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WATER RESOURCES PLANNING FOR RIVERS DRAINING INTO MOBILE BAY

A NON-CONSERVATIVE SPECIES TRANSPORT MODEL FOR MOBILE BAY

by

Hua-An Liu, Graduate Assistant
Gary C. April, Principal Investigator

Prepared for

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

January 1975

BER Report No. 185-112

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PREFACE

This is an interim report covering the research completed under contract grant number NAS8-29100 titled "Water Resources Planning for Rivers Draining Into Mobile Bay. Part II: Non-Conservative Species Transport Models." This report covers the period January 1 to December 31, 1974, and serves as Mr. Hua-An Liu's M.S. thesis which will be used as partial fulfillment of the requirements for that degree at The University of Alabama.

A third report, "Part III: Application of Developed Models to User Needs" will be issued at the termination of the next grant period.

VITA

Hua-An Liu, the fourth son of Shui-Chien and Cheng-Hsia Liu, was born in [redacted] on [redacted]. He completed his high school education at the High School of Taiwan Normal University in July, 1967. He entered Taiwan Cheng-Kung University in August, 1967. He graduated with a degree of Bachelor of Science in Chemical Engineering in June, 1971. He went to military service in the Army of the Republic of China in September, 1971 and served until July, 1973. In August, 1973 he entered The University of Alabama. In June, 1974 he married the former Miss Ting-Wen Yeh from Taipei, Republic of China. The author is currently a M. S. candidate at the Department of Chemical and Metallurgical Engineering of The University of Alabama.

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The author also wishes to recognize and thank the persons who assisted most willingly in this study: to Dr. Donald O. Hill for his continued interest and assistance; to Mr. Stephen E. Slocovich who initiated the work in converting the model to the new computer system which resulted in a valuable contribution to this study; to Dr. H. S. Hosty of the Alabama State Department of Health for providing valuable field data; to Dr. Albert H. Story of the Public Health Service, Department of Health, Education and Welfare for providing a field map; to Mr. Charles F. Hains of the Alabama Geological Survey for providing river flow rate data; to Dr. William J. Hatcher, Jr. and Dr. William C. Clements, Jr. for their continued interest and concern; to Mr. and Mrs. Shui-Chien Liu, the author's parents, for their continued encouragement and love; to Dr. and Mrs. Hua-Kuang Liu for their continued encouragement and concern; to Ting-Wen Yeh Liu, the author's wife, for her encouragement, patience, and continued devotion throughout the course of this work.

ABSTRACT

The purpose of this research effort is to expand the mathematical modeling capabilities of the hydrodynamic and salinity models of Hill and April to include a description of non-conservative species transport in the Mobile Bay system. In so doing, the knowledge gained provides a clear insight into the effect that rivers draining into the bay have on water quality conditions.

Total coliform group bacteria were selected because of their relationship to commercial fishing ventures within bay waters. This item was also chosen on the basis of data availability sufficient for model calibration and verification. Results are presented as monthly average distributions corresponding to the data base used.

In addition to the above, a parametric study was also conducted. In this study river flow rates, wind conditions and bay system temperatures were investigated to determine their influence on the total coliform concentration patterns. Of these factors temperature and river flow rate had a pronounced effect on the concentration profiles, while wind conditions showed only slight effects. Shifts in concentration profiles as much as 8 kilometers were observed in extreme cases.

The effect of changing total coliform group loading concentrations at constant river flow rates and temperature was also investigated. As expected these loading changes had an appreciable influence on total coliform distribution within Mobile Bay.

Utilization of the Non-conservative Species Transport Model to predict trend behavior in the Mobile Bay system is demonstrated. Continuing efforts to improve the data collection programs in support of mathematical modeling are encouraged to increase the utility and predictive capabilities of the models.

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NOMENCLATURE

B = total coliform group concentration (MPN/100ml)

BOD = biochemical oxygen demand concentration (ppm)

C.F. = correction factor

D = dissolved oxygen concentration (ppm)

D_{AB} = mass diffusivity (ft^2/sec)

D_{ABt} = turbulent diffusivity (ft^2/sec)

D.F. = dilution factor

DO = dissolved oxygen

E = tidal-averaged dispersion coefficient (ft^2/sec)

e = eddy diffusivity (ft^2/sec)

$\bar{e}$ = dispersion coefficient (ft^2/sec)

HDI = tidal elevation at Dauphin Island (ft)

HCP = tidal elevation at Cedar Point (ft)

I = counter

j = counter

K = rate constant of reaction, reaeration, or dieoff (day^{-1})

L = concentration of carbonaceous BOD (ppm)

MPN = most probable number (laboratory-determined estimate of the most probable amount of total coliform bacteria within the water mass from which the sample was collected)

N = concentration of nitrogeneous BOD (ppm)

n = Manning's friction coefficient

$\bar{N}_A$ = mass flus of species A

$\bar{N}_B$ = mass flus of species B

NCSTM = abbreviation for the Non-conservative Species Transport Model

P = rate of photosyntheses generation of dissolved oxygen (ppm/day)

R = rate of respiration consumption of oxygen (ppm/day)

r_A = rate of reaction of species A

S = standard deviation

$S_{\bar{X}}$ = standard deviation of the mean

S_b = rate of benthic untake of DO (ppm/day)

S_{max} = maximum velocity over a tiday cycle (ft/sec)

T = Temperature (^oC)

t = time

T_o = a tidal period (hr)

TC_{31} = total coliform concentration sampled at station No. 31 (MPN/100ml)

u = x-component velocity

v = y-component velocity

U = x-component net velocity over a tidal cycle (ft/sec)

U_{max} = x-component maximum velocity over a tidal cycle (ft/sec)

V = y-component net velocity over a tidal cycle (ft/sec)

V_{max} = y-component maximum velocity over a tidal cycle (ft/sec)

W_A = mass rate of flow of species A

x = x-coordinate (latitudinal direction)

y = y-coordinate (longitudinal direction)

z = z-coordinate (depth or tidal elevation)

z_b = z at the surface of the bay water (ft)

z_s = z at the bottom of the bay water (ft)

Δx = finite spatial increment in the x-direction (ft)

Δy = finite spatial increment in the y-direction (ft)

ρ_A = mass density of species A

Δs = spatial increment (ft or km)

Δt = time increment (sec or min)

θ = characterization constant for the K values

ΣS_i = the sum of generation (source) and dissipation (sink) terms

CHAPTER I

INTRODUCTION

Sewage, industrial waste disposals, and storm water overflows discharged into Mobile River and surrounding creeks from the Mobile metropolitan area, and excessive concentrations of bacteria in the Mobile River, result in the pollution of Mobile Bay. A location map showing these sources of waste is shown in Figure 1-1. One method for expressing the bacterial content of these waters is to determine the total coliform bacteria group count which gives an indication of the disease carrying bacteria or pathogenic content in the water. Because of this pollution, Alabama, under state laws and the regulations of the State Board of Health, closes the bay to oyster harvesting as a safeguard to human health. The criterion on which closing the bay is based is either a total coliform concentration in excess of 70 parts per 100 ml at specific locations adjacent to oyster reefs, or whenever the concentrations of 10% of all samples collected are in excess of 230 parts per 100 ml.(3,6) These samples are obtained in the field and analyzed in the State Laboratories at Montgomery, Alabama. In current years, this policy has led to the permanent closing of the upper third of the bay, the intermittent closing of the middle third, and closing of the lower third during extremely high pollution periods. These sections of the bay are more clearly defined in Figure 1-2. From 1954 to 1967 bay closures

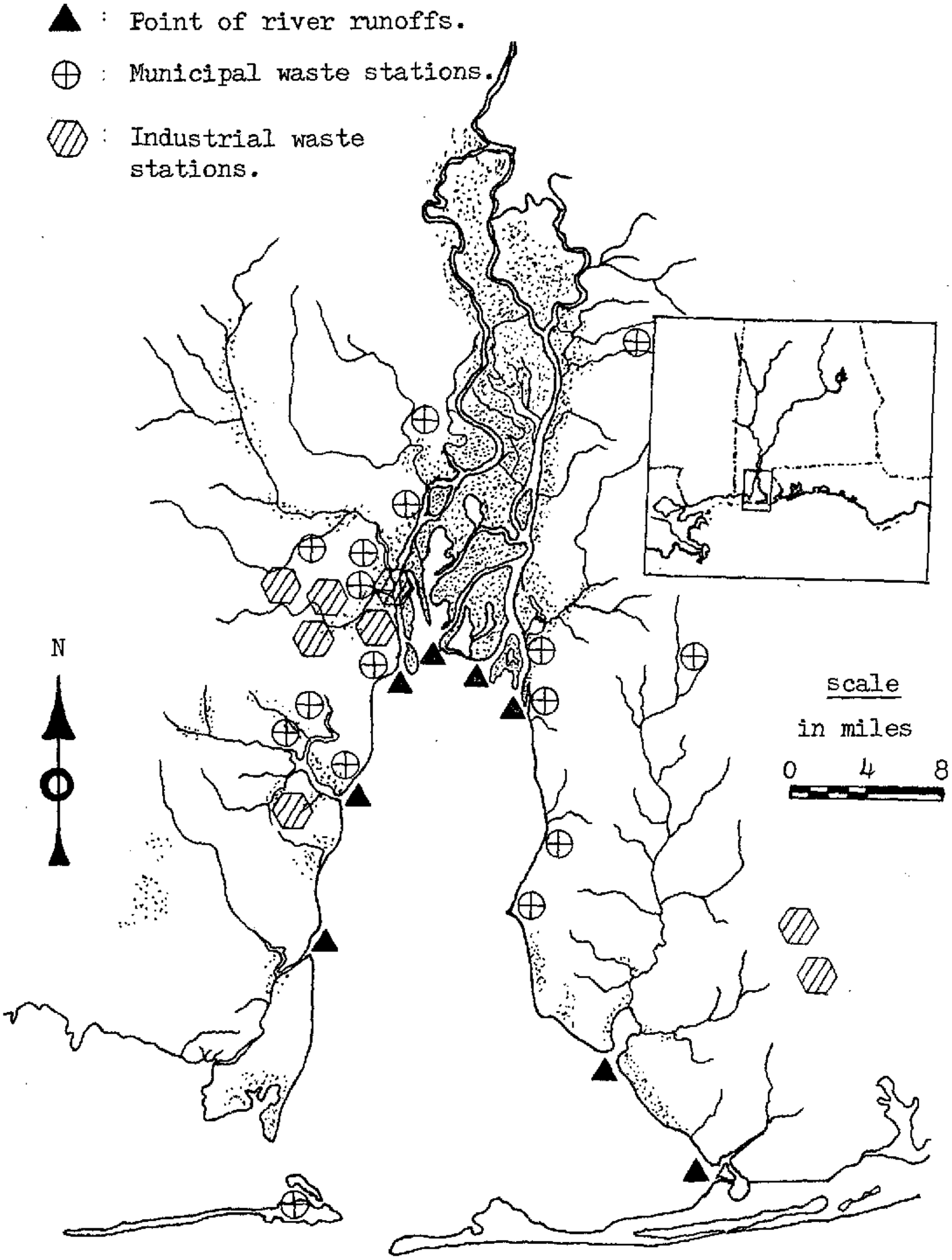


Fig. 1.1 Waste Locations and Points of River Runoffs of the Mobile Bay System.

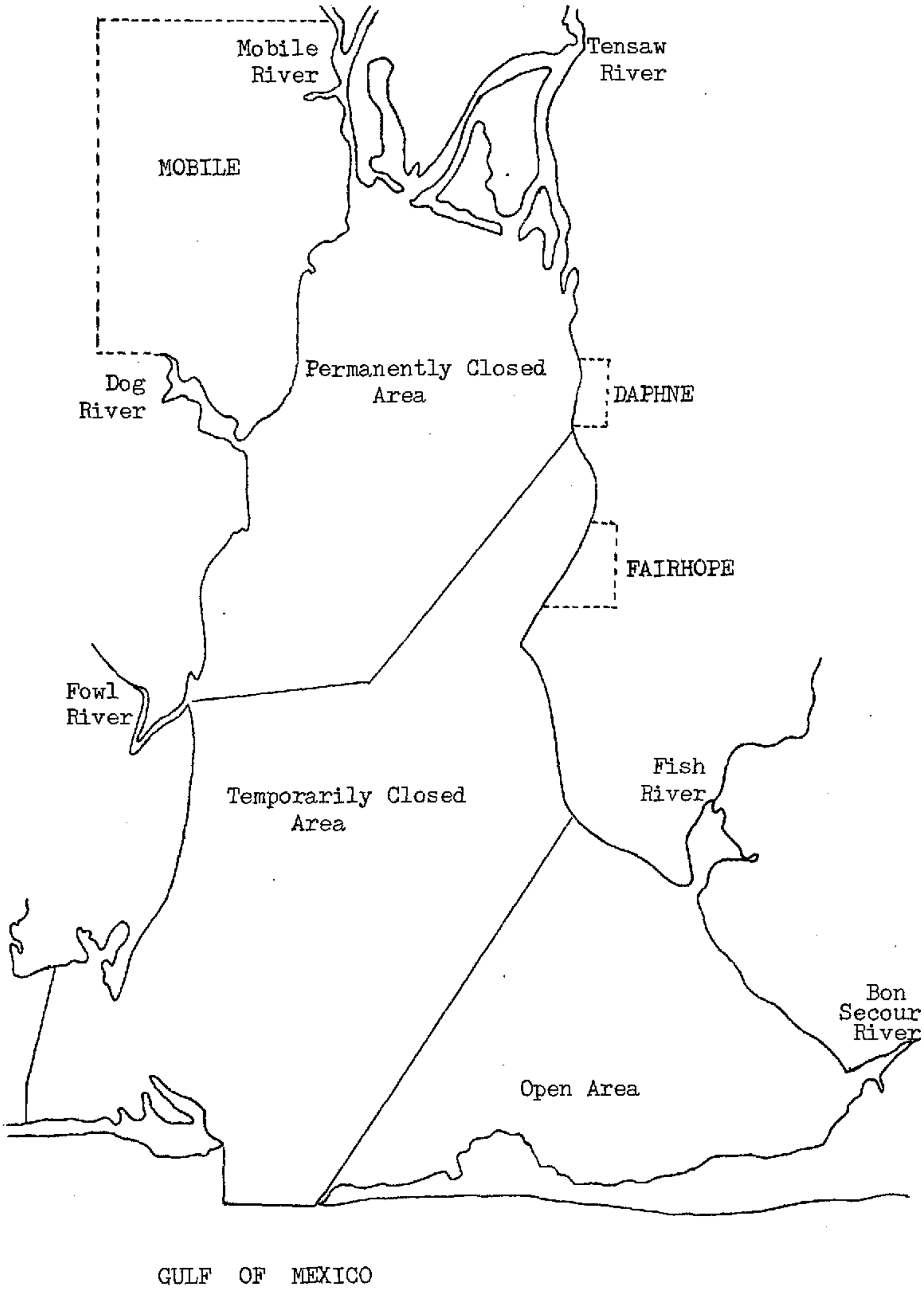


Fig. 1.2 Classified Shellfishing Areas in Mobile Bay.

resulted in annual losses of approximately a quarter of a million dollars from oyster harvesting alone.(10)

It becomes apparent, from the economic considerations associated with the maintenance of safe oyster harvesting conditions, that a rapid predictive method, supplemented with spot analytical support, could result in substantial savings of time and effort. Furthermore, the method could provide a way of determining the effects system variables, such as river flow rates, runoff, degree of waste treatment, and expansion of waste treatment facilities, have on the coliform distribution in the bay. This technique could also provide clues as to ways in which these most serious upsets to the bay could be abated.

This study provides such a method which has as a basis the application of conservation of mass and species equations subject to the bay ecosystem constraints. For this purpose, a two dimensional (surface), non-conservative species transport model is developed for Mobile Bay. The model is solved with a finite difference method and implemented by computer solution using a UNIVAC 1110 system. The hydrodynamic model for Mobile Bay developed by Hill and April(12) is used to provide basic current and dispersion coefficient data required by the non-conservative species transport model. The resultant package, referred to as the Non-conservative Species Transport Model (NCSTM) is verified with available total coliform bacteria data obtained from the State Department of Health. Extension of the NCSTM can be made to analyze the biological oxygen demand (BOD) and dissolved oxygen (DO) levels within the bay. Model verification for BOD and DO are deferred until field data become available.

Parametric studies are included to determine the effect that system variables such as wind speed and direction, river flow rates and temperature have on the coliform concentration distributions within the bay. Based on these studies conclusions are drawn which indicate the conditions most conducive to pollution flushing and dispersion in the Mobile Bay ecosystem.

CHAPTER II

BACKGROUND

Due to the complex nature of estuarine systems it very often is not feasible or practical to study the behavior of the systems by field data analysis. Many sampling stations must be monitored in a way to determine meaningful results about what one part of the system is doing relative to another. These so called synoptic sampling plans require a great number of research vessels and man hours to obtain accurate and precise data to determine the real behavior of the system. Additionally, during periods in which bad weather occurs, the system data collection plan is often inoperable. Mathematical and physical modeling of these systems have been demonstrated to be reasonable methods to circumvent these problems.

2.1 Model Concept

A model is, in short, a representation of the real system. Various models have been used to study the hydrodynamic behavior and water quality conditions of streams and estuaries. An acceptable model is one in which specific responses caused by variations in system parameters can be reasonably and accurately described. In order to show acceptability there are two phases which must be demonstrated when models are utilized. These are the calibration and the verification phases.

Some characteristics of the real system may not be sufficiently understood and some empirical equations may be required to correlate the resulting behavior. These correlations would substantially depend on the specific real system and may vary from system to system. Before the model can be verified, it is necessary to find the set of correlations which best describes these characteristics for the specific system under consideration. This is called model calibration. After the model is calibrated, the correlations are fixed to perform the verification of the model. The use of a model to successfully predict what would happen in the real system due to variation in system parameters for a given period results in verification. This phase requires the availability of sound data to show that model predicted results are in fact duplicative of system behavior. Failure to achieve comparative results during this phase of the study could result in either recalibration of the model or collection of field data more representative of the real system behavior, or the development of a new model. Statistical analysis during this phase of the study is essential.

Once verified, sensitivity of the model predicted results can be studied by a parametric investigation. In this phase of the project, system variables thought to be important can be varied individually with measurement of the response in the objective function. Significant changes in the objective function (in this study the concentration of non-conservative species) for each perturbation of the independent variable are then a measure of its sensitivity.

These phases of the study are intended to establish confidence in the model predicted results.

2.2 Modeling Estuarine Systems

Generically, models used to describe estuarine systems can be divided into two types, physical models and mathematical models.

A physical model is a scaled imitation of the real system. There is a physical model for Mobile Bay at the Water Experimental Station of the Corps of Engineers at Vicksburg, Mississippi constructed in 1973 at a cost of approximately $1,000,000. It has been successfully used to reproduce tidal and current conditions and to simulate dispersion effects with dye tracer release experiments which in turn provide useful information about mass transfer rates in the bay. Characteristics of the physical modeling have been discussed by Masch(18).

A mathematical model is a functional representation of the real system, i.e. a set of partial differential equations describing the system under study and the associated assumptions and constraints that apply to its formulation. Mathematical models can be divided into analog models and digital models according to the type of computing facilities used to implement the numerical solution to the partial differential equations. With the development of high speed digital computers, mathematical models using finite difference methods to solve the partial differential equations have become widely accepted. The model used for the study of Mobile Bay is a mathematical model implemented by a high speed digital computer.

Many mathematical models for estuarine water quality have been developed for various systems (25). These models are further classified in terms of the spatial and temporal conditions over which they are designed to perform. These include one-, two- and three-dimensional steady and transient models. The application of the specific model to be used is dependent on the system geometry, hydrology, and the time frame for which information is desired.

One-dimensional Models

The transient species continuity equation for one dimensional systems can be written as

$$\frac{\partial c}{\partial t} = -u \frac{\partial c}{\partial x} + \frac{\partial}{\partial c}\left(E \frac{\partial c}{\partial x}\right) + \Sigma S_i \qquad \cdots\cdots (2-1)$$

where c = concentration of the water quality species along the direction of stream flow

t = time

u = velocity of stream over the cross-section of flow

E = dispersion coefficient

x = distance in the direction of flow

S_i = sources or sinks of the water quality species

For narrow waterways where cross-sectional variations in physical and water quality parameters are negligible, such as creeks, rivers, and narrow estuaries, the one-dimensional model is justified. Again, due to the complexities in the physical systems, complete analytical solutions are not always possible. Two approaches, i.e. the continuous solution approach and the finite section approach, have been utilized in solving one-dimensional problems in estuaries.

In the continuous solution approach, it is necessary to divide the system into a number of individual sections or subsystems, each of which is characterized by physical and hydraulic parameters. Sections are joined by related concentration and flux terms. Analytical solution of the one-dimensional equation (2-1) may then be obtained for each section; they are then summed up to give the overall solution for the system. This approach was adopted in the East River Model(25).

With the finite difference approach the differential equation is replaced with a difference equation and the system is divided into a number of sections with the assumption of complete mixing in each section. Matrix inversion or relaxation is then used to obtain solutions. This approach was used by the Thames Estuary Model, the Delaware Estuary Model, the Potomac Estuary Model, and the San Francisco Bay System Model which consists of San Francisco Bay, San Pablo Bay, Suisun Bay, and Sacramento-San Joaquin Delta.

Two- and Three-dimensional Models

The two-dimensional transient species model equation can be written as

$$\frac{\partial c}{\partial t} = -\left(u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial x}\left(E_x \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(E_y \frac{\partial c}{\partial y}\right) + \sum S_i \quad \cdots (2\text{-}2)$$

where x and y are the two dimensions over which c is varying.

For water bodies which are well mixed in one of the three dimensions, the use of two-dimensional models which describe the variation of conditions in the second and third dimensions, is justified. Most wide, shallow bay systems which are vertically well mixed fall into this category. Several examples of modeling studies involving bays in the United States are summarized below.

(1) San Francisco Bay System Model——— This model was principally developed by Water Resources Engineers, Inc. The basic approach was to represent the estuary with a network of uniform channels interconnected at junctions or nodes. This allowed a one-dimensional treatment of a two dimensional system. It has been effectively and extensively applied to the San Francisco Bay system. The computational experience thus developed was then utilized in modeling Sydney Harbor, San Diego Bay and the Columbia River, etc. Verification was made on salinity data(25).

(2) Hillsborough Bay Model ——— The finite difference approach as applied to the one-dimensional model was extended to two dimensions in Hillsborough Bay which is a natural arm of Tampa Bay, Florida. The bay was horizontally segmented such that in each segment the depth is approximately uniform. Verification was made on bay salinity and investigations were performed to study the effect of diverting the Hillsborough River as a means of smoothing the fluctuations of salinity in the bay.

(3) Galveston Bay Model ——— This is a time-dependent two dimensional model using finite difference methods to solve the model

equations. The bay system as well as the Houston Ship Channel were segmentized into squares of uniform size. The model was extensively verified using salinity, BOD, and DO collected from water quality stations maintained in the system.

(4) Louisiana Coastal Marsh Area Model ——— Two-dimensional, time-dependent models were developed which predict the velocity profiles, tidal fluctuations, and temperature and salinity profiles for the Barataria Bay region of coastal Louisiana. An alternating-direction implicit, finite difference method was used to solve the differential equations numerically. Results were reported for the dynamics of tidal fluctuations, velocity profiles, and salinity and temperature distributions for conditions encountered in May 1970(11).

(5) Mobile Bay Model ——— This study covered the hydrodynamics and salinity of Mobile Bay, Alabama. It accurately predicted time-varying tidal heights, current patterns, and averaged salt concentration distributions of the Bay. A two-dimensional finite difference method was used to approach the explicit solution to the model equation. A salinity wedge was used in the lower reach of the bay to simulate the saline water intrusion without going to a much more costly three-dimensional computational scheme.

In some cases, in addition to changes in the horizontal dimensions, the flow may be highly stratified in the vertical direction, causing significant gradients in the depth direction. This phenomenon is frequently observed at locations near waste outfalls. A three-dimensional model would find particular application under such conditions.

Any water quality model relies on its hydrodynamic counterpart for hydrodynamic parameters such as current velocities and dispersion coefficients. The basis for the Non-conservative Species Transport Model presented in this study is the Hydrodynamic model of Mobile Bay developed by Hill and April(12).

2.3 Non-conservative Species vs. Conservative Species

The term "non-conservative species" is used to refer to the materials dissolved in the estuarine water in which the concentrations are subjected to rather rapid and appreciable changes. These changes are caused by various mechanisms of generation (source) and dissipation (sink) depending on the characteristics of the species itself, the physical environments to which they are exposed, and other aquatic ecosystems with which they are interacting. For example, most water quality entities of great concern to us, such as total coliform, BOD, and DO, are very sensitive to physical, biological or chemical upsets which result in changes in the environmental balance within the system. They are essentially non-conservative in nature, and are generally named "non-conservative species" in water quality studies.

The "conservative species" label, on the other hand, is used to refer to materials dissolved in estuarine water in which the concentrations are rather stable as compared to non-conservative species. Most of these species are not chemically or biologically reactive substances. For example, salinity concentration is affected by freshwater discharge, rainfall, evaporation, and sea water intrusion, instead of any appreciable biochemical or chemical effects. However, in some cases salinity may also be considered a non-conservative species. A salinity model (conservative) for Mobile Bay has been developed by Hill and April(12).

2.4 Non-conservative Species Modeling in Bay System Analysis

It has been estimated that approximately one third of the total population of the United States, or 40 of the 110 Standard Metropolitan Statistical Areas are located on estuaries(17). The vulnerability of estuarine systems to human influence has been demonstrated in recent years by observed upsets. Methods for the abatement of pollution of these delicate systems are being sought with increased intensity. With the advance of technology and the rapid growth in population, people are making much more use of the natural environment and at the same time dispose much more waste into it. Estuarine systems, which have long been depended on for their ability to assimilate a variety of wastes, are now becoming the first victims. Unlike the Olympic National Forest in the State of Washington(26), which is known for its ecological stability, estuarine systems are unstable, and subject to an increasing number of man-made and natural disturbances.

While digesting the waste input from various sources, estuarine systems have to maintain their own natural balances. When changes are occurring gradually, estuarine systems can adjust to them quite well. However, present day upsets are occurring over extremely short periods, which overburden the evolutional process or homeostatic ability of the systems. These processes do not always have time to optimally operate, and the stability of the systems becomes critical. This threatens the existence of the ecosystems within the estuaries and seriously reduces the ability of the estuaries to provide people with those resources taken for granted for such a long time. This in turn affects the quality of life of the entire population. The yearly closing of Mobile Bay to oyster harvesting or the elimination of recreational activities in Lake Pontchartrain in Louisiana or the permanent restriction of waterways to navigation status only are just a few examples of loss of natural resources utilization. Most upsets in these waters result from excessive waste disposal from municipal, industrial or agrarian sources.

Water serves as a good medium for disease-carrying organisms. The bacteria of typhoid fever, cholera, and dysentery are all water borne pathogenes. It is assumed that the number of disease-carrying microorganisms in water is proportional to the total number of microorganisms. Due to the variety of microorganisms, it is impossible to perform quantitative tests determining all the species. The total coliform bacteria group count, which is a count of the total bacteria content, therefore, becomes an indication of the disease-carrying bacteria, or the pathogenes within the water system. A high pathogene content renders water hazardous to the persons using the estuary for havesting, recreation, and even navigation. The total coliform concentration standard for shellfish harvesting in coastal and marine water adopted by the State of Alabama is "not to exceed a median MPN (most probable number)(10) of 70/100 ml and not more than 10% of the samples shall ordinarily exceed an MPN of 230/100 ml for a 5-tube decimal dilution," which is consistent with standards used by the National Shellfish Sanitation Program as well as some other states(3). When these criteria are exceeded, the bay waters are declared hazardous to health and are closed to public use. This form of pollution is often seasonal, occurring during periods of heavy rainfall and correspondingly high runoff rates.

Another kind of pollution results when discharges of organic materials occur. These organic materials can serve as nutrients for microorganisms. These organisms digest the wastes with the excretion of more elementary type materials which can serve as food to be absorbed by phytoplankton and plants within the system. In these digesting processes oxygen is consumed. Therefore, when a sudden excessive amount of nutrients is introduced, the oxygen content may rapidly decrease to a very low level or even entirely vanish, because the reaeration mechanisms are not able to keep pace with the oxygen consumption rates. This total depletion of oxygen, although lasting only a short period of time, often results in fish kills. The "Jubilee" recorded in the northeastern coast of Mobile Bay(17) and some other parts of the Gulf Coast areas, are examples of this phenomenon. Under such circumstances, the organic materials introduced as wastes are no longer nutrients, but are instead pollutants. The control of such waste materials is predicated on the sound knowledge of the system behavior including those hydrodynamic, biological and chemical processes which describe its assimilating capacity. To analyse such behavior, description of those species which make up the system are essential. This investigation is directed at the development of a rapid, accurate, predictive method for describing non-conservative species transport patterns in Mobile Bay.

CHAPTER III

DERIVATION OF THE NON-CONSERVATIVE SPECIES TRANSPORT MODEL FOR MOBILE BAY

The differential equations used in the Non-conservative Species Transport Model (abbreviated as NCSTM) are derived in this chapter. The general differential equation developed is modified according to spatial and temporal simplifications, and through characteristic constraints of the real system. Numerical form of the model equation is then presented together with the solution procedures.

3.1 The Physical Setting

Mobile Bay is approximately 49 km. (31 miles) long and has an area of 1070 km.^{2} (419 square miles)$^{(22)}$. It has a ship channel which has a total length of 36.5 miles and is 40 feet deep and 400 feet wide. The channel runs through the left half of the bay from the Main Pass at the Gulf of Mexico in the south to the Mobile River in the North. An intercoastal waterway, which is 12 feet deep and 200 feet wide, runs from west to east from Grant's Pass between Little Dauphin Island and Cedar Point toward the lower right corner (Bon Secour) of the Bay. Except for the ship channel and the Intercoastal Waterway, the Bay is shallow with a flat bottom. The average depth is 9.81 feet at mean low tide. Six rivers drain into Mobile Bay from its perimeter (see Fig. 1.2). Naming them in a counterclockwise manner beginning in the northwest these rivers are the Mobile, Dog, Fowl, Bon Secour, Fisn and Tensaw Rivers. The Mobile and Tensaw Rivers are the largest of the six, with average combined volumetric rate of discharge of 59,000 cfs. The Mobile River perennially discharges large amounts of highly contaminated waters and is considered the main source of pollution loading to the bay. Dog River, located near the Mobile River to the southwest, may also contribute substantially to the pollutant concentration in the bay.

Average atmospheric temperatures over the Mobile Bay area have been accumulated by the Weather Bureau of the U. S. Department of Commerce(27). Monthly averages range from approximately 50 °F in the cold months to the low eighties in the warm months. Wind speeds and directions over the bay are also included in the climatological data collected by the Weather Bureau(27). Monthly averages range from approximately 5 mph. to 13 mph. for the period January to August, 1962.

3.2 Development of the Model Equations

In order to describe the non-conservative species transport of water borne constituents in Mobile Bay, knowledge of the current pattern and mixing characteristics must first be available. This information was developed in the study by Hill and April(12) titled " A Hydrodynamic and Salinity Model for Mobile Bay" and is used to input velocity and dispersion coefficient data for use by the NCSTM model. With this as background, the remaining portions of the chapter will be used to develop the NCSTM for Mobile Bay as applied to total coliform bacteria, BOD (biochemical oxygen demand), and DO (dissolved oxygen).

The differential equations used in the Non-conservative Species Transport Model originate from the application of the law of conservation of mass over a differential element in space through which the liquid under consideration is flowing. Because of the shallow nature of Mobile Bay and relatively good mixing characteristics resulting from the interaction of fresh river water with seawater from the Gulf, the general equation can be modified to a two dimensional non-steady-state form. This equation can be adapted to describe the transport and fate of various non-conservative species by application of specific source and sink terms occurring at the boundaries of the system. In this study these models are referred to as the Total Coliform Bacteria, BOD, and DO models.

3.2.1 Assumptions and Restrictions

In order to derive an equation that will accurately predict bay system behavior while remaining solvable, a series of assumptions and restrictions applicable to Mobile Bay are defined. These assumptions and restrictions are summarized in the following paragraphs.

(a) Two Dimensional System

As has been described in Section 3.1, the depth of Mobile Bay is very small (average 9.81 ft.) as compared to its length (approximately 31 miles) and width (ranging from 8 to 24 miles). Because of the effect of prevailing tidal action, the bay system as a whole can be considered vertically well mixed. Values of the system variables at any point within the bay can thus be considered a constant average value at any depth. The system can be reduced to a two dimensional one in which only changes in the longitudinal and latitudinal directions will be studied.

(b) Tidal Cycle Average

Data available for total coliform for verification of the NCSTM are collected on a spot sampling basis and do not represent within-tidal sampling. Because of this sampling method, verification of the model must conform to this pattern, i.e. a tidal-average basis. In all cases where current and dispersion coefficient are used by the NCSTM, tidal average values are computed. These values are subsequently used to calculate coliform distribution patterns representative of the data available for verification. Furthermore, these data are combined to form monthly average coliform concentrations to permit the analysis of the computed results. The NCSTM can be exercised on a within-tidal cycle basis provided that suitable data become available to permit calibration and verification on that basis.

As a result of this method of solving the equation, the NCSTM becomes a quasi-steady state solution of the equation of change.

(c) Constant Density and Viscosity

Because of the interaction between seawater and fresh water in estuaries, density variations can exist. These density variations are observed as salt wedges, bores and other phenomena which result in sharp discontinuities within the water masses. Mobile Bay is no exception to this rule; a salt wedge forms near the Main Pass and extends to various levels depending on the seasons and fresh water discharge rates. However, when considering bulk fluid transport, density induced current and mass transport effects are normally negligible. Furthermore, when variations are averaged over a period exceeding the tidal cycle, they can likewise be neglected with little error introduced. Such is the case in this study. Monthly average mass transport distribution patterns are projected for total coliform, BOD and DO. In this model, density variations are considered negligible and are omitted from the model equations. Similarly, viscosity changes are also considered negligible, and the Newtonian law of fluid motion applies.

(d) Binary Mixing and Variable Dispersion Coefficients

The NCSTM considers species transport to be governed by Fick's Law. This is to say that the species in question forms one component while the rest of the water phase (including all other species) forms the second component of the system. There is no evidence indicating the effect that other water borne components have on mass transport of the components under study. In the absence of such information the assumption that the system behaves as a binary mixture will be adopted.

The dispersion coefficients (E_x, E_y) in this study are affected by three elements, i.e. the turbulence of the water column, the vertical mixing, and the tidal-cycle-averaging computation procedure. Because laboratory estimations of these coefficients differ greatly from field observations, the confirmation of a set of dispersion coefficients that describe the mixing behavior of a system is difficult to obtain. In this study, the empirical equation developed by Holley, et al.(13) is employed, which states that the dispersion coefficient is a function of the bottom friction, the maximum current velocity over the tidal cycle, and the water depth. For Mobile Bay the bottom friction and depth are nearly constant; thus the change in current velocity outweighs the influence of the others, and becomes the controllig factor. The dispersion coefficient is therefore calculated using the maximum localized velocity over the tidal cycle. This correlation will be detailed later in this chapter.

(e) Homogeneous Water Temperature

In this study the water temperature of Mobile Bay is assumed to be constant at a unique temperature all over the bay. This assumption may introduce some inaccuracy for some locations within the bay where localized temperature gradients exist, e.g. the lower portion of the bay where seawater at a slightly different temperature intrudes and causes moderate temperature inhomogeneity. However, for a well-mixed tidal-smoothed model applied to Mobile Bay, the errors caused are negligible and the assumption of homogeneous temperature is reasonable.

Based on the above restrictions and assumptions, the general species continuity equation will be simplified to a form applicable for use in describing material transport in Mobile Bay.

3.2.2 The General Species Continuity Equation

Consider a differential element having length, width and height of x, y, z, respectively, fixed in space. Next consider the flow of a binary liquid into this volume containing species A with a concentration of ρ_A.

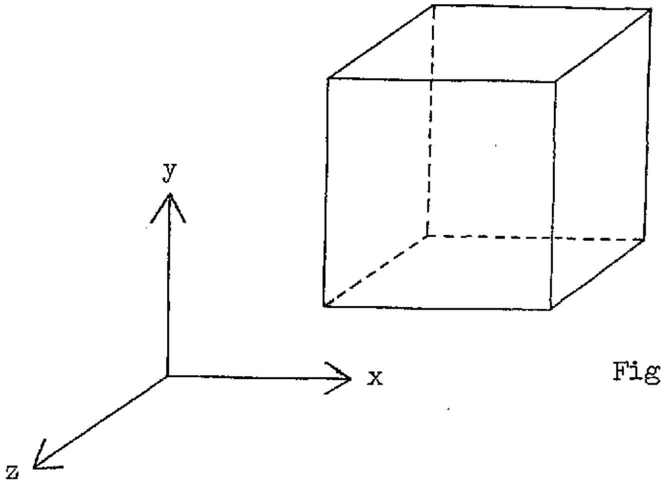


Fig. 3.1 A differential element

The law of conservation of mass for this system, simply stated, is:

(rate of mass of A in) - (rate of mass of A out)

+ (rate of production of A by chemical or biological reaction or other sources other than by convective flow or diffusion)

= (time rate of change of mass A in the element).

Therefore, the following quantities may be formulated:

Input of A across face at x : $(\bar{N}_{Ax}|_{x}) \Delta y \Delta z$

Output of A across face at x+Δx : $(\bar{N}_{Ax}|_{x+\Delta x}) \Delta y \Delta z$

Input of A across face at y : $(\bar{N}_{Ay}|_{y}) \Delta x \Delta z$

Output of A across face at y+ Δy : $(\bar{N}_{Ay}|_{y+\Delta y}) \Delta x \Delta z$

Input of A across face at z : $(\bar{N}_{Az}|_{z}) \Delta x \Delta y$

Output of A across face at z+ Δz : $(\bar{N}_{Az}|_{z+\Delta z}) \Delta x \Delta y$

where $\bar{N}_A$ = mass flux.

Rate of production of A by chemical reaction (or any other generation and/or dissipation mechanism other than the advective flux term) : $r_A \Delta x \Delta y \Delta z$.

Time rate of change of mass of A in volume element :

$\frac{\partial \rho_A}{\partial t} \Delta x \Delta y \Delta z$.

Substituting the above terms in the general mass balance equation, dividing by the differential volume $\Delta x \, \Delta y \, \Delta z$, and taking limits as Δx, Δy, Δz approach zero, gives Eq. (3-1).

$$\frac{\partial \rho_A}{\partial t} + \left(\frac{\partial \bar{N}_{Ax}}{\partial x} + \frac{\partial \bar{N}_{Ay}}{\partial y} + \frac{\partial \bar{N}_{Az}}{\partial z} \right) = r_A \quad \ldots\ldots (3\text{-}1)$$

The quantities $\bar{N}_{Ax}$, $\bar{N}_{Ay}$, and $\bar{N}_{Az}$ are the rectangular components of the mass flux vector defined by Bird, Stewart and Lightfoot(2) as:

$$\bar{N}_A = \rho_A \bar{V}_A. \quad \ldots\ldots\ldots (3\text{-}2)$$

In vector notation, Eq. (3-1) becomes

$$\frac{\partial \rho_A}{\partial t} + (\nabla \cdot \bar{N}_A) = r_A . \quad \ldots\ldots (3\text{-}1a)$$

From Fick's first law of binary diffusion(2),

$$\bar{N}_A = W_A (\bar{N}_A + \bar{N}_B) - \rho D_{AB} \nabla W_A, \quad \ldots\ldots\ldots (3\text{-}3)$$

where $W_A = \dfrac{\rho_A}{\rho}$ = mass fraction of A,

D_{AB} = mass diffusivity in the binary system.

Equation (3-4) is obtained by substituting $\bar{N}_A$ in Eq. (3-2) and transposing terms.

$$\frac{\partial \rho_A}{\partial t} + \nabla \cdot (W_A (\bar{N}_A + \bar{N}_B)) = \nabla \cdot (\rho D_{AB} \nabla W_A) + r_A \quad \ldots\ldots (3\text{-}4)$$

where $W_A = \dfrac{\rho_A}{\rho}$ .... (3-5)

$\bar{N}_A = \rho_A \bar{V}_A$, ... (3-6)

$\bar{N}_B = \rho_B \bar{V}_B$ .... (3-7),

and $\bar{V}$ = mass average velocity $= \dfrac{1}{\rho}(\rho_A \bar{V}_A + \rho_B \bar{V}_B)$..(3-8)

Using Eq. (3-8) in expanded form,

$$W_A\ (\bar{N}_A+\bar{N}_B) = \frac{\rho_A}{\rho}\ (\rho_A \bar{V}_A + \rho_B \bar{V}_B) \qquad \text{..... (3-9)}$$

$$= \rho_A \cdot \left[\frac{1}{\rho}\,(\rho_A \bar{V}_A + \rho_B \bar{V}_B)\right]$$

$$= \rho_A \cdot \bar{V}, \qquad \text{..... (3-10)}$$

Eq. (3-4) can be rewritten as

$$\frac{\partial \rho_A}{\partial t} + \nabla\cdot(\rho_A \bar{V}) = \nabla\cdot(\rho D_{AB}\ \nabla W_A) + r_A \qquad \text{..... (3-11)}$$

Expanding the divergence on the left hand side of Eq. (3-11) gives:

$$\frac{\partial \rho_A}{\partial t} + \rho_A(\nabla\cdot\bar{V}) + (\bar{V}\cdot\nabla\rho_A) = \nabla\cdot(\rho D_{AB}\nabla W_A) + r_A \qquad \text{..... (3-12)}$$

If ρ, the overall density of the liquid system, is constant, then $(\nabla\cdot\bar{V}) = 0$ and

$$\nabla\cdot(\rho D_{AB}\nabla W_A) = \nabla\cdot(D_{AB}\nabla\rho W_A) \qquad \text{...... (3-13)}$$

$$= \nabla\cdot(D_{AB}\nabla\rho_A), \qquad \text{...... (3-14)}$$

and Eq. (3-11) becomes

$$\frac{\partial \rho_A}{\partial t} + (\bar{V}\cdot\nabla\rho_A) = (\nabla\cdot D_{AB}\nabla\rho_A) + r_A \qquad \text{..... (3-15)}$$

This equation, expanded in rectangular coordinates, is

$$\frac{\partial \rho_A}{\partial t} + \left(\bar{V}_x\frac{\partial \rho_A}{\partial x} + \bar{V}_y\frac{\partial \rho_A}{\partial y} + \bar{V}_z\frac{\partial \rho_A}{\partial z}\right)$$

$$= \frac{\partial}{\partial x}\left(D_{AB_x}\frac{\partial \rho_A}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_{AB_y}\frac{\partial \rho_A}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_{AB_z}\frac{\partial \rho_A}{\partial z}\right) + r_A \qquad \text{..... (3-16)}$$

In this equation the instantaneous fluctuation in velocities and concentration with time (the turbulent phenomena) are not considered yet. In estuarine flow where tidal action is a controlling influence, turbulent effects are important. It is convenient to describe a turbulent variable by a time-smoothed term and a fluctuational deviation term, as illustrated for ρ_A, $\overline{V}$ and D_{AB} below:

$$\rho_A = \overline{\rho}_A + \rho_A' \qquad \ldots\ldots\ (3\text{-}17)$$

$$V = \overline{V} + V' \qquad \ldots\ldots\ (3\text{-}18)$$

$$D_{AB} = \overline{D}_{AB} + D_{AB}' \qquad \ldots\ldots\ (3\text{-}19)$$

where barred variables are time smoothed parts and primed variables are fluctuational deviation parts. In Eq. (3-18), for example,

$$\overline{V} = \frac{1}{t_o} \int_{t}^{t+t_o} V\,dt$$

$$= \text{time smoothed } V, \qquad \ldots\ldots\ (3\text{-}20)$$

where t_o is a time interval which is large with respect to the time of turbulent fluctuation.

Figure 3.2 shows this relation for the velocity V; this figure can be equally applied to ρ_A and D_{AB}. If we take the time average of Eq. (3-16) by integrating each individual terms over the time interval t_o and then dividing by t_o, then all the fluctuational deviation terms ρ_A', V' and D_{AB}' will vanish under integration. However, a quantity

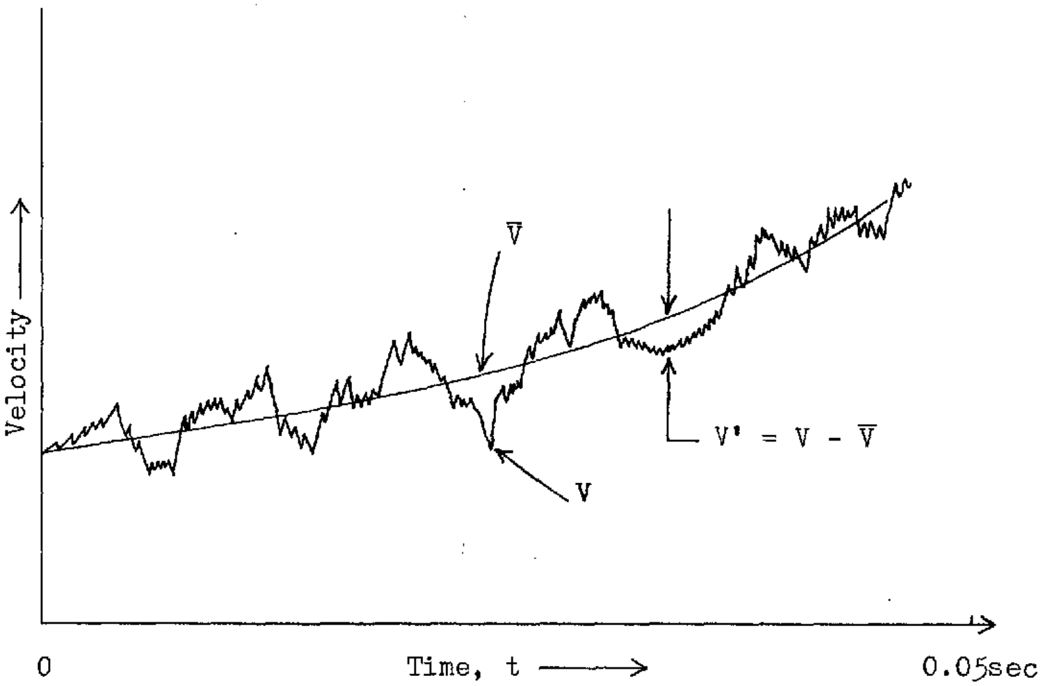


Fig. 3.2 Fluctuation of velocity component about a mean value.

such as $\overline{V_x' \rho_A'}$, the time-average of the product of two fluctuational terms, would not vanish under integration. In fact, it contributes appreciably to mass transfer, and can be represented with a diffusivity term which will be discussed later in this section. Attention will now be turned to the time-averaging of Eq. (3-16).

Assuming the term r_A in the right hand side of Eq. (3-16) can be represented by a first order reaction, we have

$$\frac{\partial \rho_A}{\partial t} + \frac{\partial}{\partial x}(\rho_A V_x) + \frac{\partial}{\partial y}(\rho_A V_y) + \frac{\partial}{\partial z}(\rho_A V_z)$$

$$= \frac{\partial}{\partial x}\left(D_{AB_x}\frac{\partial \rho_A}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_{AB_y}\frac{\partial \rho_A}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_{AB_z}\frac{\partial \rho_A}{\partial z}\right)$$

$$- k_1 \rho_A \qquad \cdots\cdots\cdot \quad (3\text{-}21)$$

where $r_A = - k_1 \rho_A$,

and overbars denoting vectors are dropped for the sake of simplicity. When ρ_A, V, D_{AB} are each replaced with Equations (3-16), (3-17) and (3-18), we obtain after time-averaging

$$\frac{\partial \rho_A}{\partial t} + \frac{\partial}{\partial x}(\bar{\rho}_A \bar{V}_x) + \frac{\partial}{\partial y}(\bar{\rho}_A \bar{V}_y) + \frac{\partial}{\partial z}(\bar{\rho}_A \bar{V}_z)$$

$$+ \frac{\partial}{\partial x}(\overline{\rho_A' V_x'}) + \frac{\partial}{\partial y}(\overline{\rho_A' V_y'}) + \frac{\partial}{\partial z}(\overline{\rho_A' V_z'})$$

$$= \frac{\partial}{\partial x}\left(\bar{D}_{AB_x}\frac{\partial \rho_A}{\partial x}\right) + \frac{\partial}{\partial y}\left(\bar{D}_{AB_y}\frac{\partial \rho_A}{\partial y}\right) + \frac{\partial}{\partial z}\left(\bar{D}_{AB_z}\frac{\partial \rho_A}{\partial z}\right)$$

$$- k_1 \rho_A \qquad \cdots\cdots\cdot \quad (3\text{-}22)$$

Eq. (3-22) is the time-averaged species continuity equation in which $\overline{\rho_A' V_x'}$ is the so called turbulent mass flux term. Overbars in Eq. (3-22) denote time-averages.

By analogy with Fick's law of diffusion$^{(2)}$,

$$\overline{\rho_A' V_x'} = - D_{AB_{t_x}} \frac{\partial \rho_A}{\partial x} \quad \ldots\ldots \quad (3\text{-}23)$$

where D_{AB_t} is the "turbulent diffusivity".

Substituting Eq. (3-23) in Eq. (3-22) and rearranging gives

$$\frac{\partial \rho_A}{\partial t} + \frac{\partial}{\partial x}(\bar{\rho}_A \bar{V}_x) + \frac{\partial}{\partial y}(\bar{\rho}_A \bar{V}_y) + \frac{\partial}{\partial z}(\bar{\rho}_A \bar{V}_z)$$

$$= \frac{\partial}{\partial x}\left[(\bar{D}_{AB_x} + D_{AB_{t_x}}) \frac{\partial \rho_A}{\partial x}\right] + \frac{\partial}{\partial y}\left[(\bar{D}_{AB_y} + D_{AB_{t_y}}) \frac{\partial \rho_A}{\partial y}\right]$$

$$+ \frac{\partial}{\partial z}\left[(\bar{D}_{AB_z} + D_{AB_{t_z}}) \frac{\partial \rho_A}{\partial z}\right] - k_1 \rho_A \quad \ldots\ldots. \quad (3\text{-}24)$$

where $\bar{D}_{AB_x}$ and $D_{AB_{t_x}}$ may be combined to give a single term e_x which is called the "eddy diffusivity".

Thus

$$e_x = \bar{D}_{AB_x} + D_{AB_{t_x}} \quad \ldots\ldots \quad (3\text{-}25)$$

$$e_y = \bar{D}_{AB_y} + D_{AB_{t_y}} \quad \ldots\ldots \quad (3\text{-}26)$$

$$e_z = \bar{D}_{AB_z} + D_{AB_{t_z}} \quad \ldots\ldots \quad (3\text{-}27)$$

Combining Equations (3-24) to (3-27) gives

$$\frac{\partial \rho_A}{\partial t} = - \frac{\partial}{\partial x}(\bar{\rho}_A \bar{V}_x) - \frac{\partial}{\partial y}(\bar{\rho}_A \bar{V}_y) - \frac{\partial}{\partial z}(\bar{\rho}_A \bar{V}_z) + \frac{\partial}{\partial x}\left(e_x \frac{\partial \rho_A}{\partial x}\right)$$

$$+ \frac{\partial}{\partial y}\left(e_y \frac{\partial \rho_A}{\partial y}\right) + \frac{\partial}{\partial z}\left(e_z \frac{\partial \rho_A}{\partial z}\right) - k_1 \rho_A \quad \ldots\ldots. \quad (3\text{-}28)$$

Breaking the mass flux term, dropping the bars, rearranging, and noting that $(\nabla \cdot V) = 0$ for an incompressible fluid, Equation (3-28) becomes

$$\frac{\partial \rho_A}{\partial t} = -\left(V_x \frac{\partial}{\partial x} \rho_A + V_y \frac{\partial \rho_A}{\partial y} + V_z \frac{\partial \rho_A}{\partial z}\right) + \left(\frac{\partial}{\partial x} e_x \frac{\partial \rho_A}{\partial x}\right.$$

$$\left. + \frac{\partial}{\partial y} e_y \frac{\partial \rho_A}{\partial y} + \frac{\partial}{\partial z} e_z \frac{\partial \rho_A}{\partial z}\right) - k_1 \rho_A \quad \ldots\ldots. \quad (3\text{-}29)$$

Eq. (3-29) is the three-dimensional general equation for the non-conservative species. However, in its present form, this equation is difficult to apply and requires numerical solutions which are lengthy and complex. Moreover, even if a solution to this equation could be obtained, the accuracy required for the initial conditions and boundary conditions would demand field measurements in excess of the capability of conventional field surveys. To circumvent this, the equation can be simplified to a two-dimensional form, then averaged over a tidal cycle to match existing field data for calibration and verification purposes.

3.2.3 Simplification into a Two-dimensional Form

According to the description cited in Section 3.2.1, the general equation for the NCSTM can be reduced to a two-dimensional form. This is done by neglecting the third-dimensional component of each variable and then vertically integrating Eq. (3-29) from the bottom to the surface of the bay water, then dividing the integral by the depth of the water column. For example, the depth-smoothed current velocity may be written as

$$\overline{V}_x = \frac{1}{D}\int_{z_b}^{z_s} V_x \, dz \, , \qquad \ldots\ldots \text{(3-30)}$$

where z_b = z at the bottom of the bay water,

z_s = z at the surface of the bay water,

$D = z_s - z_b$ = depth of the bay water,

V_x = x-component of the current velocity.

Similar expressions can be written for V_y and other variables.

Eq. (3-30) is exactly similar to Eq. (3-20) for the time-smoothed turbulent velocity, and a figure exactly similar to Fig. 3.2 may be drawn for V_x in Eq. (3-30) except that the horizontal axis must now be replaced with the depth of the water column. Another three equations similar to Equations (3-17) to (3-19) can be written for each of the variables ρ_A, $\bar{V}$ and e, and they can in turn be substituted in Eq. (3-29). By doing so another set of non-vanishing $\overline{\rho_A' \cdot V'}$ terms will occur which, as in the time-smoothing operation, can be replaced by another analogy to Fick's law of diffusion. This gives rise to other diffusional mass flux terms which can again be combined with the eddy diffusivity terms to form a new set of diffusivity terms $\bar{e}_x$ and $\bar{e}_y$ which are the so called dispersion coefficients.

By assuming negligible variation in depth over the bay and by going through the averaging procedure similar to that from Eq. (3-22) to Eq. (3-29), a two-dimensional species continuity equation is obtained:

$$\frac{\partial \rho_A}{\partial t} = -\left(V_x \frac{\partial \rho_A}{\partial x} + V_y \frac{\partial \rho_A}{\partial y}\right) + \frac{\partial}{\partial x}\left(\bar{e}_x \frac{\partial \rho_A}{\partial x}\right) + \frac{\partial}{\partial y}\left(\bar{e}_y \frac{\partial \rho_A}{\partial y}\right) - k_1 \rho_A , \qquad \ldots\ldots\ (3\text{-}31)$$

where ρ_A, V_x, and V_y are each vertically-averaged variables, and $\bar{e}_x$ and $\bar{e}_y$ now include the diffusional effect of vertically averaging the general species continuity equation. To suit the presently available data for the NCSTM, Eq. (3-31) must be further simplified into a tidal-smoothed form.

3.2.4 Tidal-smoothed Non-conservative Species Continuity Equation

Eq. (3-31) is further simplified by averaging over the tidal cycle period T_o. This is done by a procedure similar to that in Section 3.2.2 for the time-smoothing of turbulent variables except that the time interval for integration now is the tidal cycle period T_o which is much larger than t_o. The variable V_x, for instance, in smoothed form becomes

$$\overline{V}_x = \frac{1}{T_o} \int_t^{t+T_o} V_x \, dt \qquad \ldots\ldots\ (3\text{-}32)$$

Similar expressions can be written for V_y and other variables.

Here again it is noted that Eq. (3-32) bears an exact resemblance to Eq. (3-20), and again a figure identical to Fig. 3.2 can be drawn for V_x, except that t is now replaced by T_o (approximately 25 hours). As was done in Section 3.2.3, another set of expressions similar to Equations (3-17) to (3-19) can be written for the variables, and again a set of non-vanishing mass flux terms would occur. They can similarly be replaced by an analogy to Fick's law of diffusivity. The newly created diffusivity terms can be combined with $\bar{e}_x$ and $\bar{e}_y$ in Eq. (3-31) to form a new set of diffusional terms E_x and E_y. Therfore by going through steps similar to those used in obtaining Equations (3-22) to (3-29), a tidal-smoothed two-dimensional non-conservative species continuity equation may be obtained:

$$\frac{\partial \rho_A}{\partial t} = -\left(V_x \frac{\partial \rho_A}{\partial x} + V_y \frac{\partial \rho_A}{\partial y} \right) + \frac{\partial}{\partial x}\left(E_x \frac{\partial \rho_A}{\partial x} \right) + \frac{\partial}{\partial y}\left(E_y \frac{\partial \rho_A}{\partial y} \right) - k_1 \rho_A , \qquad \ldots\ldots\ (3\text{-}33)$$

in which E_x and E_y are the tidal-averaged dispersion coefficients. They contain the diffusional and dispersional mass transfer effects from time-smoothing, depth-smoothing, and tidal-smoothing the non-conservative species continuity equation.

For the sake of notational convenience, Eq. (3-33) can be written into a more general form:

$$\frac{\partial \rho_A}{\partial t} = -\left(U \frac{\partial \rho_A}{\partial x} + V \frac{\partial \rho_A}{\partial y} \right) + \frac{\partial}{\partial x}\left(E_x \frac{\partial \rho_A}{\partial x} \right) + \frac{\partial}{\partial y}\left(E_y \frac{\partial \rho_A}{\partial y} \right) + \sum S_i \, , \qquad \ldots\ldots\ldots (3\text{-}34)$$

where U = net x-component current velocity over the tidal cycle,

V = net y-component current velocity over the tidal cycle,

E_x = x-component dispersion coefficient,

E_y = y-component dispersion coefficient,

ΣS_i = all the sources and sinks of the non-conservative species A.

Equation (3-34) is the equation used in the NCSTM for the Mobile Bay system. This equation can assume different forms according to the difference in the term ΣS_i, the mechanisms of generation and/or dissipation of the specific non-conservative species under study.

3.3 Model Equations for Different Non-conservative Species

Eq. (3-34) is applied to various non-conservative species, each having a distinctive mechanism of replenishment or consumption in the real system. This results in the total coliform, BOD (biochemical oxygen demand) and DO (dissloved oxygen) models for Mobile Bay.

3.3.1 Total Coliform Bacteria

Total coliform bacteria group mean MPN has long been used by control agencies as an indication of the pathogenic bacteria content in waterways(16,28) and as a criterion for the certification of waters for the harvesting of shellfish. The fecal coliform group, which is an indication of pathogenic bacteria derived from the excreta of human and other warm-blooded animals, has been recommended as a substitute standard for the certification of shellfish growing waters, and total coliform-fecal coliform relationship has been studied(24). This relationship, usually expressed in the form of coliform-fecal coliform ratios, are subject to variations in the various bacteriological sources. Moreover, since all types of coliform organisms (fecal, non-fecal and intermediate) are found in feces, the absence of fecal coliform alone in waters designated for human use and contact is not a satisfactory criterion of acceptability. For the sake of safety, the standard test of the sewage pollution remains in terms of the total coliform group, although it has been argued that it is too stringent(10). In this study, the use of mathematical modeling as a predictive tool in determining the distribution of the total coliform group is studied for Mobile Bay.

In studies of streams, the generation and dissipation terms for total coliform may contain:

(1) Upstream runoff,

(2) Replenishment along the stream,

(3) Reaction dissipation (die-off).

In this study, the runoff term is expressed in terms of loadings (boundaries) at the mouths of rivers flowing into the bay, the replenishment term is neglected, and the die-off dissipation term becomes the main sink of total coliform bacteria.

The coliform bacteria transported into waterways are investigated and assumed to diminish by dying off at a rate proportional to the residual concentration, which is the same as a first order reaction for the stabilization of organic matter, radioactive decay, and many other natural phenomena(30). In equation form this is expressed as:

$$\frac{dB}{dt} = K_r \cdot B \qquad \ldots\ldots\ (3\text{-}35)$$

The ΣS_i term in Eq. (3-34) is thus

$$r = -\frac{dB}{dt} = -K_r \cdot B \qquad \ldots\ldots\ (3\text{-}36)$$

where B = total coliform concentration in MPN/100ml,

t = time in days or seconds,

K_r = dieoff rate constant in day^{-1} or sec^{-1}.

Substituting r in Eq. (3-34) gives

$$\frac{\partial B}{\partial t} = -\left(u\frac{\partial B}{\partial x} + v\frac{\partial B}{\partial y}\right) + \left(\frac{\partial}{\partial x}E_x\frac{\partial B}{\partial x} + \frac{\partial}{\partial y}E_y\frac{\partial B}{\partial y}\right) - k_r B \qquad \ldots\ldots\ (3\text{-}37)$$

Attention will now be turned to the correlations of dispersion coefficients E_x and E_y and the dieoff rate constant K_r.

Correlation for Dispersion Coefficient

The dispersion coefficients E_x and E_y have been studied by many workers, and several correlating equations have been derived through analytical treatment followed by experimental verification(8, 13). Experimental results in natural streams, however, have not been within the expected range; deviations as large as several orders of magnitude have been found. In this study, the correlation by Holley, *et al*.(13) is adopted for the calculation of dispersion coefficients:

$$E = 100^n \, S_{max} \, R^{5/6}, \qquad \text{.......} \; (3\text{-}38)$$

where E = dispersion coefficient,

n = Manning's coefficient of bottom friction,

S_{max} = maximum absolute velocity over the tidal cycle,

R = hydraulic radius

$$= \frac{\text{cross sectional area of flow}}{\text{wetted perimeter}} \; .$$

When R is in ft. and S_{max} is in ft./sec., E is in ft^2/sec. In the case of Mobile Bay(12),

n = 0.015 to 0.018,

$R \approx 0.5$ D,

where D = average depth of the bay.

From Eq. (3-38),

$$E \approx 4.024 \text{ to } 4.080 \text{ times } S_{max} \; . \qquad \text{.......} \; (3\text{-}39)$$

The dispersion coefficient is therefore a linear function of the amplitude of the tidal velocity. The E value best suitable for a certain species is then obtained by multiplying maximum tidal velocity calculated by the Hydrodynamic Model by a correction factor constant (C.F.), that is

$$E = (C.F.) \cdot S_{max} \qquad \ldots\ldots\ (3\text{-}40)$$

In the calibration period, this factor is found by interfacing the dispersion coefficient with other model parameters; various values are used until the calculated results match the actual data. Different species behave differently in the physical system, therefore it is expected that different values may be required for the calculation of other substances.

Correlation for the Dieoff Rate Constant

The dieoff rate constant, K_r, as in any first order chemical reaction, is a function of temperature. Surveys performed by many workers on a number of rivers have given a range of K_r values from 0.26 to 0.46 in cool weather, and a range from 0.46 to 0.96 in warm weather(30). These ranges are adopted in this study, since field data to establish the reaction rate coefficients for Mobile Bay are non-existent.

The temperature dependence of K_r is expressed in the form

$$K_T = K_{20} \cdot \theta^{T-20} \qquad \ldots\ldots\ (3\text{-}41)$$

where K_T = K at any temperature T°C in day^{-1} or sec^{-1},

K_{20} = K at 20°C in day^{-1} or sec^{-1},

θ = a constant characteristic of the reaction, dimensionless,

T = temperature °C.

As an approximation, 0.96 day^{-1} is designated as corresponding to 86°F or approximately 30°C, and 0.26 day^{-1} is designated as corresponding to 50°F, which is 10°C. These two K's give the value of θ as 1.067 and the value of K_{20} as 0.50 day^{-1}. Thus

$$K_T = 0.50 \times (1.067)^{T-20} \qquad \ldots\ldots\ (3\text{-}42)$$

is used for calculating the death rate of coliform in this study.

Assumptions and restrictions specific to this section are summarized below:

(1) A first-order dieoff mechanism is assumed, for the coliform bacteria.

(2) The reference temperature for the dieoff rate constant obtained from literature is arbitrarily assumed to apply (due to lack of information).

(3) Replenishments along the perimeter of the Bay are ignored.

(4) Upstream runoff is considered in terms of river discharges associated with a certain pollutant concentration, and in terms of boundary conditions at any apparent loadings.

3.3.2 Biochemical Oxygen Demand

BOD (biochemical oxygen demand) is the amount of oxygen required by bacteria while stablizing decomposable organic matter under aerobic conditions. The decomposable organic matter can serve as food for the bacteria, and energy is derived from its oxidation. The BOD test is widely used to determine the pollutional strength of sewages and industrial wastes in terms of the oxygen that they will require if discharged into natural waterways in which aerobic conditions exist.

Studies of the kinetics of BOD reactions have established that, like the dieoff of coliform, the reactions are first order in character(30), i.e. the rate of the reaction is proportional to the amount of oxidizable organic matter remaining at any time. A second order reaction mechanism has been under study for systems having critical oxygen deficiency. Positive results have been reported in the literature(32). Nevertheless, under the present bay conditions, the assumption of a first order reaction mechanism has been confirmed by most of the studies in other similar systems and is regarded as the standard practice.

Carbonaceous BOD and Nitrogeneous BOD

Figure 3.3 shows a typical BOD, or oxygen use curve, which is typical of laboratory BOD tests. This figure shows that there are two stages of BOD reaction, i.e. the Carbonaceous BOD and the Nitrogeneous BOD. Extensive studies have shown that the bacteria derived from soil or domestic sewage are actually a mixed culture of organisms corresponding to large numbers of saprophytic bacteria (and other organisms that utilize the carbonaceous organic matter) with

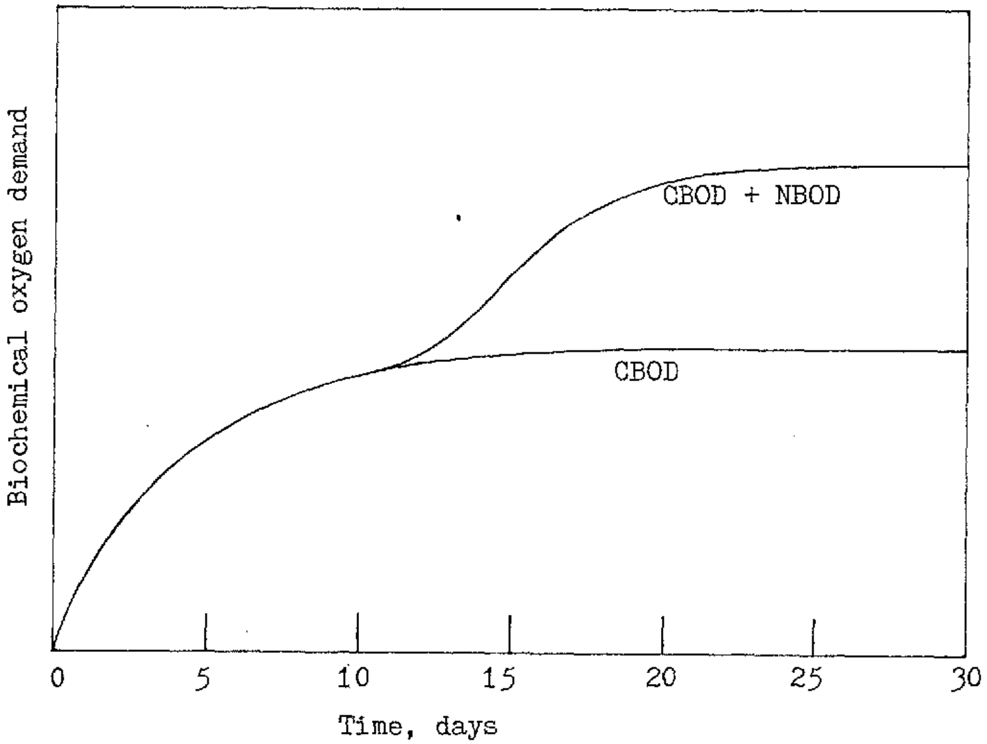


Fig. 3.3 The BOD curve.

a certain amount of autotrophic bacteria, particularly nitrifying bacteria, which are capable of oxidizing noncarbonaceous organic matter(23). The nitrifying bacteria are found to be usually present in relatively small amounts in untreated domestic sewage. However, they are capable of reproduction; their reproductive rate is small enough so that their population does not become sufficiently large to exert an appreciable demand for oxygen until 8 to 10 days have elapsed in regular BOD tests. In stream and estuary systems, their presence is affected by the nature of the waste material; field surveys are required to find the amount and rate of reaction for nitrogeneous BOD. Total omission of it as an important input can only be justified if a time of passage of less than 8 to 10 days at 20°C (or the equivalent time period at other temperature) exists. Therefore it is always safer to assume the coexistence of NBOD (nitrogeneous BOD) and CBOD (carbonaceous BOD) in any system with complex flushing characteristics.

The generation and dissipation terms for BOD, that is the " ΣS_i" term in Eq. (3-34), should contain

(a) Replenishment along the watercourse (source),
(b) Input from upstream runoff (source),
(c) Resuspension from the benthic layer (source),
(d) Deposition or sedimentation into the benthic layer (sink),
(e) Oxidation reaction use (sink).

Eq. (3-34) may now be written for CBOD as

$$\frac{\partial L}{\partial t} = - \left(U \frac{\partial L}{\partial x} + V \frac{\partial L}{\partial y} \right) + \frac{\partial}{\partial x} \left(E_x \frac{\partial L}{\partial x} \right) + \frac{\partial}{\partial y} \left(E_y \frac{\partial L}{\partial y} \right) - (K_d + K_{3d}) L + L_R \qquad \text{.......} \; (3\text{-}43)$$

and for NBOD as

$$\frac{\partial N}{\partial t} = - \left(U \frac{\partial N}{\partial x} + V \frac{\partial N}{\partial y} \right) + \frac{\partial}{\partial x} \left(E_x \frac{\partial N}{\partial x} \right) + \frac{\partial}{\partial y} \left(E_y \frac{\partial N}{\partial y} \right) - (K_n + K_{3n}) N + N_R, \qquad \text{.......} \; (3\text{-}44)$$

where L, N = concentration of CBOD and NBOD respectively in mg/liter,

K_d, K_n = reaction rate constant of CBOD and NBOD respectively in day^{-1} or sec^{-1},

K_{3d}, K_{3n} = rate constant of resuspension and sedimentation in day^{-1} or sec^{-1},

L_R, N_R = replenishment along the watercourse in mg/liter-day.

K_n and K_{3n} are sometimes grouped into K_{rn}; K_d and K_{3d} are sometimes grouped into K_{rd}. Values of $K_{rd} = 0.34 \text{ day}^{-1}$ and $K_{rn} = 0.14 \text{ day}^{-1}$, both at 20°C, are used by the Galveston Bay study(5,6). Again, as in the case of total coliform bacteria, the replenishment terms L_R and N_R are assumed negligible for both CBOD and NBOD. Upstream runoff is also expressed in terms of loadings at the mouths of rivers draining into the bay and appears in the boundary conditions.

It would be ideal if there are enough informations on all the entities involved in the above equations for Mobile Bay or for other similar systems. When niether is available, specification is done on the basis of similar behavior in waterways and streams.

In some stream studies(6), values of K_d ranging from 0.49 to 3.5 day^{-1} are used, and values of K_n ranging from 0.1 to 2.5 day^{-1} are used. At 28°C, K_n/K_d ratios of 2.375 and 2.362 have been used for streams flowing at 0.922 and 0.510 ft/sec respectively; K_d values of 0.76 to 0.95 day^{-1} and K_n values of 1.9 to 2.5 day^{-1} were used at 28°C. These values are extrapolated to 20°C with the expression

$$K_T = K_{20}\,\theta^{T-20} \quad \text{or} \quad K_{20} = K_T\,\theta^{20-T} \qquad \ldots\ldots\ (3\text{-}45)$$

for the BOD reaction, $\theta = 1.03$ is suggested(6). Values of K_d and K_n, both at 20°C, are correlated as

$$K_{d,20} = 0.68 \pm 0.08\ \text{day}^{-1} \qquad \ldots\ldots\ (3\text{-}46)$$

and

$$K_{n,20} = 1.74 \pm 0.24\ \text{day}^{-1} \qquad \ldots\ldots\ (3\text{-}47)$$

These values can be adopted in place of K_{rd} and K_{rn}, respectively, as a first approximation. Eq. (3-45) can then be used to extrapolate to temperatures other than 20°C. In adoption of information from other systems, it is assumed that the aquatic ecosystems from which information is solicited behave similarly to those in the Mobile Bay system. This is an approximation, and a trend analysis of the model results can be made.

3.3.3 Dissolved Oxygen

DO (dissolved oxygen) in waterways is important to aerobic aquatic lives as atmospheric oxygen is important to men. Severe deficiencies of DO in water often result in fish kills. Therefore it is required that DO levels be maintained to support aquatic lives in a healthy condition at all times. Most of the critical conditions related to DO occur during the summer months when temperatures are high, rates of biological oxidation increase, and DO contents decrease to minima. Fig. 3.4 shows a solubility curve for dissolved oxygen in water saturated with air at 1 atm. The saturation solubility of oxygen is usually used in estuarine DO studies.

Sources and sinks of DO are:

(1) Surface reaeration (source),

(2) Photosynthesis generation (source),

(3) Upstream runoff (source),

(4) Biochemical oxidation demand (sink),

(5) Benthic layer uptake (sink),

(6) Respiration use by all aquatic lives (sink).

Eq. (3-34) thus becomes, for DO,

$$\frac{\partial D}{\partial t} = - \left(U \frac{\partial D}{\partial x} + V \frac{\partial D}{\partial y} \right) + \frac{\partial}{\partial x} \left(E_x \frac{\partial D}{\partial x} \right) + \frac{\partial}{\partial y} \left(E_y \frac{\partial D}{\partial y} \right)$$

$$- K_1 L + K_2 (D_s - D) + P - R - S_b \qquad \ldots\ldots\ldots (3\text{-}48)$$

where D = DO concentration in mg/liter,

D_s = Saturation solubility of oxygen in water in mg/liter,

K_1 = rate constant of biochemical oxidation demand in day^{-1},

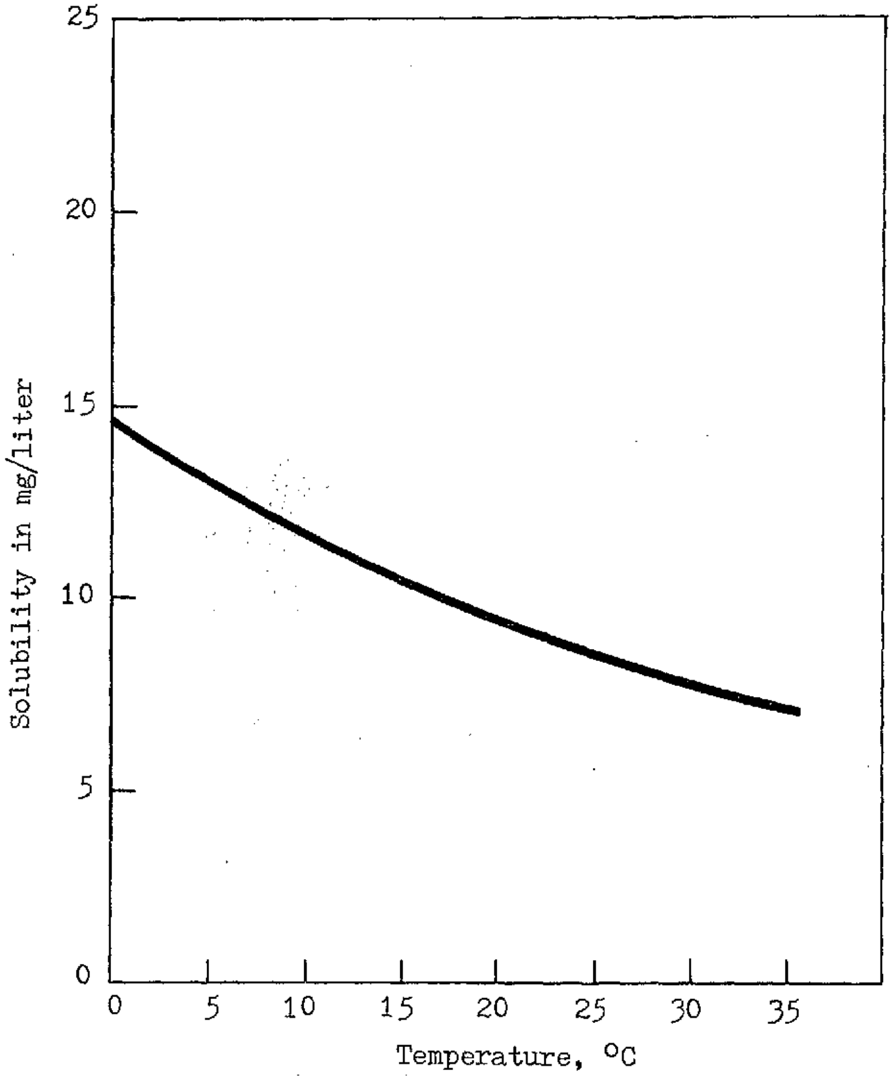


Fig. 3.4 Solubility of oxygen in water saturated with air at 1 atm.

K_2 = rate constant of surface reaeration in day^{-1},

L = BOD concentration in mg/liter,

P = Photosynthesis generation in mg/liter-day,

R = Respiration use in mg/liter-day,

S_b = uptake by benthic organisms.

The following paragraphs will discuss various terms in Eq. (3-48).

Biochemical Oxidation Sink K_1L

This sink is the consumption of DO by BOD. Strictly it should be written as $K_dL + K_nN$ instead of K_1L to account for CBOD and NBOD separately.

Surface Reaeration Source

This source and the photosynthesis generation are considered the primary sources for DO. The reaeration is regarded as first order as it is in many similar studies. At atmospheric pressure the rate constant K_2 is considered as a function of temperature and other physical effects. In laboratory studies for obtaining K_2, the temperature effect is first fixed by finding K_2 at 20°C. Values of K_2 at other temperatures are then extrapolated using an equation of the form similar to Equations (3-41) and (3-45).

Studies by many workers on various streams and estuaries have resulted in the following empirical equations for K_2(19).

$$K_2 = \frac{5.026\ V^{0.969}}{H^{1.673}} \qquad \text{.......} \ (3\text{-}49)$$

$$K_2 = 3.739 \frac{V}{H^{1.5}} \qquad \text{.......} \ (3\text{-}50)$$

$$K_2 = 0.00125\ (\ 1 + N_F{}^{0.5}\ ) \sqrt{\frac{gs}{H}} \qquad \text{.......} \ (3\text{-}51)$$

$$K_2 = \frac{480 \sqrt{D_M}\ S^{0.25}}{H^{1.25}} \qquad \text{.......} \ (3\text{-}52)$$

$$K_2 = \frac{(\ D_M\ V\ )^{0.5}}{2.303\ H^{1.5}} \qquad \text{.......} \ (3\text{-}53)$$

Of these, Eq. (3-53) by O'Connor and Dobbins is by far the one most often used. It is recommended for use in this study because of its consistency in dimensions and covenience in use. In Eq. (3-53),

V = stream velocity,

H = depth,

D_M = molecular diffusivity of oxygen

= 0.81×10^{-4} ft^2/hr at 20°C.

K_2 at any other temperature T is calculated by

$$K_{2,T^oC} = K_{2,20^oC}\ \theta^{T-20}, \qquad \text{.......} \ (3\text{-}54)$$

where a suggested value of θ for the DO reaction is 1.02(6), and T is in °C.

Photosynthesis Generation P and Respiration Sink R

Recent studies(20) show that oxygen contribution by photosynthetic activity P is a primary source of DO; its value can predominate, or be equal to the respiration sink R, or be smaller than R under different circumstances, and should be experimentally evaluated instead of being stochastically neglected by assuming an gross equivalence with R.

The photosynthetic rate P is a function of radiation intensity and the phytoplankton population, which can in turn be functions of time, temperature, depth, and position.

A time-varying P of the form of a half-cycle sine wave is suggested by O'Connor and Di Toro(20):

$$P(t) = P_m \sin \left[\frac{\pi}{P}(t-t_s) \right] \quad \text{when } t_s \leqslant t \leqslant t_s + P \quad \ldots\ldots \quad (3\text{-}55)$$

$$= 0 \quad \text{when } t_s + P \leqslant t \leqslant t_s + 1 \quad \ldots \quad (3\text{-}56)$$

where $P(t)$ = time varying rate of photosynthetic oxygen production in mg/liter-day,

P_m = maximum value of $P(t)$,

t_s = the time at which generation begins in days,

P = the fraction of the day over which photosynthesis exists.

The periodic expression of Eq. (3-55) can be expressed as a Fourier series and used for the long-term effect of photosynthetic oxygen generation, or can be used in the time-varying DO model to calculate DO at different times within a tidal cycle. It can also be integrated over a tidal cycle to provide an average term P_{av}, as is of interest in this study due to the lack of time-varying field data. The respiration term, unlike the photosynthesis term, is assumed to be constant over a certain period. The temperature effect on respiration can be expressed in the equation

$$R_T = R_o \cdot e^{rT} \qquad \ldots\ldots\ (3\text{-}57)$$

where R_T = respiratory rate at some temperature T,

R_o = respiratory rate at 0 °C,

r = constant to be determined by experiment,

e = base of the natural logarithm.

Studies made by Riley(9) on Long Island Sound found R_o for winter and for summer to be 0.020 and 0.015 mg. of carbon consumed/day/mg. of phytoplankton carbon respectively. Conversion of units is required in adopting these values in the DO model.

Wright(9) tabulated monthly averages of P and R for various streams during different months (April to October, 1957 and April to October, 1958) as a function of phytoplankton densities. These values can be adopted before more suitable data become available for Mobile Bay.

Benthic Uptake S_b

Although in streams this term is often neglected by assuming bottom scour due to high speed of flow, this term deserves more consideration in an estuary like Mobile Bay. However, data on this sink are not available. In the Galveston Bay Study(6), the equation

$$S_b = 2.0\ e^{0.07(T-20)}\ \frac{\text{gm}}{\text{m}^2\ \text{day}} \qquad \ldots\ldots\ (3\text{-}58)$$

was adopted due to lack of data for Galveston Bay as of the time of report issuance. In this study, the benthic uptake can be (a) neglected by assuming that is is mainly due to benthic bacterial respiration(21) and is included in the respiration term R (the nature of R data adopted have to justify this), or (b) calculated using Eq. (3-58) with conversion of gm/m^2·day into mg/liter-day by incorporating the local depth of bay cells.

With the development, simplification and adaptation of the general non-conservative species continuity equation to total coliform, BOD, and DO completed, attention is now turned to the numerical method used to effect solutions. This will be followed in the next chapter by a discussion of the calibration and verification methods used to test the coliform model. Results of the coliform model including parametric studies involving varying river discharge rates, wind conditions and temperatures are presented and discussed in Chapter V.

3.4 Numerical Solution of the Non-conservative Species Equation

Finite difference equations can be written for the partial differential equations developed for the various models in the preceding sections. Finite space increments, Δx and Δy, and a finite time increment Δt, are selected based on the stability criteria insuring a correct solution. As shown in Figure 3.5, a grid system consisting of 38 rows and 21 columns formulating 798 square grid

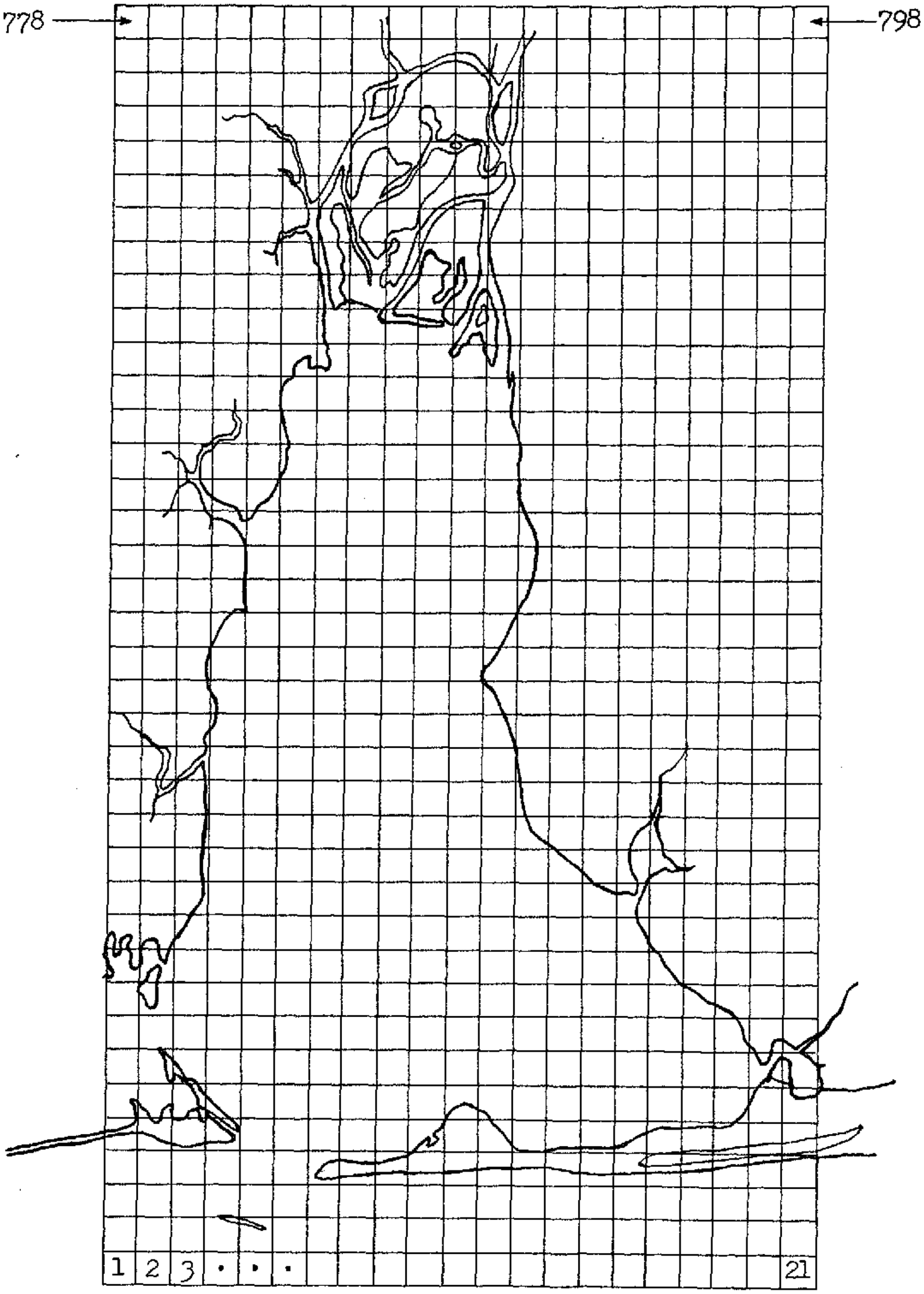


Fig. 3.5 The grid system (21 x 38) superimposed on the Mobile Bay system for the finite differencing technique.

cells of 2 km. by 2 km., is superimposed on the Mobile system. The computer program for the Salinity Model developed by Hill and April(12) is adopted and modified to implement the finite difference equations for the NCSTM for Mobile Bay. Initial and boundary conditions are supplied and grid to grid computations are effected until relaxation occur, that is, until results computed for two consecutive sweeps of the grid system are within tolerable differences.

3.4.1 Finite Difference Techniques

Forward, backward, and central differences have been used in finite differencing methods for solving ordinary and partial differential equations. Their basic forms are summarized below.

Upon proper selection of Δx and Δy(4),

forward difference $$\frac{dx}{dy} \approx \frac{x(I+1) - x(I)}{\Delta y} \quad \ldots\ldots \ (3\text{-}59)$$

backward difference $$\frac{dx}{dy} \approx \frac{x(I) - x(I-1)}{\Delta y} \quad \ldots\ldots \ (3\text{-}60)$$

central difference $$\frac{dx}{dy} \approx \frac{x(I+1) - x(I-1)}{2\,\Delta y} \quad \ldots\ldots \ (3\text{-}61)$$

By properly subscripting the dependent variables, the finite difference equations can be written to include values from both neighboring columns and neighboring rows, that is, the two dimensions x and y. In this study, the forward difference is used for first order derivatives, and the combination of forward and central difference formulas is used for second order derivatives.

3.4.2 Finite Difference Equations for the NCSTM

Application of the finite difference method is made here to the computation of total coliform concentration in Mobile Bay, beginning with Eq. (3-37) rewritten here as Eq. (3-62).

$$\frac{\partial B}{\partial t} = -\left(U\frac{\partial B}{\partial x} + V\frac{\partial B}{\partial y} \right) + \frac{\partial}{\partial x}\left(E_x\frac{\partial B}{\partial x} \right) + \frac{\partial}{\partial y}\left(E_y\frac{\partial B}{\partial y} \right) - K_r B \qquad \text{.......}\ (3\text{-}62)$$

Upon finite differencing,

$$\frac{\partial B}{\partial t} \approx \frac{B'(I,J) - B(I,J)}{\Delta t} \qquad \text{.......}\ (3\text{-}63)$$

$$\frac{\partial B}{\partial x} \approx \frac{B(I+1,J) - B(I,J)}{\Delta x} \qquad \text{.......}\ (3\text{-}64)$$

$$\frac{\partial B}{\partial y} \approx \frac{B(I,J+1) - B(I,J)}{\Delta y} \qquad \text{.......}\ (3\text{-}65)$$

$$U \approx \frac{U(I+1,J) - U(I,J)}{2} \qquad \text{.......}\ (3\text{-}66)$$

$$V \approx \frac{V(I,J+1) - V(I,J)}{2} \qquad \text{.......}\ (3\text{-}67)$$

where $B(I,J) = B$ at time t, $B'(I,J) = b$ at time $t + \Delta t$, in cell (I,J).

Furthermore, by the product rule,

$$\frac{\partial}{\partial x}\left(E_x\frac{\partial B}{\partial x} \right) = \frac{\partial E_x}{\partial x}\left(\frac{\partial B}{\partial x} \right) + E_x\left(\frac{\partial^2 B}{\partial x^2} \right) \qquad \text{.......}\ (3\text{-}68)$$

$$\frac{\partial}{\partial y}\left(E_y\frac{\partial B}{\partial y} \right) = \frac{\partial E_y}{\partial y}\left(\frac{\partial B}{\partial y} \right) + E_y\left(\frac{\partial^2 B}{\partial y^2} \right) \qquad \text{.......}\ (3\text{-}69)$$

For the x-component,

$$\frac{\partial E}{\partial x} \approx \frac{E(I+1,J) - E(I,J)}{\Delta x} \approx \frac{E(I+1,J) - E(I-1,J)}{2\Delta x}, \quad \ldots (3\text{-}70)$$

$$\frac{\partial B}{\partial x} \approx \frac{B(I+1,J) - B(I,J)}{\Delta x} \approx \frac{B(I,J) - B(I-1,J)}{\Delta x} \quad \ldots (3\text{-}71)$$

$$\frac{\partial^2 B}{\partial x^2} = \frac{\dfrac{B(I+1,J) - B(I,J)}{\Delta x} - \dfrac{B(I,J) - B(I-1,J)}{\Delta x}}{\Delta x}$$

$$= \frac{B(I+1,J) - 2B(I,J) + B(I-1,J)}{(\Delta x)^2}. \quad \ldots (3\text{-}72)$$

Combining Eq. (3-68) with Equations (3-70), (3-71) and (3-72) gives

$$\frac{\partial E}{\partial x}\,\frac{\partial B}{\partial x} \approx \left[\frac{E(I+1,J) - E(I,J)}{\Delta x}\right] \cdot \left[\frac{B(I+1,J) - B(I,J)}{\Delta x}\right]$$

$$+ \; E(I,J)\left[\frac{B(I+1,J) - 2B(I,J) + B(I-1,J)}{(\Delta x)^2}\right],$$

$$\approx \left[\frac{E(I+1,J) - E(I-1,J)}{2\,\Delta x}\right]\left[\frac{B(I+1,J) - B(I,J)}{\Delta x}\right]$$

$$+ \; E(I,J)\left[\frac{B(I+1,J) - 2B(I,J) + B(I-1,J)}{(\Delta x)^2}\right]$$

$$= \frac{1}{2(\Delta x)^2}\; E(I+1,J)\;\left[B(I+1,J) - B(I,J)\right]$$

$$- \frac{1}{2(\Delta x)^2}\; E(I-1,J)\;\left[B(I+1,J) - B(I,J)\right]$$

$$+ \; E(I,J)\cdot \frac{1}{(\Delta x)^2}\left[B(I+1,J) - 2B(I,J) + B(I-1,J)\right]$$

$$\approx \frac{1}{2(\Delta x)^2}\; E(I+1,J)\;\left[B(I+1,J) - B(I,J)\right]$$

$$- \frac{1}{2(\Delta x)^2} \; E(I-1,J) \; \left[B(I,J) - B(I-1,J) \right]$$

$$+ \frac{1}{(\Delta x)^2} \; E(I,J) \; \left[B(I+1,J) - 2B(I,J) + B(I-1,J) \right]$$

$$= \frac{1}{2(\Delta x)^2} \; E(I+1,J) \left\{ \left[B(I+1,J) - B(I,J) \right] \right.$$

$$- E(I-1,J) \; \left[B(I,J) - B(I-1,J) \right]$$

$$\left. + 2E(I,J) \; \left[B(I+1,J) - 2B(I,J) + B(I-1,J) \right] \right\} \; \ldots \; (3\text{-}73)$$

Similarly for the y-component

$$\frac{\partial}{\partial y} \left(E_y \frac{\partial B}{\partial y} \right) \approx \frac{1}{2(\Delta x)^2} \left\{ E(I,J+1) \left[B(I,J+1) - B(I,J) \right] \right.$$

$$- E(I,J-1) \left[B(I,J) - B(I,J-1) \right]$$

$$\left. + 2E(I,J) \left[B(I,J+1) - 2B(I,J) + B(I,J-1) \right] \right\}$$

$$\ldots\ldots\ldots \; (3\text{-}74)$$

Finally all these finite difference formulas are substituted into Equation (3-62) to give

$$
\begin{aligned}
&\frac{B'(I,J) - B(I,J)}{\Delta t} \\
&= -\left\{ \left[\frac{U(I+1,J) - U(I,J)}{2} \right] \left[\frac{B(I+1,J) - B(I,J)}{\Delta x} \right] \right. \\
&\quad \left. + \left[\frac{V(I,J+1) - V(I,J)}{2} \right] \left[\frac{B(I,J+1) - B(I,J)}{\Delta y} \right] \right\} \\
&\quad + \frac{1}{2(\Delta x)^2} \Big\{ E(I+1,J) \left[B(I+1,J) - B(I,J) \right] \\
&\quad - E(I-1,J) \left[B(I,J) - B(I-1,J) \right] \\
&\quad + 2E(I,J) \left[B(I+1,J) - 2B(I,J) + B(I-1,J) \right] \Big\} \\
&\quad + \frac{1}{2(\Delta x)^2} \Big\{ E(I,J+1) \left[B(I,J+1) - B(I,J) \right] \\
&\quad - E(I,J-1) \left[B(I,J) - B(I,J-1) \right] \\
&\quad + 2E(I,J) \left[B(I,J+1) - 2B(I,J) + B(I,J-1) \right] \Big\} \\
&\quad - K_r B(I,J). \qquad \cdots\cdots \quad (3\text{-}75)
\end{aligned}
$$

Rearranging and solving for B'(I,J) results in the desired equation to be applied to each grid cell in the bay,

$$\begin{aligned}
&B'(I,J) \\
&= B(I,J) - \frac{(\Delta t)}{2}\left\{ \frac{1}{\Delta x}\left[U(I+1,J) - U(I,J)\right]\left[B(I+1,J) - B(I,J)\right]\right. \\
&\quad \left. + \frac{1}{\Delta y}\left[V(I,J+1) - V(I,J)\right]\left[B(I,J+1) - B(I,J)\right]\right\} \\
&\quad + \frac{\Delta t}{2(\Delta x)^2}\left\{ E(I+1,J)\left[B(I+1,J) - B(I,J)\right]\right. \\
&\quad - E(I-1,J)\cdot\left[B(I,J) - B(I-1,J)\right] + 2E(I,J)\left[B(I+1,J)\right. \\
&\quad \left.\left. - 2B(I,J) + B(I-1,J)\right]\right\} \\
&\quad + \frac{\Delta t}{2(\Delta x)^2}\left\{ E(I,J+1)\left[B(I,J+1) - B(I,J)\right]\right. \\
&\quad - E(I,J-1)\left[B(I,J) - B(I,J-1)\right] \\
&\quad \left. + 2E(I,J)\cdot\left[B(I,J+1) - 2B(I,J) + B(I,J-1)\right]\right\} \\
&\quad - (\Delta t)\, K_r\, B(I,J) \qquad \cdots\cdots\cdots \; (3\text{-}76)
\end{aligned}$$

This finite difference equation is used to implement computer solution of the species continuity equation for total coliform in Mobile Bay.

3.4.3 Application to Mobile Bay

Details of the development of the computer program have been cited in the work of Hill and April(12). They not only include specific derivation of the species continuity equation for conservative species, but the development of equations needed to specify the current distribution in the bay which is a critical input to this study. The specific aspects from that study which apply to the NCSTM are summarized below.

Finite Increments

There are specific limitations on the sizes of the finite increments for the finite difference solution to be stable or to converge. For the species continuity equation(12) these limitations are

$$\Delta x < \frac{2E_x}{U_{max}} \qquad \text{.......} \quad (3\text{-}77)$$

$$\Delta y < \frac{2E_y}{V_{max}} \qquad \text{.......} \quad (3\text{-}78)$$

$$\Delta t \leqslant \frac{(\Delta s)^2}{2(E_x + E_y)} \qquad \text{.......} \quad (3\text{-}79)$$

where $\Delta s = \Delta x = \Delta y$ in this study.

The spatial increments in the x and y directions (Δx and Δy) were chosen to be 2 km (6561.68 ft) each (see Fig. 3.5 on p. 53). A time increment Δt of 240 seconds was chosen to insure stability.

Boundary Conditions and Initial Conditions

Boundary conditions (concentrations for certain border line cells) and initial conditions (concentrations for all cells at time $t = 0$) must be specified in order to solve the partial differential equation describing a system using a finite difference technique. For Mobile Bay all the land cell concentrations are set equal to zero and the partial derivatives at water-land connecting cells are set equal to zero. The concentrations of cells on the Gulf front of the grid system are set equal to zero in the coliform model. This is reasonable because the coliform bacteria levels become negligibly low in Gulf water.

The Mobile River and the Tensaw River are each simulated with an idealized channel ten grids long flowing from the north to the south draining into the bay. Upstream runoffs from the rivers are expressed as boundary conditions at the mouths of the rivers where they flow into the bay. Values of these boundary conditions are adopted from data collected at water quality stations corresponding to or located near the boundary cells under consideration. Grid cells in the bay near suspected outfall of waste as reflected in field data are also assigned as boundary cells. Alabama Port (see Fig. 4.1) is an example of this behavior as reflected by the high coliform levels in waters adjacent to it. Therefore a boundary cell is assigned to the bay water near Alabama Port where the concentration is fixed in performing the computation. The value of the concentration is taken from a station corresponding to that cell.

Initial conditions are set equal to zero for all the cells for the first computation when prior knowledge of the system behavior cannot be estimated. The first computed results are then stored into a data file. Provisions are made for subsequent computations to utilize the previous result as initial conditions. This serves to conserve some computing time which is important for this kind of calculation.

Sources of Data

In order to exercise the NCSTM, specific information from various sources must be supplied. These data and their sources are summarized below. Their formats are listed later in the appendices.

(1) Monthly average river flow rates for Mobile River, the main source of pollution of Mobile Bay, are provided by the Alabama State Geological Survey at Tuscaloosa, Alabama. Data for the period January-August 1962 are selected for use in the coliform study to match the available coliform data. River flow rates for other periods starting from August 1928 are also available. The Geological Survey also provides daily river discharge rates for the Alabama River and Tombigbee River which can also be valuable to the short-term water quality study of Mobile Bay. (See Appendix B2, p. 181)

(2) Wind data are obtained from the climatological data collected by the Weather Bureau of the Department of Commerce. Prevailing

wind speed and direction for each month are used for the study of total coliform. (See Appendix B3, p. 184)

(3) Atmospheric temperature data over the Mobile Bay area are collected by the U. S. Weather Bureau. Bimonthly average bay water temperature profiles of Mobile Bay have been compiled and presented by Bault(1). The latter forms the basis for the determination of water temperatures to be used in the study of total coliform. (See Appendix B3, p. 184)

(4) Total coliform data are provided by the Alabama State Department of Health for the period January-August 1962. Numbers of data points for each station range from two to five per month. They are averaged on a monthly basis to be utilized in the study on total coliform distribution in Mobile Bay. (See Appendix B1, p. 169)

Data specific to the hydrography of Mobile Bay are necessary for the NCSTM; they are adopted directly from the work by Hill and April(12). Formats of input and output data of the NCSTM, computer program listings, and descriptions of the model variables are summarized in Appendices A1 to A4.

General Computation Procedures

The above data are used in the NCSTM to obtain the total coliform profiles for Mobile Bay in the subsequent chapters. Other water quality species can be investigated provided that pertinent field data are available. The general procedures of computation of the NCSTM are summarized below:

Step 1. River discharge rates, wind speed and direction, and other hydrographic data of Mobile Bay are fed to the Hydrodynamic Model of Mobile Bay(12). The Hydrodynamic Model calculates the net current velocities over one tidal cycle and the maximum velocities for each of the water cells of the bay. These data are then written into data files and stored in the memory of the computer.

Step 2. Temperature, boundary conditions of total coliform concentration, and pertinent hydrographic data of Mobile Bay are fed to the NCSTM. Starting with zero initial concentrations, the NCSTM reads in the data file created by the Hydrodynamic Model and computes the total coliform concentrations for each cell of the bay.

Step 3. Each pair of consecutive computations are compared until the computed results converge, that is, when the results yielded by two consecutive "sweeps" over the grid system are within acceptable deviation. In the computations performed in the following chapters, calculated results usually converge to within ± 1%.

The final results are then compared to the field data for the purposes of calibration and verification. The following chapter deals with the verification of the NCSTM for total coliform bacteria distributions in Mobile Bay.

CHAPTER IV

CALIBRATION AND VERIFICATION

Total coliform group concentration data for various locations in Mobile Bay were collected by the Alabama State Department of Health for the period from January 1962 to August 1962. Figure 4.1 shows the locations of the coliform sampling stations in Mobile Bay (14). Figure 4.2 shows the grid locations with corresponding station numbers at which coliform concentration data are available. It is these data that are used for the purpose of verification of the Non-conservative Species Transport Model for Mobile Bay. These coliform group concentrations are obtained by analysis as described in the outline entitled "The Significance of EC Positive Organisms in Gulf Shellfish Growing Waters" (see Appendix B1, p. 170).

The model is verified on a monthly basis, i.e. monthly average conditions are used, and the model results are tabulated and compared to the monthly average values of actual data. The 70% confidence ranges of the actual data are also tabulated to indicate the range in the monthly field data averages. The criterion for model verification is based on how well model-predicted results fall within the field data range at the several locations within the bay for any given monthly period.

It will be shown in the following sections that the model predicts resonable results as compared to the measured data.

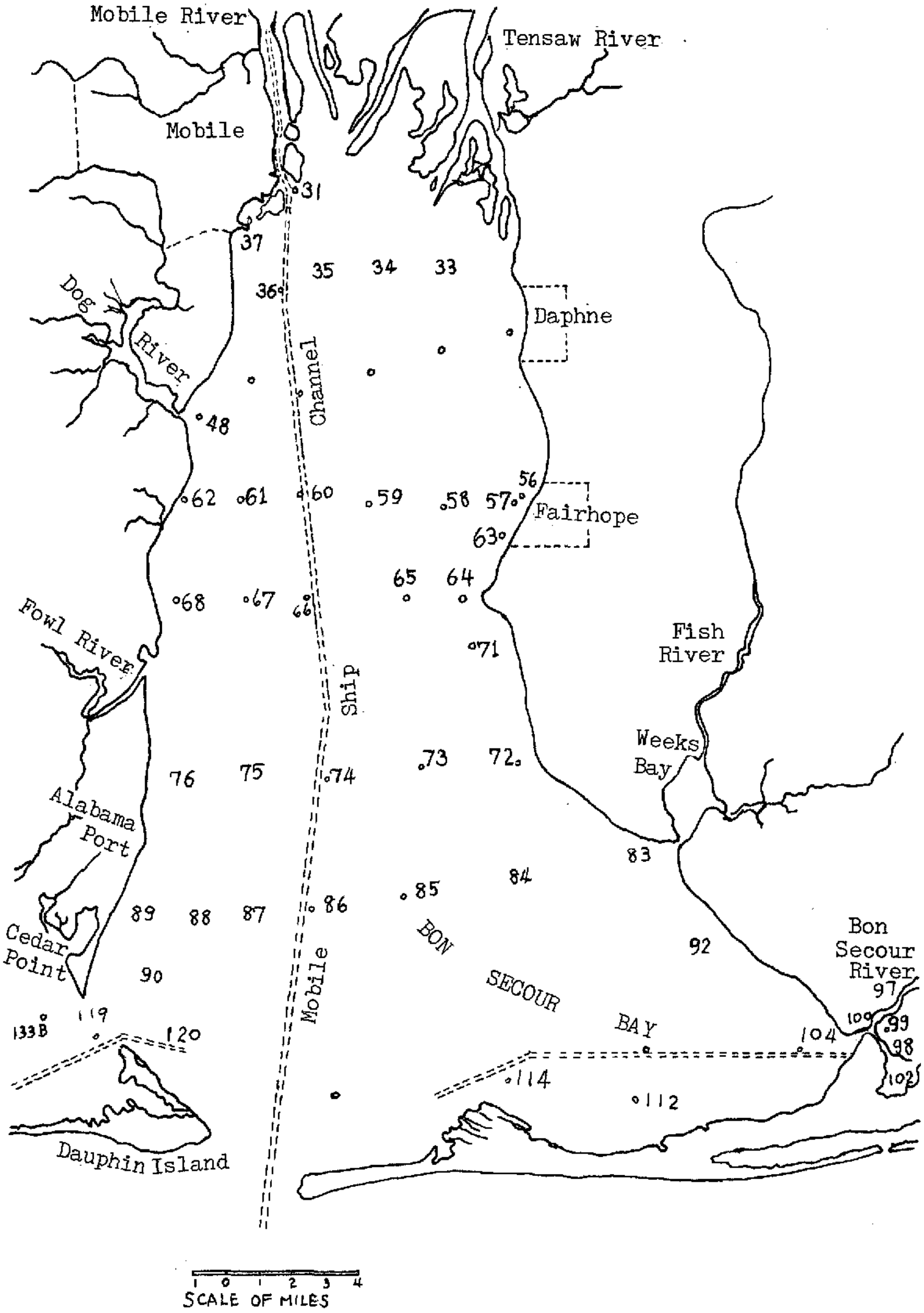
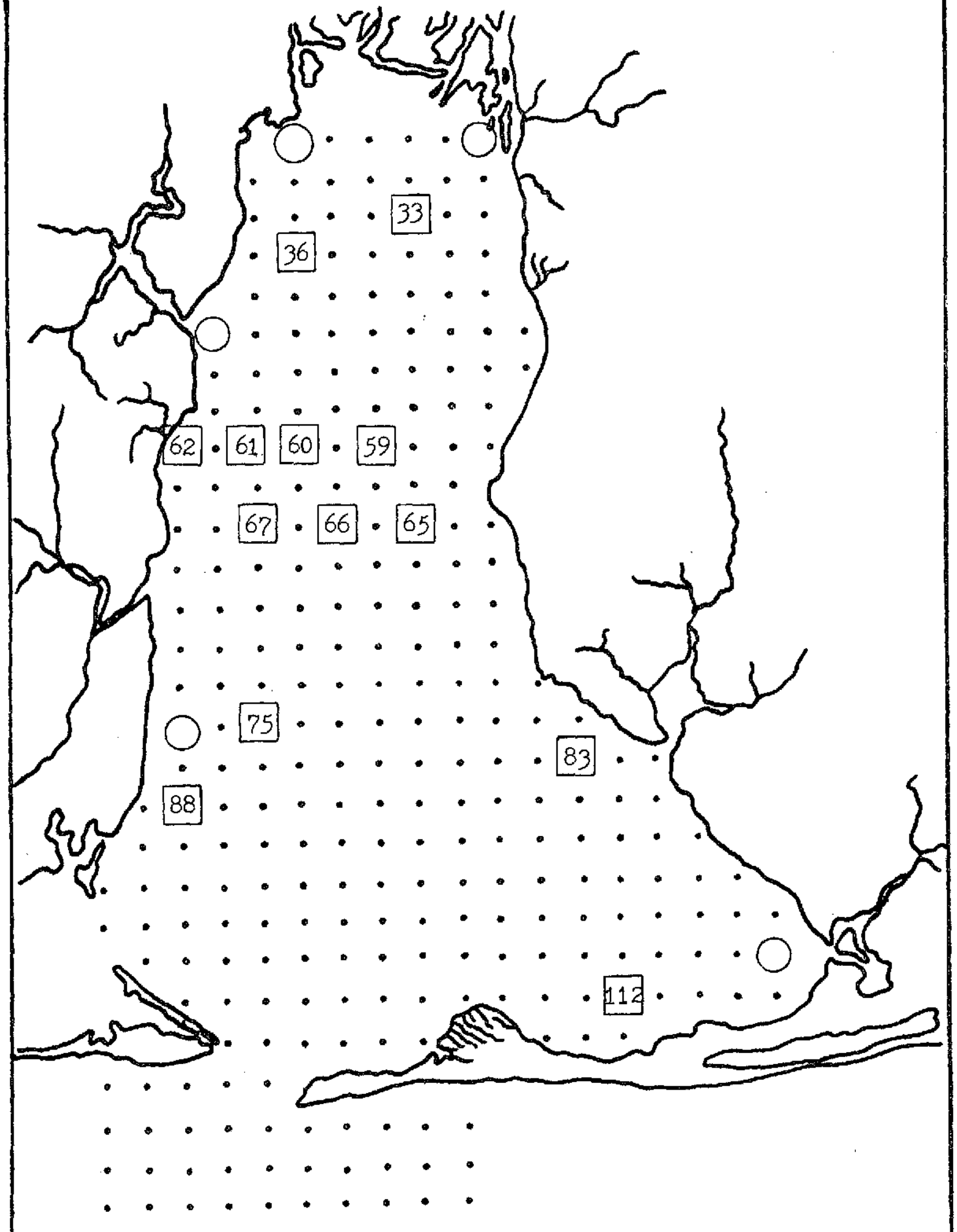


Fig. 4.1 Coliform Sampling Stations in Mobile Bay



☐ Grid Locations of Stations Where Data Are Available

○ Grid Locations of Loadings

Fig. 4.2 Locations of Total Coliform Stations and Loadings

However, it should be indicated that collected field data used in the verification were not specifically obtained for mathematical modeling purposes, and thus represent selections based on availability. A more detailed verification program, including synoptic data collection specifically in support of mathematical modeling efforts, would be required to confidently use model predicted results for trend analyses on less than monthly frequencies.

Additionally, there are no sources of data of any magnitude to suitably verify the biological oxygen demand (BOD) and dissolved oxygen (DO) models. As a result, the verification of the NCSTM is based solely on total coliform group concentration data. Extrapolation of conditions, using the experience gained from the total coliform model and available literature surveys concerning those concepts and laws governing the calculation of BOD and DO concentrations in estuarine waters, can be used for preliminary trend studies. However, verification studies of the BOD and DO models will have to be made, including design and implementation of suitable data collection programs in support of mathematical modeling, before the BOD and DO model results can be used in a truly predictive capacity.

4.1 Calibration and Verification Procedures

Interaction with the Hydrodynamic Model

Because of the dependence of the species continuity equation on the hydrodynamic model of Mobile Bay for current distributions and dispersion coefficients, the first step in the verification procedure involves specification of data necessary for the proper description of the hydrodynamic behavior of the Bay. This includes the calculation of monthly average river flow rates, wind conditions and tidal conditions for the period for which total coliform group concentration data are available.

Monthly average river flow rate data are available from the Alabama Geological Survey at Tuscaloosa, Alabama for the Mobile River near Mount Vernon, Alabama. These are reasonably split into two parts for the river discharges of the Mobile River and the Tensaw River which empty into Mobile Bay in the north. River discharge rates for Dog River are varied between 500 cfs and 5000 cfs, depending on the month in which the model is to be exercised. Values used for verification studies during the period January to August 1962 are shown in Table 4.1.

Wind conditions, including speed and direction, are calculated as statistical averages for each monthly period during 1962. These data are obtained from climatological data provided by the U. S. Weather Bureau(27). Wind speed in knots and wind direction in degrees from the x-axis are listed in Table 4.2 for the period January to August 1962.

The tidal cycle conditions are described by equations developed by Hill and April(12) for each of two locations where the bay

Table 4.1 River Discharge Rates for the Period January to August, 1962 in cfs

Month	Mobile River	Dog River	Tensaw River
January	130,000	5,000	73,800
February	100,000	3,000	51,700
March	90,000	2,500	53,100
April	130,000	4,000	56,900
May	20,000	2,000	18,500
June	15,400	1,500	10,000
July	10,000	1,000	9,200
August	8,000	500	4,500

Table 4.2 Temperatures, Dieoff Rate Constants, and Wind Conditions for the Period January to August, 1962

Month	Temperature °F	Dieoff Rate Constant K_r day^{-1}	Wind Conditions		
			Speed knots	Direction	
				from	θ deg.
January	49.5	0.26	12.3	N	90.0
February	53.2	0.29	12.0	S	270.0
March	61.3	0.39	12.6	N	90.0
April	67.9	0.50	10.7	SSE	292.5
May	78.1	0.72	7.9	SW	225.5
June	81.4	0.81	5.7	NE	45.0
July	83.7	0.88	5.9	SW	225.5
August	84.2	0.90	5.2	ENE	22.5

interfaces with Gulf of Mexico waters. These equations describe the tidal level at the Cedar Point and Dauphin Island-Gulf boundaries and are represented as:

$$HDI = 1.090 + 1.295 \cdot \cos (0.004188 \cdot t + 0.0567114)$$

$$HCP = 1.089 + 1.177 \cdot \cos (0.004188 \cdot t + 0.0032453)$$

Unless there is evidence of conditions altering tidal behavior in the Gulf (i.e. storms, diurnal periods, etc), it is assumed that normal tidal conditions prevail over the monthly cycle.

Using the above data as input to the hydrodynamic model, the corresponding output, including tidal cycle average velocities and dispersion coefficients for points within the bay, provides a description of the period for which total coliform group data are available.

Non-conservative Species Model for Coliform

Specification of inputs for the NCSTM for total coliform includes two types of information which are classified as follows:

(1) cell data which includes velocity distributions and dispersion coefficients for each grid of the model as calculated in the Hydrodynamic Model; temperature data used in the calculation of the total coliform dieoff rate constants K_T; and

(2) boundary and initial conditions of total coliform concentration data dealing with specific inputs at the spatial and temporal limits of the model. These inputs are discussed below.

Cell Data and Conditions

Net velocities over one tidal cycle for the grid cells are used as the x-component (U) and y-component (V) velocities in the Coliform Model. Maximum velocities over the tidal cycle for the grid cells are used to calculate dispersion coefficients (E_x and E_y) according to Holley's correlation equation (3-40). The dispersion coefficients thus calculated are used, after being modified by a correction factor suitably defined by monthly average field data during model calibration. These modified dispersion coefficients are selected to provide the best description of the macroscopic mixing characteristics for the given species and conditions that exist within the bay.

Additionally, the total coliform dieoff rate constant K_r used in the model is calculated as a function of monthly average water temperature of the bay according to equation (3-42). These temperatures are estimated from the bimonthly average water temperatures of Mobile Bay compiled by Bault(1). It is recognized that water temperatures are not uniform in the bay. The degree of mixing that occurs between sea water and river water within the bay will affect the temperature distribution. In this study temperatures are considered homogeneous throughout the bay. Temperatures can be adjusted linearly between the values corresponding to Gulf of Mexico water temperature and river water temperature to approximate real system behavior. In this study where monthly average values are investigated the sea water intrusion effect can be neglected. This point will be explained later in the discussion section (Section 4.3) of this chapter.

Initial and Boundary Conditions

Initial and boundary conditions for total coliform group concentrations are specified as described in Section 3.4.3 on page 61.

Cell Loadings and Dilution Factors

Total coliform group concentration data for points recognized as having severe pollutant input into the bay are used as loading concentrations at each relevant grid cell as shown in Fig. 4.2. They are held constant throughout each computation. These points include (1) the mouth of the Mobile River leading into the bay, (2) the mouth of the Tensaw River leading into the bay, (3) the mouth of the Dog River leading into the bay, (4) the water adjacent to the Alabama Port, (5) Cedar Point, and (6) the mouth of the Bon Secour River leading into the bay. Loading at the Mobile River has been found to be the main source of pollution of Mobile Bay(10). Values of the cell loading total coliform concentrations are shown in Table 4.3.

Loading concentrations for the mouth of the Mobile River, when directly taken from the total coliform concentrations at station no. 31 (TC_{31}), result in calculated profiles within the bay which exceed observed levels. Knowing that station no. 31 is located in the ship channel (see Fig. 4.1) and that the concentration measured

Table 4.3 Loadings of Total Coliform at Various Locations in MPN per 100 ml

Month	Mouth of Mobile River	Mouth of Tensaw River	Mouth of Dog River	Alabama Port	Cedar Point	Mouth of Bon Secour River
January	20,500	2,000	19,000	23,800	2,500	1,500
February	18,125	2,000	13,800	5,000	4,150	1,300
March	99,000	2,000	47,500	2,100	1,100	170
April	54,000	2,000	7,750	2,750	550	120
May	40,000	200	1,800	1,100	200	40
June	700	300	330	15	1	8
July	3,600	1,000	330	60	0	45
August	1,500	200	200	15	2	20

there is a point concentration instead of one characteristic of the entire model cell, a conversion of the point source concentration to a cell loading concentration suitable for model input becomes necessary. This conversion requires a dilution of the point source concentration to one distributed through the entire grid cell corresponding to station no. 31. By definition, the dilution factor can be expressed as

$$\text{D.F.} = \frac{\left(\begin{array}{l}\text{volume of the actual water mass}\\ \text{possessing the total coliform concentration}\\ \text{observed in the field sample}\end{array}\right)}{\left(\begin{array}{l}\text{volume of the grid cell corresponding to}\\ \text{the location where field sample was taken}\end{array}\right)} .$$

However, due to the lack of detailed information about the magnitude of the waste discharge at point sources, and to the irregularity of the configuration of the water mass at the points of sampling, the dilution factor (D.F.) is determined by a calibration method involving actual data. Point source data collected at coliform stations in the bay, especially samples collected in the ship channel or near possible waste outfalls where non-homogeneous mixing may exist, may not be representative of cell concentrations utilized in the NCSTM. Care must exercised in interpreting such kinds of data prior to their use as model input or for comparison purposes.

Model Calibration

The calibration procedure involved the adjustment of the source loading dilution factor (D.F.) and the adjustment of the correction factor (C.F.) for the dispersion coefficients according to Equation (3-40). A trial and error method was used, based on the June, 1962 total coliform data in which both the D.F. for point source loading concentrations and the C.F. for dispersion coefficients were varied. Values of these factors producing most consistent results over the entire range of the calibration data were selected and fixed for final use in the verification and the parametric phases of this project. The reason for choosing June, 1962 data for model calibration was that for this month the river flow rate of the Mobile River-Tensaw River system (1) is close to the average value of 59,000cfs, and (2) corresponds closely to the acceptable verification levels of the Hydrodynamic Model reported by Hill and April(12). The river flow rate of May, 1962 is closer to 59,000 cfs; however, the total coliform data for May is not satisfactory for verification purposes (see Table 4.1 and Figures 4.11 to 4.23).

4.2 Results of the Verification Study

The results are shown tabulated in Tables 4.4 to 4.11 for each month during which the verification phase of this study was conducted. Included in each table are the monthly mean total coliform concentration (in MPN/100ml) and the 70% confidence ranges calculated for the field data on a monthly basis. These values are compared with model-predicted total coliform concentrations for the cells corresponding to the stations in the bay where point concentration data are available. Furthermore, Figures 4.3 to 4.10 show the model-calculated total coliform profiles within Mobile Bay for each month from January to August , 1962, during which the verification phase is performed. Total coliform concentration vs. time (month) curves are also presented to indicate the trend of concentration changes with season. Data at some stations lying very close to the bay perimeter were not selected for comparison, since data at these stations are not representative of the cell concentrations.

Notations for Tables 4.4 to 4.11

$\overline{x}$ = monthly average total coliform field data

t = the statistic used for confidence range correlation

$S_{\overline{x}} = S/\sqrt{n}$ = stadard deviation of the mean

where S = standard deviation of the data

n = no. of field samples for the month

TC_{31} = total coliform concentration field data at station no. 31 (corresponding to the mouth of Mobile River)

D.F. = dilution factor to convert TC_{31} into a cell loading source concentration

K_r =dieoff rate constant of total coliform bacteria

E = dispersion coefficient

Notations for Figures 4.11 to 4.23

○———	Actual total coliform concentration data
▬▬▬	Model-calculated monthly average total coliform concentrations
↓	Less than

Table 4.4 Total Coliform Concentration for Mobile Bay - January 1962

Loading at Mobile River Mouth = 1/4 TC_{31} (D.F. = 4)

Correction Factor for E = 500

$K_r = 0.26$ day^{-1}

Station No.	Measured Data				Model Calculated Result
	No. of Field Sampling	Monthly Average $\bar{X}$	70% Confidence Range		
			$\bar{X} - tS_{\bar{X}}$	$\bar{X} + tS_{\bar{X}}$	
33	4	1,800	1,656	1,944	1,977
36	4	44,500	21,625	67,375	17,958
59	3	5,000	4,206	5,794	6,731
60	3	7,170	5,762	8,578	12,897
61	4	38,000	14,562	61,437	14,235
62	3	24,700	9,496	39,904	15,788
65	2	11,000	-3,157	25,157	4,610
66	4	17,000	10,563	23,438	8,908
67	5	10,400	7,138	13,661	12,360
75	5	7,900	4,175	11,624	9,249
83	3	2,250	1,529	2,970	2,218
88	5	10,100	8,025	12,175	12,422
112	4	530	330	730	1,233

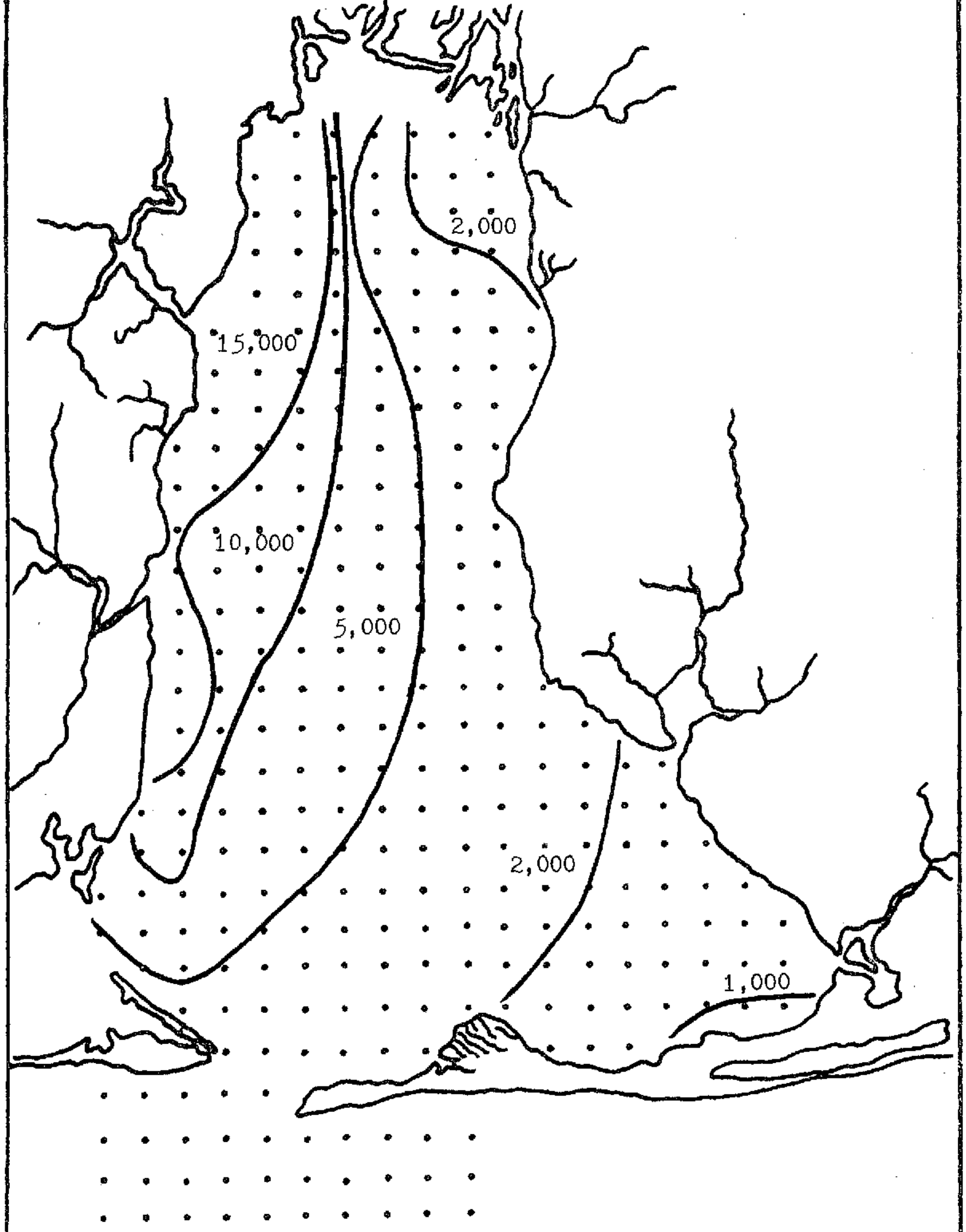


Fig. 4.3 Model-Calculated Total Coliform Concentration Profiles for January, 1962

Table 4.5 Total Coliform Concentration for Mobile Bay -February1962

Loading at Mobile River Mouth = 1/5 TC_{31} (D.F. = 5)

Correction Factor for E = 500

$K_r = 0.29$ day^{-1}

Station No.	Measured Data				Model Calculated Result
	No. of Field Sampling	Monthly Average $\bar{x}$	70% Confidence Range		
			$\bar{x} - tS_{\bar{x}}$	$\bar{x} + tS_{\bar{x}}$	
33	2	4,500	338	8,662	1,981
36	4	23,000	18,125	27,875	15,415
59	4	5,000	3,312	6,688	5,273
60	4	17,000	10,750	23,250	9,677
61	4	63,500	41,000	86,000	10,548
62	4	27,500	13,750	41,250	10,549
65	4	1,650	881	2,419	3,514
66	4	8,000	7,531	8,468	6,421
67	4	51,500	33,562	69,438	8,407
75	4	15,000	7,312	22,688	5,302
83	3	1,100	300	1,900	1,491
88	4	5,300	1,800	8,800	3,783
112	3	1,380	603	2,156	709

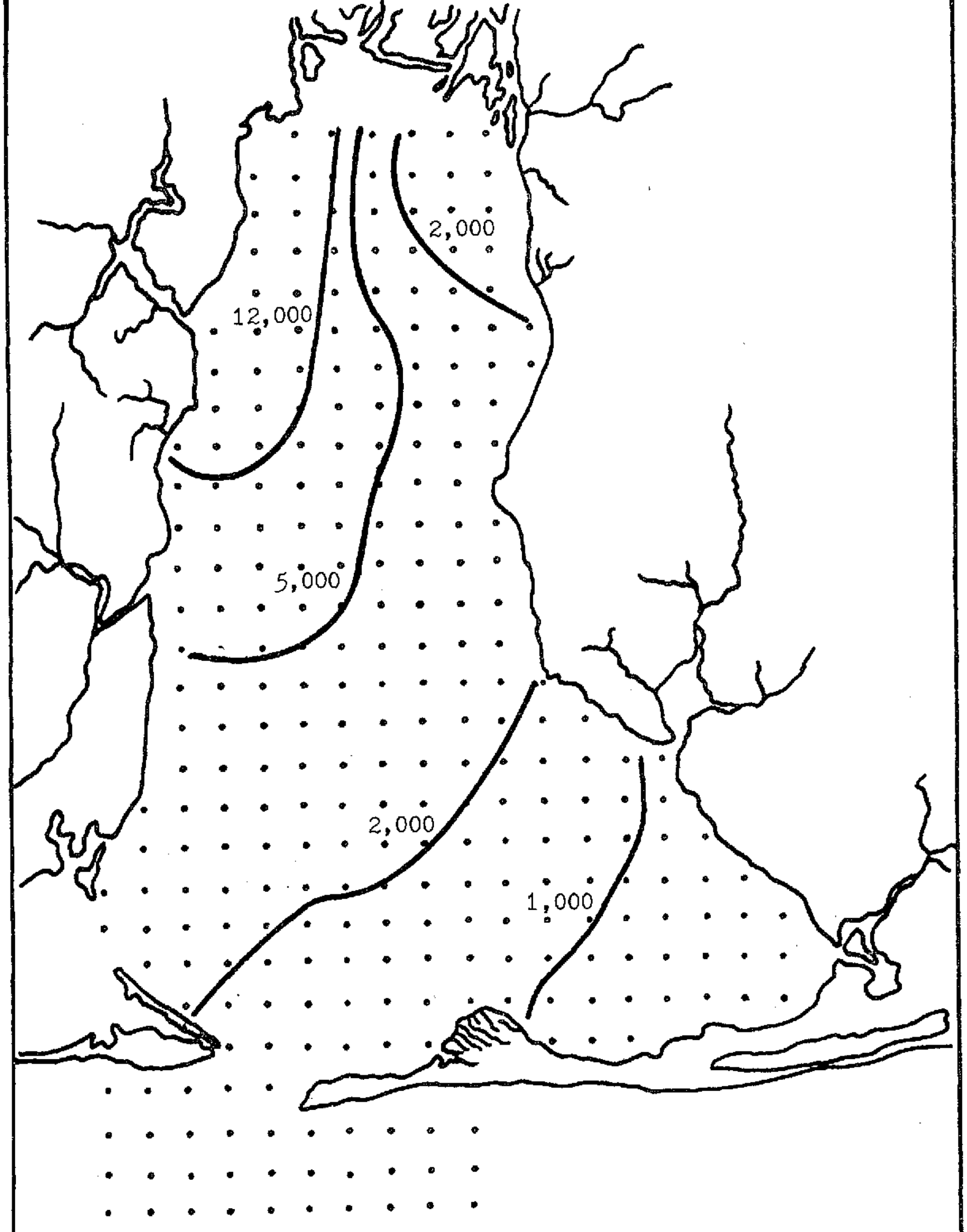


Fig. 4.4 Model-Calculated Total Coliform Concentration Profiles for February, 1962

Table 4.6 Total Coliform Concentration for Mobile Bay - March 1962

Loading at Mobile River Mouth = 1/5 TC_{31} (D.F. = 5)

Correction Factor for E = 500

K_r = 0.39 day^{-1}

Station No.	Measured Data				Model Calculated Result
	No. of Field Sampling	Monthly Average $\overline{X}$	70% Confidence Range		
			$\overline{X} - tS_{\overline{X}}$	$\overline{X} + tS_{\overline{X}}$	
33	2	8,000	4,126	11,874	3,938
36	3	25,000	13,638	36,362	80,734
59	4	160,000	-27,500	347,500	20,108
60	4	69,500	49,688	89,313	41,863
61	4	35,000	15,000	55,000	43,519
62	4	14,000	6,625	21,375	35,070
65	4	4,160	4,060	4,260	11,815
66	4	36,000	11,625	60,375	25,338
67	4	19,250	8,625	29,875	31,766
75	4	15,750	1,763	29,738	17,326
83	4	255	186	324	3,159
88	4	2,800	1,363	4,283	5,375
112	3	55	-3	113	1,089

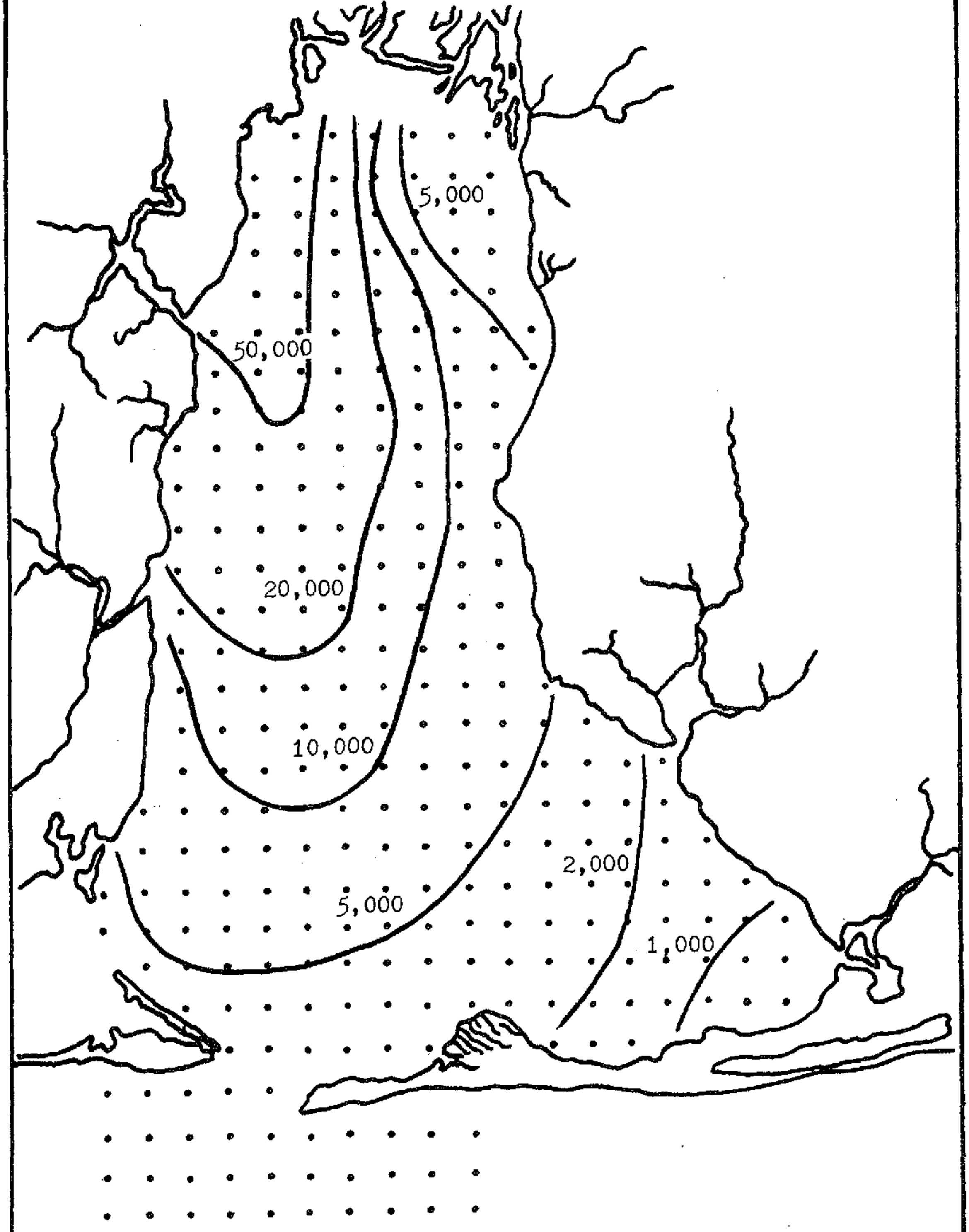


Fig. 4.5 Model-Calculated Total Coliform Concentration Profiles for March, 1962

Table 4.7 Total Coliform Concentration for Mobile Bay - April 1962

Loading at Mobile River Mouth = 1/4 TC_{31} (D.F. = 4)

Correction Factor for E = 500

K_r = 0.50 day^{-1}

Station No.	Measured Data				Model Calculated Result
	No. of Field Sampling	Monthly Average $\overline{X}$	70% Confidence Range		
			$\overline{X} - tS_{\overline{X}}$	$\overline{X} + tS_{\overline{X}}$	
33	5	1,540	1,008	2,072	2,727
36	5	76,600	44,669	108,531	44,613
59	4	162,000	-50,500	374,500	12,425
60	4	7,250	5,688	8,813	24,451
61	4	27,500	14,313	40,688	23,589
62	4	17,000	7,000	27,000	9,722
65	4	7,100	4,263	9,938	7,201
66	4	8,100	2,725	13,475	15,166
67	4	2,750	2,063	3,438	16,592
75	4	5,600	1,975	9,225	9,283
83	4	30	25	35	2,094
88	5	850	488	1,212	3,349
112	4	55	44	66	638

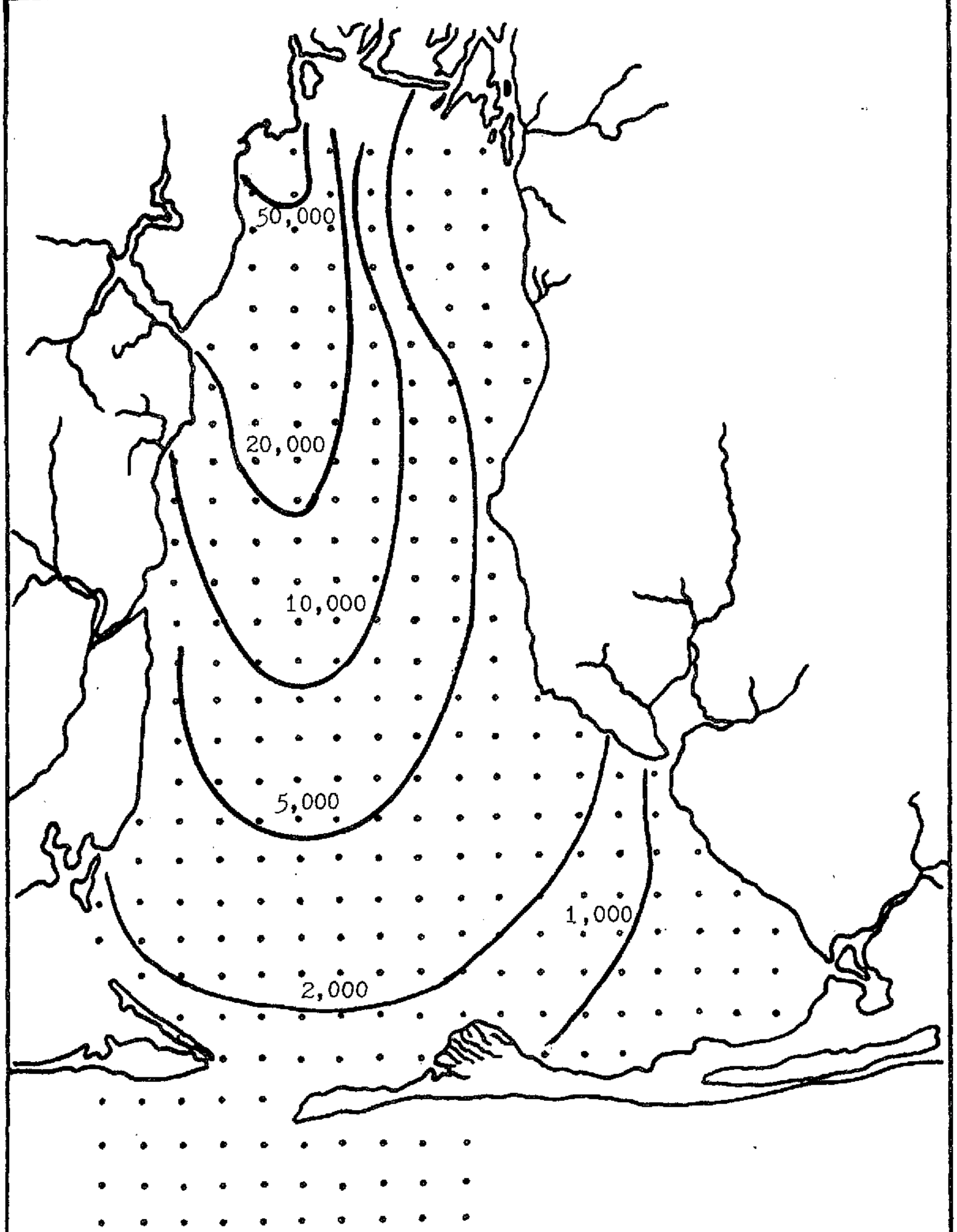


Fig. 4.6 Model-Calculated Total Coliform Concentration Profiles for April, 1962

Table 4.8 Total Coliform Concentration for Mobile Bay - May 1962

Loading at Mobile River Mouth = 1/5 TC_{31} (D.F. = 5)

Correction Factor for E = 500

K_r = 0.72 day^{-1}

Station No.	Measured Data				Model Calculated Result
	No. of Field Sampling	Monthly Average $\overline{X}$	70% Confidence Range		
			$\overline{X} - tS_{\overline{X}}$	$\overline{X} + tS_{\overline{X}}$	
33	4	150	56	244	1,515
36	5	91,600	25,077	158,123	18,166
59	4	600	-13	1,213	1,456
60	5	10,600	-1,108	22,308	3,287
61	5	6,000	-1,108	13,108	2,824
62	4	670	91	1,249	1,250
65	4	3,500	906	6,094	638
66	5	5,240	717	9,763	1,523
67	5	20,000	5,578	34,422	1,514
75	5	3,000	925	5,075	582
83	4	19	13	25	72
88	4	260	16	504	434
112	5	12	7	17	22

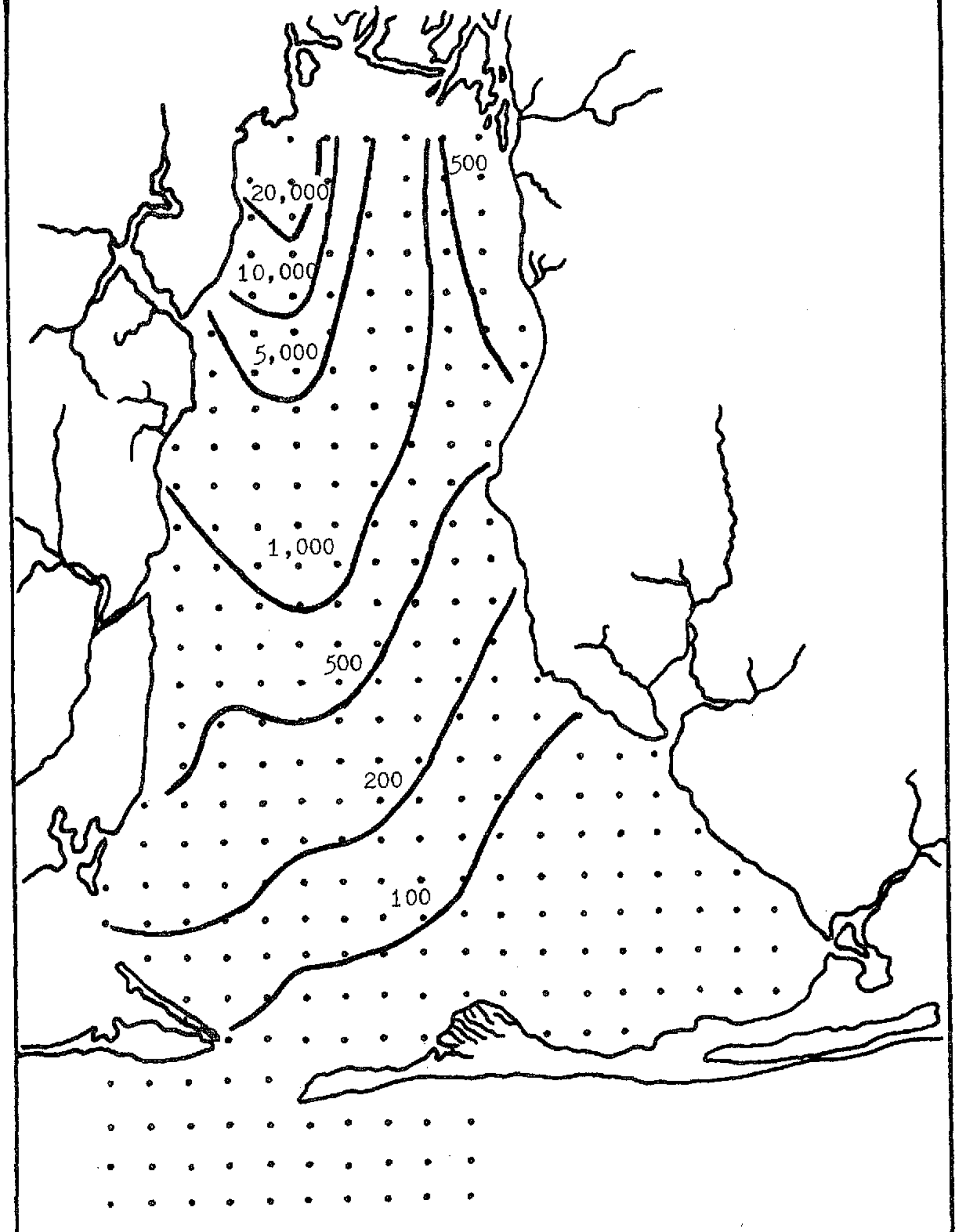


Fig. 4.7 Model-Calculated Total Coliform Concentration Profiles for May, 1962

Table 4.9 Total Coliform Concentration for Mobile Bay - June 1962

Loading at Mobile River Mouth = 1/4 TC_{31} (D.F. = 4)

Correction Factor for E = 500

K_r = 0.81 day^{-1}

Station No.	Measured Data				Model Calculated Result
	No. of Field Sampling	Monthly Average $\overline{x}$	70% Confidence Range		
			$\overline{x} - tS_{\overline{x}}$	$\overline{x} + tS_{\overline{x}}$	
33	3	250	145	355	70
36	3	600	320	880	293
59	4	12	7	17	26
60	4	25	10	40	61
61	4	50	27	73	81
62	4	110	19	201	124
65	4	20	7	33	12
66	3	7	4	10	26
67	3	132	14	250	46
75	3	20	8	32	16
83	4	10	9	11	1
88	3	15	14	16	7
112	4	10	6	14	1

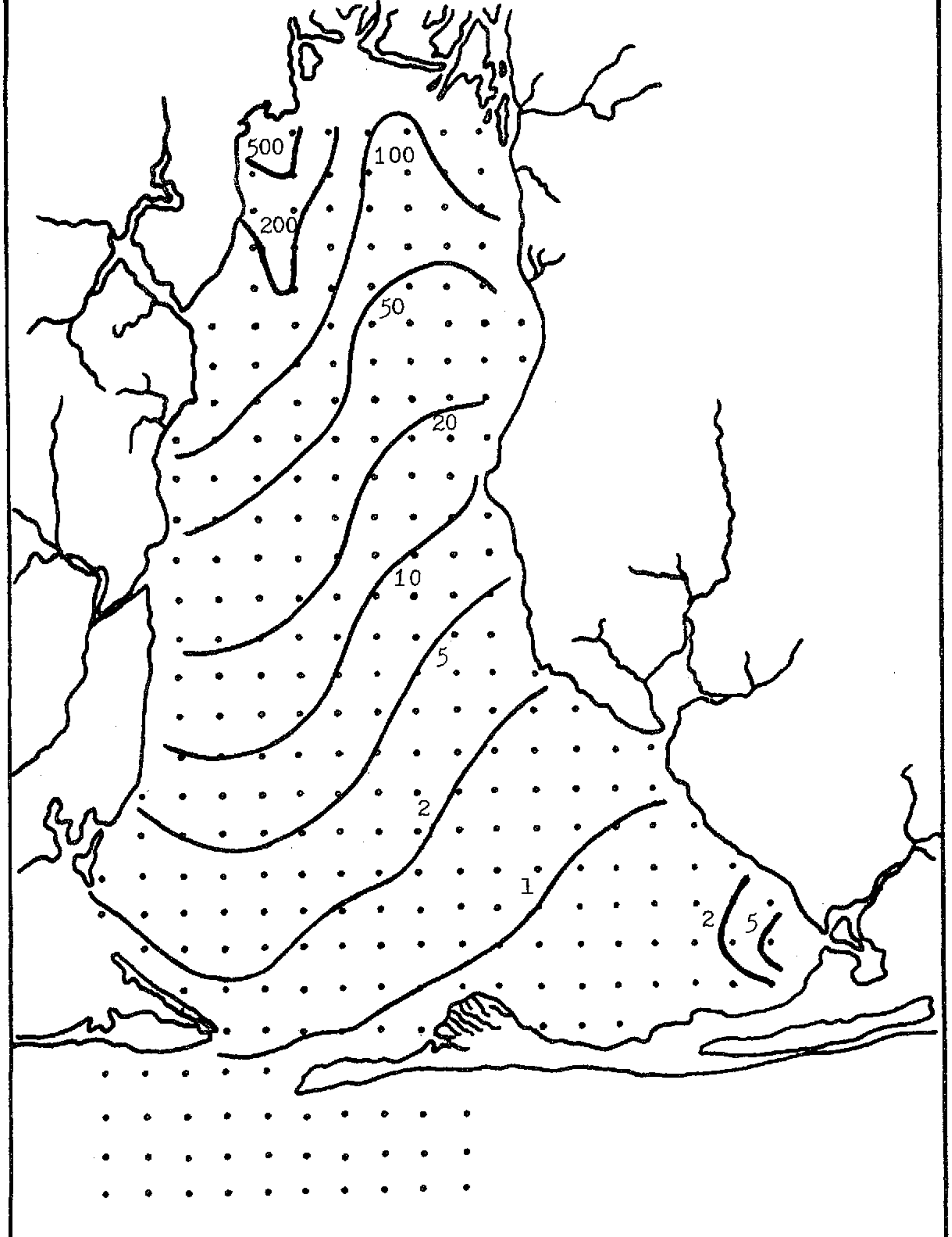


Fig. 4.8 Model-Calculated Total Coliform Concentration Profiles for June, 1962

Table 4.10 Total Coliform Concentration for Mobile Bay - July 1962

Loading at Mobile River Mouth = 1/6 TC_{31} (D.F. = 6)

Correction Factor for E = 500

K_r = 0.88 day^{-1}

Station No.	Measured Data				Model Calculated Result
	No. of Field Sampling	Monthly Average $\overline{x}$	70% Confidence Range		
			$\overline{x} - tS_{\overline{x}}$	$\overline{x} + tS_{\overline{x}}$	
33	4	360	154	566	249
36	4	300	144	456	1,272
59	4	9	6	12	86
60	4	35	12	58	176
61	4	161	69	101	166
62	4	100	50	150	138
65	4	20	9	31	40
66	4	40	15	65	78
67	4	33	13	53	86
75	4	120	10	230	29
83	5	10	9	11	3
88	5	13	5	21	20
112	5	40	20	60	2

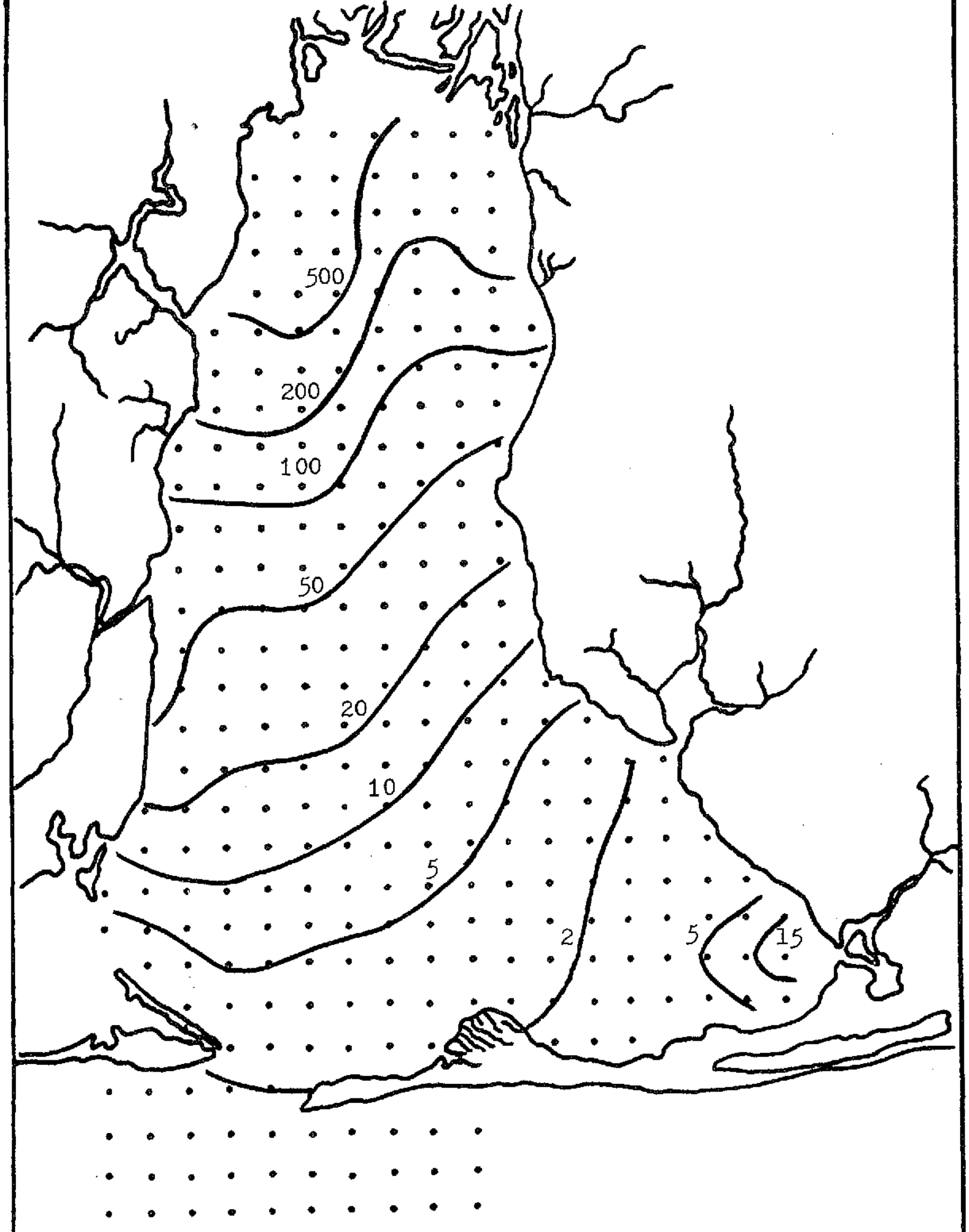


Fig. 4.9 Model-Calculated Total Coliform Concentration Profiles for July, 1962

Table 4.11 Total Coliform Concentration for Mobile Bay -August 1962

Loading at Mobile River Mouth = 1/6 TC_{31} (D.F. = 6)

Correction Factor for E = 500

$K_r = 0.90$ day^{-1}

Station No.	Measured Data				Model Calculated Result
	No. of Field Sampling	Monthly Average $\overline{x}$	70% Confidence Range		
			$\overline{x} - tS_{\overline{x}}$	$\overline{x} + tS_{\overline{x}}$	
33	5	50	32	68	74
36	5	250	160	340	528
59	2	4	2	6	36
60	2	10	8	12	104
61	2	15	1	31	162
62	3	15	12	18	282
65	3	10	3	17	15
66	3	7	4	10	40
67	3	5	4	6	89
75	4	4	3	5	27
83	4	8	5	11	1
88	3	3	2	4	8
112	4	7	1	13	1

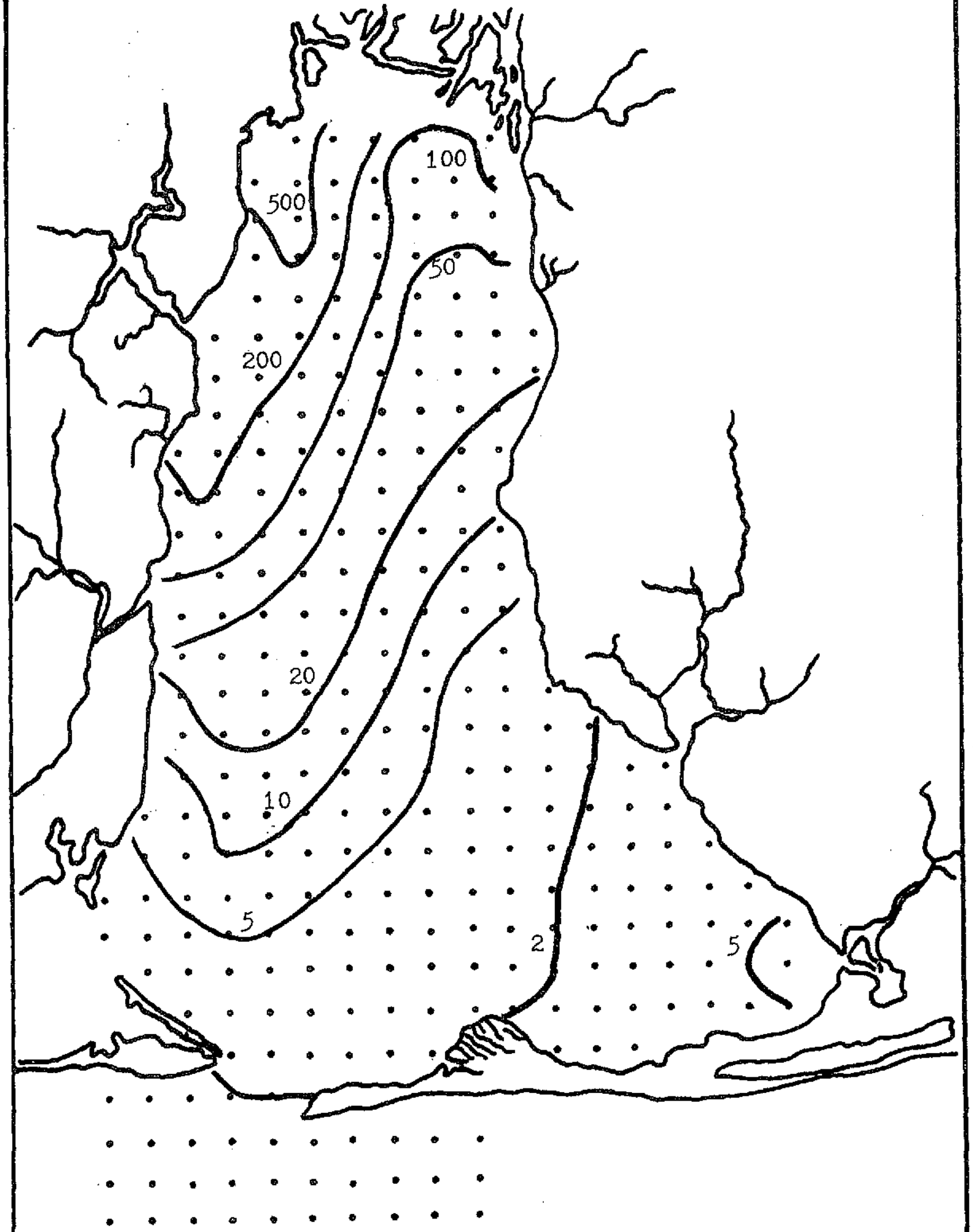


Fig. 4.10 Model-Calculated Total Coliform Concentration Profiles for August, 1962

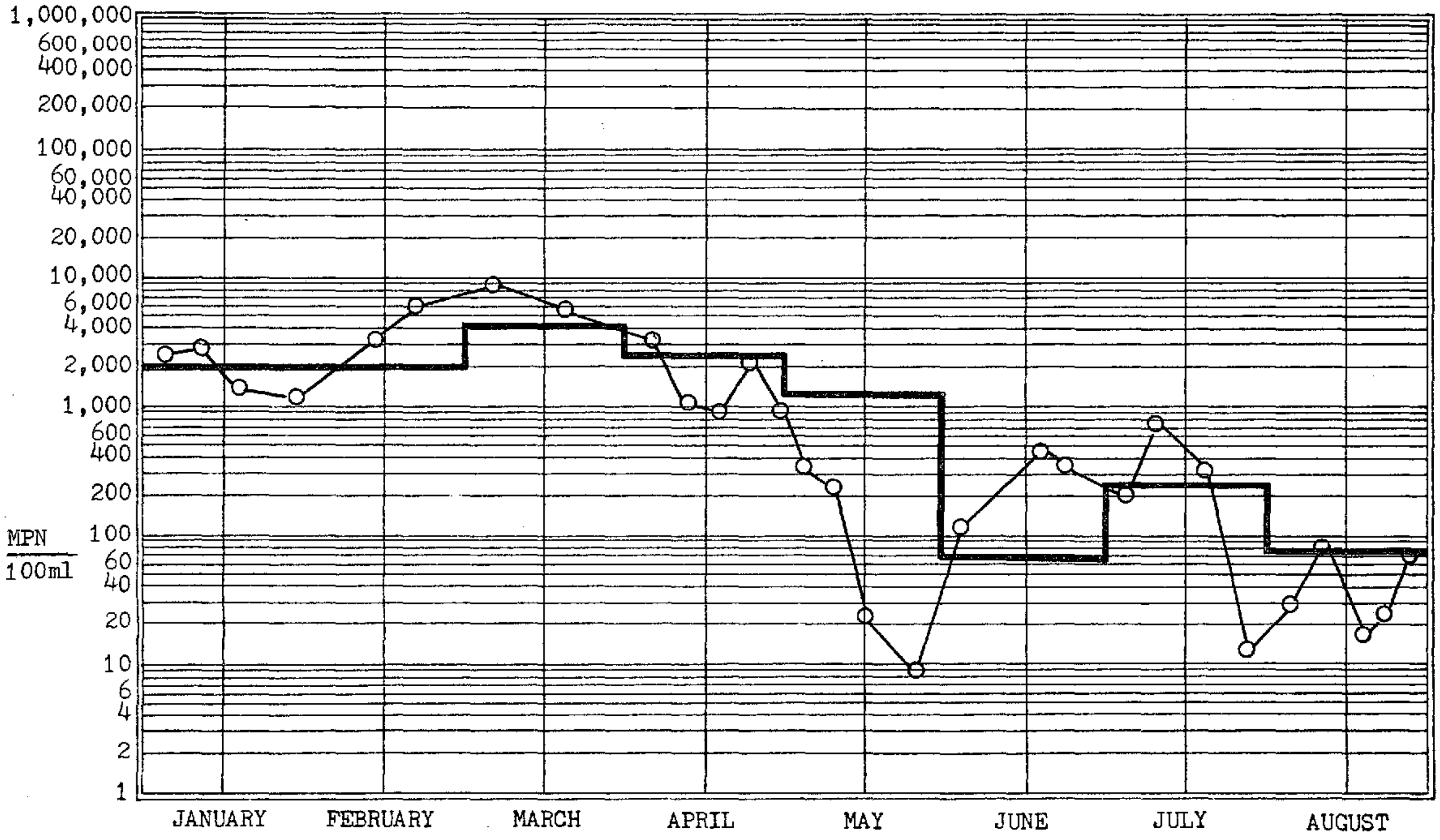


Fig. 4.11 Model calculated averages compared with actual data of total coliform concentration at station No. 33.

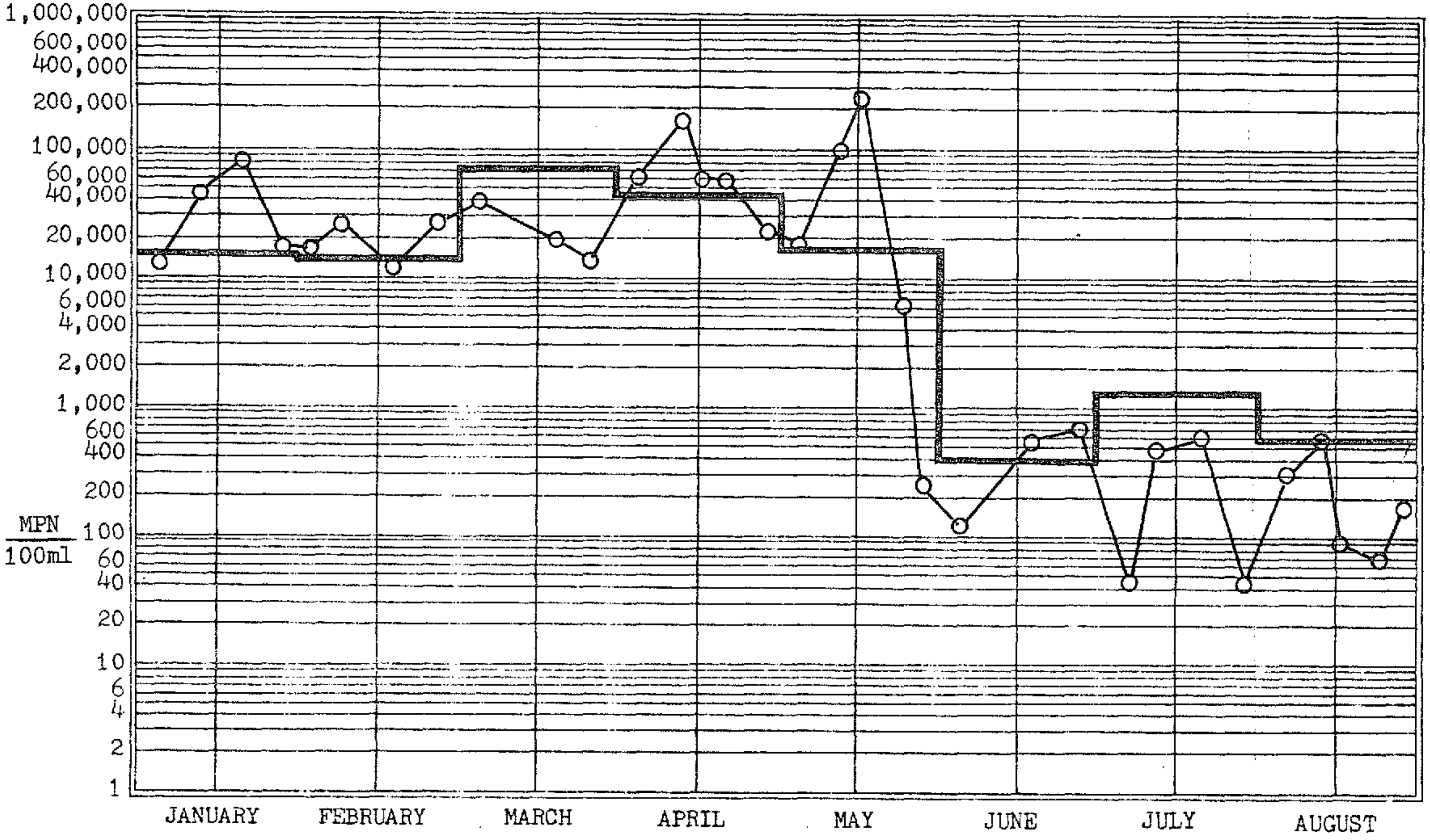


Fig. 4.12 Model calculated averages compared with actual data of total coliform concentration at station No. 36.

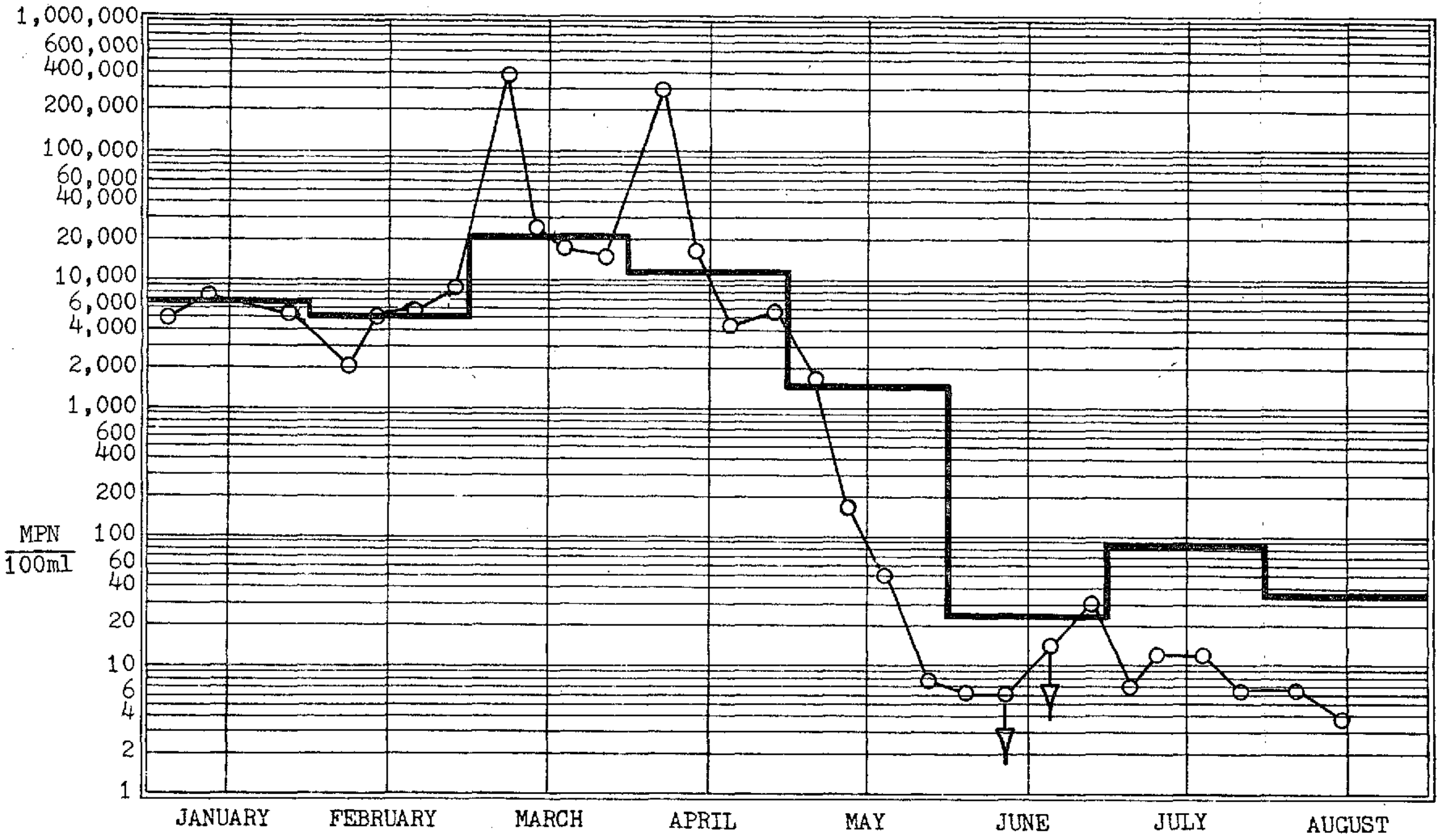


Fig. 4.13 Model calculated averages compared with actual data of total coliform concentration at station No. 59.

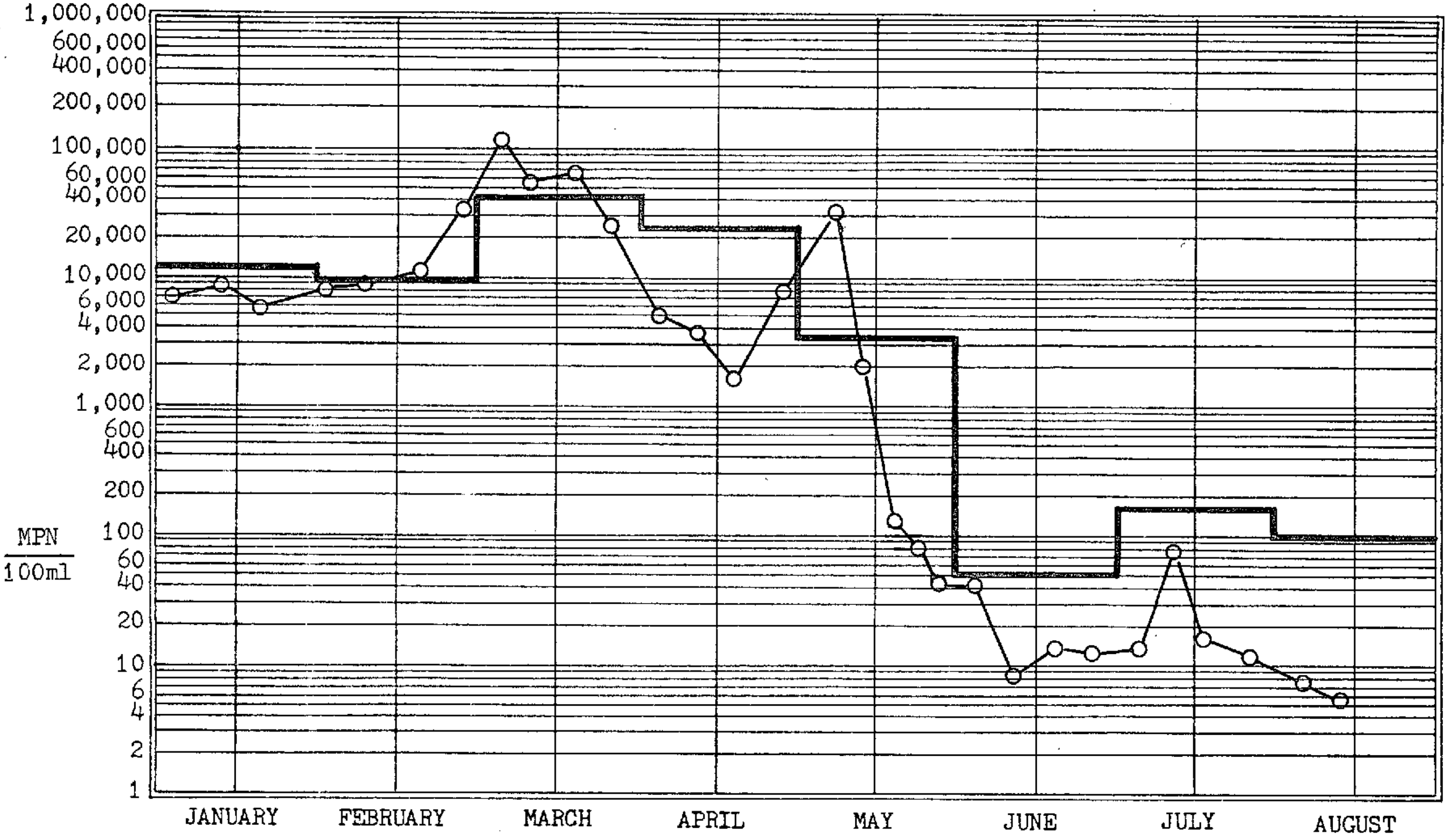


Fig. 4.14 Model calculated averages compared with actual data of total coliform concentration at station No. 60.

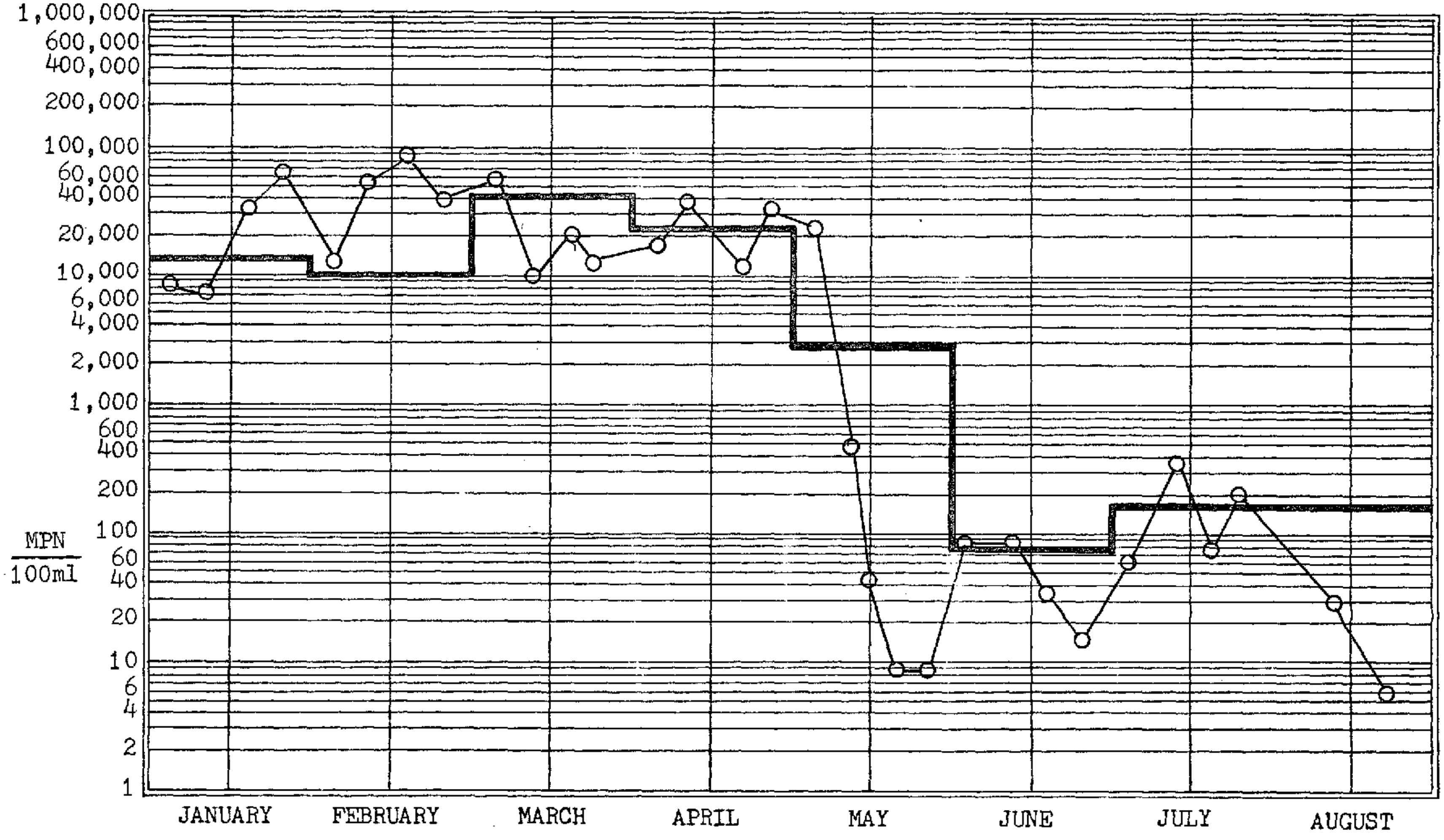


Fig. 4.15 Model calculated averages compared with actual data of total coliform concentration at station No. 61.

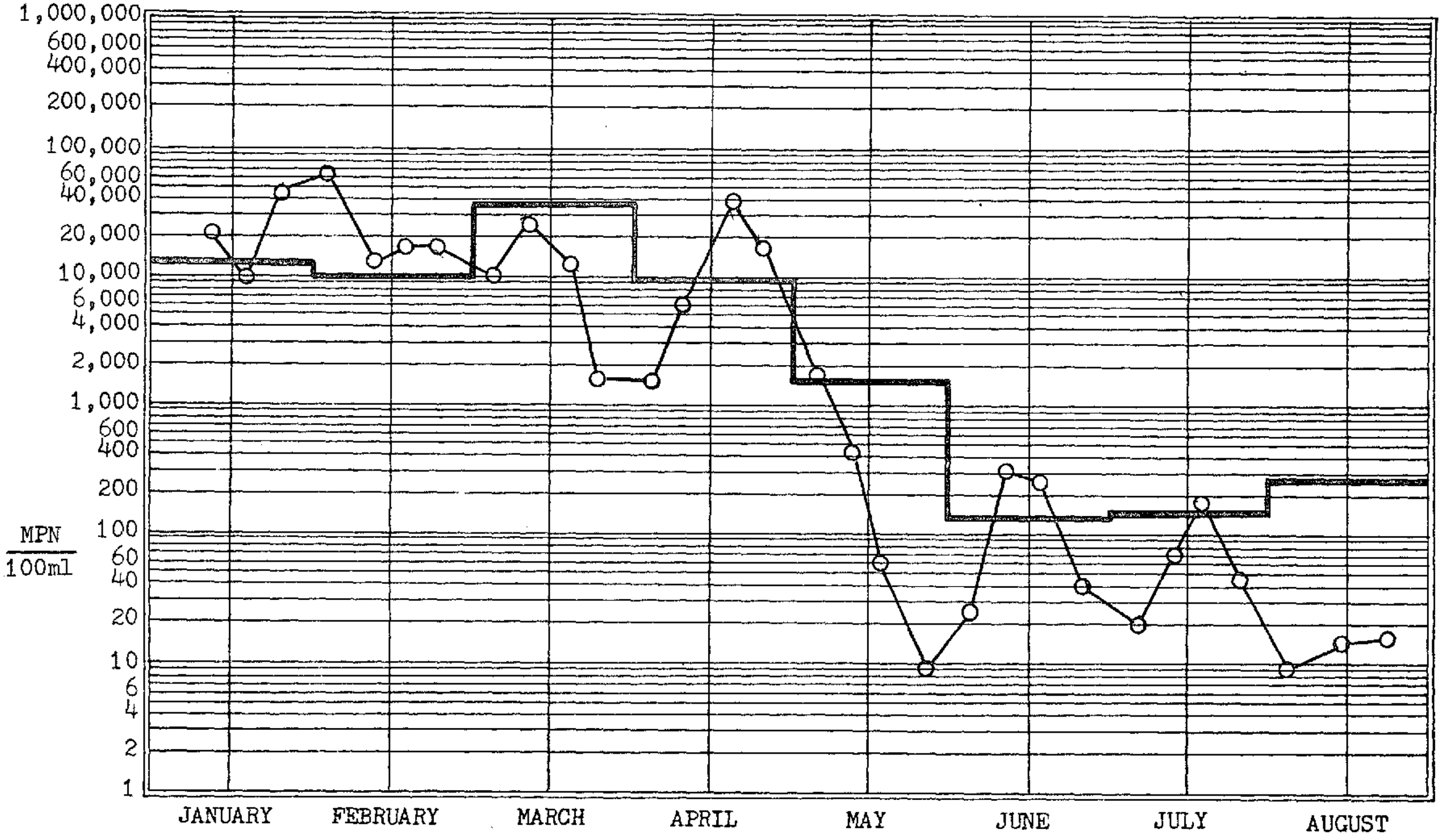


Fig. 4.16 Model calculated averages compared with actual data of total coliform concentration at station No. 62.

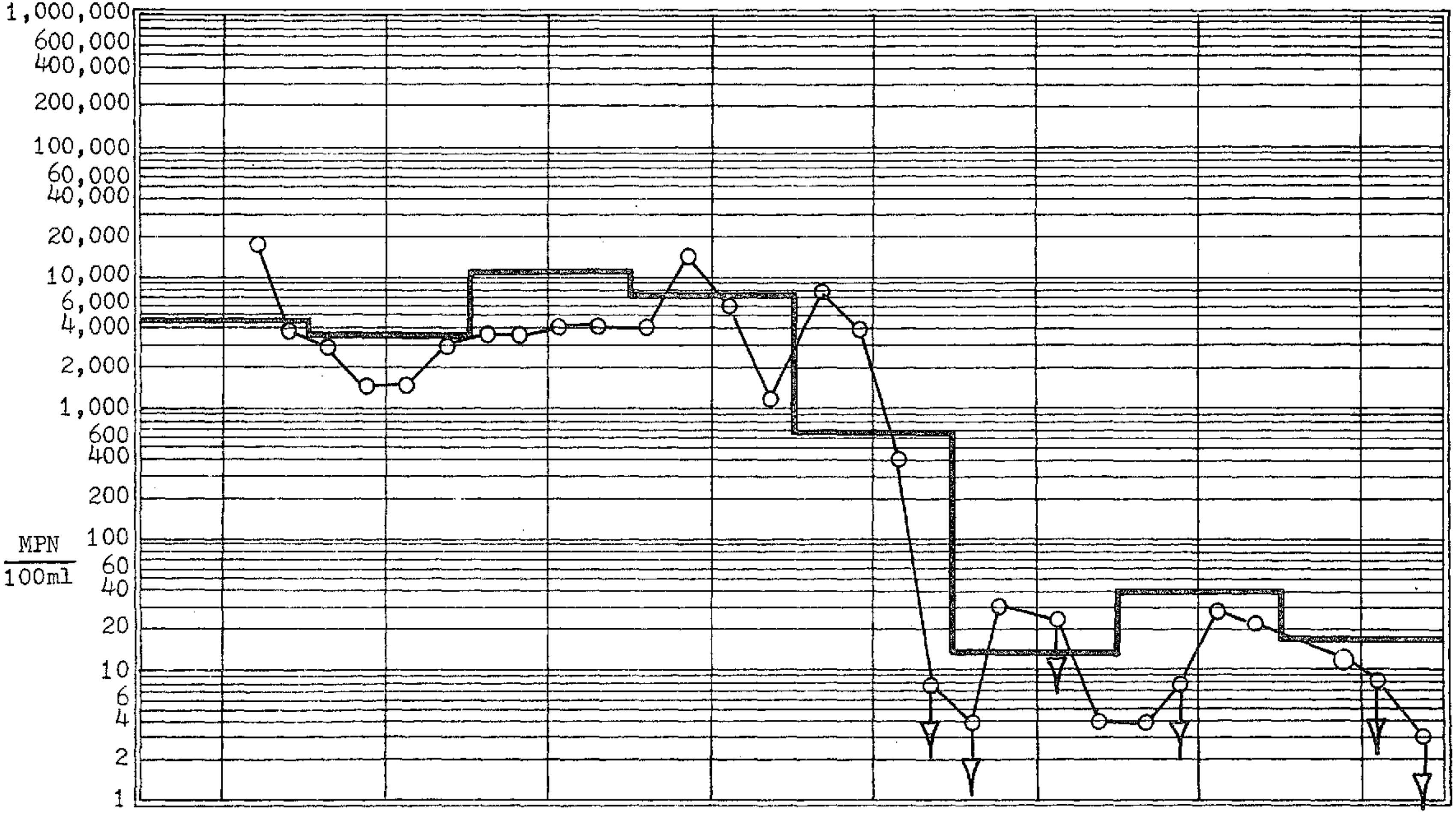


Fig. 4.17 Model calculated averages compared with actual data of total coliform concentration at station No. 65.

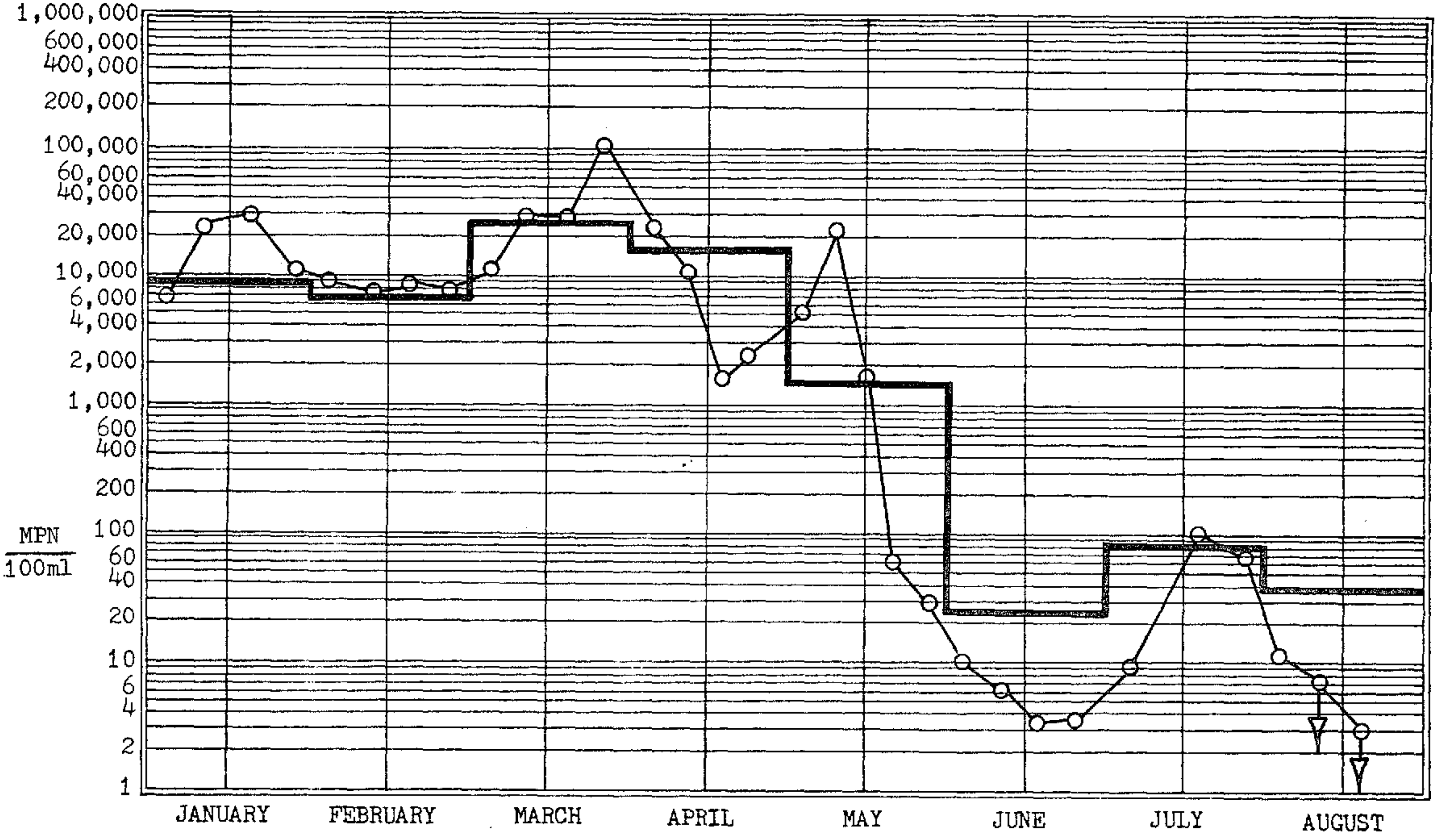


Fig. 4.18 Model calculated averages compared with actual data of total coliform concentration at station No. 66.

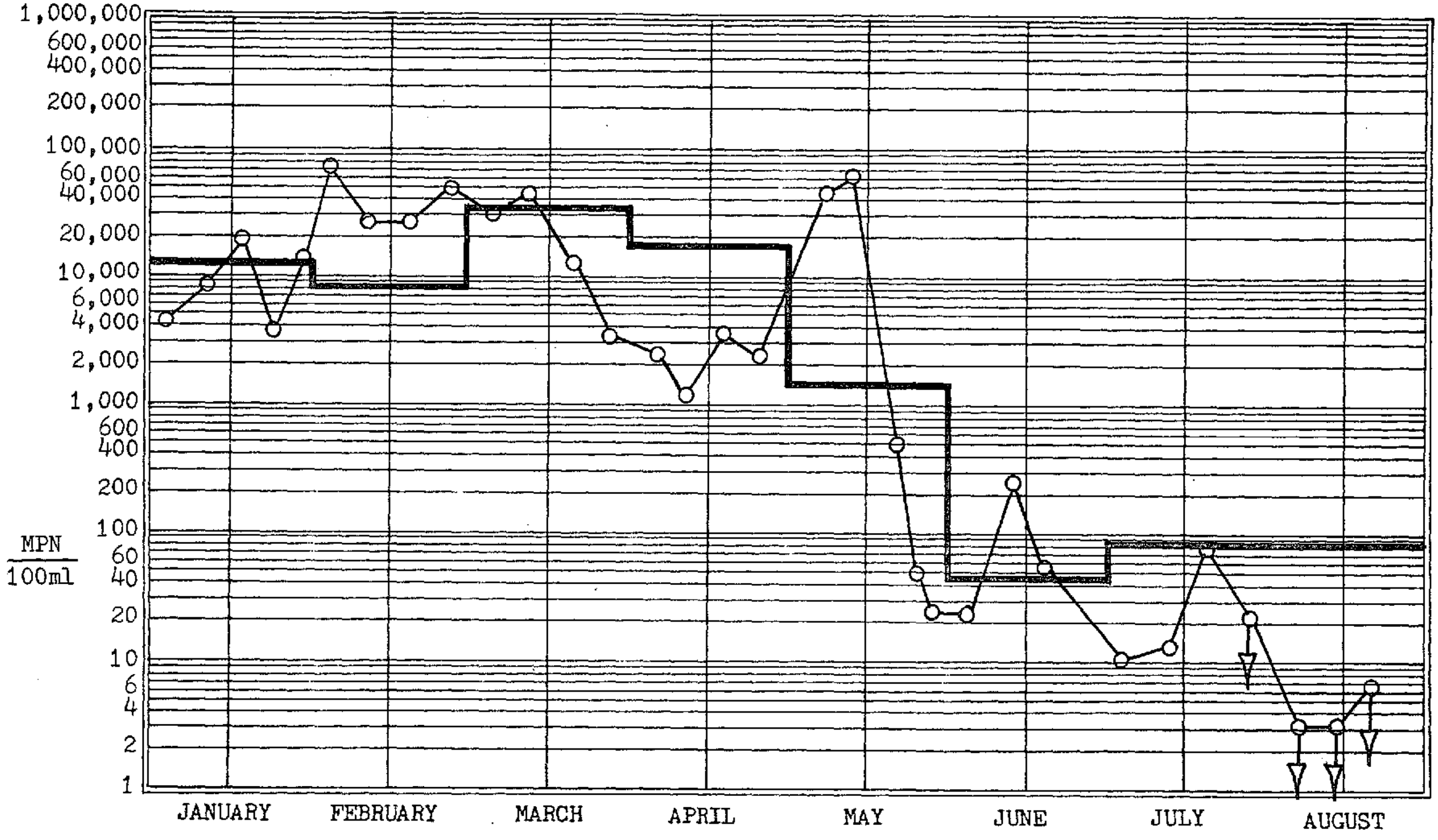


Fig. 4.19 Model calculated averages compared with actual data of total coliform concentration at station No. 67.

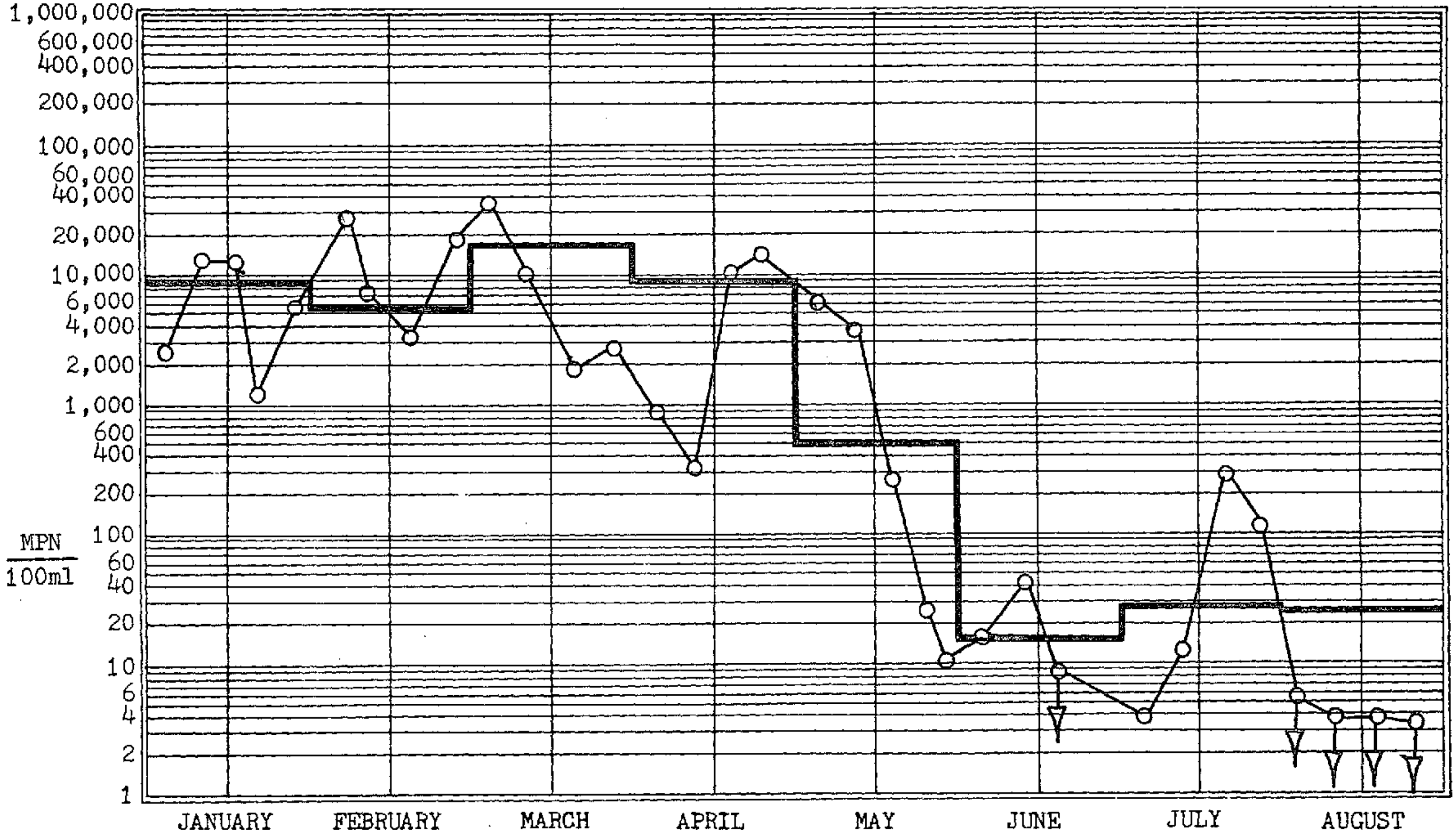


Fig. 4.20 Model calculated averages compared with actual data of total coliform concentration at station No. 75.

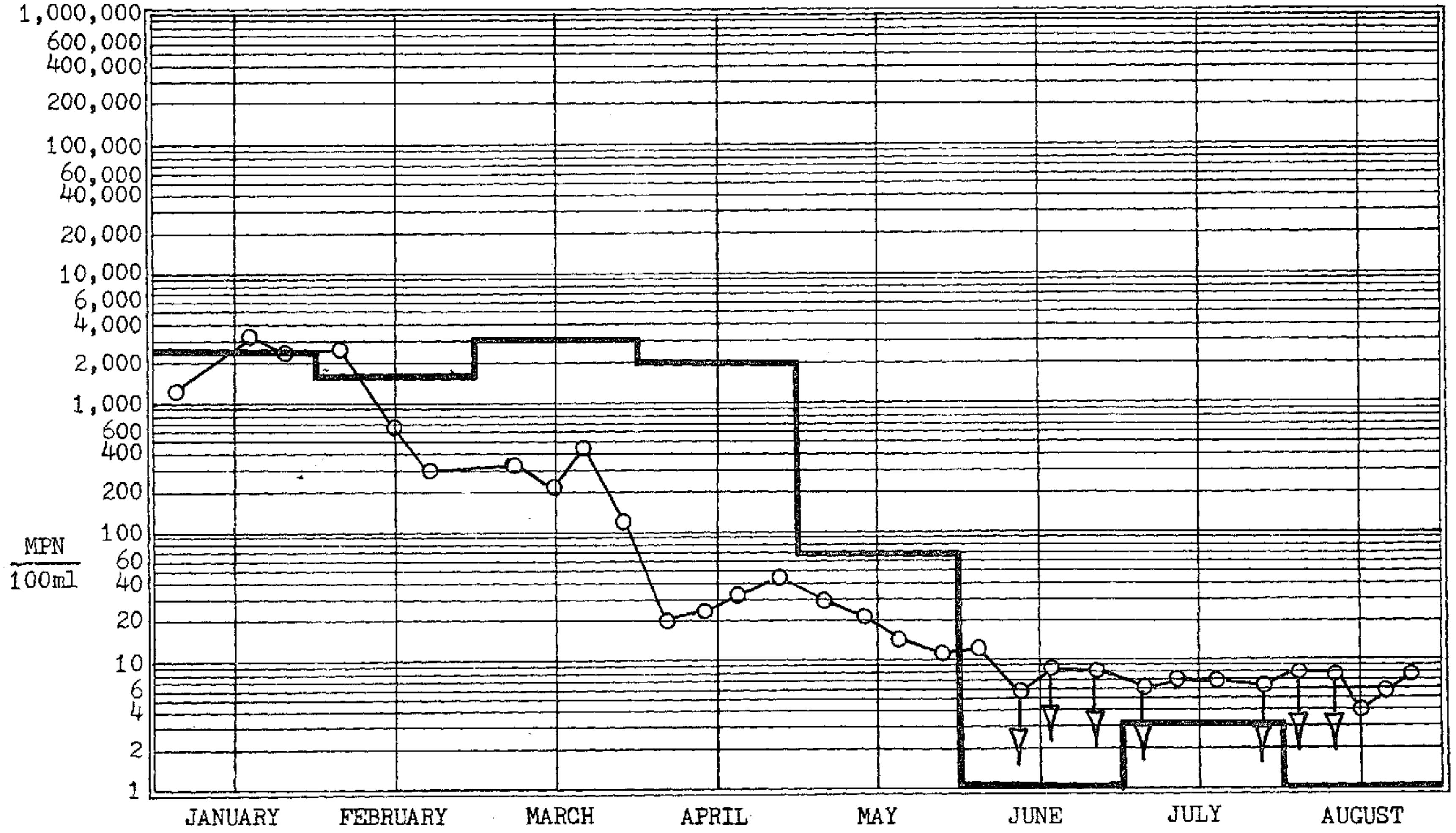


Fig. 4.21 Model calculated averages compared with actual data of total coliform concentration at station No. 83.

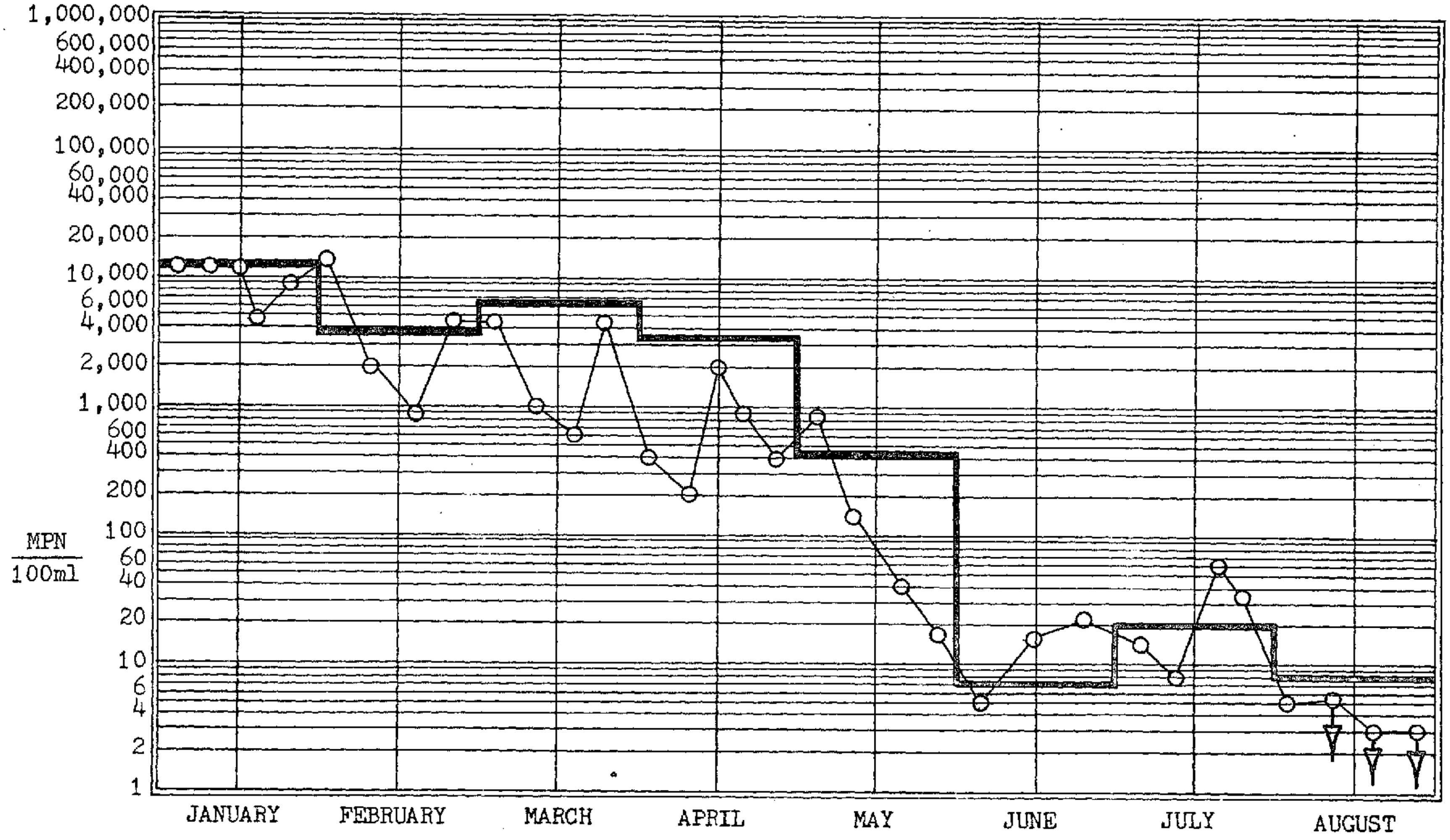


Fig. 4.22 Model calculated averages compared with actual data of total coliform concentration at station No. 88.

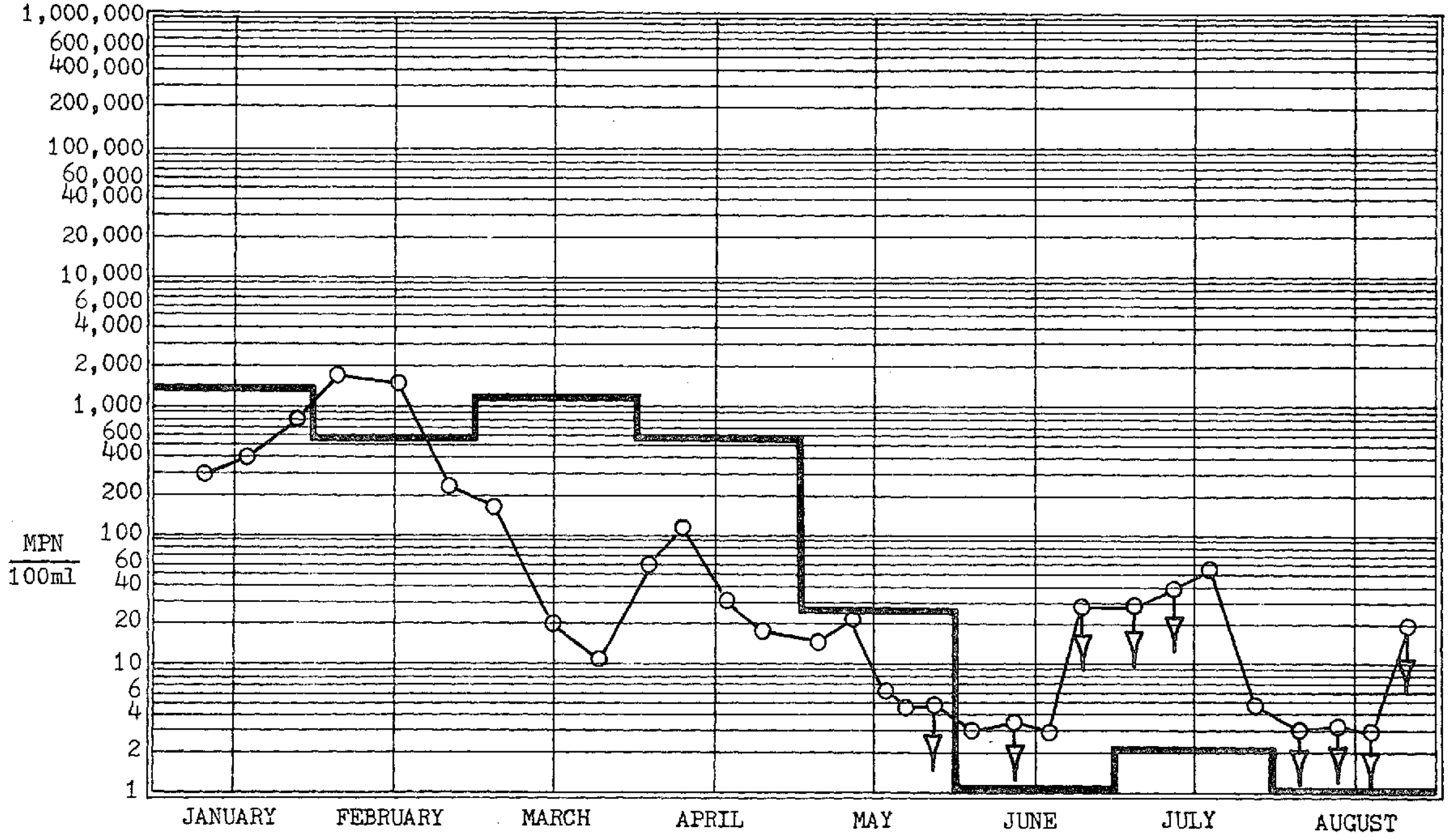


Fig. 4.23 Model calculated averages compared with actual data of total coliform concentration at station No. 112.

4.3 Discussion of Verification Results

Verification of the NCSTM for total coliform is based on the comparison between the model-calculated monthly average results and the monthly average actual field data. The total coliform concentration, unlike DO levels which usually become saturated between 7 to 15 ppm (see Fig. 3.4 on p. 47) and estuarine BOD levels, which normaly are below 1000 ppm, is a much more variable entity described by rather broad ranges of numerical values. This results in the restriction of the verification phase to essentially trend-analysis levels.

Numbers of field samples varied from 2 to 5 per month for each station during the months January to August, 1962 (see Table 4.4 to Table 4.11). These data are scattered as a result of varying field conditions and sampling accuracy, and when averaged over the monthly periods, wide variations in the standard deviations occur. The standard deviations, S_X, of these samples were used to calculate the standard deviations of the mean, $S_{\bar{X}}$, for each datum on a monthly basis. $S_{\bar{X}}$ was in turn used with the t-distribution to calculate the 70% confidence range for each datum for each month. Details of the use of the statistic "t" are cited by Volk(30).

Trend Analysis Verification Comparisons

The verification comparison (trend analysis) consists of three steps, as summarized below.

Step 1: The comparisons between the model-calculated results and actual field data for each of the 13 stations shown in Figures 4.11 to 4.23 indicate that the model is capable of following the trends of the total coliform concentration within Mobile Bay. Except for station no. 59 (see Fig. 4.5), where extraordinarily high monthly mean concentrations were measured for March and April, most of the trends for seasonal variation shown for other stations are reasonably accurate. Stations 36, 60, and 61 are located in the chip channel (see Fig. 4.1). Deviations in model-predicted results for these stations are found to be in agreement with expected trends based on the hydrodynamic behavior of the ship channel. Station no. 88 is located near Cedar Point; stations no. 83 and 112 are located in Bon Secour Bay (see Fig. 4.1). These three stations tend to show deviations which are more pronounced in these regions as a result of seawater intrusion from the Gulf of Mexico. It is found that except for station no. 112 in February, all the deviations can be explained by the seawater intrusion process; that is, positive deviations (calculated results greater than actual data) in cold months during which actual K_r values are lower in the bay area than in the Gulf, and negative deviations (calculated results less than actual data) in warm months during which K_r values are higher in the bay area than in the Gulf. The reflectional month is May at which time total coliform concentrations at all stations change drastically. Total coliform concentration data for many stations for the periods October to December, 1962 and September, 1961 are not available for the water year 1962, and therefore they are not included in this study.

Step 2: By inspection of the total coliform concentration profiles shown in Figures 4.3 to 4.10, the western half of Mobile Bay is usually suffering more severely from pollution than the eastern half of the bay. At the same time during the months of high river flow rates, there are very obvious "tongue" effects in which the total coliform concentration profiles reach far down the bay. During months of low river flow rates this "tongue" effect becomes much smaller. These behaviors are coincident with what has been evaluated in the work by Gallagher, et al.(10), and shown by the studies of Hill and April(12).

Step 3: By inspection of Figures 4.11 to 4.23, it is found that model-calculated results fall within the ranges covered by the actual field data 66.5% of the time for the period January to August, 1962. It should be indicated that this percentage includes stations located within the ship channel which are not expected to show good agreement with model-calculated results as a consequence of the way in which the model is formulated (i.e. two-dimensional, no stratifications). Due to the inclusion of the ship channel data in addition to the obvious scatter in the available field data, model verification for total coliform can only be made for trend analysis purposes. More detailed point analyses must be deferred to a time when more accurate and precise field data measurements can be obtained.

More specific factors relating to the verification of the model-predicted total coliform distribution are itemized and their effects are discussed in the following paragraphs.

Dilution Factor Correlation

Dilution factors (D.F.) were varied between 2 and 10 in the preliminary model calibration study. A D.F. of 4, together with a value of 500 for C.F. for the dispersion coefficients (see Eq. 3-40 on p. 39) were found to produce reasonable total coliform distributions based on the June, 1962 data. This set of factors was fixed to exercise the NCSTM for other periods for verification purposes. Subsequent fine tuning of the model in the verification phase showed that the D.F. may be regarded as a function of the river discharge rates and the total coliform source concentration at the mouth of Mobile River draining into the bay. Different river discharge rates result in different flow velocities and different degrees of mixing. In a portion of the verification study refinements of the dilution factor values indicated the following: a dilution factor of 4 was required for the months with highest river discharge rates (January and April), a dilution factor of 5 was required for months with medium river flow rates (February and March), and a dilution factor of 6 was required for months with low river flow rates (July and August). This is in agreement with the fact that mixing is greater for high river discharge rates and therefore a smaller dilution factor would be required (i.e. the grab sample would be more closely representative of the cell concentration.) Verification results for June are exceptions to this trend, where a dilution factor of 4 was used with good results. Note, however, that the source loading concentration for this month at the mouth of the Mobile River (i.e., TC_{31}) was extremely low compared to other summer months (see Table 4.3), while the river discharge rate remained high. This may be explained by the fact that better mixing was attained at station no. 31, and therefore a small dilution factor was required for the conversion to a cell input concentration. A D.F. of 4 used for May gave best results compared to the monthly averages of data collected for that month. The total coliform group concentration for all stations within the bay undergoes nearly a step change from high levels to low levels in May. Data are especially scattered, as shown in Table 4.8, and the comparison should be regarded as less significant.

For points where serious pollutant transport is expected, such as at points near the mouths of the rivers and loading sites, calculated values of total coliform concentration are usually smaller than the actual data. This is because the model calculates cell concentrations, while actual data are grab samples collected from water which is not well mixed. The ship channel is rather narrow as compared to the grid cells that encompass it. Concentrations calculated for grids located in the ship channel are usually smaller than the actual data; that is, at stations no. 36, 60, and 66, etc. This is due to the high current velocities in the ship channel; the retention time for total coliform bacteria is reduced, resulting in higher point concentrations compared with adjacent, slower moving bay waters. For higher river flow months this effect was so pronounced that total coliform profile contours reached far down the left half of the bay (see Figures 4.4 to 4.7). This is consistent with the observations by Gallagher, et al.(10) and Hill and April(12).

Dispersion Coefficients

Dispersion coefficients are calculated by Eq. (3-40). Values of 250, 500, 750, and 1000 were tried for the correction factors (C.F.) on both x- and y-component maximum tidal velocities in the model calibration phase. It was found that a value of 500 gave reasonably good results for both the x-component and the y-component dispersion coefficients, E_x and E_y. It was also found that smaller C.F. values usually elevate coliform concentrations in the upper portion of the bay near the waste sources and decrease coliform concentrations in the portions of the bay far removed from the waste sources. For each monthly period, the smaller the C.F. used, the more pronounced is this observation.

Dieoff Rate Constants

Larger values of the dieoff rate constant K_r decrease the total coliform concentration values in any given location within the bay. The opposite is true for smaller K_r values. Therefore it is important that correct temperatures be used to calculate the corresponding K_r values needed by the model equation.

Seawater from the Gulf of Mexico and from the Mississippi Sound causes a slight temperature shift within the southern section of the bay. Seasonal average sea surface temperatures of the Gulf of Mexico, obtained from the National Atlas of the U. S. A.(29), are listed in Table 4.12. Temperatures used in the verification are also listed for comparison. It is seen that the temperature of Gulf waters is more stable, i.e., is varying over a smaller range than that of the bay water. Due to seawater intrusion, the water temperatures in the lower portion are also more stable than those at other portions of the bay. Since dieoff rate constants are directly related to temperature, it is expected that actual concentrations (data) at those stations in the lower portion of the bay will be affected. This is particularly true in the Bon Secour Bay area and for points near Main Pass and Cedar Point. Observed concentrations should be lower in warm seasons and higher in cool seasons, as compared to what would be calculated by the model based on homogeneous bay temperatures. Station no. 88 is located near Cedar Point; station no. 83 and station no. 112 are located in the Bon Secour Bay area (see Fig. 4.1). They are subjected to intrusion of seawater from the Mississippi Sound and

Table 4.12 Comparison of the surface water temperature of the Gulf of Mexico near Mobile Bay and the bay water temperatures used in verification of the NCSTM for total coliform.

Seasons	Gulf surface temperatures, °F			Bay water temperature used for verification study, °F	
	Maximum	Minimum	Average		
Spring	82	70	76	March	61.3
				April	67.9
				May	78.1
Summer	86	78	82	June	81.4
				July	83.7
				August	84.2
Fall	78	64	71	September	-
				October	-
				November	-
Winter	74	58	66	December	-
				January	49.5
				February	58.3

the Gulf of Mexico. Most data at these stations are noted to be different from calculated results in the described direction. The extent of seawater intrusion is seasonal in nature, and therefore the area affected by this phenomenon varies. In this study it is found that except for stations no. 83 and 112 in the months of March and April, all the deviations are small (see Tables 4.4 to 4.11), and for the purpose of trend analysis based on monthly average calculation, this effect can be neglected without introducing too significant errors.

In the following chapter, attention will be turned to the parametric study in which the sensitivity of the model-predicted results toward various changes in system behavior was investigated.

CHAPTER V

PARAMETRIC STUDY

There are four major parameters which affect the total coliform distribution in Mobile Bay. These are:

(1) river flow rates, which influence the total coliform concentration introduced into the bay and the retention time of the bacteria within the bay;

(2) wind conditions, which influence the current distribution and therefore the retention time of bacteria within certain portions of the bay;

(3) temperature, which influences the death rate of total coliform bacteria; and

(4) waste loadings, which influence the input concentration of total coliform bacteria introduced into the bay from various sources.

These variables are examined in a parametric study to determine how sensitive the total coliform group concentrations are to changes in variable magnitude and/or direction which simulate real system conditions. The first three of the four parameters, i.e., river discharge rates, wind conditions and temperature, will be studied in Section 5.1; the waste loading effect will be studied in Section 5.2.

5.1 Effects of River Flow Rates, Wind Conditions, and Temperature

Table 5.1 shows the input data used for the 18 parametric runs performed to study the effects of river flow rates, wind conditions, and temperatures. Two levels of wind, i.e., 15 knots and 25 knots, are studied and compared with results calculated for no wind. Three directions of wind are studied. They are: from the north ($\theta = 90^{\circ}$), from the southwest ($\theta = 225^{\circ}$), and from the southeast ($\theta = 315^{\circ}$). The value θ is the wind direction in degrees, as measured in the counter-clockwise direction from the x-axis in the Cartesian-coordinate system. For medium river flow rates all three directions are studied to determine the effect of variation of wind direction (see Table 5.1, runs a to g). For low and high river flow rates (see Table 5.1, runs h to j and k to m), wind from the southwest, the most prevailing direction, is studied.

Total coliform source concentrations used in the parametric study come from the data used in the verification analysis (1962 period) having comparative levels of river flow rates. Thus those loading concentrations of May, 1962 are used for medium river flow, those of August, 1962 are used for low river flow, and those of April, 1962 are used for high river flow (see Table 4.3 on p. 75), to exercise the model.

To study the effect of variations of river flow rates, the conditions experienced in May, 1962 are used as a reference. The reason for selecting this month is that river flow rates are more

Table 5.1 Data Used for Parametric Study Runs a to r

Run	Wind		River Discharge Rates			Temperature	Die-off Rate K
	Speed knots	θ deg.	Mobile River cfs	Dog River cfs	Tensaw River cfs	^oF	day^{-1}
a	0	-	24,000	2,000	20,000	78.1	0.72
b	15	225	"	"	"	"	"
c	25	225	"	"	"	"	"
d	15	90	"	"	"	"	"
e	25	90	"	"	"	"	"
f	15	315	"	"	"	"	"
g	25	315	"	"	"	"	"
h	0	-	7,000	500	5,000	84.2	0.90
i	15	225	"	"	"	"	"
j	25	225	"	"	"	"	"
k	0	-	145,000	5,000	100,000	67.9	0.50
l	15	225	"	"	"	"	"
m	25	225	"	"	"	"	"
n	7.9	225	10,000	1,000	9,250	78.1	0.72
o	"	"	40,000	4,000	37,000	"	"
p	"	"	20,000	2,000	18,500	"	"
q	"	"	"	"	"	85.8	0.94
r	"	"	"	"	"	68.1	0.50

representative of average conditions and those conditions under which the Hydrodynamic Model for Mobile Bay was initially verified (see Table 4.1 on p. 70). By holding wind conditions and temperature constant, the value of river flow rates is first doubled, then halved (see Table 5.1, runs n, o, and p), to determine the effect on total coliform concentration within the bay.

Similarly, to study the effect of variations of temperature, May, 1962 data are again used as a baseline in which river flow rates and wind conditions are held constant. The temperature used to exercise the model is first raised from 78.1°F to 85.8°F (see Table 5.1, run q) to give an increase in the dieoff rate constant K from 0.72 day^{-1} to 0.84 day^{-1}. The temperature is then reduced to 68.1°F (see Table 5.1, run r) to give a decrease in the dieoff rate constant from 0.72 day^{-1} to 0.50 day^{-1} to exercise the model.

The computational procedures are similar to that used in the verification study (see Sections 3.4.3 and 4.1). The results of the parametric study runs as listed in Table 5.1 are shown in Figures 5.1 to 5.9. On each figure, comparisons are made at three levels of total coliform concentration in units of MPN/100ml. Each coliform concentration contour is marked with the letter identifying the corresponding parametric study run. The way parametric runs listed in Table 5.1 are combined for various comparison purposes is given in Table 5.2. In the following paragraphs, discussions of the effect each variable has on total coliform distribution within Mobile Bay are presented.

Table 5.2 List of Figures for Parametric Study Comparisons

Figure	comparison among runs	indicating the effect of variation of	at constant
5.1	p q r	temperature	river flow rates and wind
5.2	n o p	river flow rate	wind and temperature
5.3	a b c	speed of wind from SW	medium river flow
5.4	a d e	speed of wind from N	medium river flow
5.5	a f g	speed of wind from SE	medium river flow
5.6	h i j	speed of wind from SW	low river flow
5.7	k l m	speed of wind from SW	high river flow
5.8	a b d f	direction of wind at 15 knots	medium river flow
5.9	a c e g	direction of wind at 25 knots	medium river flow

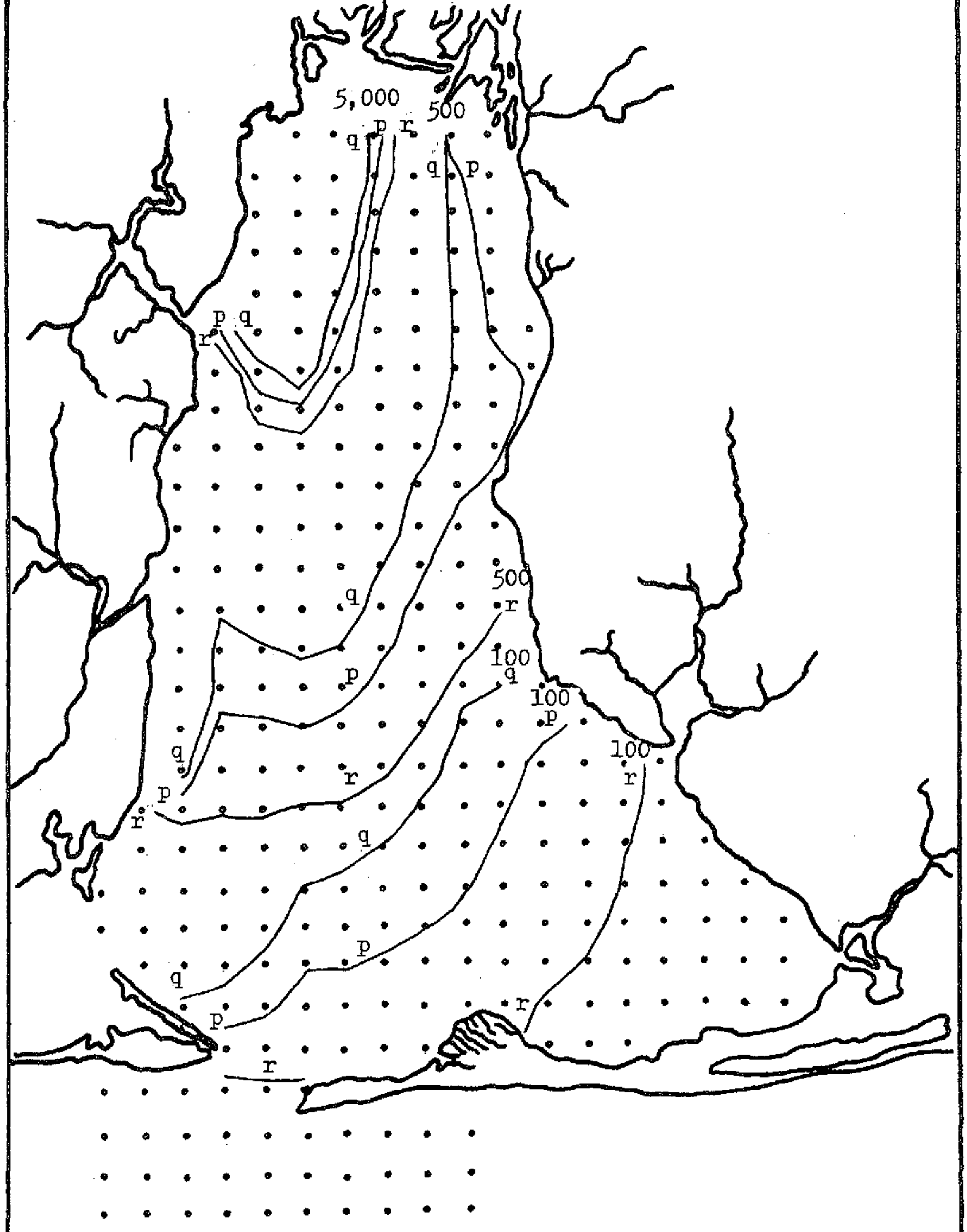


Fig. 5.1 Total coliform concentration profiles from runs p, q, and r; displacements of profiles due to variations of temperature

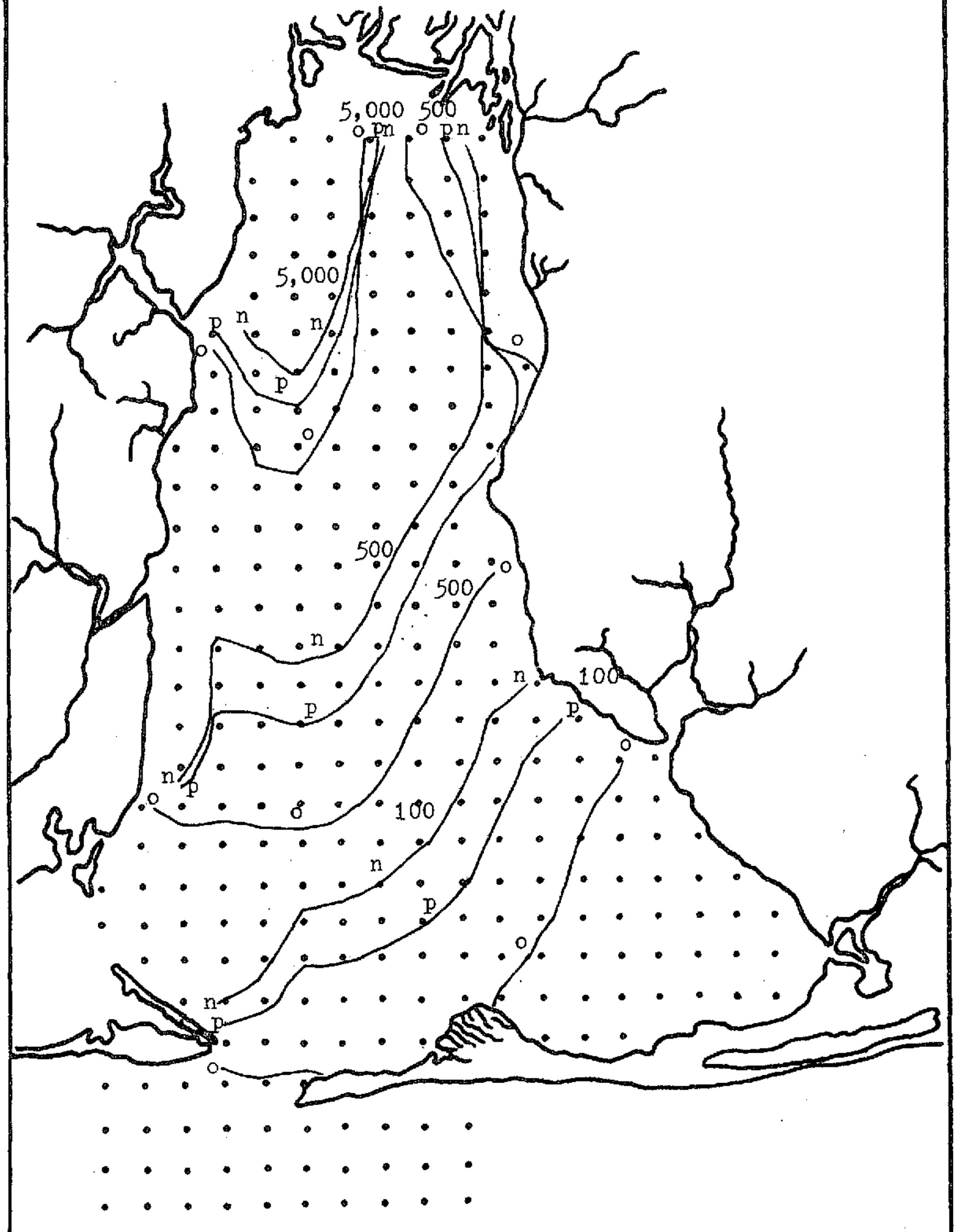


Fig. 5.2 Total coliform concentration profiles from runs n, o, and p; displacements of profiles due to variations of river flow rates

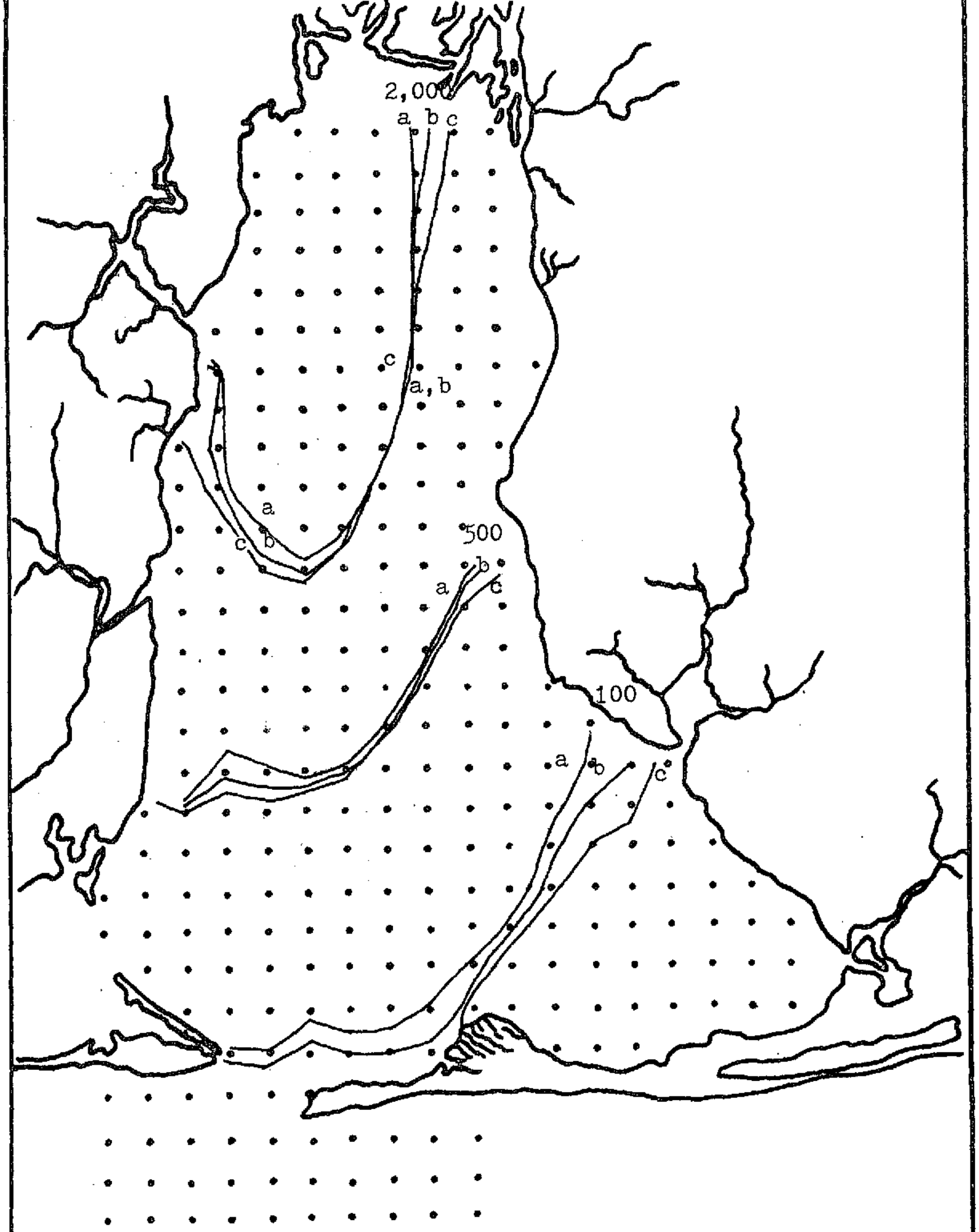


Fig. 5.3 Total coliform concentration profiles from runs a, b, and c, medium river flow rates; wind from SW at 0, 15, and 25 knots

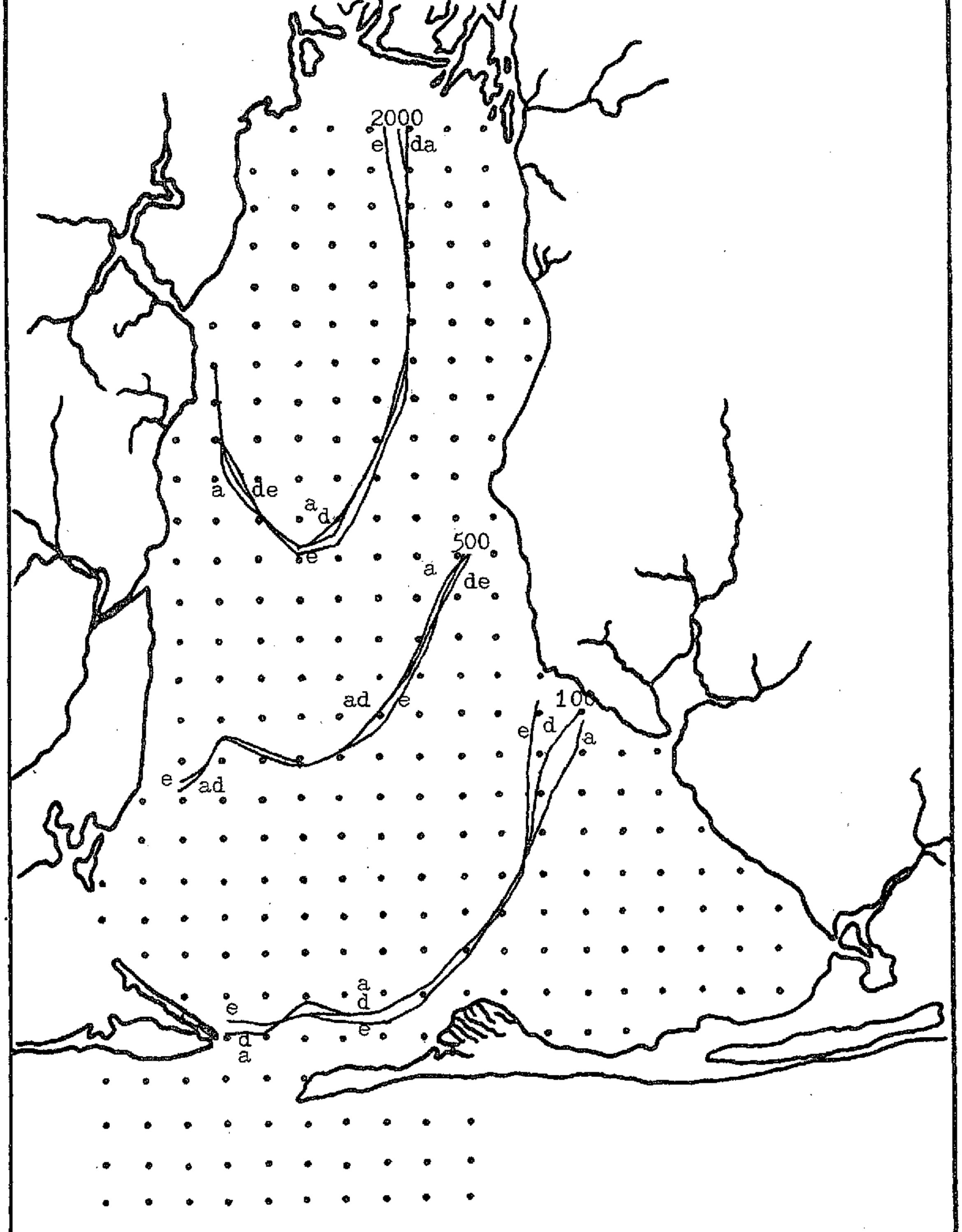


Fig. 5.4 Total coliform concentration profiles from runs a,d, and e for medium river flow rates; wind from N at 0, 15, and 25 knots.

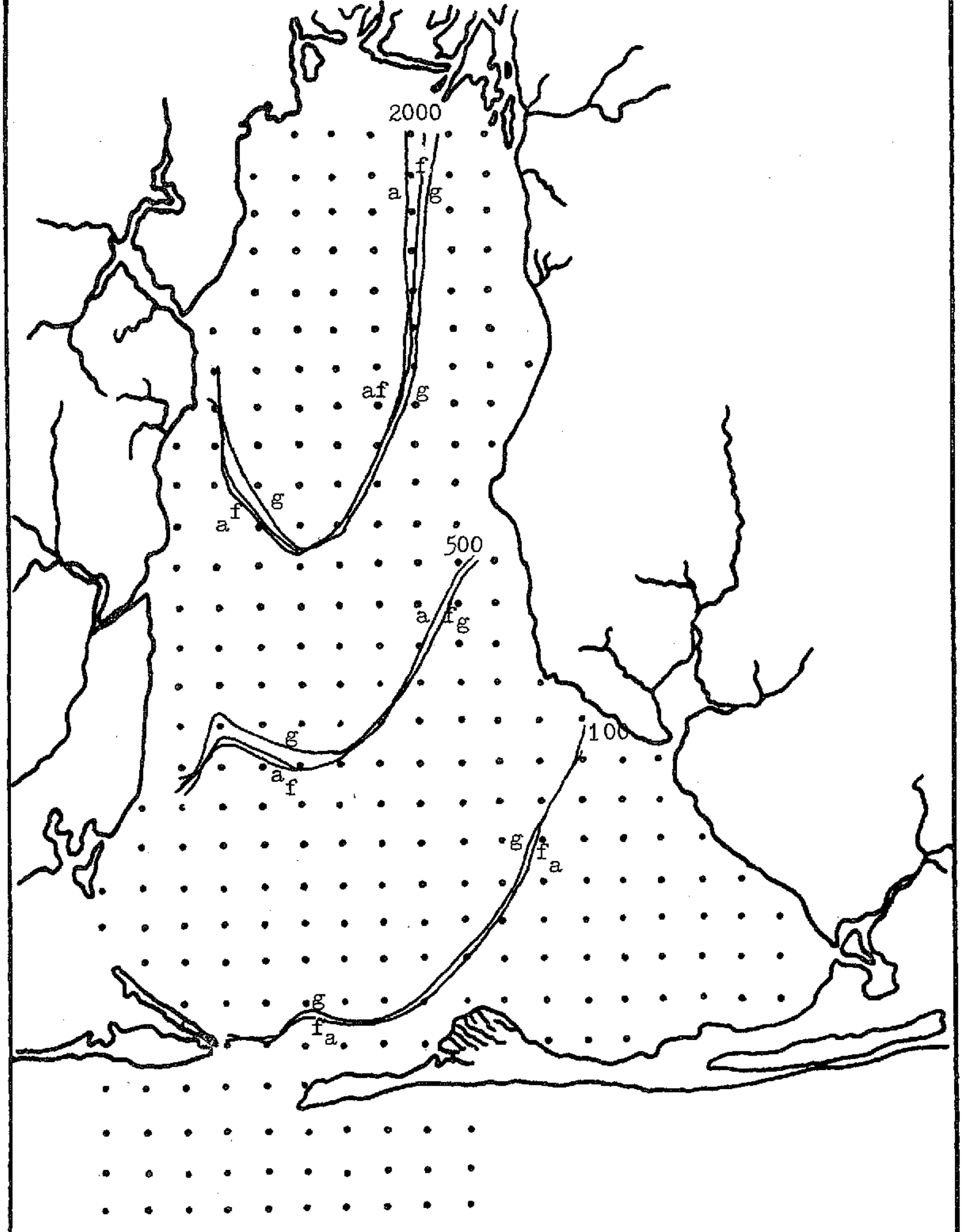


Fig. 5.5 Total coliform concentration profiles from runs a, f, and g for medium river flow rates; wind from SE at 0, 15, and 25 knots.

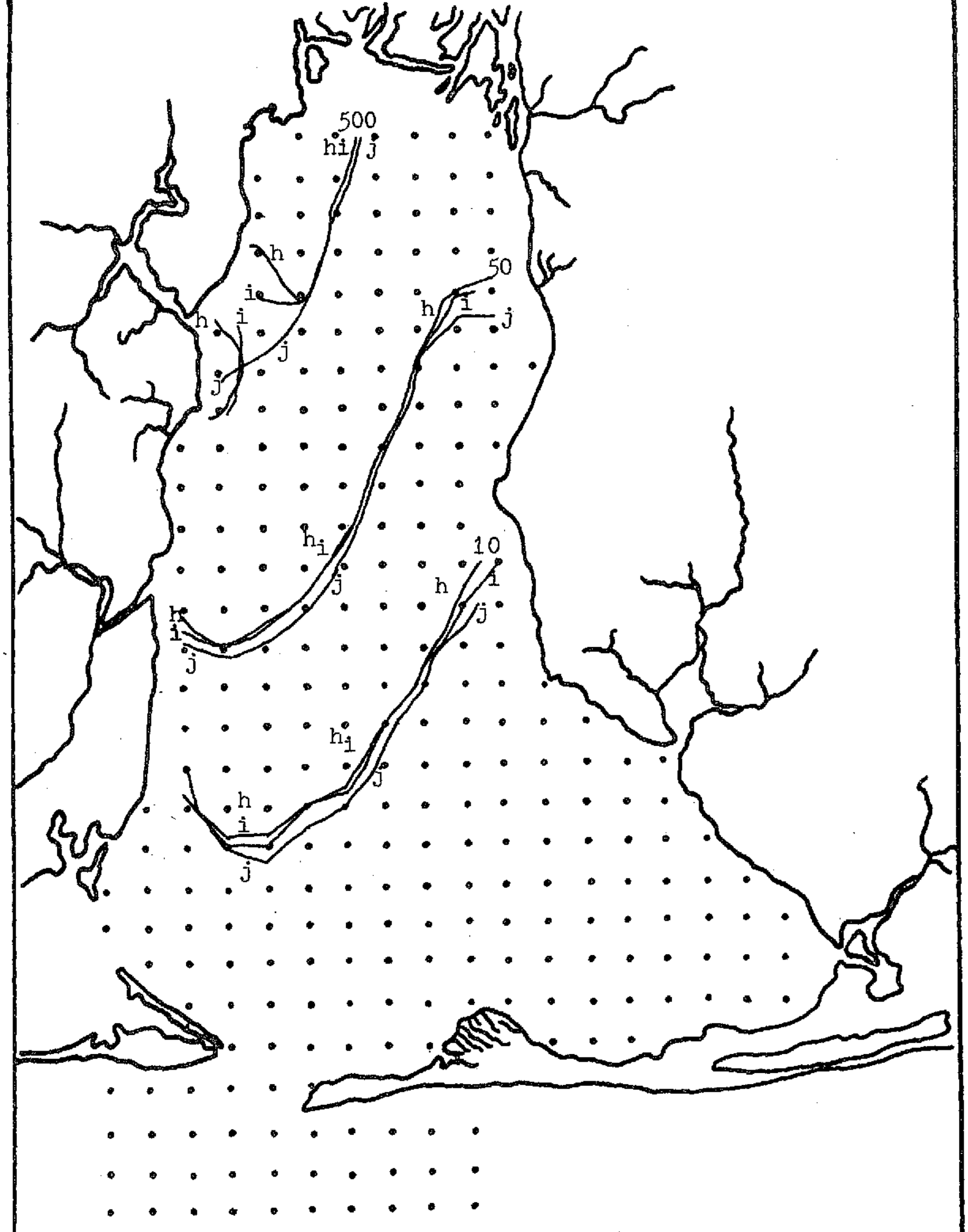


Fig. 5.6 Total coliform concentration profiles from runs h, i, and j for low river flow rates; wind from SW at 0, 15, and 25 knots.

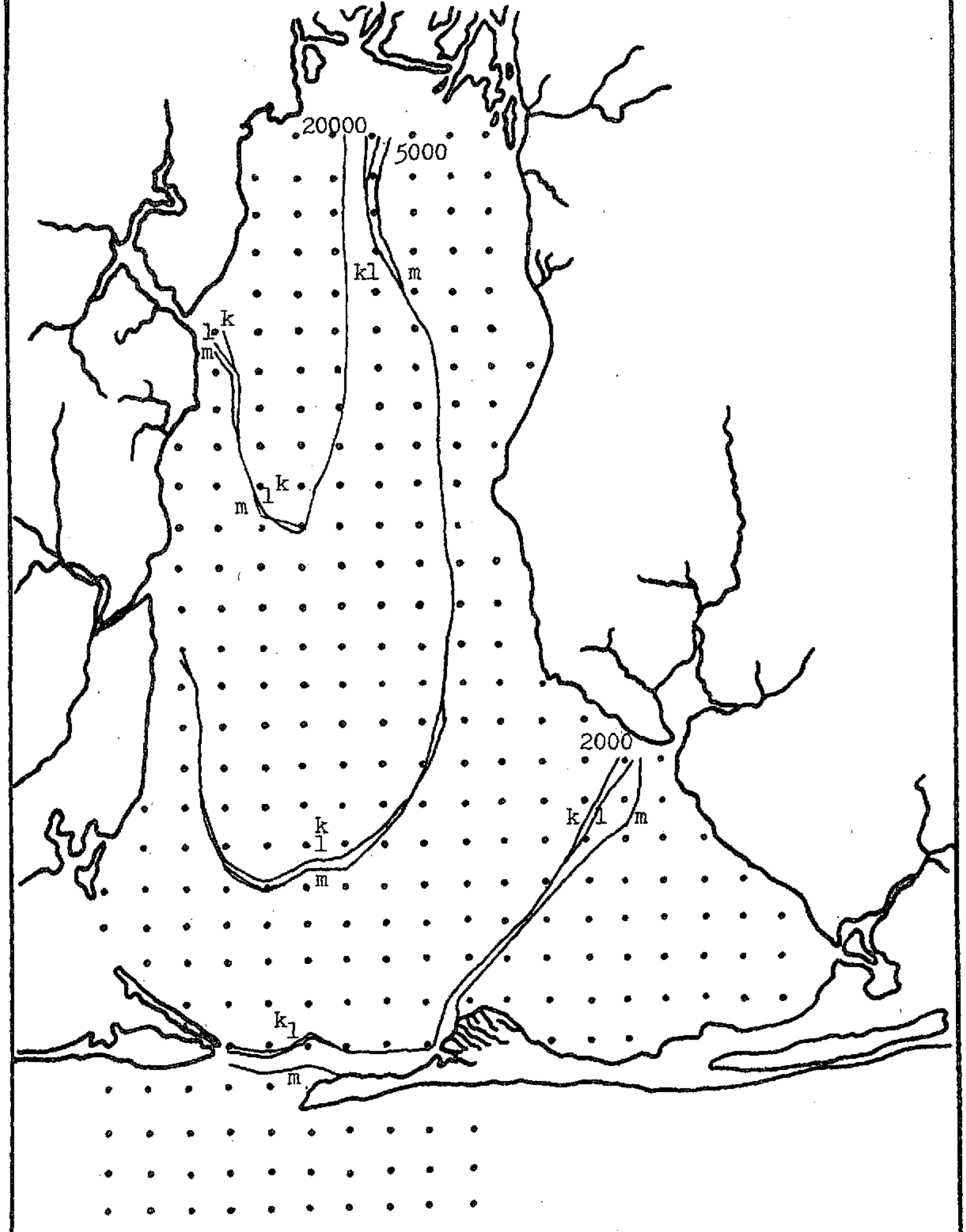


Fig. 5.7 Total coliform concentration profiles from runs k, l, and m for high river flow rates; wind from SW at 0, 15, and 25 knots.

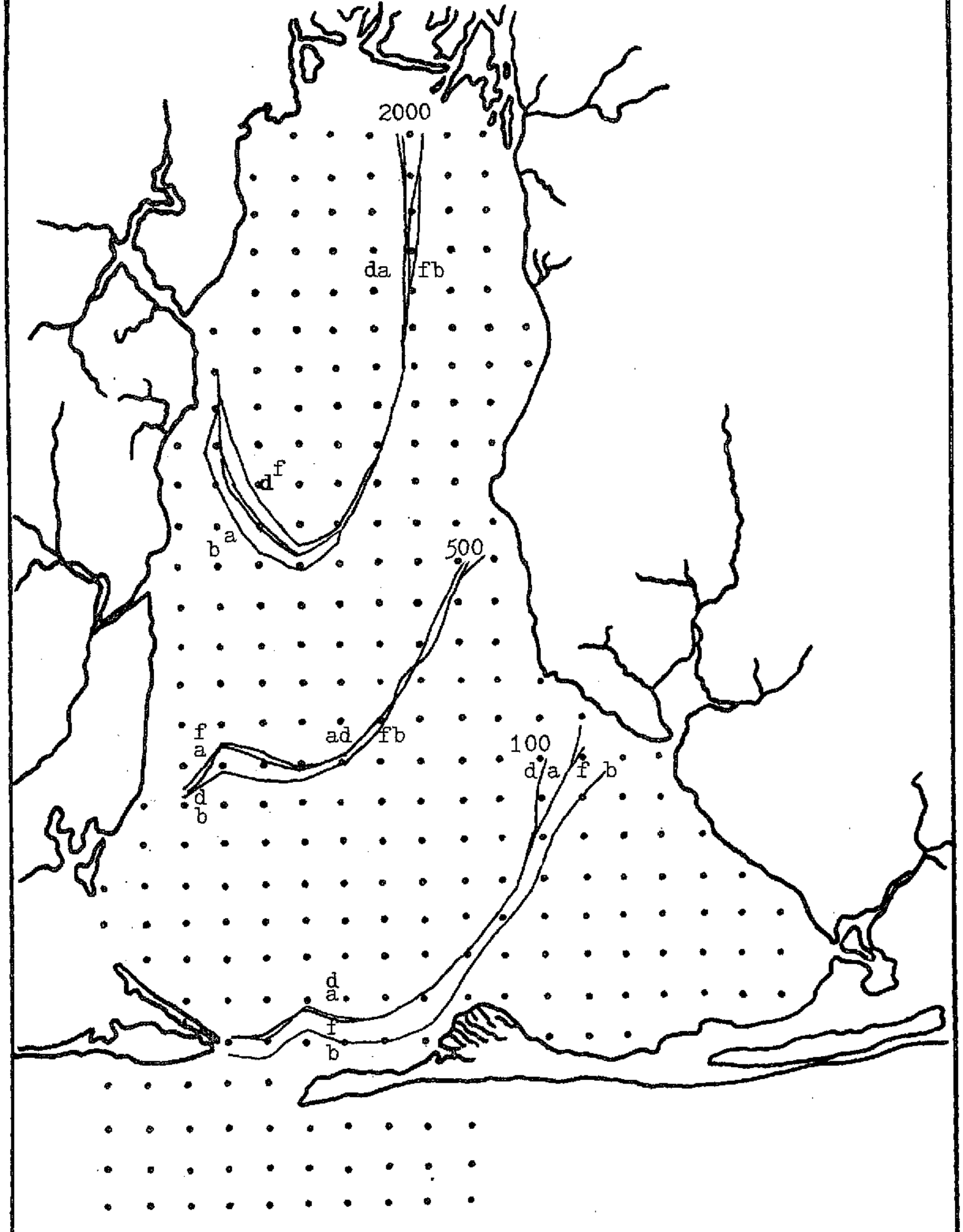


Fig. 5.8 Total coliform concentration profiles from runs a, d, f, and b for medium river flow rates; wind constantly at 15 knots from SW, N, and SE.

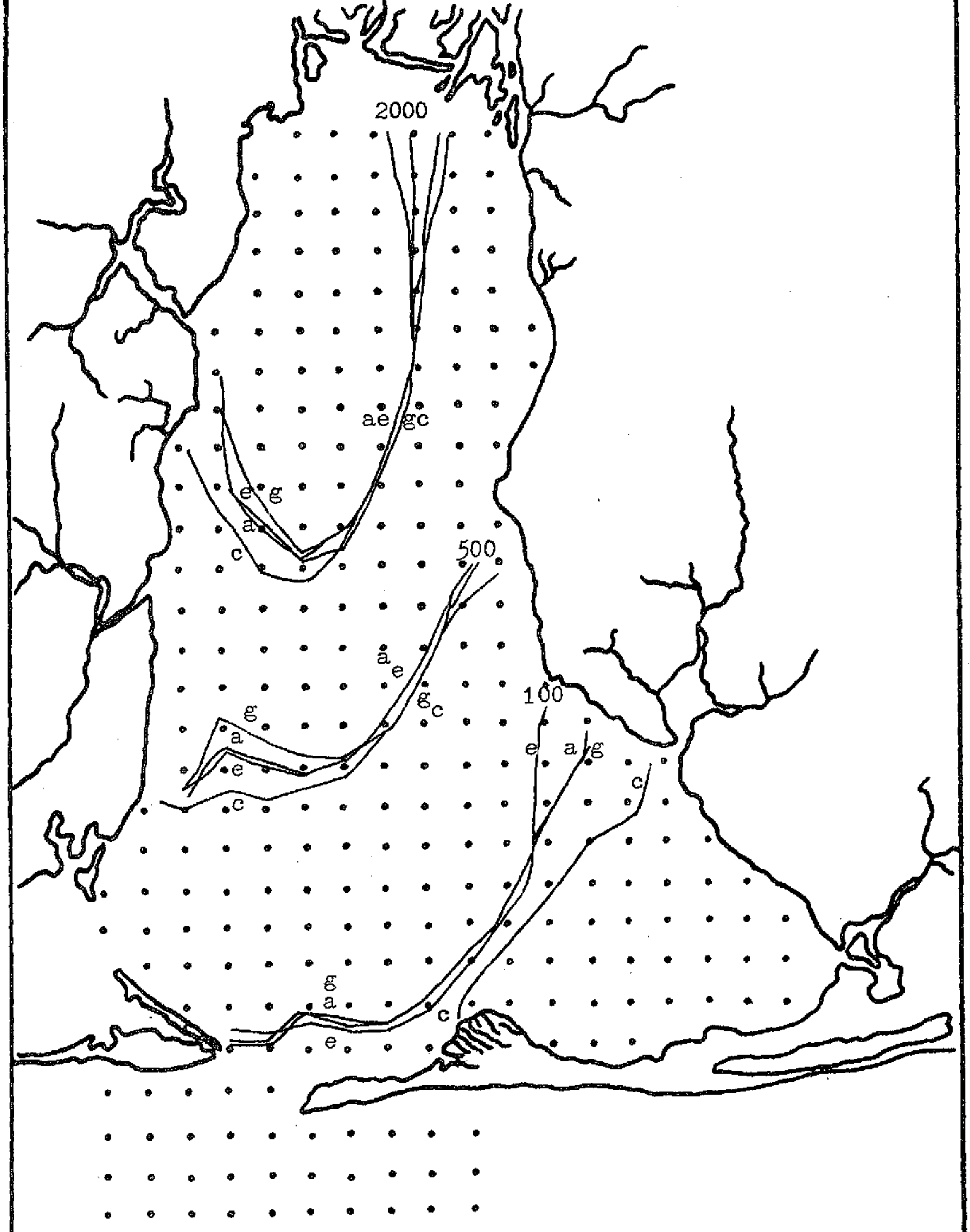


Fig. 5.9 Total coliform concentration profiles from runs a, c, e, and g for medium river flow rates; wind constantly at 25 knots from SW, N, and SE.

Temperature

Fig. 5.1 shows the effects of changing temperatures on total coliform distribution. The shifts of the 100 and the 500 MPN/100ml total coliform concentration isolines as seen in Fig. 5.1 are in the order of 2 to 4 grid widths (4 to 8 km.) from run to run, which can seriously affect the shellfish harvesting activities in the bay, especially in the Bon Secour Bay area. This simulates what can happen to the coliform distribution in case of sharp temperature variation, when all the other system variables, i.e., river flow rates, wind conditions, and waste loadings, remain unchanged. The reason for such pronounced shifts of coliform concentration profiles is the change in dieoff rate constant, K, caused by temperature variation. The change in K follows Eq. (3-42), which indicates that K is a function of bay water temperature alone. When water temperature in the bay is higher, total coliform bacteria dissipate at a higher rate, and the coliform concentration in the bay becomes lower. When the water temperature is lower, K is smaller, the total coliform bacteria die off at a lower rate, and the coliform concentration in the bay becomes higher. This effect also partly accounts for seasonal variation of total coliform concentration within Mobile Bay. Seasonal variations of coliform concentration profiles have also been depicted in the work of Gallagher, et al.(10)

River Discharge Rates

The effect of variations in river discharge rates on the total coliform distribution profiles in Mobile Bay is shown in Fig. 5.2. The values of the river discharge rates using May, 1962 data as a baseline are first doubled, than halved, to run the model. The results are then compared to the actual flow rate observed during 1962. For decreases in river flow rates, the contours obviously shift upward, which results in a lower overall coliform distribution within the bay. For higher river flow rates, the contours all shift downward, which results in a higher overall coliform distribution. The reason for these changes is two-fold. By holding the loading concentrations constant and increasing the river flow rates, more total coliform bacteria are introduced into the bay, while at the same time the net current velocities in the negative y-direction (north to south) are increased. This latter condition allows less retention time for the total coliform group to die off, and results in higher residual coliform concentrations at any part within the bay. For lower river flow rates the reverse is true. These effects caused the changes observed in the runs in Fig. 5.8, and are consistent with actual observations in Mobile Bay(10).

When river flow rates are higher due to either rainfall or storm, the amount of coliform group bacteria loaded into the river water by runoff is indeed higher. However, the loading concentration at those loading grids may not be constant. In parametric runs n, o, and p they are assumed to be constant. This assumes a linear relation between amount of total coliform group input and fresh water runoff, and neglects the difference in fresh water runoff from agricultural areas and those from municipal areas. A more realistic way of assessing the effects of changing waste loading independent of river discharge rate is discussed in Section 5.2.

Wind Effect

For medium river flow rates (see Table 5.1), Fig. 5.3 to 5.5 show the effects of variations in wind speed (0, 15, and 25 knots) blowing from three different directions (N, SE, SW). Fig. 5.6 and 5.7 illustrate for low and high river flow rates, respectively, the effects of changing wind speed originating from the southwest direction. Fig. 5.8 and 5.9 show the effects of variation in direction of wind at 15 and 25 knots, respectively, at medium river flow rates.

In each comparison, the temperature of the bay water is held constant, and the observed variation is exclusively due to variation in net velocities and dispersion coefficients resulting from varying wind and river discharge values. Increasing the net current velocities in the negative y-direction (from the north to the south) will shorten the retention time the coliform bacteria would spend within the bay, allow less time for coliform to die off, and thus increase the total coliform concentration at any location within the bay. From the model calibration study of Chapter III it has been found that deliberately increasing the dispersion coefficients (by manipulating the correction factor for dispersion coefficients) would tend to decrease higher coliform concentrations and increase lower coliform concentrations, i.e., would tend to shorten the range of concentrations. In the parametric study comparisons (Fig. 5.3 to Fig. 5.9), however, the change in either net velocities or dispersion coefficients is neither uniformly increasing nor uniformly decreasing for all the grid cells. The final changes in coliform distribution are the gross totals of the effects of all the local changes in x- and y-component net velocities and dispersion coefficients. For most comparisons it may be summarized that the displacements of profile contours are in the direction of the wind, i.e., the winds have caused the profiles to shift in the directions of the winds. However, the displacements rarely exceed the width of one grid (2 km). Run identifications are used to indicate their relative positions, as shown in Figures 5.3 to 5.9. For many cases, the profile contours are so close together that their difference are not discernible. Due to the fluctuations in physical environments, these displacements would readily be masked and become undetectable. Therefore, the effects of changing wind speed and direction on the monthly average total coliform distribution within Mobile Bay can for all practical purposes be regarded as negligible. To determine if wind has a greater influence on distribution of total coliform for periods less than one month, more detailed data must be used to verify the model. These data are not available at the present time.

5.2 Effect of Waste Loadings

Cell loading concentration of total coliform at the mouth of a river reflects the pathogenic pollution potential the river has on the bay. This concentration is contributed by waste loadings from various sources such as municipal, industrial, and rural areas. Table 5.3 shows the parametric runs performed in the study on the effect of changing levels of waste loading, which are expressed in the form of total coliform concentrations at the boundary cells representing the mouths of the rivers. The conditions experienced in May, 1962 are again used as a reference. River flow rates, wind conditions, and temperature are held constant. The only changes made are on the loading concentrations of total coliform bacteria at the mouths of Mobile River and Dog River. Values are reduced to 1/2, 1/4, and 1/8 of the values experienced in May, 1962 to exercise the NCSTM. The resulting total coliform concentration profiles are shown in Fig. 5.10. Comparisons are made at two concentration levels, i.e., 70 and 1000 MPN/100ml. Each concentration contour is labeled with the letter identifying the corresponding parametric study run. Fig. 5.10 shows that each of the shifts of the coliform concentration profile is in the order of 2 grid widths (4 km). It is noted that the 70 MPN/100ml contour shifts as many as 6 grid widths from run p to run u, as 7/8 of the original total coliform bacteria is removed or reduced. These changes in total coliform loading are more realistc of conditions that might be achievable for varying degrees of treatment.

Table 5.3 Data used for parametric runs p, s, t, u.

Run	River Flow Rates, Wind Conditions, and Temperature	Loading Concentration (MPN/100ml) at		
		Mobile River Mouth	Dog River Mouth	Other Location
p	Same as run p in Table 5.1	40,000	1,800	Same as those of May, 1962 in table
s	"	20,000	900	"
t	"	10,000	450	"
u	"	5,000	225	"

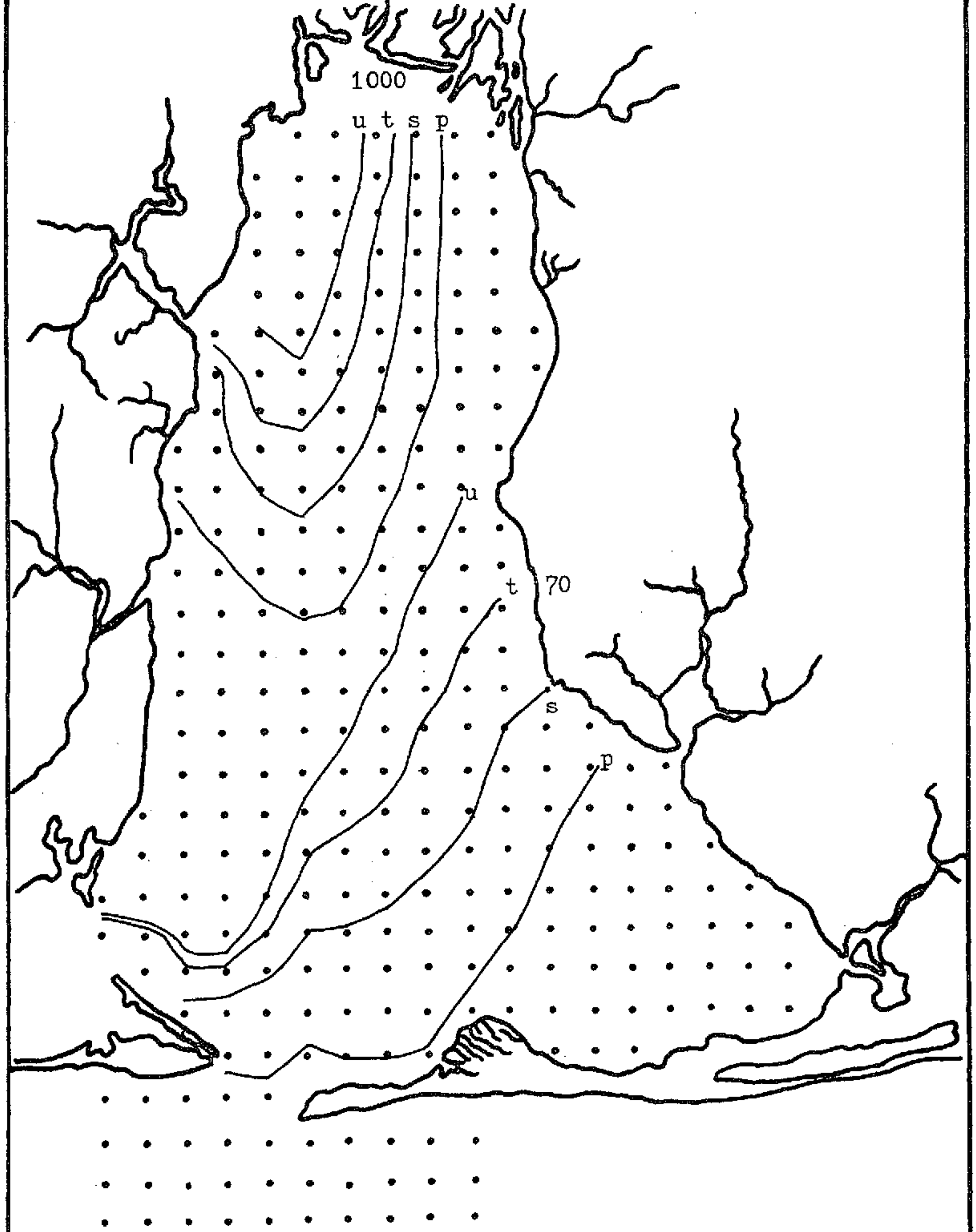


Fig. 5.10 Total coliform concentration profiles from runs p, s, t, and u; displacements due to changes in treatment levels.

This study provides a method for describing total coliform bacteria concentration distributions in Mobile Bay, and for describing how these distributions might be affected by various changes in the real system. As a result of these preliminary investigations, a series of conclusions and recommendations related to the use and extension of ideas generated within this study is presented in Chapter VI.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Chapters IV and V presented results demonstrating the feasibility of using a two dimensional model to describe the transport of a non-conservative species within Mobile Bay. The particular species investigated was the total coliform bacteria group. The intent of Chapter VI is to present the concluding observations from this study, the limitations of the present model, the contributions resulting from this study, and the recommendations for continued research in related areas.

Concluding Observations

A model for the prediction of trend behavior of the total coliform bacteria distribution within Mobile Bay has been developed. This model allows for:

(1) variability in the total coliform source concentration at several locations along the boundary of the bay system,

(2) variability of the correlation coefficients for the x- and y-component dispersion coefficients to best describe the mixing characteristic of the specific non-conservative species,

(3) variability in river flow and wind conditions by interacting with the Hydrodynamic Model developed by Hill and April(12),

(4) variability in temperatures that result in changes in the dieoff rate constant of the total coliform bacteria.

This model is based on established engineering practice and constitutes the necessary framework for the development of other similar non-conservative species transport models for BOD and DO. Additionally, the model formulation is made in such a manner as to facilitate rapid execution and easy interpretation of computed results, which are printed in the same configuration as the bay.

Specific observations related to various phases of this study should also be presented. In the verification phase of this study, the model was calibrated with the June, 1962 total coliform concentration data taken from the bay. Values of the dilution factors (for the conversions of point source loading concentrations to cell loading concentrations suitable for model input) and the correction factors (for the correlation of x- and y-component dispersion coefficients based on the x- and y-component maximum current velocities over the tidal cycle) that best describe total coliform mixing characteristics were calibrated. They were then used for the verification of the model based on the actual data collected during January to August, 1962. In the parametric study phase of this investigation, temperature was found to have the most pronounced effect on the total coliform distribution within Mobile Bay. A change in temperature of 10°F can cause the total coliform concentration profiles in the bay to be displaced as much as 8 kilometers. Variations in river flow rates also showed a pronounced effect upon the total coliform distribution pro iles within the bay. The May, 1962 condition was used as a baseline to study the effect of changing river flow rates. When the river flow rates were doubled and then halved to exercise the model, displacements of total coliform concentration profiles by as much as 6 kilometers were obtained. Wind conditions (speed and direction) were studied at three speeds and three directions, interfacing with three levels of river flow rates. It has been found that wind conditions have the least influence on monthly average total coliform distributions within Mobile Bay as compared with other parameters. However, it is believed that reduction of the time basis to a tidal level will result in the observation of more pronounced wind effects than those observed from the monthly averaged results.

In addition to the above, total coliform source concentration levels were varied at constant temperature, river flow rates, and wind conditions to simulate the possible effects different treatments would have on total coliform distribution within the bay. Conditions experienced in May, 1962 were again used as a baseline. Source loading concentrations of total coliform experienced in May, 1962 were reduced to 1/2, 1/4, and 1/8 to exercise the model. Displacements were found to be in the order of 2 to 8 kilometers from run to run.

Limitations of the Model

At the present time, the most limiting factor involved with any modeling activity on Mobile Bay is the availability of suitable field data for calibration and verification of the formulated models.

This fact restricts the NCSTM developed in this study to a trend analysis tool. By this, it is meant that specific predictive capabilities related to source or cell concentrations can not be assured with any degree of confidence that the results reproduce real system behavior. However, monthly trend analyses of species concentrations for given regions of the bay system resulting from natural or man-made phenomena can be assessed with relatively high accuracy.

Also, the present NCSTM is limited to those conditions for which calibration and verification of the Hydrodynamic Model were achieved. These conditions include (1) combined river flow rates of the Mobile River-Tensaw River system between 12,000 and 245,000 cfs, and (2) wind speeds lower than 25 knots. Any conditions which approach the limits of the above should not be expected to produce reliable results unless further testing is made.

Also included as limitations to the model formulated in this study are:

(1) constant density of water throughout the bay,
(2) normal tidal conditions at the Gulf boundaries,
(3) binary mixing behavior within each cell of the bay model,
(4) homogeneous temperature throughout the bay for each month, and
(5) tidal average velocities and dispersion coefficients.

These limitations should be reevaluated as more sophisticated model capabilities are developed and more reliable data are obtained.

Contributions of This Study

The greatest contributions of this research lie in the development of a tool for the rapid assessment of conditions within Mobile Bay, and, the provision of a base from which other pertinent models may be developed. This study represents a continuing effort in the development of a comprehensive model for a detailed analysis of many proposed activities pertinent to a progressive society. Contributions were made, also, in areas summarized below.

(1) A trend analysis of the total coliform was made, to better understand how this species is transported through the bay. This hopefully will lead to a better understanding of those variables affecting total coliform distributions, as that progress can be made to reduce their levels to allow for better economic growth within the shellfish harvesting industry.

(2) The trend analysis should also provide insight into the development of models for related non-conservative species which are indicators of water quality within the bay. These additional species include BOD and DO, which are widely accepted as standards for measuring industrial and municipal pollution loadings in natural water systems.

(3) The interactive effect of physical and biological terms has been demonstrated in this study, opening the door for interdisciplinary research and development projects. Through these inter-

disciplinary programs, better understanding of coastal ecosystems can be achieved. At a time when the coastal zones are being developed to provide the resources for energy related projects (i.e. deep water port development, off-shore and near-shore oil explorations, on-shore refining and processing facilities, etc), an understanding of the effects that these developments might have on this complex, interactive system is essential.

Recommendations for Further Study

Based on the experience gained in this study, several recommendations are made concerning further studies in related areas. These recommendations are summarized below.

(1) Establish a system within the bay area for routine, synoptic data collection in support of the mathematical modeling efforts. This could be achieved with little additional expenditures, provided that cooperation among those agencies and organizations conducting active research programs within the bay can be established.

(2) Investigate the use of the NCSTM to predict BOD and DO within the bay.

(3) Investigate more closely the mechanisms that govern the reproduction, dieoff, and reactions of the various species related to water quality in the bay.

(4) Identify the agencies within the region which have a need for the predictive capabilities of such models. These agencies include,

but are not limited to:

Alabama State Department of Health
Alabama Water Improvement Commission
Alabama State Geological Survey
U. S. Corps of Engineers (Mobile District)
Marine Environmental Sciences Consortium
Alabama State Department of Conservation
Private Industries including:
Petroleum Companies,
Petrochemical Companies,
Chemical Companies, etc,

which have active interests in developments within and adjacent to the bay.

Hopefully these recommendations can be implemented to such an extent that mathematical modeling efforts can be used to assist in the development of protective systems for our coastal environment to keep pace with the ever-increasing population and industrial development.

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APPENDICES

A. USER'S GUIDE FOR THE NCSTM

B. EXAMPLES OF RAW DATA USED IN THE NCSTM

APPENDIX A

USER'S GUIDE FOR THE NCSTM

A1 Procedures for Exercising the NCSTM

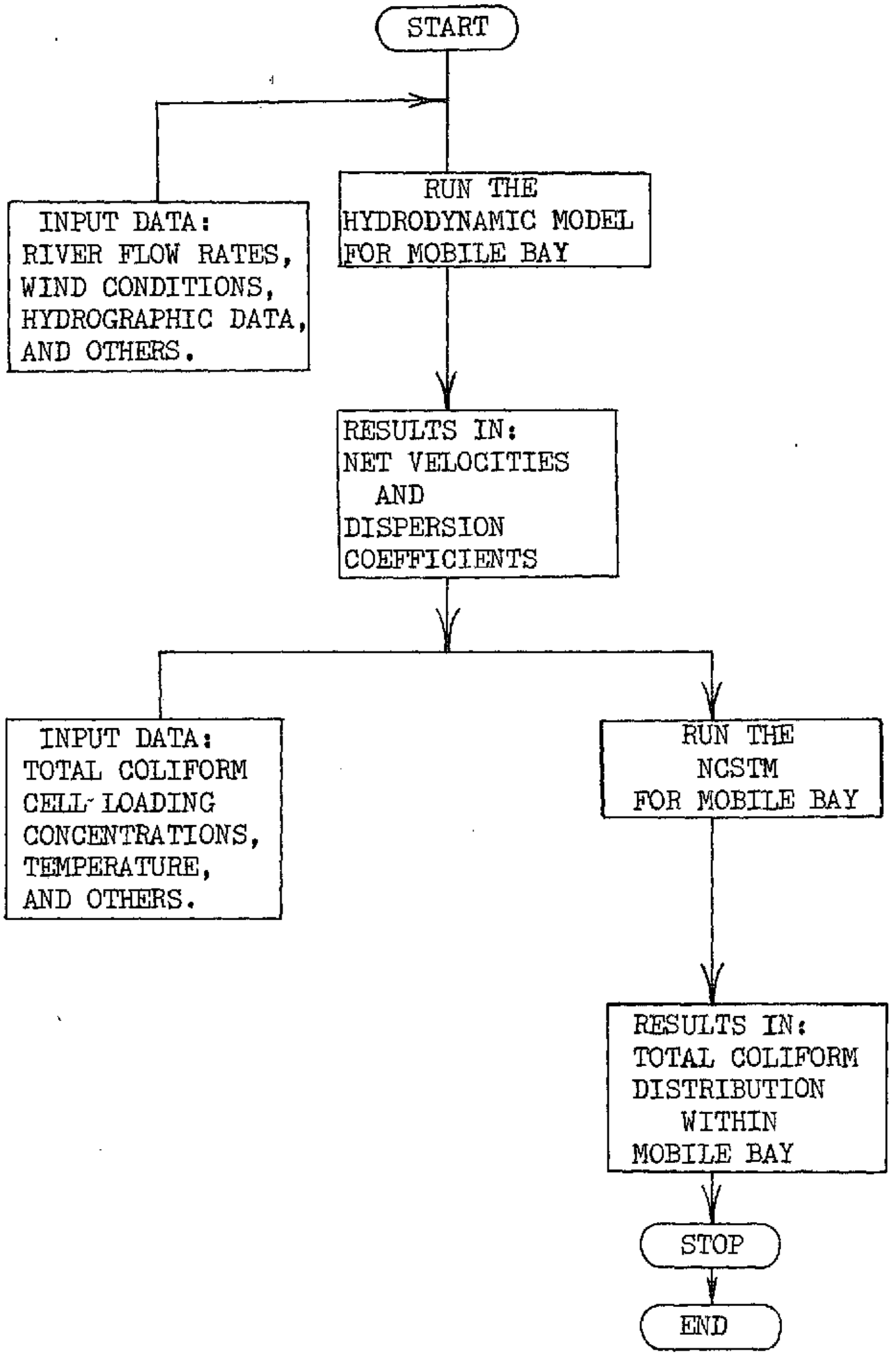
A2 Description of Variables Appearing in the Computer Program

A3 Program Listings

A4 Input Data Specifications

A1 PROCEDURES FOR EXERCISING THE NCSTM

(I) Flow Diagram Representation of the Procedures of Exercising the NCSTM for Mobile Bay



(II) Explanation

River flow rates, wind conditions, hydrographic information, and other data were input to the Hydrodynamic Model for Mobile Bay developed by Hill and April(12). For details of exercising the Hydrodynamic Model which is the first step of exercising the NCSTM, users are referred to the work by Hill and April. For the computation involving different periods, the main changes in input data are the river flow rates and the wind conditions. These changes can be made by altering two data cards. Two consecutive runs (the second one is initiated with the results obtained by the first one) are usually required to obtain convergent results of net velocities and maximum current velocities over the tidal cycle. These results are then stored into data files in the mass storage of the computer system, later to be retrieved by the NCSTM as input data.

Bay water temperature, total coliform cell loading concentrations, and other pertinent data are input to the NCSTM together with the data created by the Hydrodynamic Model. The NCSTM then computes the desired total coliform distribution within Mobile Bay. The distributions are printed with variable format to simulate the configuration of the bay. Only total coliform concentration values at water cells are printed. Values at those cells representing the river channels and at those cells corresponding to land cells are not printed (values at land cells are zeroes).

Computations were performed with a UNIVAC-1110 computer system on which provisions exist for users to store the main program in the mass storage of the system. This saves the users the time required to read the source program deck into the system, especially when a large number of punched cards are used. In this study both the main program of the Hydrodynamic Model and that of the NCSTM involve large numbers of cards, and therefore are stored in the system. Descriptions of the control cards for the storage and retrieval of stored programs and calculated data are cited in Appendix A3.

A2 DESCRIPTION OF VARIABLES APPEARING IN THE COMPUTER PROGRAM

Variable Name	Definition
A	= 6561.68 ft
A1	storage term in the computation of cell total coliform concentration, in (MPN/100 ml)·(ft/sec)
A2	"
A3	"
A4	"
A5	"
A6	"
A7	storage term in the computation of cell total coliform concentration, in (MPN/100 ml)
BRK	dieoff rate constant of total coliform bacteria, (day^{-1})
C	total coliform concentration (MPN/100 ml)
COLC	total coliform cell loading concentration at Cedar Point, (MPN/100 ml)
COLG	total coliform concentration in the water of the Gulf of Mexico, (MPN/100 ml)
COLM	total coliform cell loading concentration at Mobile River mouth, (MPN/100 ml)
COLT	total coliform cell loading concentration at Tensaw River mouth, (MPN/100 ml)
D	depth of water in a cell, (ft)
DELS	x- and y-direction grid size (=6561.68 ft)
DELT	time increment (=240 sec)
EX	x-component dispersion coefficient, (ft^2/sec)
EY	y-component dispersion coefficient, (ft^2/sec)

Variable Name	Definition
I	counter
IB	number of rows possessing boundary cells
IBNDL	cell numbers of the left hand side boundary cells
IBNDR	cell numbers of the right hand side boundary cells
IFLD	specification used in variable format to designate position of decimal point
IFRM	specification used in variable format to designate start-printing position, number of variables, spacing, etc.
IKK	counter
IPRNT	specification used in variable format as printer control code
IQUIT	number of the cell to stop printing in that row
IRCB	number of cells in each of the two ideal river channels(=10)
IREP	number of cells in each row where results are to be printed
ISTRT	number of the cell to start printing in that row
I1	counter
I2	counter
I3	counter
I4	counter
J	counter
K	counter
KIK	counter
NC	number of cells in the grid system(=798)
NUM	spacing to be indented before printing begins

Variable Name	Description
TCALP	total coliform cell loading concentration at Alabama Port, (MPN/100 ml)
TCBSM	total coliform cell loading concentration at the mouth of Bon Secour River, (MPN/100 ml)
TCDRM	total coliform cell loading concentration at the mouth of Dog River, (MPN/100 ml)
TCHK	number of tidal cycles elapsed after which computation is stopped
TDEL	time expended in computation (sec)
TDLE	number of tidal cycles elapsed (=25 hr. each period)
TEMPF	bay water temperature (°F)
TEMPC	bay water temperature (°C)
TIM	maximum time for run (=4800 hr.)
TPRNT	time interval between printing of results (=360,000 sec)
ULNT	x-component net velocity over one tidal cycle, (ft/sec)
VLNT	y-component net velocity over one tidal cycle, (ft/sec)

A3 Program Listings

(I) "CREATE NCSTM"(Storing of the Main Program of the NCSTM in the UNIVAC-1110 Computer System)

(1) Card Arrangement(Control Cards)

```
@RUN,A/TPC HUAAN,(account no.),LIU,2,30/0
@ASG,CP HUAAN,F
@FOR,IS HUAAN.NONC
```

Card Deck of the Main Program

```
@MAP,I ,HUAAN.NONC
 IN HUAAN.NONC
@PREP  HUAAN.
@PACK  HUAAN.
@PRT,I HUAAN.
@@
```

Blank Card

(2) Listing of the Main Program

THE MAIN PROGRAM OF THE NCSIM FOR MOBILE BAY

```
MAIN PROGRAM OF THE NCSIM FOR MOBILE BAY
      DIMENSION EX(800),EY(800),ULNT(800),VLNT(800),NUM(70) ,IREP(70),  NONC0010
     < IBNDL(70),IBNDR(70),C(800),D(800)                                NONC0020
     2INTEGER*2 IPRNT(2)/'H0','H '/                                     NONC0030
      INTEGER*2 IFRM(9)/'(1','H0',',T','  ',' ,','  ','F6','.0',') '/   NONC0040
      INTEGER*2 IFLD(3)/'.2','.1','.3'/                                 NONC0050
      READ(5,105)IB,NC,IRCB                                             NONC0060
  105 FORMAT(3I5)                                                       NONC0070
      WRITE(6,4010)IB,NC,IRCB                                           NONC0080
 4010 FORMAT(T2,'IB,NC,IRCB,=',4I5)                                     NONC0090
      READ(5,10)DELS,DELT,COLM,COLT,TIM,TPRNT,COLG,COLC                 NONC0100
   10 FORMAT(8F10.2)                                                    NONC0110
      READ(5,1812)TCOSM,TCALP,TCDRM                                     NONC0120
 1812 FORMAT(3F10.2)                                                    NONC0130
      TDEL=0.                                                           NONC0140
      READ(5,11)TEMPF                                                   NONC0150
   11 FORMAT(F20.2)                                                     NONC0160
      TEMPC=(TEMPF-32.)/1.8                                             NONC0170
      BRK=0.50*(1.067**(TEMPC-20.))                                     NONC0180
      A=6551.68                                                         NONC0190
      WRITE(6,4020)COLM,COLT,COLG,COLC                                  NONC0200
 4020 FORMAT(T2,20HCOLM,COLT,COLG,COLC=,4F10.2)                         NONC0210
      WRITE(6,1813)TCOSM,TCALP,TCDRM                                    NONC0220
 1813 FORMAT(T2,18HTCOSM,TCALP,TCDRM=,3F10.2)                           NONC0230
      WRITE(6,1814)TEMPF                                                NONC0240
 1814 FORMAT(T2,6HTEMPF=,F10.2)                                         NONC0250
      WRITE(6,4021)DELS,DELT,TIM,TPRNT                                  NONC0260
 4021 FORMAT(T2,20HDELS,DELT,TIM,TPRNT=,4F10.2)                         NONC0270
      WRITE(6,4022) BRK                                                 NONC0280
 4022 FORMAT(T2,4HBRK=,F20.2)                                           NONC0290
      BRK=BRK/86400                                                     NONC0300
      TIM=TIM*3600.                                                     NONC0310
      READ(5,1)(IBNDL(I),I=1,IB)                                        NONC0320
      WRITE(6,4000)(IBNDL(I),I=1,IB)                                    NONC0330
      READ(5,1)(IBNDR(I),I=1,IB)                                        NONC0340
    1 FORMAT(20I4/18I4)                                                 NONC0350
      WRITE(6,4000)(IBNDR(I),I=1,IB)                                    NONC0360
 4000 FORMAT(T2,19I5/(2,19I5)) ,                                        NONC0370
      READ(5,5)(NUM(I),I=1,IB)                                          NONC0380
      WRITE(6,5000)(NUM(I),I=1,IB)                                      NONC0390
      READ(5,5)(IREP(I),I=1,IB)                                         NONC0400
    5 FORMAT(20A4/18A4)                                                 NONC0410
      WRITE(6,5000)(IREP(I),I=1,IB)                                     NONC0420
 5000 FORMAT(T2,19A4/T2,19A4)                                           NONC0430
      READ(5,101)(D(I),I=1,NC)                                          NONC0440
  101 FORMAT(21F8.0)                                                    NONC0450
      READ(5,26)(EX(I),I=1,NC)                                          NONC0460
      READ(5,26)(EY(I),I=1,NC)                                          NONC0470
      READ(5,18)(ULNT(I),I=1,NC)                                        NONC0480
      READ(5,18)(VLNT(I),I=1,NC)                                        NONC0490
   26 FORMAT(T2,7F8.5)                                                  NONC0500
   18 FORMAT(T2,7F8.5)                                                  NONC0510
      DO 444 I=1,NC                                                     NONC0520
      ULNT(I)=ULNT(I)*1000.                                             NONC0530
  444 VLNT(I)=VLNT(I)*1000.                                             NONC0540
      DO 1000 I=1,NC                                                    NONC0550
 1000 D(I)=D(I)+1.2                                                     NONC0560
```

```
CCCCCCCCC     CCCC   CCCC   CCCC   CCCC   CCCC   CCCC   CCCC   CCCC   CCNONC0570
C        SET INPUTS AT THE TWO PARALLEL RIVER CHANNELS                    NONC0580
CCCCCCCCC     CCCC   CCCC   CCCC   CCCC   CCCC   CCCC   CCCC   CCCC   CCNONC0590
      C(784)=COLM*0.025                                                   NONC0600
      C(789)=COLT*0.025                                                   NONC0610
      J=1                                                                 NONC0620
      ISTRT=IBNDL(J)                                                      NONC0630
      IQUIT=IBNDR(J)                                                      NONC0640
      DO 600 I=ISTRT,IQUIT                                                NONC0650
  600 C(I)=COLG                                                           NONC0660
CCCCCCCCC     CCCC   CCCC   CCCC   CCCC   CCCC   CCCC   CCCC   CCCC   CCNONC0670
C     CORRECTION FACTOR MULTIPLICATIONS FOR THE DISPERSION COEFFICIENTS  NONC0680
CCCCCCCCC     CCCC   CCCC   CCCC   CCCC   CCCC   CCCC   CCCC   CCCC   CCNONC0690
      DO 300 I=1,NC                                                       NONC0700
      EX(I)=EY(I)*500.                                                    NONC0710
  300 EY(I)=EY(I)*500.                                                    NONC0720
      WRITE(6,30)                                                         NONC0730
   30 FORMAT('1',T2,'DISPERSION COEFF IN X-Y DIRECTION*500')              NONC0740
      J=IB                                                                NONC0750
      DO 617 K=1,IB                                                       NONC0760
      ISTRT=IBNDL(J)                                                      NONC0770
      IQUIT=IBNDR(J)                                                      NONC0780
      IFRM(4) = NOR(J)                                                    NONC0790
      IFRM (6) = IREP(J)                                                  NONC0800
      IFRM(2)=IPRNT(1)                                                    NONC0810
      WRITE (6,IFRM)(EX(I), I=ISTRT,IQUIT)                                NONC0820
      IFRM(2) = IPRNT(2)                                                  NONC0830
      WRITE (6,IFRM)(EY(I),I=ISTRT,IQUIT)                                 NONC0840
  617 J=IB-K                                                              NONC0850
      WRITE(6,31)                                                         NONC0860
   31 FORMAT('1',T2,'NET VELOCITIES IN X-Y DIRECTION * 1000')             NONC0870
      J=IB                                                                NONC0880
      DO 616 K=1,IB                                                       NONC0890
      ISTRT=IBNDL(J)                                                      NONC0900
      IQUIT=IBNDR(J)                                                      NONC0910
      IFRM(4)=NOR(J)                                                      NONC0920
      IFRM(6)=IREP(J)                                                     NONC0930
      IFRM(2)=IPRNT(1)                                                    NONC0940
      WRITE(6,IFRM)(ULNT(I),I=ISTRT,IQUIT)                                NONC0950
      IFRM(2)=IPRNT(2)                                                    NONC0960
      WRITE(6,IFRM)(VLNT(I),I=ISTRT,IQUIT)                                NONC0970
  616 J=IB-K                                                              NONC0980
      DO 445 I=1,NC                                                       NONC0990
      ULNT(I)=ULNT(I)/1000.                                               NONC1000
  445 VLNT(I)=VLNT(I)/1000.                                               NONC1010
  604 CONTINUE                                                            NONC1020
CCCCCCCCCC   CCCC   CCCC   CCCC   CCCC   CCCC   CCCC   CCCC   CCC   CC   NONC1030
C        SET LAND BOUNDARIES TO CONCENTRATION OF ADJACENT WATER CELL     NONC0040
CCCCCCCCC      CCCC     CCC   CCC   CCC   CCC   CCC   CCC   CCC   CCC   NONC1050
  621 DO 605 K=1,IB                                                       NONC1060
      I=IBNDL(K)                                                          NONC1070
      J=IBNDR(K)                                                          NONC1080
      C(I-1)-C(I)                                                         NONC1090
  605 C(J+1)=C(J)                                                         NONC1100
      KIK=IB-1                                                            NONC1110
  615 DO 616 K=2,KIK                                                      NONC1120
      ISTRT=IBNDL(K)                                                      NONC1130
```

THE MAIN PROGRAM OF THE NCSTM FOR MOBILE BAY

```
      IQUIT=IBNDR(K)                                                    NONC1140
      IF(K.GT.6)GO TO 3001                                              NONC1150
      GO TO (3000,3000,3003,3004,3005,3006),K                           NONC1160
 3000 GO TO 3001                                                        NONC1170
 3003 DO 2003 I=71,84                                                   NONC1180
 2003 C(I)=C(I-21)                                                      NONC1190
      GO TO 3001                                                        NONC1200
 3004 C(71)=C(70)                                                       NONC1210
      DO 2004 I=85,86                                                   NONC1220
 2004 C(I)=C(I-21)                                                      NONC1230
      GO TO 3001                                                        NONC1240
 3005 C(88)=C(89)                                                       NONC1250
      C(95)=C(94)                                                       NONC1260
      C(96)=C(97)                                                       NONC1270
      C(100)=C(99)                                                      NONC1280
      DO 2005 I=71,73                                                   NONC1290
 2005 C(I)=C(I+21)                                                      NONC1300
      DO 2006 I=76,78                                                   NONC1310
 2006 C(I)=C(I+21)                                                      NONC1320
      GO TO 3001                                                        NONC1330
 3006 C(88)=C(109)                                                      NONC1340
      C(108)=C(109)                                                     NONC1350
      DO 2007 I=95,96                                                   NONC1360
 2007 C(I)=C(I+21)                                                      NONC1370
      DO 2008 I=100,103                                                 NONC1380
 2008 C(I)=C(I+21)                                                      NONC1390
      GO TO 3001                                                        NONC1400
 3001 CONTINUE                                                          NONC1410
      A7=0.0                                                            NONC1420
      DO 616 I=ISTRT,IQUIT                                              NONC1430
      I1=I+1                                                            NONC1440
      I2=I-1                                                            NONC1450
      I3=I+21                                                           NONC1460
      I4=I-21                                                           NONC1470
      A1=EX(I)*(C(I1)-2.*C(I)+C(I2 ))/A                                 NONC1480
      A1=EX(I)*(C(I1 )-2*C(I)+C(I2 ))/(2.*A)                            NONC1490
      A2=(EX(I1 )*(C(I1 )-C(I))-EX(I2 )*(C(I)-C(I2 )))/(2.*A)           NONC1500
      A3=(EY(I)*(C(I3)-2. *C(I)+C(I4  )))/A                             NONC1510
      A4=(EY(I3  )*(C(I3  )-C(I))-EY(I4  )*(C(I)-C(I4  )))/(2.*A)       NONC1520
      A5=(UENT(I)+UENT(I1 ))*(C(I1 )-C(I2 ))/4.                         NONC1530
      A6=(VENT(I)+VENT(I3  ))*(C(I3  )-C(I4  ))/4.                      NONC1540
      A7=RRX+C(I)*DELT                                                  NONC1550
  616 C(I)=C(I)+(A1+A2+A3+A4-A5-A6)*DELT/A                              NONC1560
     1-A7                                                               NONC1570
CCCCCCCCC    CCCC    CCCC    CCCC    CCCC    CCCC    CCCC    CCCC    CCCC   NONC1580
C     SET THE CELL LOADING CONCENTRATIONS                               NONC1590
CCCCCCCCC    CCCC    CCCC    CCCC    CCCC    CCCC    CCCC    CCCC    CCC    NONC1600
      C(574)=COLM                                                       NONC1610
      C(579)=COLT                                                       NONC1620
  200 C(149)=TOUC                                                       NONC1630
      C(145)=TCBSM                                                      NONC1640
      C(277)=TCALP                                                      NONC1650
      C(446)=TCURM                                                      NONC1660
CCCCCCCCC    CCCC    CCCC    CCCC    CCCC    CCCC . CCCC    CCCC .  CCCC  CCNONC1670
C     SET BOUNDARY CONCENTRATIONS AT GULF BOUNDARIES                    NONC1680
CCCCCCCCC    CCCC    CCCC    CCCC    CCCC    CCCC    CCCC    CCCC    CCCC   NONC1690
      DO 202 I=2,65,21                                                  NONC1700
```

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```
     THE MAIN PROGRAM OF THE NCSTM FOR MOBILE BAY

  202 C(I)=COLG                                                            NONC1710
      DO 204 I=11,53,21                                                    NONC1720
  204 C(I)=COLG                                                            NONC1730
      IF(AMOD(TDEL,TPRNT).GT.0.0001)GO TO 542                              NONC1740
      WRITE(6,303)                                                         NONC1750
  303 FORMAT(1H1,T2,46HTOTAL COLIFORM BACTERIA IN MPN PER 100 MILITER)     NONC1760
      TDLE=TDEL/90000.                                                     NONC1770
13132 WRITE(6,13131)TDLE,DELT                                              NONC1780
C       *****      PRINT THE TOTAL COLIFORM DISTRIBUTION      *****        NONC1790
13131 FORMAT(T2,2HT=,F10.2,6HCYCLES,2X,5HDELT=,F10.2)                      NONC1800
      IFRM(2)=IPRNT(1)                                                     NONC1810
      J=10-IRCH                                                            NONC1820
      IKK=J                                                                NONC1830
      DO 541 K=1,IKK                                                       NONC1840
      ISTRT=IBNDL(J)                                                       NONC1850
      IQUIT=IBNDR(J)                                                       NONC1860
      IFRM(4)=NUM(J)                                                       NONC1870
      IFRM(5)=IREP(J)                                                      NONC1880
      WRITE(6,IFRM)(C(I),I=ISTRT,IQUIT)                                    NONC1890
  541 J=J-1                                                                NONC1900
      TCHK=ABS(10.-TDLE)                                                   NONC1910
      IF(TCHK.LT.0.0001)GO TO 747                                          NONC1920
  542 TDEL=TDEL+DELT                                                       NONC1930
  543 IF(TDEL.LT.TIM)GO TO 621                                             NONC1940
  747 WRITE(6,81)(C(I),I=1,NC)                                             NONC1950
   81 FORMAT(21F6.0)                                                       NONC1960
      STOP                                                                 NONC1970
      END                                                                  NONC1980
```

(II) "RUN NCSTM" (Call the Main, Input with Data, and Compute.)

(1) Card Arrangement (Control Cards)

```
@RUN,A/TPC HUAAN,(account No.), LIU,2,30/0
@ASG,A HUAAN
@ASG,T 3
@FOR,SU HUAAN.NONC,.NONC

Updating Cards

@PREP HUAAN.
@PACK HUAAN.
@MAP,SI ,HUAAN.NONCXQT
 IN HUAAN.NONC
@XQT HUAAN.BODXQT

Card deck for the Input Data

@ADD,P APRIL.PDATA
@ADD,P HUAAN.IIDAT*
@ELT,IL HUAAN.IIDAT
@ADD,P 3
@PACK HUAAN
@@

Blank Card
```

* This control card serves to pick up the results obtained by the previous run as initial conditions. When the NCSTM is run for the first time, leave this card out. After the first run is completed, put this card in and insert the FORTRAN statement

```
READ(5,81) (C(I),I=1,NC)
```

in between statements NONC1050 and NONC1060 of the main program of the NCSTM as listed in the preceding pages.

(2) Listing of Typical Input Data

```
        TYPICAL INPUT DATA FOR THE NCSTM FOR MOBILE BAY

TYPICAL DATA CARDS OF THE NCSTM FOR MOBILE BAY

   CARD  1    IB,NC,IRCB

   38  798    10

    CARD  2     DELS,DELT,COLM,COLT,TIM,TPRNT,COLG,COLC

6561.38   240.        5000.   200.      4300.     360000.   0.          0.

    CARD  3     TCBSM,TCALP,TCDRM

  40.      1100.     900.

    CARD  4     TEMPF

           76.1

    CARD  5-6     IBNDL

   2  23  44  65  89 109 129 149 170 192 213 235 256 277 298 319 340 361 382 403
 425 446 467 489 510 531 552 574 595 616 637 658 679 700 721 742 763 784

    CARD  7-8     IBNDR

  11  32  53  70  99 124 145 166 166 206 226 247 266 286 306 327 348 368 389 411
 432 454 474 495 516 537 558 579 600 621 642 663 684 705 726 747 768 789

    CARD  9-10     NUM

   8   8   8   8  26  20  14   8   8  14  14  20  20  20  20  20  20  20  20  20
  26  26  26  32  32  32  32  38  38  38  38  38  38  38  38  38  38  38

    CARD  11-12     IREP

  10  10  10   6  11  16  17  18  18  15  14  13  11  10   9   9   9   8   8   9
   8   9   8   7   7   7   7   6   6   6   6   6   6   6   6   6   6   6
```

TYPICAL INPUT DATA FOR THE NCSTM FOR MOBILE BAY

```
   CARD  13-50     D(I)

  40  40  30  39  21  21  26  35  37  40  37  38  35  32  33  36  38  40  40  40  40
  37  34  39  28  17  30  16  27  38  39  40  40  32  25  30  32  33  37  39  35  37
  38  35  21   9   9  20  30  23  30  35  40  40  39  33  26  23  30  33  33  35  34
  31  29   6  11   9  23  30
                   5   6  20  20  10   2   1   1   3   6   5
   0               4   5   9  14  17  14  12   3   7   7   9   7   8   4   5   4
           4   6  10  12  10  12  12  12  12  12  10   9   7   8   8   8   5
      10  10  11  12  12  12  11  10  10  10  11  11  10   7   9   8   8   5
       6   8  10  12  11  11  10  10  10  10  11  11  11   7   9   8   4
           7  10  11  10  11  10  10  10  10  10  12  12  12   8   3
           3  10  11  11  12  11  11  10  11  10  10   9   7   3
               7  10  10  11  10  11  10  10  10   9   8   5   1
               7   9  10  12  10  11  11  10  10   8   2
               5   9  10  11  10  11  11  10   7   2
               6  10  10   9  12  11  11  10   5
               3  10  10   9  11  11  10  10   4
               4  10  10   9  11  12   9   7   4
               6  10  10  10  12  10   9   4
               6   9   9  10  11  10  11   6
               3   7   8  11  11  11  11   9   5
                   7   8   9  10  10  11  10   9
                   7   8   9  10  10  10   9  10   5
                   6   7   8  10  11  11  10   7
                       6  10   5  10   9   4   6
                       2  10  10  10   9   7   5
                       2   7  10   9   8   5  10
                       2   7   5   9   6   4   3
                           6   2   4   3   1   6
                           5   1   1   1   1   6
                          10   1   1   1   1  10
                          10   1   1   1   1  10
                          10   1   1   1   1  10
                          10   1   1   1   1  10
                          10   1   1   1   1  10
                          10   1   1   1   1  10
                          10   1   1   1   1  10
                          10   1   1   1   1  10
                          10   1   1   1   1  10
```

(III) Computing Scheme

The card sequence of the "CREATE NCSTM" was used to catalogue the main program of the NCSTM into the mass storage of the UNIVAC-1110 computer cyctem. The card sequence of the "RUN NCSTM" was used to call the main program, feed in data, and calculate the total coliform distribution within Mobile Bay. Once the main program is catalogued, only the "RUN NCSTM" deck is needed to effect computation. Changes in cell loading concentrations of total coliform and change of temperature for different months can be made by altering values of the data on data cards no. 2, 3, and 4 (see Appendix A4). Statements in the main program can be corrected, deleted, or the whole main program can be deleted from the mass storage by using appropriate control cards.

(IV) Listing of Typical Output of the NCSTM

```
           RUN TOTAL COLIFORM FOR  PARAMETRIC STUDY  U

   TOTAL COLIFORM BACTERIA IN MPN PER 100 MILITER
   T=      12.00CYCLES  DELT=     240.00

                                    10000.  3432.  1522.   492.   204.   200.

                                  6197.  7656.  3194.  1251.   458.   222.   186.

                                  4501.  5935.  2496.  1014.   411.   220.   173.

                                  3389.  4544.  2017.   852.   386.   215.   158.

                                  2590.  3403.  1664.   729.   354.   212.   152.

                           1195.  1947.  2463.  1365.   630.   339.   209.   150.

                            450.  1440.  1769.  1029.   545.   313.   200.   152.   136.

                            446.  1065.  1193.   771.   456.   274.   184.   147.

                     374.   434.   723.   832.   602.   370.   235.   162.   136.

                     365.   382.   522.   620.   481.   302.   198.   140.

                     390.   329.   407.   469.   389.   249.   165.   116.

                     464.   295.   326.   356.   314.   205.   137.    99.    84.

                     595.   274.   267.   278.   253.   169.   115.    83.    66.

                     795.   261.   223.   221.   202.   140.    96.    69.    53.

                    1106.   251.   191.   180.   161.   116.    81.    58.    43.    37.

                     747.   230.   165.   149.   127.    96.    69.    50.    37.    30.    25.

                     812.   205.   142.   123.   101.    79.    59.    44.    33.    25.    20.    15.     7.

              311.   343.   185.   123.    95.    81.    65.    51.    39.    29.    22.    17.    12.     8.

              213.   235.   152.   104.    71.    63.    54.    44.    35.    27.    20.    15.    11.     8.     6.

       107.   132.   151.   121.    86.    57.    50.    44.    37.    30.    24.    19.    14.    10.     8.     6.     6.

         0.    50.    65.    69.    70.    46.    41.    37.    31.    26.    22.    17.    13.    10.     8.     8.    10.    15.

               53.    69.    68.    56.    37.    35.    32.    28.    23.    19.    16.    12.    10.     8.    10.    17.    40.

                      55.    51.    44.    30.    30.    28.    25.    21.    17.    12.    10.     8.     7.     6.     8.    11.

                             36.    34.    25.    25.    25.    24.    21.    17.     8.     6.     5.

         0.     3.    10.    21.    21.    19.

         0.     2.     5.     8.    11.    12.     4.     2.     1.     0.

         0.     1.     2.     4.     6.     7.     3.     1.     0.     0.

         0.     0.     0.     0.     0.     0.     0.     0.     0.     0.
```

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A4 INPUT DATA SPECIFICATIONS

Card No.	Column No.	Variable* Name	Input Unit	Input Format
1	1-5	IB	--	Integer
	6-10	NC	--	Integer
	11-15	IRCB	--	Integer
2	1-10	DELS	ft.	Real
	11-20	DELT	sec.	Real
	21-30	COLM	MPN/100ml	Real
	31-40	COLT	MPN/100ml	Real
	41-50	TIM	hr.	Real
	51-60	TPRNT	sec.	Real
	61-70	COLG	MPN/100ml	Real
	71-80	COLC	MPN/100ml	Real
3	1-10	TCBSM	MPN/100ml	Real
	11-20	TCALP	MPN/100ml	Real
	21-30	TCDRM	MPN/100ml	Real
4	1-21	TEMPF	°F	Real
5-6	every 4 columns	IBNDL	--	Integer
7-8	every 4 columns	IBNDR	--	Integer
9-10	every 4 columns	NUM	--	Integer
11-12	every 4 columns	IREP	--	Integer
13-50	every 3 columns	D(I)	ft.	Real

* For description of the variables see Appendix A2.

APPENDIX B

EXAMPLES OF RAW DATA USED IN
THE NCSTM

B1 Total Coliform Bacteria

B2 River Flow Rates

B3 Wind Conditions and Temperatures

B1 EXAMPLES OF
RAW DATA OF
TOTAL COLIFORM CONCENTRATION

The Significance of EC Positive Organisms in Gulf Shellfish Growing Waters - H. S. Hosty, Alabama Health Department, Montgomery, Alabama.

The examination of Mobile Bay was divided into three separate areas during the whole course of this study. Phase 1. was to determine the significance of coliforms versus fecal coliforms as an indicator of pollution. Phase 2. was an attempt to use pathogenic E.coli as an indicator of human pollution and Phase 3. was a comparison of the sanitary quality of oysters harvested and shucked in the laboratory as compared to those harvested and shucked in individual plants.

In Phase 1 all of the procedures were those recommended by the Bacteriological Examination of Seaweed and Shellfish, third edition 1962. This investigation involved the weekly testing of 43 stations for two years or approximately 4500 coliform examinations by the three-tube test. Additionally, all positive lactose tubes were reinoculated into EC media and incubated in a water bath at 44.5° = 0.2° for 24-48 hours. For sometime, after incubation, all EC tubes positive or negative were streaked to eosin methylene blue plates. After incubation, one colony conforming to the accepted morphology of E.coli, or if no such were present, a colony which came closest to being typical, was picked and inoculated into a lactose tube. From this tube the EC test was repeated along with IMVIC determination. It soon became apparent that plating of EC negative tubes was not fruitful so the routine was altered, plating only positive EC specimens. In all some 20,000 IMVIC and repeat EC determinations were performed. No tests were performed on oysters but this is now under study.

The Mobile Bay area is roughly some 30 to 35 miles long and approximately 25 miles at its widest point. The upper part of the bay shows extreme pollution which has no effect on the Cedar Point growing areas under normal conditions. During the rainy season this immunity to contamination may abruptly change. It may be added here that last February and March Alabama experienced the worst floods in recorded history.

Figure 1 shows a general picture of the station locations as well as the normal current flow and flood pattern. A few of the upper stations, including the Alabama and Tombigbee stations, are not shown in this chart. By studying the various stations it was apparent that some areas could be grouped rather than considered independently. Alphabetically, therefore, grouped or single stations, were, in their descending order down the bay, starting with the Alabama and Tombigbee Rivers, designated as Group A, B, etc. In general we shall only discuss Group H, J, L and M. The station or stations represented by this grouping may be identified in the table showing probability percentiles.

Figure 2, Station 31, adequately shows the high pollution usually present. The overall trends suggest diluting out of EC gas positive organisms derived from the fresh sewage discharges by fresh water during periods of increased river flow. This is apparent beginning in late October, with progressively increasing separation of the coliform and EC lines throughout the flood stage which persisted until late May. When normal river flows reoccurred, there was a return to a similar pattern of the coliform and EC MPN's.

Station 48 (Figure 3) is included because it represents an area affected by run-off which reached a peak towards the end of March. The rythmical pattern of coliform and EC MPN separations were disrupted when salinity decreased. The marked increase in run-off resulted in a doubled coliform count but the EC MPN was only slightly changed. This continues until recovery of normal salinities is apparent.

Some 35 miles down the bay from Station 31, Station 88 (Figure 4) has been used as an index area. During normal salinity content in the bay the coliform count, though fluctuating, reaches sizeable peaks while the EC count remains less than three. Around the 20th of March, with falling salinity, pollution occurred and there is an immediate rise in EC MPN's. The pattern of recovery shows gradual return to the usual pattern of coliform-EC relationships.

Station 119 (Figure 5) is directly over the Cedar Point oyster area and illustrates the response of the EC test to pollution. The concurrent drop in salinity and rise in EC MPN's is dramatically evident.

The histogram (Figure 6) summarizes in percentage the confirmed EC positives as compared to coliform positive tubes and shows clearly the response of EC media to pollution as compared to the accepted coliform test. During period 1 at Group G (Station 20) immediately below the discharge of fresh sewage, the EC test was 83 percent positive compared to the coliform test and there was a gradual decline until Group M (oyster bed area) was reached where only 9.8 percent of the coliform positive tubes were EC positive. During the period 2, flood stage, no change in percent EC positiveness was apparent in area G. Some dilution by river water caused the reduction in percent EC positives at groups H and J. The most striking difference occurred in the areas immediately above and over the oyster beds. Sharp increases in percent

EC gas positives occurred. These can be explained by the influx of fresh water that received pollution in the Mobile area and, as shown in Figure 5, reached the oyster beds during the flood stage. The fact that travel time was considerably less during the flood stage with the associated reduction in dieoff rate might also be a factor which influenced the increases in percent EC gas positiveness. It is also significant that when river discharges returned to normal low rates (recovery period), the progressive decrease in percent EC positiveness, associated with distance from pollution, was demonstrated.

Table 1 shows these same grouped stations as coliform and EC percentile probabilities. Again, as one descends the bay, improvement is noted over the oyster beds (Group M) the 50 and 90 percentiles fall well within accepted norms during the normal and recovery periods but completely outside the range during the flood stage.

From 8,400 positive E.C. tests incubated for 24 to 48 hours the following was recovered: 24 hour period 88.4 percent types 1 and 11 E. coli strains, 7.9 percent irregular Vl's and 1.3 percent as other. By contrast incubation for an additional 24 hours resulted in the recovery of only 0.2 percent more E. coli but an additional two percent were irregular Vl's and others. Should this trend continue it seems to be that we are lowering the specificity of the test without increasing the sensitivity by the additional 24 hour incubation.

Some 600 strains of types 1 and 11 E. coli and 181 isolates of A. aerogenes were subjected to the E.C. test run at 44.5 and 45 C. Raising the temperature one half degree eliminated 60 percent of the aerogenes isolates while less than one percent of the E. coli strains were lost.

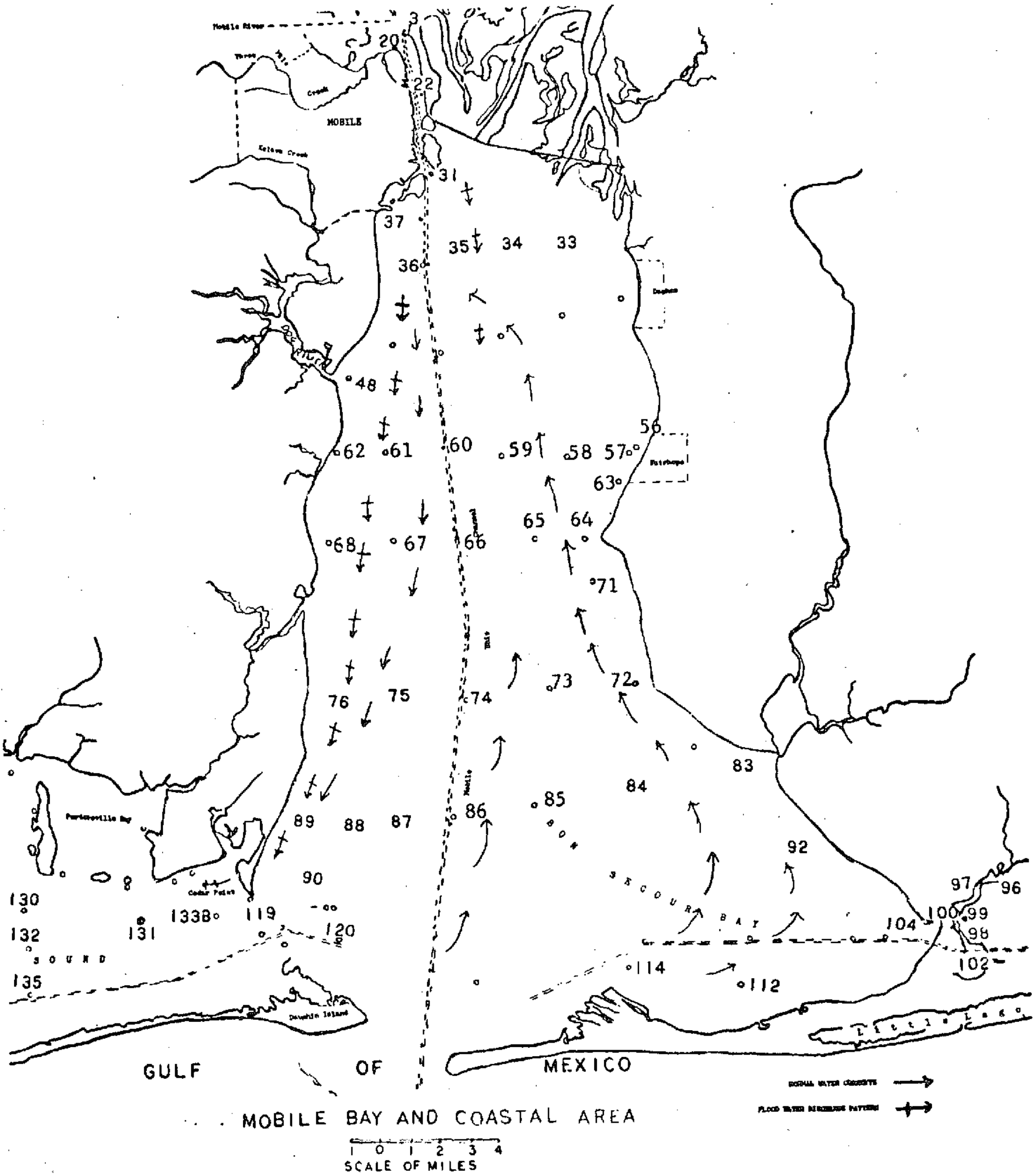


Figure 1. Coliform Sampling Station Locations in Mobile Bay.

Figure 2

STATION 31

COLIFORM and EC MPN'S with SALINITY CHANGES SEPTEMBER 1961 to SEPTEMBER 1962

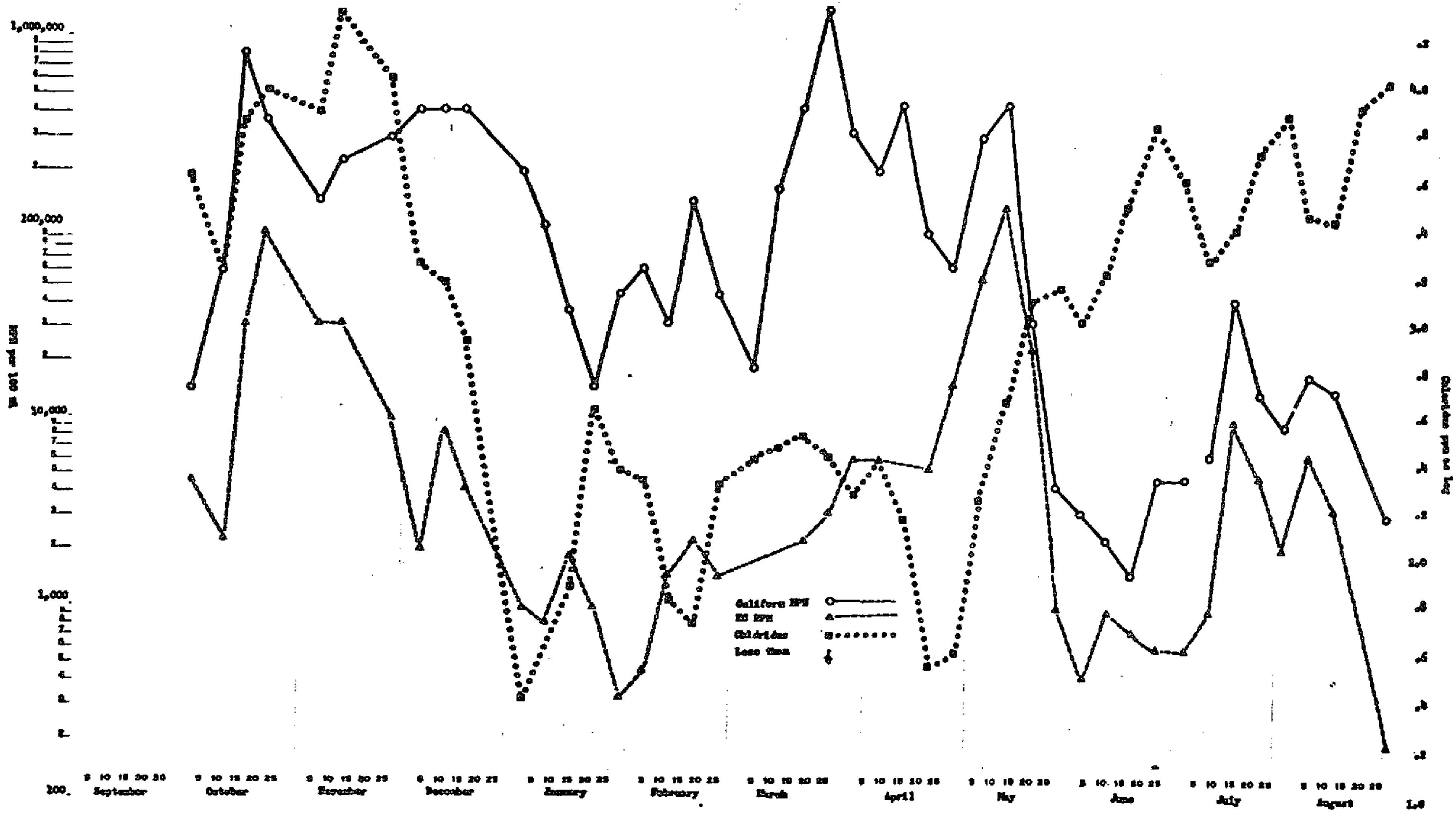


Figure 3

STATION 48

COLIFORM and EC MPN'S with SALINITY CHANGES SEPTEMBER 1961 to SEPTEMBER 1962

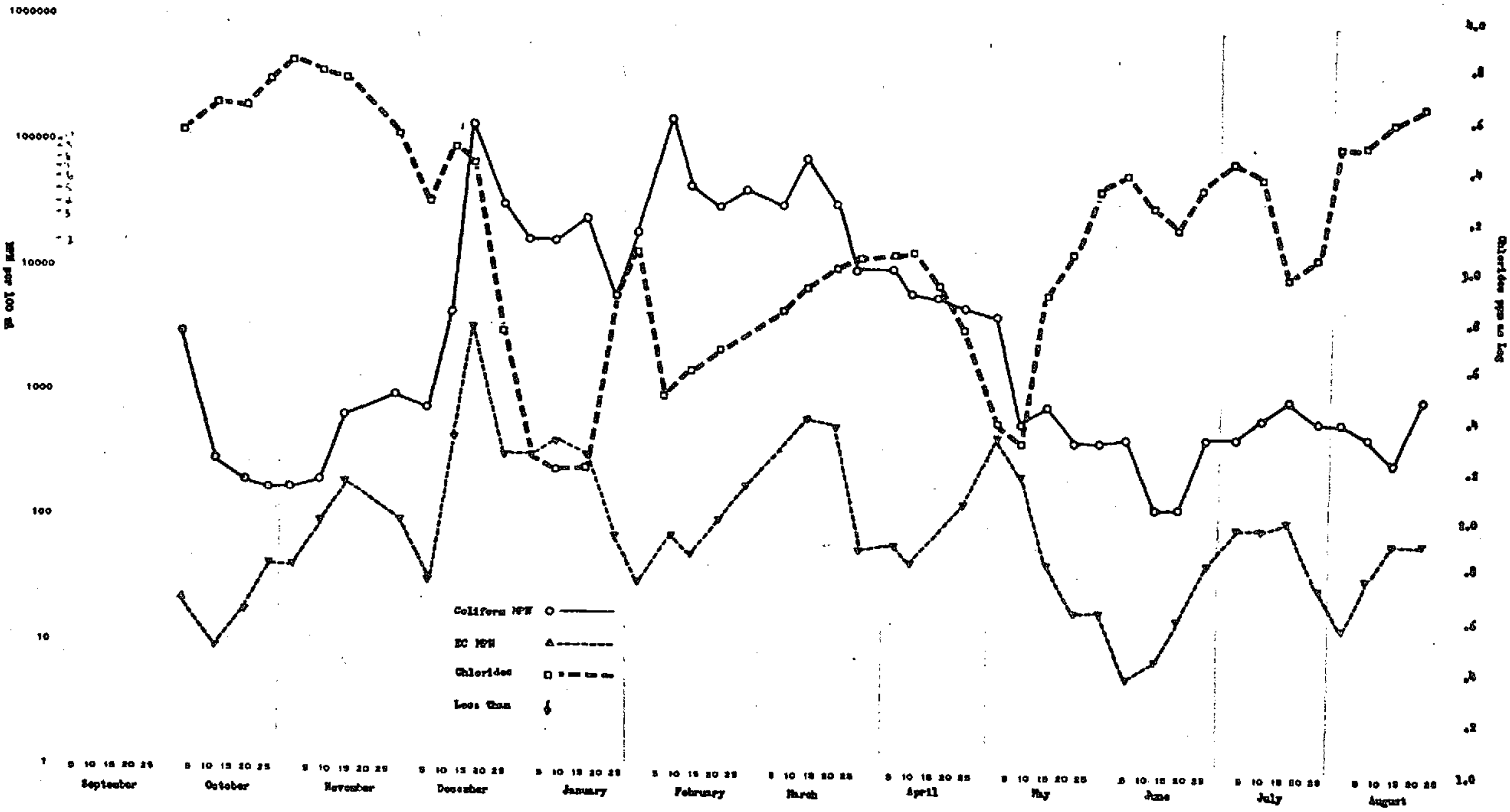


Figure 4

STATION 88
COLIFORM and EC MPN'S with SALINITY CHANGES
OCTOBER 1961 to SEPTEMBER 1962

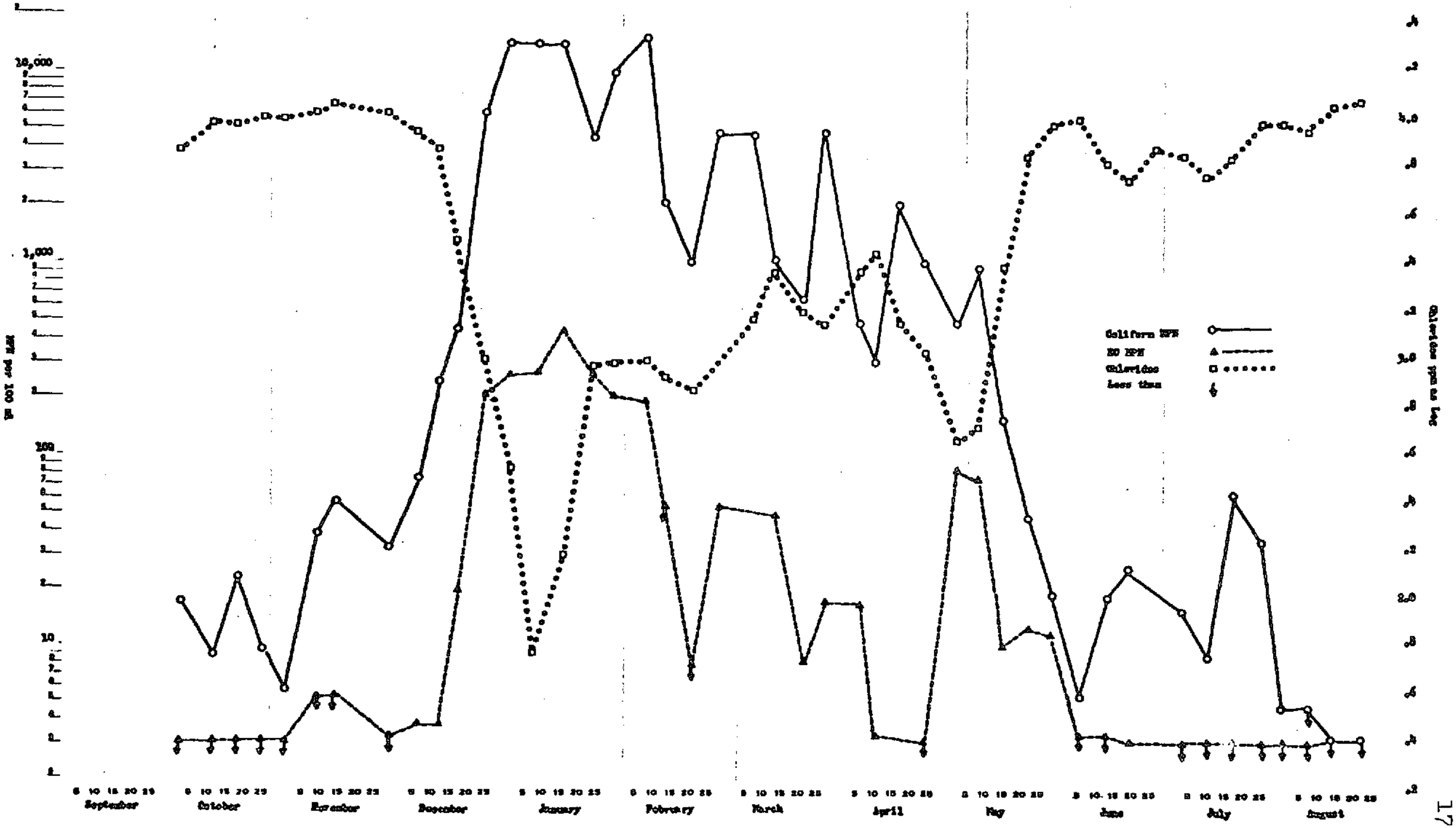
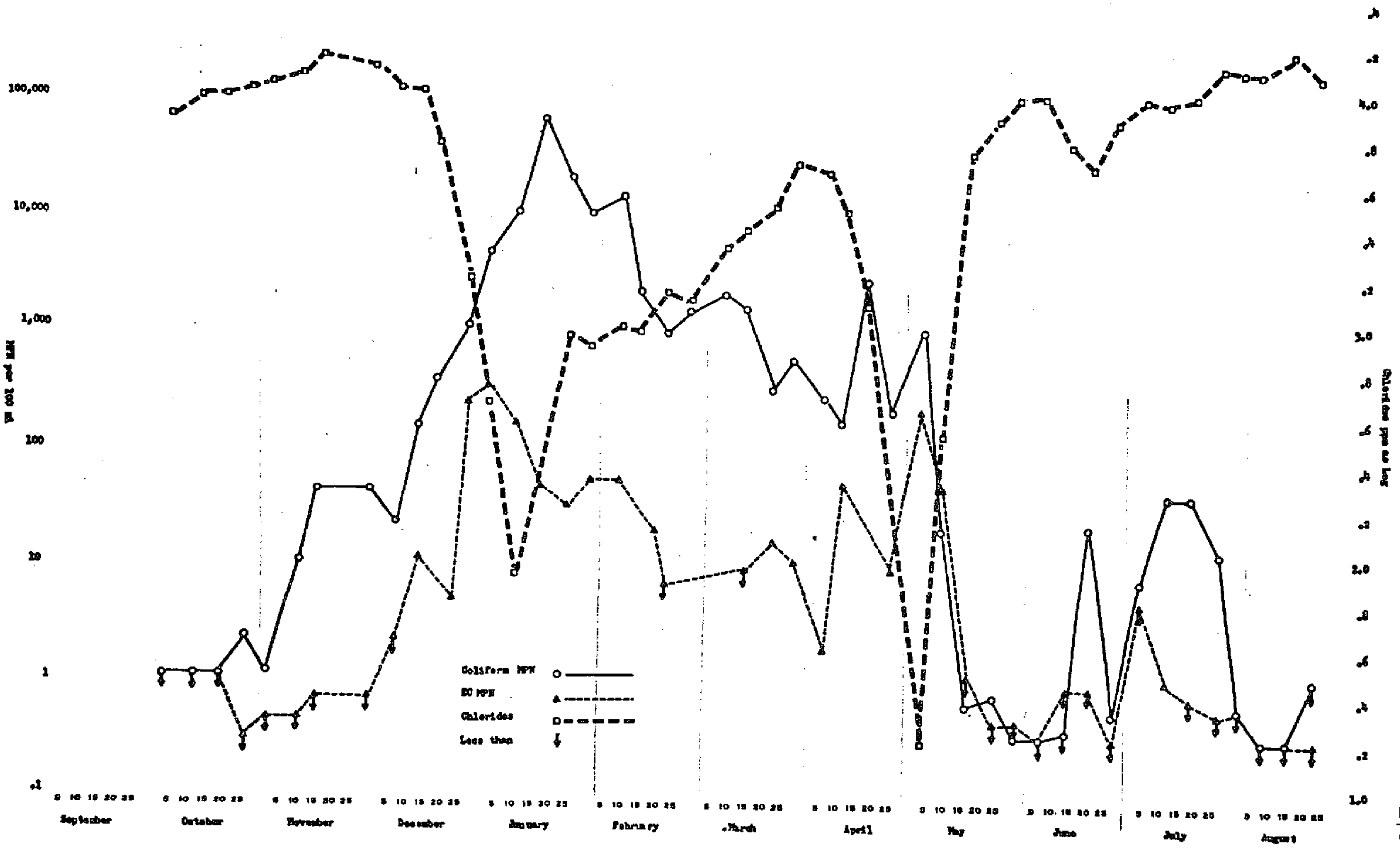


Figure 5
STATION 119
COLIFORM and EC MPN'S with SALINITY CHANGES
OCTOBER 1961 to SEPTEMBER 1962



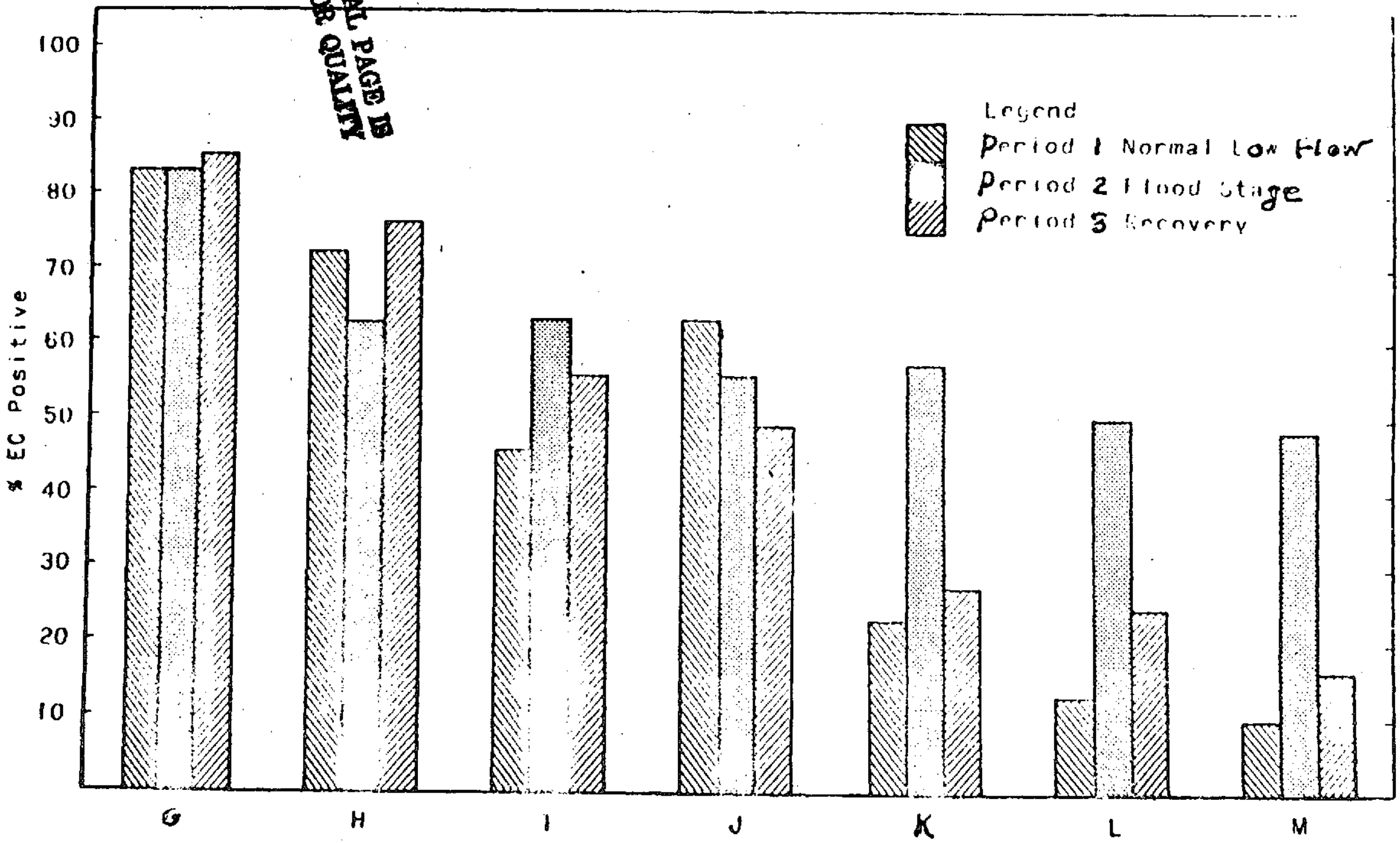


Fig. 6. Relation of Confirmed EC Positive Tubes to Coliform Positive Tubes by Period

Table 1. RELATION of COLIFORM POSITIVE TUBES to CONFIRMED EC and IMViC TYPES by PERIODS

Group	Station	Period	Coliform ÷ Tubes	Confirmed EC ÷	Incubation			
					24 Hour		48 Hour	
					E.coli I & II	Other	E.coli I & II	Other
G	20	1	327	83.10%	79.51%	3.35%	0.00%	0.30%
		2	211	82.90%	80.56%	1.42%	0.00%	0.94%
		3	260	85.70%	78.46%	5.37%	0.00%	1.92%
H	22,31 36,37	1	801	72.03%	61.92%	9.11%	0.24%	0.78%
		2	517	62.47%	56.47%	4.05%	0.19%	1.74%
		3	725	76.27%	60.68%	10.33%	0.00%	5.10%
I	33,34 35	1	64	45.31%	43.75%	1.56%	0.00%	0.00%
		2	253	62.84%	53.35%	7.89%	0.39%	1.18%
		3	233	55.36%	32.61%	17.16%	0.00%	5.57%
J	48	1	111	63.06%	53.15%	9.00%	0.90%	0.00%
		2	121	55.37%	51.23%	3.30%	0.00%	0.82%
		3	84	48.80%	32.14%	14.28%	0.00%	2.38%
K	74,75 76	1	287	23.34%	16.03%	6.26%	0.00%	1.04%
		2	263	57.03%	50.95%	4.56%	0.00%	1.52%
		3	149	27.51%	8.05%	18.79%	0.00%	0.67%
L	87,88 89	1	209	12.91%	10.04%	2.38%	0.43%	0.47%
		2	232	50.00%	47.41%	0.43%	0.00%	2.15%
		3	131	24.42%	14.50%	6.86%	0.00%	3.05%
M	90,133B 119,120	1	172	9.88%	8.72%	0.58%	0.00%	0.58%
		2	294	48.63%	42.17%	5.78%	0.00%	0.68%
		3	145	16.55%	9.65%	5.51%	0.00%	1.37%

Period 1 Normal Salinity Period 2 Flood Stage Period 3 Recovery

B2 EXAMPLES OF
RAW DATA OF
RIVER FLOW RATE

Table B2.1

2-4705 MOBILE RIVER NEAR MOUNT VERNON ALA
LOCATION--LAT 31 06 50 LONG 87 58 05 IN SE 1/4 SEC 41 T2N R1E AT BOAT PIER ON
WEST BK OF LAKE DAVID .5MI US FR LAKE OUTLET TO MOBILE RV 2.5MI NE OF MT VERNON
+ AT MILE 41.3 FR MOBILE /DRAINAGE AREA---43000 /RECORDS AVAILABLE---OCT 1953
TO SEPT 1954 / GAGE---STAGE RECORDER DATUM ABOUT 2FT BELOW MSL BY COMPARATIVE
GH READINGS AUX GAGE AT ALA ST DOCKS
THRU 1967 MOUNT VERNON FLOW =(CLAIBORNE FLOW + HY 43 FLOW) * 1.05
AFTER 1967 MOUNT VERNON FLOW =(CLAIBORNE FLOW + COFFEEVILLE FLOW) * 1.07
MONTHLY AND YEARLY DISCHARGE IN CUBIC FEET PER SECOND

W.Y.	OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	THE YEAR
1928											26500.0	28200.0	
1929	20500.0	20700.0	23400.0	45000.0	90300.0	347600.0	146700.0	132300.0	36200.0	27000.0	20200.0	20800.0	77700.0
1930	24000.0	164600.0	103600.0	71800.0	98900.0	117500.0	53700.0	54300.0	40000.0	15800.0	18400.0	23000.0	65100.0
1931	19100.0	54300.0	39400.0	58000.0	42300.0	55100.0	73500.0	34600.0	15400.0	16600.0	19500.0	10400.0	36500.0
1932	9190.0	9120.0	74400.0	126600.0	180200.0	100600.0	83200.0	49000.0	25900.0	47400.0	26700.0	35400.0	63700.0
1933	67100.0	72500.0	175100.0	211000.0	141000.0	147000.0	138500.0	46000.0	21500.0	33900.0	21200.0	19500.0	91100.0
1934	16300.0	16200.0	21100.0	39400.0	31800.0	132200.0	47900.0	28200.0	33400.0	24800.0	31700.0	19100.0	37000.0
1935	56300.0	30000.0	41100.0	72400.0	73800.0	178700.0	116000.0	75300.0	29700.0	17000.0	18400.0	16300.0	61200.0
1936	12000.0	21100.0	27000.0	184500.0	220100.0	59900.0	184200.0	38600.0	19300.0	24800.0	26500.0	15500.0	68800.0
1937	16200.0	14900.0	34400.0	177800.0	155400.0	104700.0	65900.0	123300.0	25300.0	19500.0	16600.0	30500.0	66600.0
1938	28900.0	34100.0	30100.0	53200.0	46300.0	98300.0	302800.0	43300.0	34900.0	41600.0	41400.0	17600.0	64200.0
1939	12200.0	14700.0	15200.0	42800.0	131400.0	160700.0	89400.0	38100.0	89900.0	31100.0	115700.0	27400.0	63600.0
1940	18500.0	15100.0	18900.0	45900.0	128700.0	105500.0	84500.0	48500.0	34300.0	141900.0	25600.0	15000.0	56700.0
1941	12500.0	19000.0	46000.0	54200.0	54100.0	81500.0	45800.0	20400.0	13000.0	41000.0	40500.0	15100.0	36900.0
1942	12400.0	14200.0	55100.0	51600.0	76900.0	143500.0	72800.0	25700.0	34300.0	22200.0	31700.0	19500.0	46500.0
1943	15800.0	15500.0	44000.0	123800.0	70100.0	153700.0	130200.0	39900.0	20400.0	23000.0	22000.0	16900.0	56300.0
1944	11600.0	17200.0	18500.0	45700.0	87700.0	172600.0	266900.0	126800.0	26200.0	17900.0	27500.0	21000.0	69700.0
1945	13100.0	14600.0	26300.0	66400.0	115100.0	165200.0	101300.0	92600.0	23900.0	21200.0	18800.0	13200.0	55700.0
1946	15300.0	18700.0	54000.0	205200.0	212700.0	172700.0	106800.0	91800.0	67300.0	54200.0	49300.0	32800.0	89400.0
1947	18000.0	46300.0	40800.0	195100.0	128000.0	132900.0	157100.0	73000.0	44200.0	33100.0	17200.0	15000.0	74800.0
1948	12100.0	39000.0	68900.0	46500.0	187600.0	214300.0	135900.0	28300.0	20200.0	23800.0	29400.0	16600.0	68100.0
1949	15100.0	76000.0	235100.0	204300.0	223500.0	125600.0	132500.0	103600.0	46200.0	50000.0	29400.0	32300.0	105700.0
1950	17000.0	24400.0	30700.0	101300.0	112500.0	134700.0	62800.0	52400.0	28400.0	35600.0	35300.0	69000.0	58400.0
1951	21300.0	23200.0	39200.0	66500.0	114200.0	102600.0	242900.0	45600.0	23200.0	22200.0	15300.0	14100.0	60400.0
1952	12600.0	22600.0	81800.0	91300.0	84800.0	145700.0	77100.0	34900.0	24000.0	12800.0	16800.0	12900.0	51400.0
1953	11200.0	11900.0	28600.0	100200.0	109800.0	150300.0	80500.0	144800.0	22700.0	27200.0	15000.0	12600.0	59500.0
1954	15500.0	13500.0	68400.0	70400.0	73800.0	61000.0	74800.0	34700.0	16400.0	11000.0	10500.0	9430.0	38100.0
1955	7610.0	9420.0	12500.0	47200.0	89800.0	72400.0	160100.0	40500.0	28900.0	27100.0	22200.0	10800.0	43600.0
1956	10100.0	14000.0	18300.0	13900.0	124100.0	137600.0	137800.0	38000.0	16800.0	24000.0	10400.0	11800.0	46000.0
1957	15600.0	12900.0	48700.0	49900.0	127800.0	79000.0	159000.0	51000.0	31500.0	29100.0	12600.0	21700.0	52600.0
1958	34900.0	93600.0	127700.0	65900.0	108900.0	142200.0	90200.0	105800.0	24000.0	58800.0	24800.0	25300.0	75100.0
1959	23400.0	19600.0	25900.0	56800.0	108400.0	85800.0	87900.0	37900.0	71100.0	18900.0	13800.0	17900.0	46600.0
1960	29900.0	32200.0	43300.0	83400.0	129800.0	155100.0	103000.0	38800.0	18600.0	13000.0	18000.0	15800.0	56500.0
1961	22100.0	21300.0	28500.0	37600.0	127900.0	335900.0	179400.0	45500.0	44200.0	51800.0	21200.0	22000.0	77800.0
1962	13800.0	22000.0	217600.0	203800.0	151700.0	143100.0	186900.0	38500.0	25400.0	19200.0	12500.0	15400.0	87200.0
1963	17800.0	23400.0	24100.0	66600.0	75800.0	124100.0	38000.0	70900.0	41900.0	46300.0	21000.0	13900.0	47100.0
1964	14200.0	13300.0	37700.0	86400.0	101600.0	210300.0	277100.0	133500.0	23700.0	30500.0	24100.0	15600.0	80500.0

Table B2.2

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                              2-4705 MOBILE RIVER NEAR MOUNT VERNON ALA
                    LOCATION--LAT 31 06 50 LONG 87 58 05 IN SE 1/4 SEC 41 T2N R1E AT BOAT PIER ON
                    WEST BK OF LAKE DAVID .5MI US FR LAKE OUTLET TO MOBILE RV 2.5MI NE OF MT VERNON
                    + AT MILE 41.3 FR MOBILE  /DRAINAGE AREA---43000 /RECORDS AVAILABLE---OCT 1953
                    TO SEPT 1954 / GAGE---STAGE RECORDER DATUM ABOUT 2FT BELOW MSL BY COMPARATIVE
                    GH READINGS AUX GAGE AT ALA ST DOCKS
                    THRU  1967  MOUNT VERNON FLOW =( CLAIBORNE FLOW + HY 43 FLOW) * 1.05
                    AFTER 1967  MOUNT VERNON FLOW =( CLAIBORNE FLOW + COFFEEVILLE FLOW) * 1.07
                                         MONTHLY AND YEARLY DISCHARGE IN CUBIC FEET PER SECOND
   W.Y.    OCTOBER NOVEMBER DECEMBER JANUARY FEBRUARY    MARCH    APRIL      MAY      JUNE      JULY  AUGUST SEPTEMBER THE YEAR

   1965    33800.0  26800.0  79300.0  88200.0 153200.0 130500.0 113000.0  21500.0  26400.0  20700.0  18700.0  17300.0   60200.0

   1966    22900.0  15800.0  21900.0  48400.0 151800.0 129300.0  58900.0 106000.0  25200.0  16700.0  19000.0  20500.0   52500.0
   1967    27800.0  37900.0  41700.0  56100.0  73400.0  50800.0  18400.0  48400.0  21900.0  52400.0  49600.0  44500.0   43600.0
   1968    25500.0  49600.0 160400.0 200800.0  47800.0  83600.0  95600.0  78000.0  23000.0  27500.0  23800.0  13700.0   69500.0
   1969    11700.0  17100.0  52400.0  71400.0 108400.0  84800.0 131900.0  79900.0  26700.0  18100.0  17000.0  21400.0   53000.0
   1970    21500.0  16000.0  39600.0  72600.0  55400.0 127400.0 116700.0  67300.0  43900.0  14800.0  23700.0  18200.0   51400.0

   1971    23400.0  27300.0  34600.0  75600.0 133800.0 247400.0  95900.0  79400.0  29200.0  34300.0  37300.0  29700.0   70400.0
   1972    17200.0  16500.0  94700.0 204200.0  95300.0 116000.0  51300.0  43000.0  25000.0  26500.0  19200.0  18700.0   61100.0
   1973    12700.0  20000.0  94600.0 167700.0 121900.0 172600.0 229600.0 141000.0  94900.0  48300.0  28000.0  19000.0   96200.0
   TOTAL  890500.01329640.02651000.04251400.05077800.06190400.05424400.02891100.01458500.01415400.01184000.0 952330.0 2794000.0
 AVERAGE   19788.9  29547.6  58911.1  94475.6 112840.0 137564.4 120542.2  64246.7  32411.1  31453.3  25739.1  20702.8   62088.9
          ROUND OFF AVERAGES TO 3 SIGNIFICANT FIGURES
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B3 RAW DATA OF
WIND CONDITIONS
AND TEMPERATURES

Table B3.1

CLIMATOLOGICAL DATA

CONTINUED

ALABAMA
FEBRUARY 1962

Station	Temperature													Precipitation									
										No. of Days								Snow, Sleet			No. of Days		
										Max.		Min.											
	Average Maximum	Average Minimum	Average	Departure From Normal	Highest	Date	Lowest	Date	Degree Days	90° or Above	32° or Below	32° or Below	0° or Below	Total	Departure From Normal	Greatest Day	Date	Total	Max. Depth on Ground	Date	.10 or More	.50 or More	1.00 or More
SELMA	72.8	46.1	60.5	7.4	85	27	25	7	162	0	0	3	0	4.08	-.86	1.53	22	.0	0		5	2	2
TUSKEGEE 2	71.3	45.5	58.4	6.8	83	27	22	7	201	0	0	4	0	3.99	-.55	.82	22	.0	0		7	5	0
UNION SPRINGS 5 S	70.4H	44.1H	57.3H	5.1	84	28+	21	7	233	0	0	3	0	4.66	+.06	1.80	16	.0	0		6	3	2
DIVISION			58.0	6.2										3.29	-1.49			.0					
COASTAL PLAIN																							
ANDALUSIA 1 NW	71.3	45.4	58.3		87	28	28	7	225	0	0	3	0	6.05		3.65	19	.0	0		7	3	1
ATMORE STATE FARM	72.8	48.1	60.5		82	27+	26	7	153	0	0	2	0	7.34		4.00	19	.0	0		9	4	1
BRANTLEY	72.4	43.3	57.9		86	14	20	7	233	0	0	5	0	4.39	-.42	2.67	19	.0	0		6	3	1
BREWTON 3 SSE	75.2	47.3	61.3	7.6	87	13	22	7	154	0	0	4	0	9.91	5.32	4.50	19	.0	0		8	4	3
CAMDEN 3 NW	73.5	48.2	60.9		85	27+	21	7	157	0	0	3	0	2.77		.97	26	.0	0		6	2	0
CHATOM	74.7	45.4	60.1		85	26+	20	7	178	0	0	5	0					.0	0				0
CLAYTON			M				24	7		0	0		0	4.05	-.79	2.00	19	.0	0		5	4	1
DOTHAN FAA AIRPORT	72.3	49.4	60.9		84	27	26	7	164	0	0	2	0	6.99	2.41	2.60	18	.0	0		6	3	3
ENTERPRISE	74.6	48.4	61.5		85	27+	26	7	143	0	0	1	0	6.32		4.21	19	.0	0		7	2	1
EUFAULA	73.9	45.5	59.7	6.6	85	13	23	8+	164	0	0	2	0	4.99	.41	3.10	19	.0	0		7	2	1
EVERGREEN	72.0	44.3	58.2		86	14	25	7	223	0	0	5	0	4.80		2.07	19	.0	0		4	4	2
FRISCO CITY	70.9	47.4	59.2		84	28	25	7	193	0	0	4	0	3.81	-.71	2.09	19	.0	0		6	2	1
GENEVA	72.4	46.0	59.2		85	28+	23	7	201	0	0	3	0	7.11	2.80	4.78	19	.0	0		5	2	2
GILBERTOWN	74.3	45.1	59.7		85	27	20	7	187	0	0	5	0	2.05		.67	16	.0	0		5	2	0
GREENVILLE	74.3	47.8	61.1	7.6	86	27+	25	7	192	0	0	3	0	3.27	-1.67	.93	19	.0	0		5	3	0
HEADLAND	72.3	46.4	58.9		84	14	25	7	203	0	0	3	0	6.18		4.60	19	.0	0		8	2	1
HIGHLAND HOME	70.5	45.4	58.0	5.2	85	14	24	7	224	0	0	5	0	3.58	-1.44	1.50	19	.0	0		5	2	1
LOCKHART	71.9	49.1	60.5		86	14	24	7	166	0	0	2	0	12.08		8.20	19	.0	0		4	3	2
NATCHEZ	73.9	45.0	59.5		85	13	19	7	189	0	0	4	0	1.93		.70	19	.0	0		5	1	0
OZARK 6 NNW	72.4	44.3	58.4	4.2	87	15	24	7	215	0	0	4	0	5.42	.77	2.21	19	.0	0		7	4	2
PHENIX CITY 2 NNE	69.3	41.8	55.6		82	14	22	6+	272	0	0	5	0	4.93		2.22	22	.0	0		5	3	2
PUSHMATAHA	71.0	41.2	56.1	5.0	85	14	20	8+	269	0	0	8	0	2.45	-2.74	.85	22	.0	0			1	0
SEALE	73.0	44.2	58.6		85	13	21	7	209	0	0	7	0	3.12		1.16	19	.0	0		6	2	1
THOMASVILLE	69.8	45.0	57.4	5.6	83	28+	23	7	237	0	0	4	0	2.55	-2.59	.87	16	.0	0		5	2	0
TROY	73.3	48.9	61.1	8.5	85	13	25	7	147	0	0	3	0	5.32	.92	2.39	19	.0	0		7	4	1
WHATLEY	73.6	45.2	59.5		86	13	20	7	186	0	0	4	0	2.30		.73	24	.0	0		6	2	0
DIVISION			59.3	6.0										4.98	.27			.0					
GULF																							
BAY MINETTE	72.2	50.3	61.3		84	27	28	7	140	0	0	1	0	9.74				.0	0				
CITRONELLE	72.4	49.8	61.1	6.1	84	13	26	7	136	0	0	2	0	4.48	.03	.93	18	.0	0		9	3	0
CODEN	71.3	52.1	61.7		80	28+	29	7	133	0	0	1	0	1.28		.67	19	.0	0		4	1	0
FAIRHOPE 2 NE	72.6	52.3	62.5	7.3	84	27	30	7	121	0	0	1	0	2.26	-1.62	.63	19	.0	0		6	2	0
FORT MORGAN	67.3	55.1	61.2		75	27	35	7	125	0	0	0	0	1.88		.75	18	.0	0		7	1	0
MOBILE WB AIRPORT	71.5	51.8	61.7	7.0	84	13	28	7	141	0	0	2	0	6.57	1.98	2.72	18	.0	0		8	4	1
MOBILE	68.7	52.6	60.7	5.7	81	13	32	7	150	0	0	1	0	4.92	.85	1.80	19	.0	0		8	4	2
ROBERTSDALE 1 E	70.6	49.1	59.9		83	28	28	7	174	0	0	2	0	2.88	-1.29	1.07	19	.0	0		6	1	1
DIVISION			61.3	4.0										4.25	.05			.0					

SUPPLEMENTAL DATA

Station	Wind direction		Wind speed m. p. h.				Relative humidity averages - percent				Number of days with precipitation								
	Prevailing	Percent of time from prevailing	Average	Fastest mile	Direction of fastest mile	Date of fastest mile	Midnight CST	6:00 a CST	Noon CST	6:00 p CST	Trace	.01-.09	.10-.49	.50-.99	1.00-1.99	2.00 and over	Total	Percent of possible sunshine	Average sky cover sunrise to sunset
BIRMINGHAM WB AIRPORT	SSE	12	10.6	38	W	23	73	83	55	58	-	-	-	-	-	-	-	58	6.9
HUNTSVILLE WB AIRPORT	SE	16	9.4	35++	SSW	23	74	83	59	65	0	2	5	3	2	1	13	-	6.3
MOBILE WB AIRPORT	S	18	12.0	32++	N	6	88	89	66	78	4	5	4	3	0	1	17	-	6.8
MONTGOMERY WB AIRPORT	S	10	9.6	34	SW	22	77	82	56	60	4	4	4	1	0	0	13	52	5.4

Table B3.2

CLIMATOLOGICAL DATA

CONTINUED

ALABAMA
JULY 1962

Station	Temperature: Average Maximum	Average Minimum	Average	Departure From Normal	Highest	Date	Lowest	Date	Degree Days	No. of Days: Max. 90° or Above	Max. 32° or Below	Min. 32° or Below	Min. 0° or Below	Precipitation: Total	Departure From Normal	Greatest Day	Date	Snow, Sleet: Total	Max. Depth on Ground	Date	No. of Days: .10 or More	.50 or More	1.00 or More
SELMA	95.4	72.0	83.7	1.9	100	23+	65	10	0	31	0	0	0	.53	- 4.68	.16	6	.0	0		2	0	0
TUSKEGEE 2	93.0	70.7	81.9	1.2	98	23+	63	10	0	25	0	0	0	6.20	.81	1.64	4	.0	0		10	3	3
UNION SPRINGS 5 S			M						0		0	0	0	5.52	- .60	1.50	7	.0	0		5	4	3
DIVISION			82.4	.9										3.40	- 2.07			.0					
COASTAL PLAIN																							
ANDALUSIA 1 NW	94.6	70.0	82.3		101	25	63	10+	0	29	0	0	0	1.25		.48	27	.0	0		3	0	0
ATMORE STATE FARM	95.0	71.2	83.1		100	21	67	20+	0	30	0	0	0	4.17		1.57	7	.0	0		5	3	2
BRANTLEY	95.0	68.4	81.7		99	24+	60	10	0	29	0	0	0	3.82	- 2.12	1.27	5	.0	0		9	3	1
BREWTON 3 SSE	95.2	69.1	82.2	1.6	100	22	63	13	0	31	0	0	0	7.68	- .11	2.84	6	.0	0		8	6	2
CAMDEN 3 NW	95.3	70.1	82.7		99	27	64	20	0	30	0	0	0	3.95		1.52	7	.0	0		8	3	1
CHATOM	95.4	67.5	81.5		98	31+	59	20	0	30	0	0	0	3.72		1.98	26	.0	0		8	1	1
CLAYTON	93.7	71.3	82.5		97	23+	66	10	0	27	0	0	0	4.13	- 1.97	.76	21	.0	0		8	4	0
DOTHAN FAA AIRPORT	93.0	72.9	83.0		99	22	66	10	0	28	0	0	0	2.76	- 3.34	.95	25	.0	0		6	2	0
ENTERPRISE	93.4	72.2	82.8		97	23	67	10	0	28	0	0	0	6.37		2.41	7	.0	0		7	4	2
EUFAULA	94.9	68.9	81.9	.3	101	21	60	10	0	30	0	0	0	3.44	- 3.16	.87	24	.0	0		9	2	0
EVERGREEN	94.1	69.6	81.9		99	25+	64	11	0	28	0	0	0	3.60		.98	30	.0	0		5	4	0
FRISCO CITY	93.6	70.8	82.2		97	25+	66	20+	0	30	0	0	0	6.49	.29	2.02	7	.0	0		8	4	3
GENEVA	95.4	70.5	83.0		103	23	65	11+	0	30	0	0	0	4.28	- 2.18	2.14	23	.0	0		10	2	1
GILBERTOWN	96.8	68.3	82.6		101	23+	60	20	0	31	0	0	0	2.75		.90	7	.0	0		6	2	0
GREENVILLE	94.8	71.5	83.2	1.8	99	21	67	1	0	29	0	0	0	6.69	- .12	2.48	8	.0	0		9	4	2
HEADLAND	92.9	71.6	82.3		97	22	68	11+	0	30	0	0	0	6.23		1.82	10	.0	0		8	4	3
HIGHLAND HOME	91.0M	70.2	80.6M	- .5	95	24	67	1	0	25	0	0	0	7.64	1.17	2.80	29	.0	0		6	5	2
LOCKHART	93.5	71.4	82.5		98	23	67	11+	0	28	0	0	0	2.95		.82	6	.0	0		5	3	0
NATCHEZ	95.7	67.2	81.5		99	22+	61	20+	0	31	0	0	0	4.81		1.55	30	.0	0		7	4	2
OZARK 6 NNW	92.8	71.0	81.9	.9	98	23	65	10	0	21	0	0	0	5.47	- .89	1.72	5	.0	0		8	4	2
PHENIX CITY 2 NNW	92.5	71.6	82.1		98	24	68	10	0	25	0	0	0	4.82		.84	26	.0	0		11	5	0
PUSHMATAHA	95.3	69.5	82.4	1.8	101	22	61	20+	0	30	0	0	0	4.02	- 2.34	1.87	31	.0	0		6	2	1
SEALE	94.0	68.6	81.3		98	24+	63	10+	0	28	0	0	0	2.30		.63	29	.0	0		7	1	0
THOMASVILLE	94.8	70.7	82.8	2.1	100	23	65	10	0	29	0	0	0	3.13	- 3.47	.92	27	.0	0		6	4	0
TROY	93.7M	70.6M	82.2M	1.6	99	21	66	10	0	30	0	0	0	3.83	- 2.57	1.10	30	.0	0		9	2	1
DIVISION			82.7	1.2										4.42	- 2.42			.0					
GULF																							
BAY MINETTE	92.8	73.5	83.2		98	21	70	27+	0	29	0	0	0	3.84		3.08	8	.0	0		3	1	1
CITRONELLE	94.9	72.2	83.6	2.6	102	4	69	27+	0	30	0	0	0	7.90	- .41	3.83	26	.0	0		9	4	2
CODEN	93.7	73.6	83.7		97	19+	69	11+	0	31	0	0	0	7.11		1.64	7	.0	0		14	5	3
FAIRHOPE 2 NE	93.2	73.8	83.5	2.2	97	9	69	11	0	29	0	0	0	5.38	- 3.51	1.70	18	.0	0		8	3	2
FORT MORGAN	90.8	78.6	84.7		94	31	73	8	0	25	0	0	0	1.94		.93	8	.0	0		3	2	0
MOBILE WB AIRPORT	93.3	73.5	83.4	2.4	98	9	70	27+	0	29	0	0	0	5.44	- 4.29	1.94	18	.0	0		9	3	2
MOBILE	94.2	75.9	85.1	2.8	100	22+	70	8	0	30	0	0	0	7.62	- .86	2.50	8	.0	0		9	5	3
ROBERTSDALE 1 E	93.6	71.3	82.5		97	22	67	11+	0	30	0	0	0	5.13	- 4.67	1.69	6	.0	0		8	4	2
DIVISION			83.7	2.4										5.55	- 3.30			.0					

SUPPLEMENTAL DATA

Station	Wind direction: Prevailing	Percent of time from prevailing	Wind speed m. p. h.: Average	Fastest mile	Direction of fastest mile	Date of fastest mile	Relative humidity averages - percent: Midnight CST	6:00 a CST	Noon CST	6:00 p CST	Number of days with precipitation: Trace	.01-.09	.10-.49	.50-.99	1.00-1.99	2.00 and over	Total	Percent of possible sunshine	Average sky cover sunrise to sunset
BIRMINGHAM WB AIRPORT	NE	8	6.3	34	NW	4	77	80	49	54	1	3	8	0	1	0	13	69	6.5
HUNTSVILLE WB AIRPORT	N	8	5.8	25++	NNW	5	78	84	48	51	4	6	1	0	1	0	12	-	5.8
MOBILE WB AIRPORT	SW	10	5.9	23++	SSW	28	91	91	56	73	2	8	6	1	2	0	17	-	6.2
MONTGOMERY WB AIRPORT	N	11	6.8	34	N	7	81	82	53	59	3	3	3	0	2	0	11	58	5.9

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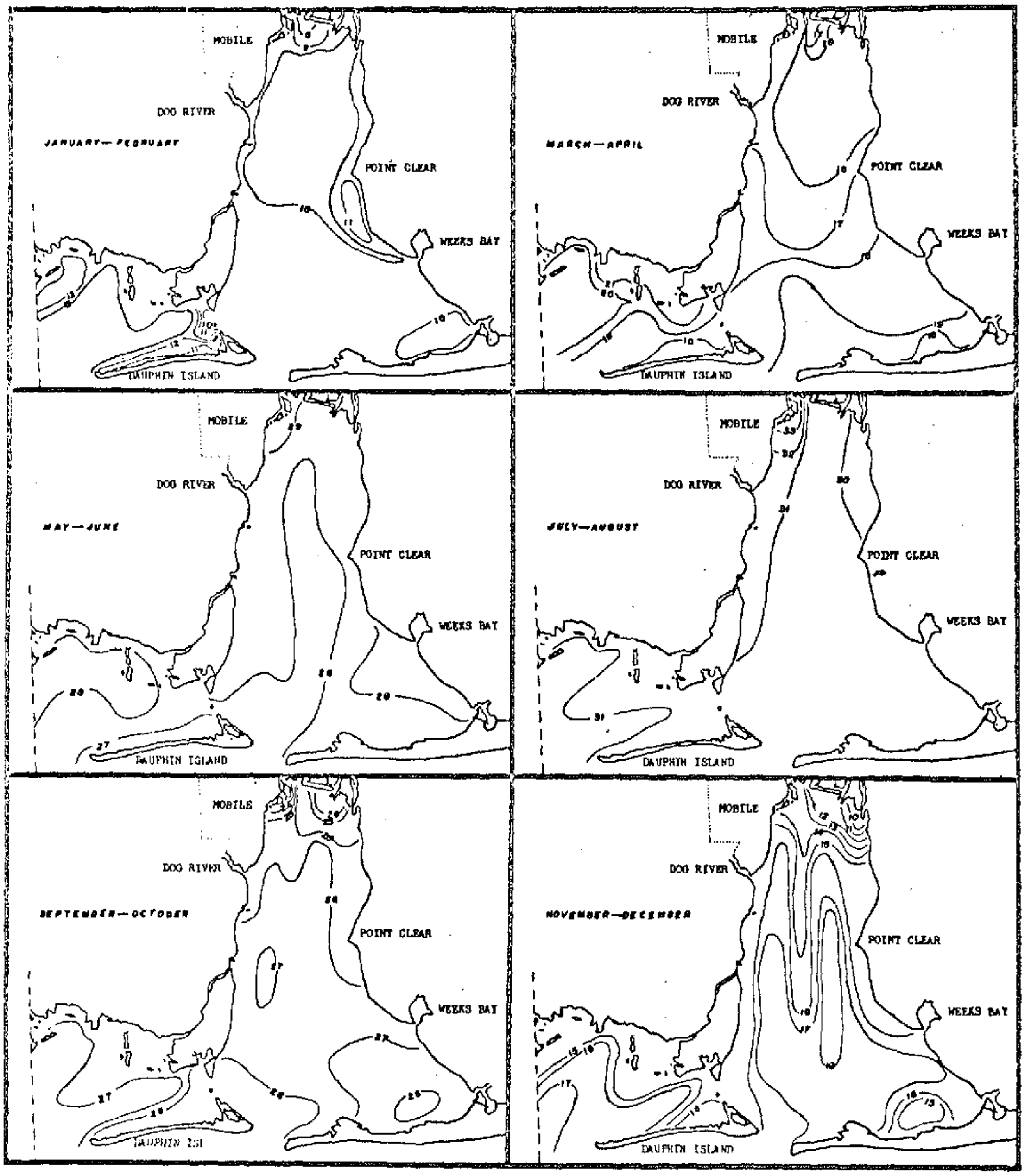

Fig. B3.1 Bimonthly surface isothermal maps of Mobile Bay and Mississippi Sound, Alabama. Combined data from 1963-64, 1965-66 (McPhearson, 1970) and January, 1968 through March, 1969.

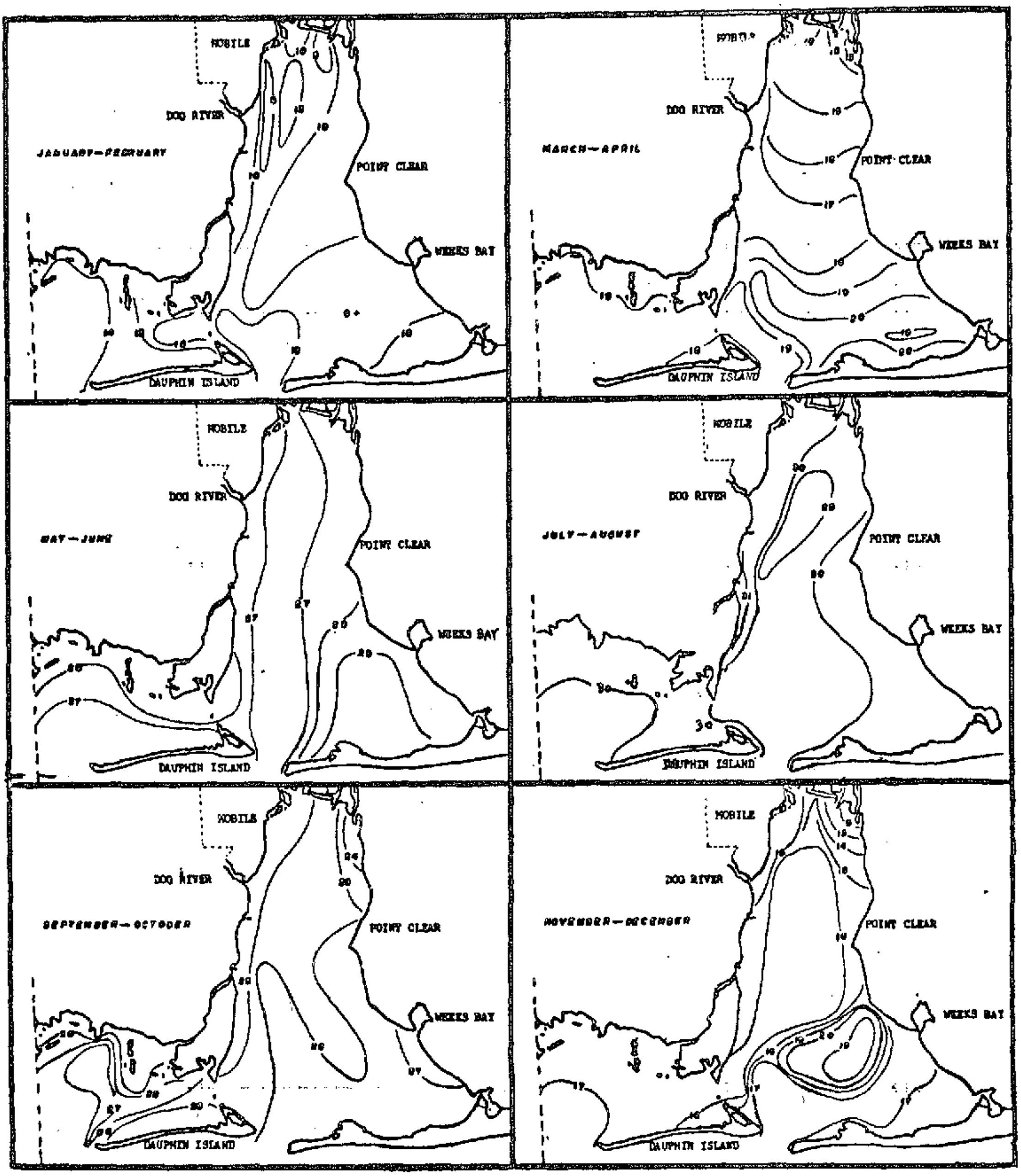

Fig. B3.2 Bimonthly bottom isothermal maps of Mobile Bay and Mississippi Sound, Alabama. Combined data from 1963-64, 1965-66 (McPhearson, 1970) and January, 1968 through March, 1969.