shellfish they produce. In fact, approximately 85% of all commercially harvested marine fish are estuarine dependent for all or part of their lives.[1]

The second important effect of freshwater inflow is that it serves to establish a salinity gradient across the length of the estuary that goes from fresh to marine water. Since the young of many marine species are better osmoregulators than their parents, they can develop safely in the low salinity of the upper estuary. This is especially important since most marine preditors cannot tolerate such low salinities.

Life cycle patterns that involve the estuarine salinity gradient are best illustrated by giving a simplified description of the life cycles of several individual species. The semi-anadromous Striped Bass (*Roccus saxatilus*) spawns near the freshwater/brackish water interface above the estuary. The larvae hatch and drift downstream feeding and developing until they reach maturity in the estuary or open Gulf. The mature fish then swim back upstream to repeat the cycle.

Another example is the Oyster (*Crassostrea virginica*) which depends on estuarine waters for its very existance. It cannot live in freshwater, and is the victim of disease and predators in full seawater. The dilute seawater of the estuary suits the oysters physiology and is lethal to its marine pathogens and predators.

The Shrimp (*Penaeus* spp.) spawns in the sea, but the developing shrimp move toward the estuaries. Once they arrive, they grow rapidly in the food rich and protective environment. As they mature the shrimp begin to migrate back toward the sea where they complete maturation and reinitiate the cycle.

The Spotted Seatrout (*Cynoscion nebulosus*) spends its entire life in the estuary. They are physiologically and morphologically attuned to an estuarine existance, but can move to the sea for short periods when the salinity or temperature of the estuary get too low.

Many pelagic species such as the Bluefish (*Pomatomus saltarix*) Tarpon (*Tarpon atlanticus*), and King Mackeral (*Scomberomorus cayalla*) move into the lower estuaries to feed on the abundant smaller species that occur there. In fact, many oceanic species occasionally enter the estuaries, and some undertake regular seasonal feeding forays into them.

All of these patterns of use exist simultaneously (see Figure 1) as each species follows its own seasonal sequence. The resulting complexity of movement may include the regular or occasional presence of up to several hundred species, many of which depends on the estuaries.[2]

It can be seen from the above examples that food production and the salinity gradient are important factors in the survival of estuarine dependent species, and both depend on surface runoff. Other factors that influence an estuary include density differences between water masses, tidal movements, currents, the physical shape of the basin, the earth's rotation, friction, wind action, air temperature, sunlight, and chemical composition of the waters. Seasonal changes effect many of these parameters while more recently man's influence has effected river flow, shape of the basin, temperature, and addition of chemical compounds. It can also be seen that estuaries are monetarily important because vast numbers of valuable fish depend on them.

It is difficult to place a monetary value on an estuary. Even if only commercial and sport fisheries are considered, thus negating the value of the estuary in storm protection, as a wildlife habitat, and for other recreational uses, accurate values are not easily obtained. The method used most widely to estimate commercial fishery values is to collect and tabulate the worth at dockside value. The value for the District averages about 5.8 million dollars from 1968 through 1972.[3]

The commercial fishery is difficult enough to calculate, but when one attempts to put a monetary value on the sports fishery, the problem becomes almost insurmountable. Some papers[4] address the problem by saying that the value must be at least equal to the commercial fishery in value. This would put the District's sport fishery at 5.8 million dollars. The Summary of Florida Commercial Marine Landings, 1974,[5] places the sport fishery for the District at 5 times the commercial value, or 29 million dollars. By using the publication "Outdoor Recreation in Florida, 1976",[6] along with Lindall's paper[1] and recent commercial landing values, a figure of 270 million dollars is produced. These numbers vary considerably, but all three show that estuarine dependent fisheries are financially important to the people of the area.

3. Factors Affecting Runoff Volume To The District Estuaries

The quantity and quality patterns of overland flow are dramatically affected by the distinct seasonal fluctuations in the rainfall of the area. The pulsing hydrological cycle of river flows helps maintain the estuaries as a stable productive system. As can be seen in Figure 2, there is a season of high stream flow from June through October with a smaller peak in February and March. The winter peak is caused by passing cold fronts while the summer high is the result of localized thunderstorm activity.

During periods of high flow, the majority of water in the District's streams comes from overland runoff. This water has higher color and turbidity, but, lower pH and mineral content than low flow water.

The reason for marked changes in quality as the volume of runoff fluctuates is that while high flow comes from runoff, low flow is generally sustained by seepage from groundwater sources such as the Floridan Aquifer. Water from the aquifers is usually clear, contains calcium carbonate (high pH), and is highly mineralized. Periods of low flow are September through January and April/May with May usually being the month of least river flow. In general, stream flows in the northern part of the District have groundwater as a larger part of their discharge, while in the southern District, groundwater contribution is not as extensive. The exceptions to these generalizations are the coastal springs. The majority of their flow comes from groundwater discharge regardless of the season.

Over time, the organisms of the estuarine environment have become adjusted to the fluctuations in freshwater inflow and their concommitant dramatic physical and chemical changes. The location and extent of the estuary shifts up and down stream as runoff diminishes and increases. This natural rhythum is affected by manipulations of the freshwater source. Changes in such rhythums can alter the characteristics of an estuary as has been noted in South Florida[1,7] and Dona and Roberts Bay.[8] Increased rates of runoff caused by development may also alter the nature of an estuary.[8,9] For example, changes in the Anclote River probably caused by clearing and drainage improvements have caused the stream discharge to respond almost instantly to rainfall. Back in 1949, prior to watershed alteration, there was a lag between rainfall and increased runoff in the stream.[9] Coble[10] has noted that development of groundwater through wellfields has also reduced the base flow of the Anclote River.

As domestic, industrial, power, and agricultural demands for freshwater increase, the number of surface water diversions and wellfield withdrawals increase to meet the demand, and overland flow to the coast is reduced. The purpose of the seminar is to illustrate scientifically sound methods for determining the amount, quality, and temporal distribution of runoff an estuary needs in order to be maintained in a productive state. More simply stated, to determine when and how much runoff can be harvested without significantly altering the estuary.

This field of endeavor is so complicated that methods of calculating the harvestable amount, or excess flow, in the past have been based on guess work and numbers games without careful consideration of all the relevant factors. Some have stated that excess flow is defined as the difference between minimum flow and the average flow of a stream. Others say that 1/3 of minimum flow is all the water that can be safely withdrawn. It is the charge of the seminar to bring engineers, biologists, and economists together to yield enlightened methods for tackling this complicated problem.

4. The Tributaries And Estuaries Of The SWFWMD

The following section introduces the major estuarine systems of the District. They are, from north to south, the Withlacoochee River, the Coastal Springs, the Pithlachascotee River, the Anclote River, the Tampa Bay System, the Manasota Coast, and the Charlotte Harbor System.[13-16] Two excellent summaries of the marine and estuarine environment of the area are the special issue of the Florida Scientist (Vol. 37(4))[11], and the "Summary of Knowledge of the Eastern Gulf of Mexico 1973" coordinated by the State University System of Florida.[12]

The Withlacoochee River rises in northern Polk County and flows northwestward to the Gulf of Mexico. It drains approximately 2020 square miles and its average discharge at the mouth is 1160 million gallons per day (mgd). The upper reach of the river has low mineral content (30 ppm), and a low flow, only about 51 mgd at the Polk-Lake County line. The lower reach of the river receives approximately 50% of its flow from the Floridan Aquifer with about 445 mgd coming from Rainbow Springs alone. This water is to the calcium carbonate type and also has a low mineral content (200 ppm), but approaches that of the Gulf near the coast. The tidal range in the Withlacoochee area is 3.0 feet.[17]

The river was dammed west of Dunellon in the early 20th century to form Lake Rosseau and the channel was also intersected in the 1960's by the Cross Florida Barge Canal. As a result, all river water going to the Gulf passes through control structures on its way.

The Coastal Springs area is comprised of four major springs, the Crystal, Homosassa, Chassahowitzka, and the Weekiwachee. All four originate short distances inland, but virtually all of the flow is contributed by the springs instead of overland runoff. The estimated average flow for all four springs is 965 mgd. The mineral content of their waters varies due to several factors including the different physical configurations of each river and the level of minerals in the water issued from each spring.

Crystal River receives most of its water from a group of springs collectively called Crystal Springs at the community of Crystal Spring in Citrus County. The river drains an estimated 80 square miles in its 7 mile path to the coast. The mineral content is approximately 200 ppm at the springs and 12000 ppm near the coast. The river water is well mixed with an estimated average flow of 389 mgd.

Homosassa River receives negligible overland flow on its 6 mile course to the Gulf. Thw waters of Homosassa Spring and Hall River, two of the three tributaries of the Homosassa River, have a high mineral content (approximately 1830 ppm and 3000 ppm respectively). Water from the third tributary, the Southeast Fork of Homosassa Springs, has a low mineral content (218 ppm). Seawater migrates as far upland as the main springs and to the head waters of the Hall River. The combined flow of this complex is approximately 280 mgd.

The springs that feed the Chassahowitzka River are also in Citrus County. These numerous springs make up the river flow and their mineral content ranges from 174 ppm at Crab Creek to 2930 ppm at the mouth. The estimated average discharge is 115 mgd.

The length of the Weekiwachee River is about 7 miles from its headwaters to the Gulf, and it is located entirely in Hernando County. The estimated average flow at the mouth is 190 mgd. Its channel is well defined and cuts into bedrock along its route, thus creating numerous small springs. Its mineral content is only 192 ppm 2 miles from the coast. The other coastal springs have broad meandering streams which allow saltwater intrusion from the Gulf which does not occur here.

The Pithlachascotee River drains apprixmately 260 square miles of Pasco and Hernando Counties and its estimated average flow at the mouth is 64 mgd. The mineral content of the upper reach is generally less than 100 ppm with higher contents during the dry season and lower concentrations during the wet season. During low flow most of the rivers water originates as seepage, whereas during high flow, most of it comes from overland runoff. The lower reach is subject to urban runoff from New Port Richey and Port Richey, and is influenced by tidal action.

The Anclote River drains approximately 110 square miles of Pasco County and has a flow at the mouth of about 83 mgd. Groundwater contributes most of the rivers flow during the dry season, while during the wet season, overland runoff is the major contributor. Upper reach waters have a mineral content of about 80 ppm while it is approximately 5000 ppm near the coast.

The above rivers contribute water to the District's northern estuarine systems. The most striking difference between the northern and southern estuaries is that the dominate terrestrial vegetation form in the north is the salt marsh, while in the south the mangrove swamp is more prevalent. The area just north of Tampa is usually considered the transition zone.

Tampa Bay receives water from a watershed area of 2235 square miles.[17-18] The principal rivers and streams discharging into the Bay are the several small creeks of Old Tampa Bay, The Hillsborough River, Palm River, Alafia River, Little Manatee River and the Manatee River. Boca Ciega Bay receives drainage from the Pinellas Peninsula. Morphometric features of Tampa Bay[18] are presented in Table 1. Tides in Tampa Bay are mixed.[17-18] The diurnal tide range averages 2.0-2.8 feet in the Tampa Bay area.

The small creeks emptying into Old Tampa Bay drain most of Hillsborough County northwest of Tampa, and northeast Pinellas County. All generally flow south into the bay although Brooker Creek drains east into Lake Tarpon which is then drained by a canal with structure south into the bay. Lake Tarpon formerly drained through a sink into the Anclote River estuary. Runoff in the basin is affected by groundwater withdrawals from four wellfields. Rocky Creek streamflow is controlled by two salinity barriers.

The City of Tampa withdraws the great majority of its water supply (averaging 55 mgd) from the reservoir behind the dam on the Hillsborough

River. The average inflow of water into Old Tampa Bay and Upper Hillsborough bay is 588 mgd.

The watershed of the Alafia River has been extensively altered by phosphate mining which also draws heavily on the groundwater resources of the watershed. The average flow of the Alafia River is 323 mgd.

The Little Manatee River is relatively undeveloped although Florida Power and Light withdraws roughly 23 mgd (12% of the rivers flow). Its average flow is 194 mgd. The Manatee River is also impounded and its reservoir provides water (19-20 mgd) for Manatee County and parts of Sarasota County. The Braden River, a tributary of the Manatee is also impounded. Ward Lake serves as a water supply for the City of Bradenton. The Manatee River discharges 297 mgd into Lower Tampa Bay.

Tampa Bay has a pH that averages about 8.0. Dissolved oxygen levels have a mean of 5.9 mg/l although extended periods of low DO have been recorded with Hillsborough Bay and blind and canals. Nutrient levels have been high in the estuary. Total phosphorous levels have progressively increased since 1952 with the Alafia River responsible for the majority of phosphorous input. KJELDAHL nitrogen have decreased slightly from 1962 levels. Water clarity of Tampa Bay increases from the head to the mouth, with average turbidity values varing over a range of 4-10 JTU. Seasonal water temperatures average 30^{o} C in the summer, 23^{o} C in the fall, 16^{o} C in the winter and 27^{o} C in the spring.[18]

No major estuary is found off the Gulf Coast of Manatee and Sarasota County between Tampa Bay and Charlotte Harbor. Some local drainage in Manatee County enters Sarasota Bay. Eastern Sarasota County is drained by the Myakka River. Western Sarasota is drained mainly by small creeks emptying directly into the Gulf. However, one larger system, Cow Pen Slough-Shakett Creek and Curry and Hatchett Creeks, drains into a bifurcated estuary known as Dona and Roberts Bay. A study of this estuary was made by Mote Marine Laboratory.[8]

The Cow Pen Slough-Shakett Creek basin drains almost 90 square miles. Cow Pen Slough drains an area in Northern and Central Sarasota County south to Dona Bay. A small watershed drainage project is almost half-built. It has had a significant impact on the physical chemical and biological environment of Dona Bay.[8]

Charlotte Harbor receives freshwater principly from the Myakka, Peace and Calooshatchee Rivers. Their total watersheds cover and area of about 4200 square miles.[19] Morphometric features of Charlotte Harbor are presented in Table 1.

The Myakka River with an average flow of 388 mgd drains the eastern parts of Manatee County and a large portion of Sarasota County as it flows south into the Charlotte Harbor. The Peace arises in Central Polk County and flows almost due south to its mouth. South of Bartow, little structural works have taken place on the Peace River, although many tributary areas are influenced by phosphate mining. The Peace has a large average flow of 1551 mgd. The Myakka River has one structure on Upper Myakka Lake and some drainage improvements made in the headwaters above Upper Myakka Lake. The Caloosahatchee River is controlled by a system of flood control and navigational works.

Proposed withdrawals from the Peace River include water supply for development in the Port Charlotte area, and cooling needs for a power plant in Hardee County. Several dams have also been proposed along the river and its tributaries.

Charlotte Harbor is probably the "least contaminated estuarine complex" in Florida. Nutrients are not at a high level, pH is near 8, and dissolved oxygen averages close to 6 mg/l. The diurnal tide range averages from 1.7-1.9 feet in Charlotte Harbor.[19]

Current groundwater and surface water diversions within the District are summarized by county in Table 2. These values will increase as Florida's population increases. The charge to this seminar is to determine when and what quantity of runoff can be developed for water supply without significantly changing the productivity of our estuaries.

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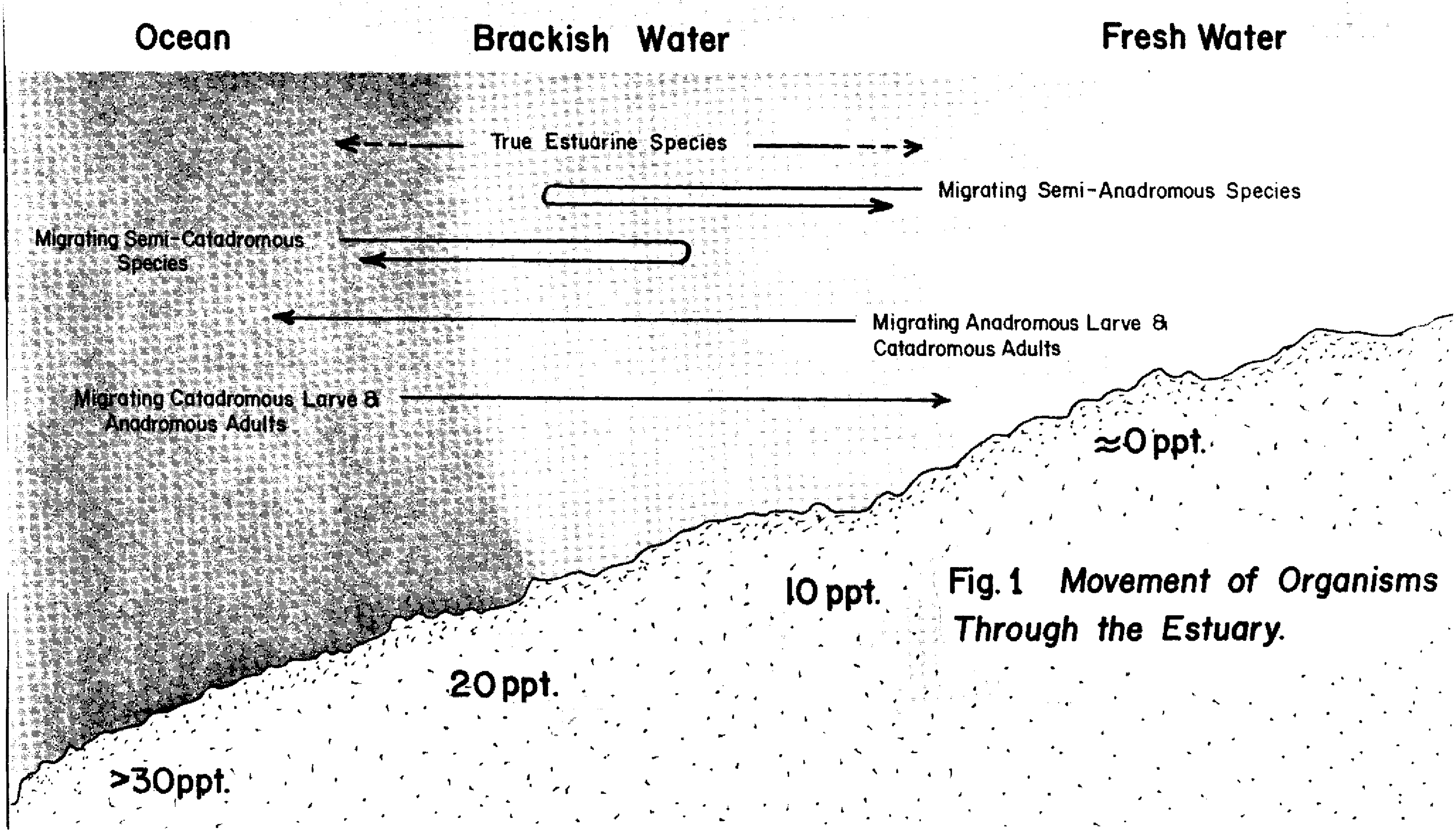

Fig. 1 *Movement of Organisms Through the Estuary.*

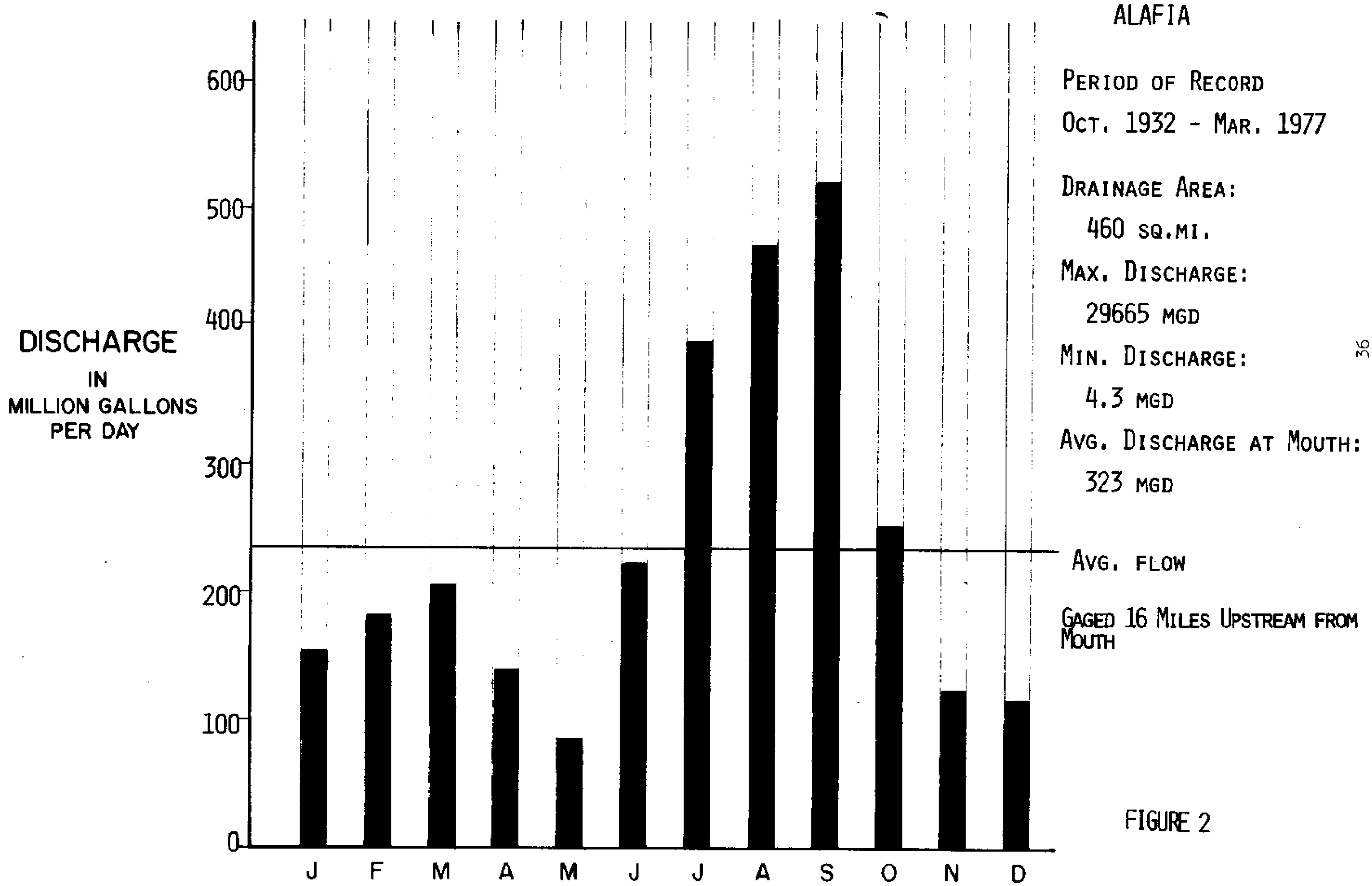
DISCHARGE
IN
MILLION GALLONS
PER DAY
600
500
400
300
200
100
0
J
F
M
A
M
J
J
A
S
O
N
D
ALAFIA
PERIOD OF RECORD
OCT. 1932 - MAR. 1977
DRAINAGE AREA:
460 SQ.MI.
MAX. DISCHARGE:
29665 MGD
MIN. DISCHARGE:
4.3 MGD
AVG. DISCHARGE AT MOUTH:
323 MGD
AVG. FLOW
GAGED 16 MILES UPSTREAM FROM MOUTH

FIGURE 2

	TAMPA BAY	CHARLOTTE HARBOR
Length (mi)	35	35
Ave. Width (mi)	9.9	-
Area (sq. mi)	340.6	280
Volume (in miles)	0.687	0.583
Max. Depth (ft.)	57	51
Mean Depth (ft.)	11	10-12
Length of Shoreline (mi)	-	Over 200

TABLE 1. Morphometric Features of Tampa Bay and Charlotte Harbor Estuarine Systems

TOTAL WITHDRAWALS (MGD)

Counties	Groundwater	Surface Water*	Consumptively Used
Charlotte	24.17	3.90	11.48
Citrus	6.16	.24	1.97
De Soto	67.19	2.00	46.25
Hardee	143.36	.00	66.00
Hernando	67.85	.41	31.40
Highlands	24.45	108.16	44.24
Hillsborough	109.59	65.13	35.18
Lake	3.85	1.73	3.99
Levy	1.48	.04	.67
Manatee	30.84	45.29	16.97
Marion	7.68	.31	6.10
Pasco	94.02	10.43	50.85
Pinellas	94.73	.02	79.97
Polk	376.98	304.03	71.82
Sarasota	38.00	3.32	20.72
Sumter	22.00	.17	7.25
TOTAL	1,018.33	545.18	494.86

SOURCE: USGS Water Use Inventory - 1975 (Preliminary Data)

*Most surface water withdrawals represent lakes, not streams.

TABLE 2

DEVELOPMENT AND THE HYDROLOGY AND GEOHYDROLOGY OF COASTAL DRAINAGE BASINS

by

B. A. Christensen[1]

ABSTRACT

The prosperity and well-being of the population of Florida's coastal areas is highly dependent on a balanced interaction of man on one side and the region's freshwater and saltwater systems on the other side. However, the rapid growth of the population and the mostly service oriented industry that follows this growth has in many cases an adverse effect not only on the coastal zones hydrosystems but also on the water quality of the marine environment.

The immediate response of today's environmentally alert citizens is an understandable demand for a moratorium on many types of development, such as establishment of coastal canal communities, that may cause serious water quality problems and in many cases eliminate highly productive wetlands, construction of shopping centers with large parking lots that increases the rate of runoff and cut off the natural percolation to the coastal aquifers, or the paper and pulp industry's deforestation practice that causes significant changes in the pH of the receiving waters.

A moratorium of this nature is usually temporary and lasts until a better knowledge of the problem in question is obtained. Unfortunately,

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however, such a moratorium in too many cases has been followed up by an emotionally based demand for a complete and permanent stop of all development. This is of course neither wise nor necessary. It is possible for rational development to go hand in hand with preservation of the environment. As a matter of fact, the enhancement of environmental qualities is many times the consequence of a well planned and designed development.

A thorough understanding of the hydrological cycle and how man's activities may influence it is the first requirement for the successful coastal planner or manager. The present paper addresses itself to that problem. Methods for avoiding adverse effect such as increased rates of freshwater runoff, low water quality and last but not least saltwater intrusion in the coastal aquifers are discussed.

A REVIEW AND EVALUATION OF SELECTED NUMERICAL MODELS FOR COASTAL ZONE WATER MANAGEMENT

by

Steve Graham[1]

1. Utility of Numerical Models

Advances in digital computer technology have permitted development of numerical models which can simulate water quantity and quality characteristics over space and time. Previous analytic solutions commonly required many simplifying assumptions in the equations of motion, regular geometry and uncomplicated boundary conditions. Physical models were expensive to build, difficult to modify and could not simulate water quality information. The last decade and a half has been a period of development and refinement of numerical models and now many are available in a format suitable to application by engineers and planners. Many successful ones have been verified, are available at low cost, are adequately documented and can be modified with only moderate effort to cover many specific problems. As the cost of computation time continues to decline, they become more and more attractive as management tools.

The availability of numerical models should not be the sole criterion for their employment for a specific problem. Indeed the choice of an inapplicable model will only increase one's ability to err by orders of

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magnitude. Before the decision to simulate numerically is made, one should define the problem clearly and decide exactly what information is needed that cannot be derived from a less sophisticated analysis. A complete survey of available proven models can then be made to see if one which is germane exist , and then a decision can be made whether or not to use it on the basis of input requirements, time available, labor and processing costs.

An advantage of numerical modeling is that one is forced to evaluate the ability of the available data to answer the problem at hand, and then to decide among the alternative scenarios that the model can provide. In systems terminology, an 'objective function' must be explicitly defined.

2. Types of Models Reviewed

Only a very limited number of model types can be reviewed here because of time limitation, and only a few of the most popular models in each category can be outlined. The categories will be covered in the following order:

i) nonurban basin models

ii) urban basin models

iii) river models

iv) estuary models

3. Nonurban Basin Models

These models are used to simulate quantity and/or quality of runoff from nonurban drainage basins. They can be used in conjunction with statistical analyses of long-term gage records which may be nonsteady if the basin characteristics have been changing during the period of record.

The SCS Procedure

The Soil Conservation Service (USDA) developed a nonnumerical procedure (1) which is often employed to derive an estimate of peak flows from small watersheds. A rainfall-runoff relation is used with storm rainfall and soil characteristics as independent parameters. Antecedent moisture conditions are included. Routing is by a unit hydrograph which is assumed to be triangular in shape so that only the time to concentration and the ratio of time of recession to time of peak need be specified. This procedure can work well in small basins. It is important in that the empirical relations are used in other numerical basin models and it has been incorporated as an option in the STORM model.

STORM

The Storage, Treatment, Overflow and Runoff Model (STORM) is a water quality model which can be used for simulation of either nonurban or urban watersheds. It is simple and flexible. It was designed to aid in sizing of storage and treatment facilities by allowing variation in treatment, storage, and land use. It is not a particularly sophisticated model, but it can be run quickly and inexpensively so that it is primarily used to initially screen alternatives or define data needs.

The runoff simulation portion was designed as an alternative to the design storm approach. An option is given to select either a constant rainfall/runoff coefficient (for each discretized portion of the basin) or the SCS Curve Number Technique (1) previously described which includes antecedent conditions. The SCS Unit Hydrograph procedure is also used.

Input data include hourly precipitation, daily temperature, land use and runoff parameters (from SCS), pollutant accumulation and washoff information (for urban areas) and land surface erosion data. Sediment losses are predicted by the Universal Soil Loss equation (1,2) and a simple ratio method is used to calculate their delivery to a river. More will be said of its utility for urban water quality prediction presently. See references (2,3,4,5).

SWM - HSP

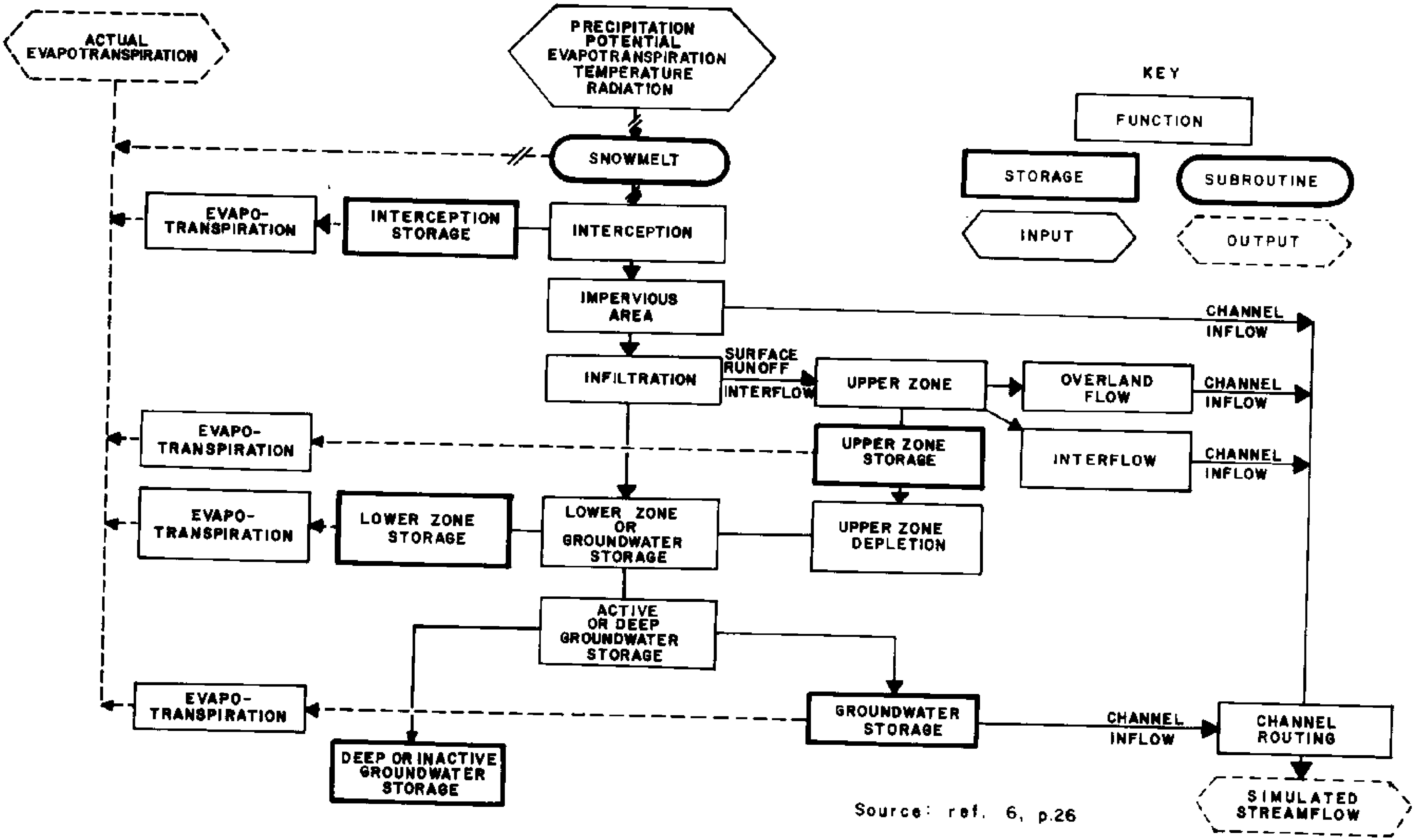
The outstanding basin simulation model available today is the Hydrocomp Simulation Programming (HSP) model which is available from Hydrocomp, Inc. This is an advanced version of the earlier Stanford Watershed Models (SWM to SWMIV) (4,6,7,8,9,12) which were complete water-balance models. A diagram of the logic is shown in figure 3-(1). A concise review of the procedures is given in Biswas (6).

HSP can simulate continuous flow and quality (of up to 18-20 constituents) for basins ranging in size from a few square kilometers up to an instance of 150,000 Km^2 in Brazil. River stage, reservoir levels and flow diversions can be included in the output. Output can be prepared for any point in the watershed.

The inputs required for the quantity module are time series of hourly rainfall, daily potential evapotranspiration and quantitative descriptions of basin parameters. The quality module requires temperature, radiation, wind and dew point (if possible), and loading data in addition. Routing is done by the kinematic wave (Muskingum) method.

Figure 3-(1)

Flow Chart for the LANDS
Module of the Hydrocomp Simulation Program



Source: ref. 6, p.26

The drawbacks of this model are that it is not as good for sewered urban catchments as SWMM , that it is proprietary, and that is not linked explicitly to an estuarine dispersion model. The EPA laboratory in Athens, Georgia is expected to issue a nonproprietary version of HSP in Fortran presently. An advantage of the proprietary nature of the model is that it is being continuously improved and excellent advice is available about its use.

Fleming and Franz (13) compared HSP to nonnumerical methods for several watersheds and found HSP a superior predictor.

For HSP references, see (4,5,6,10,11,13).

4. Urban Catchment Models

Because of their high ratios of impervious areas and intensive use, urban catchments tend to produce large amounts of low quality runoff with little time lag with respect to the rainfall. Routing is made difficult because of the interconnected maze of pipes and associated surface flows. Many models have been developed which would be useful to study the effects of urban drainage into a river or estuary (see 5), and a few of the more promising ones will be outlined here.

STORM

STORM was previously discussed as a basin model. It can also be used as a simple urban water quality model which can handle up to 6 constituents. The format is illustrated in figure 4-(1).

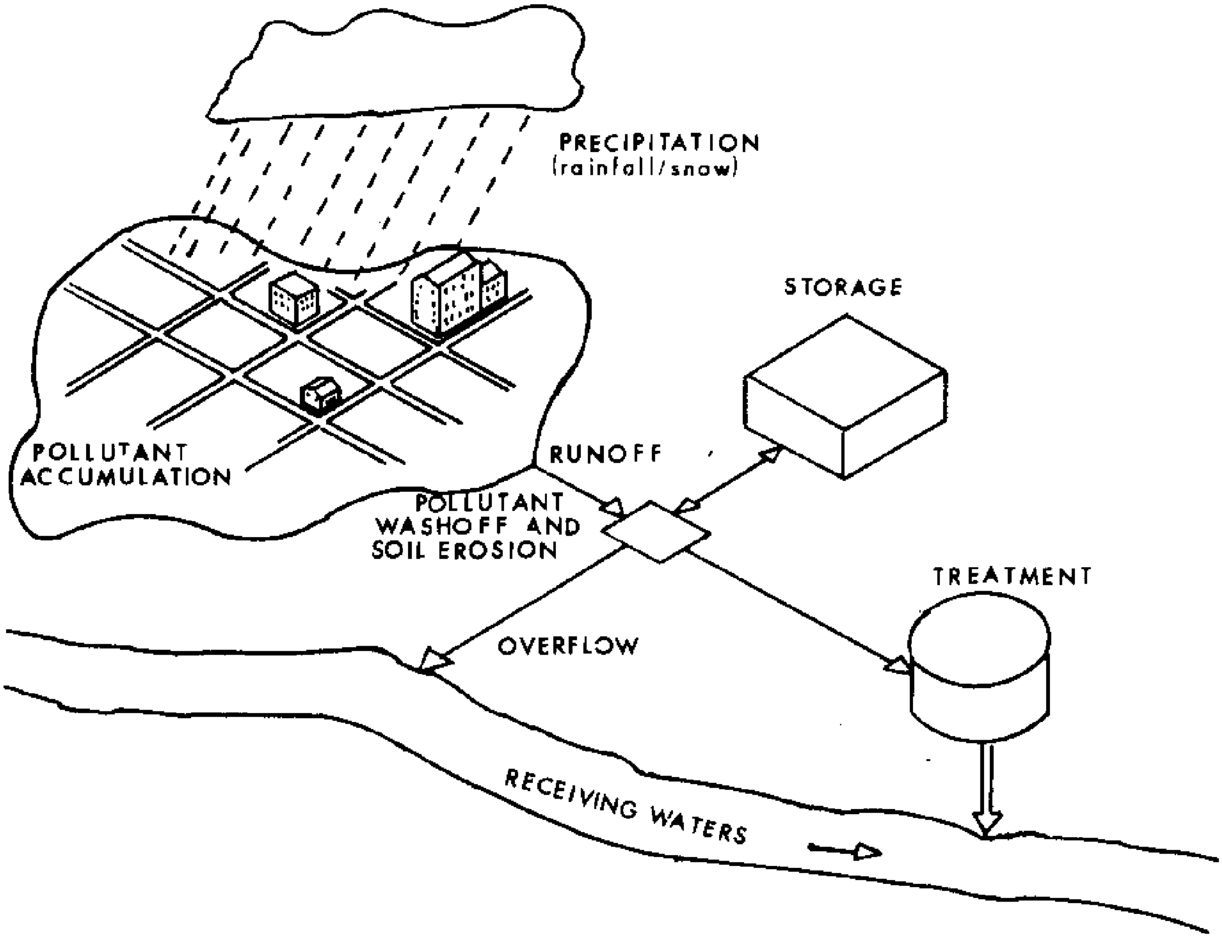


FIGURE 4-(1)

Conceptualized View of Urban System Used in 'STORM'

Dry weather flows and pollutant concentrations are estimated. Runoff and storage are computed by simple procedures and the degree of treatment can be varied. No receiving water simulation is available, and the hydrodynamic and routing procedures are unsophisticated. The model is easy and inexpensive to run however and can be used to screen alternatives to quality management involving storage and treatment.

HSP

The HSP model, with some modifications, has been run on urban catchments in Denver, Seattle and Spokane. Flow frequency is defined at all critical points in the system and pipesand channels are sized accordingly. Quality data at outfalls or other points can be output. See (4).

MITCAT

The MIT Catchment Model is a simple basin model which has worked well for simulation of quantity criteria in urban basins. It was developed at MIT, verified at the Johns Hopkins, and is maintained currently by Resource Analysis, Inc. It has been used in Denver, Baltimore and Puerto Rico.

This model can inexpensively screen the effects of the urbanization of a catchment on runoff by varying infiltration and streamflow parameters, storage, detention, and drainage, network configuration. It does not compute water quality, nor does it consider groundwater.

See references (4,5,14,15,16).

SWMM -- SWMM - WRE

The last urban drainage model to be discussed is the EPA Stormwater Management Model (SWMM) which was developed, in part, at the University of Florida. It is a comprehensive sophisticated model which can calculate runoff, routing, storage, receiving water advection, quality components and costs. A Water Resources Engineering, Inc. modified version permits more efficient calculation thru the pipe system. The model structure is presented as figures4-(2) and 4-(3).

Extensive inputs are required, including 1)watershed characteristics, 2) rainfall hyetograph, 3)land use data, 4) gutter characteristics, 5) street cleaning frequency, 6) treatment devices and their sizes, 7) cost indices, 8) storage volume and location, 9) boundary conditions and receiving waters, 10) pipe characteristics, and 11) inlet characteristics.

Hydrographs, pollutographs and cost data can be output.

The RECEIV block is used to simulate quality characteristics in the receiving water body. The hydrodynamic calculations are dynamic but the quality routine is purely advective although some numerical dispersion enters. An inproved version, RECEIV2, can handle more quality constituents. The RECEIV block can simulate quality in a river or vertically-mixed estuary.

See references (4,5,17-21).

Discussion of Basin and Urban Runoff Models

Several excellent models exist for simulation of quality and quantity of basin runoff. STORM is good for initial screening, expecially of large basins. It can predict hourly runoff and weight of pollutants. Storage-

FIGURE 4-(2)

OVERVIEW OF THE STORM WATER MANAGEMENT MODEL FROM (5)-I

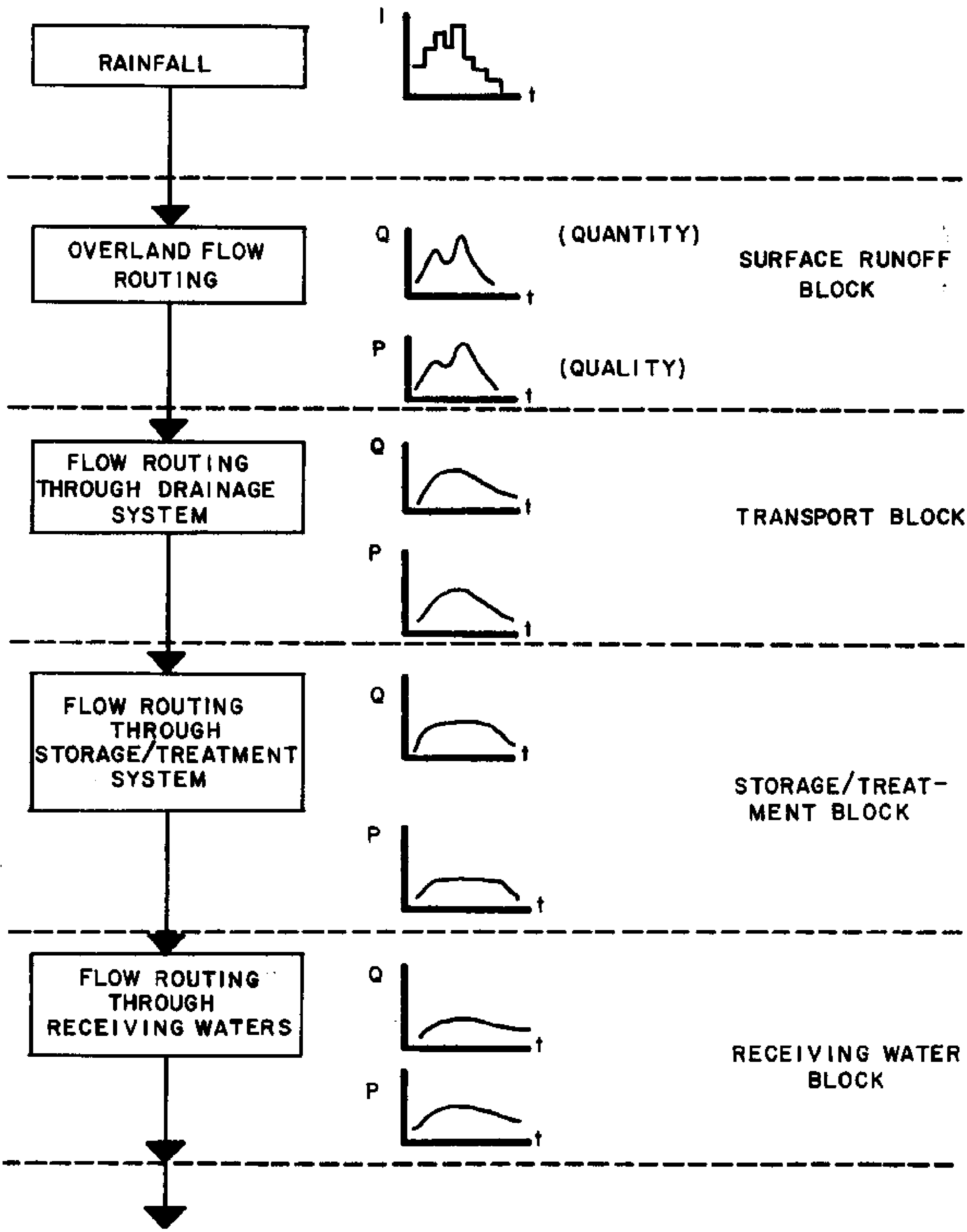
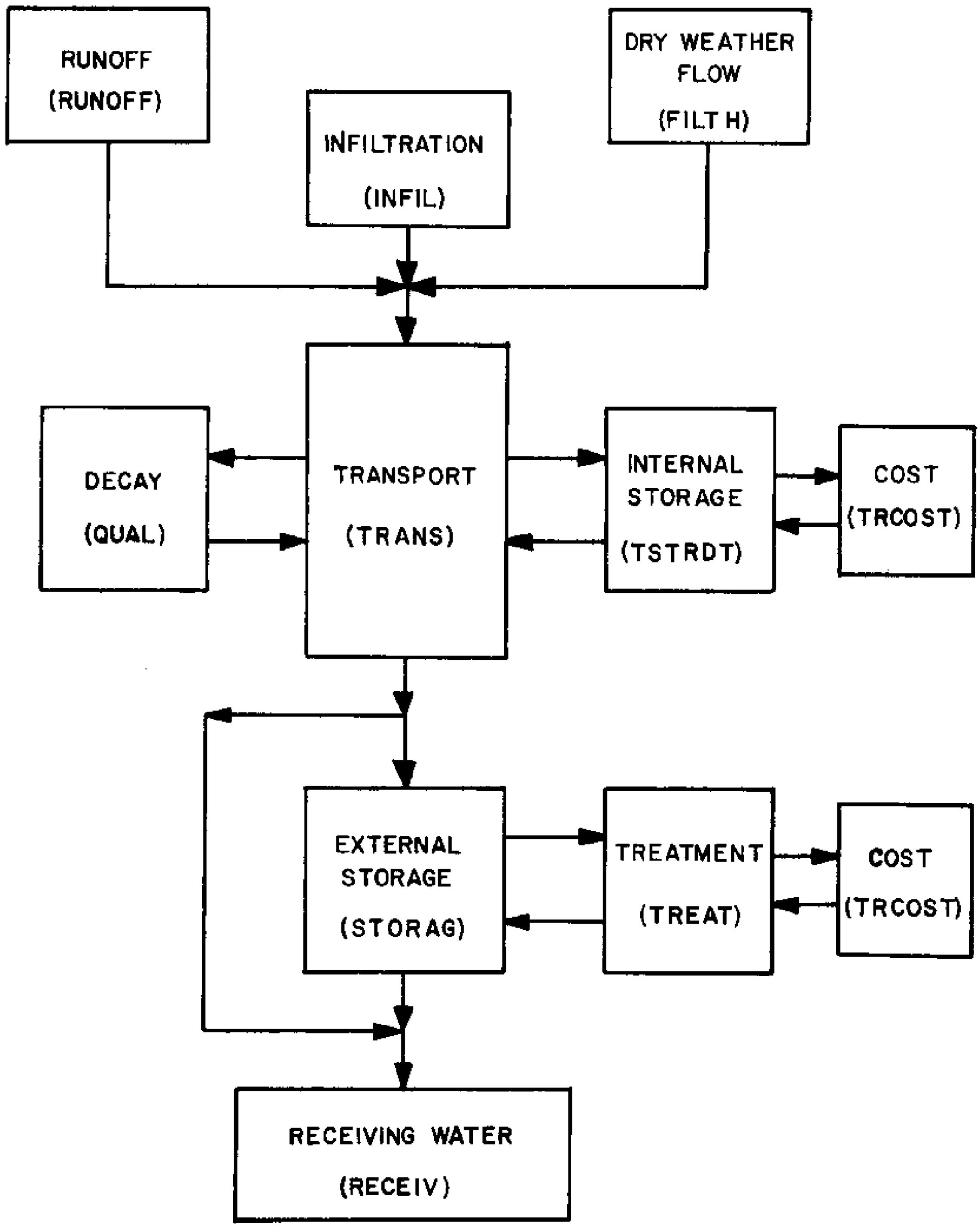


FIGURE 4-(3)

OVERVIEW OF
SWMM MODEL STRUCTURE FROM (5)-2



Note: Subroutine names are shown in parentheses treatment alternatives can be tested. The HSP model is more sophisticated and has yielded good results for large and intermediate scale nonurban catchments. For urban basins MITCAT can provide inexpensive estimates of quantity parameters while SWMM can simulate quality, loadings, transport and receiving water quality for smaller urban basins.

A general model categorization in (5) is reproduced as an appendix.

5. River Models

Several numerical models exist which can be used to predict the quality and quantity of river water. Since this is a basic input to estuarine models, some of the more popular ones are outlined.

Sophisticated basin models such as SWMM and HSP incorporate open channel routing as part of the program. In HSP for instance the LANDS and QUALITY modules can route through channels and lakes and account for up to 20 constituents including DO, coliforms and pH. Thermal stratification in lakes is also simulated.

Some less sophisticated models can be used for more specific aspects of fluvial discharges. They may be classified as either steady-state or dynamic. The steady-state models are, of course, much simpler.

Steady State Stream Models

DOSAG-I

DOSAG-I is a computerized version of the Streeter-Phelps DO-sag equation. 1-4 DO targets and up to 5 degrees of treatment may be specified.

20 junctions and 50 reaches may be included. Both carbonaceous and nitrogenous BOD are accounted for (4,22,23,24).

SNOSCI

This is a Systems Control, Inc. version of DOSAG-I. It can account for DO, BOD, T. and F. coli, NH_3, NO_2, NO_3, OPO_4, Cu, Pb, temperature excess and four conservatives. (22,25,26).

SSM

The Simplified Stream Model of Hydroscience, Inc. is a nonnumerical methodology for calculating stream quality. A desk calculator is all that is required. It can predict coupled BOD-DO, singular nonconservatives with first order decay (BOD, coli, nutrients) and conservatives. Only point sources may be considered (22, 27).

Quasi-Dynamic Stream Models

QUAL-I, QUAL-II

QUAL-I is an improved version of DOSAG-I. It is an integrated system of modules which can simulate 1) temperature, 2) BOD-DO and 3) conservative substances through a 1-dimensional branching stream system. Flow augmentation for DO maintenance can be determined.(4,22,28,29).

QUAL-II is an improved version and can simulate 8 more quality constituents - (NH_3, NO_3, NO_2, algae, phosphorous, coliforms, benthic demand, radioactive materials). (22,30).

Discussion

The dynamic models cost more to run than do steady-state ones, but can simulate transient water quality conditions. The choice depends upon whether the problem concern instantaneous or average quality 'violations'. Advanced models like HSP, SWMM, and QUAL-II also provide a more realistic simulation of linkages between quality parameters than do simple BOD-DO relationships.

6. Estuarine Models

Estuarine Characteristics

An estuary may be defined as a semi-enclosed shallow body of water subject to tidal motion in which fresh and saline waters commingle. Mass transport in such an oscillating baroclinic flow field is one of the most difficult, and interesting, geophysical problems today.

It has become increasingly apparent that estuaries are valuable because of their large biotic productivity and waste assimilation capacity. While the utility of these functions is often difficult to quantify, the effects of mismanagement of fish populations, harbor sedimentation, and ambient water quality have been noted around the country.

The most important fact to realize with respect to estuaries is that a unique hydrodynamic flow structure exists. The notion that all fresh water that reaches the sea is 'wasted' must be refuted. Indeed the viability of the coastal environment is dependent upon inputs of characteristic magnitudes of fresh water and sediment at characteristic times.

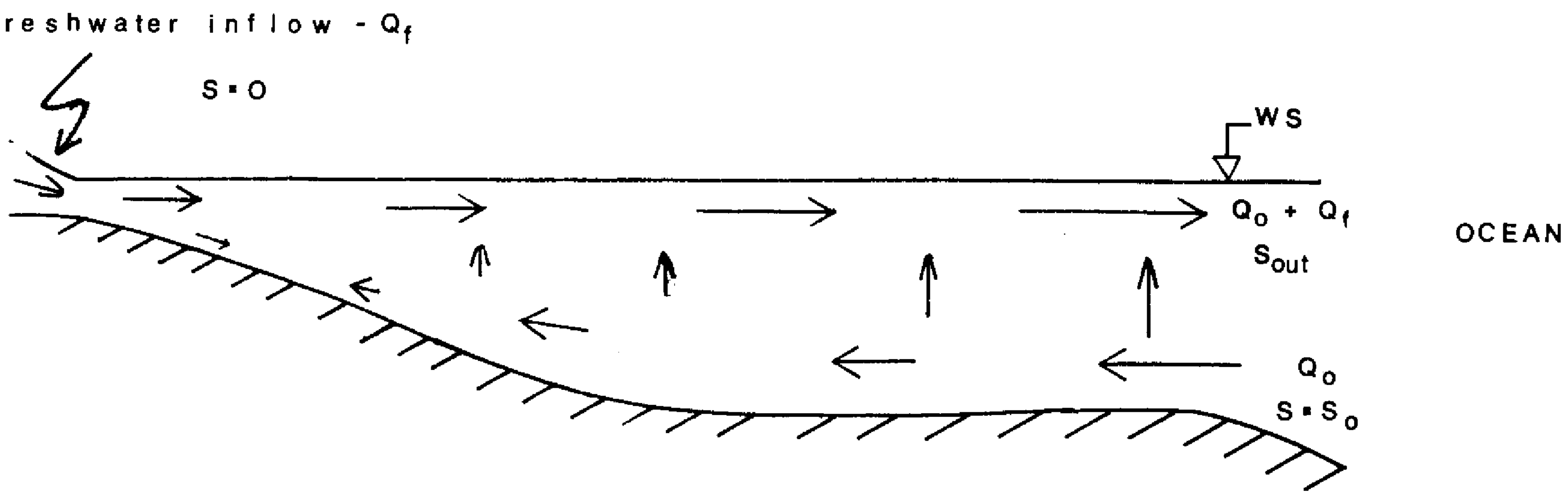
The tidally-averaged net velocities along the axis of a partially-mixed estuary are illustrated in figure 6-(1). Note that the density differences induce a baroclinic flow system in which saline water moves 'upstream' near the bottom while freshening, and mixed fresh water moves seaward along the surface. Even imperceptible density variations have induced this motion, and the concept of a vertically-mixed estuary may not be hydrodynamically valid (52). In partially mixed estuaries on the East Coast of the U.S. one unit of fresh water inflow commonly induces about 9 units of seawater to circulate through the estuary. The magnitude of estuarine circulation is therefore very sensitive to any change in freshwater inflow caused by retention, diversion or consumptive water use.

Only the net velocities are illustrated in figure 6-(1). These may be defined as having been time-averaged over a tidal cycle. Net velocities are usually small compared with the tidal ones, and they are therefore difficult to measure. Characteristic East Coast estuarine tidal velocities are illustrated in figure 6-(2), (reference 40, p.58). Note that during flood tide, for instance, water throughout the depth column moves landward, but the bottom water moves faster. Dispersion of pollutants is accomplished by shear in tidal flows. A mass transport analysis based upon net velocities alone can describe advection but large artificial 'apparent' dispersion coefficients must be included in the equations of motion to account for the observed dispersion.

Estuaries may be subdivided into various types according to the general format of table 6-(1). Tidal motion tends to mix an estuary whereas the lighter fresh water tends to stratify it. The ratio of the volume

FIGURE 6-(l)

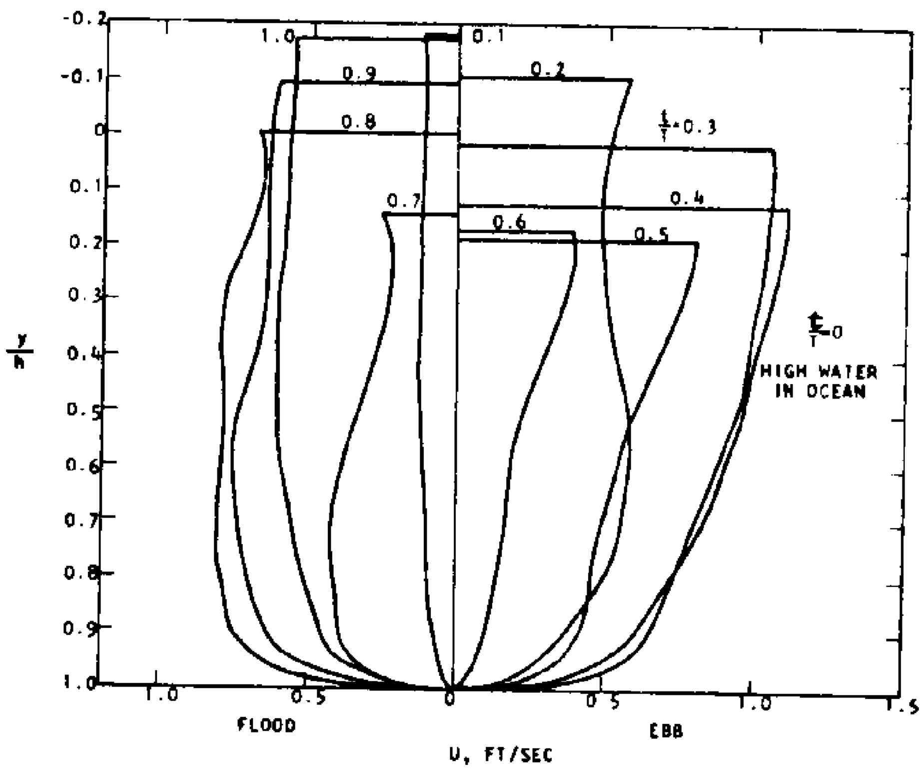
NET VELOCITY DISTRIBUTION IN A PARTIALLY-MIXED ESTUARY



length of line proportional to discharge

$$S_{out} = \frac{Q_o S_o}{Q_o + Q_f}$$

Fig. 6-(2) Horizontal velocities throughout tidal cycle, Test 14, Sta. 40. From (40, p. 58).



1 ft. = 0.3048 meters

Table 6-(1)

Pritchard's Estuarine Classification System

V→				
TIDAL CURRENT DOMINANT	D	D	D	D
	C	C	C	D
	B	B	C	D
RIVER FLOW DOMINANT	A	B	C	D
L→	DEPTH DOMINANT		WIDTH DOMINANT	

Type A Salt Wedge

Type B Partially Mixed

Type C Vertically Homogeneous

Type D Sectionally Homogeneous

Source: ref. 52, p. 21

of the tidal prism to the freshwater discharge per tidal cycle therefore determines the degree of mixture in large part. Shallower estuaries tend to be better mixed than deep ones because of enhanced wind and bottom shear stresses. The Gulf of Mexico has relatively low tides, so that a tendency to stratification should be present. The characteristic shallowness of this coastal region may mitigate this effect however.

If an estuary be moderately confined, the modeling can be rendered simpler in many cases by a reduction in dimensionality. If tidal or aeolian processes dominate, then the estuary may be completely mixed and a one-dimensional model based on net advection with tidal exchange will suffice. Narrow estuaries are often relatively homogeneous laterally so that only the vertical density stratification need be considered. The Potomac is an example. Very shallow estuaries are often well-mixed vertically so that an analysis based on plan geometry can be made. The first thing to be done then is to determine what type of estuary you have and whether any proposed change of fresh water input will modify it. An increase in fresh water to Charleston Harbor, SC caused a change in type from partially mixed to stratified which has resulted in localized sediment deposits which cost millions of dollars per year to dredge (54).

The first criterion for model selection then is to ascertain the dimensionality of the system. At present no readily available and verified 3-D models exist, except for some which predict near-field temperature distributions near diffusers. One- and two-dimensional hydrodynamic models exist which can predict tidal heights and velocities quite accurately on a real-time basis thruout the tidal cycle. This is usually accomplished by linking the continuity and momentum equations. Intrusion lengths and salinities can be predicted numerically quite well also for laterally-homogeneous cases. See references (40, 44 , 51 and 54).

When water quality parameters are being simulated, two other choices in model types must also be made. The first deals with the temporal averaging method. Obviously the magnitude of the problem is reduced by temporal as well as spatial averaging. Two techniques have been used. One is to average over a tidal cycle and use mean values. Since tidal flow is oscillatory, the problem is reduced to one of apparent simple advection. The other technique is to look at the system only at one point of the tidal cycle, usually slack tide before ebb. This is analogous to movement viewed with stroboscopic light. Many older water quality models were based on a temporally-simplified basis in order to be amenable to solution. Such techniques are still useful if a long-term steady-state prediction is required, or if many alternatives are to be screened thru simpler models prior to detailed numerical analysis. The problem with temporally averaged solutions is that apparent dispersion coefficients must be used to describe all the tidally induced motion being averaged out. Such coefficients must be determined empirically thru field measurements, and even then their applicability is only valid for that particular set of circumstances measured. Advances in computer speed and software now allow so-called real-time transient solutions in which the time steps are small relative to the tidal period so that a constant hydraulically predictable 'Taylor' dispersion coefficient can be used. Real-time simulations are made many times per tidal cycle and are therefore much more expensive to compute. They also require large computers. More details on the comparability of the temporal averaging techniques are given in reference 40, (p. 76). I believe the discussion among the experts on that article, which was presented as an addendum to chapter IX, may be interesting to resource managers:

JAWORSKI: On the Potomac we've got the advantage of applying both the Orlob or "real time" model and the Thomann or "tidal average" model. One thing about the tidal-average approach is that one can perform sensitivity computations very cheaply. In some of our work we can tell if we have to go to a real-time solution just by varying the dispersion and testing the sensitivity. This is very simple. So I think using the tidal-averaged model for the DO-BOD reaction system, which has high rates, is at times a very uncomplicated method of getting a fast answer and order of magnitude.

The opposite appears to hold for nutrient transport on an annual flow cycle. We are running into trouble using the tidal-averaged model over a range of flows while keeping constant the dispersion coefficient. I think the applicability of either the tidal-averaged or the real-time model comes in in what kind of answer you want and what you're willing to pay for it.

HORNE: In this quick sensitivity test, you are saying to turn the dispersion knob?

JAWORSKI: Yes. We'll run various tests with the Thomann model just to see how sensitive it is to dispersion. On the work we just finished doing, we found for low flow range the predicted profile was the most sensitive to the decay rate. The same thing was observed using the Orlob approach. So there it didn't matter what you were using, a tidal-average or a real-time model, you've got to know the reaction rates.

A final choice to be made is that of the coordinate system. A few studies have used an oscillatory coordinate system moving with the tide as an alternative to temporal tidal averaging. Coordinates have also been placed on a hypothetical volume of river water moving seaward (ref. 25). However most models use a standard Eulerian, or spatially fixed, coordinate system.

Because of the complicated nature of estuarine hydrodynamics it is almost necessary to develop a model for each individual case and verify it with extensive and intensive field measurements. Literally hundreds of models exist (see ref. 49 and 53), but only a very few have been accepted and verified for water management uses. Some of the most promising for Florida conditions will be reviewed briefly.

The DECS Model (41)

This was an early water quality model of the Delaware River developed for the FWPCA by Thomann and his associates (refs. 34, 41, 6). It is a steady-state tidally-averaged segmented water quality model. Complete diffusive tidal mixing in each segment is assumed. Inputs are geometry, net flows and BOD loadings, while DO is predicted. It has been updated to account for nitrogen also.

The steady-state feature makes it computationally rapid, but the unsophisticated hydrodynamic terms and coarse space and time scales are drawbacks. It is quite sensitive to the apparent diffusion coefficients, so must be carefully calibrated. It can be used for efficient rapid screening of a few water quality parameters, especially DO.

It has been used for the Delaware and Potomac Rivers, and a modified version was used for Hillsborough Bay.

The Dynamic Estuary Model (42)

This is an extension of the Bay-Delta Model developed for the

FWQA for the San Francisco Bay and Delta complex. Much of the formulation was done by Orlob and Shubinski of Water Resources Engineers. Feigner and Harris (12) provide a documentation. This differs from the DECS model in that the computations are carried out in real-time (Δt=5 minutes characteristically) and the model is two-dimensional in plan. The model is based upon a one-dimensional network of nodes and links which can approximate a shallow vertically-mixed system of interconnecting canals and embayments.

The DEM model is comprised of 3 parts. An estuarine hydrodynamic model calculates tidal heights, currents and discharges. A dynamic water quality model uses this information to compute mass transport of up to 5 constitutents. These can be conservative or not, and linked to one another, but must have first order decay characteristics. Finally, a steady-state water quality model similar to DECS is available. This is less reliable than the dynamic model, but is cheaper to run and to calibrate (since the results of the dynamic model can be used to estimate dispersion coefficients). The steady-state portion can be used for initial screening of alternatives.

Some drawbacks to the DEM are

1) vertical homogeneity is required
2) wind stress, lateral and vertical velocity variations within channels and changes in channel cross-section with the tides are neglected.
3) the quality model is sensitive to time step size (thru the apparent dispersion coefficient)
4) the ocean boundary condition of a particular water quality parameter must be specified explicitly over the entire

tidal cycle.

This model has been tested extensively for salinity variations. It is most applicable to shallow vertically-mixed systems with many islands and distributaries.

The Leendertse RAND Model (43-46)

This model is applicable for vertically well-mixed estuaries and coastal seas. The hydrodynamic equations are solved more rigorously and presumably are more accurate than the DEM results. The water quality portion uses an implicit-explicit scheme in which the equations are solved by incorporating their parameters directly into the hydrodynamic portion of the model, rather than using averaged results of the hydrodynamic calculations as imputs. It can handle up to 6 first-order nonconservative linked constitutents. Salinity has been checked in Jamaica Bay, and it has been used in Tampa Bay.

The Gulf Coast Models

Masch et al. (35) developed a model for shallow vertically-mixed embayments along the Texas coast. The hydrodynamic portion of the model, called HYDTID, employs a time-centered explicit scheme and a spatial net of about 800 square cells to compute average depths and velocities to input into the associated water quality portion which appears to be still under development (6). A package called SAL, which is available for conservative substances, has been verified for salinities in several Texas Gulf estuaries.

SWMM and SRMSCI

These models differ from the previous dynamic estuary models in that they accept transient inputs such as the quality and quantity of storm water inflow and provide transient solutions which tend to return to an average dynamic equilibrium. Selection of these models therefore depends on whether inputs are to be considered constant or transient.

The RECEIV block of SWMM can handle transient inputs to a vertically well-mixed estuary. The first version had a dynamic quantity package which was coupled to backwater curves, but treated quality parameters as being purely advective. An improved version called RECEIV2 can handle up to 6 linked non-conservative quality parameters. The RECEIV block is essentially an improved DEM model. An advantage of RECEIV is that constitutent concentrations at the ocean boundary are computed rather than explicitly specified.

The entire SWMM model system was designed to simulate urban stormwater runoff, so application of this model is particularly suited for the case of urban runoff entering an estuary.

SRMSCI is a modified version of RECEIV which can handle more quality parameters. See reference (48).

Huber et al. (57) describe an application of the RECEIV block to the St. Johns River in northeastern Florida. One particular advantage of the SWMM model is that it was developed at the University of Florida, so that expert advice is proximate.

MIT Finite Element Models

Dailey and Harleman (36) developed a vertically-averaged two-dimensional finite-element model. The advantage of this model is that the ocean boundary condition is easier to model and that irregular geometry can be more easily simulated. The quality solution is transient and can handle four constitutents: salinity, temperature, BOD and DO. Linkages were not included. This model is particularly suited to cases where steep concentration gradients exist, since these are liable to error from numerical dispersion in finite difference models.

Recent improvements to this model by Wang (58, 59, 61) have resulted in a renaming of the package. The model now consists of a hydrodynamic portion entitled CAFE-1 and an associated dispersion package called DISPER-1. Both use a finite element technique to solve the equations of motion for a two-dimensional vertically-mixed estuary. Both Users' Manuals and tapes are now available (51). This model has been applied to Boston Harbor (59) and Great Bay, N.H. (60).

Discussion of Estuarine Models

Several tested models exist which can be used to simulate estuarine quality for planning purposes. Unfortunately all of them require the prototype to be vertically well-mixed and are therefore inapplicable if this not be the case. In order to select the most desirable model it is necessary to decide if a steady-state or transient solution is required, and if the quality and quantity inputs are to be considered steady or transient. Steady-state models are less expensive to run and should be used in conjunction with transient models for screening purposes.

If the impacts of river basin management upon the estuary are to be considered, then an estuary model which is directly linked to a basin model is most desirable. At the present time only the SWMM model has this capability.

Only very few of the available models have been mentioned here, and the selection of the proper one will require a thorough search after the problem has been properly defined.

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Appendix

Two tabular compilations comparing urban runoff models
which were found in the literature
are included as an appendix

Table A-(1) MODEL CHARACTERISTICS BY ROESNER FROM (5)

UTILITY OF URBAN RUNOFF MODELS FOR VARIOUS STAGES OF STORMWATER MANAGEMENT PLANNING

	STORM	MITCAT	HYDROCOMP	EPA SWMM	SF-WRE
Large-Scale Planning (Alternative Screening)	Excellent	Good	Good	Poor	Poor
Intermediate Scale Planning	Poor	Excellent	Excellent	Excellent	Excellent*
Detailed Planning/Analysis (No Significant Backwater)	Poor	Excellent	Fair	Excellent*	Excellent*
Detailed Planning/Analysis (Complex Drainage Networks)	Poor	Poor	Poor	Fair	Excellent
Runoff Quality Simulation	Yes	No	Yes	Yes	Yes
Flow Computation	Rational Formula	Kinematic Wave	Kinematic Wave	Kinematic Wave+ Manning Equ. with Dynamic Continuity	Kinematic Wave+ Complete Eynamic Flow Equations

*The Runoff Model is best suited for these applications.

Table A-(1) References and Model Acquisition

STORM

Description

Roesner, L.A. et al., Water Resources Engineers. The Hydrologic Engineering Center of the Corps of Engineers and Department of Public Works/ City and County of San Francisco. "A Model for Evaluating Runoff Quality in Metropolitan Master Planning". ASCE Urban Water Resources Program Research Program, Technical Memorandum No. 23, New York, NY, April 1974.

Acquisition - in Public Domain

1. HEC/Corps of Engineers, Davis, CA.
2. WRE, Walnut Creek, CA.

MITCAT

Description

Harley, B.M., F.E. Perkins and P.S. Eagleson. "A Modular Distribution of Catchment Dynamics". MIT, Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics Report No. 133. Dec. 1970.

Aquisition - Proprietary

Resource Analysis, Cambridge, Massachusetts

HYDROCOMP

Description

Crawford, N.H. and R.K. Linsley. "Digital Simulation in Hydrology: Stanford Watershed Model IV" Stanford University, Palo Alto, CA, Department of Civil Engineering Technical Report No. 39. July 1966.

Table A-(1) continued

Acquisition - Proprietary

Hydrocomp International, Inc., Palo Alto, CA.

EPA SWMM

Description

Metcalf and Eddy, Inc., University of Florida and Water Resources Engineers, Inc. "Storm Water Management Model", U.S. nvironmental Protection Agency Report 11024 DOC 07171, 4 Volumes, Oct. 1971.

Acquisition - in Public Domain

Storm and Combined Sewer Technology Branch - EPA, Washington, D.C.

SF-WRE

Description

Shubinski, R.P. and L.A. Roesner, "Linked Process Routing Models", Paper presented at AGU Annual Spring Meeting, Washington, D.C. April 1973.

Acquisition - in Public Domain essentially

1. Division of Sanitary Engineering, Department of Public Works, City of San Francisco.
2. Water Resources Engineers, Walnut Creek, CA.

The following document gives, for the most part, a good and fair comparison of the capabilities of eleven urban stormwater models:

Bradstatter, Albin, "Comparative Analysis of Urban Stormwater Models," Battelle Memorial Institute, Richland, Washington.

Table A-(2) Model Characteristics Summary by Huber From (5)

Model	Surface Routing	Sewer Routing	Quality Routing	Degree of Sophistication of Surface Flow Routing	Degree of Sophistication of Sewer Flow Routing	Accurate Modeling of Surcharging	Flexibility of Modeling of Sewer Components	Explicit Modeling of In-System Storage	Treatment Modeling	Receiving Model Available	Degree of Calibration/Verification Required	Simulation Period	Availability	Documentation	Data Requirements
Rational Method	Peak Flows Only	Peak Flows Only	No	L	L	No	L	No	NA	NA	Usu. not verified	IS	NP	Good	L
Chicago	Yes	No	No	M	NA	NA	NA	NA	NA	No	M	IS	NP	Fair	M
Unit hydrograph	Yes	In combination w/surface	No	L	L	No	L	No	NA	No	H	IS	NP	Fair	M
Unit pulse	Yes	In combination w/surface	No	L-M	L-M	No	L	No	NA	No	H	IS	NP	Fair	M
STORM	Yes	In combination w/surface	Yes	L	L	No	L	No	Yes	No	L	LT	NP	Good	M
RRL	Yes	Yes	No	M	L-M	No	L	No	NA	No	M	IS	NP	Good	M
MIT	Yes	No	No	H	NA	NA	NA	NA	NA	No	M	IS	P	Fair	M
Battelle	Yes	Yes	Yes	L	M	No	M	Yes	No	No	M	IS	NP	Poor	M
EPA-SWMM	Yes	Yes	Yes	H	M	No	H	Yes	Yes	Yes	M	IS	NP	Good	E
WRE-SWMM	Yes	Yes	Yes	H	H	Yes	H	No	Yes	Yes	M	IS	P	Poor	E
Cincinnati(UCUR)	Yes	Yes	Yes	H	L	No	L	No	No	No	M	IS	NP	Fair	E
Dorsch (HVM)	Yes	Yes	No	H	H	Yes	H	?	NA	Yes	M	IS or separate	P	Poor	E
SOGREAH	Yes	Yes	?	H	H	Yes	H	?	?	Yes	M	IS	P	Poor	E
Hydrocomp	Yes	Yes	Yes	M	M	No	L	No	No	Yes	H	IS or LT	P	Fair	E
Illinois (ISS)	Yes	Yes	No	M	H	No	L	No	NA	Yo	M	IS	NP	Good	E

L=Low
M=Moderate
H=High
IS=Individual Storms

LT=Long term
NP=Non-proprietary
P=Proprietary
E=Extensive

Table A-(2) Urban Drainage Model Characteristics
Summary by Huber From (5)

Identification of Current Urban Runoff Models
and Representative References

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3. Unit Hydrograph	P.S. Eagleson, "Unit hydrograph characteristics for sewered areas", ASCE Proc., 88, (HY2), March 1962.
4. Unit Pulse	W.S. Grigg et al., "Metropolitan Water Intelligence Systems", Completion Report, Phase II, Water Resources Systems Program, Department of Civil Engineering, Colorado State University, June 1973.
5. STORM	Urban Storage Treatment and Overflow Model - STORM, HEC, U.S. Army Corps of Engineers, Davis, CA., Sept. 1973.
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7. MIT	Harley et al., A Modular Distributed Model of Catchment Dynamics. MIT Parsons Lab. Report No. 133.
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9. EPA-SWMM	Metcalf and Eddy, Inc., University of Florida and Water Resources Engineers, Inc. "Storm Water Management Model", U.S. Environmental Protection Agency Report 11024 DOC 07171, 4 Volume, Oct. 1971.
10. WRE-SWMM	Shubinski, R.P. and L.A. Roesner, "Linked Process Routing Models", Paper presented at AGU Annual Spring Meeting, Washington, D.C. April 1973.
11. Cincinnati(UCUR)	C.N. Papadakis and H.C. Preul."University of Cincinnati urban runoff model" Proc. ASCE, 98, (HY10) Oct. 1972.
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Table A-(2) continued

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FRESHWATER AND THE FLORIDA COAST:
REVIEW AND UPDATE - SOUTHWEST DISTRICT

by

Daniel P. Spangler[1]

ABSTRACT

Fundamental to an understanding of freshwater and the Florida west coast is a review of the surface snd subsurface geology, particularly the structure, stratigraphy, lithology, geomorphology, and chemical aspects, for it is here - in addition to climate and vegetation - that "natural" characteristics of water quantity and quality are controlled. The oldest exposed rock unit in Florida (Levy County) is the Avon Park Limestone (Late Middle Eocene). This unit crops out on the crest of the Ocala Arch and is surrounded on portions of the flanks by suceedingly younger units, i.e. Ocala Group (Late Eocene), Suwannee Limestone (Oligocene), Tampa Limestone and Hawthorne Formation (Miocene). Underpinning, essentially paralleling and slightly to the east of the Ocala Arch is the huge Peninsular Arch, an immense northwest-trending, subsurface, anticlinal structure of Pre Cambrian ot Triassic igneous and metamorphic rocks. Draped over the crest (-3200 feet MSL) of the Peninsula Arch are Mesozoic units (mostly evaporites, dense limestones and dolostones, but not containing fresh water) which thickens outward in all directions from 1600 feet to more than 12,000 feet in south and northwest Florida. The overlying Cenozoic formations range in thickness from near 1700 feet at the crest to more than 6,000 feet in south Florida. The lower three units, Cedar Keys Limestone (Paleocene), Oldsmar Limestone and Lake City Limestone (Lower and Middle Eocene) are not exposed, and known only through cuttings and cores. Overlying the Hawthorn Formation is a very variable and frequently heterogeneous thickness (0-200 feet) of sands, clays, marls, shale beds, phosphate bearing units, hardpans and organics of Pliocene, Pleistocene and Halocene Age. Generally these more or less unconsolidated units constitute the shallow aquifer, while the beds of lowly permeable clay, clayey marls, and silts (generally Hawthorne), serve as a confining unit above the commonly solution-riddled Tertiary limestones and dolomites collectively known as the Floridan Aquifer.

Topography is largely controlled (particularly the coastal area) by a series of marine terraces associated with sea level changes during the

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Pleistocene. At least five have been recognized within 200 feet MSL. The youngest, the Pamlico Terrace, forms a relatively flat coastal lowland, is generally less than 20 feet MSL, and contains the upper limits of our modern estuaries. A well perserved scarp with a base at 20 to 25 feet MSL along with other features mark the shorelines of the Pamlico sea.

The Floridan Aquifer is the principal storage and transmitting component between the Green Swamp High and the west coast. The potentiometric surface and thus the depth to the base of potable water is controlled by structure, topography and rainfall. The amount of fresh water in streams, lakes, springs, swamps, sinks and aquifers and the boundaries contributing fresh water to them fluctuate in response to recharge and discharge and universal statements are almost impossible to formulate which would cover the intricate interrelationships from one area to another. For example, the percentage of runoff, derived from groundwater ranges from near 100 percent in the northern part of the district (mostly springs) to approximately 10 percent in the middle to southern part. Many published values of transmissivity and storage for the shallow aquifer(s), and the Floridan Aquifer, or zones within, plus values of leakance for the aquiclude vary because of facies changes, thicknesses, and post-depositional changes. Large discrepancies are noted between values derived by flow-net methods vs. pump test or other methods.

The quality of water in the shallow and deep aquifers is generally good, the former more acidic and lower mineral content. Both have low mineral content in recharge areas and increase to where concentration approaches sea water near the coast. Generally, water in wells deeper than 100 feet near the coast contains chloride in excess of 250 mg/l.

GROUNDWATER FLOW

by

Joel G. Melville[1]

INTRODUCTION

As water moves through the tortuous skelton of an aquifer, an equilibrium is established between the viscous drag and the propulsive head, h.

$$h = p/\gamma + z \tag{1}$$

where

p = pressure (lb/ft^2)

γ = weight density of fluid (lb/ft^3)

z = vertical elevation relative to an arbitrary fixed datum (ft)

Under laminar flow conditions, groundwater flow is accurately modeled by Darcy's Law:

$$v = -K\ \partial h/\partial \ell \tag{2}$$

where

K = hydraulic conductivity (ft/sec)

ℓ = coordinate in direction of flow (ft)

v = discharge velocity (volumetric flow rate per unit area of porous media)

Darcy's law can be started in vector form as a model of more complex 3-dimensional flow situations. With equation (2), the physical principle of conservation of mass determines the governing equations which describe the movement of groundwater.

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The word model already been used many times and deserves some definition in the context of this paper. Basically, a groundwater model is a mathematical statement based on observation and understanding of the phenomenon which then can be used for predictive purposes. The complexity of the model can vary from a simple arithmetic statement to a 3-dimensional, time dependent, dispersion, thermal computer simulation. Darcy's law is a model. It should be pointed out that the model may not represent the details of groundwater flow. The discharge velocity in equation (2) does not model the sinuous point-to-point variation of groundwater flow, but (2) does model the average flow per unit cross section which permits prediction of water tables, storage, runoff, recharge, etc.

In this paper analytical and numerical models are discussed. The list of models is not intended to be complete, but rather representative of current capabilities. The level of the presentation is introductory and fundamental and not directed toward working groundwater hydrologists. The goal of the paper is to give managers, biologists and economists an overall picture of groundwater analysis.

The ultimate source of all groundwater is precipition which seeps through the surface layers to the aquifer. The aquifer, or water bearing geological formation, then acts as a large, nearly rigid sponge which distributes the water in time and space as the water makes it way toward the oceans. Particularly in Florida where many streams are formed by artesian springs, there is a significant interaction of stream flow and groundwater flow. Darcy's Law, equation (2), shows that groundwater flows toward regions of lower head. Thus, when the water table (equivalent to head) is higher than the stream surface elevation, then flow is toward the stream. When the water table is lower (for example, during a heavy storm when surface runoff has greatly increased in the stream depth), the water flows to the aquifer. Careful study of stream basin geology and the water table must precede a successful uitlization of a stream for water supply.

ANALYTICAL MODELS

The Theis equation (Theis, 1935) predicts the head as a function of the rate and duration of pumping of a single well in a confined aquifer.

$$h = h_o - \frac{Q}{4\pi T} \int_u^\infty \frac{e^{-x}}{x} \, dx \qquad (3)$$

where

h_o = the undisturbed piezometric surface (head) (ft)
Q = well discharge (ft^3/sec)
T = transmissivity of the confined aquifer (ft^2/sec)
s = storage coefficient
$u = r^2S/4Tt$
r = radial position from the well (ft)
t = time (sec)

The restrictions of equation (3) are that the aquifer properties must be constant and the aquifer must be of infinite lateral extent (i.e., any other disturbances such as wells, streams, and geological boundaries must be sufficiently far from the well. Equation (3) can be used in the "inverse problem", the calculation of aquifer parameters S and T based on time and observation well head measurements. The use of image theory with equation (3) permits the calculation of heads which are influenced by water bodies and impervious boundaries which penetrate the confined aquifer. Also, well fields can be analyzed by superposition of equation (3) for several different wells.

A bank storage analytical model quantifies an interaction of surface and groundwater flow. Glover (1974) shows the derivation of the model shown in Figure 1. The accumulated flow of groundwater to the reservoir, q_o, is calculated.

$$q_o = H_o e \quad \frac{4\alpha t}{\pi} \qquad (ft^3/ft) \qquad (4)$$

where

α = KD/e (ft^2/sec)

t = time measured from the time of instanteneous reservoir level change (sec)

e = voids ration of the aquifer

H_o = undisturbed water table elevation (ft)

Of course there are many simplifying assumptions necessary for the derivation of equation (4). For example, if the bank storage contributes to water level change or if there are nonuniform aquifer parameters then adjustments must be made. Observation of water table changes and correlationwith stream surface elevation changes are necessary for accurate modeling of bank storage. Walton (1970, p. 183-187) discusses the interaction of groundwater levels and stream stage hydrographs more completely showing the variation with time of bank storage and groundwater runoff.

Because of decreased natural recharge due to urbanization and increased groundwater use, artificial recharge may become necessary. One of the most successful recharge methods is with seepage ponds which serve the dual purpose of stormwater runoff reduction and increased groundwater recharge. In Figure 2, vertical leakage controlled by head differences, permeability, and surface area; is shown creating a groundwater mound which in time decays to contribute to the groundwater supply. The design and performances of seepage ponds particular to Florida are discussed by Glass (1976). Analysis and discussion of seepage ponds are presented in Walton (1970, p. 368-373) and Glover (1974). Hantush (1967) presented the original analysis of groundwater mounds resulting from uniform percolation.

Figure 3 shows the natural state of a freshwater lens "floating" on the saline aquifer. This lens of freshwater, which is the source of the fresh groundwater supply in coastal areas, depends on the dynamic condition of continuous freshwater recharge. Indeed in a completely static situation, the salt-freshwater interface would eventually become horizontal. Then, because of molecular diffusion and mixing all water would become saline. Thus, the seaward flow of fresh groundwater is not wasted water ; the seaward flow is necessary to maintain the freshwater lens. In Figure 3, the Ghyben-Herzberg relationship

$$z = 38\ h$$

is based on hydrostatic theory (DeWiest, 1965, p. 295). This equation implies, of course, that a one foot depression of the freshwater table due to pumping results in an upconing of 38 feet by the saltwater. While quite simplified, the Ghyben-Herzberg model is a good rule of thumb and usually estimates intrusion on the safe side, i.e., the G-H model estimates a more severe intrusion than that measured or predicted by more sophisticated models (Hubbert, 1940, Henry, 1959, Cooper, 1959). Intrusion also occurs in confined aquifers although Figure 3 is shown for a free surface or water table aquifer. In confined aquifers, a wedge of saltwater advances with the leading toe of the wedge at the bottom of the aquifer, (Harleman, 1962).

Mathematically, the Darcy velocity or discharge velocity of equation (2) is quite far removed from the tortuous velocity field which exists in the rigid skeleton of the porous media as shown in Figure 4. It is this spatial variation of the velocity which accounts for dispersion in groundwater flow. Imagine a small zone injected with a dye of concentration, c_0, in an aquifer. As the flow proceeds, it is clear that longitudinal and lateral "spreading" of the dye zone will occur. This dispersion is the primary cause for the lack of a distinct fresh-saltwater interface. Referring again to Figure 3, as the freshwater moves seaward adjacent to the interface, considerable lateral diffusion occurs. Dispersion is complicated and generally increased with high Reynolds number, time dependent (tidal) effects, and anisotropic aquifer properties (Harleman, 1962).

Another interface and dispersion problem occurs with injection wells. Injection wells serve three purposes: (1) inhibit or reverse intrusion, (2) dispose of runoff effluents and wastes, (3) create temporary storage. Figure 5 shows the creation of a favorable freshwater lense with 4 injection wells and one pumping well. In contrast, Figure 6 shows an unfavorable situation where saltwater is contaminating the pumping well. Aside from the regulatory and political unknowns of injection; lense formation, deformation, and stability under the stresses of pumping and existing groundwater flow are difficult problems. Kimbler et al. (1975) have proposed the cyclic storage of groundwater. As imported water costs increase, the expense of injection will become justified when the water quality problems can be overcome.

NUMERICAL MODELS

A few specific numerical models are discussed. The fundamental advantages of numerical models is that they can simulate flows in complex, irregular domains. Also in flow problems where dispersion and geothermal effects are important, very few analytical models are available. The USGS Circular 737 provides a list and evaluation of current numerical models.

In Figure 7, a hypothetical basin is sketched. The flow problem in the plan view can be expressed in terms of the x-y coordinate system.

Clearly, the natural boundaries in this example are not simple geometric shapes. If the river was reasonable straight, intersecting the lake at a right angle, etc., then an analytical model could be attempted. Numerical or computational models are easily applied to complex geometries in the x-y plane. Similarly, geometric complications occur in the cross section as shown in Figure 7. The aquifer transmissivity, T = Kb, is often variable. Likewise, numerical models can simulate these difficulties. Of course, the use of a more sophisticated model requires more sophisticated data.

Numerical models also have application when the governing equations of the flow are coupled with more equations. For example, the usual confined aquifer flow problem is express in terms of single partial differential equation,

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{T}\frac{\partial h}{\partial t} - \frac{W}{T} \qquad (6)$$

which is based on Darcy's Law and conservation of mass (Walton, 1970, p. 192)

where

W = recharge/unit area.

However, when other factors become significant such as water quality variations, geothermal effects, and moving boundaries (such as intrusion); then more equations become involved. As the number of governing equations increases, the possibility of analytical solution decreases and numerical models become necessary.

The choice of a numerical model depends primarily on the user objectives. Budget and time contraints are significant. The cost of modeling with the most sophisticated models and collection of the necessary data is expensive.

But modeling costs are a small percentage when compared with the cost of a water supply system. Many decisions must be made immediately, and the 3 months to a year necessary to implement a complex model may be unreasonable. Thus, it is the time contraint which is often more significant. A point made recently at the Groundwater Model User's Workshop, April 6-8, 1977, Tampa, Florida (sponsored by the USGS, Southwest Florida Subdistrict and the Holcomb Research Institute) was that a large gap has developed between sophisticated computer models and "in field" techniques. With the development of programmable calculators, the gap will certainly close. Other factors influencing the model choice are: capabilities of personnel, availability and accuracy of data, and the desired accuracy of the output. Biswas (1976) lists 5 general inputs necessary for aquifer modeling:

1. hydrogeological boundaries
2. quantification of existing recharge
3. existing groundwater flow
4. existing groundwater quality
5. source and quantity of pollutants.

SPECIFIC NUMERICAL MODELS

Five specific models will be presented. In Figure 9, an aquifer evaluation model due to Pinder & Bredehoeft (1968) is depicted. The sketch on the left of Figure 9 is schematic indicating that arbitrary boundaries in the x-y plane can be handled with both head (rivers, lakes) and discharge (impermeable) boundaries. Variable transmissivity and leakage through the confining layer can be simulated. The section view of the confined aquifer is shown on the right of Figure 9. The output of the model is the head, or potentiometric surface. This model requires considerable data. In their publication, Pinder & Bredehoeft describe the procedure used to predict long term pumping effects in a small river basin. Short term pumping and observation well data was collected. Then the model was run 37 times, each time adjusting the aquifer parameters based on modeler's intuition and hydrologist's experience until the model output matched the observed short term data. Finally, the model was run, with the adjusted transmissivities, to predict long term pumping effects on the aquifer.

The second model (Frind & Pinder, 1970) deals with the inverse problem, i.e., calculation of aquifer transmissivity based on observed heads. The goal of this model is to reduce the guess-work assocciated with the adjustments necessary in model no. 1. The input necessary for this model is an approximation of the head at every point in the two-dimensional domain shown in Figure 10. Also, this net discharge across some line, Γ, must be known.

The third model (Bredefoeft and Pinder, 1970) is an extension of the first model which simulates flow in several layered aquifers when there is leakage through the confining layers. In Figure 11 just two aquifers are shown. As indicated, the x-y geometry is again arbitrary as discussed in the example of Figure 7. The outputs of this model are the heads in all the aquifers. Certainly the data necessary for this model are numerous and any adjustment of parameters as discussed with model no. 1 would be extremely difficult.

The fourth model is the INTERCOMP model (1976) which was developed to simulated deep waste injection. It is a model in the development stage which is three-dimensional, i.e, it considers flow in the x, y and z-directions. It also includes dispersion and geothermal aspcects as shown in Figure 12.

Finally, the fifth model is a saltwater intrusion model (Pinder & Cooper, 1970) which simulates the transient movement and dispersion of saltwater fronts. This model does predict saltwater recirculation and salinity profiles similar to those observed in coastal aquifers. The model is classified operational by USGS Circular 737.

CONCLUSION

The discussed list of analytical and numerical models is incomplete. An overview of modeling has been presented. The impression of "exactness" associated with computer output should have been restrained with the presentation. There is probably more engineering judgement made of less understood phenomena in computer modeling than analytical modeling. There are models which can predict aquifer response, with desired accuracy, to hydrologic stresses. The output of these models should provide a valuable and necessary input for water management decisions.

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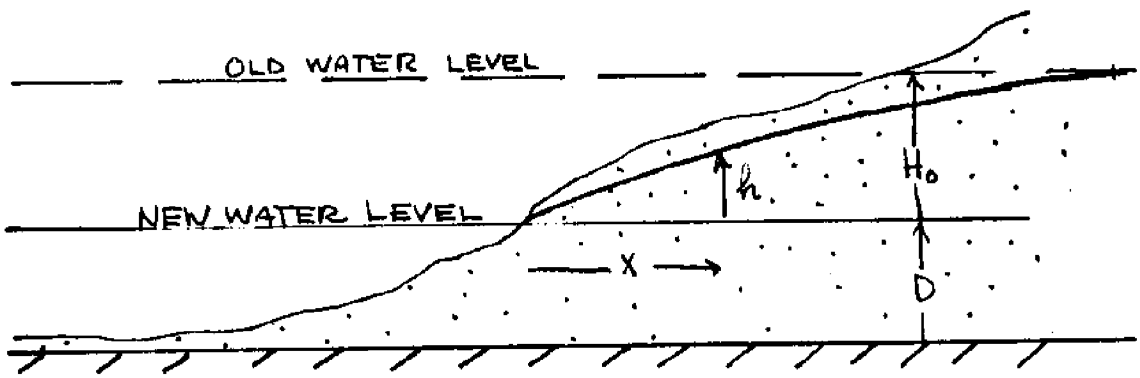
BANK STORAGE (Glover, 1974)



$$q_o = H_o e\sqrt{\frac{4\alpha t}{\pi}}$$

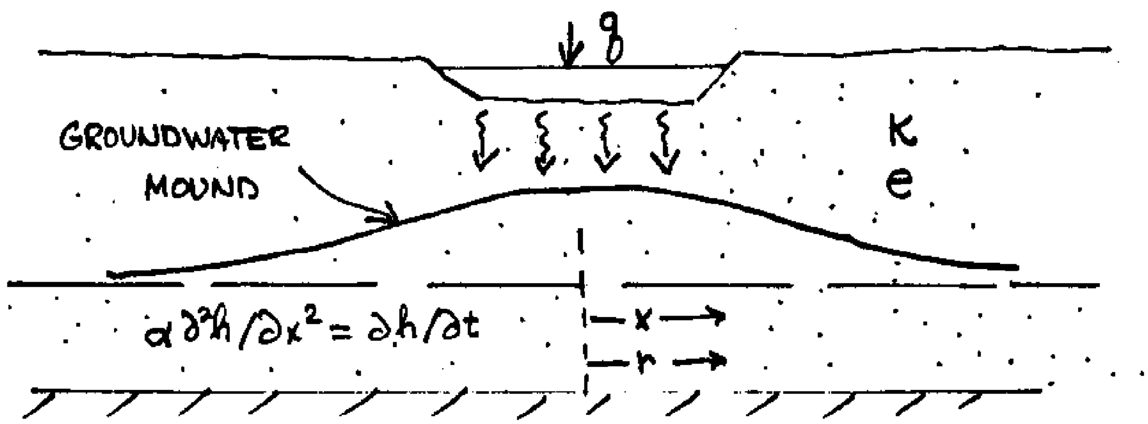
$h << D$

$$d = \frac{KD}{e}$$

Reservoir water supply applications in severe droughts
"exact" numerical model (W. T. Moody, 1962)

FIGURE 1

STORM WATER SEEPAGE PONDS
Glover, 1974
Glass, 1976



Glass (1976) - literature review, pond inspection (Orange and Marion Co.), design oriented mathematical and numerical analysis, size, clogging, groundwater pollution.

FIGURE 2

SALT WATER INTRUSION

(decreased or reversed natural freshwater flow seaward)

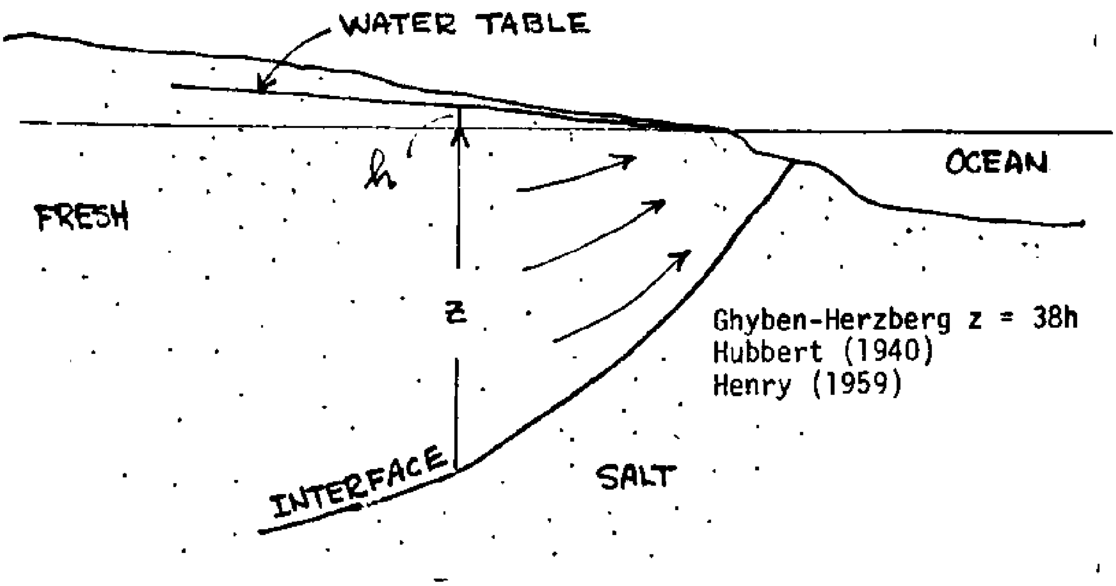
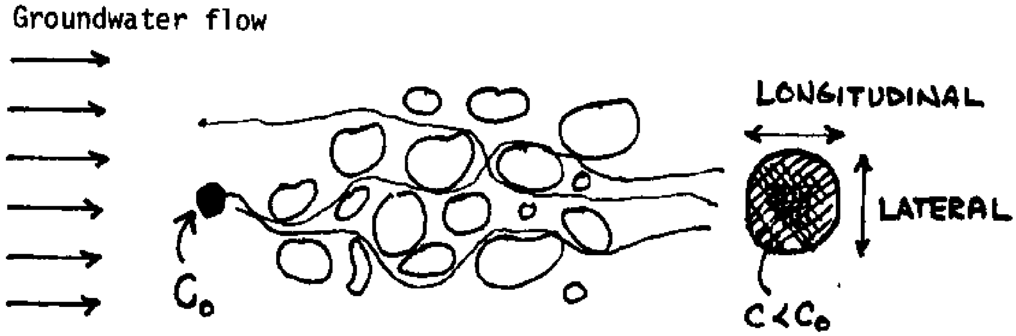


FIGURE 3

DISPERSION



1. laminar or turbulent (high velocity or cavernous aquifer)
2. time dependent (tidal effects)
3. nonhomogeneous or a isotropic

FIGURE 4

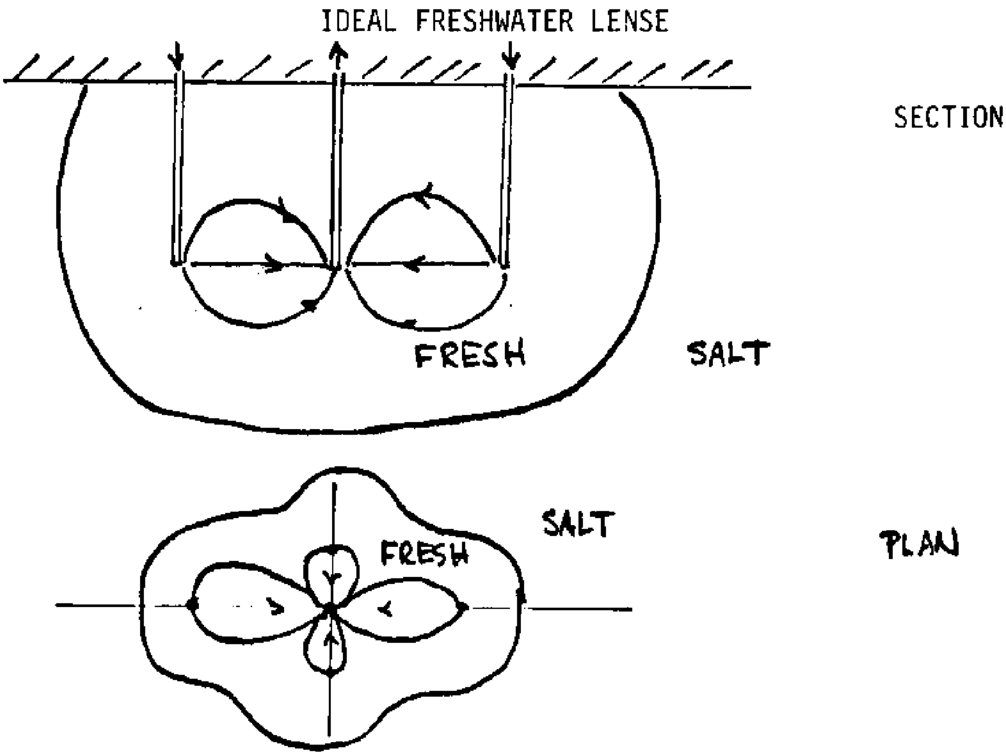


FIGURE 5

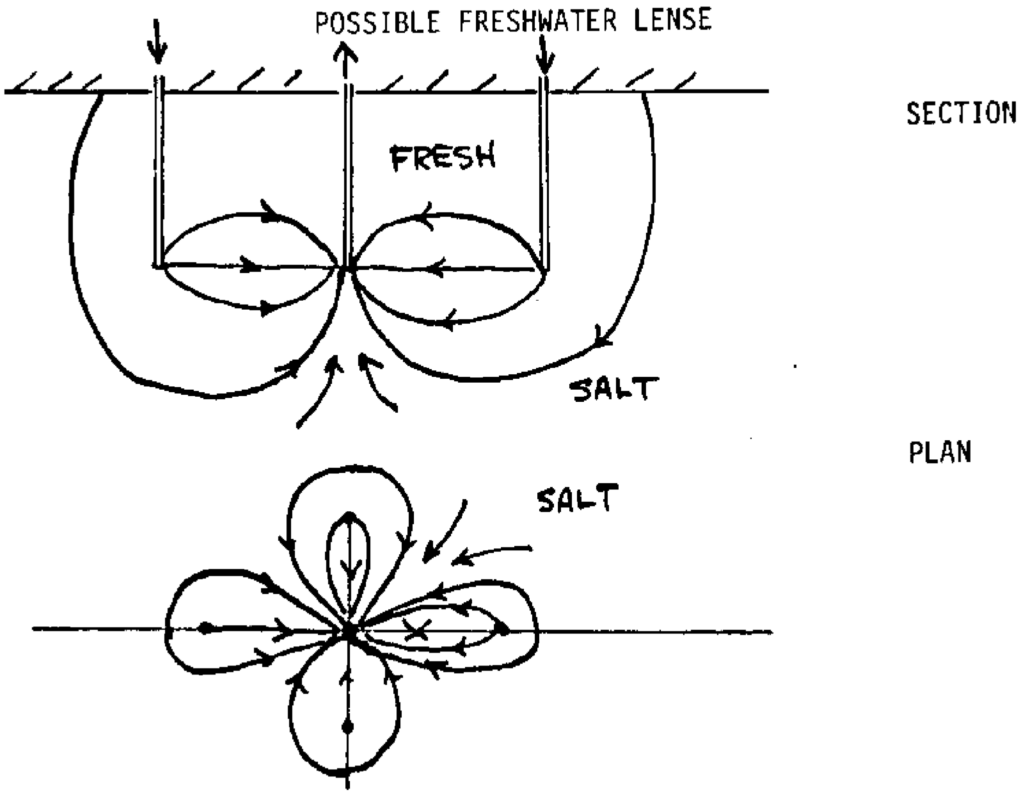
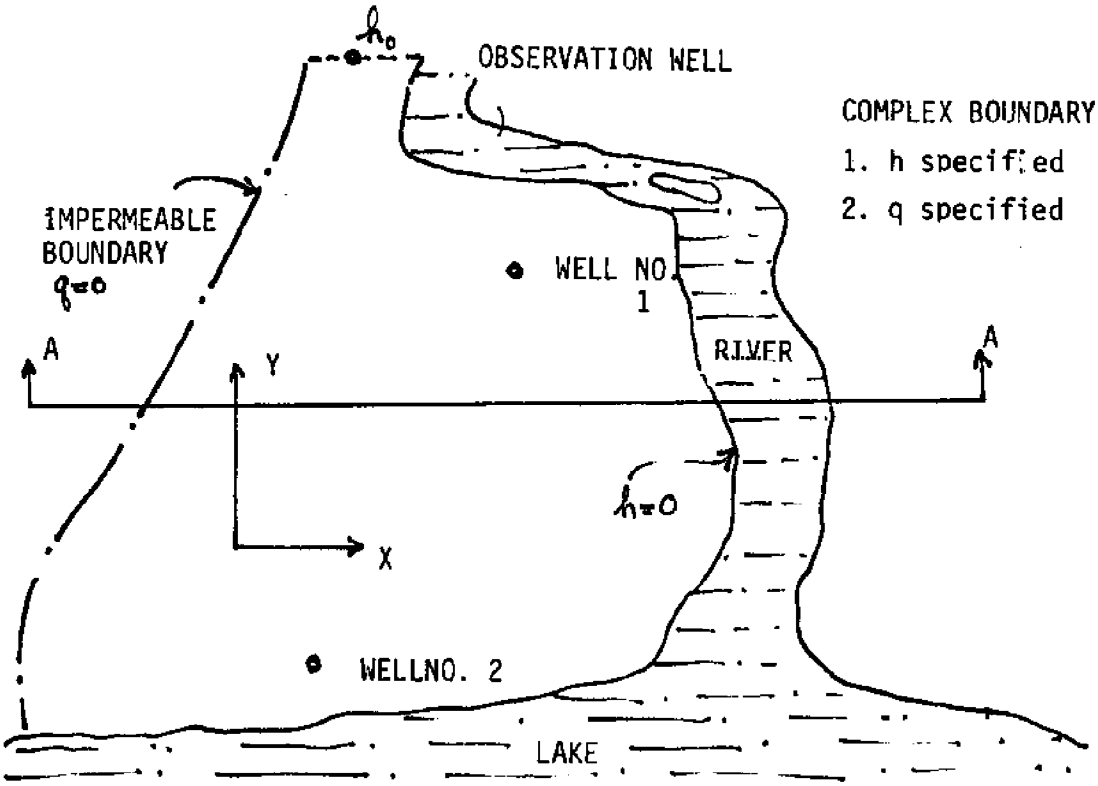


FIGURE 6



h_0
OBSERVATION WELL
COMPLEX BOUNDARY
1. h specified
2. q specified
IMPERMEABLE BOUNDARY
q=0
WELL NO. 1
A
Y
RIVER
A
h=0
X
WELLNO. 2
LAKE

FIGURE 7

T = kb = transmissivity

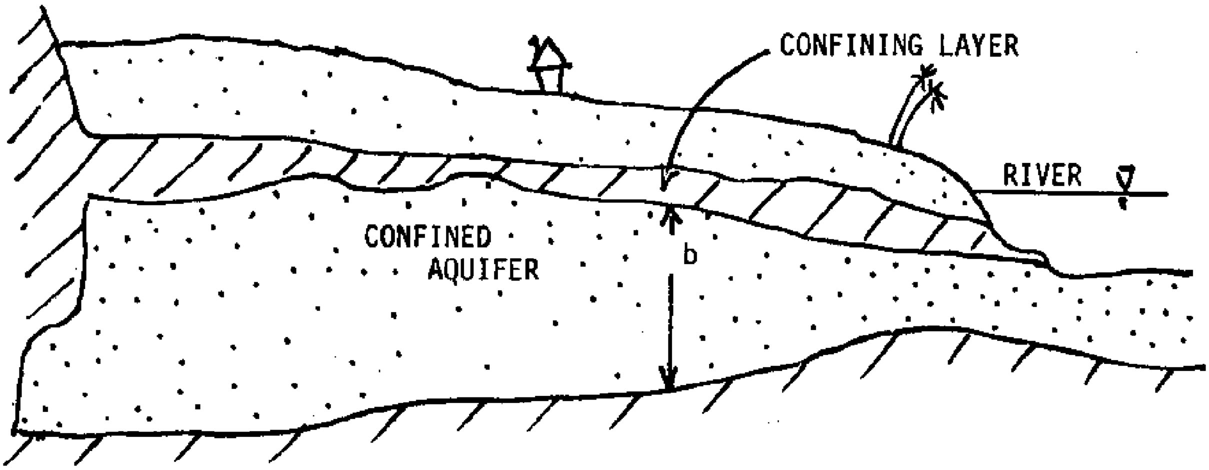
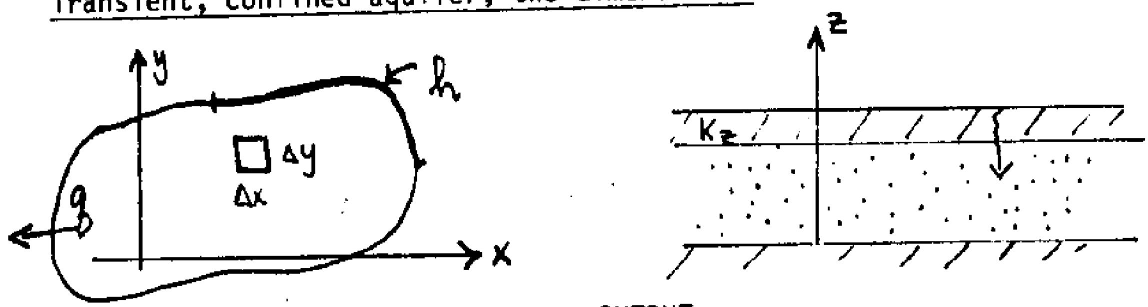


FIGURE 8 SECTION A-A

MODEL NO. 1 AQUIFER EVALUATION (Pinder and Bredehoeft, 1968)

Transient, confined aquifer, two-dimensional



INPUT

T_{xx} (x,y)

T_{yy} (x,y)

Boundary conditions
 head
 flow

K_z

Δx, Δy, Δt

OUTPUT

h(x,y)

METHOD

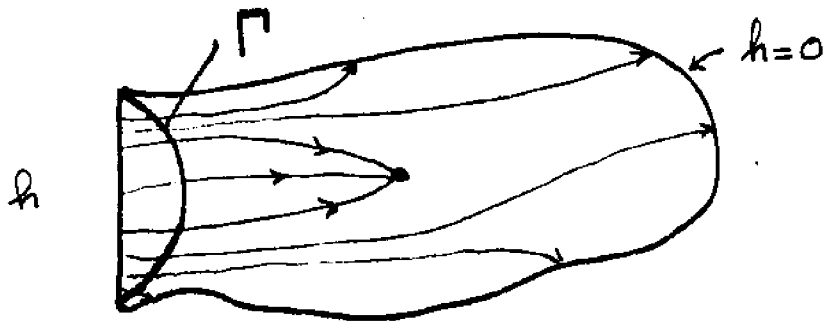
Implicit finite difference

*"Adjust" aquifer parameters to match short term pumping data.

FIGURE 9

MODEL NO. 2 INVERSE PROBLEM OF AQUIFER TRANSMISSIBILITY
(Frind and Pinder, 1973)

Steady, confined, two-dimensional isotropic



INPUT

$h = h(x,y)$

The transmissibility or discharge must be known on Γ.

OUTPUT

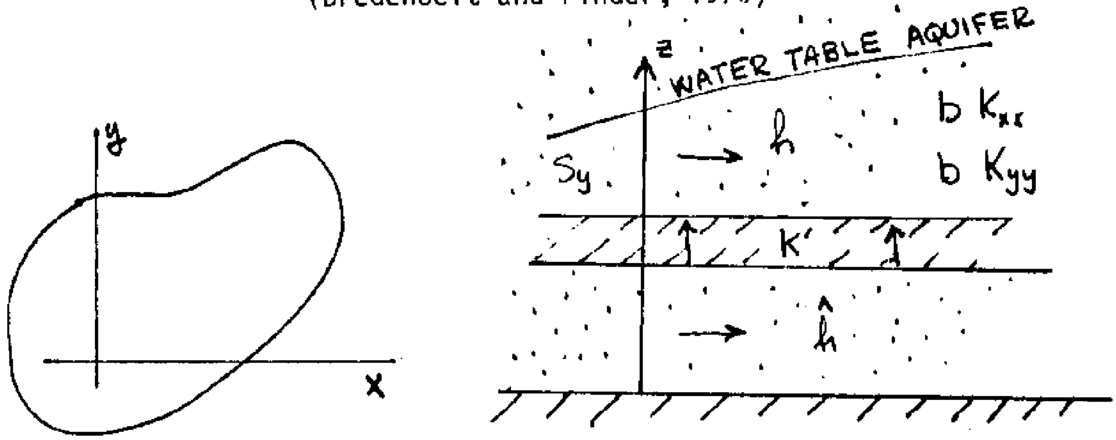
$T = T(x,y)$

METHOD

Galerkin finite element

FIGURE 10

MODEL NO. 3 QUASI-THREE-DIMENSIONAL MODEL
(Bredehoeft and Pinder, 1970)



transient, two-dimensional (with allowable vertical flow through confining layers)

OUTPUT h(x,y) and ĥ(x,y) - any number of layers

FIGURE 11

MODEL NO. 4 INTERCOMP - LIQUID WASTE DISPOSAL (1976)

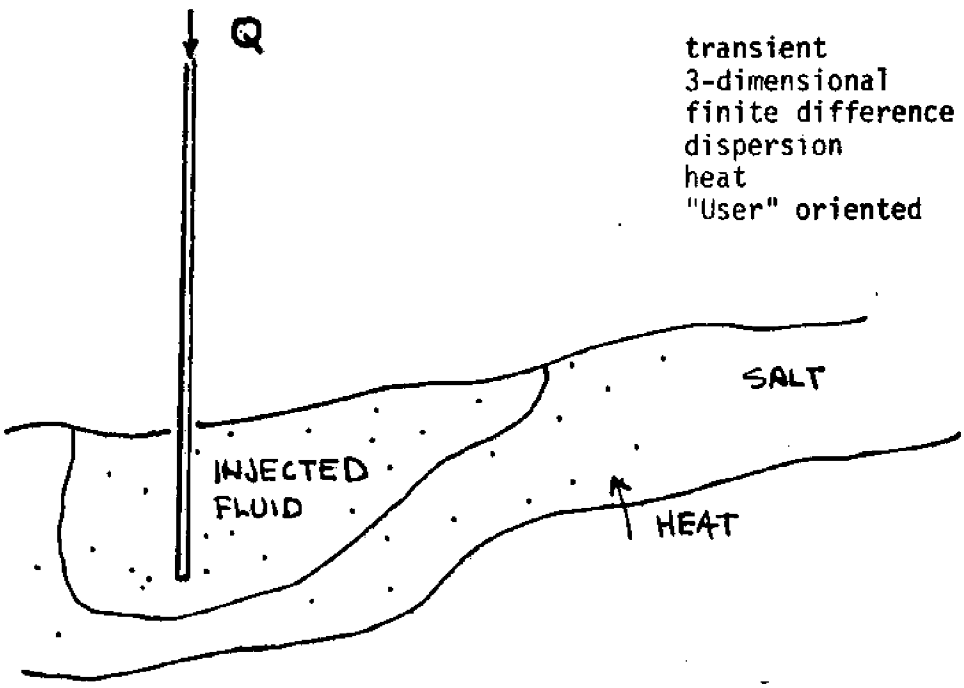
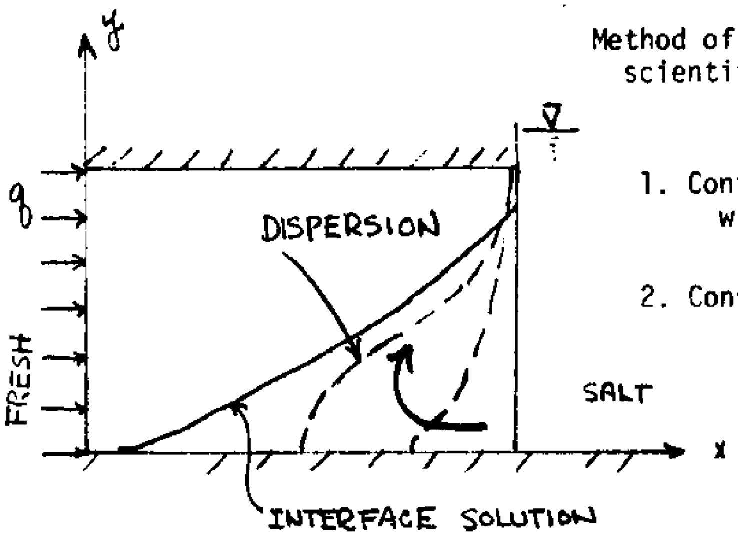


FIGURE 12

MODEL NO. 5 SALT WATER FRONT (Pinder and Cooper, 1970)

transient, dispersion included



Method of characteristics, scientific program

1. Continuity of equation with Darcy's Law

2. Conservation of salt mass

FIGURE 13

THE MARINE ECOSYSTEM FROM AN ENGINEERING VIEWPOINT

BY

Robert M. Snyder, P.E.[1]

INTRODUCTION

All development in the coastal zone sooner or later passes through the purview of engineers. Since the advent of "environmental awareness" the engineer's role has expanded to include impact of development on the total hydrological cycle and the concomitant influence on aquatic environments.

Environmental engineering, as such, is in its infancy. There are as yet no "cookbooks" like those we have for many aspects of electrical, mechanical and civil engineering. The hydro-bio-chemical inter-relationships are complex and our knowledge, even within well defined subject areas, is often inadequate to reliably predict the quantitative influence of our actions even if the inter-relationships were well understood.

In addition to these uncertainties of science, there have developed certain doctrines that are heavily promoted by the "reflex environmentalists" and seldom questioned publicly. These doctrines are not completely dissimilar to the theory of geocentricity for the questioning of which Galileo earned pontifical dissatisfaction and house arrest in spite of his warning that it would be "a terrible detriment for the soils if people found themselves convinced by proof of something that it was made then a sin to believe."

DOCTRINES OF ECOCENTRICITY

I can readily identify three such doctrines of "ecocentricity" which deserve greater public scrutiny and honest

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[1]President, SNYDER OCEANOGRAPHY SERVICES, Jupiter, FL 33458.

consideration by scientists, engineers and coastal zone management personnel. I will list the three and deal briefly with each one by offering observations from within the environmentalist camp who have no engineering or development axes to grind. In reaction to the "ecocidal" jargon of the modern Malthusians, I will call these miscreant beliefs the Detrimental Doctrines of Ecocentricity:

Doctrine #1: *The balance of nature is delicately poised.*

Doctrine #2: *Nature knows best.*

Doctrine #3: *The use of numerical models is the only valid approach to analysis of complex ecosystem interactions.*

Let me emphasize that I have no desire or intention to polarize thinking at the opposite end of the spectrum but merely to point out that it can be detrimental not to believe something we find convinced by proof to believe.

Regarding Doctrine #1, Lord Ashby - a Fellow of the Royal Society, one of the world's leading botanists and educators, and for three years a member of the Royal Society on Environmental Pollution, stated:

> *"The notion that the 'balance of nature' is delicately poised and easily upset is nonsense. Nature is extraordinarily tough and resistant, interlaced with checks and balances, with an astonishing capacity for recovering from disturbances in its equilibrium."*(1)

Regarding Doctrine #2, Rene' Dubos - professor emeritus at Rockefeller University - in response to receiving the first Tyler Ecology Award, remarked as follows:

> *"Nature is like a great river of materials and forces that can be directed in this or that channel by human intervention. Such intervention is justified because the natural channels are not necessarily the most desireable, either for the human species or for other species. It is not true that 'nature knows best'. It often creates ecosystems that are inefficient, wasteful, and destructive. By using reason and knowledge, we can manipulate the raw stuff of nature and shape it into ecosystems that have qualities not found in the wilderness."*(2)

Regarding Doctrine #3. This doctrine is a bit more subtle and can be best illustrated by use of example. In *THE LIMITS TO GROWTH* sponsored by the Club of Rome, the bottom line was that without the equality of the rates of birth and death and without the equality of capital investment and capital depreciation, the economic and industrial systems of affluent countries would collapse about the year 2100. Upon examination, it was shown that many of the assumptions fed into the computer were..

> "*not scientifically established and the use of data was often careless and casual.*" (3)

For example, one of the inputs fed to the computer was the reserve estimates published by the U.S, Bureau of Mines which warned that 80% of the data had a confidence level of less than 65%. This tremendous error band was withheld from the computer. One need only to contemplate the influence of error at the front end of an exponential function to appreciate the potential error in the output. It is the difference between 1,000 megawatts of useful nuclear energy and 1,000 megatons of destruction. A difference of somewhat more than modest import to the consumer. Regarding such numerical predictions made by extrapolating trends, Lord Ashby comments:

> "*...computers have made this sort of long-range forecasting not more reliable, but more dangerous; for the computer confers an impression of precision and determinism upon the assumptions fed into it, and this meretricious treatment gives the assumptions an unwarranted air of accuracy.*" (1)

Somewhat closer to home to the group assembled here, is numerical modeling of oxygen distribution in a residential canal system. I have been provided with such a model as an example of the type of analysis apparently sometimes used to make management decisions influencing coastal zone development. The model makers forthrightly point out that, assuming a 95% probability of correctness of some 17 interrelated hypotheses, the resulting predictions would have a probability of correctness of only 40% (more accurately, 42%). One of the hypothesis involves the reaeration coefficient which, for a given canal could conceivably vary over two orders of magnitude, ie. a 1% probability of correctness.(4) Assuming the remaining 16 hypotheses do have a 95% probability of correctness, the probability of correctness of the final result would be 0.4%. The authors point out that this model, or any model, to be useful, must be verified by actual field measurements. But with such a complex model even a thorough verification may only be good for a specific canal under specific conditions. The point is this: the model makers or users may well understand all this, but once the computer results have been distilled to represent one of many inputs to a managerial decision, the "impression of precision and determinism" will very likely over-power any feeling of honest uncertainty.

In March, 1976, the National Commission on Water Quality (NCWQ) reported:

> *"We are encouraged that, in many areas of the country, the water is not only improving, but improving faster than some had expected."-*

partial refutation of Doctrine #1. The report continues:

> *"We also find that there is still a major lack of adequate information. We simply do not know enough."-*

a reflection on Doctrine #3. Abel Wolman*in *SCIENCE* (5) comments:

> *"Areas of ignorance abound in virtually all of the fields with which we are concerned. Decision making is an exercise in which two extremes compete. In some cases, insistance on scientific underpinning, no matter how meager, prevails. In others, pressure for action, without understanding, is by no means uncommon. A middle ground between the perfectionist and the opportunist is not easy to maintain in the present climate of desire for speed in regulatory action."*

But this middle ground is exactly where competent engineering dwells. And by a competent engineer, I mean one who knows enough to acknowledge his ignorance but understands enough to apply sound principlestoward achieving the desired goals with appropriate safety factors.

A LOOK BACK

Aerospace and nuclear engineering aside, most of what we do today is still based on principles formulated between 40 and 200 years ago. In hydraulics especially, much of our data base is empirical and the present challenges dealing with sluggish, alternating current canal hydrodynamics is best attacked in large part by extending our empirical knowledge through experiment. Numerical modeling in this area is a valuable learning tool in that, with proper judgment, it can be used to put bounds on a particular parameter or to indicate trends associated with complex interactions. In many cases we gain insight by observation and deduction, eg. water flows downhill: therefore a continuous slope should transport water in a downslope direction.

* Co-recipient of the Tyler Ecology Award with René Dubos and Charles S. Elton.

A backward journey of about 2000 years may lend some perspective to my argument.

- The first overhead aquaduct was constructed in Rome in the year 144 B.C.
- An overhead aquaduct constructed in Segovia, Spain in the first century A.D. is still in working order.
- The first formal education in civil engineering was instituted in 1747 - nearly 19 centuries after successful construction of the first overhead aquaduct.

How about theory?

- In the first century A.D., Hero of Alexandria correctly described valid streamflow measurement techniques. This was largely ignored throughout the next 16 centuries during which time it was agreed that the quantity of flow (Q) was equal to the cross-sectional area (A), ie. $Q = A$.
- In 1628 Castelli (a student of Galileo's) successfully refuted $Q = A$ in favor of the now familiar $Q = vA$, although Leonardo had conducted accurate velocity - distribution measurements a century earlier.

With these humbling bits of information to digest, let us turn back to the 20th century with a hopefully less encumbered mind and take a rational look at development in our coastal zone.

THE RATIONAL APPROACH

Advances in engineering are brought about by the same mechanism as advances in science. This is by asking: "What if?" As we have seen, successful engineering can preceed successful science because engineers are concerned primarily with results within an acceptable performance envelope, where it is the goal of science to gain explicit understanding. Fortunately for the engineer, the systems of nature are not highly tuned (as Doctrine #1 would have it) and obey their own laws rather than those of a theoretician or legislator. Nature has no concern with simplifying assumptions and, outside of atomic physics, shows no discontinuities of behavior. F still equals ma in the coastal zone although $E = mc^2$ may influence our local heat budget.

Before going further, I must iterate my position. I do not favor a return to the practices of the pre-1970's nor do I propose that we choose to travel the exact center of the road. The two poles are mere dimensionless points - our entire planet lies between. I am concerned that the modelers of doom may strain their credibility;and their loss of perspicuity, if too sudden, will allow the pendulum to swing back undamped.

When confronted, a few years ago, with the problem of moving forward with coastal zone development in the face of specious resistance, I sat down, agreeing that much of our past development was bad, and asked:"How did we accomplish it?"

Figure 1 shows my answer, not that I believe that anyone consciously developed such an approach, merely that, because environmental concern was absent, the long term results were poor. Next I asked: "What if we redo our approach in light of our present understanding with concern for the environment paramount?" The result was Figure 2. You will note that the front end is modified only by inclusion of environmental concern with the output end completely reversed.

The next question is: "Is this possible or realistic?" One does not need a computer to see that elimination of pollutional inputs can take a tremendous load off the system. Retention of shallows and vegetation establishment are certainly in the right direction as are groundwater recharge and increased mixing. To evaluate this approach we must have some numbers. We must also find out: "How much is enough?"

Breaking down the rational approach with respect to Canal Hydrodynamics, we arrive at Figure 3. Most of the information required is generally readily available. The canal design parameters are chosen by making a preliminary design layout. The field measurements are fairly standard except that we don't really understand two-dimensional dispersion all that well and haven't yet made turbulent energy spectra measurements. Most of the determinations and calculations are straightforward except again for dispersion and the fact that we haven't arrived at a good "mixing coefficient" as yet. It is becoming increasingly clear that we need to understand canal circulation in 3-dimensional space and time, to serve as a foundation for predicting water quality as influenced by, and as an influence on, canal biochemistry and on the quality of the receiving waters. We will return to this subject later, but first let us look at what is involved in canal or estuarine biochemistry.

GOAL	INCIDENTAL FACTORS	ENGINEERING CRITERIA	RESULTING DEVELOPMENT	ENVIRONMENTAL IMPACT
	NO CENTRAL SEWAGE TREATMENT		SEPTIC TANK SEEPAGE	DOMESTIC WASTE POLLUTION
		NAVIGABLE DEPTHS TO SHORELINE	ELIMINATION OF SHALLOWS	NO NATURAL WATER TREATMENT
RESIDENTIAL UTILIZATION OF WATERFRONT		MAXIMIZE FRONT FOOTAGE PER ACRE	STRAIGHT LINE CANALS WITH RIGHT ANGLE BENDS	POOR MIXING (LOW DISPERSION)
		INCREASED ELEVATION FOR FOUNDATIONS	DEEP NARROW CANALS	
		MINIMUM LOSS OF PROPERTY TO WATER AREA	VERTICAL BULKHEADS	LIMITED HABITAT
		RAPID DRAINAGE OF RAINFALL	DIRECT STORM-WATER DISCHARGE	STORMWATER POLLUTION
		SIMPLIFIED SURVEYING & CONSTRUCTION METHODS	WATER TABLE DRAWDOWN FROM LOCAL WELLS	SALTWATER INTRUSION
	NO OFFSITE WATER SUPPLY		*CONVENIENT LOCATIONS FOR SEWAGE OUTFALLS AND OFFSITE STROM DRAINAGE*	------------
				DEGRADATION OF WATER QUALITY AND BIOLOGICAL HABITAT

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EARLY CANAL DESIGN

FIGURE 1

GOAL	REQUIREMENTS	ENGINEERING CRITERIA	RESULTING DEVELOPMENT	ENVIRONMENTAL IMPACT
	OFFSITE SEWAGE TREATMENT OR PACKAGE PLANT	ELIMINATE DOMESTIC WASTE SEEPAGE		ELIMINATION OF POLLUTANTS
		ELIMINATE DIRECT STORMWATER DISCHARGE	BALANCE SALT-WATER INTRUSION WITH FRESHWATER HEAD	NATURAL WATER 'TREATMENT'
	OFFSITE WATER SUPPLY	RECHARGE GROUND-WATER ON SITE		GROUNDWATER RECHARGE
RESIDENTIAL UTILIZATION OF WATERFRONT		NO DRAWDOWN OF WATER TABLE	VEGETATION FOR NUTRIENT UPTAKE	
	RETENTION OF SOME SHALLOWS	DESIGN SHALLOW AREAS FOR REVEGETATION	VARIED HABITAT FOR EURYHALINE SPECIES & NURSERY GROUNDS FOR NERITIC SPECIES	COUNTERACTING SALTWATER INTRUSION
WITHOUT ENVIRONMENTAL DEGRADATION	HABITAT DIVERSITY	USE COMBINATION OF STABLE SLOPES, RIP-RAP & VERTICAL BULKHEADS		GOOD MIXING
	INCREASE CIRCULATION	INCREASE UPLAND WATER AREA	'NATURAL' LOOKING WATERWAYS	REDUCED DEBRIS COLLECTION
		FOLLOW NATURAL DRAINAGE SLOUGHS	NATURAL PRESERVES FOR BIRDS AND SHORE CRITTERS	REDUCED SHOALING & EROSION
		ELIMINATE NARROW DEAD ENDS		BETTER FLUSHING
	PROMOTE MIXING	'NATURAL' LAYOUT WITH GENTLE BENDS		AMENITIES OF NATURAL LAND AND WATER-SCAPING
		BALANCE DEPTHS WITH WIDTHS & SHALLOWS		
		PROVIDE ROUGHNESS (BANKS & BOTTOMS)		
	ELIMINATE SCOUR FOR SPECIFIED CONDITIONS	PROVIDE STABLE SECTIONS		*GOOD HABITAT AND GOOD WATER QUALITY*

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THE RATIONAL APPROACH TO CANAL DESIGN

FIGURE 2

INFORMATION REQUIRED FROM:	SPECIFIC DATA USED	FIELD MEASUREMENTS	DETERMINATIONS & CALCULATIONS	RESULTS
INDEPENDENT SOURCES				
CLIMATIC CONDITIONS	WINDS EVAPOTRANSPIRATION RAINFALL-FREQUENCY, DURATION & INTENSITY	BORINGS	BASIN HYDROGRAPHS GROUNDWATER TABLE, HEAD & FLOW	FRESHWATER INFLOW
SOILS MAPS	HYDRAULIC CONDUCTIVITIES VEGETATION COVER RUNOFF COEFFICIENTS	SOIL SAMPLES	GRAIN SIZE DISTRIBUTION EQUIVALENT GRAIN SIZE COHESIVENESS ANGLE OF REPOSE CRITICAL SHEAR STRESS SPECIFIC WEIGHT OF GRAIN MATERIAL SHIELD'S ENTRAINMENT FUNCTION	CRITICAL HORIZONTAL SHEAR STRESS EROSION POTENTIAL
TIDES ON RECEIVING WATERS	TIDAL RANGE TIDAL CURRENTS VARIATIONS	TIDAL ELEVATION VS. TIME AT REPRESENTATIVE LOCATIONS	SURFACE SLOPES TIDAL PRISM MEAN DISCHARGE VS. TIME	
BATHYMETRIC CHARTS	AREA BATHYMETRY	CURRENT VELOCITIES VS. DEPTH, LOCATION & TIME TURBULENT ENERGY SPECTRA NET TRANSPORT VS. TIME & LOCATION DISPERSION	BED SHEAR VELOCITIES EQUIVALENT SAND ROUGHNESS (NIKURADSE'S k) SPATIAL MEAN VELOCITIES 'MIXING COEFFICIENT' DISPERSION COEFFICIENTS TAYLOR'S K	INSTANTANEOUS TRANSPORT CURRENT CIRCULATION CURRENT SECONDARY CURRENTS EDDY CURRENT DISTRIBUTIONS
CANAL DESIGN PARAMETERS				
CANAL PLAN	CROSS-SECTIONAL AREA VS. POSITION DEPTHS, WIDTHS, LENGTHS HYDRAULIC RADII ROUGHNESS ELEMENTS SURFACE AREA ACREAGE OF SHALLOW AREAS ACREAGE OF CHANNEL DEPTHS LINEAL FEET OF BULKHEAD & RIP-RAP	BATHYMETRY OF RECEIVING WATERS SALINITY & TEMPERATURE VS. DEPTH, LOCATION & TIME		

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CANAL HYDRODYNAMICS

FIGURE 3

INFORMATION REQUIRED FROM:	SPECIFIC DATA USED	FIELD MEASUREMENTS	DETERMINATIONS & CALCULATIONS	RESULTS
CANAL DESIGN PARAMETERS				
CANAL PLAN	ACREAGE OF VEGETATABLE SHALLOWS			
	ATTACHMENT SURFACES - TYPES, QUANTITY & LOCATIONS			
	BOTTOM & BANK PROPERTIES			
	EXPECTED SEDIMENTATION DISTRIBUTION & CHARACTERISTICS			
CANAL HYDRODYNAMICS	FRESHWATER INFLOW			
	EROSION POTENTIAL			
	INSTANTANEOUS TRANSPORT			
	CIRCULATION CURRENTS			
	SECONDARY CURRENTS			
	EDDY CURRENT DISTRIBUTION			
INDEPENDENT SOURCES	PLANTING & PROPAGATION METHODS	BIOLOGICAL SURVEYS	REVEGETATION PLANS & SCHEDULES	WATER QUALITY VS. LOCATION, TIME & DEPTH
	SENSITIVITY TO POLLUTANTS		HABITAT PLACEMENT	BIOLOGICAL PRODUCTION
AREA ECOLOGY (BIOECOLOGY)	NUTRIENT UPTAKE CAPACITY OF INDIGENOUS FLORA	HABITATION DYNAMICS	SPECIES STOCKING PLANS & SCHEDULES	
	DETRITUS PRODUCTION			EXPORTATION OF FOOD
SPECIES ECOLOGY (AUTECOLOGY)	FOOD WEBS			WATER TREATMENT
	TROPHISM			
	OXYGEN CONSUMPTION			
HISTORICAL WATER QUALITY	WATER QUALITY - CONSTITUENTS & CYCLES	WATER QUALITY MEASUREMENTS VS. POSITION, DEPTHS & TIME		
POINT & NON-POINT POLLUTION SOURCES	SUNLIGHT PENETRATION			
CLIMATIC CONDITIONS	INSOLATION			
	RUNOFF CHARACTERISTICS			
	SEASONAL TEMPERATURES			
SOILS DATA	CHEMICAL CONSTITUENTS			

CANAL BIOCHEMISTRY

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FIGURE 4

A properly designed canal system should function like a naturally productive estuarine channel. Taking our modern canal design parameters and our projected hydrodynamics, "What can we say about natural biochemical water 'treatment' and productivity?"

While the principles of hydrodynamics are valid for any area (locally dependent on soils, rainfall, etc.) canal biochemistry is more area-specific. It is also more complex and subject to "natural" perturbations beyond our control, eg. the winter of 1976-77.

We could take Figures 3 and 4 and produce a real impressive causal-loop diagram with all kinds of feedback, and program it into a computer. We could also cross a 1950's developer with a reflex environmentalist and end up with a politician. Both would accomplish about the same thing. Until we can produce a computer constructed around multi-level instead of binary devices, nature herself will remain her own best analog.

Almost every item in Figures 3 and 4 is receiving sound research attention, primarily through Sea Grant sponsorship. Patterns are already beginning to emerge. Revegetation of dredge spoil and disturbed shorelines is reaching the "cookbook" stage. Nutrient uptake is being quantified. Direct pollutant sources, including stormwater, are being systematically eliminated and non-point sources are being studied. (If we aren't careful, we may have to actively fertilize our wetlands in the future to maintain their productivity.) The intricacies of habitat diversity are coming to light as are the inter-relationships between pioneer, transition and climax plant communities (Doctrine #2).

"If we can't place the burden on the computer, then how can we proceed?" There is general agreement among marine biologists regarding what makes a healthy and productive estuarine ecosystem. We also have many examples of unproductive waterways, ie. certain man-made residential canals. There is good evidence that we can construct a healthy and productive estuarine ecosystem by insuring good circulation and by planting and fertilizing appropriate aquatic vegetation. We can easily calculate potential flushing ratios, mean tidal current flows, etc. The big question is, "Can we modify a natural system or create a new aquatic system that will be of economic value to the land owner and, at the same time, a productive element of the environment?" "And, if so, where between the two extremes does it lie?"

Rather than try to deal explicitly with uncounted variables, it is sometimes instructive to stand back and ask, "What can we say in a general way about the behavior of a complex system?"

Agreeing for the moment that nature is not delicately poised and that she is her own best analog, let's invent a diagram showing productivity vs. tuning for an ecosystem.

Figure 5 shows two familiar bell shaped curves as a plot of response vs. a forcing function. These curves are typical of simple mechanical and electrical systems. The high "Q" or sharply tuned system represents Doctrine #1. Lord Ashby would have it that the response curve is considerably flatter, as indicated in the diagram.

The expression, in natural tuned systems, for the sharpness of tuning (referred to as the "figure of merit" or "quality") is:

$$Q = c\sqrt{\frac{1}{km}}$$

where c = damping coefficient
k = restoring coefficient
m = inertia coefficient

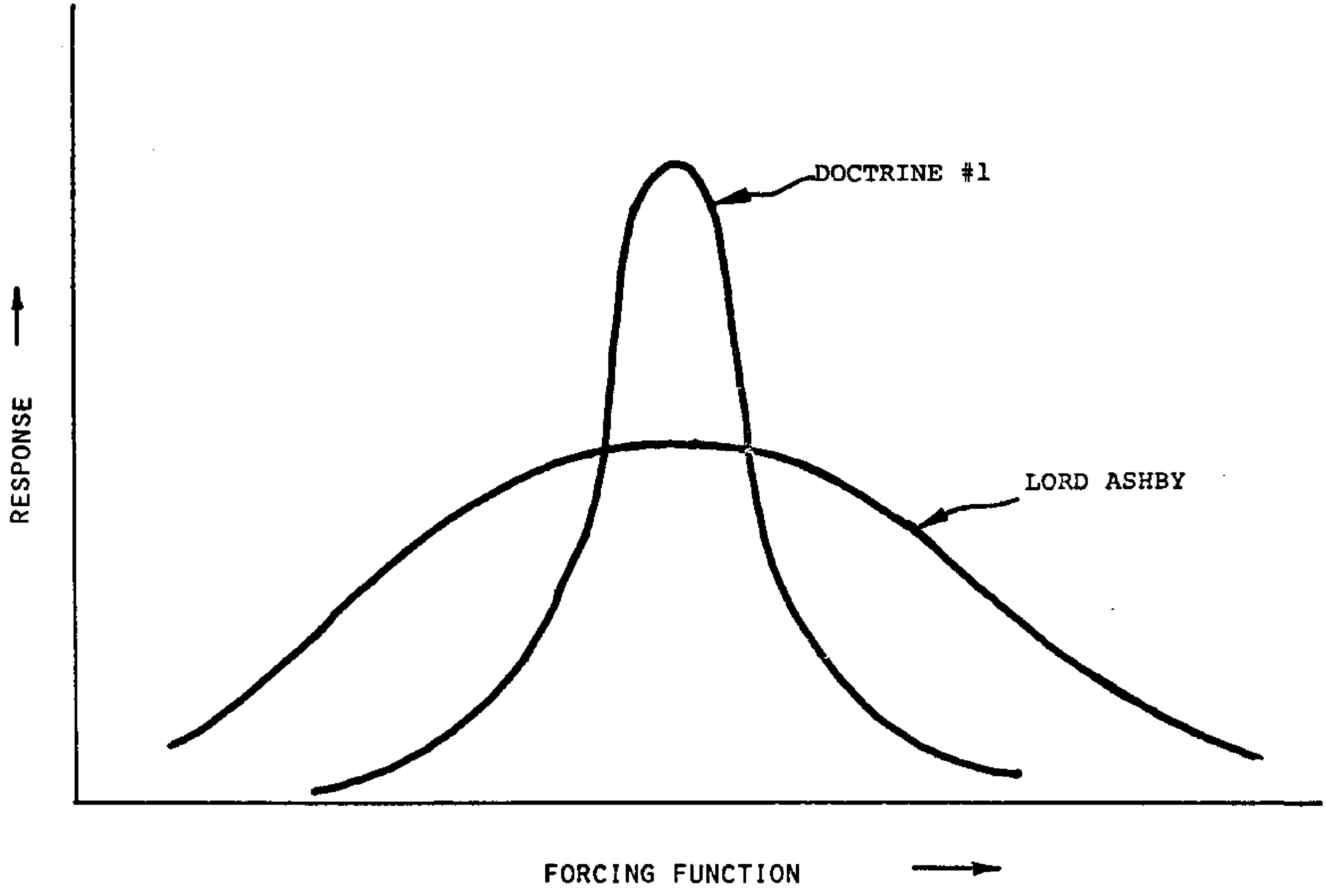
In a created ecological system we would prefer that it not be sharply tuned as shown by the Doctrine #1 curve. To accomplish this we should strive for a lower "Q".

To lower the "Q", we must decrease the damping and increase both the mass and the restoring force in the system. As shown by the equation, the damping has a greater influence than either the inertia or the restoring coefficients. However, as the inertia and restoring coefficients go to zero, the tuning sensitivity or "Q" become infinite. On the other hand, we don't want the "Q" to go to zero either or we won't have a definable ecosystem.

Now let's see if we can interpret the various coefficients in terms of a canal ecosystem.

The inertia coefficient "m" is fairly obvious. It involves the mass of the system, ie., the spacial magnitude, the total biomass, the volume of water involved. Its limits are broad, ranging from the world ocean on one hand to a duck pond on the other.

The restoring coefficient "k" could be the tendency of the system to quickly recover from perturbances. This is related to good flushing and turnover, hardy vegetation types and appropriate habitats for critters to escape the harmful influence of the



LINEAR SYSTEM TUNING

FIGURE 5

perturbances such as lowered temperatures, pollutant slug loads, etc.

The damping coefficient "C" is a little more difficult to transpose. Damping is the resistance to the rate of change. A healthy ecosystem will quickly respond to changes in environment and quickly change back when conditions revert to normal. A system resistant to rapid change may completely die off if the perturbation is persistent. I would offer that the damping coefficient is the inverse of ecological diversity.

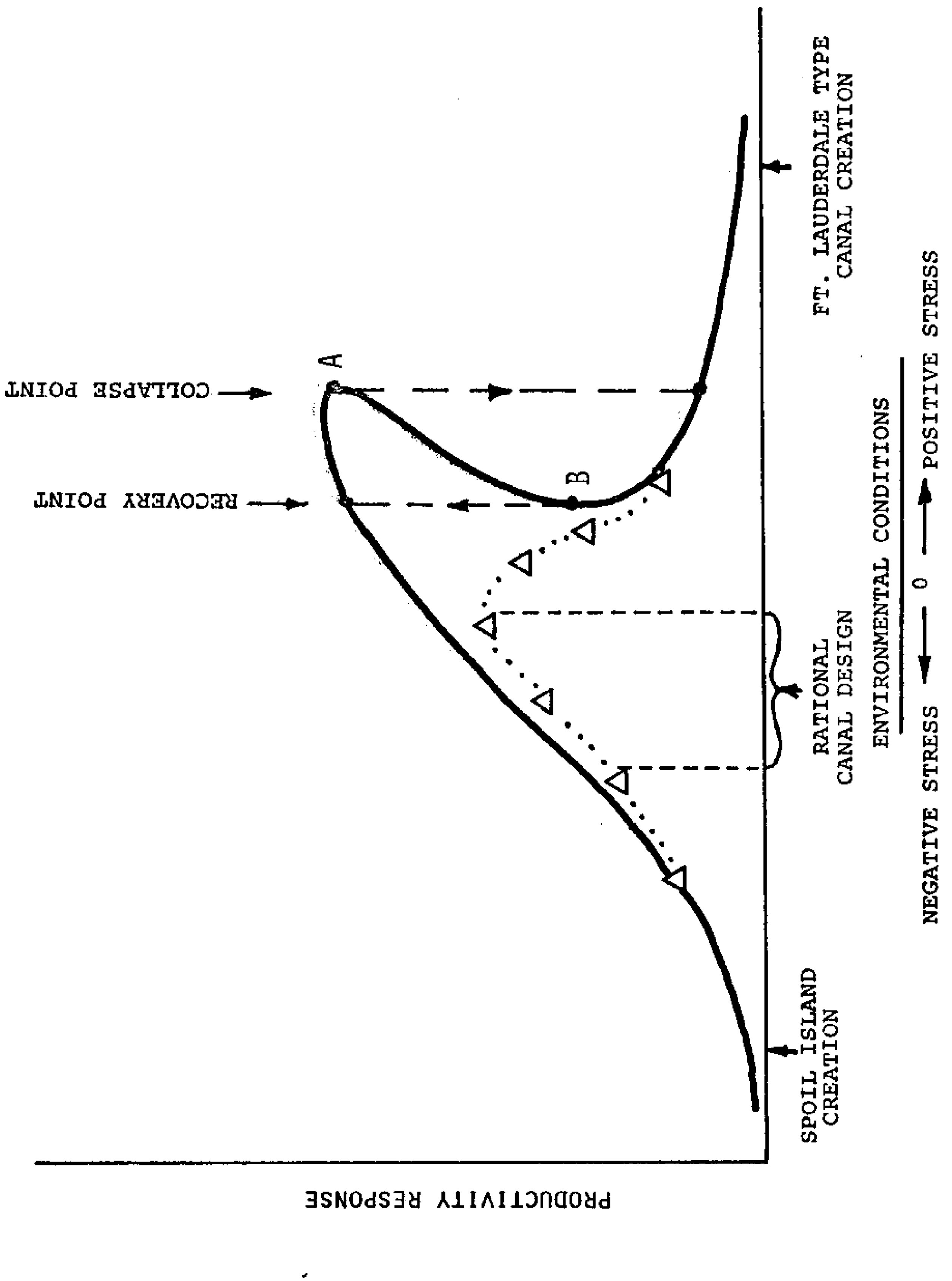
Calling $\frac{1}{Q}$ a measure of canal ecosystem stability we can restate our equation as:

$$S = D\sqrt{RI}$$

where S = stability
D = diversity
R = restorativity
I = inertia

Assuming our analogy holds true, the system stability is less dependent upon restorativity and inertia than it is on diversity. Obviously, in a natural ecosystem, these coefficients are not completely independent from each other. Like all real world systems, an ecosystem is non-linear. Because I do not believe that the concept of non-linearity is widely appreciated, I will take a moment to explain its significance.

Probably the most widely experienced phenomenon of non-linearity in mechanical systems is the front-end shimmy in an automobile. You may be driving along smoothly at 50 miles per hour. To pass another vehicle you increase your speed to 55 mph at which time the front-end goes into a wild vibration. You may have noted that you have to slow down to 30 or 25 mph to make the shimmy disappear. This is because response, in a non-linear system, depends not only upon the immediate conditions but upon the system's past history. For any specific conditions, three different responses are possible near the peak of the response curve. One response will result from an increasing forcing function, another from a decreasing forcing function and the third from initiation of a given forcing function from a zero condition. Figure 6 indicates the type of response curve associated with a non-linear system with an increasing restoring force. This is not necessarily a time history of a natural estuarine canal system, but a given system can travel along the curve in either direction as a response to changing forcing function. The forcing function in our case is a combination of factors including all aspects of water chemistry, circulation and biokinetics. To begin with, it will be easier to



NON-LINEAR SYSTEM TUNING

FIGURE 6

take one or two parameters and follow through the diagram as the parameters change. Let us consider the left side of the curve to be unmoving, pristine water with no dissolved gases. As we begin to add gases and nutrients and seeds from local vegetation, the system will respond by moving up the curve which we will interprete as an increase in productivity. In the center (or tuned) portion, the system will be interactive, ie. phytoplankton, for example, will use carbon dioxide and nutrients and produce oxygen and food for critters. The critters, in turn, consume oxygen and produce CO_2 and nutrients. Nature has many hidden checks. For example, oxygen, in high concentration can be lethal. But in aquatic systems, the concentration cannot even be forced to lethal levels because it will escape to the atmosphere at slightly above 10 ml/l for cold fresh water and about 3 ml/l for warm ocean water. Even the complete absence of oxygen provides habitat for anerobic bacteria without which the sulphur entering our hydrosphere from the atmosphere would long ago have turned our waters acid.

As we continue adding nutrients, however, we can make the water unlivable. Following the curve to the right, we reach the point where the curve drops sharply and bends backward. At this point (point "A"), if our system is further loaded, the response will decend vertically along the dashed line. This crashing of an ecosystem can be eutrophication, response to chemical spills or the gradual buildup of pollutants. Once a system is in a highly stressed state, a greater improvement of conditions is needed before the system again becomes "productive" or "healthy". As we travel back along the curve to point "B", the system will leap upwards along the dashed line. The greater the system's non-linearity, the greater will be the gap between collapse conditions and recovery conditions.

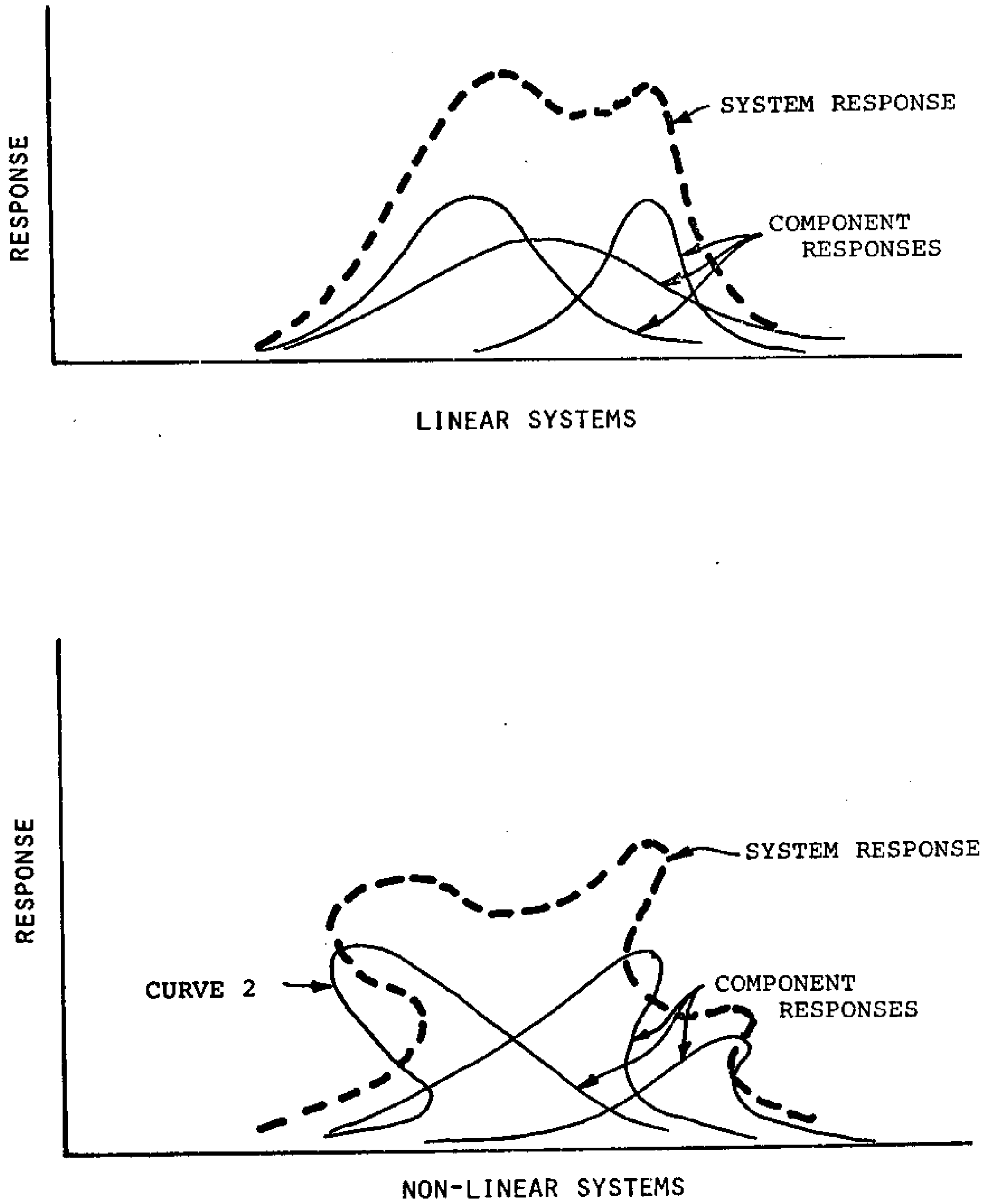
For an instantaneously created system, such as a residential canal built on upland or a spoil island created offshore, the response position will be something like that described by the triangles and dotted line. A spoil island would enter the curve at the left side as indicated in Figure 6. A Ft. Lauderdale type canal would enter at the right. A relatively long time is required for the spoil island to travel up the curve by natural revegetative processes. It may be hindered in this by strong currents or wave action. Conversely, even if all pollutants are eliminated from a Ft. Lauderdale type canal, there are no vegetatable shallows to help raise productivity.

A properly designed canal system, with vegetated areas, will enter the curve somewhere in the "tuned" area and should remain there if excess pollutants are kept out, circulation is good and siltation is not great. The results of revegetation as opposed to natural vegetative encroachment are phenomenal.

This is an example of Dubos' comment about man's justifiable intervention.

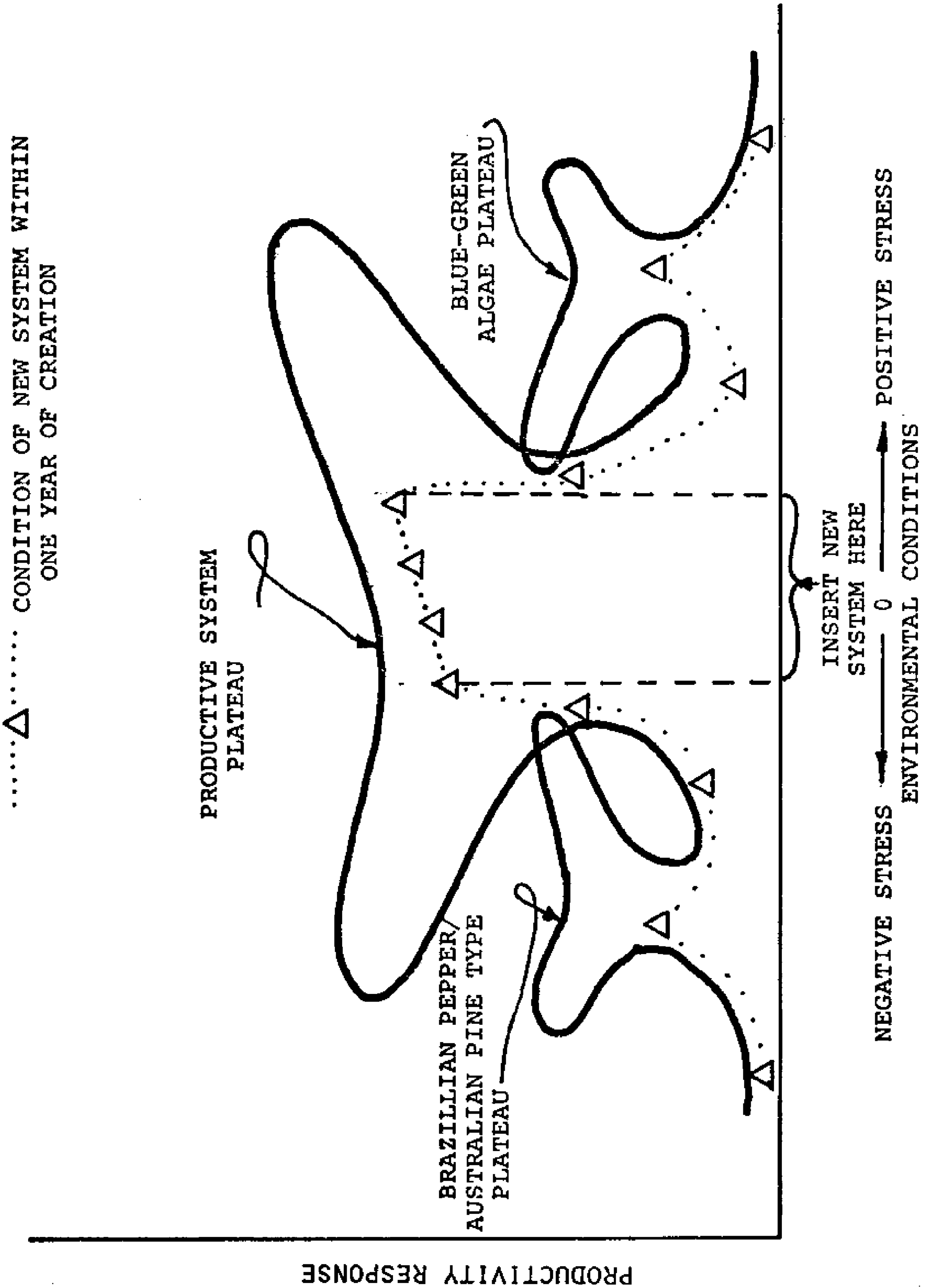
Before leaving this inspectional analysis of ecosystem response, we should take a brief look at interaction between non-linear systems. Figure 7 shows response curves for 3 separate linear systems and a total system response. The total system is still linear though more complex than any of the elements. Also figure 7 shows 3 non-linear systems and, while it is not strictly accurate to combine non-linear responses as it is with linear responses, we are dealing here with inspectional analysis to determine the shape of things rather than their magnitude. The result of combining 3 non-linear responses presents an interesting picture not inconsistent with our observations of nature in the wild. Curve 2, in mechanics, would represent a system with a gradually decreasing spring stiffness or, in an ecosystem, a decreasing resistance to further change, eg. once vegetation took hold and stabilized, critters would be attracted, biochemical activity would become established and the system would be self-tending and self-stabilizing. This combination of different kinds of non-linear response provides a stable operational plateau which is much broader than the base. If a new system can be injected into the base area and given a chance to become established, its stability or resistance to negative or positive stress, ie. starvation or pollution, would be great. On the other hand, a system inserted under high negative or positive stress and left to fend for itself, might end up in a lesser, stable state which is not the most desirable for either man or beast. Figure 8 is a hypothetical complex non-linear response curve which might fairly represent a natural ecosystem. The two lesser, stable "parasite" states, ie, of the Australian pine or blue-green algae plateaus, may even overlap the base area of the preferred state. Unless we can "create" our system to enter into the productive base area it may never, by itself, get out of one of the parasite states. It is well accepted that, in some cases and within limits, environmental stress can be beneficial to survival and productivity, which "explains" the dip at zero stress.

The hypothetical ecosystem response curve has been arrived at by interpreting one natural phenomenon (the ecosystem) in the light of another but better understood natural phenomenon (non-linear mechanics). We know that nature is non-linear and we know something about non-linear behavior. By using inductive reasoning, we have arrived at a hypothesis which does much to explain our observations of nature and gives us clues as to how we might intervene in a positive way to improve systems altered in the past or to create new systems that are, at the same time, useful to man and productive in nature.



SYSTEM INTERACTIONS

FIGURE 7



HYPOTHETICAL ECOSYSTEM RESPONSE

FIGURE 8

As pointed out by Bernie Le Méhauté in a keynote address to the ASCE 1975 Modeling Conference in San Francisco, (6):

> *" ...; nature follows the laws of physics whether or not they have been mathematically formulated."*

In comparing numerical models with physical scale modeling he states:

> *"Mathematical modeling of complex phenomena could not really prove that scale modeling is erroneous because the mathematical models are an over-simplification of nature. As such, they are probably more misleading than their physical analogs."*

A small ecosystem is a hydro-bio-chemical scale analog of a larger ecosystem and while we may still be in the Q equals A stage in our engineering, we would be amiss to wait 16 centuries to construct a much needed aquaduct. Dr. Le Méhauté quotes L.F. Vernon Harcourt, a disciple of Reynolds, on the applicability of using physical analog models:

> *"If I succeed in demonstating with the model that the originally existing conditions can be reproduced typically; and if, moreover, by placing regulating works in the model, the same changes can be reproduced that were brought about by the training works actually built, then I am sure that I can take the third and most important step, namely, of investigating, with every promise of success, the probable effect of the projects that have been proposed..."*

Digital computers can handle quadratic drag, which is non-linear damping, to yield accurate results. But there is no way that numerical modeling - no matter how big the machine or how complex the model - can handle interacting non-linearities which are the hallmark of natural systems.

This may not satisfy the perfectionists who demand "scientific underpinning, no matter how meager" or those who press for action without understanding. But to me this is the essence of environmental engineering just as it was the essence of civil engineering 17 centuries before the advent of formal education where Q equaled A and when overhead aquaducts were constructed that are still in working order 18 centuries later.

Much remains to be accomplished in extending and refining our knowledge in water chemistry, marine botany, marine zoology and canal hydrodynamics. Perhaps the hypothetical Ecosystem

Response curve that I have presented here will aid researchers in directing programs, engineers in designing their projects and managers in making their decisions. It is speculative and open to critique and modifications. It is offered, however, as a tool to assist in one's thinking rather than as a replacement for it.

In the meantime, I would suggest that we design by the rational method, continue our research into areas of poor understanding, look to nature herself for refinement in that understanding by creating and monitoring new estuarine ecosystems, and leave the causal-loop diagrams and meretricious assumptive programming to the Malthusian sociologists who, in spite of themselves, will continue to enjoy the benefits of rational and honest engineering.

I will close with what I think is an appropriate quotation ascribed to one Sydney Smith:

> *"Have the courage to be ignorant of a great number of things, in order to avoid the calamity of being ignorant of everything."*

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THE ROLE OF FRESHWATER IN AN ESTUARY

by

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ABSTRACT

Estuaries are essential to the production of much of the world's protein in the form of fish and shellfish. The physical and chemical characteristics that allow estuaries to function in this important role are largely dependent, both directly and indirectly, upon inflows of freshwater.

The increasing diversion of river flows to fulfill the need for water by cities and agriculture has raised the question of how this action will affect marine resources. On the practical level the question becomes, how much water might we divert from an estuary without significant damage to its marine resource support capability. The main directive of a literature search was to assemble all scientific literature that might be pertinent to this question, particularly as it relates to the estuaries on the west coast of Florida.

There are three types of estuaries, based on the quantity of river flow relative to the amount of tidal flow:

(1) stratified, where river flow approximately equals tidal flow;

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(2) partially mixed, where tidal flow is from 10 to 100 times greater than river flow; and

(3) vertically mixed, where tidal flow is a 1000 times or greater than river flow.

Circulation patterns and vertical salinity gradients are very different in these different types of estuaries. One might expect that some other physical factors and the biological life they support will differ as well.

On the Florida west coast, the major estuaries can vary from partially mixed to well-mixed, depending on seasonal rainfall and the annual tidal cycle.

The smaller the tidal fluctuation the greater the importance of freshwater inflow in the horizontal mix of estuarine and outside waters. In Florida, where evaporation rates are very high and the tidal fluctuation is small, there is a tendency in partially enclosed estuaries for salinity levels to exceed that of seawater, particularly during the dry season, when there is little or no freshwater inflow. Stagnant conditions, with an excess of nutrients and organic wastes and low oxygen levels, may sometimes ensue, and algal blooms may occur.

Horizontal salinity gradients exist in all estuaries and form barrier that exclude some organisms and let others past, effectively screening them from potential predators. This aspect of estuaries is particularly important to juvenile fishes and sessile organisms such as oysters.

Due to changes in salinity gradients alone, a reduction in freshwater flow to an estuary can be expected to change predator prey relationships and species balance and may also change total biomass.

Between 66% and 85% of the U.S. fishery is dependent upon estuaries, demonstrating that the economic value of estuaries is very high. The value of estuaries to the fisheries rests primarily on (1) the abundance of food, which stimulates fast growth, and (2) on salinity barriers, which reduce predation. An inflow of freshwater is necessary to both of these functions.

The case of the Aswan Dam provides a well documented example of damage to fisheries caused by a reduction in the flow of freshwater. At the eastern end of the Meditteranean Sea, the once great fisheries for both sardines and herrings have largely been destroyed by a decrease in primary productivity due to lack of nutrients once provided by the Nile.

Although "too little" freshwater flowing into an estuary is not desirable, the reported relationship between red tides and large pulses of freshwater discharge indicates that "too much" freshwater can be damaging also. Red tides not only are unpleasant esthetically but also can do considerable damage to fisheries.

The general results of the literature survey suggest that a reduction in freshwater flow will change the physical and chemical characteristics of an estuary and that biological changes can be expected to follow. The extent of changes and their impact on fisheries and other environmentally and economically linked factors, such as recreational fishing and boating, will differ depending on: (1) the extent to which the estuary is enclosed, (2) the tidal fluctuation, (3) the ratio between tidal flow and river flow,

(4) river flow in relation to the total volume of the estuary, (5) the amount of the reduction in river flow, and (6) the timing of withdrawal.

THE ESTUARY - WHAT'S IT TO YOU?

by

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As the popular song questioned "Where have all the flowers gone?" Floridians often lament "Where have all the fishes gone?" This question frequently is the result of idle rumors or speculations without basis in fact. Unfortunately, however, it may be a realization of a substantial reduction in the actual or potential yield of selected coastal fisheries due to urban population stress around our estuaries. The pressure of people, with their concomitant needs for water, can cause shifts in balance not easily recognized which usually occur in places far removed from the pressure points.

The focus of this imbalance is the estuary, but the cause originates in the headwaters and drainage basin of the river feeding into that estuarine system. Chadwick (1971) recognized the direct relationship of California's fisheries with ecological changes in rivers and estuaries resulting from other uses of fresh water. Salo and Stober (1971) emphasized that the greatest threat to Puget Sound's fishery resources was posed by failure to identify and evaluate estuarine effects of land use, not only on the waterfront, but upstream. Yet the importance of fresh water is not confined only to anadromous fishes, which are the paramount fisheries of our northwest coastal states.

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In 1968, 1.3 billion pounds of fish and shellfish worth $125 million to the fisherman were harvested from the Gulf of Mexico (Chapman, 1971). Most of this harvest consisted of species dependent on estuaries. Douglas (1971) estimated that "...well over half of the marine fisheries resources of the Continental Shelf adjacent to the U.S. land mass is fully dependent upon estuaries as spawning and/or nursery areas."

To better understand why estuaries are so ecologically prominent, we must briefly review their composition as well as the life histories of some of the important animals which live there. Basically, "an estuary is a mixture of a river and a sea" (Cronin and Mansuetti, 1971). It is a body of water open to the sea, within which the sea's salinity is diluted by fresh water from land drainage and rivers. A balance is thus achieved which makes estuaries, acre for acre, one of the richest environments on this planet.

The estuarine-tidal marsh system is really a natural factory with the end product, as valued by people, being stocks of fish and shellfish harvested in the readily accessible, shallow, nearshore waters. The brackish water of the estuary receives fertilizing minerals from the upland. Powered by the radiant energy of the sun, plant growth develops in this fertile environment. The plants may be marsh grasses, algae, or tiny one celled phytoplankters. Each is a photosynthesizing, food-producing component where nothing is wasted. Plants store nutrients such as nitrates and phosphates in one season, and release them by death and decay in the next.

Described by Odum (1970) as a "nutrient trap," an estuary is richer in nutrients and produces a higher annual yield of organic matter than either the incoming land drainage or the opposite sea. Nutrients are retained by estuarine sediments, which tend to be of fine composition and highly sorbable. When nutrients such as phosphorous are removed from the water by bacterial or microscopic algae, these sediments release their absorbed phosphorous, thus maintaining a relatively constant level of nutrients in the water column. Filter feeding mollusks (oysters, clams, and scallops) and crustaceans (barnacles) remove suspended particles from the water. These particles are compacted and sink to the bottom when extruded by the filtering organism. Other organisms may feed on these biologic deposits, or the deposits may become part of the sediments used by plants and burrowing animals. Thus estuarine nutrients travel though endless cycles, sustaining great numbers of creatures due to the complementary action of sediments and water circulation. The downstream flow of river borne nutrients, augmented by their mixing with tidal return, permit interactions of sediments, biologic deposits, and water circultation in an estuary to effectively concentrate the raw materials of this food factory and produce the distinctive animal and plant populations of the estuarine environment.

Over and over the importance of freshwater in maintaining the estuarine ecosystem has been avowed by all who have examined it. Of all the hazards faced by estuarine life, drying out, freezing, baking, or being buried by unfortuitous combinations of winds, temperatures and tides, the greatest hazard of all is alien water, i.e., too fresh or too salty (Ingle, 1954). Yet, fired in this tumultuous osmotic crucible, is an evolutionary process yielding a bountiful diversity of delectable denizens.

The salty water of the sea meeting fresh water flocculates or precipitates particules of soil, plant material, and masses of bacteria, holding them in the system as detritus (Tabb, 1966a). Phytoplankton flourish in this rich broth and become a source of food for zooplankton, worms, and small mollusks. This food factory is self sustaining as long as fertile waters flow in and the balance is undisturbed. Crabs, shrimp, and oysters feed close to the base of this food chain, and in turn become food for fish in the shelter of the estuary. "The astonishing thing about all this," Tabb commented, "is that man does not have to turn a hand to make this great crop ready for harvest. There is no fertilizer bill to pay; the food produced is free for the taking." Estuarine crops can disappear, however, by physical destruction of the natural factory (removing or overtuning sediments), by interruption of the sunlight fuel (excessive sedimentation or opaque pollutants), or by interruption of the flow of a dependable supply of raw materials (river borne nutrients).

Sessile animals, like oysters, are common in the well balanced estuary. Unable to search for food supplies, an oyster must rely on the abundance of microorganisms and detritus suspended in the water. The nutrient rich estuary provides a veritable feast phytoplankton, bacteria, and zooplankton. Even the distribution of larval oysters throughout the estuarine system is influenced by the mix of the outgoing river flow and incoming tides. Although oyster larvae have limited swimming ability, Haskin (1964) found them responsive to changes in salinity. Increasing salinities stimulated older stage larvae to swim. Salinity decreases caused younger larvae to remain on the bottom. The changing salinity of the estuary then serves to widely distribute oyster spat as well as pose a barrier to many of the oyster's predators such as oyster drills, starfish, and certain fungal diseases. Reid (1961) considered an oyster reef a significant feature of most estuaries. Often "a salient factor in modifying estuarine current systems and sedimentation," it is a unique community harboring a wide assortment of organisms. All of these organisms contribute to and depend heavily upon the fertile fresh waters of the estuarine system.

The three species of economically valuable shrimp all use the estuary as a nursery ground. Pink, brown, and white shrimp spawn offshore and the post-larvae migrate inshore. The tiny shrimp burrow into the substrate to await successive incoming tides upon which they hitch rides into the estuary. There they find abundant food and shelter. There, too, they grow rapidly and return offshore to spawn when mature. The young shrimp respond to salinity differences as small as one part per thousand (Hughes, 1969), becoming most active in water of high salinity but settling into the bottom at lower salinities. Such a behavior pattern allows tiny shrimp to travel two or three miles on each flood tide when entering an estuary. Postlarval and juvenile shrimp respond so strongly to salinity differences that there is a direct correlation between commercial catches of shrimp and the previous year's rainfall.

While young shrimp have a broad salinity tolerance and are well suited to the variable salt content of the estuarine environment, older shrimp prefer the more constant salinity of offshore waters. In shallow inshore areas, growing shrimp are bottom feeders grazing on submerged grasses, algae, diatoms and dinoflagetates, polychaete worms, small crustaceans, mollusks, and even larval fishes. All of these foods are available in abundance in an estuary where the input of fresh and salt waters is balanced over a period of time (Eldred, et al., 1961).

Most of the species of fish valued by sport and commercial fishermen spend some part of their life cycle in an estuary. Anglers consistently land more spotted sea trout than any other fish from Florida's inshore waters, according to Futch (1970). This species is essentially a non-migratory fish whose entire life history is tied to the estuary. Wide tolerance to the normal changes of the estuarine habitat has permitted spotted sea trout to occupy an ecological niche not used by other species. It spawns, feeds, and resides mainly in the confines of this unique environment (Tabb, 1966b). Tagging studies indicate that few marked fish left their natal estuary to move to another, consequently, alteration of a given estuary may result in permanent harm to the spotted sea trout fishery of that system.

Though spotted sea trout are permanent estuarine residents, the majority of commercially valuable fishes are transient. Menhaden, for example, spawn offshore. The young move into the estuary for food and shelter and, as they mature, move offshore to repeat the cycle. The list of fishes dependent on the estuary in some phase of their life cycle is long. The number of species reported varies with geographical area, but a reasonable total comprises up to 70% more of the economically important fishes. In Florida, mullet support a major fishery. Except for fall spawning runs to sea, mullet spend most of their time in estuarine habitats. Numerous other species of fish are also estuarine dependent transients while young (tarpon, snook, black grouper, red grouper, red drum, and several sardines and anchovies), but live as adults all along the coast and even offshore.

One of the most forceful events to document the significance of the balance of fresh water flow into an estuary was the construction of the Aswan High Dam on the Nile. The purpose of the Aswan project was to provide hydro-electric power and irrigation. This was accomplished, but the more subtle effects of decreased water flow only recently have become apparent. The Aswan dam halted the flow of nutritive solubles and silts down the Nile. These nutrients supported a major portion of marine plant and animal populations in the southern Mediterranean Sea. With nutrients depleted, important parts of the food chain which sustained fisheries were lost and fish catches have reportedly declined.

Cutting off the load of silt that the Nile once carried has also increased salt water intrusion and facilitated erosion of the fertile river delta. Before the dam was constructed, silting and salt water erosion balanced one another, but now the delicate equilibrium between the two has been destroyed because with completion of the dam in 1964, Nile sediments have been impounded in Lake Nasser (Sharaf El Din, 1977). The effects of the Aswan High Dam are dramatic and visible. The effects of decreasing fresh water flow into an estuarine system are usually more subtle, but just as dramatic in time. In Florida, we now face the prospect of repeating this tragedy by allowing the flow of our Nile, the Apalachicola River, to be altered by dams constructed for continual access by barges serving the agricultural interests of Georgia and Alabama.

Closer to the immediate concerns of this Conference, the Southwest Florida Water Management District contains a complex system of estuaries stretching from Citrus to Charlotte Counties. Each embayment has been severely stressed through the years by people and pollutants. The 1930 population of the Florida Gulf coast was 614,616 and in 1972, 3,320,226. The greatest share of this increase has settled in the vicinity of the Tampa Bay system (McNulty, et al., 1972). This dense concentration of humanity has put severe stress on these estuarine systems.

As noted earlier, 70% of the economically important species of fin fish are estuarine dependent. If you include invertebrate fisheries dependent on the estuary, such as oysters, blue crabs, and shrimp, up to 90% of the total landed value relies on this ecosystem (Skud and Wilson, 1906; Thompson, 1971).

The estuary imparts value to both the recreational and economic health of an area. Seafood catches from the Gulf of Mexico have increased sevenfold in 30 years from 0.25 billion pounds in 1940 to 1.70 billion pounds landed in 1970. Lindall and Saloman (1977) note that this increase in quantity and value of Gulf catches during the last three decades was due primarily to the expanded fisheries for shrimp, menhaden, and blue crab, along with the initiation of a new fishery in 1952 for bottom fishes (primarily spot and croaker) for the pet food industry. All of these species are estuarine dependent. In addition, approximately 30% of the entire United States marine recreational catch in 1970 occurred in the Gulf of Mexico. Roughly three quarters of these recreational fisheries are dependent at some time on estuarine habitats (Lindall and Saloman, 1977).

In a natural estuarine environment, free of encroaching dense human populations, fresh water input is normally moderated by runoff across marshes, mangroves, and uplands; thus rainfall is delivered to the estuary over a period of days to months. Though the estuary is a rigorous habitat, requiring highly specialized adaptations to wide variations in salinity and temperature, overall it is a system of relatively moderate and gradual change which encourages a "steady state of productivity." If, however, one end of the system (fresh water input), is depressed permanently or for extended intervals, the entire system becomes unbalanced. Changes resulting from this imbalance may be subtle and slow to appear, but eventually saltier water intrudes farther into the estuary and shoreline vegetation is altered or destroyed by the new regime. Then emerges an awareness that certain species are no longer readily available. By the time that realization dawns, it may be too late to save this valuable resource and rich habitat, or it may cost us dearly to do so. Thus the flowers, in this case the marsh flora, and the fishes are gone simply because the fields were unwisely tended.

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THE ESTUARY VIEWED AS A DYNAMIC SYSTEM

by

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INTRODUCTION

The inflow of fresh water is a dominant force in estuaries, influencing not only salinity but also mixing, temperature, turbidity, organic content, nutrient availability, and other physical and chemical characteristics of the water. The inflow of freshwater is primarily responsible for the unique properties of estuaries enabling them to support a large proportion of the ocean's primary productivity and to serve either directly or indirectly as the basis of many of the world's fisheries.

What will be the consequence of interrupting the flow of freshwater to an estuary by diverting it for man's use? How can undesirable affects be prevented or mitigated? How much water can be safely diverted? What is the economic, social, and environmental value of freshwater flowing into an estuary, compared to its value when used elsewhere? These are questions that decision makers are asking for the first time. The future of estuaries such as those of Florida's southwest coast depend upon the quality of the answers.

Decisions are based on the best information available. Information, if available at all, usually comes to the decision maker as disconnected statements of results and sets of data. Needed is a formal means by which this information can be integrated to form a holistic picture and a procedure that will allow the testing of different management alternatives.

Energy systems analysis is a new integrative science (Odum et al., 1975) that provides such a formal methodology for problem analysis and is directly applicable to the problems raised in this symposium. The approach of energy systems analysis is to organize available information concerning a system according to a set of "general principles," some of which are:

> Systems are composed of compartments interconnected by flows.

> The flows of a system are energy transformations, each involving an energy loss or "cost."
>
> Energy is the common denominator by which compartments or flows can be compared.
>
> Systems are subsystems of larger systems with which they interact.
>
> Systems receive inputs from the larger systems and produce outputs used by the larger systems.
>
> Without inputs, outputs cease.
>
> Because energy and matter cannot be created or destroyed, inputs to systems can be accounted for as outputs, growth, or "costs."
>
> The type of system existing at any location is determined by the particular group of inputs it receives, their combination, and the spatial and temporal pattern of their variation.
>
> Due to natural selection, the collection of organisms--i.e., the system--existing at any location tends to be that which most effectively utilizes available energy.

An approach based on the above principles can be very useful in analyzing systems because it allows general predictions to be made concerning a system's response to different conditions.

A basic tool of energy systems analysis is the energy circuit diagram, which shows the system as a set of inputs, interconnected compartments, and outputs. Diagramming a system in these terms help to visualize it within the framework of the general principles--in particular, as a functioning unit under the influence of inputs of energy and material from a larger system and producing things of value to the larger system. A new level of understanding is reached when available data is organized by giving values to the stocks and flows of the diagram. The systems principles provide a structure that allows missing data to be approximated with some confidence by balancing inflows with growth and outflows of compartments. Magnitudes of different stocks and flows can then be compared and their relative importance to the system can be estimated.

Once values are assigned to the compartments and pathways, the diagram can be translated into mathematical equations or models for digital or analog computer simulations. Because the mathematical relationships are inherent in the design of energy circuit diagrams, translation to a computer model is relatively easy. Management alternatives can be simulated by executing the model using different values for the parameters that alternative management schemes would affect. Simulated results allow both short term and long term effects of different management alternatives to be compared.

The visual model diagrams can be understood without a knowledge of differential equations and higher mathematics. Anyone can enhance his intuitive understanding of a system and visually and verbally communicate this understanding by using energy circuit diagrams. Constructive interaction between the analysts and the decision makers can be promoted by use of these visual models.

A view of the estuary from the system's perspective will be presented using energy circuit diagrams and available data will be used to partially quantify an energy circuit diagram for Charlotte Harbor. A suggestion based on available data will be made concerning a design to determine how much water can be diverted from estuaries such as Charlotte Harbor without serious effects.

THE ESTUARINE SYSTEM -- DESCRIPTIVE MODELS

The estuary is an interface between upland and ocean. A diagrammatic view of the estuary as part of a larger system is shown in Figure 1. By means

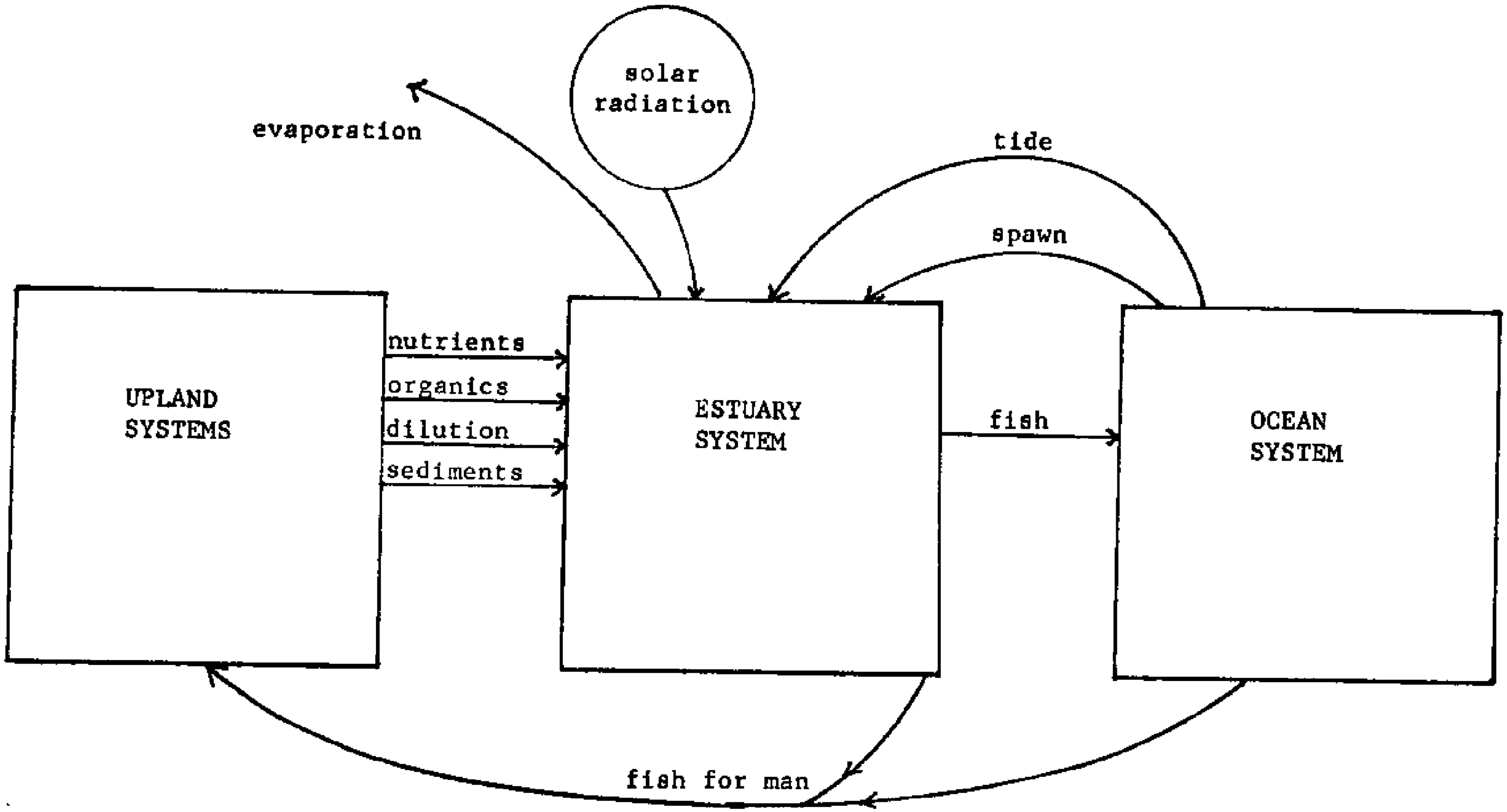


Figure 1. The estuary as a productive interface between land and ocean.

of rivers and groundwater flow, upland systems contribute dilution, nutrients, organic matter, and sediments to the estuary, which converts them into fish, shellfish, and other marine organisms, some of which are harvested by man, either directly from the estuaries or from the oceans. Many migratory fish normally thought of as pelagic are highly dependent upon estuaries for their food. King and Spanish mackerel are good examples of high level marine consumers that harvest the productivity of estuaries as they migrate along the coast. The mackerels feed on estuarine dependent organisms, such as menhaden, sardines, and other Clupeids, as well as mullet and shrimp (Shaw and Warner, 1977).

Figure 2 is an energy circuit diagram of the estuarine system, showing not only the interactions with other systems, in the form of inputs and outputs, but also the major compartments and flows within the system. Major inputs, such as river flow, and structural components assumed to be constant, such as area of marshes, are indicated with circles. Variable compartments of the system are indicated with "tanks." The main primary production units of the estuary are indicated with "bullets." Animal compartments, which are considered to be "self-modifying," are represented by the "hexagons." Interactions, or flows of energy or materials, are indicated by connecting lines with arrows showing the direction of flow. The output of the system is indicated by the pathway marked "fish and shellfish."

Inputs and Their Interactions

The major forces impacting on an estuary are tidal flow, river (or subterranean groundwater) flow, solar radiation, and wind. The model depicts circulation as a function ot tide, wind, and freshwater flow, and indicates that salinity is a function of freshwater input, evaporation, and circulation.

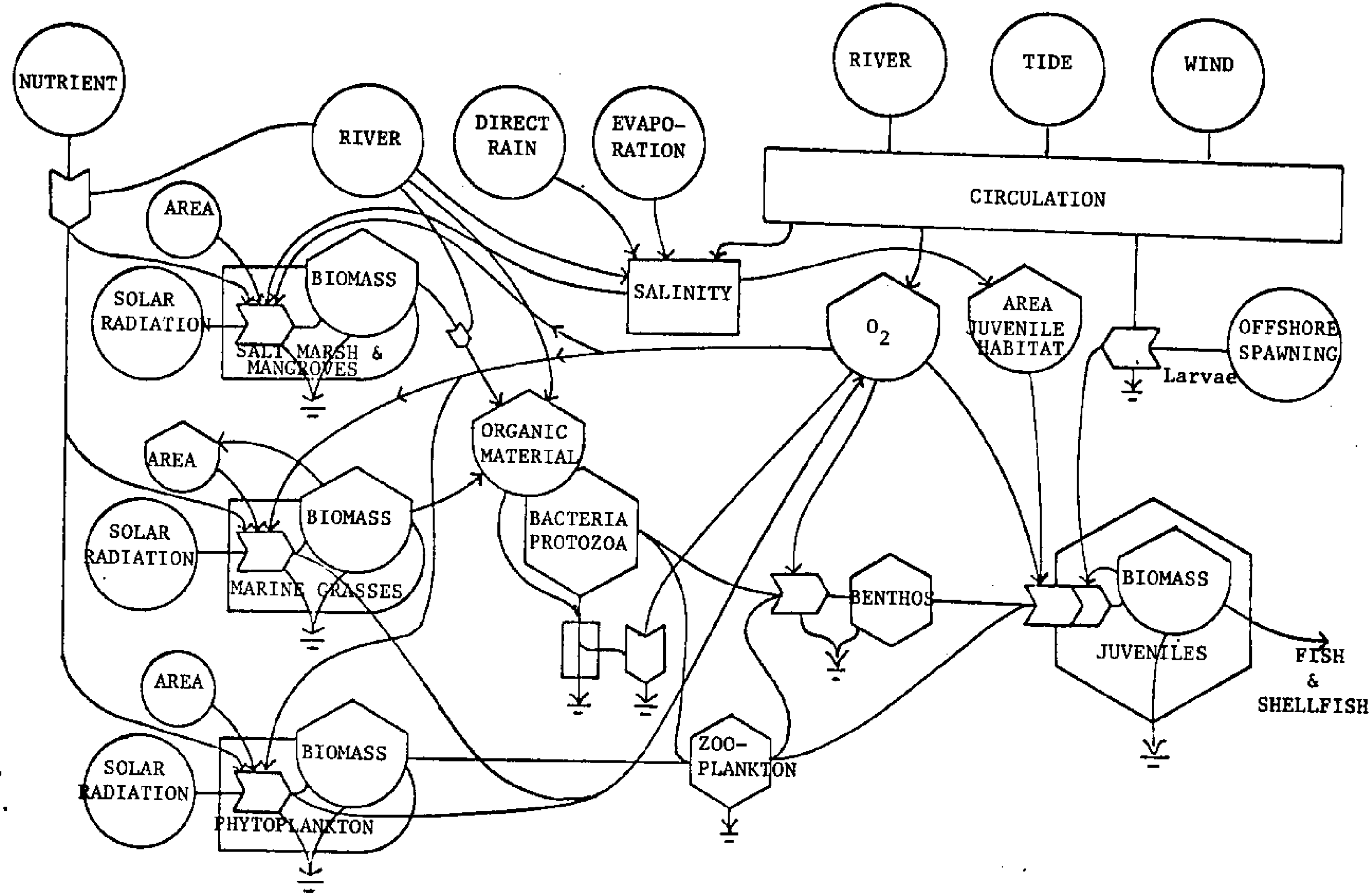


Figure 2. Energy circuit diagram of the estuarine ecosystem.

Evaporation is, of course, a function of solar radiation and wind. Direct rainfall over the estuary, although included in the model, is thought to play a very minor role in dilution. All of the forcing functions are important to the estuary's circulation patterns and biological support capability. A knowledge of their seasonal variation and interaction is important in developing a plan for altering river flow that will preserve the vital estuarine functions.

Temperature

Temperature, an important determinant of animal growth and movements in estuaries, is a direct function of solar radiation, but influenced by river flow and vertical and horizontal circulation. Even in south Florida most fish species move out of the estuaries into warmer offshore waters during the winter. The immigration of larval organisms occurs predominantly in the spring, and the juvenile growth period coincides with the warmer summer months.

Circulation and Salinity

Wind speed and direction affect both vertical and horizontal circulation in estuaries. The wind effect is greatest when the wind direction is parallel to the orientation of the estuary (Van de Kreeke, pers. comm.). According to Tabb *et al*. (1974) late fall and early winter winds from the northeast flush water out of the estuaries of Everglades National Park, while spring winds coming from the east-southeast fill the estuaries with highly saline water. Van de Kreeke (pers. comm.) suggests that horizontal and vertical mixing will occur whether the wind is blowing into or out of the estuary. Wind speed and direction appear to have a greater importance to estuarine circulation during the dry season than during the wet season. According to Lee and Rooth (1972) wind influence may be the most important factor in flushing shallow estuaries.

Tides in Florida are not large compared to most other areas. Daily tidal cycles are superimposed on annual cycles that cause seasonal variation in tidal amplitude and the volume of water exchanged by tidal action. An 18.5 year cycle causes variation from year to year.

Surprisingly, neither river flow nor tidal action alone are major forces in horizontal circulation. Tide is important mainly in maintaining vertical circulation; and river flow can actually be so great as to inhibit rather than promote mixing in both the horizontal and vertical plane. River flow primarily affects estuarine circulation by establishing a density gradient. Density gradients and wind are thought to be the primary forces involved in horizontal mixing in estuaries.

Based on the quantity of river flow (over a tidal period) relative to tidal prism; (tidal amplitude multiplied by area of the estuary); three types of estuaries exist:

1) stratified (river flow approximately equals tidal flow);

2) partially mixed (tidal flow from 10 to 100 times greater than river flow); and

3) vertically homogeneous, (tidal flow 1000 times or greater than river flow).

If river flow is smaller than tidal prism by a factor of 1000, vertical mixing tends to be complete but no density gradients drive horizontal mixing. When river flow is approximately equal to tidal prism, the vertical density gradient is often so steep that neither vertical nor horizontal mixing occur. When river flow is smaller than tidal prism by 10-100 times, optimum conditions for horizontal mixing of the estuary exist. Of course, other factors such as bottom contour and length of shoreline also influence vertical and horizontal mixing. Circulation patterns and vertical and horizontal salinity gradients are different in these three types of estuaries. Other physical factors and the biota they govern are also affected.

Historically, partially mixed conditions prevailed in most major estuaries of the Florida west coast, although stratification or vertical mixing sometimes occurred as a result of drought or rainfall extremes.

In Figure 3A monthly rainfall at one southwest Florida station, Ft. Myers, is shown for a 25-year period from June 1950 through May 1975.

Rainfall peaks once in the early summer and again in the fall in southwest Florida. A long dry season from November into May usually is interrupted during January and/or February by winter rain storms caused by cold fronts.

Peak runoff lags peak rainfall by a month or more depending upon the topographic gradient of the watershed, whether receiving basins are already filled, and the amount of canalization and development. Drainage and development of river basins has altered the seasonal runoff regime affecting some Florida estuaries. Accelerated runoff, has:

> 1) altered the balance between evapotranspiration and runoff so that runoff relative to rainfall has been increased; and
>
> 2) increased and seasonal variation in runoff, causing higher peak flows during the wet season than would normally occur and longer periods of low flow - or now flow - during the dry season.

The change in quantity and timing of runoff has had four net effects on the estuaries:

> 1) increased stratification, or decreased vertical and horizontal circulation, during the wet season, and

2) increased vertical homogeneity, and decreased horizontal circulation, during the dry season.

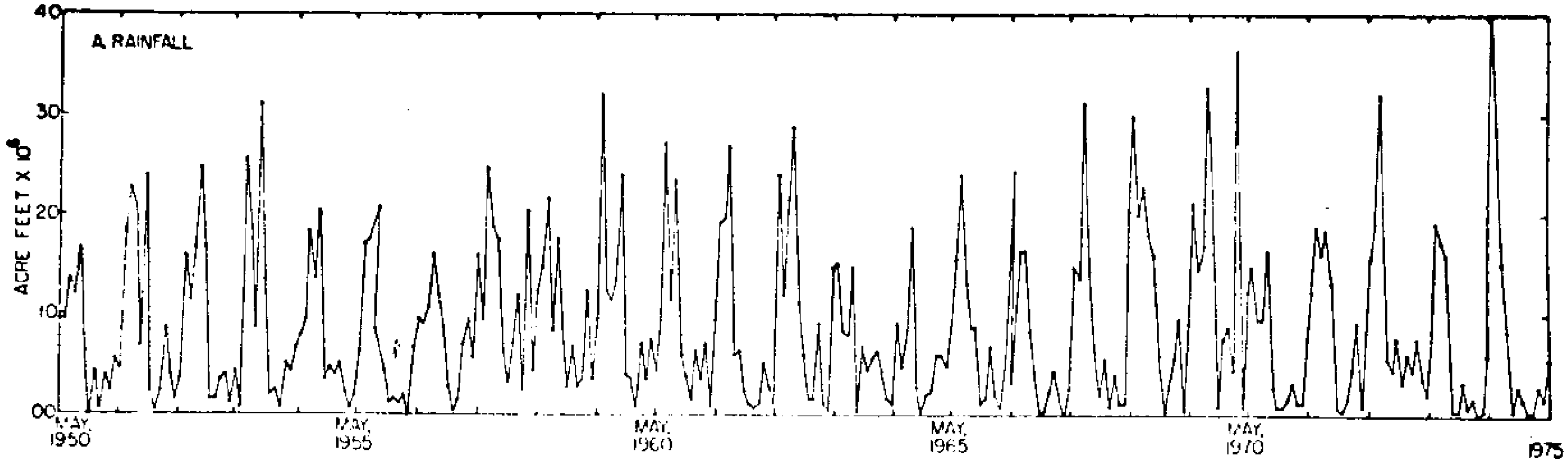
3) created steep salinity gradients during the summer

4) increased the frequency of hypersaline conditions during the dry season.

A digital computer model using empirical hydrologic equations and hydrologic data specific to the area has simulated monthly runoff from a three county area of southwest Florida (Lee, Collier, and Hendry) under natural (predrainage) and altered (post-drainage or present) conditions (Browder, 1976). Evapotranspiration under predrained (a) and drained (b), and runoff under drained (c), and predrained (d) conditions simulated by this model are shown in Figure 3B. Only three coefficients (drainage density, volume capacity of surface catchments, and cross-sectional area for groundwater discharge) were changed to represent the two conditions. The input for both simulations was the same monthly rainfall record from Ft. Myers (Figure 3A). The simulations approximate the effect of drainage on the seasonal runoff pattern.

Figure 4 shows annual totals for evapotranspiration and runoff simulated under predrainage (primitive) and postdrainage (present) conditions. Total annual evapotranspiration is lower and total annual runoff is higher under the drained conditions. The simulations suggest that yearly runoff was only 13% of yearly rainfall under primitive conditions but is 25% of rainfall under drained conditions. Total runoff to the estuaries of this study area has almost doubled due to drainage of the basins.

Carter _et al_. (1972) made a comparison study of the fish life in two adjacent estuaries, Fahka Union Bay and Fahkahatchee Bay, at the southwest tip of Florida. The first bay receives drainage from an extensive canal system.



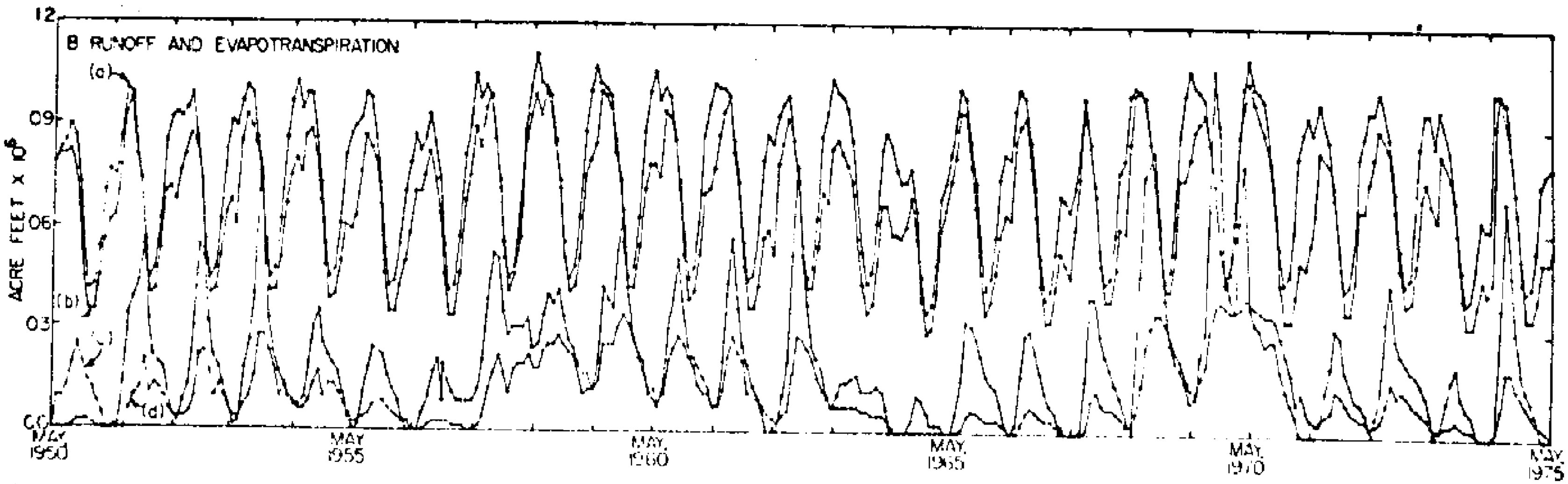


Figure 3. Monthly rainfall at Ft. Myers and simulated monthly runoff and evapotranspiration from southwest Florida for 25 yr period under same rainfall conditions before and after drainage and development:

(a) evapotranspiration, predrainage; (b) evapotranspiration, postdrainage; (c) runoff, postdrainage; (d) runoff, predrainage (from Browder, 1976).

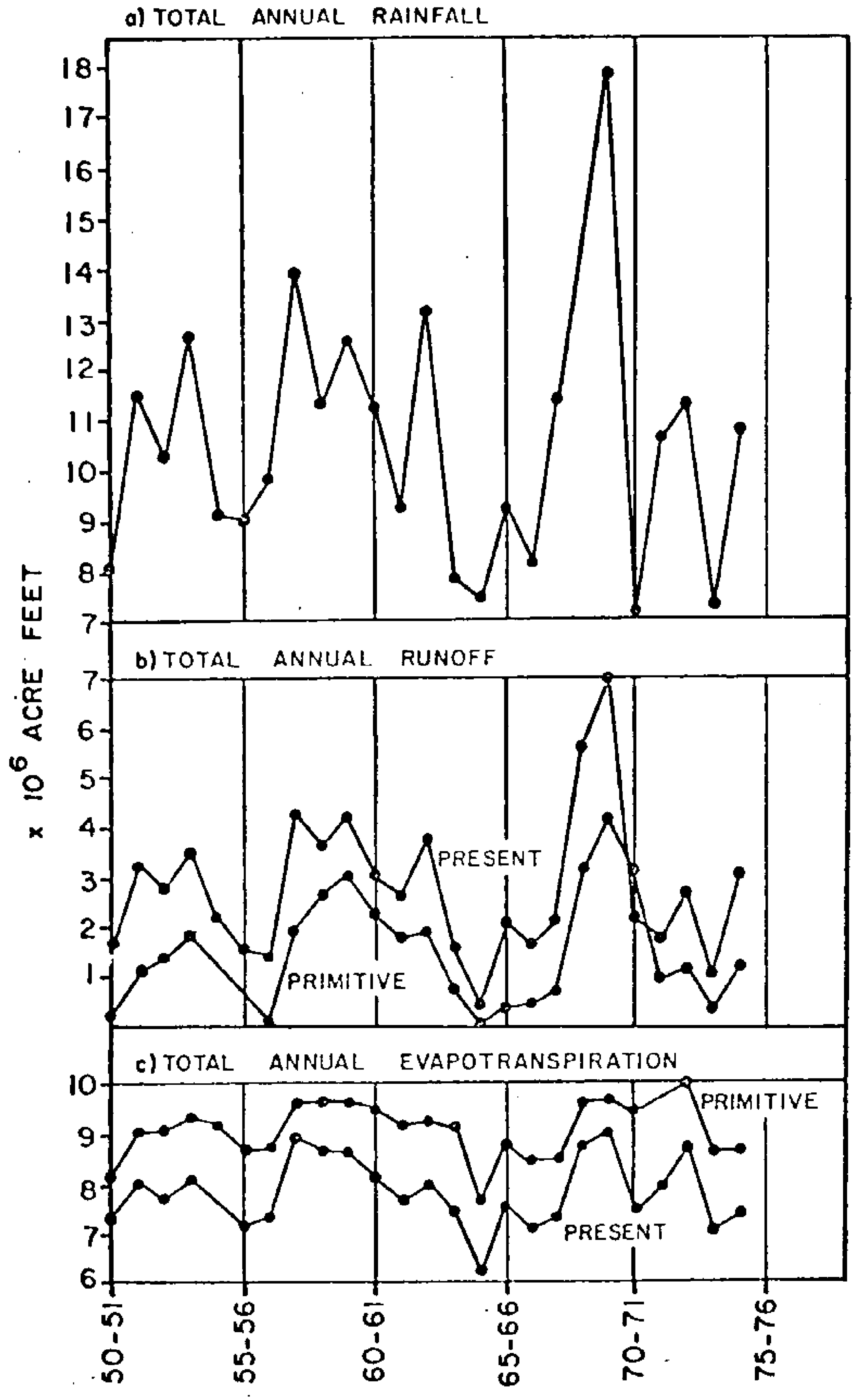


Figure 4. Actual annual rainfall at Ft. Myers and simulated annual runoff and evapotranspiration under present (postdrainage) and primitive (predrainage) conditions in southwest Florida (from Browder, 1976).

The second receives a more natural flow of freshwater. These researchers concluded, "more favorable ecological conditions, particularly in reference to the structure of the bottomfish and plant communities, existed in Fahkahatchee Bay than in Fahka Union Bay." This study suggests that the artificial flow regime caused by the drainage system damaged the estuary.

Horizontal Salinity Gradient

Near-freshwater conditions are found in estuaries during the wet season in south Florida. The horizontal salinity gradient caused by the freshwater flow excludes many predators, because many adult marine fish avoid or cannot tolerate brackish water. As a result the juvenile fish species which live in the estuaries have higher survival rates. Oysters and other shellfish also are subjected to lower predation when fresh water reduces salinity. The smallest juvenile Atlantic croakers are found in areas of lowest salinity in estuaries (Hansen, 1969). As the juveniles grow they move into areas of successively higher salinities. This tends to partition habitat and decrease intraspecific predation. Broad horizontal salinity gradients should therefore maximize fish production. When river flow equals tidal prism, the salinity gradient tends to be steep and narrow. A broad horizontal salinity gradient accompanied by ideal mixing conditions is provided when the balance between river flow and tidal flow causes the estuary to be partially mixed.

To further optimize growth potential, the salinity bands appropriate for juvenile fish should coincide with areas of the estuary where the greater area of good juvenile habitat is provided; where there are many tidal creeks and/or grass beds. Carter et al. (1972) found that the tidal creeks of Fahkahatchee Bay were important as habitat for juvenile snook, seatrout, and redfish. Seagrass beds were the favored habitat of juvenile shrimp.

Figure 5 is a map showing three segments of a hypothetical estuary-river complex. If the salinity range ideal for juvenile fish coincided with the boundaries of segment 2, juvenile fish habitat would be maximized, because the marsh-water interface thought to provide ideal habitat for juvenile fish is greater in segment 2 than in segment 1, which is a channel with a relatively unbroken shoreline, or in segment 3, which is bulkheaded.

Any change in survival rate of young such as that which might be caused by a change in the area of suitable brackish habitat or available food can have a very dramatic effect on the population levels of marine organisms. For organisms with short life spans such as shrimp and some tropical fishes, the effect on population level is particularly strong.

The behavior of fish and other marine organisms may be under the influence of estuarine qualities related to the flow of freshwater - currents and chemical cues, to name just two. For instance, shrimp larvae are transported by the currents resulting from the interaction of salt and freshwater masses.

Nutrients and Organic Matter

The transport by rivers of minerals and organic materials of terrestrial origin to the estuaries causes growth rates dependent upon both direct photosynthesis and detrital food chains to be much higher in estuaries than in the deep ocean. Vertical mixing induced by freshwater inflow further replenishes the nutrient concentration of estuarine waters. Some major sources of organic input to the estuaries are the salt marshes and mangroves along the shoreline. River flow and tides acting in concert with winds are the transport mechanisms by which the dead organic production of the shoreline marshes and mangroves is carried to the open water, where it can be utilized.

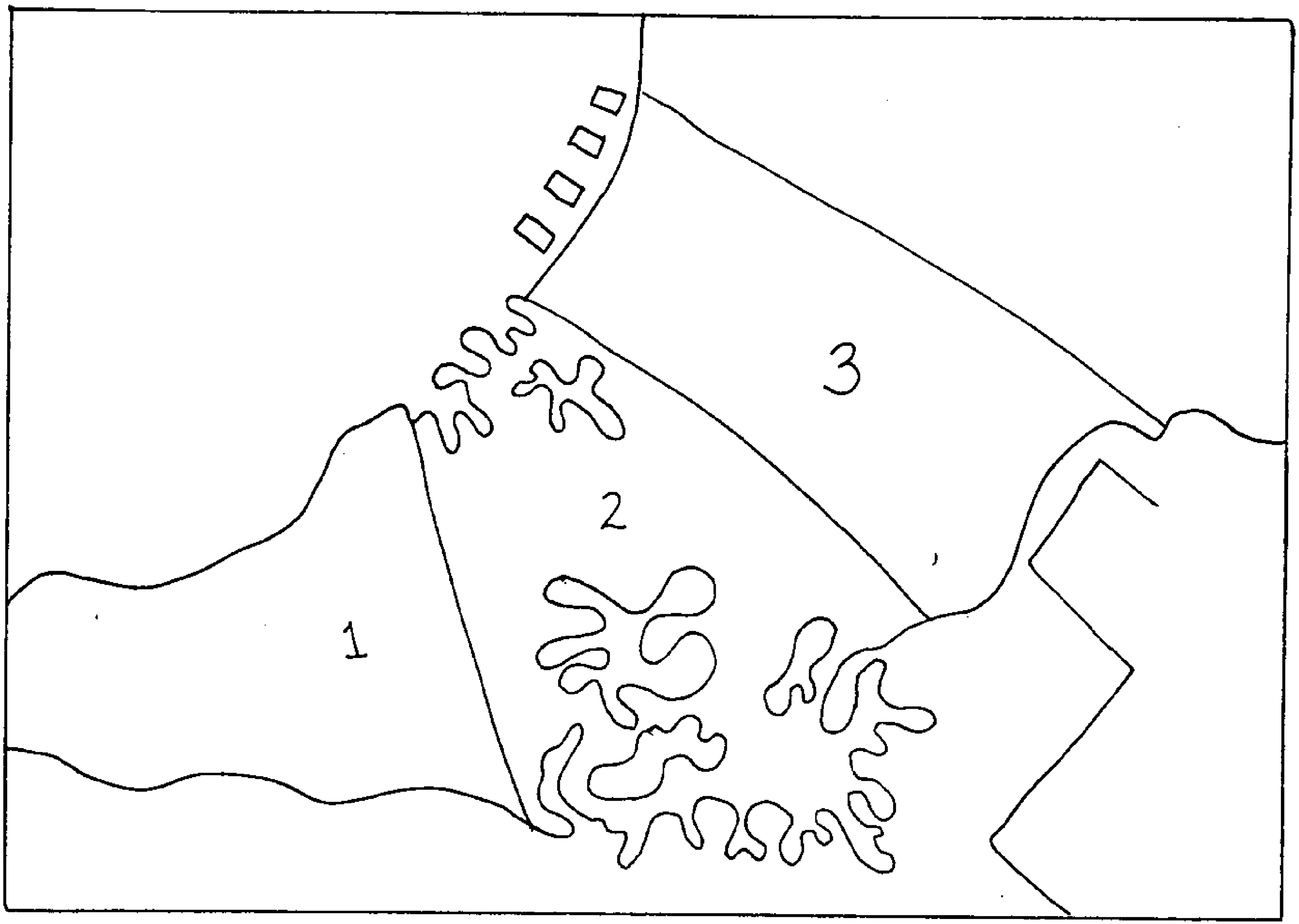


Figure 5. Map of hypothetical estuary showing possible segments of possible juvenile habitat (ie. location of appropriate horizontal salinity gradient).

Compartments

Food Chains

Primary producers of the Florida west coast estuaries are the mangroves, the salt marshes, the marine meadows (seagrass and benthic algae), and phytoplankton. Phytoplankton serves as the base of the grazing food chain. Plant material of the other systems is more important after it is dead. The detrital food chain based on dead organic matter from mangroves, salt marshes, and marine meadows is probably the most important food chain of the estuaries. The impact of river flow on these food chains can be demonstrated with one example. Figure 6 is a simplified version of Figure 2, showing the mangrove food chain and the forces that affect it.

The production of plant material by mangroves is stimulated by the transport to the mangroves of essential nutrients in overland flow from rivers. Dead plant material, which falls to the ground in pulses, is washed into the aquatic system by a combination of river flow and tidal action. Microorganisms that develop in dense colonies on mangrove detritus act as a rich source of protein and energy to zooplankters and benthic organisms, which in turn become food for fishes. A high productivity of benthic macrofauna is associated with higher dissolved oxygen levels, which also are important in maintaining fish populations. Dissolved oxygen in the water column is also thought to be an important factor in the productivity of mangroves. Although primary producers on the bottom or in the water column add to the oxygen content of estuarine waters during active photosynthesis, they draw oxygen out of the water at night and on cloudy days. Circulation is probably the single most important factor in maintaining higher dissolved oxygen levels in estuaries.

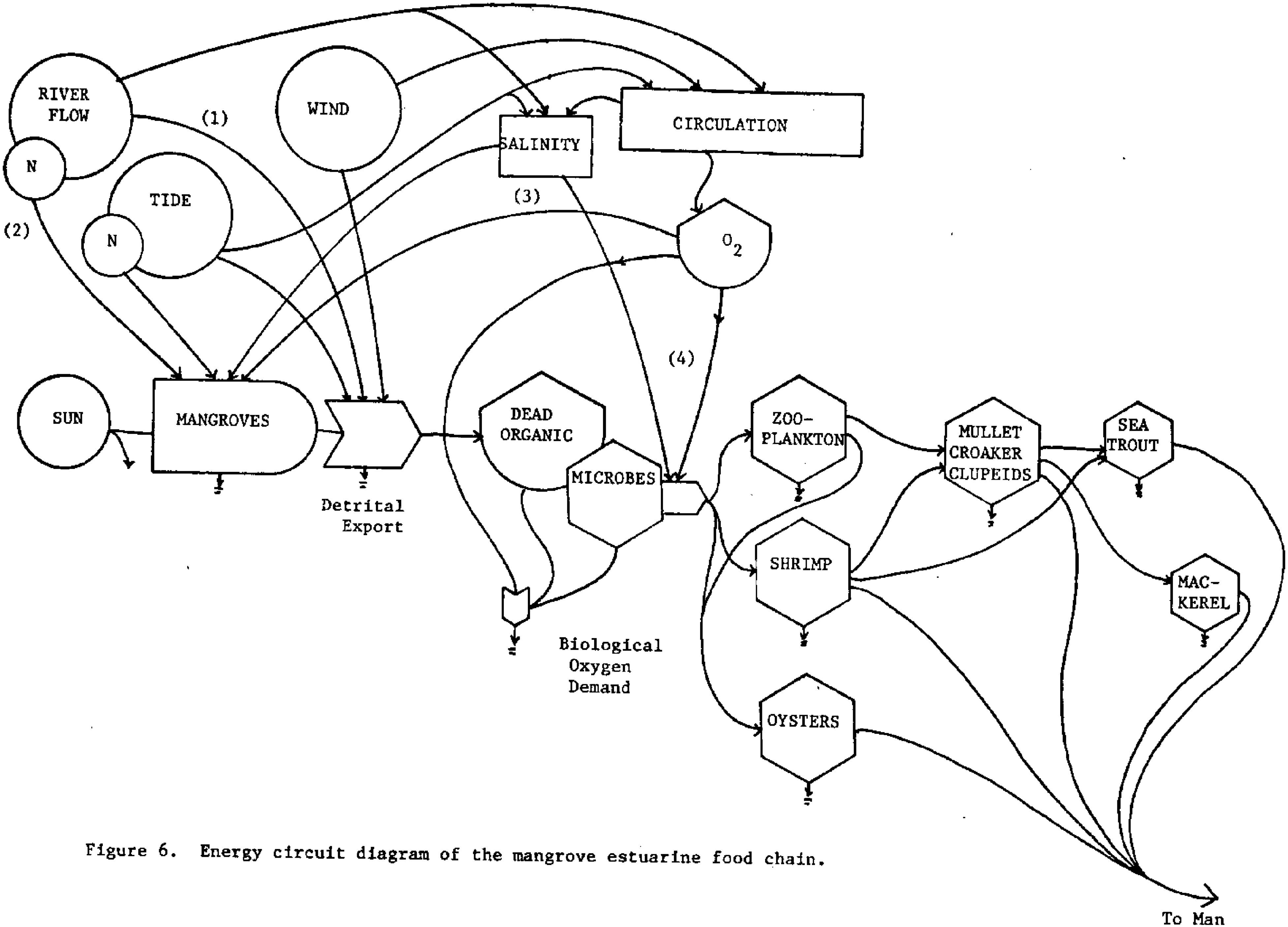


Figure 6. Energy circuit diagram of the mangrove estuarine food chain.

The diagram (Figure 6) points out four different places in the food chain where the river effects production, directly, as in detrital export (1) and the transport of nutrients such as nitrogen and phosphorus (2), and indirectly through its role in mixing, which by maintaining high dissolved oxygen levels, stimulates the growth of mangroves (3) and benthic macrofauna (4), as well as making the area inhabitable for fish.

The river is thought to be as important to the grassbeds as to the mangroves in supplying nutrients and stimulating mixing. Photosynthesis by phytoplankton also is stimulated by river flow.

Outputs

In terms of the larger system of the sea and the marine resources of major interest to man, the two most important functions of estuaries are (1) to reduce predation on young life forms and sessile organisms by maintaining salinity gradients that exclude most large fishes and (2) to stimulate high growth rates by providing an abundance of the "starter materials" necessary to both food chains: grazing and detritus. The result is a very high production of fish and other marine organisms in estuaries. Some of these are harvested by man directly from the estuaries but many are harvested at sea. Others serve as the food supply of larger marine animals harvested by man at sea. The autochthonous productivity of the ocean is actually very low except in areas of upwelling. Food for man from the sea to a large extent means the direct or indirect production of estuaries.

CHARLOTTE HARBOR

Each estuary is a distinct system in which the aforementioned physical forces combine uniquely and differences are found in bottom contour, depth, area, orientation, and degree of enclosure from outside bodies of water. Following is a summary of the Charlotte Harbor system based on information available in the literature.

The Charlotte Harbor estuary covers 982 km^2 and includes 725 km^2 (74%) open water, 75 km^2 (7.5%) salt marsh, and 181 km^2 (18.5%) mangrove (Taylor, 1974). Benthic vegetation covers 30% of the open water area, or 215 km^2 (Taylor, 1974). This estuary receives the freshwater flow of three rivers, the Peace, the Myakka, and the Caloosahatchee. The Peace River, with a drainage area of 3,541 km^2, contributes 77.5% of the total freshwater input. Total annual runoff from the Peace River for the water years (Oct.-Sept.) 1971-72 through 1973-74 (USGS 1972-74) was 23, 562, 34, 171, and 36,762 km^2.m. During the driest of these three years, 1971-72, good mixing conditions prevailed on the average every month. River runoff from the Peace River alone maintained the partially mixed situation.

Total annual net primary productivity of the estuary as estimated by Taylor (1974) is:

Mangrove	1.67×10^5 metric tons	(8,000 lb/acre.yr)
Salt marsh	1.69×10^5	(20,000 lb/acre.yr)
Benthic	4.54×10^5	
Phytoplankton	0.18×10^5	
TOTAL:	7.89×10^5 metric tons	

Approximately 2,631 metric tons (5.8 million lbs.) of pink shrimp, blue crab, and stone crab were harvested from the vicinity of Charlotte Harbor in 1972. The annual harvest of finfish was approximately 8,119 metric tons (15.9 millions lbs.) (Taylor, 1974). On the basis of these values it can be estimated that energy conversion efficiency of the Charlotte Harbor estuary, in terms of converting solar radiation (1.46×10^6 kcal/m^2.yr) to plant material is 0.26%. The energy conversion efficiency of the estuary in terms of converting plant production to production of commercial fish and shellfish is 1.25%. These values are organized on the diagram in Figure 7. A cursory review of the literature suggests that the data necessary to complete the quantification are probably available.

The efficiency of conversion of solar radiation to net primary productivity is very high compared with other systems (E.P. Odum, 1971). The high conversion rate may be due to the unusually high input of phosphorus to this system because the rivers feeding the estuary pass through rich phosphate beds. According to Dragovich et al. (1968) phosphorus is not limiting to primary production in the Charlotte Harbor system. The limiting nutrient may be nitrogen, which has a much lower concentration in proportion to phosphorus than that found in most waters or in living systems (Dragovich et al., 1968). Nitrogen input to Charlotte Harbor is thought to be directly proportional to river flow (Dragovich et al., 1968).

The high productivity of the Charlotte Harbor estuary may also reflect the fact that in estuaries the benefits derived from the sun's energy are enhanced by auxiliary energy forms such as the tide and the river. When these energy inputs are well balanced, they reduce the internal maintenance costs of the system and allow more of the energy captured in photosynthesis to be channeled into growth (Odum, 1967).

DISCUSSION AND RECOMMENDATIONS

Four important generalities can be made about changing the volume and pattern of freshwater flow to west coast Florida estuaries:

1) Changing the total annual quantity and seasonal pattern of an input to a system will change the system. Even a small change could have a large effect on systems outputs such as fish production, because of nonlinear relationships.

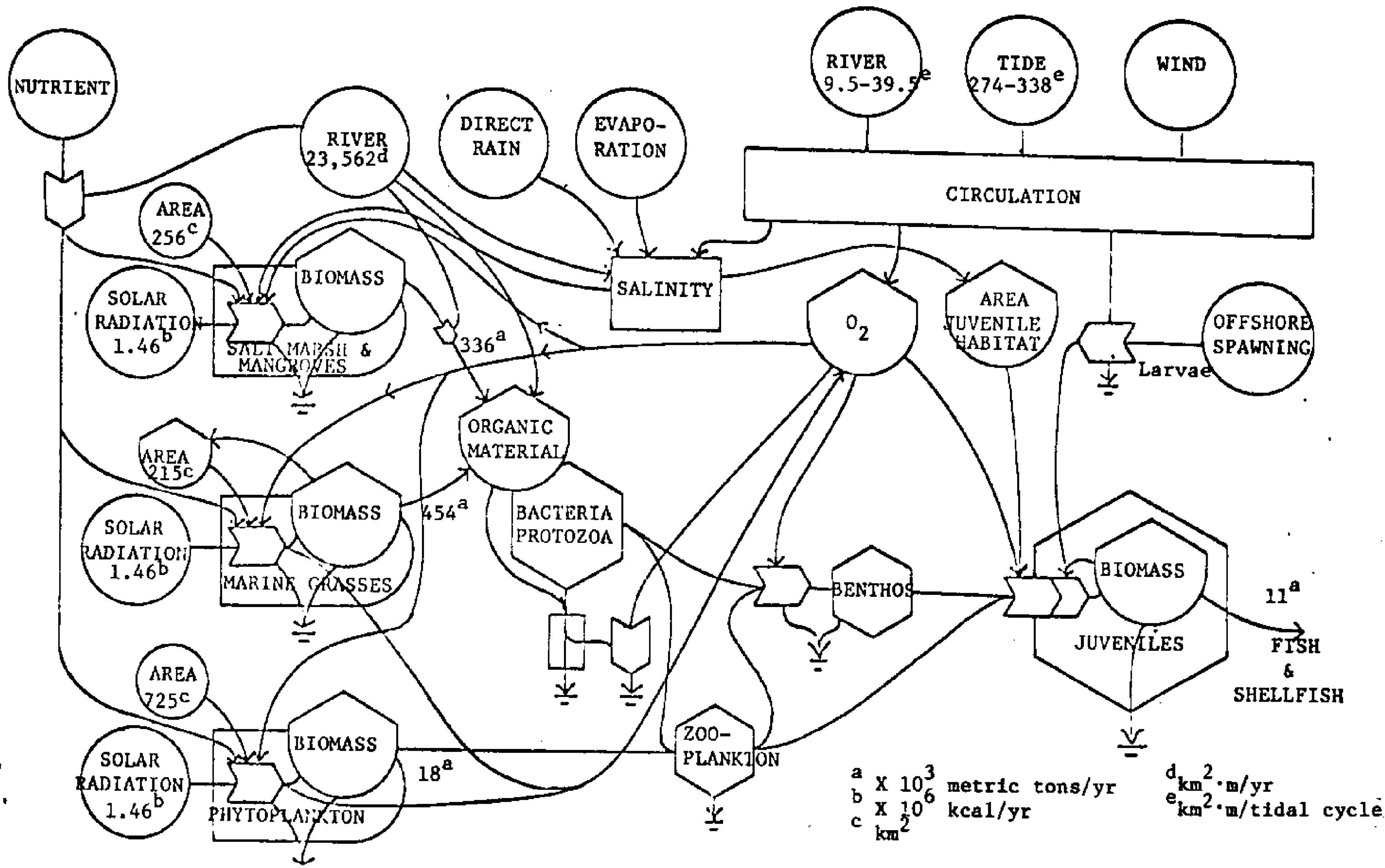


Figure 7. Energy circuit diagram partially quantified for Charlotte Harbor.

2) The current quantity and seasonal pattern of freshwater flow to most Florida west coast estuaries is NOT NATURAL because land use changes and drainage to the watershed have:

   a) increased the total annual runoff to estuaries, perhaps by as much as double the natural flow; and

   b) increased the seasonal variation so that more water now enters during the wet season and less water now enters during the dry season.

3) A withdrawal schedule that creates a more artificial pattern of runoff such as one that further decreases freshwater flow during the dry season would be very detrimental.

4) A withdrawal schedule that reduces freshwater flow to an estuary will not necessarily be detrimental and may even be beneficial if withdrawals are made in such a way that a more natural quantity and seasonal pattern of runoff is reestablished.

Although the present living systems of the estuaries may be adapted to some extent to the current pattern of seasonal extremes, natural selection has had a relatively short time to shape systems that will function at maximum capacity under this regime; whereas the systems normal to Florida's west coast estuaries have been shaped by as much as 10,000 years of natural selection; they are adapted to less oscillation than is experienced in our estuaries today. It is therefore likely that the productivity of Florida's west coast estuaries would be greatly improved by providing a more natural cycle of water releases. It should be advantageous economically and politically as well as environmentally if the natural cycle could be restored by the same action with which the area's expanding water needs are provided.

The natural seasonal pattern of runoff to each estuary can be approximated using a water model such as that by Browder (1976). A seasonal schedule of water withdrawals can be developed on the basis of the difference between present and natural seasonal runoff. "Water crop" has previously been defined as total freshwater runoff.

A withdrawal schedule such as that recommended would call for the diversion of a large percentage (perhaps as much as 50%, depending upon the estuary) of the wet season flow into storage facilities such as aquifers, swamps, and reservoirs. Little or no water should be diverted during the dry season. Dry season flow will be augmented inadvertently due to seepage from storage, which will increase the river's base flow. Some additional loss from storage will occur due to increased evapotranspiration.

Some Florida rainfall records show cycles of five to six years and longer. It is possible to develop a predictive rainfall model based on these cycles and to continuously modify the model based on the difference between current actual and predicted values. Such a model, known as a time series model, can be coupled with the runoff model previously described to fine tune the withdrawal schedule according to current conditions.

An evaluation of this natural cycle withdrawal plan should include an estimate of its seasonal effect on the five most important functions of freshwater in the estuary, which are:

1) to provide a density gradient to stimulate vertical and horizontal circulation to prevent anaerobiasis (oxygen deficit) of bottom waters and sediments and to resuspend nutrients in the water column;

2) to establish and maintain a broad salinity gradient in the maximum area of appropriate habitat to effectively screen juvenile fishes from predation and to reduce predation and parasitism on other marine organisms, particularly sessile forms such as oyster.

3) to provide organic materials to the estuary to act as the basis of the detrital food chain -- in particular, to carry dead organic production of estuarine marshes and mangroves into open water where it can be fully utilized.

4) to introduce essential nutrients to the estuary to stimulate primary productivity.

5) to prevent estuaries from becoming hypersaline due to concentration of salts by evaporation.

To consider how restoration of the natural cycle of flow might effect the estuary, investigations should aim not only at answering the question of "how much" water is needed to fulfill each of these functions but "when" it is needed most.

A comparison of the natural cycle of river input to the present cycle and other alternatives in terms of productivity of fishes can be made with a computer model based on an energy circuit diagram such as that for Charlotte Harbor.

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SOME RELATIONSHIPS BETWEEN RIVER FLOW, ESTUARINE CHARACTERISTICS, AND ECONOMICS IN A FLORIDA GULF COAST REGION

by

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SOME RELATIONSHIPS BETWEEN RIVER FLOW, ESTUARINE CHARACTERISTICS AND ECONOMICS IN A FLORIDA GULF COAST REGION

INTRODUCTION

The central purpose of this paper is to present a case study of a coastal area where the quantity, quality and seasonal pattern of freshwater input to an estuary may, in the future, be changed. This paper is an abstract of a larger study which considered, in general, the principals that may be organizing man and nature in the coastal zone. Most of us here are familiar with recent phenomena where there has been an increasing harvest drawn from both recreational and commercial marine fisheries at the same time that coastal developments were removing habitat and interfering with the necessary food chain base of coastal fisheries. In many areas there was a burst of economic activity, followed by periods of over-fishing, coastal disturbance, loss of the fishery, and replacement with urban development that may have unnecessarily decimated our natural resources. This case study considered the general problem of co-existence of economic development and marine resources using as a study area Franklin County, Florida, which includes the mouth of the Apalachicola River and a very valuable resource of oyster and shrimp landings. Major developments potentially effecting Franklin County included changing prices of purchased goods and fuels, river flow and coastal modifications, development of the coastal islands for tourism and changing population pressures for tourist and retirement developments. To gain an understanding of the consequences of these changes system models were constructed and some were simulated. These included an oxygen balance model of production, respiration, exchange and diffusion in Apalachicola Bay with special emphasis on the role of the river as a source of nutrients and organic matter and a regional model showing trends caused by changes in external driving functions (river flows, money supply, etc.) as they interacted with the estuary and fishery activities that together constitute the economy of Franklin County, Florida.

Issues for Decision in Franklin County

From discussions with local leaders in Franklin County, from synthesis of data collected in previous and on-going studies in the county, and from general principals of systems ecology (Odum, 1971), the following list of questions was developed:

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

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

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

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

Description of Study Area

Franklin County is located on the northwest Gulf Coast of Florida (Fig. 1). The county is rural with most of the county's 7,000 residents living

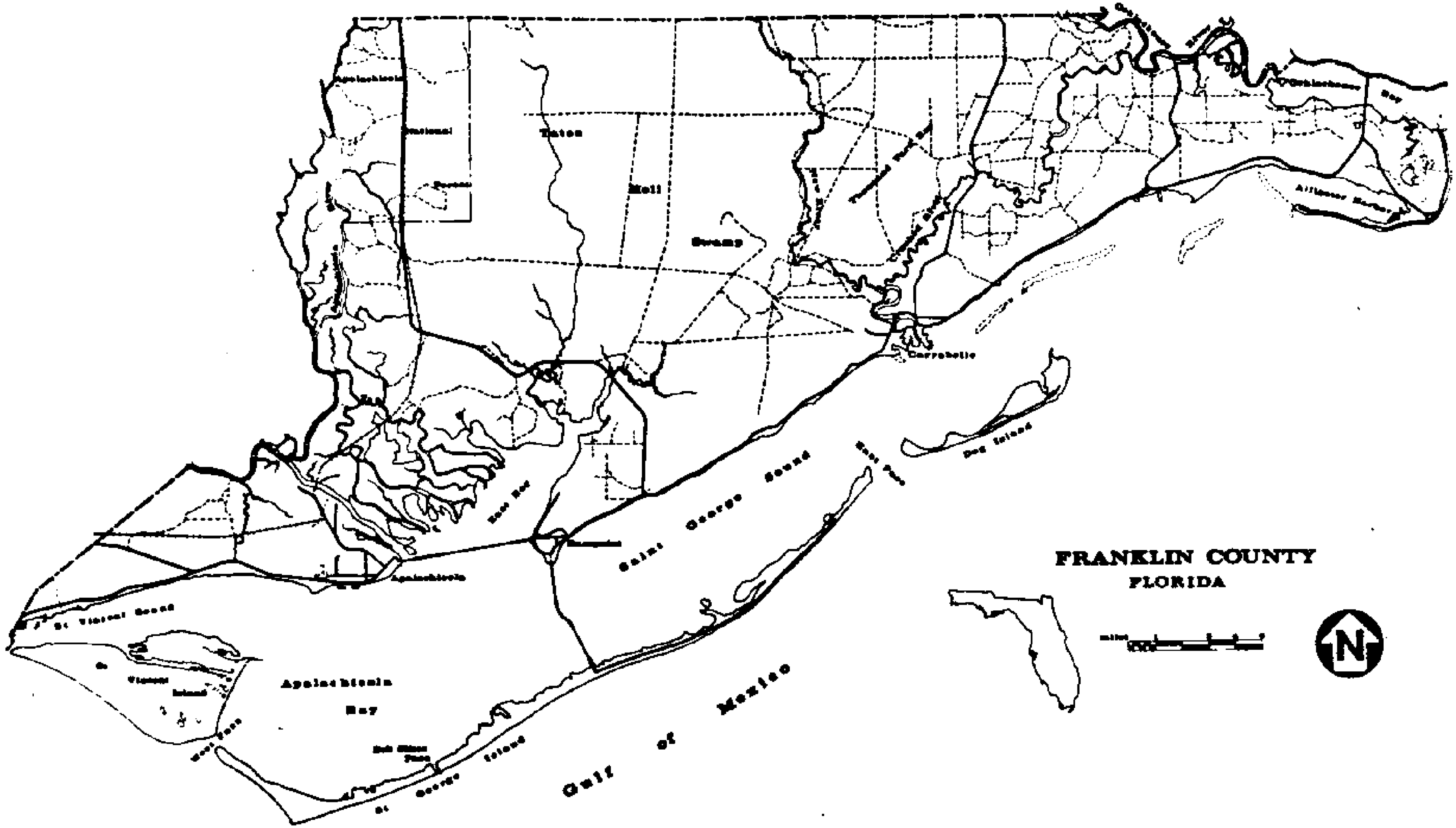


Fig. 1. Map showing major features of Franklin County and Apalachicola Bay, Florida.

along the coast in close proximity to Apalachicola Bay, a medium salinity estuary separated from the Gulf of Mexico by several offshore islands. Apalachicola Bay has been well described by Livingston et al. (1974) and many others and details can be found in those publications. Several features of the freshwater input will be given here since that is the main thrust of this paper. Gorsline (1963) estimated that river water remained in the bay system for a few days in the winter and up to a month in the summer. However, the oyster producing area of Apalachicola Bay is smaller than the area defined by Gorsline and the retention time for this area may be less. During the winter season the Bay appears to be well mixed but has salinity produced stratifications around the inlets. In warmer seasons stratification is generally observed with salt wedge penetration extending well into the Bay at times (Estabrook, 1973). This condition may be a recent feature as previous hydrologic studies (Dawson, 1955; Gorsline, 1963) reported no stratification except in dredged channels. High turbidity was associated with river discharge also being highest in the winter. The Apalachicola River has an average yearly discharge of about 27,000 cfs (6.5×10^7 m^3/day) draining a watershed of about 18,000 square miles which includes part of Georgia and Alabama. In addition, river flow has a well defined seasonal cycle with highest and lowest flows occuring in March and September, respectively.

The local economy is predominantly dependent on water resource based activities centered on Apalachicola Bay. The Bay produced in the early 1970s about 90% of the commercial oyster harvest in Florida and supported shrimp, crab and finfish industries with an annual dockside value of several million dollars (Rockwood, 1973). The largely undeveloped forestlands, inland and coastal waters, and barrier islands in Franklin County support a tourist business and provide recreational opportunities for the residents (Florida Tourist Study, 1970). Other details of the terrestrial ecosystems and features of the local economy can be found in numerous reports some of which are summarized in dissertation form (Boynton, 1975). Based on reviews of previous literature, interviews with people knowledgeable about particular aspects of the county, a simplified model suggesting relationships within the county was developed and is shown in Fig. 2. This diagram shows major inputs and aggregated storages of urban activities, a plankton system and oystery reefs. Shown on the left hand side of the diagram are urban sources of goods, fuels, services, money sources and new residents and tourists. Associated with these inputs are dash lines representing money flows. Shown below the urban resources are the natural resources including inputs of sunlight, river water, and the materials associated with river input. Notice also that each of the main components within the model are connected one to the other. The urban system delivers nutrients and coliform bacteria to the plankton ecosystem in the bay, the plankton system contributes food in the form of detritus to the oyster reefs and the oyster reefs are linked to the urban system again via the sale of oysters. When this simplified model was prepared for simulation other connections between the components were added.

TECHNIQUES

Evaluation of the energy basis of Franklin County included systems models, energy calculations, direct field measurements, and aerial maps.

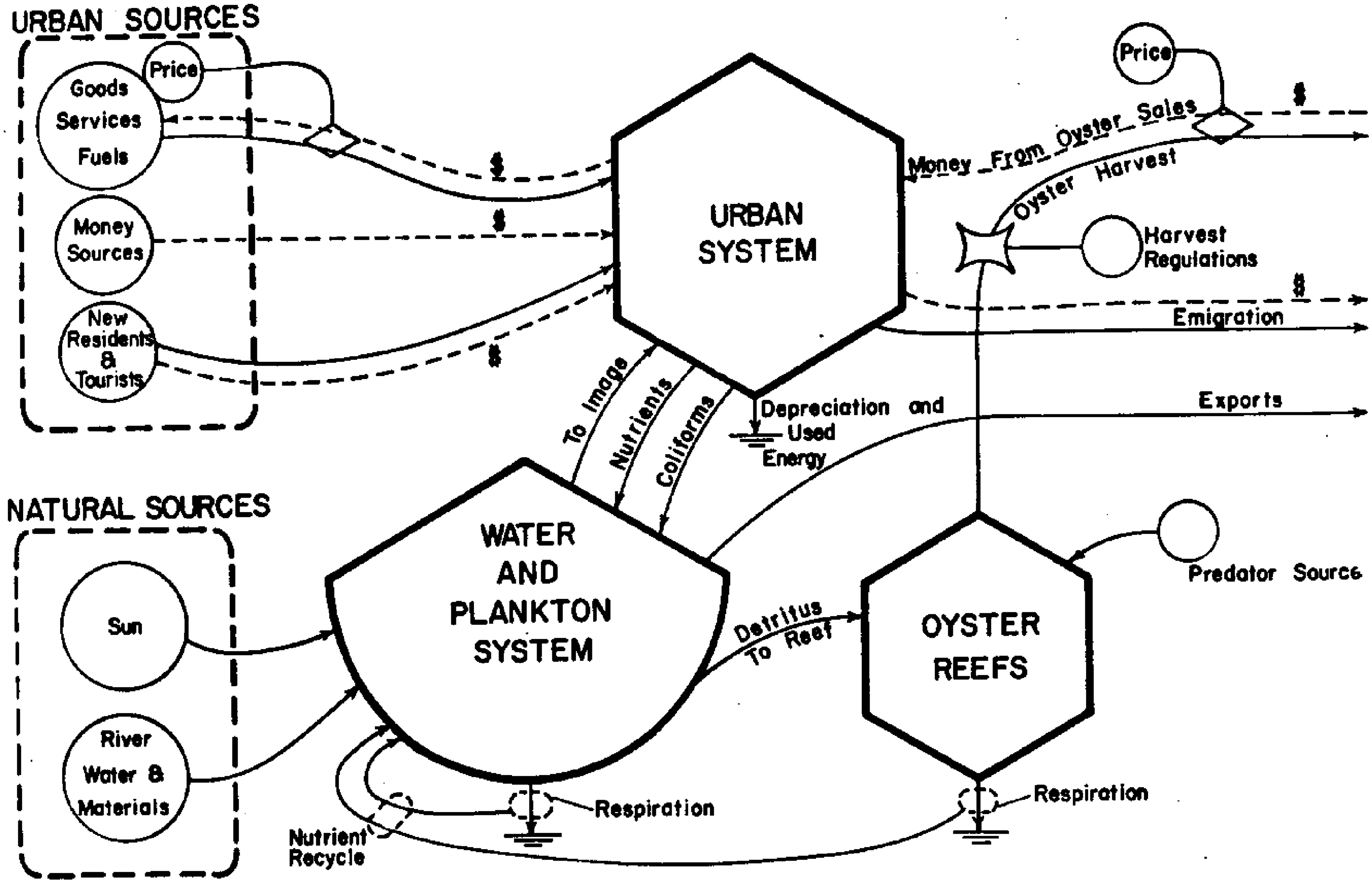


Fig. 2. Simplified model of Franklin County and Apalchicola Bay, Florida. Model shows major inputs (Urban and natural), components (urban, plankton, and oyster reef systems) and pathways connecting components and external markets.

The first technique was used extensively in the section dealing with river flow and so some features of the approach will be described here. The general modelling procedure used in this work is summarized in Table 1. Symbols used in the energy diagrams are given in Table 2. In brief, energy and material flows and storages were identified and their interactions characterized with the diagrams. Model diagrams indicated critical data to be collected in the field and served as an organizational basis for simulations and energy calculations. Once the diagrams were evaluated computer simulations or simplified models were used to test our concept which were generally indicated by field data. After sensitivity checks and validations, simulation results suggested future county trends. I should like to note here that we do not have a long experience in understanding the real validity of models such as the one that will be presented here. Rather than view the model as a final predictive tool at this point it is my opinion that it is more constructive to view it as an improvement over more intuitive methods of predicting the consequences of changes.

FIELD MEASUREMENTS

This section presents selected data on Apalachicola Bay collected as a part of a large project conducted in the Apalachicola Bay region. I've emphasized those aspects dealing with freshwater input to estuarine ecosystems.

Table 1

Modeling Methods*

Given below is the general procedure for model development and simulation.

1. Define the main system components (state variables) and forcing functions (outside energy sources).

2. Using discussions and existing understanding of processes, diagram the pathways of interaction and energy flow including switching and threshold actions. These pathways constitute algebraic terms when translated into equations.

3. For a particular or average situation, include the numbers for stocks and flows. Solve term for each pathway for its coefficient after substituting the flow and stock values existing at that time. The relative importance of pathways becomes evident.

4. Usually, the first draft of a model having much of what we know of details and minor as well as major flows may have 50 components and many more pathways. Next, we try to group, simplify, eliminate by setting many effects constant for the study consideration, and thus, make a complex model into a simplistic macromodel that focuses on the main issue in terms of its main driving functions and causative internal pathways.

5. For each storage unit write a differential equation as the sum of the input and outflow pathway terms. Each term has a numbered coefficient.

6. Translate differential equations into computer language.

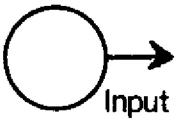
7. Simulate the model, testing for steady states and transient patterns, for sensitivity of response to varied forcing functions and coefficients, and for similarities to observed time graphs (validation). Relate to public issues at question.

8. Revise models to incorporate improvement to fit observations and do it in a way that is dynamically explainable in terms of known mechanisms of the systems parts rather than as empirical curve fitting.

9. Draw conclusions about the consequences of the models and actions on them. Try to find test examples that will validate in real world tests the experiments done on the models. Often, this requires looking at historical trends.

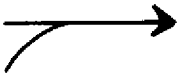
*Adapted from Odum, H. T., 1972.

Table 2.
Symbols of the Energy Circuit Language Used in this Paper.



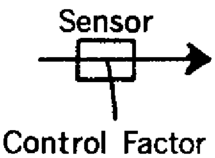
Forcing Function. An outside source of energy or materials entering the system of interest.

Pathway of energy or materials. The arrow indicates the direction of travel.

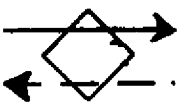


Adding Junction. Intersection of two similar flows capable of adding.

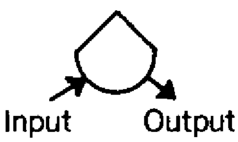
Pathway of money flow.



Rate Sensor monitors flow rate of carrier and controls the input of a quantity in proportion to the flow of the carrier. Sensor can also be used for similar purposes with a storage.

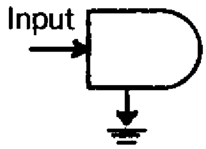


Economic Transaction. Flow of money is opposite to the flow of energy as in sales at a grocery store.

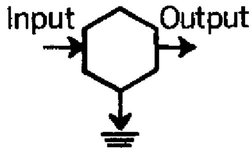


Passive Storage. A storage of energy or materials within the system of interest.

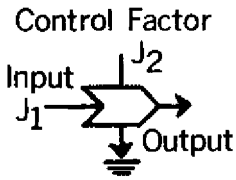
Heat Sink. Indicates a loss of potential energy as a consequence of the Second Law of Thermodynamics.



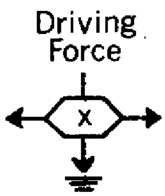
Green Plant. Normally used to illustrate photosynthesis, but utilized in regional diagrams to represent an entire ecosystem.



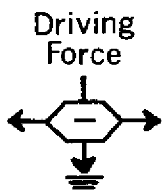
Self-Maintaining Consumer. Combination of storage and workgate symbols whose response is autocatalytic, e.g., an animal, city, industry.



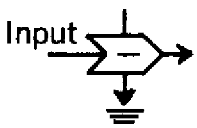
Workgate. Intersection at which one flow (J_2) makes possible a second, (J_1).



Two-Way Workgate. The direction of flow is determined by a gradient, hydrostatic head, etc. and the rate is in proportion to the gradient times the driving force.



Two-Way Workgate. As in above except driving force inhibits the flow.



Workgate. Special case of the above in which the intersection has a retarding effect on the process.

Adapted from Young et al., 1974.

Salinity Measurements

Given in Figs. 3 and 4 are maps showing surface and bottom salinity distributions in Apalachicola Bay during periods of low and high river flow. During the period of lower river flow, salinity stratification was evident over most portions of the bay. Area weighted average surface top and bottom salinities differed by approximately a factor of two. In the spring sample (Fig. 4) both surface and bottom salinities were lower averaging 4.9 and 11.5 ppt, respectively. High salinity bottom water was evident in a large portion of the bay along the barrier island and on both sides of Bob Sykes Pass, an artificial inlet that was created to facilitate access between the Port of Apalachicola and the open Gulf of Mexico.

Metabolism Measurements

Diurnal metabolism measurements (a measure of photosynthetic and respiratory activity) were also taken in the Bay during the summer of 1973. These data were developed for use in simulation models and to characterize different bay ecosystems. As a summary of these data, Figure 5 shows daytime net photosynthesis plotted against nighttime respiration at each station. The diagonal line represents a PR ratio of 1.0 or represents what would be expected if the system consumed as much as it produced over a 24 hr period. When plotted in this fashion those stations near the river mouth and stations suspected of receiving man related waste all had PR ratios much less than 1.0. Medium salinity plankton system stations, that is those stations in the open bay where phytoplankton are the major producers, had PR ratios of about 1.0 or somewhat greater. Those stations dominated by grass flats all had PR

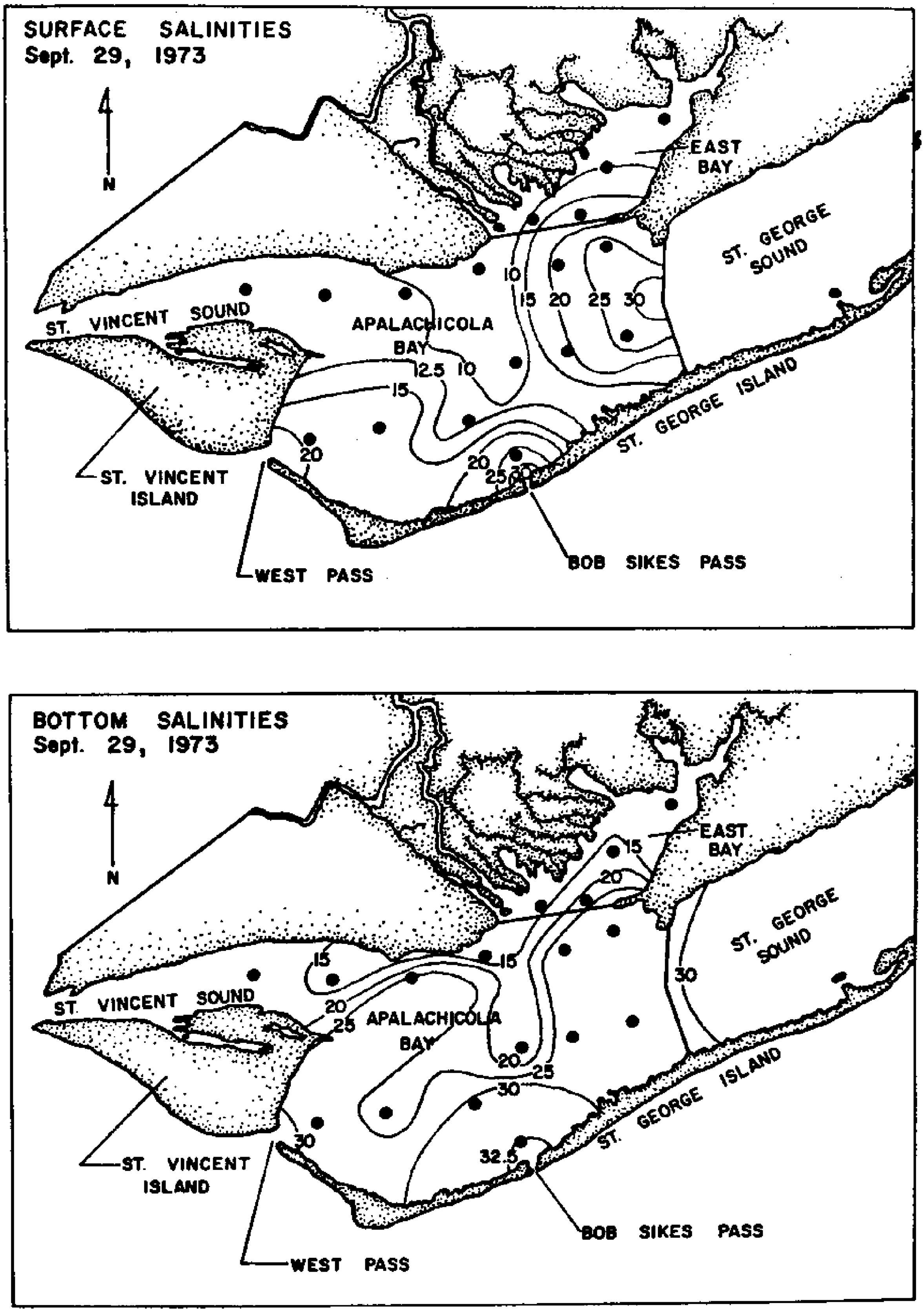


Fig. 3. Salinity pattern in Apalachicola Bay on September 29, 1973, (a) surface; and (b) bottom. River flow was 15,060 cfs and wind was from the southeast. Salinity stations are indicated by dots.

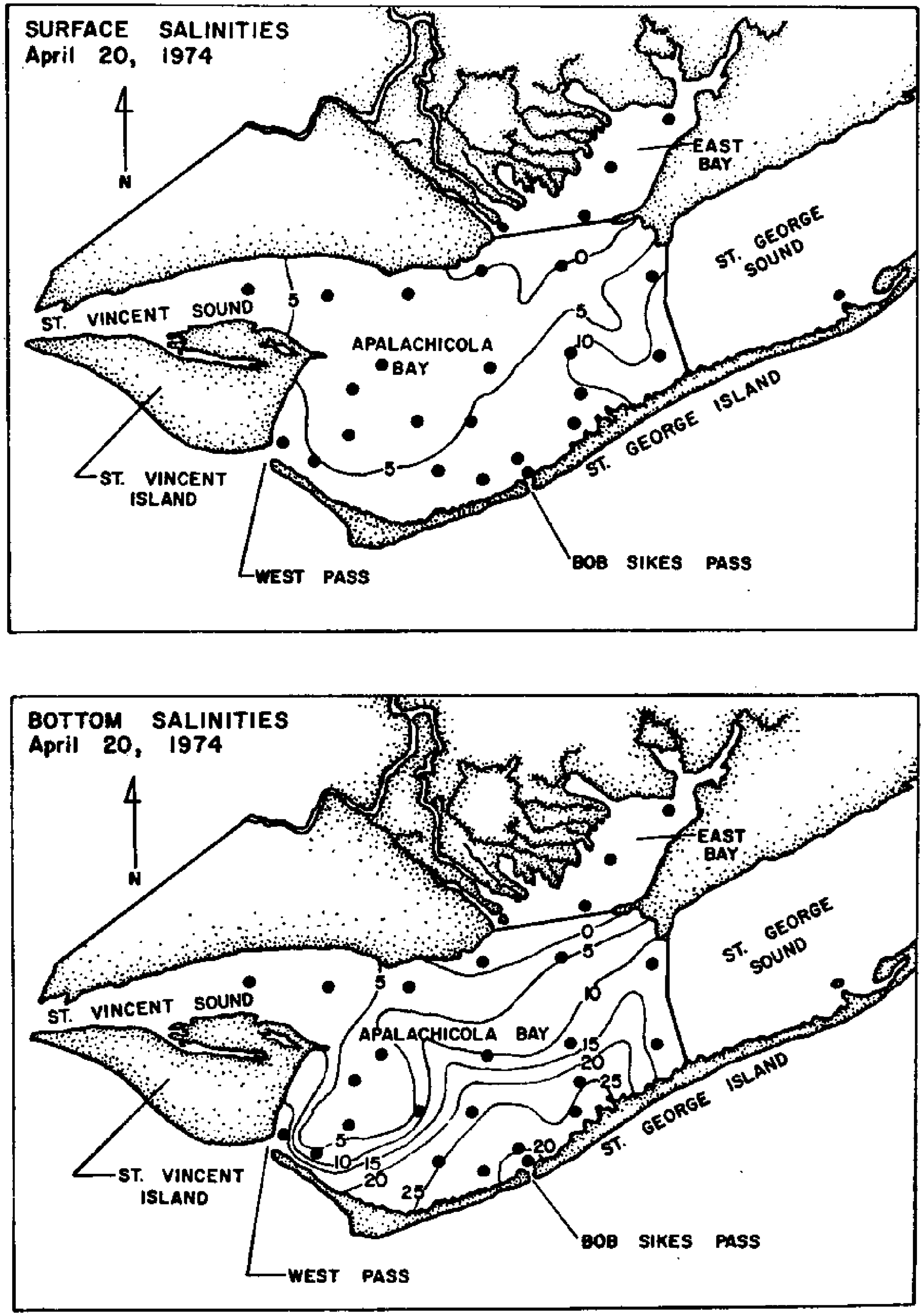


Fig. 4. Salinity pattern in Apalachicola Bay on April 20, 1974, (a) surface; and (b) bottom. River flow was 49,390 cfs and the wind was from the east at 10-15 knots. Salinity stations are indicated by dots.

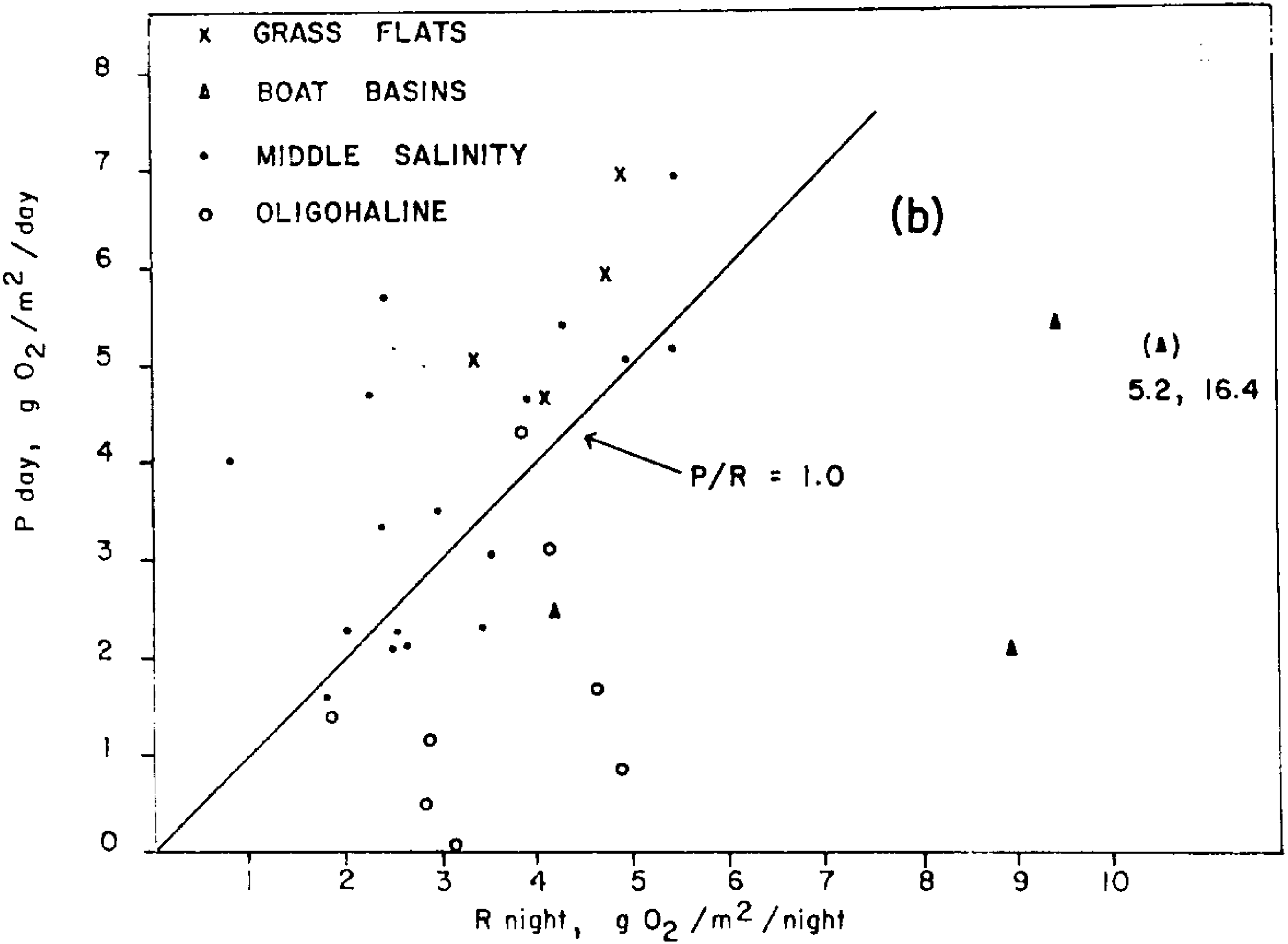


Fig. 5. Graph of daytime net photosynthesis as a function of nighttime respiration for systems in Apalachicola Bay (grass flats x; boat basins Δ; medium salintiy plankton system · and oligahline system o). The diagonal line represents a P/R ratio of one.

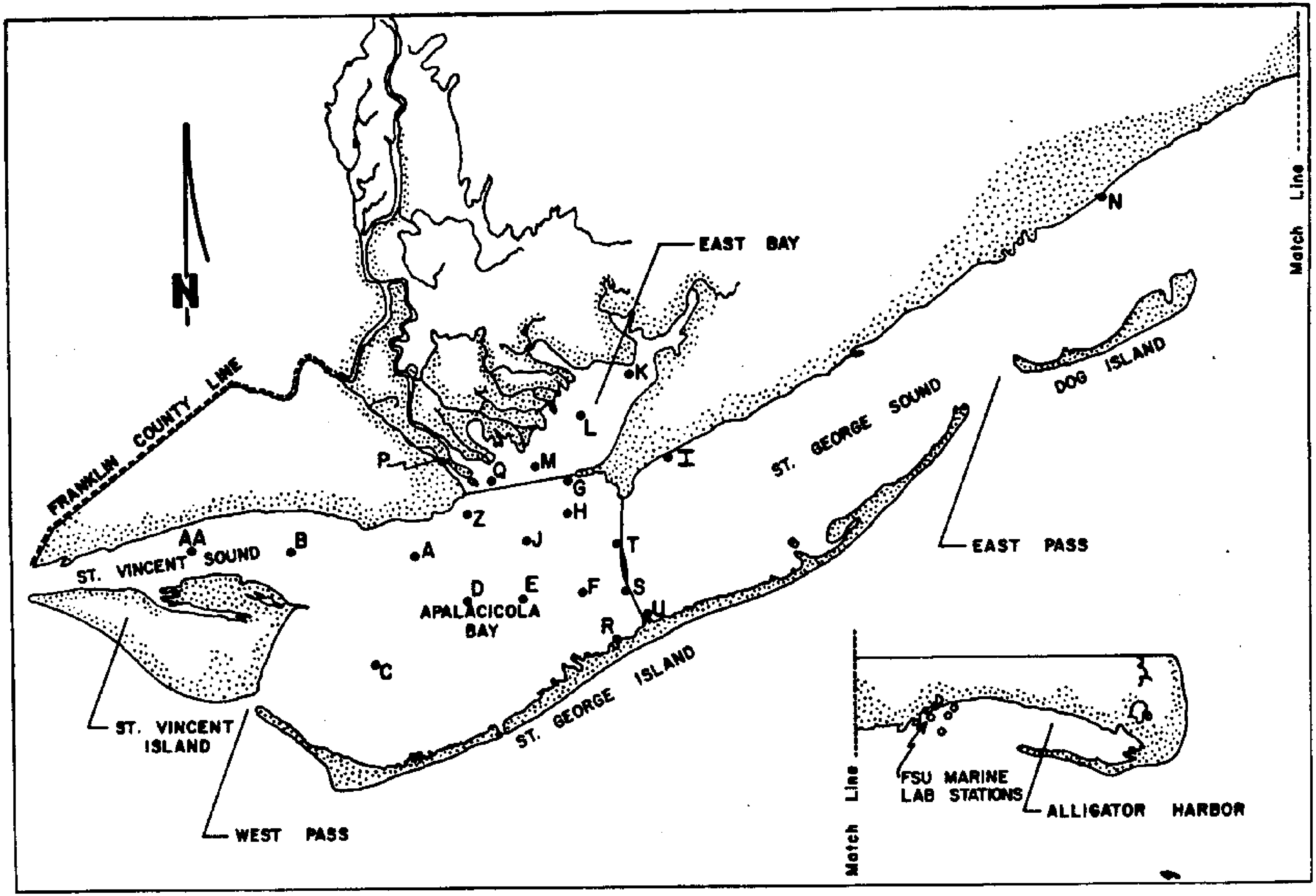


Fig. 6. Map of Apalachicola Bay showing location of stations used for diurnal metabolism and organic carbon measurements. Stations G, I, N, R, S, T and U were near-shore stations sampled from the shore, bridges or docks,

ratios greater than 1.0 indicating that the system was adding biomass in excess of that which was being consumed. Fig. 6 shows the placement of those stations.

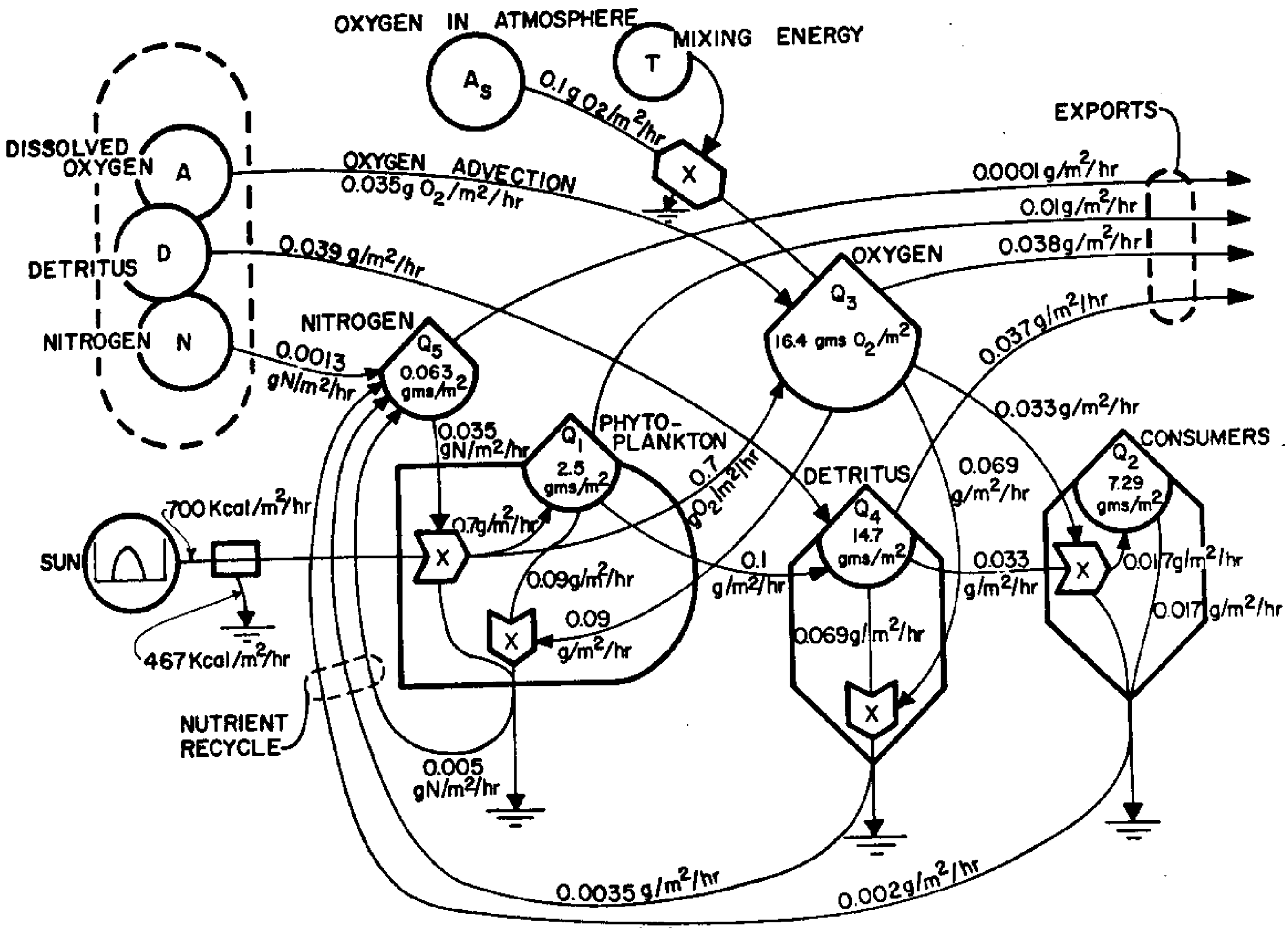
Data Assembled From Other Sources

Many other types of data were also assembled from other on-going and previously conducted studies. These data were assembled for use in developing several simulation models and included information on river flow, sunlight, salinity, water temperature, plankton production, nutrient concentrations and biomass levels of various consumer species. Space does not permit extensive presentation here but much of this information has been summarized by Boynton (1975) and Livingston et al. (1974).

SIMULATION MODELS

Diurnal Activity Model

The diurnal activity model shown in Fig. 7 was developed to investigate the relationships between phytoplankton, consumers, dissolved oxygen, organic matter in the water, and nitrogen. Of particular interest in this model was the response of dissolved oxygen in the water to changes in input from the river as well as changes in the movement of the water once it reached the bay. At the top of the diagram oxygen in the atmosphere (AS) exchanges with oxygen dissolved in the water depending on the saturation gradient and the amount of turbulence. On the left, sunlight and nutrients interact to pro-



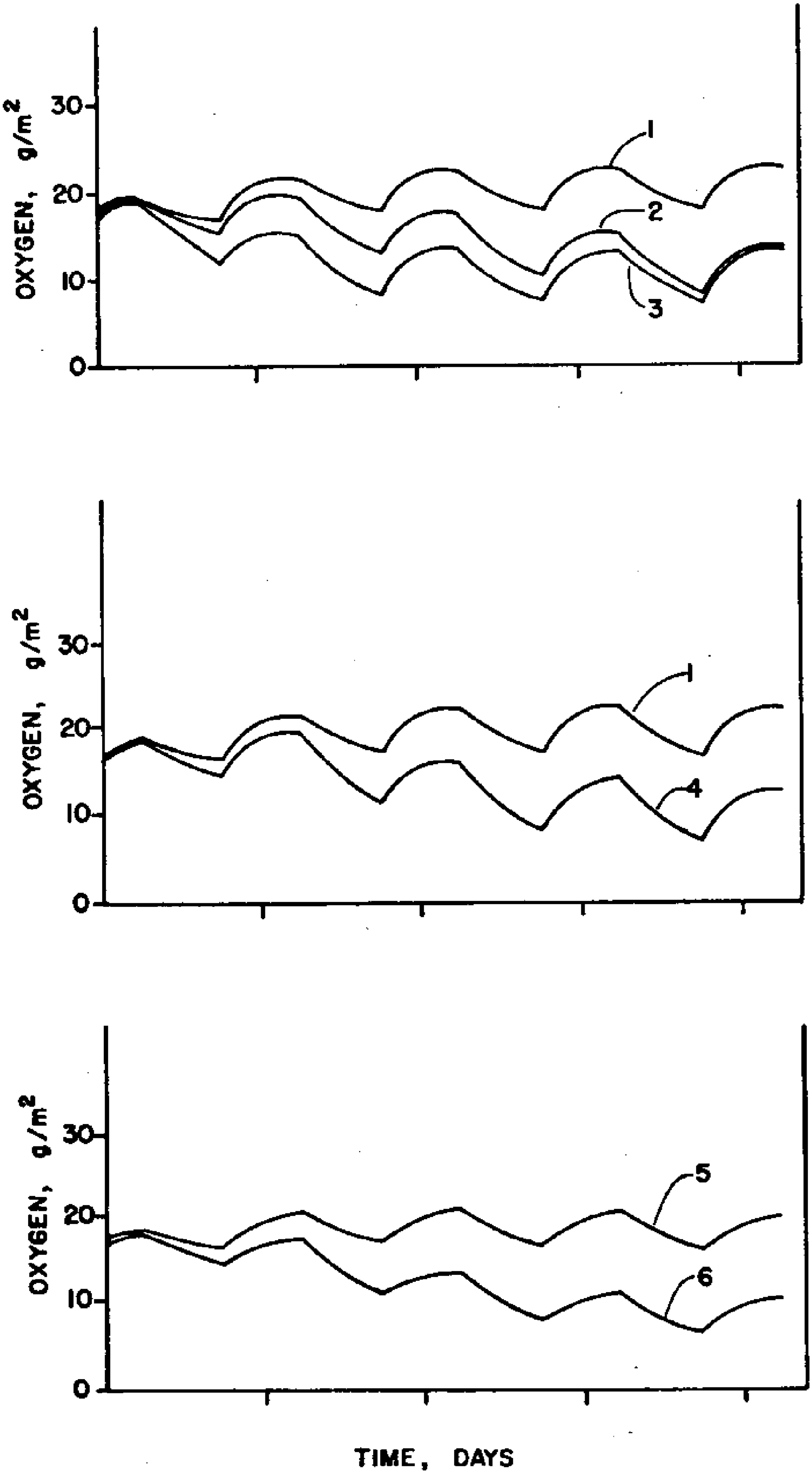
(b)

Fig. 7. Model of diurnal activity of Apalachicola Bay. Symbols used in the diagram are explained in Table 2. Estimates of mean values used to start the simulation tests are shown on the diagram.

duce oxygen and phytoplankton biomass. Losses from phytoplankton include respiration, death and exports. Input to the nitrogen source came from an external source and from recycle along various pathways. Losses included flushing and utilization in photosynthesis. The detritus storage operated in a similar fashion. The oxygen content in the water was determined by the net balance of respiratory utilization, phytoplankton production, advection and reaeration. Justification for the model configuration, data development and many simulation results are given in detail in Boynton (1975). In the control situation, that is the situation that attempts to mimic present summer conditions, dissolved oxygen ranged between an afternoon high of 9.5 and an early morning low of about 7.3 ppm. Phytoplankton production was the major source of oxygen producing the daily pulse. Levels of oxygen were considered normal for a phytoplankton dominated estuary. Numerous experiments were conducted using the model and these included increasing the rate of detritus and nitrogen input from the river, decreasing the amount of sunlight available for photosynthesis and a combination of effects which included both increasing the detritus load, increasing the nutrient load and reducing the turbulent energies available for reaeration. The reduction in turbulent energies could be achieved in the Bay by adding constrictions, docks or other structures which limit the movement of the water. Given in Fig. 8 is an example of computer output for the case just described above. In simulation runs 4 and 6 turbulence was reduced to 10% of the normal estimated level and detritus and nitrogen inputs were increased by a factor of 4 above the normal rate. In case 6 sunlight input was also

Fig. 8. Graphs of oxygen resulting from simulating the model in Fig. 7 with the reaeration rate reduced to 10 percent of control conditions, varying inputs of detritus, nitrogen, and sunlight, and with sunlight as a square wave.

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



OXYGEN, g/m²
30
20
10
0
1
2
3
OXYGEN, g/m²
30
20
10
0
1
4
OXYGEN, g/m²
30
20
10
0
5
6
TIME, DAYS

reduced to half the normal rate in an attempt to simulate increased turbidity conditions. Under these conditions, early morning oxygen concentrations were about 3 ppm, approaching the level where some bay species might avoid the area. Increases in nutrient and detritus loading beyond those levels further depressed oxygen concentrations.

Regional Model

Shown in Fig. 9 is a detailed model of Franklin County and Apalachicola Bay. Details of this model, justification for the configuration, data sources, etc., have been described previously by Boynton (1975) and Boynton, Hawkins and Gray (1976). This model is an elaboration of the energy circuit model given earlier with major groupings showing an urban system, a water and plankton system and an oyster reef system. The purpose of this model was severalfold. First, it was used to organize our understanding of relationships in the estuary and in the urban sector. Initial drawings of this model were far more complex, but quantitative evaluation of many pathways suggested many simplifications and thus tended to allow us to focus on major issues rather than details. Secondly, the model aided our search for data and suggested areas where we could best expend our research resources. With the model shown in Fig. 9 simulation trials were conducted testing many of the possible modifications that may come to pass in the area and checking the model for responses. An initial case, or a present day situation, was also simulated and, in a preliminary way, validated against field data. The major impression that was developed from the present day situation was one of very slow growth based mainly on the fishery resources. I've selected

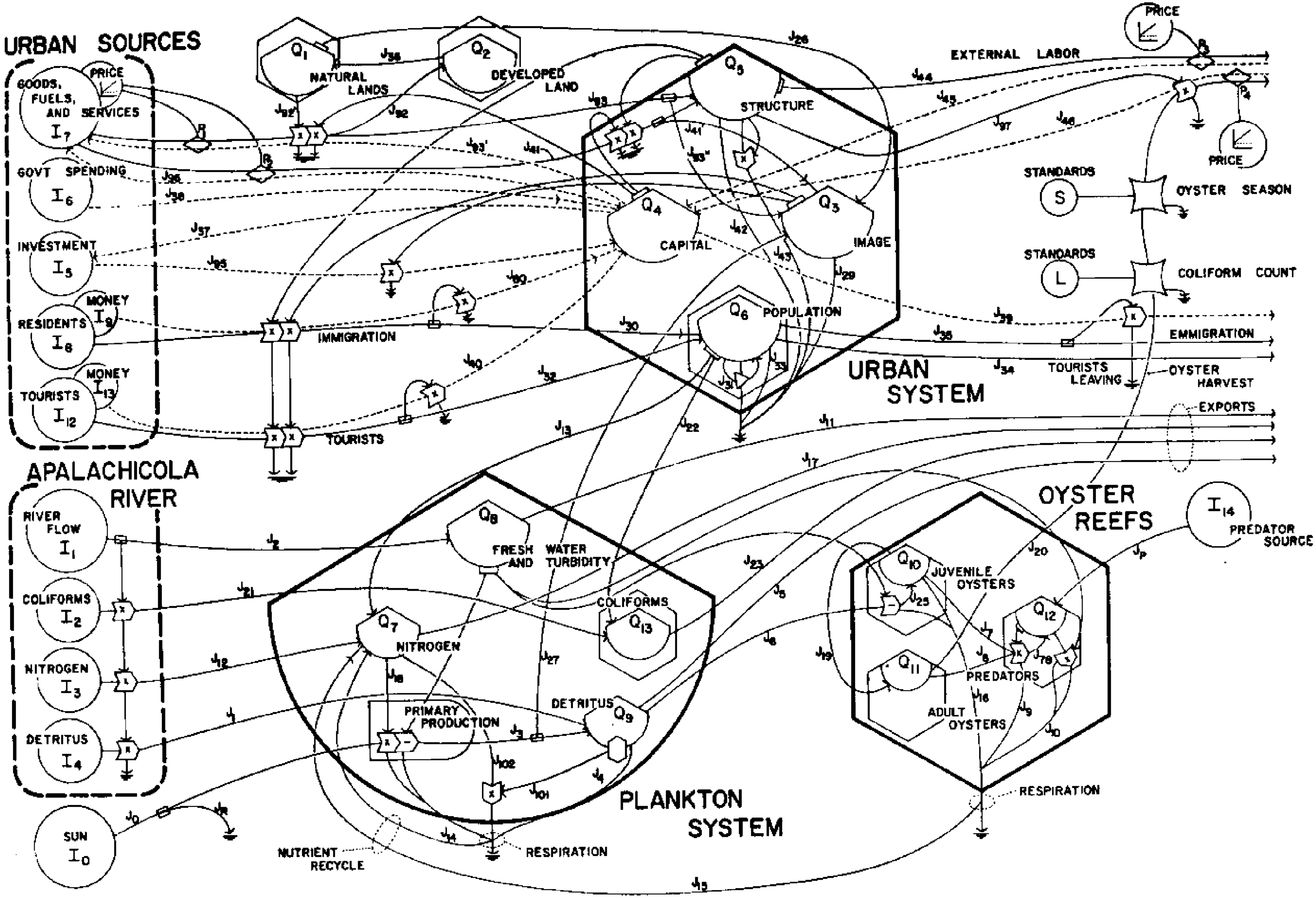
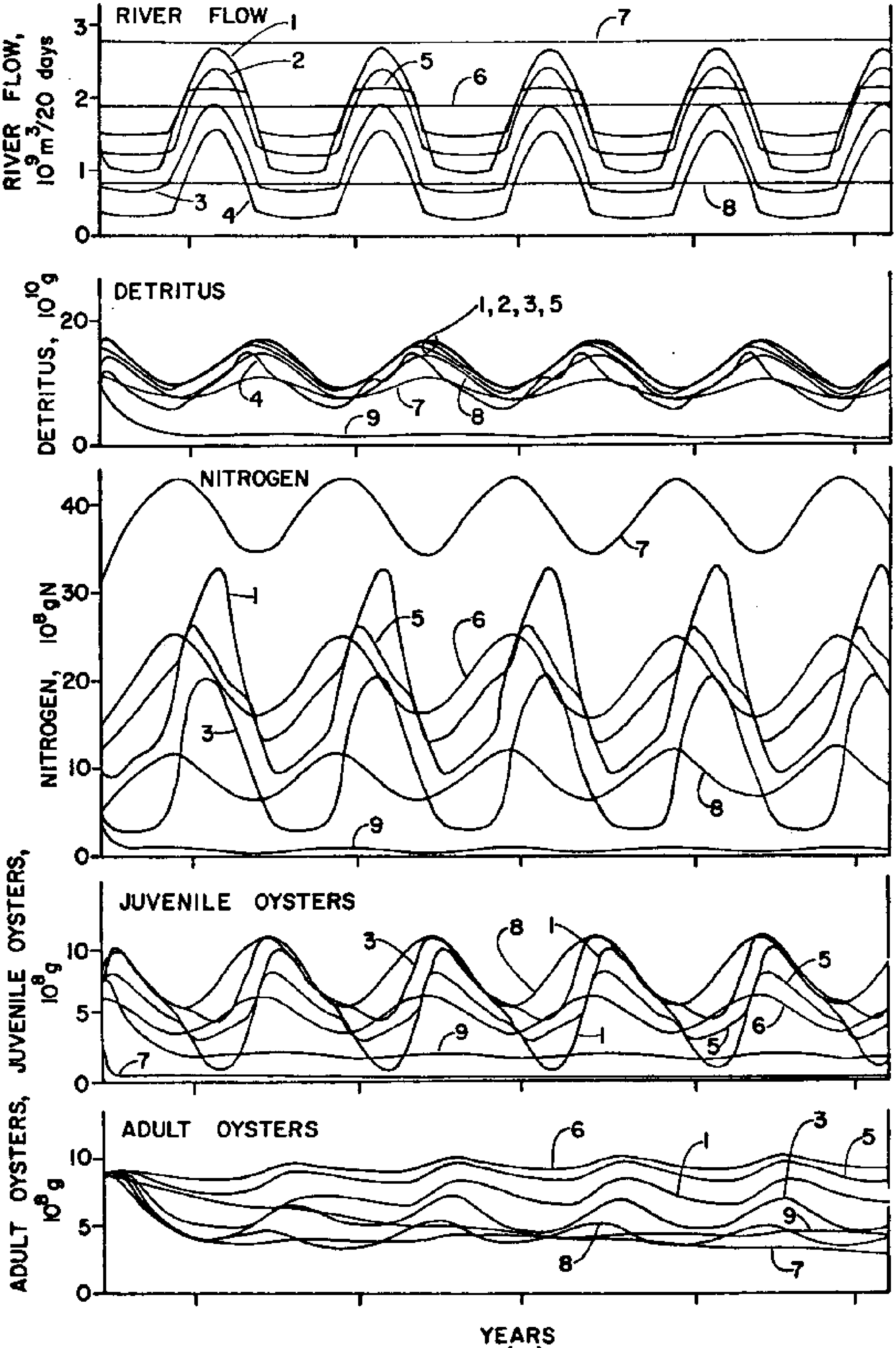


Fig. 9. Regional model of Franklin County and Apalachicola Bay, Florida.

one simulation output to indicate what this model suggests might happen under conditions where river flow quality and quantity were modified and one to show responses when investment money became a large feature. Figure 10 shows response of several model components to changes in both river flow volume and a seasonal change in river flow. Three types of river flow modifications were examined. These included changes in the seasonal pulse, elimination of the pulse, and elimination of river flow entirely. Notice that adult oyster biomass increased with river flow patterns that had seasonal pulses smaller than the control pulse but had approximately the same amount of total freshwater input. However, river flows much higher (Case 7) and much lower (Cases 8 and 9) than the normal produced smaller than normal oyster stocks. Smaller than normal predator stocks were observed in Cases 5, 6, and 7 due to freshwater stress. With no river flow, predator biomass was small because their food source was small. Whenever the juvenile oyster stock and predator stock was above normal the adult stock was below normal. Model responses for capital, residents and structure followed the response of adult oysters. When adult oyster biomass increased, each of the above variables increased. Even slight decreases in oyster biomass caused declines in urban variables. The second example of simulation output was designed to examine the level of investment in the county needed to offset general declines caused by inflation. The response of local structure, capital, adult oysters and predators under conditions of 10% per year price inflation for both sales and purchases are shown. In Fig. 11a, the level of investment was about 10 times the normal investment rate, while in

Fig. 10. Simulation results from the model in Fig. 9 with varying flow and amplitude of river pulse. Total yearly river flow volume and pulse height are given below as percentages of average river flow and pulse height. (a) Estuarine storages, (b) Urban storages.

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



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

(a)

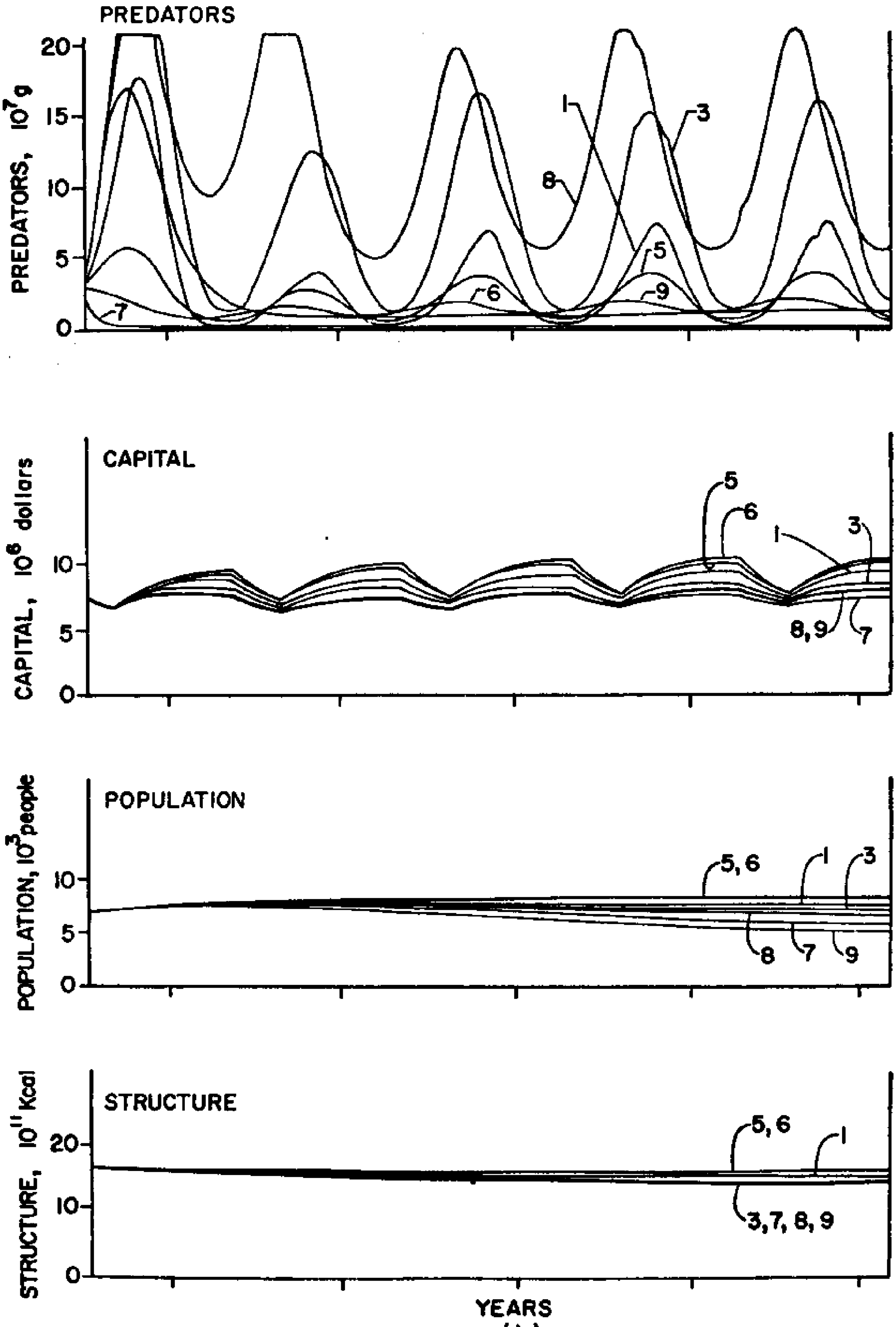

PREDATORS
PREDATORS, 10^7g
20
15
10
5
0
1
3
8
5
6
9
7
CAPITAL
CAPITAL, 10^6 dollars
10
5
0
5
6
1
3
8, 9
7
POPULATION
POPULATION, 10^3people
10
5
0
5, 6
1
3
8
7
9
STRUCTURE
STRUCTURE, 10^{11} Kcal
20
10
0
5, 6
1
3, 7, 8, 9
YEARS
(b)

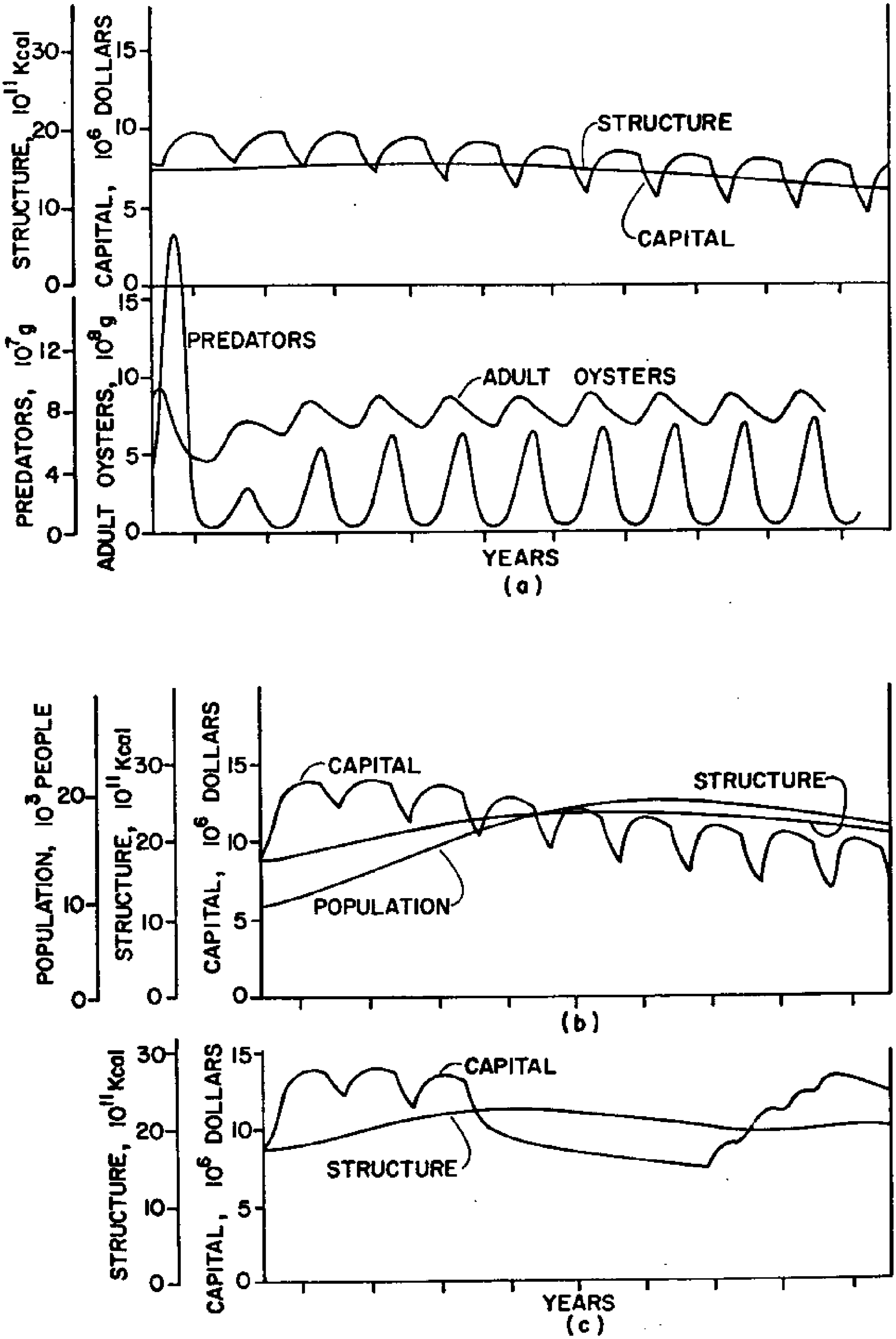
Fig. **11b**, the investment rate was about 20 times the normal investment rate. In both cases there was an initial increase in population, structure and capital followed by eventual declines. In Fig. **11c** the investment rate was 20 times the control rate and showed the leveling effect that the loss of the oyster fisheries has when forced to close for a period of three years due to excessive coliform levels. The results suggest that during the early stages of growth the oyster fishery remains a key feature of the local economy. Loss of the fishery at that stage could completely reverse growth trends as shown.

GENERAL DISCUSSION

Within the framework of this study, several general findings emerged that have only been eluded to earlier. For purposes of showing more clearly the perspective of the total study, which was regional, and to couch the effects of river flow in a regional perspective several of these findings are given below.

Using a data baseline of 1973, we found that Franklin County was indeed a rural area as is suggested by even a casual drive through the county. In our study the notion of rural was supported by quantitative information and thus the question of "how rural" could be addressed. Approximately 84% of all inputs to the county came from natural sources, that is, sources such as sunlight, wind, tidal action, freshwater input from the river, and others. The remaining 16% was associated with the importation of goods, fuels, and services for which payment was made. The ratio of urban to natural input (investment ratio) was about 0.19

Fig. 11. Simulation results from the model in Fig. 9 for the response of variables to inflation rates of 10% per year for purchases and sales with increased investment. (a) 10 times normal investment rate, (b) 20 times normal investment rate, (c) 20 times normal investment rate with temporary 3-year closure of the oyster fishery.


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

indicating a very rural region. Zucchetto (1975) reported an investment ratio for the Miami-Dade region of Florida of about 3.9. The ratio for South Florida was 2.4 in 1974 while the overall United States ratio in 1974 was 2.5 (Odum and Brown, 1975). Franklin County in 1973 was about 13 times less developed than the national average.

Using several criteria developed from energy analysis we also found that a proposed tourist development in the county was probably a desirable addition but, as planned, had housing densities that were too high. In other words, energy criteria indicated that best results might be had by spreading the development over a larger area.

Energetic considerations of a region which included Franklin County and a five-county region along the Florida portion of the Apalachicola River was taken as a study area when considering the advisability of adding a dam for purposes of improving navigation on the Apalachicola River. Investment ratio theory indicated that additional purchased fossil fuel based activities in the region would not overdevelop the area relative to other surrounding areas. However, an energetic cost-benefit analysis indicated that the benefits accruing from the dam, in most cases, would not exceed the cost and thus the proposal would not be self sustaining. Numerous features of environmental change associated with the proposed project were included in the cost-benefit calculation through conversion of processes to common energy units (Boynton, 1976).

WATER QUANTITY CONSIDERATIONS

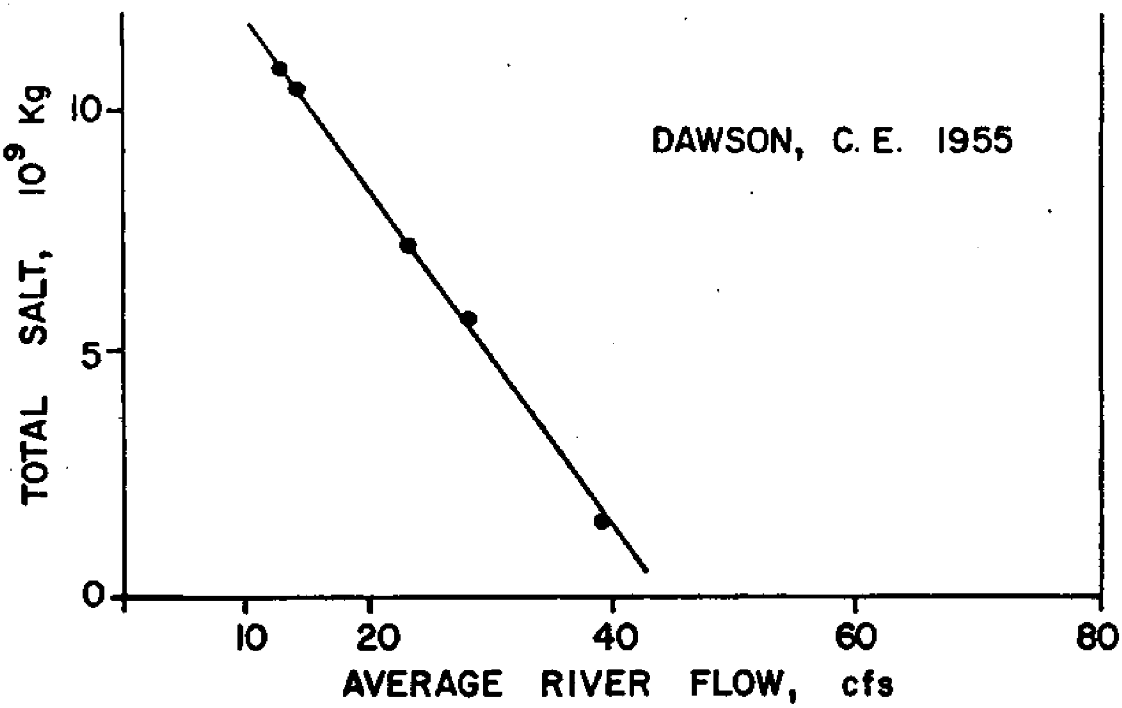
The very character of an estuary is determined and is indeed defined by the fact that it is an area where freshwater measurably dilutes more saline ocean water. Along with freshwater come a variety of materials which eventually mix with seawater in the estuarine area. Copeland, Odum and Cooper (1970) have summarized the importance of freshwater in estuarine sources. They identified four main energy sources characterizing estuaries. First, as in all ecosystems, sunlight is a required input. The remaining three were associated with river flow and included the importation of organic matter, nutrients and, associated with river flow itself, the stirring/mixing subsidy derived directly from flowing water. In a simplistic way then, if the quantity of freshwater reaching an estuary is decreased, we could anticipate that three main energy sources characterizing an estuary would also decrease. While this manner of viewing estuarine dynamics is highly aggregated there is a considerable amount of information available at this time to indicate that the trends suggested are probably correct. For instance, Copeland (1966) has found in Texas estuaries (where freshwater input may be near a threshhold) that shrimp and oyster harvests were greatest in years following years of heavier rainfall and higher than normal freshwater input to the estuary. Aleem (1972) studied the Nile River delta where the freshwater from the Nile River has recently been impounded behind Laker Nasser. In that case there was a drastic reduction in phytoplankton and zooplankton production and a sharp decline in several commercially valuable fish stocks. In that same area, Sharaf El Din (1977) also found that the abrupt decline in freshwater input altered circulation patterns and caused erosion of the delta. Other examples of clear relationships between freshwater input and characteristic outputs are also available. However, it is also important to note that many intermediate patterns could develop and effects are not always clear. For instance, in areas where freshwater input to an estuary decline, turbidity may also decline and as Copeland (1966) noted, the primary productivity of the estuary may not change because of a switch from a phytoplankton dominated system to a rooted aquatic system. In the Egyptian case, while fishery declines and shoreline erosion became problems there were obviously substantial benefits derived from increased hydroelectric power generation and a large increase in irrigated cropland.

Salinity Control

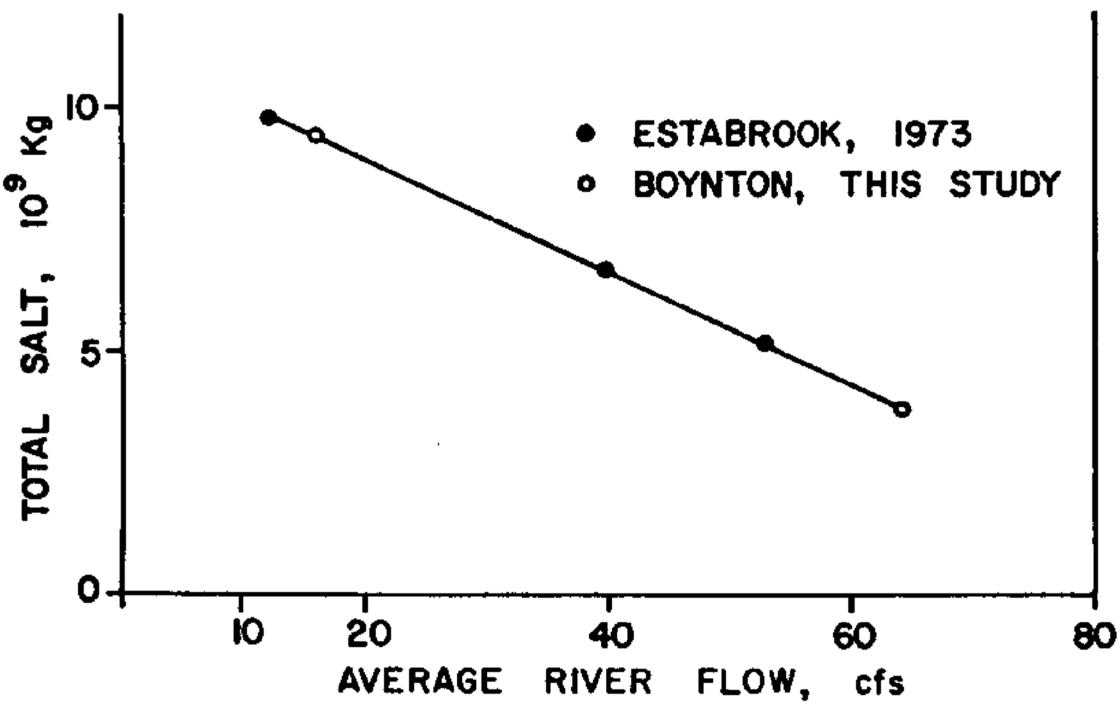
Figures 3 and 4 indicated high salinity water was associated with Bob Sikes Pass. To estimate if there have been changes in the bay salinity after construction of the pass, area weighted estimates of total salt in the bay were calculated and plotted against average river flow. Figure 12 shows data from Dawson (1955) plotted in this way for a period just prior to the construction of the pass and data collected in 1973 plotted in the same way. Both plots indicate that total salt in the bay was inversely correlated with river flow. Comparison of the two plots suggests that during periods of low river flow there was little difference before and after the shrimp boat pass was cut. However, the plots suggest that during high river flow periods there was more salt in the bay after construction of the pass. This suggests that the degree of mixing of bay and river water has decreased and that river water is reaching the Gulf of Mexico faster than before the pass was cut. It seems possible that the shrimp pass had caused this general increase in salinity.

Salinity control has implications for the oyster industry. It appears that oyster communities do best in areas that have seasonally changing salinities (Menzel et al., 1957). One reason for this is that many oyster

Fig. 12. Plot of total salt versus river flow. (a) Data from Dawson (1955) taken just prior to construction of Bob Sikes Pass, (b) Data from Estabrook (1973) and this study. Average river flow was calculated using average daily river flow for a two-week period prior to salinity measurements.


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

(a)


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

(b)

predators cannot withstand low salinity water. Each year when salinity drops these species are either killed, migrate to other areas or become dormant and oyster predation decreases. Additionally, the influx of freshwater kills many fouling organisms that are attached to oyster shell. After these organisms die, cultch is clean and available for new oyster spat (Gunter, 1953). Other mechanisms are also probably active that favor oyster dominance in estuarine areas with changing salinities.

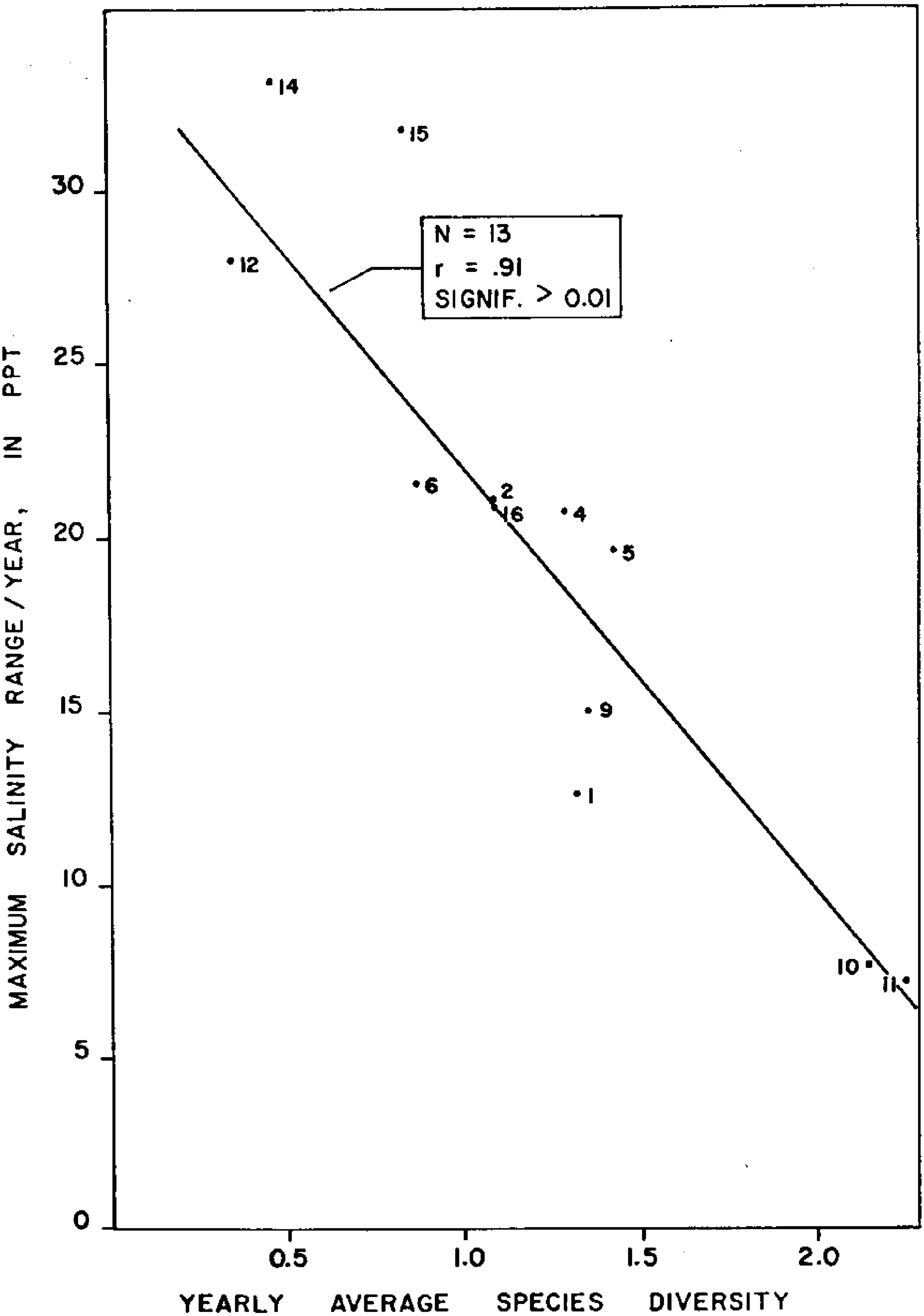
Data from Menzel and Cake (1969) (Fig. 13) show a fairly clear relationship between environmental change (as indicated by salinity range) and diversity. Low diversity was associated with large yearly salinity changes. High diversity was associated with areas with stable salinities, in this case, areas near the ocean. Oyster bars in Apalachicola Bay were associated with areas of moderate salinity change (15-20 ppt).

Shown in Fig. 14 is a long-term plot of the lowest yearly salinity recorded at two oyster bars in Apalachicola Bay. Station II is near the river mouth while Station III is near the open Gulf of Mexico. Data and station numbers are from Menzel et al. (1966). There is some indication of increasing salinity at Station III especially after construction of Jim Woodruff Dam and the boat pass. Station II does not show this trend. The lower graph in this figure shows monthly salinity values at these same oyster bars. Station II was a very productive reef, had few predators, and was subjected to a well-defined seasonal dip in salinity. Station III was depleted, with only small spat present. Predators were common. Salinities at this reef did not drop as low as at Station II and were often above 30 ppt. This reef had previously been quite productive.

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

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

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



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

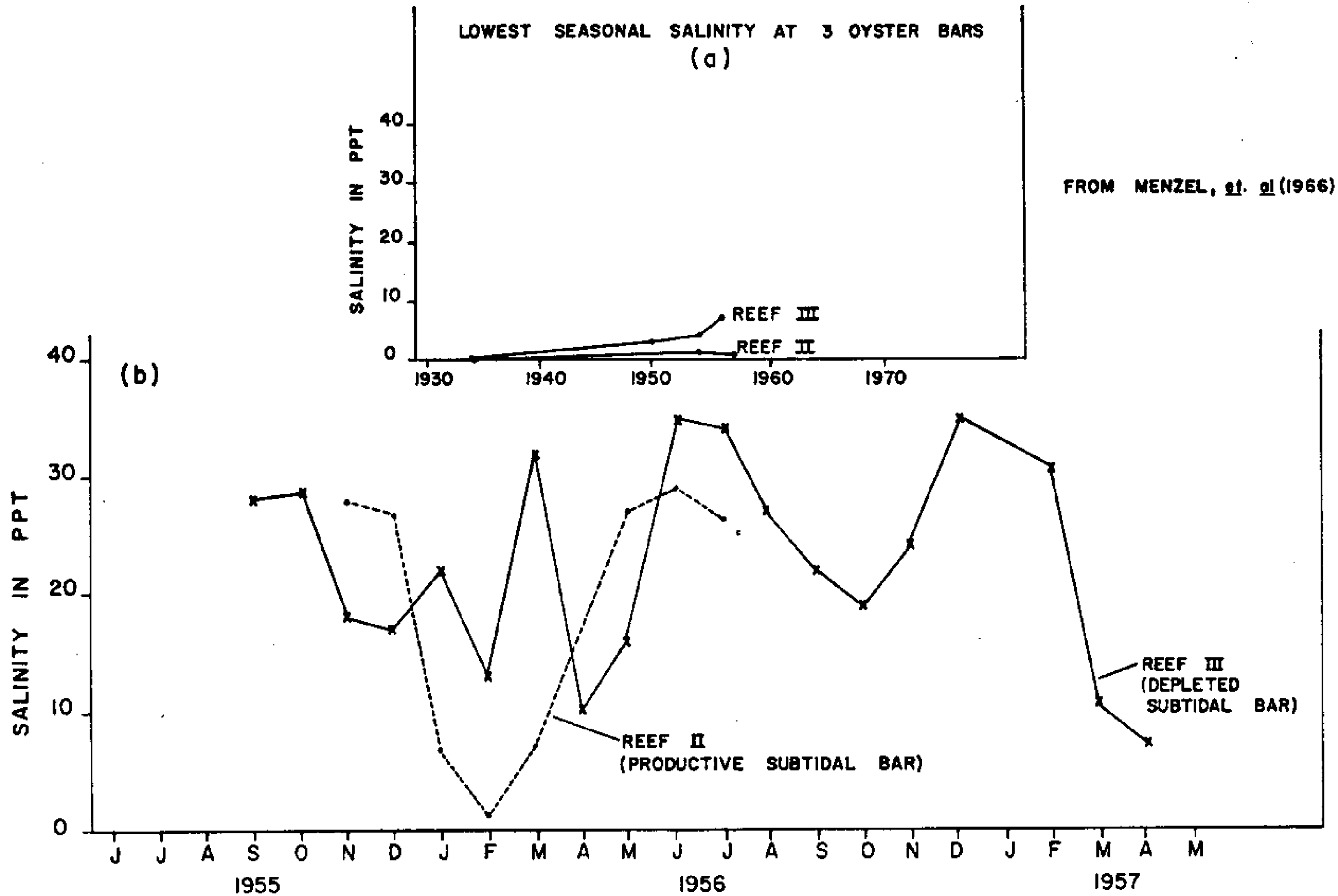


Fig. 14. Salinity data at two oyster reefs in Apalachicola Bay. (a) Yearly lowest salinity recorded at reefs II and III. (b) Monthly salinity recorded at reefs II and III. All data are from Menzel et al. (1966).

The data suggest that salinities are higher and have less seasonal change now than before the pass was constructed. Since stable salinity regimes do not favor oyster production, a quantitative assessment of the boat pass and its relation to salinity and stratification may be advisable, especially if some additional loss of freshwater associated with a proposed navigation dam on the Apalachicola River can be anticipated. If the pass proves to be a major factor in changing salinity and mixing, it may be possible to modify the pass slightly so that freshwater is retained and mixed in the bay while the recreational and commercial uses of the pass can be continued.

Primary Production

Calculations used in the diurnal activity model given earlier indicated that most of the nitrogen used in phytoplankton photosynthesis originally entered the bay as organic nitrogen bound in particulate or dissolved organic matter. The nitrogen from this source, when recycled, constituted about 85% of the total input of nitrogen in the early summer. Inputs from urban areas constituted only about 1% of the inorganic nitrogen entering the bay. Since phytoplankton production was the major source of food material during the summer, continued high production rates depend on continued nutrient supplies from the river.

Seasonal River Flow

Over the course of the year there is a gradual rise and fall in sunlight, temperature, river flow, productivity and other factors in Apalachicola Bay. It has been hypothesized elsewhere (Odum, 1971) that estuarine communities have adapted periods of reproduction and growth to coincide with periods of peak production in the estuaries. Estuaries characteristically have populations of fish and shellfish moving in and out on a seasonal program that seems related to estuarine production. Such migrations have been recorded in Texas estuaries by Hellier (1962), Copeland (1965), and Odum (1967), and in Apalachicola Bay by Livingston et al. (1974).

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

This concept was incorporated into the regional model given in Fig. 9. Model responses were tested to changes in both the amount of freshwater entering the bay and the amplitude of the seasonal pulse. Some results were shown earlier. In this simulation, pulsing river flows tended to maintain oyster stocks. River flows much higher and lower than normal and without seasonal pulses caused oyster stocks to decline. Menzel et al. (1957) have shown that predator stocks increased on one reef in Apalachicola Bay when the salinity pattern stabilized for several years. Adult oysters disappeared from the reef during this time. While no quanitative value has been given to the pulse of the Apalachicola River, the maintenance of established oyster reefs was shown in this model to be related to river pulse.

In the Patuxent River Heinle et al. (1975) has found that in a year of extreme cold, the spring zooplankton crop was about four times higher than normal. He has suggested that the mechanism controlling this phenomena is related to the precipitation in the basin remaining in a frozen form. The resulting ice cover, especially on marshes, tends to scour the area and deliver above normal amounts of organic matter to the estuary. Associated with higher organic matter input are higher phytoplankton and zooplankton stocks as well as larval stocks of commercially important species. In a somewhat similar fashion Boynton (1977) has found in the Potomac River that striped bass, a species characterized by strong year classes, has over the past 17 years produced strong year classes only in those years when there was an above normal amount of freshwater flow just prior to the spawning season preceded by a colder than normal winter. In this case again, a food chain type explanation was suggested. Thus, not only is the quantity of freshwater delivered to an estuarine important but also the timing of the flow.

Oyster System

Most reefs in Apalachicola Bay occur in the areas occupied by the medium salinity plankton ecosystem. This area covered about 80,000 acres. Rockwood (1973) suggested that this area could support many more oyster reefs than present. Energy used in maintaining the oyster reefs was compared to total sunlight input to the medium salinity plankton system. Total sunlight input, when translated into an equivalent amount of food, was used as an estimate of the total energy available for oyster growth. The calculated energy used by oysters was about 2.5×10^{14} Kcal/year while the total amount available was about 5×10^{14} Kcal/year. Comparison of these numbers suggests that the Bay may be able to support twice the present population of oysters. Oyster reefs are supported by large areas of the estuary through water movement. Energy calculations suggest that the support of each acre of oyster reef was derived from about five acres of estuary. Should freshwater input, with its associated nutrients, organic matter and stirring energies decline because of changes in river flow, this factor alone should lead to a decline in the ability of the bay to support oyster populations. In addition, salinity would most probably increase and with this increase favor increased predation.

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THE COASTAL ZONE: MULTI-USE RESOURCE ALLOCATION AND INSTITUTIONAL FAILURE

by

David Mulkey*

INTRODUCTION

An important first step in attacking any problem is to identify the cause of that problem. For water and coastal zone management problems in Florida, one does not have far to look to determine the cause of the problem nor is a great deal of genius required in the course of that determination. From a virtual wilderness of millions of acres and less than a half-million people at the turn of the century[1], Florida has grown explosively to the modern, sophisticated state of today with an estimated population in excess of nine million, a figure which is expected to increase to over fourteen million by the year 2000.[2] However, this is only part of the story. The other aspect of demographic change in Florida has been the concentration of population in the coastal zone of the state. In 1970 sixteen of Florida's thirty-eight coastal counties contained over seventy percent of the state's population on a very small percentage of the land area of the state, and if present trends continue, the year 2000 will see over ten million people concentrated in the coastal zone. The result has been impacts on the natural values of the coastal zone which represent threats to the health, safety and welfare of Florida's citizens.[3]

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The basic cause of resource management problems in Florida then may be capitalized under the heading of "change", and in this respect Southwest Florida is not atypical. A thirteen county area--corresponding roughly with the borders of the Southwest Florida Water Management District--experienced a population increase of approximately seventy percent over the 1950-1970 period. These data, however, understate the severity of the change in certain areas. Charlotte County experienced a population increase of 543 percent over the 1950-1970 period while five other counties experienced population increases ranging from 179-317 percent. Again, the process has been population increase and concentration in the coastal zone.[4]

Further, Florida in general and Southwest Florida in particular, has had significant increases in agricultural, mining and manufacturing activities all of which served to intensify the competition for available land and water resources, and for the discussion to follow, it is important to note that the intensity of this competition is not likely to abate in the future. In fact, the competition over the available resources is likely to increase as public officials are faced with the complex task of balancing the use of valuable and sometimes fragile natural resource systems in the face of a multiplicity of competing uses, all in the vein of the rather nebulus concept of the "public interest". In an attempt to contribute something useful to this process, this paper will--rather than attempt to identify "the" solution--focus on an understanding of the problem and the establishment of a framework within which resource management problems can be approached in a systematic manner. The remainder of this paper is predicated on the belief that a clear need exists for planning and institutional design in an effort to achieve the rational resolution of current and potential conflicts over the allocation of resources in the coastal zone.

INSTITUTIONS: A DEFINITION

The previous section's focus on the cause of resource management problems was rather straightforward. Unfortunately, solutions to these problems are not very straightforward. As noted, the essence of the problem is change and the resulting pressures on natural resource systems. However, the key to a clear understanding of the problem lies one step beyond establishing causation, and that step involves an understanding of the basic nature of the problem and the way in which the problem manifests itself to the public eye. Ask anyone--the proverbial man in the street if you wish--to identify a coastal zone problem. The answer will vary among individuals, but with repeated questioning, the result is likely to be a rather sizeable list of problems. This list would most likely enumerate issues like destruction of dunes, unnecessary filling of wetlands, salt water intrusion into fresh water aquifers, damage to marine food chains through sewage discharges and pesticide and fertilizer runoff, etc.

Although not endless, the potential list of coastal zone problems could safely be referred to as "substantial", and the nature of such a list brings us to the major thesis of this paper. That thesis is that those items usually referred to as resource management problems and lumped under some general heading like "environmental degradation" are really not problems at all. Rather, they are all merely symptoms of a more basic problem which in this paper is designated as "institutional failure". A clear understanding of this distinction will, hopefully, aid in the design of smoothly functioning management systems. With this in mind, the discussion now turns to a more precise definition of terminology and a more detailed exploration of the nature of resource management problems.

First, an exercise in definition. The term "institution" as employed by economists has been defined by various writers. The following examples are offered for your consideration:

> Institutions are sets of ordered relationships among people which define their rights, exposure to the rights of others, privileges and responsibilities.[5]
>
> .....an institution is a behavioral rule.[6]
>
> .....an institution is a social decision system that provides decision rules for adjusting and accommodating, over time, conflicting demands from different interest groups in a society.[7]

For purposes of this paper either definition will suffice. The question at hand is the allocation of resources among competing uses, and an institution is treated simply as the arrangement which specifies who decides and establishes rules whereby those decisions are made.

In a capitalistic society the majority of resource allocation decisions are made by private individuals within the framework of an economic marketplace. The extent of any individual's right to decide is embodied in the existing set of property rights--an institution--and the rules of the game are embodied in a related set of institutions--the laws which specify the rights and duties of individuals in the exchange of private property rights. The result is a set of prices for resources which serve to guide each unit of a resource into the use where it produces the greatest value, a move which is in the best interest of both the resource owner and society as a whole.

Consider the example of the labor market for skilled workers. Clearly, the right to the worker's labor resides with each individual worker. However, above a legal minimum wage and subject to certain other legal restrictions, employers are free to bid for the services of workers. By selecting the higher paying job, each worker serves his own self interest. However, in so doing he also serves society since employers who offer higher wages are likely to use the worker to greater advantage. That is, they employ the worker in a use where the value of his output is greater. This is another way of saying that one employer, in considering his decision to use resources, is forced by the price system to consider the value of that resource in alternative uses.

With reference to the simple example above, several points with implications for the management of natural resources can now be noted. First, in deciding to relegate the allocation of resources--workers in our example--to the market mechanism, society implicitly establishes a goal of maximizing the value of output produced from the given stock of resources. Further, a situation is created whereby private interests and social interests coincide in the pursuit of the established goal. By vesting the right to work in individuals and requiring employers to bid for the service's of those individuals, each employer is motivated to employ additional workers only if the value produced by the services of the workers exceeds that value which could be produced by other potential employers.

It is also important to note that under a system such as the one reflected by the labor market example, no one employer is likely to hire all the workers he would like to employ since the employment of additional workers means the payment of higher wages. Yet, each employer is satisfied with the outcome since he is always free to raise wages and hire more workers if it is in his interest to do so. In essence then, the arrangement just described represents the establishment of a goal and the creation of an institutional framework within which social interests and private interests are harmonized in the resolution of conflicting resource demands. We now are ready to turn to the functioning of institutions in the allocation of natural resources.

INSTITUTIONAL FAILURE

From the preceding discussion one can enumerate three important functions fulfilled by an institution in the allocation of resources. For purposes of emphasis, these functions are listed here:

1. the allocation of resources so as to accomplish some desired goal (implicit or explicit),
2. the establishment of a situation whereby private interests and social interests coincide, and
3. the provision of an arena for the resolution of conflicts.

With these functions in mind, we can now illustrate a case of institutional failure. Eastern water law as embodied in the riparian doctrine provides such an illustration. The discussion here is purposely related to the riparian doctrine and not to the Florida Water Resources Act of 1972 in hopes of leaving the reader with the question of whether or not the 1972 act corrects the institutional flaws of the riparian system.[8]

Under the riparian doctrine, each riparian land owner (those owning land immediately bordering on the water) had a right to use water on riparian land as long as he "were going to make a reasonable use of the water, and did not unreasonably interfere with other riparian owners to the same water".[9] For purposes of institutional evaluation, the appropriate questions inquire as to the goal of water resources allocation, the allocation mechanism, and the arena for the resolution of conflicts and whether or not social and private interests coincide in this arena.

Let us now evaluate the riparian law on each point. First, the water allocation goal can be inferred from the requirement that all uses of water be "reasonable" and not "unreasonably" interfere with other "reasonable" uses of the water. This is considerably different from our labor market example where the goal, although implicit, was the maximization of the value of output. One other major difference between the two cases is readily apparent. In the labor market the right to the worker's labor is clearly defined and rests with the worker. Our riparian water user, on the other hand, has a less certain right. His right to use water is constantly subject to being ruled "unreasonable" in view of the "reasonable" uses of other riparian owners, and this rather uncertain right can be transferred to other users only through the transfer of riparian land.

Now, as to the allocation mechanism under riparian law. Essentially, each riparian owner is free to use water as he sees fit until such time as someone objects. This freedom, coupled with the requirement that water be used only on riparian land, virtually ensures that, in some cases, private interests and social interests will be at cross purposes or that the interests of two riparians will conflict. These conflicts, when they occur, can only be resolved through the courts on a case-by-case basis. With regard to the third criterion listed above--conflict resolution--it is important to note that when conflicts are settled through the courts, the loser is likely to be unhappy. In the words of some now unknown sage, "no man ever approaches the noose with a very high opinion of the law." The point is that regardless of the fairness of court decisions regarding water allocation, losers still have the desire to use water in what they viewed as a reasonable use to begin with.

In summary, riparian law provides an institutional arrangement under which allocation goals are uncertain, allocation procedures are not specified, social and private interest often conflict, and finally, the resolution of conflicts can occur only in case-by-case court proceedings, a procedure which settles differences but does not remove the cause of the conflict. Thus, riparian law provides a classic example of "institutional failure" and this failure has, without doubt, led to efforts to design new institutional arrangements. As would be expected, states like Florida where water problems are particularly critical are in the forefront of these efforts. The chief thrust of this paper is that in the effort to design new institutional arrangements, every effort should be made to avoid the flaws which led to the failure of the old institution.

IMPLICATIONS FOR COASTAL ZONE MANAGEMENT

The preceding sections have briefly discussed the causes and basic nature of allocation problems involving natural resources. The main point is that all such problems can be traced to a failure of (or a lack of) institutions designed to accomplish the allocation of resources among competing uses. Such institutional failure has resulted in the over allocation of natural resources to some uses--usually uses for which market values are readily available--and the under allocation of resources to other uses--usually the uses for which no market value is apparent. Clearly, the situation is not optimal from society's point of view and should be corrected. The question is how do we proceed from here?

Obviously, if we, in some way, could agree on what constitutes the correct allocation of resources (if we could establish explicit goals and measure the contribution of each use of that goal), we could simply direct people to use resources "properly". But, would this approach solve the problem? Such an approach would accomplish the first of our institutional function--goal setting and resource allocation--but what of the other two. Are private and social interests harmonized, or is there incentive for people to cheat, misrepresent facts, or go to other lengths in an attempt to increase their share of available resources? Finally, are people who get fewer resources than they would like going to quietly accept the fact, or will they be more likely to engage in various political activities in an attempt to change the outcome of the allocation decision? An honest answer to each of these questions would seem to indicate that the regulatory approach offers, at best, an inefficient means of resource allocation, and at worst, a totally unworkable mechanism for the long-run solution of resource allocation problems.

The reader is now entitled to the obvious question, "If not regulation, then what?" Unfortunately, there is no obvious answer. Given the imminent, and sometimes irreversible nature of many natural resource decisions, we must, of necessity, rely on regulation in the near future. However, for the long haul, we must never forget the basic nature of the problem and never cease our search for that set of institutions which will allow the rational resolution of conflicts over the use of natural resources in accord with the criteria outlined here. For scientists and policymakers it is important that we get on with the business of collecting data and devising analytical tools which allow us to evaluate alternative institutional arrangements and their effects on social welfare. In short, as doctors who minister to society's problems, let us not be carried away with treatments which serve only to mask symptoms while the patient slowly dies.

FOOTNOTES

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ECONOMICS OF WATER PROBLEMS

by

Dr. Eugene A. Laurent*

Two centuries ago Edmund Burke proclaimed something like this-- "The age of chivalry is gone. That of economists and calculators has succeeded." Now I am not going to propose to you that this is the age of economics and that economics is the solution to all problems, or even the solution to water problems in Southwest Florida. However, I do suggest that most problems have an economic aspect to them and that the failure to consider the economic impacts and incentives resulting from proposed solutions has frustrated many a well-laid plan. As such, what I would like to do today is make a few general introductory comments and then talk a little bit about an economist's way of looking at environmental problems and discuss some items to look out for from an economic perspective when dealing with water problems.

Part of my family settled on the banks of Peace River a few miles east of here (in the 1850's) and a number of them are still there. As I come home and look around, I have used an expression which I think applies to this area of Florida -- and that is: "Even the future ain't what it used to be." Several years back, for example, who would have thought that Kissengen Springs or Starr Lake would dry up or that people would build

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houses where I used to fish? On the other hand, who would have thought that some scrub cattle land would be worth three to four thousand dollars per acre or of a development like Disney World?

In saying the future of Florida isn't what it used to be, we are saying that population growth and economic development are changing the rules under which we operate. Development has generated increased demands on natural resources that equal or exceed the supply available at any given time. That is -- land, clean water, etc. have become scarce resources. If we allocate resources such as water to one use, it may have side effects on other uses and society in general (e.g., salt water intrusion, fewer fishery resources, and so on.)

A situation such as this means that new projects or policies involving these resources, whether public or private, have costs as well as benefits -- somebody is helped and somebody is hurt. (EXAMPLE) This situation is best characterized by a favorite expression of economists -- "There ain't no free lunch."

Because one never gets something for nothing, difficult choices must be made regarding the use of resources. It is important to note that choices we make today regarding resources not only determine our immediate welfare, they also determine the various options open to us in the future. For example, if we over-allocate water to upstream users today and later learn that the water is necessary to maintain estuarine production, the costs of reallocation may be very high in both human and monetary terms. In fact, due to the costs, reallocation may not be possible.

In sum, every choice you make regarding resources brings benefits only at the expense of certain (often unanticipated) costs. As resources become scarce, you not only have to worry about jobs, income, and taxes, but you must consider your resource base as well. When you add the problem of evaluating the differing effects of various economic activities on the resource base and sometimes environmental resources a hundred miles away, the task becomes complex indeed. In fact, it probably cannot be accomplished with precision given the present state-of-the-art. However (there is always a "however"), these are a number of approaches or concepts that, if included in an analysis, can substantially improve decision making. I would like to discuss three of these approaches today. These are:

(1) The "So What?" Principle

(2) The "Who Cares?" Principle

(3) The "Obvious May Not Be True" Principle

The "So What?" principle is very close to the idea that "There ain't no free lunch." It requires that we ask questions involving benefits and costs. If someone says a new industrial plant is good or canoeing in the river is good, we should immediately ask "Good for whom?" and "Good for what?". This is because the incidence of benefits and costs falls on different segments of society.

To illustrate this point, let's look at a traditional economic impact study of a new industrial plant. In such a study, we would likely estimate the number of new jobs created directly by the plant and indirectly by service industries; we might estimate the increase in income and taxes in the local area, volume of water used, and similar variables. Unfortunately, this type of information is almost useless as a base for deciding public policy. It is nice to know how many new jobs and how much income, but this doesn't mean much unless we know who is going to receive the jobs and income. Is it those who are already well off, or is it the unemployed in the local area? The total amount of new taxes generated doesn't mean much unless we know the additional demands placed on local government in terms of hospital beds, school rooms, and police protection. Additionally, we need to know the costs of other uses of resources foregone as a result of the plant.

In summary, when evaluating whether or not a change in a local economy or local environment is good or bad, it is generally necessary to understand the types of benefits and costs resulting from the change.

The "Who cares?" principle involves the attitudes and values of people. When I talk about including attitudes and values in decision making, most people think I am discussing science fiction, so I won't say too much about the subject. However, the movements within an economic system and the uses made of an environment are determined almost solely by the attitudes and values of people.

Many a coal miner, for example, has made the decision to live to sixty in a reasonable affluence rather than to not mine coal and live in poverty. This is a rational economic decision. On the other hand, I played golf with a fellow the other day who turned down a substantial raise and left the company he had been with for fifteen years because they were going to transfer him north. This, too, is a rational economic decision. When dealing with a resource as important and pervasive as water quantity, I find it hard to understand how we can make adequate decisions concerning industrial and household uses of water versus recreation and natural uses without a good understanding of attitudes and perception of the needs of people in the local area toward recreation, additional income, and similar items.

The "Obvious is not always true" principle could be called the "Look out for indirect effects" principle. Due to the complexity of interrelationships in the economy and between the economy and the environment, the obvious is not always true. For example, most people would not consider a university a major polluter. And there is very little direct pollution (some human and solid waste). However, when we look at the products that universities consume, there is a tremendous amount of indirect pollution. Universities, for example, are a major user of electricity; they gobble up soft goods at a tremendous rate; and they generate considerable air pollution through automobile travel. If we expand higher education, we will, because of the purchasing pattern, increase pollution.

The same situation can occur with respect to the demand for water. It is very possible for an industry which uses very little water directly to substantially increase the demand for water in the area due to its purchasing pattern. That is, if they purchase a large volume of inputs from industries that do use a lot of water in their production processes, the demand for water can be increased substantially.

Along the same line, several South Carolina studies have shown that the environmental input (water used, pollution created, etc.) per dollar of economic activity is higher in an urban than in a rural setting. Interestingly, the exception to this rule is tourism which requires more resources per dollar of income generated in a rural area. The difference is due to indirect effects. In any case, the point of this discourse is that sometimes seemingly benign water uses can generate substantial demands for water due to their linkages with the local economy.

Before closing, I should mention that the ideas or questions I have been discussing are not pie-in-the-sky type considerations. There are techniques and models capable of dealing with questions like these. There are even modelling techniques that can estimate the impact of a new facility on the local economy, the resource base, and some environmental resources. Although such models can be very useful, the decision to utilize such models should be approached with extreme caution. There is nothing on which you can waste more time and money any more quickly than modelling.

To be successful in applying complex models, it is necessary to know precisely the questions you want answered, design your model accordingly, and have an understanding of the quality of your data base. I have found, for example, that it is generally better to have a small amount of relevant data than a large amount of questionable information. When faced with large amounts of questionable information, it's easy to forget its dubious parentage, especially if it comes from the computer, and poor decisions can result.

SEMINAR PROGRAM

FRESHWATER AND THE FLORIDA COAST: Southwest District

Thursday, May 26, 1977
Tampa, Florida

8:00 A.M. Registration

8:30 CALL TO ORDER
WELCOMING REMARKS
Mr. Donald R. Feaster, P.E., Executive Director, Southwest Florida Water Management District, Brooksville

SEMINAR PLAN
Dr. William Seaman, Jr., Florida Sea Grant Program Gainesville

8:45 OVERVIEW OF THE SOUTHWEST FLORIDA WATER MANAGEMENT DISTRICT (SWFWMD) AND TECHNICAL INFORMATION NEEDS

"General Description and Water Requirements of the District:
Mr. Cecil E. Palmer and Mr. John R. Wehle, SWFWMD

"Estuaries within the District:
Mr. William D. Courser and Mr. Richard V. McLean, SWFWMD

9:30 PHYSICAL PANEL
Chairman: Dr. Bent A. Christensen, Dept. of Civil Engineering, Univ. of Fla., Gainesville

"Development and the Hydrology and Geohydrology of Coastal Drainage Basins"
Dr. B. A. Christensen

"A Review and Evaluation of Selected Numerical Models for Coastal Zone Water Management"
Mr. Steve Graham, Dept. of Civil Engineering, Univ. Fla.

"Freshwater and the Florida Coast: Review and Update--Southwest District"
Dr. Daniel P. Spangler, Dept. of Geology, Univ. Fla.

10:30 BREAK

"Groundwater Flow"
Dr. J. G. Melville, Dept. of Civil Eng., Univ. Fla.

"The Marine Ecosystem for an Engineering Viewpoint"
Mr. Robert E. Snyder, P.E., Synder Oceanography Services, Jupiter, Florida

DISCUSSION

Dr. Carl Goodwin, Water Resources Div., U.S. Geological Survey, Tampa

Dr. Byron E. Ruth, Dept. of Civil Engineering, Univ. Fla. Gainesville

NOON RECESS

1:30 P.M. BIOLOGICAL PANEL

Chairman: Dr. Joseph L. Simon, Dept. of Biology, Univ. South Fla., Tampa

"The Role of Freshwater in an Estuary"

Dr. Samuel Snedaker, Dr. Donald de Sylva, Dr. M. Corbett, Dr. E. Corcoran, Mr. J. Richard, Mr. P. Lutz, Mr. E. Sullivan, & Mr. D. Cottrell, Rosenstiel School of Marine & Atmospheric Sciences, Univ. Miami, Miami, Florida

"The Estuary--What's It to You?"

Mr. Dale S. Beaumariage & Ms. Vi N. Stewart, Florida Dept. of Natural Resources, Tallahassee & St. Petersburg

"The Estuary Viewed as a Dynamic System"

Dr. Joan Browder, Rosenstiel School of Marine & Atmospheric Sciences, Univ. Miami, Miami, Florida

"Some Relationships between River Flow, Estuarine Characteristics, and Economics in a Florida Gulf Coast Region"

Dr. Walter R. Boynton, Center for Environmental & Estuarine Studies, Univ. Maryland, Prince Frederick

DISCUSSION

Dr. Thomas W. Fraser, Environmental Quality Lab., General Development Corp., Port Charlotte, Florida

Dr. Michael Kemp, Center for Environmental & Estuarine Studies, Univ. Maryland, Prince Frederick

3:30 BREAK

3:45 ECONOMICS PANEL

Chairman: Dr. Eugene Laurent, S.C. Budget & Control Board, Columbia, South Carolina

"The Coastal Zone: Multi-use Resource Allocation and Institutional Failure"

Dr. David Mulkey, Dept. of Food & Resource Economics, Univ. Fla., Gainesville

"Economics of Water Problems"

Dr. Eugene A. Laurent, S.C. Budget & Control Board, Columbia, South Carolina

DISCUSSION

Dr. Thomas D. Curtis, Dept. of Economics, Univ. South Fla., Tampa

Mr. Scott McWilliams, McWilliams Marketing Services, & Univ. South Florida, Tampa

5:00 RETURN EVALUATION FORMS
ADJOURN FOR THE DAY

Friday, May 26

8:30 A.M. SUMMARY OF PANELS
Dr. William Seaman, Jr.

9:00 WORKSHOP ON DRAINAGE BASINS
Moderators:
Biology: Dr. Joseph L. Simon
Economics: Dr. Eugene A. Laurent
Engineering: Dr. Bent A. Christensen

11:30 RECESS

1:00 P.M. WORKSHOP REPORT
By Moderators

2:00 SUMMARY--GUIDELINES AND RECOMMENDATIONS
Dr. Ariel Lugo, Dept. of Botany, Univ. Fla., Gainesville

2:30 ADJOURN

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