COMPUTER SIMULATION OF CHANGE IN GROUNDWATER ELEVATION

by

Morgan S. Ely

A report submitted in partial fulfillment

of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil Engineering

UTAH STATE UNIVERSITY
Logan, Utah
1973

ACKNOWLEDGMENTS

I would like to take this opportunity to thank the members of my graduate committee, Professors J. Paul Riley, Project Director, Joel Fletcher, and Cleve Milligan. Each of these men has been an excellent teacher and a personal inspiration. Their continued help has made it possible for me to reach this point in my college studies.

Special appreciation is expressed for the help rendered by Dr. Leon Huber and Dr Bi-Huei Wang for their assistance in interpreting and modifying the computer model which was the basis of this report.

A portion of the financial support for the studies for this paper was provided by USAID/csd-2459 contract with Utah State University. The opinions and comments are my own and do not necessarily reflect those of USAID, the United States Government, or the University.

This acknowledgment would not be complete without a special word of thanks to Miss Ruby Johnson for her help in typing this and other of my graduate school papers and reports.

Finally a word of appreciation to my wife, Puchita, and to our children Ernest and Lizzie, who have had to live on modest fare and without my full attention during this period of my studies.

TABLE OF CONTENTS

TABLE OF CONTENTS

(Continued)

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Description of the Problem

In many undeveloped low-lying areas the consumptive use of water by native phreatophytic vegetation is sufficient to maintain groundwater table levels at depths below the normal root zone of agricultural crops. However, when these areas are cleared of native vegetation and planted to various crops, there is a definite possibility that the groundwater table may rise into the root zone of the crops and drown them. This problem is further aggravated if irrigation is required. The soils of the Atlantico-3 area of Northern Colombia, South America (Figures 1 and 2) have good productive potential, but the area is underlain by high groundwater levels. To a large degree, the groundwater is recharged from the Del Dique Canal and the Rio Magdalena, which form, respectively, the southwestern and eastern boundaries of the Project area. The Government of Colombia and outside consultants are conducting extensive investigations to determine the possibility of producing agricultural crops within the Project on a permanent and sound economic basis. These studies are being carried out in the fields of engineering, economics, and social sciences to determine the feasibility of further development of the Project area.

Objectives

The basic objectives of the study reported herein are:

1. To demonstrate the utilization of a hydrologic simulation model which was developed under earlier studies.

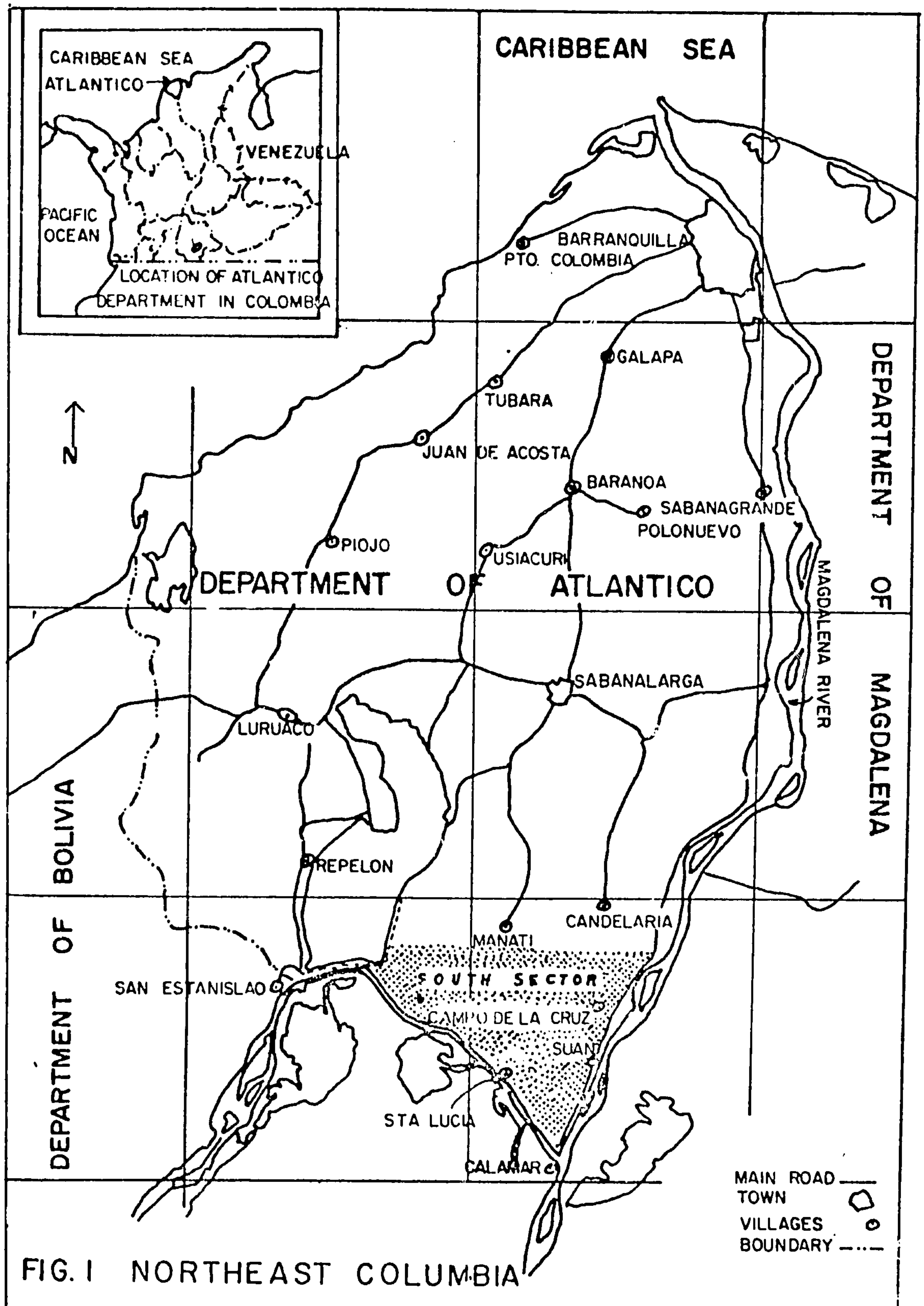


FIG. I NORTHEAST COLUMBIA

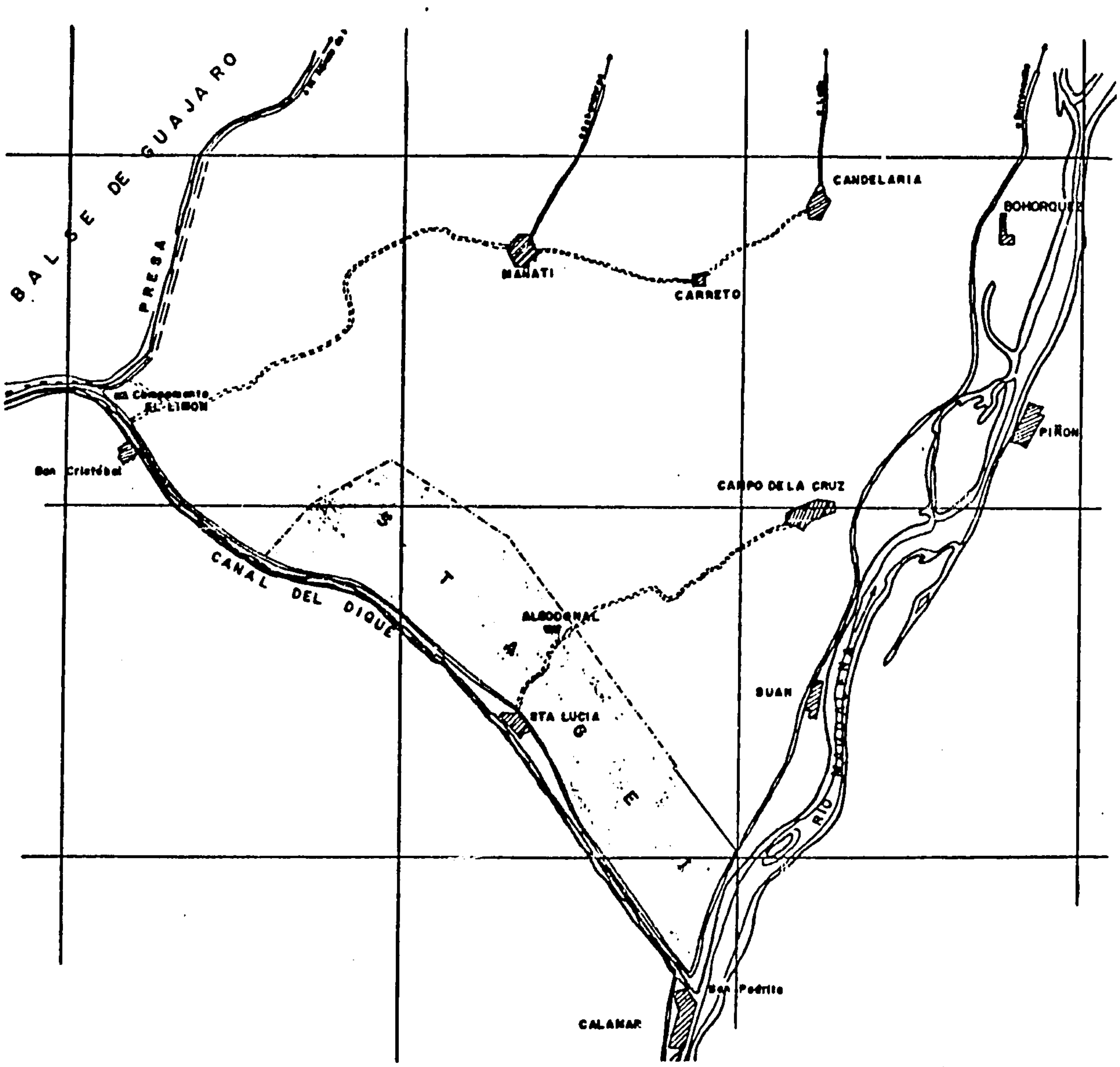


FIG. 2 ATLANTICO-3 AREA

2. to make recommendations on modifications or improvements to the model to further increase its capabilities in terms of the Atlantico-3 Project.

In order to demonstrate the utility of the model for providing needed information for management decisions, the study is divided into three specific phases. It is recognized at the outset that basic field data are deficient for the drawing of firm conclusions, but it is hoped that the report does demonstrate the applicability of the model to the kinds of engineering problems considered by each of the three phases.

The first phase is concerned with determining the effects on surface water and groundwater of a physical barrier which was recently constructed across the northern part of the area to prevent runoff from the northern highlands from entering the study area. The runoff would be conducted east to the Magdalena River and west to the Guajaro Reservoir.

Under the second phase of the study, the effects on groundwater table levels of varying phreatophyte densities are examined. The phreatophyte density varies from zero on the cleared grassy plains to about eighty percent in the densely foliaged areas. Exact densities for this vegetation are difficult to determine because no aerial photographs were available at the time of this study. It is possible to vary the phreatophyte density in the field by either clearing the land or planting additional phreatophytes to gain almost any desired effect on groundwater levels.

The third phase deals with the quantities and occurrence of surface runoff within the Project. Currently there are some problems within the

Project area which result from inadequate surface drainage. It may be possible to correct or minimize the problem by installing an adequate surface drainage system. The first step in this process is to determine the sensitivity of the hydrologic system to surface runoff, or the extent to which removal of the surface water would influence groundwater levels. Depending on the results of this study, it would then be possible to design a drainage system for the area which would take into account the intended crop patterns.

REVIEW OF LITERATURE

As suggested earlier, the computer model which was used as the basis of the studies reported here was developed gradually and has been modified several times. The initial model was developed by Morris, et al.[1] in 1970 to be run on a hybrid computer. At first, the model was designed for a specific area, but it soon became apparent that it had a more general application.

The derivation of the original model considered both the surface water system and the groundwater system in the conventional manner and linked them with the equation of continuity of mass. This model used a grid of 2000 meters on a side which was overlaid on a map of the area. The rather large grid spacing was necessary in order to remain within the capacity of the hybrid computer being used. When the model was calibrated and tested, simulated conditions conformed closely to those observed in the field.

This initial model, like those which followed, worked well especially when the deficiency of field data is considered. Meteorological data, as well as hydrographic and hydraulic data, were generally lacking or severely limited for the study area. The only exception to this was meteorological data for the period between 1967 and 1969. Information on soil transmissibility and permeability as well as aquifer characteristics were and still are almost nonexistent. As a result of these initial modeling

---

[1] W. James Morris, et al. "Combined Surface Water/Ground Water Analysis of Hydrological System with the Aid of Hybrid Computer." *Water Resources Bulletin, February, 1972, pp. 63.*

studies, the general basic data requirements for further studies were developed.

Work continued on the model and by December 1970, the grid system had been reduced to 625 meters on a side.[2] A topographic parameter was included to overcome the change in surface storage quantities (swamps) which had previously been neglected. By using a tridiagonal coefficient matrix and solutions in alternating directions,[3] as discussed by Paceman and Rachford[4] and Remson,[5] the model was able to handle irregular boundary conditions.

Continued improvement was undertaken and by mid-1971,[6] the model was used to determine the amount of groundwater withdrawal necessary to maintain or modify the groundwater elevations under conditions of a fully developed irrigated agriculture. At the same time, some additional field data became available. For example, groundwater elevations had been reported for more than 500 wells in the area.

Toward the end of 1972, a pattern search optimization technique for parameter identification, and a plotting subroutine to draw the groundwater contour lines were added to the model. To compensate for

---

[2] J. Paul Riley and Eugene K. Israelsen. "A Hybrid Computer Model of the Hydrologic System Within the Atlantico-3 Area of Colombia, South America." (Progress report). Utah Water Research Laboratory, Utah State University, Logan, Utah, June, 1971. Appendix B.

[3] J. Paul Riley, "A Hybrid Computer Model", pp. 1.

[4] D. W. Paceman and H. H. Rachford. "The Numerical Solution of Papabolic and Ellipitic Differential Equations." *Journal of Society of Industrial Applied Mathematics, Volume 3, 1955, pp. 28-41.*

[5] Irwin Remson, et al. *Numerical Methods in Subsurface Hydrology.* 1971.

[6] J. Paul Riley, "A Hybrid Computer Model".

the limited precipitation and pan evaporation data available, the three years of available data were used to generate or synthesize data for a twelve-year period of study.

Further development of the model led to its conversion from a hybrid to a digital computer program. This change, among other improvements, permitted more organizations to have access to the model and thereby expand its usage. The model is now capable of simulating various hydrologic and hydraulic processes and of investigating the effects of various cropping patterns, and irrigation and drainage plans.[7] By late 1972, the model had reached a stage of development where it could be used as a practical technique for providing managers with answers to important development questions before the implementation of any proposed plan. Reliable field data over a reasonable time period are, of course, still needed.

In his Masters thesis, Iqbal[8] studied the effect of various pumping rates for groundwater extraction and their effect on the groundwater elevation under several crop patterns and irrigation rates. Of particular interest was the rapid rise of the groundwater table when the native phreatophytes were replaced by irrigated crops. This indicated an immediate need for some form of drainage in the area.

The Consulting Engineering firm of Tahal was employed by the Colombian Government to propose development plans for the area, and to

---

[7] J. Paul Riley and Bi-Huei Wang, "A Computer Model for Simulation Groundwater Table Elevations Report." (Manuscript in publication). Utah State University, 1973.

[8] Zafar Iqbal. "Computer Simulation of Groundwater Table Fluctuations for Agricultural Lands." Unpublished Masters thesis, Utah State University, Logan, Utah, 1973

coordinate and oversee the initial operations of the Atlantico-3 Project. In this undertaking Tahal is cooperating with various Ministries of the Colombian Government. In August 1967, Tahal presented its initial plan of operation for the development of the first phase of the Atlantico-3 Project.[9] The report outlines the overall plan and objectives for the development of the Project, and sets out a detailed agricultural development plan for the Southern and Repelon sectors, along with a projected time table for the development. The report also suggests the type of planning needed in engineering, agriculture, and social sciences before any orderly development can begin.

In March of 1970, Tahal Consulting Engineers published a feasibility study for a flood protection system[10] for the northern portion of the project area. The proposal was a preliminary engineering study of a system of canals and embankments which would intercept the runoff from the northern highlands and generally divert it east to the Magdalena River and west to the Guajaro Reservoir. The feasibility report indicates specific designs and locations for the canals, berms, and other structures, and includes the backup hydrologic and hydrographic studies. Information also is presented on quantities of material, water storage, and costs.

---

[9] Instituto Colombiano de la Reforma Agraria. Tahal Consulting Engineers. *Plan of Operations for the Design and Implementation of Atlantico Project No. 3, First Phase.* Tel Aviv: August, 1967.

[10] Instituto Colombiano de la Reforma Agraria. Tahal Consulting Engineers. *Atlantico Project No. 3, South Sector Feasibility Study Flood Protection System Planning Report.* Bogota, D. E.: March, 1970.

Soil studies were conducted by the Instituto Colombiano de la Reforma Agraria (INCORA) in the Southern sector Stage I[11] and the remainder of the Southern Area.[12] Additional soil studies were conducted, which related to the reclamation of some of the saline soils.[13] The soil maps and accompanying drawings which resulted from these studies indicate the general soil characteristics of the Atlantico-3 area, including the physical, hydrophysical, and chemical characteristics, as well as soil fertility, possible land use, and measures for improving the soil for agricultural purposes. However, no samples were taken below a depth of 200 cms. from the land surface. The study by Watts was concerned primarily with identifying the extent of existing saline soil conditions, and with investigating means of leaching the salts from the soil. The report points out that the permeability of the surface soils is continuously changing from location to location. In general, the soils of slight rises or mounds within the area are characterized by higher salinity levels and lower infiltration rates than those which exist in the swales or depressions. This condition tends to increase the amount of surface flow from the higher areas, thus compounding the drainage problem in the depressions.

---

[11]Instituto Colombiano de la Reforma Agraria, Stage 1 Soils Map, Plates Nos. 8 and 9, July 1969, Scale 1:25,000 drawn by Jesus Cortez and Ana V. Barros L. INCORA, 1969.

[12]Instituto Colombiano de la Reforma Agraria, Soils Map Plate No. 5-01, no date, Scale 1:25,000 drawn by J. A. Cortez, INCORA.

[13]Darrell G. Watts. "Reclamation Studies on the Light and Medium Textured Soils of Project Atlantico-3, Colombia." (Progress report). Agricultural and Irrigation Engineering Department, Utah State University, Logan, Utah, January, 1971.

GENERAL DESCRIPTION OF THE PROJECT AREA

For each of the three phases under this study, the physical characteristics of the problem will be identified and discussed under three categories:

Physical characteristics

Climate

Agriculture

As is the case for most methods of classification, some overlapping does occur between categories.

Physical Characteristics

The study area includes approximately 300 km^2 and is roughly triangular in shape as seen in Figure 2. It is bounded on the east by the Magdalena River, on the south and west by the Canal Del Dique, on the northwest by the Guajaro Reservoir and on the north by the highlands. The elevation varies between sea level and eight meters above sea level and encompasses approximately 35,000 hectares. The surface elevations are indicated in Figure 3. In general, the land slopes downward slightly from the boundaries towards the center of the area. There is no natural drainage outlet from the low center section, and in fact, there are no significant stream channels in the area.

The water surface elevation in the canal and river is slightly above sea level, and at times in the past most of the area has been flooded from these sources. The maximum river elevation on record

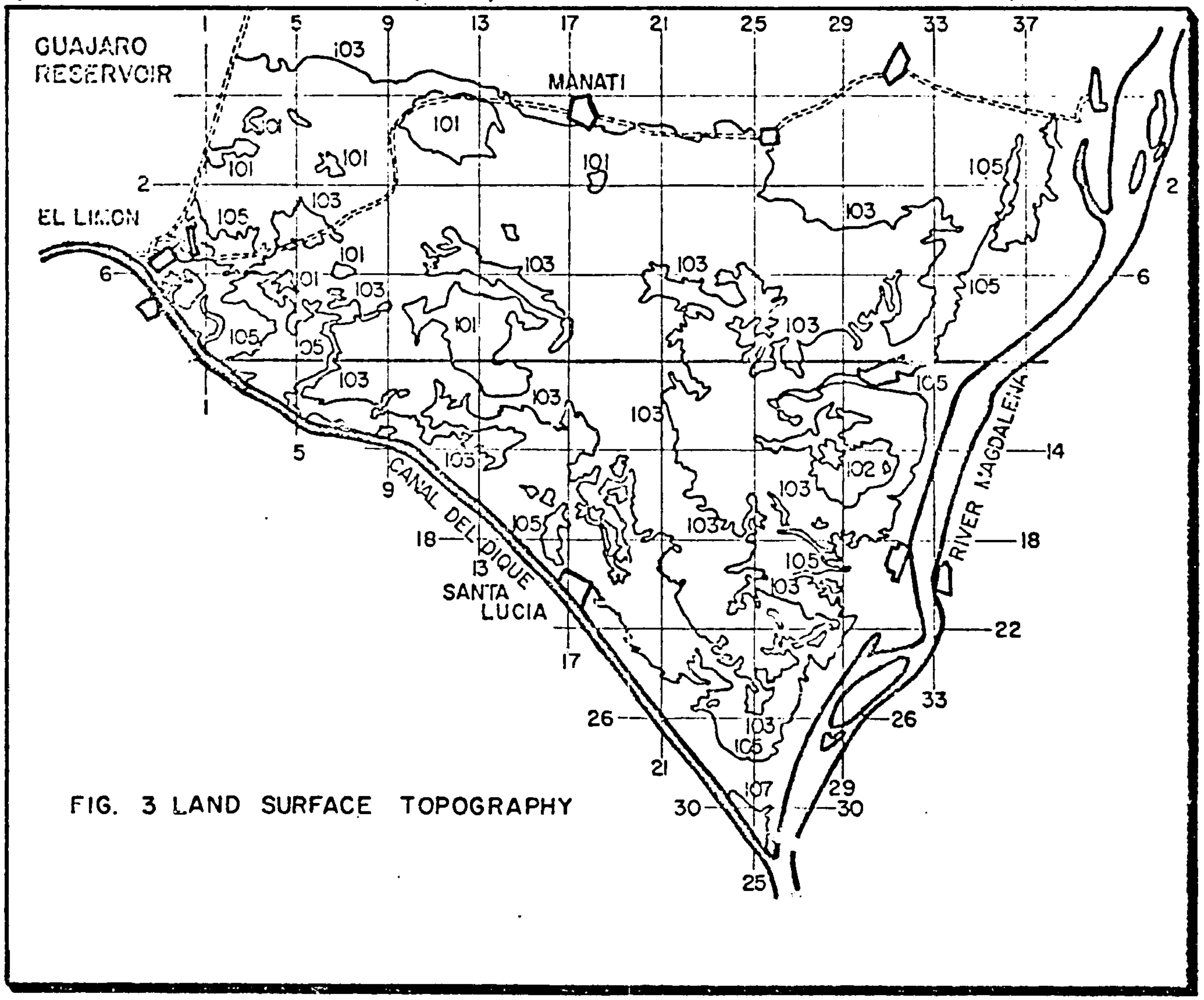


FIG. 3 LAND SURFACE TOPOGRAPHY

is 6m[14] above sea level. The construction of roads along the river and canal provided embankments which also now serve for flood protection. The hydraulic gradient from the river and the canal causes the inflow of water from these sources to the groundwater system beneath the project area. During the rainy season, the groundwater storage beneath the area also is recharged by deep percolation from the land surface.

To provide for incremental spatial resolution within the model in terms of average quantities, a grid system was superimposed on the area (Figure 4). The grid size is 625 meters on a side.

<u>Soils</u>. A soil survey[15] for the area identified eight soil types and their distribution. Figure 5 indicates these types and their locations. In order to simplify the model, the eight types were combined into the four general groups indicated as follows:

Types	Description
I, II, and III	Alluvial soils suitable for all crops, recommended for plantations and field crops.
IV and V	Medium and mainly heavy textured soils, suitable for field crops (IV), and pasture (V).
VI	Saline and alkaline soils at depth of 20-40 cm, suitable for pastures and rice.

---

[14] Tahal Consulting Engineers, *Atlantico Project No. 3*, 1970.

[15] Soil survey taken from Mapa de Suelos No. 5-0, no date, Scale 1:25,000 drawn by J. A. Cortez, INCORA and accompanying description sheet and soil map, Figure I-5, Feasibility Study, South Sector Atlantico Project (not dated).

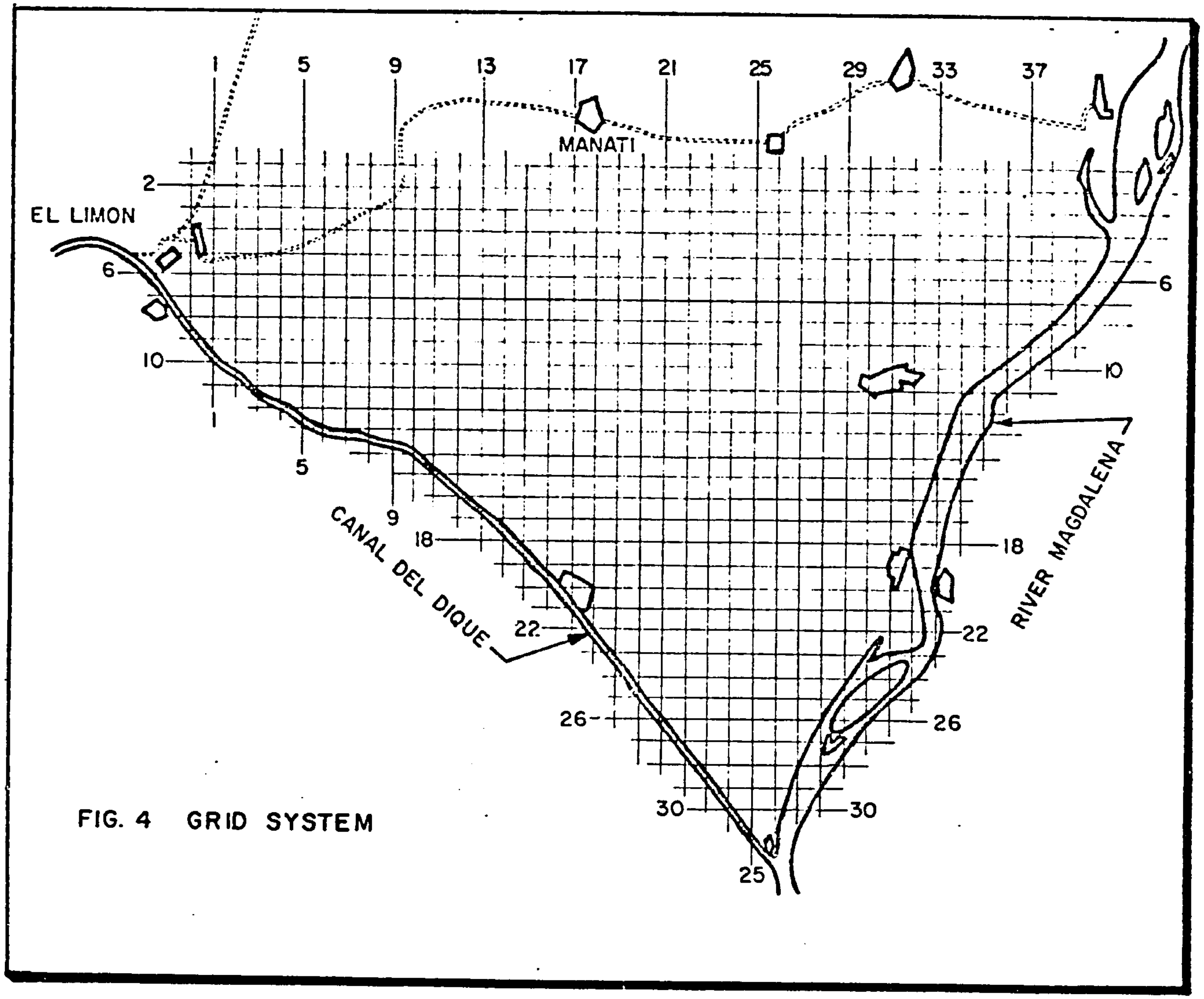
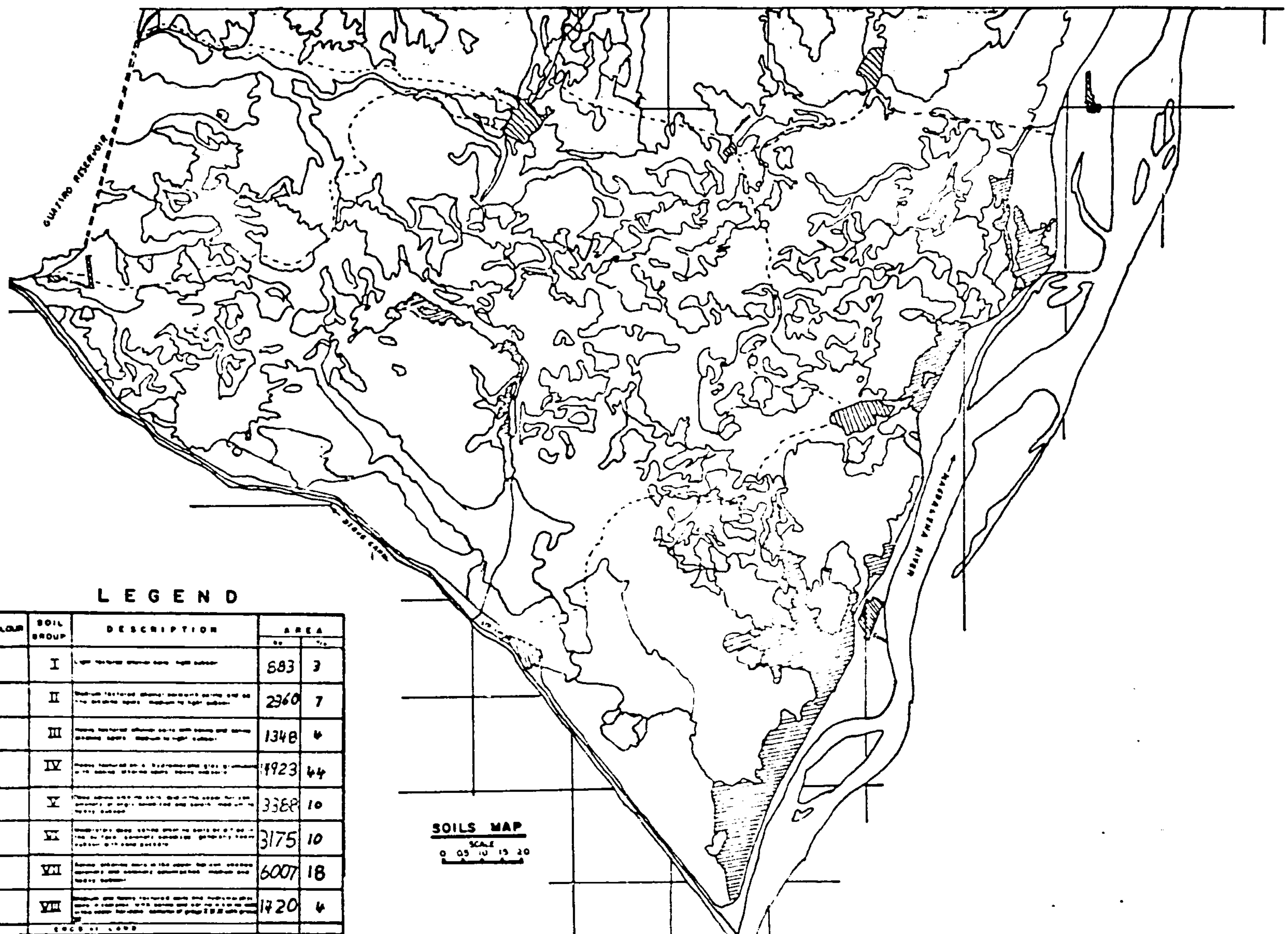


FIG. 4 GRID SYSTEM



LEGEND

COLOUR	SOIL GROUP	DESCRIPTION	AREA	
			[illegible]	[illegible]
	I	[illegible]	683	3
	II	[illegible]	2360	7
	III	[illegible]	1348	4
	IV	[illegible]	14923	44
	V	[illegible]	3388	10
	VI	[illegible]	3175	10
	VII	[illegible]	6007	18
	VIII	[illegible]	1720	4
	[illegible]			
		[illegible]	[illegible]	[illegible]

FIG. 5 SOIL TYPES AND LOCATIONS

VIII	Soils in complex of groups II, III, and VII.

Drainage. As a general rule, the area along the boundaries are higher than the interior portions of the Project area. This causes runoff to flow to the lower interior where there are several large swamps. These swamps may increase in size by as much as a factor of four during the rainy season. The degree to which surface drainage influences each grid square was determined from a topographic map and expressed in the model in terms of a topographic parameter.

Climate

There are three climatological stations in or very near the Project area. They are located at (1) El Limon, (2) Manati, and (3) Santa Lucia (Figure 3). Precipitation quantities were distributed throughout the area on the basis of the Thiessen weighting technique. Class A pan evaporation data for each grid square were taken from the nearest climatological station. At the time of the study, these data were available for a period of three years from 1967 to 1969. Because it was considered that three years might not provide sufficient time to establish groundwater equilibrium conditions in the model, available data were used to generate 12 years of data by means of statistical methods.

In general, precipitation originates as tropical storms which cover only a limited area and are of short duration. On a seasonal basis, these storms occur mainly during the June to November rainy season when the average monthly precipitation is approximately 150 mm. The average precipitation for the December to April dry season is

30 mm. The average annual temperature is 28°C, and the average relative humidity is 83 percent.

Agriculture

This is a very broad classification, but in this case it is intended to cover the following items:

a. Phreatophyte density

b. Phreatophyte consumptive use coefficients

c. Crop consumptive use coefficient

d. Groundwater consumptive use coefficients

e. Irrigation rates

f. Pump rates

In this study, the phreatophyte densities under existing conditions were assumed to vary from 20 to 80 percent over the project area. The density values used for each grid square are indicated by Figure 6.

The consumptive use coefficients for the phreatophytes vary during the year. The same is true of the consumptive use coefficients of crops with the added consideration of the stage of crop growth. For this study a specific cropping pattern was assumed as indicated by Table 1. Consumptive use coefficients were then assigned on the basis of this cropping pattern.

A wide variety of rates could be assumed for irrigation and groundwater pumping. For each combination of rates the model could be used to predict water elevation and the final or equilibrium position of the groundwater surface. During this study, the pumping rates for drainage were set at zero as this would result in the largest change in the groundwater elevation. The irrigation rates depend upon the

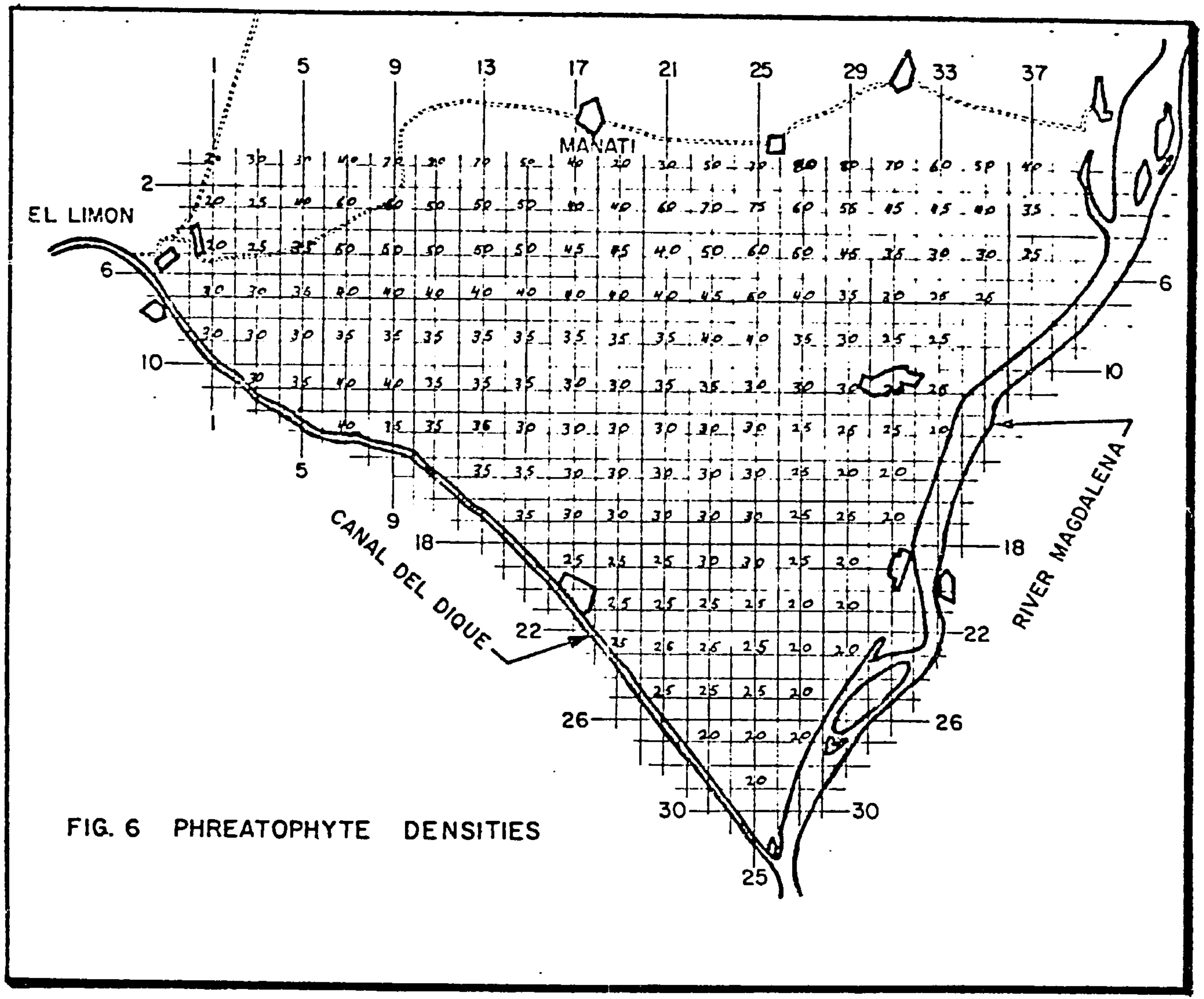


FIG. 6 PHREATOPHYTE DENSITIES

Table I. Crop-pattern, Crop-coefficients, & Irrigation for Different Soils.

SOIL GROUP	ITEM	CROP	CROP-PATTERN, WEIGHTED CROP-COEFFICIENT, AND IRRIGATION RATE											
			J	F	M	A	M	J	J	A	S	O	N	D
1	CROP PATTERN	CITRUS PEANUTS MAIZE												
	CROP COEFF.		.65	75	.55	.60	.45	.60	.75	.50	.60	.60	.60	.50
	IRR. RATE[1]		112	112	90	45	60	60	60	60	45	60	60	60
2	CROP PATTERN	COTTON SORGHUM												
	CROP COEFF.		.70	.50	.20	.20	.30	.60	.90	.60	.40	.65	.90	.90
	IRR. RATE[1]		112	.90	0	0	45	60	60	60	60	60	90	112
3	CROP PATTERN	GRASSES												
	CROP COEFF.		.80	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80
	IRR. RATE[1]		90	90	90	75	60	60	60	60	60	60	75	90
4	CROP COEFF.	BARE SOIL	.15	.15	.15	.15	.20	.20	.20	.20	.20	.15	.15	.15
	IRR. RATE[1]		0	0	0	0	0	0	0	0	0	0	0	0

[1] In mm/month.,

crop pattern and rotation, and those rates used in this study also are indicated by Table 1.

PHASE I: EFFECTS OF THE "TAHAL" BARRIER ON SURFACE AND SUBSURFACE WATER CONDITIONS

Description of the Barrier

The construction of the dam on the Guajaro Reservoir in 1964-65, just north of San Cristobal, permitted much of the area east of the dam to drain and dry up as the water, which had been covering the area, receded. There still remain within the area, however, many shallow waterways and large swamps. In the past, runoff from the tropical rains in the northern highlands caused frequent flash floods which inundated parts of villages and raised swamp levels. Because of these floods, 4000 to 5000 hectares[16] of land in the northern area were unsuitable for farming.

The Consulting Engineering firm of Tahal has been the prime professional consultant for the development of the Project area, and recently this company proposed a control project[17] to alleviate flood conditions caused by runoff from the northern highlands. Tahal's proposal was the result of studying at least 12 alternatives and considered three main components, all of which are required for the adequate control of flooding within the northern portion of the

---

[16]Instituto Colombiano de la Reforma Agraria, Tahal Consulting Engineers. *Atlantico Project No. 3.*

[17]Ibid., pp. 1.

Project area. The three parts of the proposal are shown by Figure 7 and are described as follows:[18]

1. The Western Intercepter.- Between Guajaro Reservoir and Manati which diverts the runoff into the Guajaro Reservoir.

2. The Eastern Intercepter.- Between Candelaria and Las Flores on the Magdalena River, which diverts the runoff into the Magdalena.

3. The Sabalo Reservoir.- Between Carreto and Candelaria which diverts the runoff into the existing Sabalo Swamp, and thence into the main drainage system of the area.

The western section collects surface runoff from about 56 square km. north of the line between Punta Polonia, on the Guajaro Reservoir, and Manati, and drains it into the Guajaro Reservoir. The embankment along this line is 10.2 km. long with a maximum hight of 3.5 m. The crest is 8.0 m. wide and covered with gravel for a road surface. The embankment is at the same or higher elevation as the Guajaro Reservoir dam and creates a long narrow flood control reservoir along its northern edge. The flood control reservoir varies in width from 50 m. to 400 m. and in depth from 1.5 m. to 2.5 m., which provides a storage capacity of about two million cubic meters (MCM) for runoff from all of the western streams. Discharge is through a broad-crested spillway, 16 m. wide, into the Guajaro Reservoir. The spillway crest is at the maximum elevation of the reservoir.

The eastern sector collects surface drainage from the area north of the Candelaria-Las Flores line, an area of approximately 105 km., and drains into the Magdalena River. This section consists

---

[18]Taken from Figure 2, *Flood Protection System*, Tahal Consulting Engineers, Ltd, March, 1970.

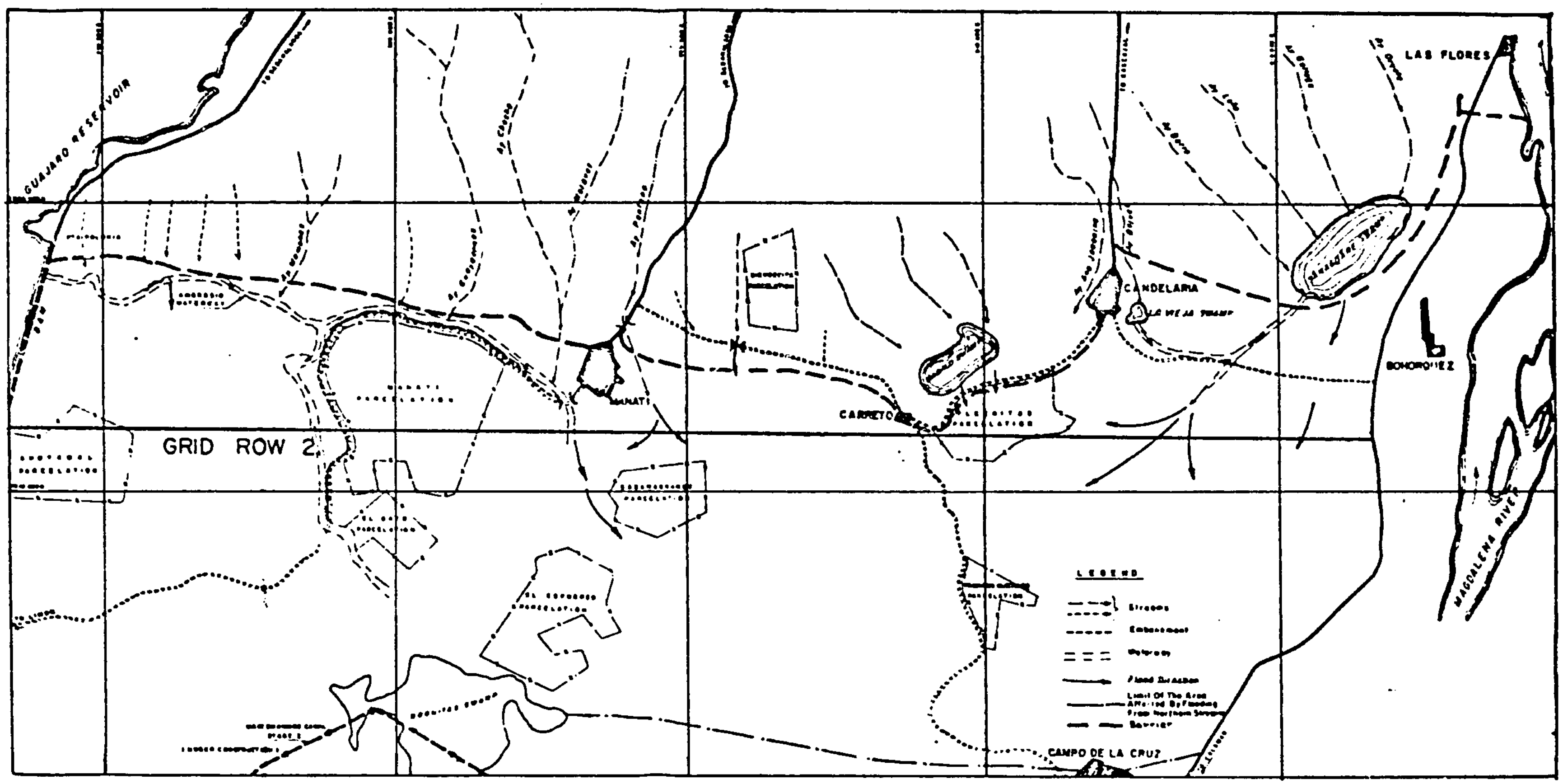


FIG. 7 EXISTING SITUATION, NORTHERN SECTOR

of approximately 7 km. of berm, with 4 km. of concrete lined canal. The reservoir created by this berm is about 4.6 km. long with an average depth of 3 m. and a storage capacity of about 3 MCM. Again, the top of the embankment provides the major roadway in the area. The embankment crest is about 11 m. above sea level and the outlet is at 6 m. above sea level which is the maximum elevation of the river.

The central section collects surface runoff from the area north of the Manati-Correto-Candelaria line, which encompasses about 40 square km. The runoff from the Carreto-Candelaria portion is collected in the existing Sabalo Swamp. This swamp acts as a retention reservoir for peak flows, and will drain into the main drainage network for the area when this system is completed. The area between Manati and Carreto will drain by a canal just north of the berm and the water will be conducted to the Sabalo Swamp.

Because this project has been completed only very recently, its effects have not been evaluated, but it is anticipated that it will reduce the quantities of both surface and subsurface water within the northern part of the Project. These changed conditions will affect, in turn, the amount of land available for agricultural crops, the types of crop that can be raised, and the times of year when they can be planted, and thus, influence the irrigation and drainage techniques needed in the area.

Modeling Procedure

The digital computer model developed by Riley and Israelsen[19] was

[19] Riley and Israelsen, "A Hybrid Computer".

used to simulate possible changes in the groundwater table elevations in the northern part of the study area as a result of the construction of the "Tahal" flood protection system.

The model was developed to simulate the response of the groundwater table to the various factors in the hydrologic cycle under conditions of a homogenious unconfined aquifer which is assumed to exist under the study area. The model consists of two linked submodels. One simulates the surface and subsurface water flow, while the other simulates the groundwater flow.

The surface and subsurface portion of the model include the processes of surface runoff, infiltration, and percolation, and these are linked together using the continuity equation. Inputs to this submodel include precipitation, pan evaporation, topographic parameters, soil type, phreatophyte distribution as well as irrigation and drainage rates. Also considered are consumptive use coefficients and soil moisture characteristics and conditions.

The groundwater portion of the model simulates the change in the groundwater table elevation as it is affected by inflow rates, including effective or net percolation. A detailed description of the mathematical model will be found in a report by Wang et al. now being prepared for publication.

Input and output data correspond to the grid points mentioned earlier and shown by Figure 4. The dimension of the grid is limited by the capacity of the computer. When the program was run on the EAI 690 computer, the grid spacing was 1875 meters while the UNIVAC 1108 permitted a grid spacing of 625 meters. If further spatial resolution were needed a smaller grid size could be used. It should be noted that model results depend very largely on the accuracy with which the prototype is described, and this usually is limited by the availability of field data.

In order to test the possible influence of the barrier on groundwater levels, two simulation runs were made. In the first run conditions before construction of the barrier were represented, while for the second run, the barrier was assumed to exist so that surface runoff could not enter the Project area. Field observations have indicated[20] that runoff from the northern highland influenced surface water conditions within the Project area for a distance as far south as a line from about the midpoint of the Guajaro Reservoir dam to Campo de la Cruz.

Computer plots were made of the groundwater surface elevations at periods of 12, 24, 36, 48, and 60 months to determine at what point in time the groundwater levels stabilized along grid row 2. In the central and eastern portions of the Project, the groundwater elevations stabilized after 36 months, while for the western portion, a period of from 48 to 60 months was required. A cross section showing computed groundwater elevations along grid row 2 at the end of 60 months is plotted in Figure 8.

Effects of the Barrier

Without the barrier the groundwater table stabilized at the elevations indicated by the solid line in Figure 8. With the barrier in place, the groundwater table stabilized as indicated by the broken line. These values were for the month of December during the dry

[20] Figure 2, *Flood Protection System,* Tahal Consulting Engineers.

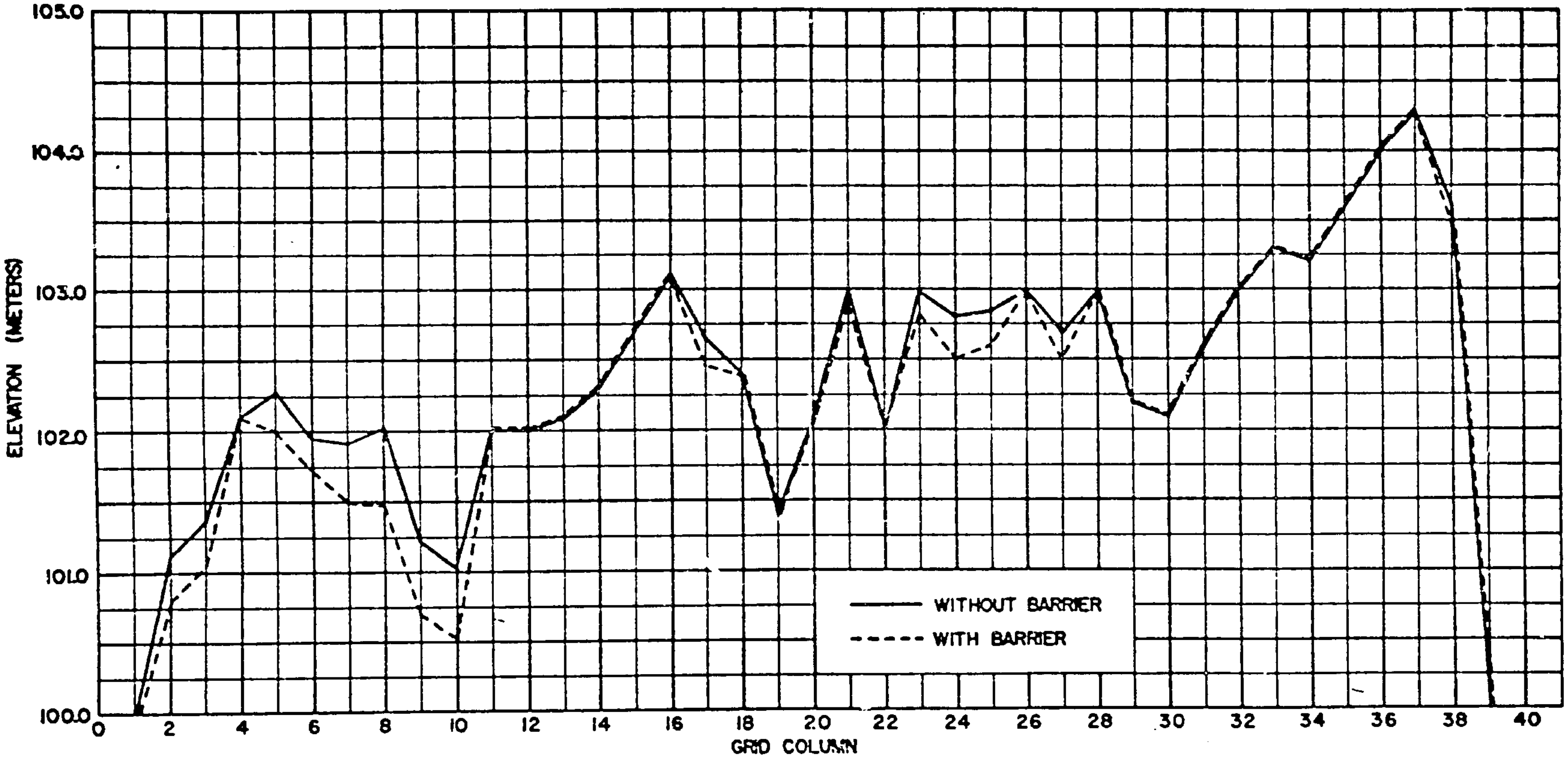


FIG. 8 EFFECT OF BARRIER AT GRID ROW 2

season. It was noted that in some areas the barrier had little effect on the groundwater elevations. Values for the month of September during the wet season (not shown), indicated a difference in groundwater elevation as a result of the barrier of about one meter between grid columns 1 and 28. East of grid column 28 the computed average difference was about 20 centimeters.

As can be seen from Figure 7, the "Tahal" barrier is located at varying distances from grid row 2. This distance, in the western portion, varies from approximately 3150 meters to 1200 meters with an average distance of about 1800 meters. In the central portion, the average distance of grid row 2 from the barrier is about 1200 meters, while in the eastern portion the average is approximately 3300 meters. These distances may help to explain why the barrier had little effect on the groundwater elevation in much of the area.

Information for Management

The "Tahal" barrier was proposed strictly as a flood control measure. In the phase of the study reported here an attempt was made to predict the effects, if any, of the barrier on groundwater levels to the south. Except for the western portion and two or three other limited areas, the barrier apparently has little effect on the groundwater elevations along grid row 2 during the dry season. In areas where some effects are indicated, the groundwater levels were reduced by the barrier, as would be expected. As previously indicated, the time increment used in this study was one month so that results are available for each month of the year. However, Figure 8 reflects output functions only for December after a certain period for groundwater levels to reach equilibrium. During the wet season the effect of the barrier is much more noticeable in lowering the groundwater table elevation south of the barrier.

PHASE II: EFFECTS OF PHREATOPHYTE DENSITY ON GROUNDWATER TABLE ELEVATIONS

The Role of Phreatophytes in Groundwater Management

Existing native vegetation within the project consists mainly of grasses and phreatophytes. Some areas have the appearance of large grassy fields with a few isolated trees, while other areas appear as dense jungle. The groundwater basin below the area is recharged by inflows from the river, the canal, and the reservoir and swamps along the boundaries, and by runoff from the northern highlands. In addition, during the rainy season, some deep percolation occurs from the surface soils. Water is extracted from the groundwater basin by deep rooted phreatophytic vegetation, which in turn, looses the water by transpiration. In the areas where phreatophyte densities are high, the groundwater table is maintained at about six meters below the land surface.

When the area is developed and shallow rooted crops are substituted for the deep rooted phreatophytes, the groundwater table can be expected to rise to unacceptably high levels for crop production. Two possible methods of maintaining the water table at a sufficiently low level are:

1. A system of drains (either subsurface or surface or both) and pumping.
2. The selective cutting and planting phreatophytes to

let nature maintain as much as possible acceptable groundwater elevations.

The second phase of this study attempted to evaluate the changes in groundwater elevations under varying conditions of native phreatophyte density or cover. This investigation thus suggested the sensitivity of groundwater elevations to changes in phreatophyte density, and indicated the feasibility of using phreatophytes to maintain the groundwater table at desirable levels.

Because there is no well documented inventory of phreatophyte density in the study area, estimates for this study were based on limited personal observations.[21] However, it is considered that the estimates do reflect realistic estimates of relative density from one location to another. The absolute values of phreatophyte density in the model were then varied, but the same relative relationships were maintained from one grid area to another.

Modeling Procedure

Because the desired model output was the "groundwater table elevation" or "change in groundwater table elevation" under conditions of changing phreatophyte density, which was the same output used in Phase I, no modifications to the model were needed for Phase II. One of the variable inputs to the model is the phreatophyte density at each grid point. It is possible to change this variable and to fix all other inputs, and thus to observe the change in the groundwater

---

[21] Described by J. Paul Riley, Project Leader, for Atlantico-3 Simulation Studies, upon his return from visiting Atlantico-3 in November, 1972.

table elevation solely as it relates to the change in this one variable. From this study it is possible to determine the relative sensitivity of the groundwater table elevation to phreatophyte density.

A wide range of assumptions can be made in the model relating to land use. For example, it is possible to assume that the entire study area will be developed using various cropping patterns, or that only specific locations will be developed for agricultural production and that native phreatophytes will remain in other parts of the area. The choices are limited only by site constraints pertaining to the varieties of rops that can be grown in the area, their possible rotation patterns, and the specific number of locations suitable for a particular crop variety. For the study report here, the particular cropping and irrigation patterns indicated by Table 1 were assumed. No pumping for drainage was assumed. Thus, all variables were fixed except phreatophyte density. Figure 6 indicates the approximate relative density of the existing phreatophytes.

The phreatophyte density for each grid square was expressed as a percentage of the total area assumed to be covered by phreatophytes. In the study the density in each grid square was varied by ±10, ±20, and ±30 percent. The results for Phase II are displayed for both grid row 2 and grid row 18. It was necessary to determine at what point in time the groundwater table elevations stabilized at these two rows for each of the assumed density conditions. Therefore, groundwater table elevations were plotted at each of rows 2 and 18 corresponding to time periods of 12, 24, 36, 48, and 60 months from the time of initiation. At row 2, these plots were made for the assumed phreatophyte density shown by Figure 5 (no change from the base). For row 18, plots were made for assumed phreatophyte densities which varied from those of Figure 5 by ±30, 0, and -20 percent. These plots indicated that the groundwater table elevation stabilized along grid row 2 at between 48 and 60 months, while for grid row 18 equilibrium conditions occurred by the end of 36 months. On the basis of these findings, groundwater table elevations for the various phreatophyte densities assumed were plotted for grid row 2 after operating the model for a period of 60 months, while the plots at row 18 were made after an operating period of 36 months. Figures 9 and 10 indicate variations in groundwater table elevations along these two rows under various conditions of assumed phreatophyte density.

Effects of Varying Phreatophyte Density

Figure 9, which sets out the results of the study for row 2, indicates that in some areas (between grid columns 3 and 10) the groundwater table elevation can be raised or lowered by more than 2.5 meters by varying the phreatophyte density between +30 and -30 percent. In other areas (grid columns 23 and 28) the groundwater table elevation can be changed by as much as 75 centimeters by varying the phreatophyte density. Figure 9 also indicates that there are other areas (grid columns 11-16, 19-22, and 28-38) where the phreatophyte density has no apparent effect on the groundwater table elevation.

Figure 10 (grid row 18) indicates that changes in phreatophyte density was effective in influencing the groundwater in only three small areas (grid columns 1-2, 5-7, and 14-16), and even then the changes in the groundwater table elevations were limited to between 40 and 80 centimeters.

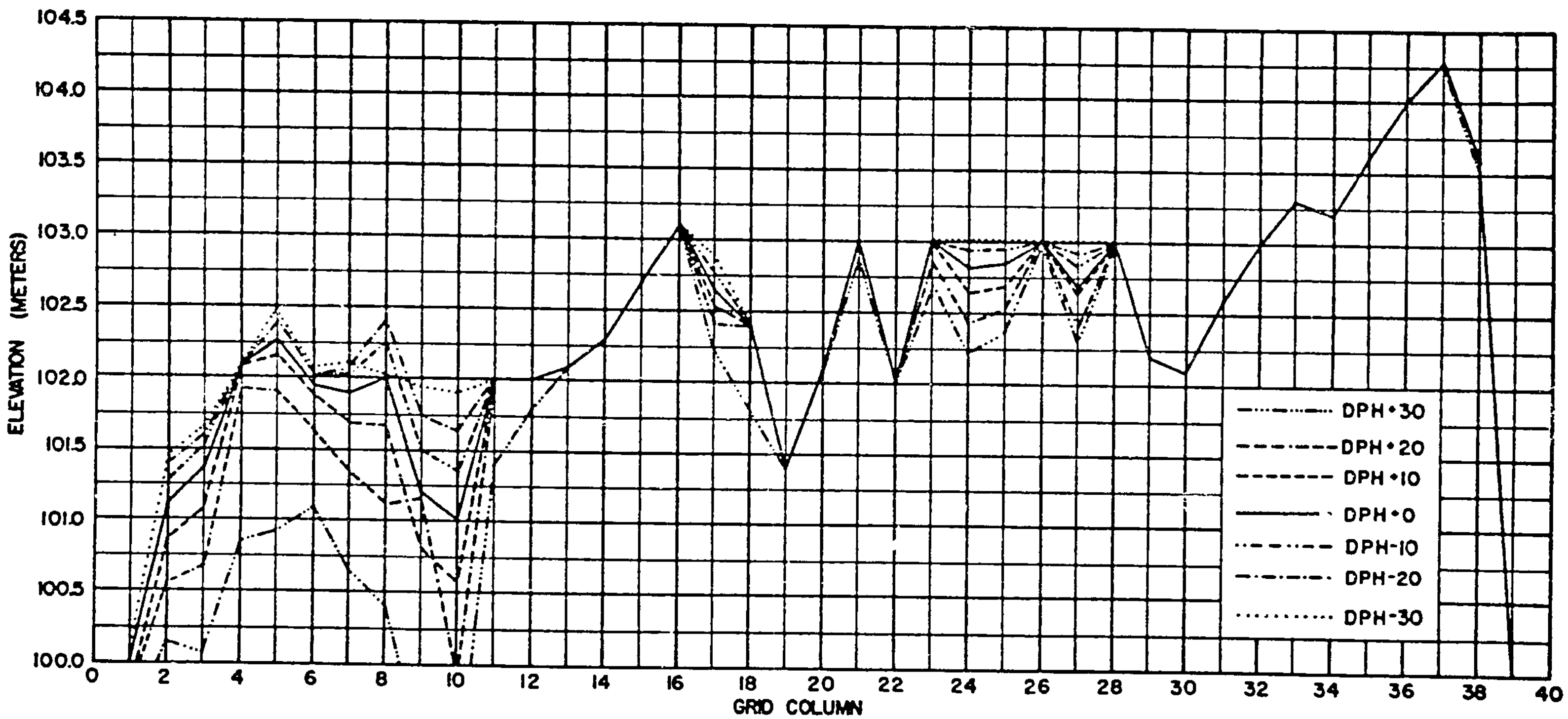


FIG. 9 EFFECT OF VARYING PHREATOPHYTE DENSITY AT GRID ROW 2

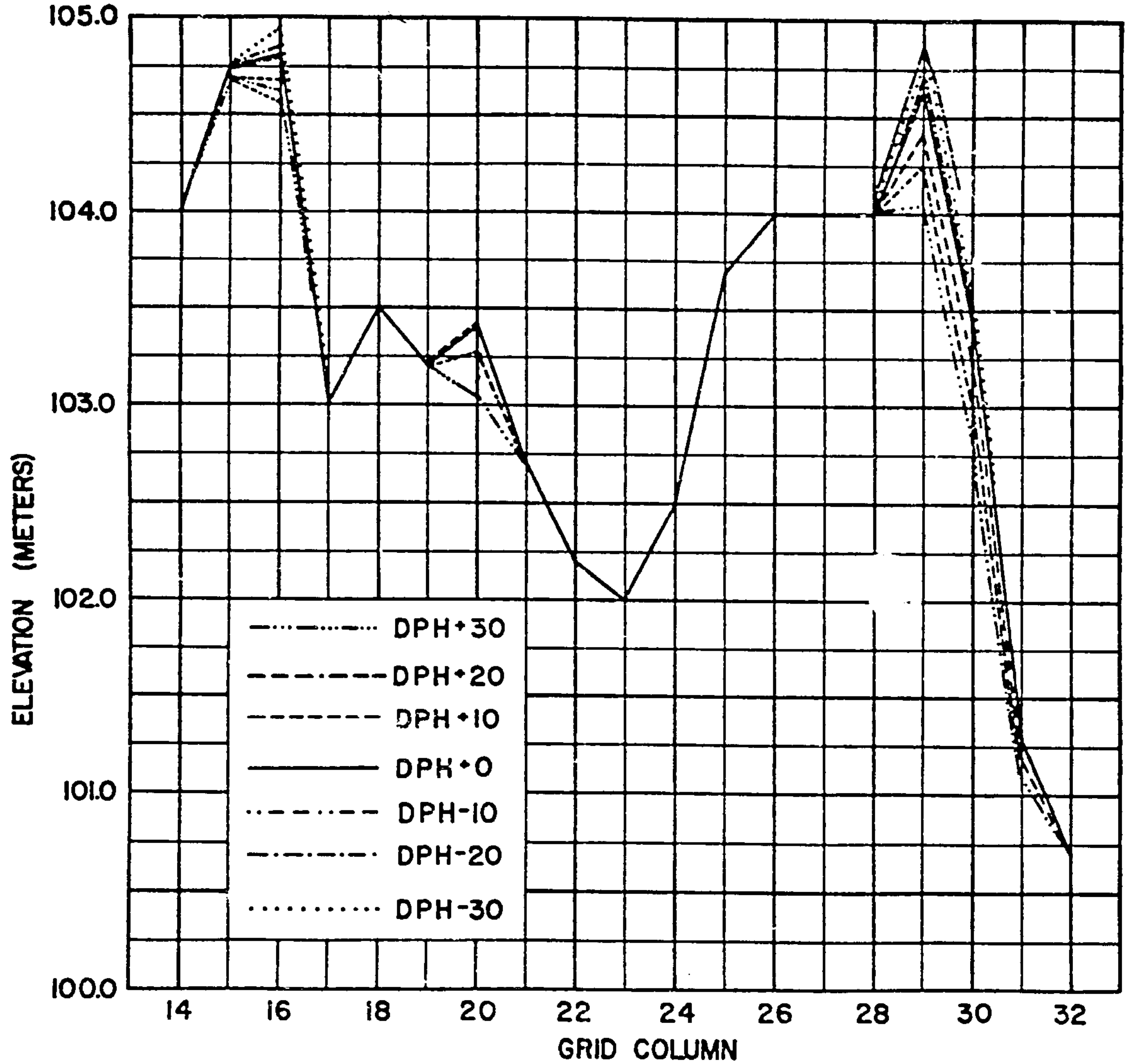


FIG. 10 EFFECT OF VARYING PHREATOPHYTE DENSITY AT GRID ROW 18

For both rows, the soil type did not seem to be the determining factor as to whether or not the groundwater table was influenced by phreatophyte density. Two or three soil types were present both in the areas where groundwater table elevations were affected by the phreatophyte density and in the areas where the phreatophyte density apparently had no effect on the groundwater table elevations.

Information for Management

The study has suggested that in some parts of the Project the native phreatophytes can be very effective in changing or controlling the groundwater table elevations, while in other locations the effects are negligible. This phase of the paper has indicated this information of only two of the 29 grid rows in the Project area. If similar plots were made for all grid rows within the Project area, insight could be gained as to the locations where native vegetation might be most effective in controlling groundwater table elevations. In turn, this information would indicate areas where the native vegetation probably could be cleared without additional studies, and further where drains and pumps might be needed in order to control or vary the groundwater table elevation.

This type of management information is important for the Atlantico-3 Project as land is being cleared and brought under cultivation. Changes in the groundwater table elevations as a result of clearing operations in a specific location may or may not be important in terms of the Project as a whole. Further studies along the lines of this Phase of the paper are needed in order to provide additional information on predicted changes in groundwater surfaces as a result of phreatophyte management at specific locations within the Project.

PHASE III: EFFECTS OF SURFACE DRAINAGE

The Role of Surface Drainage in Groundwater Management

Since there is no natural surface drainage from the Project area, all water which occurs on the land surface must remain on the surface until it either enters a low or depressed area, evaporates, or infiltrates into the ground. As yet, there has been relatively little development in the way of artificial drainage, either surface or subsurface within the Project. However, it is possible that water table levels might be considerably influenced by providing a means of collecting the surface runoff and of conducting it away from the area. A possible way of meeting these needs is to smooth the surface topography to permit surface water to move off the land to low lying depressions and then to link these depressions with a series of open drainage channels constructed throughout the area. The purpose of this phase of the study, then, was to demonstrate the utility of the model for assessing the sensitivity of groundwater table levels to surface drainage conditions.

The frequent tropical rains which occur within the area are very intense, although usually of short duration, and tend to fill the available surface storage quite rapidly. In addition, infiltration rates are generally low throughout the area so that excess water tends to move over the land surface and to accumulate as swamps in areas of depression. These swamps then act as a recharge source for the ground-water basin, thus contributing to both surface and subsurface drainage problems.

Modeling Procedure

Land slopes within the Project area are away from the boundaries toward the center of the area. The Boquitas Swamp is thus a natural collecting point for surface runoff. However, because the area is a flood plain of the Magdalena River, the land surface is uneven and numerous old flood channels cross the area. The Boquitas Swamp is now drained by a man-made channel which conveys the water to a pumping station situated near the Canal Del Dique. This pumping station lifts the water into the Canal.

For this phase of the study some minor modifications were made to the model involving two of the subroutines so as to accumulate and print the runoff for each grid point. In its present form, the model is not designed to provide exact values of surface runoff, but rather it will indicate the relative amount of runoff from one grid square to another. This is because monthly values rather than hourly or even daily values of precipitation are used. However, an indication of quantities and point of accumulation of surface runoff as provided by the model will considerably assist in the design of an adequate drainage system for the area. It might be noted that the 625 meter grid used in the model might be somewhat large to indicate exact points of surface runoff accumulation, but the general utility of the model for a study of this nature is demonstrated.

The period between 1963 and 1967 was simulated and results were printed only for September in the year of highest precipitation during this period. September falls in the middle of the rainy season when large amounts of surface runoff might be expected.

Simulation Results

Figure 11 indicates the location and relative amounts of surface runoff at various grid points. For the purpose of clarity, values are not shown for grid points where no significant amounts of runoff were predicted. Generally, there was a surface runoff problem along the Canal Del Dique and some areas along the Magdalena River. Figure 11 indicates, however, that surface runoff problems also exist in other parts of the Project.

Information for Management

The objective of this phase of the study was to demonstrate the utility of the model for indicating quantities and points of concentration of surface runoff within an area. Figure 11 provides this information for the Atlantico-3 Project. This same information is displayed in perhaps a more usable form by Figure 12. From this figure it is possible to readily see where drainage problems are likely to exist and where further design studies should be concentrated in the Project area. As a further study the model could be applied to examine the sensitivity of groundwater table levels to surface drainage conditions. In other words, the model could provide an answer to the question "To what extent could the problem of subsurface drainage be solved by providing for adequate surface drainage?"

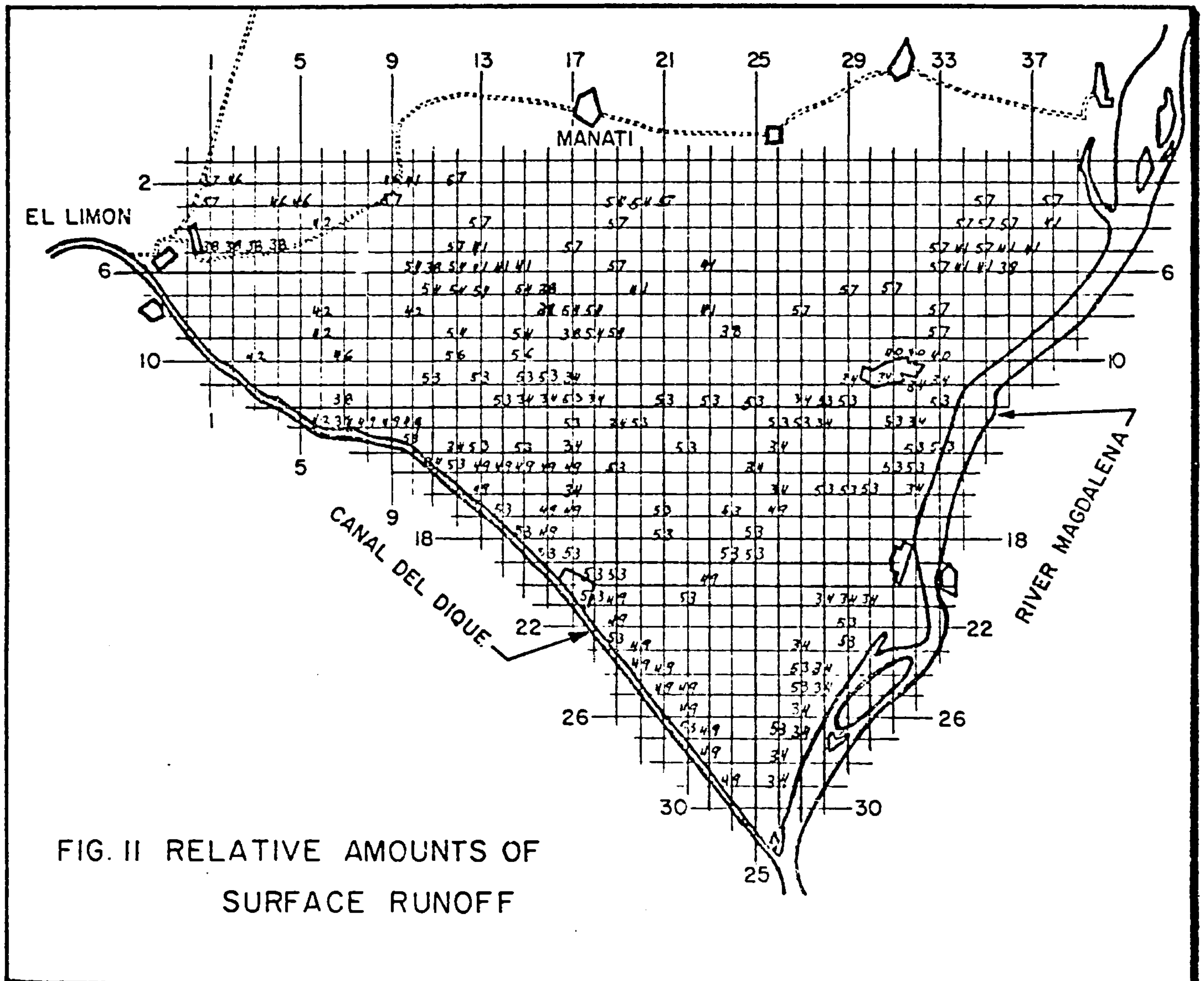


FIG. II RELATIVE AMOUNTS OF SURFACE RUNOFF

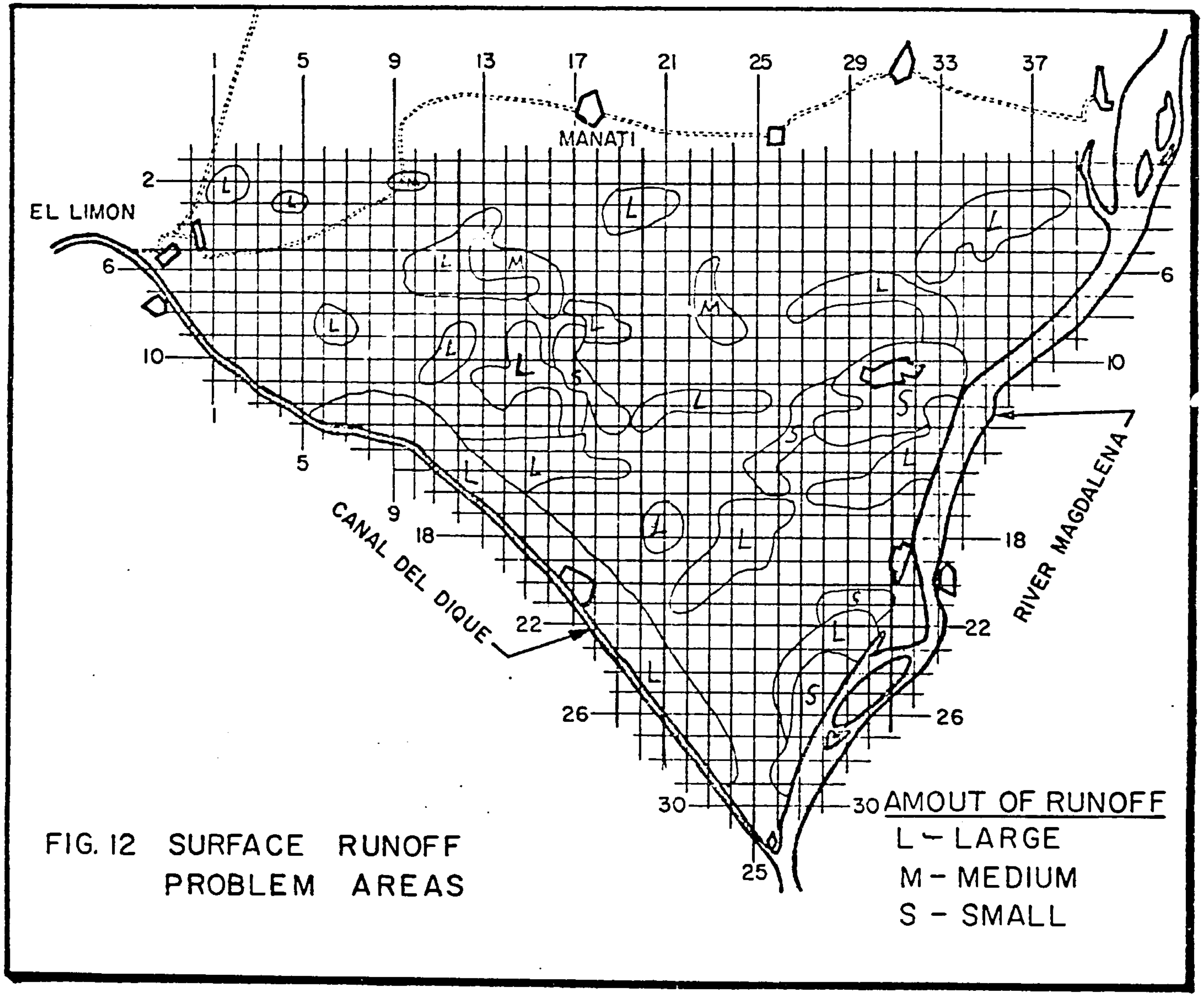


FIG. 12 SURFACE RUNOFF PROBLEM AREAS

It is again emphasized that the values of surface runoff obtained from the computer model (Figure 11) indicate relative rather than exact amounts of surface runoff.

CONCLUSIONS AND RECOMMENDATIONS

In this study, a general computer simulation model of the hydrologic system has been applied to three particular problems in a specific geographic area. The three phases into which the study was divided are as follows:

A. The effects on groundwater table elevations of a barrier to prevent surface runoff from the northern highlands from entering the study area.

B. The effects on the groundwater table elevations of varying the densities of native phreatophytes.

C. An examination of the accumulation, locations, and relative amounts of surface runoff.

Each of these phases is illustrative of the kinds of management problems which can be examined by means of the computer model, and which are typical of the problems faced by planners and managers in the development of many agricultural areas. A forest can be destroyed in a matter of days or weeks, yet it takes years to restore it once it has been destroyed. Proper use of simulation models foster the orderly development of a project, and thus avoiding many of the pitfalls that await the manager who proceeds without planning.

Recommendations

1. Improve the model to compute surface runoff more explicitly. In this way, quantities could be predicted more closely. Some specific suggestions are made in this regard.

a. Set a limit on the depth of surface storage that can accumulate in each grid square before the water becomes surface runoff.

b. Develope a subroutine to look at surface outflow through all four sides of the grid square before calculating total surface runoff from that grid square. This modification probably would replace the topographic parameter now used. It might be possible to accomplish this suggestion by double subscripting and an array.

c. Incorporate a factor or parameter which will allow the monthly precipitation data to be used, but provide a printout which would be more realistic of a storm of say six hours or less duration. This procedure will permit a more realistic estimation of surface runoff values than is now the case.

2. Use the drainage factor (LD) only along the northern boundary (grid row 1) and let the topographic parameter, or its successor from recommendation 1b above, handle the surface runoff from the northern highlands south of grid row 1.

3. Use the model to examine the sensitivity of the ground-water table levels to surface drainage conditions.

LITERATURE CITED

Instituto Colombiano de la Reforma Agraria. *Proyecto Atlantico No. 3 Sector Sur, Análisis de Aguas* (No. 21.).

________. *Proyecto Atlántico No. 3, Sector Sur, Análisis de Suelos* (No. 30.).

________. Stage I Soils Map, Plates Nos. 8 and 9, July, 1969, Scale 1:25,000 drawn by Jesús Cortez and Ana V. Barros L.

________. Soils Map Plate No. 5-01, no date, Scale 1:25,000 drawn by J. A. Cortez.

________, Tahal Consulting Engineers, Ltd. *Atlantico Project No. 3 South Sector Stage I, Soils Report Drawings.* Barranquilla: July, 1969. (No. 23.).

________, ________. *Atlantico Project No. 3, South Sector Feasibility Study, Flood Protection System.* (Planning Report) Bogota: March, 1970. (No. 29.).

________, ________. *Plan of Operations for the Design and Implementation of Atlantico Project No. 3: First Phase.* Tel Aviv: August, 1967.

Iqbal, Zafar. *Computer Simulation of Groundwater Table Fluctuations for Agricultural Lands.* Logan: Utah State University. Master's thesis. 1973.

Morris, W. James; et al. "Combined Surface Water/Ground Water Analysis of Hydrological System with the Aid of Hybrid Computer." *Water Resources Bulletin, February, 1962, pp. 63.*

Paceman, D. W. and Rachford, H. H. "The Numerical Solution of Parabolic and Ellipitic Differential Equations." *Journal of Society of Industrial Applied Mathematics, Vol. 3, 1955, pp. 28-41.*

Remson, Irwin; et al. *Numerical Methods in Subsurface Hydrology.* New York: John Wiley & Sons. 1971.

Riley, J. Paul and Israelsen, Eugene K. *A Hybrid Computer Model of the Hydrologic System Within the Atlantico 3 Area of Colombia, South America.* Logan: June, 1971. (Progress Report).

LITERATURE CITED
(Continued)

Utah State University. *Development of a Computer Simulation Model for Water Resource Management*. Logan: November 1, 1971-October 31, 1972. (Annual Progress Report). Water Management Research in Arid and Sub-Humid Lands of Less Developed Countries, Fourth Annual Progress Report, Nov. 1, 1971-Oct. 31, 1972, Contract AID/csd-2167, Department of Agricultural and Irrigation Engineering, Utah State University.

Watts, Darrell G. *Reclamation Studies on the Light and Medium Textured Soils of Project Atlantico-3, Colombia*. Logan: Utah State University. January, 1971 (Agricultural & Irrigation Engineering Department). (Progress Report).

APPENDICES

APPENDIX A:

LIST OF SYMBOLS AND DEFINITIONS

LIST OF SYMBOLS AND DEFINITIONS

LYRO	STARTING YEAR FOR SIMULATION
NPR	NUMBER OF PARAMETERS
NYR	NUMBER OF YEARS OF SIMULATION
L	VERTICAL GRID LINES
M	HORIZONTAL GRID LINES
NSL	NUMBER OF SOIL TYPES
NCL	NUMBER OF CLIMATOLOGICAL STATIONS
NHY	NUMBER OF HYDROLOGIC AREAS
INN	INPUT DEVICE
IOT1, IOT2	OUTPUT DEVICES
NITY	MAXIMUM NUMBER OF REITERATIONS
N	NUMBER OF INTERIOR POINTS
AIN	THAT PART OF THE MODELED AREA RECEIVING RUNOFF FROM THE NORTHERN MOUNTAIN AREA
AOUT	CATCHMENT OF THE NORTHERN MOUNTAINS
RPPT	RATIO OF PRECIPITATION IN NORTHERN MOUNTAIN AND THAT OF MANATI STATION IN THE MODELED AREA
CCR	CROP CONSUMPTIVE USE COEFFICIENT
CPH	PHREATOPHYTE CONSUMPTIVE USE COEFFICIENT
CGW	PHREATOPHYTE CONSUMPTIVE USE COEFFICIENT ATTRIBUTABLE TO GROUNDWATER
IBG(J)	BEGINNING INTERIOR POINT FOR ROW J
IBB(J)	BOUNDARY TYPE OF THE SAME POINT
P,Q,R,S	SEE WANG + RILEY (1971) PAGE 12
IND(J)	END INTERIOR POINT FOR ROW J
IDB(J)	BOUNDARY TYPE FOR THE SAME POINT
JBG(I)	BEGINNING INTERIOR POINT FOR COLUMN I
JBB(I)	BOUNDARY TYPE FOR THE SAME POINT
PP, QP, RP,SP	P.Q.R.S. FOR BOUNDARY POINTS IN J DIRECTION
JND(I)	END INTERIOR FOR COLUMN I
JDB(I)	BOUNDARY TYPE FOR THE SAME POINT
GSL	GROUND SURFACE ELEVATION
LS	SOIL INDICATOR 1,2,3,OR 4 CORRESPONDING TO PAGE 18 OF WANG AND RILEY (1971)
LC	CLIMATIC INDICATOR, EL LEMON = 1, MANATI = 2, SANTA LUCIA =3
LD	DRAINAGE INDICATOR THAT PART OF MODELED AREA RECEIVING RUNOFF FROM THE NORTHERN MOUNTAINS =1,OTHERWISE 0
TPG	TOPOGRAPHIC PARAMETER, IF THE AREA REPRESENTED BY THE AREA DRAIN WATER OUT, TPG = 1, IF IT DOES NOT DRAIN OUT AND ALSO DOES NOT RECEIVE SURFACE DRAINAGE FROM THE SURROUNDING AREA, TPG = 0, IF IT RECEIVES ONE SQUARE GRID TPG=-1, IF RECEIVES TWO SQUARE GRIDS,TPH = -2, AND SO ON
DPH	PHREATOPHYTE DENSITY
MS	TOTAL SOIL MOISTURE
MCSO,MCS	SOIL MOISTURE HOLDING CAPACITY
MESO,MES	CRITICAL SOIL MOISTURE FOR POTENTIAL EVAPOTRANSPIRATION
SIC,MIC	INITIAL SOIL MOISTURE
STRO	INITIAL SURFACE STORAGE IN SWAMPS
HO	INITIAL GROUNDWATER ELEVATION AT GRID POINTS
HOI,HOJ	INITIAL GROUNDWATER ELEVATION AT BOUNDARY POINTS
PPT	PRECIPITATION
PEV	PAN EVAPORATION

LIST OF SYMBOLS AND DEFINITIONS (CONTINUED)

```
L1,L2,M1,M2INDICATORS FOR  OUTPUT CONTROL
ISC1 ICS2  OUTPUT OPTION INDICATING ROW MULTIPLE DESIRED PRINTING(PRINT
           EVERY ROW, PRINT EVERY SECOND ROW)
COPH       ADJUSTMENT FOR PHREATOPHYTE DENSITY, WHEN COPH =0 ALL PHREATOPHYTE
           ARE ELIMINATED
OIR        IRRIGATION APPLICATION RATE
COIR       ADJUSTMENT FOR IRRIGATION
AOMS       ALLOWABLE ERROR FOR SOIL MOISTURE SIMULATION
DX         GRID SPACING
DT         TIME INCRIMENT
SCAL       SCALING FACTOR
PR         MODEL PARAMETERS
               1=RETURN COEFF
               2=MINIMUM INFILTRATION CAPACITY
               3=MAXIMUM INFILTRATION CAPACITY
               4=RUNOFF COEFF. FOR THE NORTHERN MOUNTAINS
               5=ADJUSTMENT FOR CONSUMPTIVE USE COEFF.
               6=THRESHOLD FOR RUNOFF FROM NORTHERN MOUNTAINS
               7=TRANSMISIBILITY
               8=STORAGE COEFF.
               9=ADJUSTMENT FOR MAXIMUM INFILTRATION CAPACITY
ET         ACTUAL EVAPORATION
EPT        ESTIMATED EVAPORATION
STR        SURFACE STORAGE
HI,HJ      BOUNDARY CONDITIONS
FI         RECHARGE TO GROUND WATER
PMP        PUMPING RATE
1
```

APPENDIX B:

COMPUTER PROGRAM WITH SUBROUTINES

```
C      SIMULATE GROUNDWATER SURFACE FOR HOMOGENEOUS AQUIFER
       COMMON /BLK1/A(38),B(38),C(38),D(38),HS(38),JBB(38),JBG(38),
      1JDB(38),JND(38),PP(38),QP(38),RP(38),SP(38),HJ(38,2),HOJ(38,2),
      2HØJ(38,2)/BLK2/IBB(29),IBG(29),IDB(29),IND(29),P(29),Q(29),R(29),
      3S(29),HI(2,29),HOI(2,29),HØI(2,29),CCR(4,12),CGW(12),CPH(12),
      4HCSO(4),HESO(4),PR(9),QIR(4,12),SIC(4),STRO(4)/BLK3/TPG(38,29),
      5DPH(38,29),FI(38,29),H(38,29),HO(38,29),H2(38,29),LC(38,29),
      6LD(38,29),LS(38,29),PHP(38,29),STR(38,29),GSL(38,29)
      7/BLK4/PEV(3,1,12),PPT(3,1,12)
       COMMON ADMS,AIN,AOUT,CDPH,CQIR,DX,DT,INN,IOT1,IOT2,L,L1,L2,
      1LYRO,M,M1,M2,NCL,NITX,NHY,NSL,NPR,NYR,RPPT,RTO,SCAL,
      2LYR,TLAM,EPS,FN,ISC1
       REAL HCSO,HESO
C
C      READ AND CHECK BASIC DATA
       READ(5,100)LYRO,NYR,L,M,NSL,NCL,NHY,NPR,INN,IOT1,IOT2,NITX,N
   100 FORMAT(20I4)
       FN=N
C
C      INFORMATION ON SURFACE CATCHMENT
       READ(INN,101) AIN,AOUT,RPPT
       RTO=RPPT*AOUT/AIN
   101 FORMAT(8F10.2)
       WRITE(IOT1,200)AIN,AOUT,RPPT
   200 FORMAT(1H1,5HAIN =,F8.2,5X,6HAOUT =,F8.2,5X,6HRPPT =,F5.2)
C
C      CROP CONSUMPTIVE-USE COEFFICIENTS
       WRITE(IOT1,201)
   201 FORMAT(/34H CROP CONSUMPTIVE-USE COEFFICIENTS)
       DO 2 II=1,NSL
       READ(INN,102) (CCR(II,KK),KK=1,12)
     2 WRITE(IOT1,202) (CCR(II,KK),KK=1,12)
   102 FORMAT(12F6.2)
   202 FORMAT(1X12F6.2)
C
C      IRRIGATION RATES
       WRITE(IOT1,203)
   203 FORMAT(/11H IRRIGATION)
       DO 3 II=1,NSL
       READ(INN,106) (QIR(II,KK),KK=1,12)
     3 WRITE(IOT1,202) (QIR(II,KK),KK=1,12)
C
C      PHREATOPHYTE CONSUMPTIVE-USE COEFFICIENTS
       WRITE(IOT1,204)
   204 FORMAT(/42H PHREATOPHYTE CONSUMPTIVE-USE COEFFICIENTS)
       READ(INN,102) (CPH(KK),KK=1,12)
       WRITE(IOT1,202) (CPH(KK),KK=1,12)
C
C      G.W. CONSUMPTIVE-USE COEFFICIENT)
       WRI   .T1,205)
   205 FOR...(/34H G.W. CONSUMPTIVE-USE COEFFICIENTS)
       READ(INN,102) (CGW(KK),KK=1,12)
       WRITE(IOT1,202) (CGW(KK),KK=1,12)
C
C      IDENTIFY BOUNDARIES
       WRITE(IOT1,210)
   210 FORMAT(//18H   ROW  BEGIN  END/)
       DO 4 J=1,M
       READ(INN,103) IBG(J),IBB(J),P(J),Q(J),IND(J),IDB(J),R(J),S(J)
   103 FORMAT(2I3,F3.1,F4.1,I4,I3,F3.1,F4.1)
       WRITE(IOT1,211) J,IBG(J),IND(J)
```

```
  211 FORMAT(3I6)
      IF(P(J).LE.0.) P(J)=.0001
      IF(Q(J).LE.0.) Q(J)=.0001
      IF(R(J).LE.0.) R(J)=.0001
      IF(S(J).LE.0.) S(J)=.0001
    4 CONTINUE
      WRITE(IOT1,212)
  212 FORMAT(//18H   COL  BEGIN  END/)
      DO 5 I=1,L
      READ(INN,103) JBG(I),JBB(I),PP(I),QP(I),JND(I),JDB(I),RP(I),SP(I)
      WRITE(IOT1,211) I,JBG(I),JND(I)
      IF(PP(I).LE.0.) PP(I)=.0001
      IF(QP(I).LE.0.) QP(I)=.0001
      IF(RP(I).LE.0.) RP(I)=.0001
      IF(SP(I).LE.0.) SP(I)=.0001
    5 CONTINUE
C
C     READ GROUND SURFACE ELEVATION
      DO 20 J=1,M
      IB=IBG(J)
      ID=IND(J)
   20 PEAD(INN,500) (GSL(I,J),I=IB,ID)
  500 FORMAT(16F5.1)
C
C     SOIL INDICATOR
      DO 6 J=1,M
      IB=IBG(J)
      ID=IND(J)
    6 READ(INN,100) (LS(I,J),I=IB,ID)
C
C     CLIMATIC INDICATOR
      DO 7 J=1,M
      IB=IBG(J)
      ID=IND(J)
    7 READ(INN,100) (LC(I,J),I=IB,ID)
C
C     DRAINAGE INDICATOR
      DO 8 J=1,M
      IB=IBG(J)
      ID=IND(J)
    8 READ(INN,100) (LD(I,J),I=IB,ID)
C
C     TOPOGRAPHIC PARAMETER
      DO 9 J=1,M
      IB=IBG(J)
      ID=IND(J)
    9 READ(INN,105) (TPG(I,J),I=IB,ID)
  104 FORMAT(16F5.2)
C
C     PHREATOPHYTE DENSITY
      DO 10 J=1,M
      IB=IBG(J)
      ID=IND(J)
   10 READ(INN,104) (DPH(I,J),I=IB,ID)
C
C     SOIL MOISTURE AND SURFACE STORAGE INDEXES
      READ(INN,104) (MCSO(II),II=1,NSL),(MESO(II),II=1,NSL),
     1(SIC(II),II=1,NSL),(STRO(II),II=1,4)
  504 FORMAT(16F5.2)
      WRITE(IOT1,504) (MCSO(II),II=1,NSL),(MESO(II),II=1,NSL),
     1(SIC(II),II=1,NSL),(STRO(II),II=1,4)
C
C     G.W. INITIAL CONDITION
```

```
      DO 11 J=1,M
      IB=IBG(J)
      ID=IND(J)
      READ(INN,105) (HO(I,J),I=IB,ID)
      DO 11 I=IB,ID
   11 H(I,J)=HO(I,J)
      READ(INN,105) ((HOI(I,J),I=1,2),J=1,M)
  105 FORMAT(16F5.1)
      READ(INN,105) ((HOJ(I,J),J=1,2),I=1,L)
C
C     INPUT OBSERVED DATA
      DO 15 II=1,NCL
      DO 13 K=1,NYR
   13 READ(INN,106) (PPT(II,K,KK),KK=1,12)
C
      DO 14 K=1,NYR
   14 READ(INN,106) (PEV(II,K,KK),KK=1,12)
  106 FORMAT(12F5.3)
   15 CONTINUE
C
C     DETERMINE OPERATION SCHEME
      READ(INN,107)L1,L2,M1,M2,CDPH,CQIR,ADHS,DX,DT,SCAL,ISC1
  107 FORMAT(4I5,3F5.3,F6.0,F4.1,F5.0,I5)
      IF(ISC1.LE.0) ISC1=1
      WRITE(IOT1,206) CDPH,CQIR
  206 FORMAT(/1X,6HCDPH =,F5.3,10X,6HCQIR =,F5.3)
      CALL GWSM
      STOP
      END
```

```
C     GROUNDWATER SIMULATION SUBROUTINE
      SUBROUTINE GWSM
      COMMON /BLK1/A(38),B(38),C(38),D(38),HS(38),JBB(38),JBG(38),
     1JDB(38),JND(38),PP(38),GP(38),RP(38),SP(38),HJ(38,2),HOJ(38,2),
     2H0J(38,2)/BLK2/IBB(29),IBG(29),IDB(29),IND(29),P(29),Q(29),R(29),
     3S(29),HI(2,29),HOI(2,29),HOI(2,29),CCR(4,12),CGW(12),CPH(12),
     4MCSO(4),MESO(4),PR(9),CIR(4,12),SIC(4),STRO(4)/BLK3/TPG(38,29),
     5DPH(38,29),FI(38,29),H(38,29),HO(38,29),H0(38,29),LC(38,29),
     6LD(38,29),LS(38,29),PMP(38,29),STR(38,29),GSL(38,29)
     7/BLK4/PEV(3,1,12),PPT(3,1,12)
      COMMON ADHS,AIN,AOUT,CDPH,CQIR,DX,DT,INN,IOT1,IOT2,L,L1,L2,
     1LYRO,M,M1,M2,NCL,NITX,NHY,NSL,NPR,NYR,RPPT,RTO,SCAL,
     2LYR,TLAM,EPS,FN,ISC1
      REAL MIC(38,29),MCSO,MESO
      REAL MS1,MS,LMDA
C
C     READ AND CHECK PARAMETER VALUES
      READ(INN,100) (PR(JJJ),JJJ=1,NPR)
  100 FORMAT(8F10.3)
      WRITE(IOT1,200) (PR(JJJ),JJJ=1,NPR)
  200 FORMAT(//17H MODEL PARAMETERS/(1X,5F12.3))
C
C     INITIAL SOIL MOISTURE AND SURFACE STORAGE
      CALL INITL(MIC,MS1,MS,LMDA)
C     REPEAT SIMULATION FOR EACH YEAR
      DO 26 K=1,NYR
      LYR=LYRO+K-1
C
C     REPEAT SIMULATION FOR EACH MONTH
      DO 26 KK=1,12
      READ(INN,105) ((HI(I,J),I=1,2),J=1,M)
      READ(INN,105) ((HJ(I,J),J=1,2),I=1,L)
  105 FORMAT(16F5.1)
      IF(K.EQ.1.AND.KK.EQ.1) CALL OUTPUT(K,KK,1)
      CALL GW1(K,KK,MIC,MS1,MS,LMDA)
C
C     OUTPUT EFFECTIVE RECHARGE
      IF(L1.EQ.1.OR.L2.EQ.1) GO TO 23
      IF(KK.EQ.M1.OR.KK.EQ.M2) GO TO 23
      GO TO 25
   23 WRITE(IOT1,201) LYR,KK,(III,III=1,10,ISC1)
  201 FORMAT(1H1,5H YEAR,I5,5X,5HMONTH,I3,5X19H EFFECTIVE RECHARGE /
     14H ROW5X10I7)
C
      DO 24 J=1,M
      IF(MOD(J,ISC1).NE.0) GO TO 24
      IB=IBG(J)
      ID=IND(J)
      WRITE(IOT1,202) J,(FI(I,J),I=IB,ID,ISC1)
  202 FORMAT(1XI3,7X10F7.3/(11X10F7.3))
   24 CONTINUE
C
   25 CALL SLVEQ(K,KK)
   26 CONTINUE
      RETURN
      END
```

```
C      INITIAL SM AND SURFACE STORAGE SUBROUTINE
       SUBROUTINE INITL(MIC,HS1,MS,LMDA)
       COMMON /BLK1/A(38),B(38),C(38),D(38),HS(38),JBB(38),JBG(38),
      1JDB(38),JND(38),PP(38),CP(38),RP(38),SP(38),HJ(38,2),HOJ(38,2),
      2H0J(38,2)/BLK2/IBB(29),IBG(29),IDB(29),IND(29),P(29),Q(29),R(29),
      3S(29),HI(2,29),HOI(2,29),H0I(2,29),CCR(4,12),CGW(12),CPH(12),
      4MCSO(4),MESO(4),PR(9),OIR(4,12),SIC(4),STRO(4)/BLK3/TPG(38,29),
      5DPH(38,29),FI(38,29),H(38,29),HO(38,29),H0(38,29),LC(38,29),
      6LD(38,29),LS(38,29),PMP(38,29),STR(38,29),GSL(38,29)
      7/BLK4/PEV(3,1,12),PPT(3,1,12)
       COMMON ADHS,AIN,AOUT,CDPH,CQIR,DX,DT,INN,IOT1,IOT2,L,L1,L2,
      1LYRO,M,M1,M2,NCL,NITX,NHY,NSL,NPR,NYR,RPPT,RTO,SCAL,
      2LYR,TLAM,EPS,FN,ISC1
       REAL MIC(38,29),MCSO,MESO
       REAL HS1,HS,LMDA
     2 DO 8 J=1,M
       IB=IBG(J)
       ID=IND(J)
       DO 8 I=IB,ID
       ISL=LS(I,J)
       MIC(I,J)=SIC(ISL)
       ITPG=-TPG(I,J)
       IF(ITPG.GE.4) STR(I,J)=STRO(4)
       IF(ITPG.EQ.3) STR(I,J)=STRO(3)
       IF(ITPG.EQ.2) STR(I,J)=STRO(2)
       IF(ITPG.LE.1) STR(I,J)=STRO(1)
     8 CONTINUE
C
C      RESET G.W. INITIAL CONDITIONS
       DO 11 J=1,M
       IB=IBG(J)
       ID=IND(J)
       DO 9 I=IB,ID
     9 H0(I,J)=HO(I,J)
C
       DO 10 I=1,2
    10 H0I(I,J)=HOI(I,J)
    11 CONTINUE
C
       DO 12 I=1,L
       DO 12 J=1,2
    12 H0J(I,J)=HOJ(I,J)
C
C
       LMDA=DT*SCAL/(DX*DX)
       TLAM=PR(7)*LMDA/SCAL
       EPS=PR(8)
C
       RETURN
       END
```

```
C     GW SUB SUBROUTINE
      SUBROUTINE GW1(K,KK,MIC,MS1,MS,LMDA)
      COMMON /BLK1/A(38),B(38),C(38),D(38),HS(38),JBB(38),JBG(38),
     1JDB(38),JND(38),PP(38),QP(38),RP(38),SP(38),HJ(38,2),HOJ(38,2),
     2HØJ(38,2)/BLK2/IBB(29),IBG(29),IDB(29),IND(29),P(29),Q(29),R(29),
     3S(29),HI(2,29),HOI(2,29),HØI(2,29),CCR(4,12),CGW(12),CPH(12),
     4MCSO(4),MESO(4),PR(9),QIR(4,12),SIC(4),STRO(4)/BLK3/TPG(38,29),
     5DPH(38,29),FI(38,29),H(38,29),HO(38,29),HØ(38,29),LC(38,29),
     6LD(38,29),LS(38,29),PHP(38,29),STR(38,29),GSL(38,29)
     7/BLK4/PEV(3,1,12),PPT(3,1,12)
      COMMON ADMS,AIN,AOUT,CDPH,CQIR,DX,DT,INN,IOT1,IOT2,L,L1,L2,
     1LYRO,M,M1,M2,NCL,NITX,NHY,NSL,NPR,NYR,RPPT,RTO,SCAL,
     2LYR,TLAM,EPS,FN,ISC1
      REAL MIC(38,29),MCSO,MESO
      REAL MS1,MS,LMDA
C
      DO 19 J=1,M
      IB=IBG(J)
      ID=IND(J)
      DO 18 I=IB,ID
      ISL=LS(I,J)
      ICL=LC(I,J)
      DDP=CDPH*DPH(I,J)
      IF(LS(I,J).EQ.4) DDP=DPH(I,J)
      QIRR=CQIR*QIR(ISL,KK)
      PRCP=PPT(ICL,K,KK)
      TSP=PRCP+QIRR
      PPTI=PPT(2,K,KK)*RTO
      IF(LD(I,J).EQ.1.AND.PPTI.GT.PR(6)) TSP=TSP+PR(4)*PPTI
      IF(TSP.LE.PR(2)) GO TO 30
      TSP=TSP*(1.-PR(1)*TPG(I,J))
      IF(TSP.LT.PR(2)) TSP=PR(2)
   30 TSP=TSP+STR(I,J)
      PR3=PR(3)
      IF(TPG(I,J).LE.-2.) PR3=PR(3)*PR(9)
      IF(TSP.LT.PR3) GO TO 13
      STR(I,J)=TSP-PR3-QIRR
      IF(STR(I,J).LT.0.) STR(I,J)=0.
      TSP=PR3
      GO TO 14
   13 STR(I,J)=0.
   14 ETP=((1.-DDP)*CCR(ISL,KK)+DDP*(CPH(KK)-CGW(KK)))*PEV(ICL,K,KK)*
     1PR(5)
      NITR=1
      MS1=MIC(I,J)
   15 FMES=MESO(ISL)
      IF(MS1.LT.0.) MS1=0.
      ET=ETP*MS1/FMES
      IF(ET.GT.ETP) ET=ETP
      FMIC=MIC(I,J)
      MS=FMIC+TSP-ET
      FMCS=MCSO(ISL)
      IF(MS.GT.FMCS) GO TO 16
      FI(I,J)=-DDP*CGW(KK)*PEV(ICL,K,KK)
      GO TO 17
   16 FMCS=MCSO(ISL)
      FI(I,J)=MS-FMCS-DDP*CGW(KK)*PEV(ICL,K,KK)
      MS=FMCS
   17 DMS=ABS(MS-MS1)
      IF(DMS.LT.ADMS.OR.NITR.GT.NITX) GO TO 18
      FMIC=MIC(I,J)
```

```
      MS1=(FMIC+MS)/2.
      NITR=NITR+1
      GO TO 15
   18 MIC(I,J)=MS
   19 CONTINUE
C
C     READ PUMPING RATES FOR MANAGEMENT STUDY
      IF(K.GT.1) GO TO 21
      DO 20 J=1,M
      IB=IBG(J)
      ID=IND(J)
   20 READ(INN,101) (PMP(I,J),I=IB,ID)
  101 FORMAT(16F5.3)
   21 DO 22 J=1,M
      IB=IBG(J)
      ID=IND(J)
      DO 22 I=IB,ID
   22 FI(I,J)=FI(I,J)-PMP(I,J)
      RETURN
      END
```

```
C     NUMERICAL SOLUTION SUBROUTINE
      SUBROUTINE SLVEQ(K,KK)
      COMMON /BLK1/A(38),B(38),C(38),D(38),HS(38),JBB(38),JBG(38),
     1JDB(38),JND(38),PP(38),QP(38),RP(38),SP(38),HJ(38,2),HOJ(38,2),
     2H0J(38,2)/BLK2/IBB(29),IBG(29),IDB(29),IND(29),P(29),Q(29),R(29),
     3S(29),HI(2,29),HOI(2,29),H0I(2,29),CCR(4,12),CGW(12),CPH(12),
     4MCSO(4),MESO(4),PR(9),CIR(4,12),SIC(4),STRO(4)/BLK3/TPG(38,29),
     5DPH(38,29),FI(38,29),H(38,29),HO(38,29),H0(38,29),LC(38,29),
     6LD(38,29),LS(38,29),PMP(38,29),STR(38,29),GSL(38,29)
     7/BLK4/PEV(3,1,12),PPT(3,1,12)
      COMMON ADMS,AIN,AOUT,CDPH,CQIR,DX,DT,INN,IOT1,IOT2,L,L1,L2,
     1LYRO,M,M1,M2,NCL,NITX,NHY,NSL,NPR,NYR,RPPT,RTO,SCAL,
     2LYR,TLAM,EPS,FN,ISC1
      REAL MCSO,MESO
C
      CALL FRSTHF(K,KK)
      IF(L1.EQ.1) CALL OUTPUT(K,KK,2)
      CALL SCNDHF(K,KK,SUM)
      IF(L2.EQ.1) GO TO 42
      IF(KK.EQ.M1.OR.KK.EQ.M2) GO TO 42
      GO TO 44
   42 CALL OUTPUT(K,KK,3)
   44 ADEV=SUM/FN
      WRITE(IOT1,600) ADEV
  600 FORMAT(//28H AVERAGE DEV. FROM INITIAL =,F5.2)
      DO 29 J=1,M
      H0I(1,J)=HI(1,J)
   29 H0I(2,J)=HI(2,J)
C
      DO 30 I=1,L
      H0J(I,1)=HJ(I,1)
   30 H0J(I,2)=HJ(I,2)
      RETURN
      END
```

```
C     FIRST HALF-TIME STEP SUBROUTINE
      SUBROUTINE FRSTHF(K,KK)
      COMMON /BLK1/A(38),B(38),C(38),D(38),HS(38),JBB(38),JBG(38),
     1JDB(38),JND(38),PP(38),QP(38),RP(38),SP(38),HJ(38,2),HOJ(38,2),
     2H0J(38,2)/BLK2/IBB(29),IBG(29),IDB(29),IND(29),P(29),Q(29),R(29),
     3S(29),HI(2,29),HOI(2,29),H0I(2,29),CCR(4,12),CGW(12),CPH(12),
     4HCSO(4),MESO(4),PR(9),QIR(4,12),SIC(4),STRO(4)/BLK3/TPG(38,29),
     5DPH(38,29),FI(38,29),H(38,29),HO(38,29),H0(38,29),LC(38,29),
     6LD(38,29),LS(38,29),PMP(38,29),STR(38,29),GSL(38,29)
     7/BLK4/PEV(3,1,12),PPT(3,1,12)
      COMMON ADMS,AIN,AOUT,CDPH,CQIR,DX,DT,INN,IOT1,IOT2,L,L1,L2,
     1LYRO,M,M1,M2,NCL,NITX,NHY,NSL,NPR,NYR,RPPT,RTO,SCAL,
     2LYR,TLAM,EPS,FN,ISC1
      REAL MCSO,MESO
C     FIRST HALF-TIME STEP
C     IMPLICIT IN X-DIRECTION, EXPLICIT IN Y-DIRECTION
    3 DO 16 J=1,M
      LBB=IBB(J)
      LDB=IDB(J)
      IB=IBG(J)
      ID=IND(J)
      IBP=IB+1
      IDM=ID-1
C
C     SET COEFFICIENT ARREYS
      DO 7 I=IBP,IDM
      A(I)=-TLAM/(2.*EPS)
      B(I)=1.+TLAM/EPS
    7 C(I)=A(I)
      B(IB)=1.+TLAM/(EPS*P(J))
      C(IB)=-TLAM/(EPS*(1.+P(J)))
      A(ID)=-TLAM/(EPS*(1.+R(J)))
      B(ID)=1.+TLAM/(EPS*R(J))
C
C     COMPUTE RIGHT-HAND SIDE VECTOR.
      DO 14 I=IB,ID
      JB=JBG(I)
      JD=JND(I)
      DUMY=FI(I,J)
      FIT=DT*DUMY/(2.*EPS)
      IF(I.GT.IB) GO TO 10
      HPS=(HI(1,J)+H0I(1,J))/2.
      IF(LBB.NE.1) GO TO 8
      HQN=H0J(I,1)
      IF(J.GT.JB) HQN=H0(I,J-1)
      JJ=J+1
      GO TO 9
    8 HQN=H0J(I,2)
      IF(J.LT.JD) HQN=H0(I,J+1)
      JJ=J-1
    9 D(I)=TLAM*HPS/(EPS*P(J)*(1.+P(J)))+TLAM*HQN/(EPS*Q(J)*(1.+Q(J)))+
     1(1.-TLAM/(EPS*Q(J)))*H0(I,J)+TLAM*H0(I,JJ)/(EPS*(1.+Q(J)))+FIT
      GO TO 14
   10 IF(I.GE.ID) GO TO 11
      IF(J.LE.JB) GO TO 300
      IF(J.GE.JD) GO TO 301
      D(I)=TLAM*H0(I,J-1)/(2.*EPS)+(1.-TLAM/EPS)*H0(I,J)+TLAM*H0(I,J+1)/
     1(2.*EPS)+FIT
      GO TO 14
  300 D(I)=TLAM*H0J(I,1)/(2.*EPS)+(1.-TLAM/EPS)*H0(I,J)
     1+TLAM*H0(I,J+1)/(2.*EPS)+FIT
```

```
      GO TO 14
  301 D(I)=TLAM*H0(I,J-1)/(2.*EPS)+(1.-TLAM/EPS)*H0(I,J)
     1+TLAM*H0J(I,2)/(2.*EPS)+FIT
      GO TO 14
   11 HRS=(HI(2,J)+H0I(2,J))/2.
      IF(LDB.NE.3) GO TO 12
      HSN=H0J(I,1)
      IF(J.GT.JB) HSN=H0(I,J-1)
      JJ=J+1
      GO TO 13
   12 HSN=H0J(I,2)
      IF(J.LT.JD) HSN=H0(I,J+1)
      JJ=J-1
   13 D(I)=TLAM*HRS/(EPS*R(J)*(1.+R(J)))+TLAM*HSN/(EPS*S(J)*(1.+S(J)))+
     1(1.-TLAM/(EPS*S(J)))*H0(I,J)+TLAM*H0(I,JJ)/(EPS*(1.+S(J)))+FIT
   14 CONTINUE
      CALL TRID(IB,ID)
      DO 15 I=IB,ID
      H(I,J)=HS(I)
      IF(H(I,J).GT.GSL(I,J)) H(I,J)=GSL(I,J)
   15 H0(I,J)=H(I,J)
C
   16 CONTINUE
      RETURN
      END
```

```
C     SECOND HALF-TIME STEP SUBROUTINE
      SUBROUTINE SCNDHF(K,KK,SUM)
      COMMON /BLK1/A(38),B(38),C(38),D(38),HS(38),JBB(38),JBG(38),
     1JDB(38),JND(38),PP(38),QP(38),RP(38),SP(38),HJ(38,2),HOJ(38,2),
     2HØJ(38,2)/BLK2/IBB(29),IBG(29),IDB(29),IND(29),P(29),Q(29),R(29),
     3S(29),HI(2,29),HOI(2,29),HØI(2,29),CCR(4,12),CGW(12),CPH(12),
     4MCSO(4),MESO(4),PR(9),QIR(4,12),SIC(4),STRO(4)/BLK3/TPG(38,29),
     5DPH(38,29),FI(38,29),H(38,29),HO(38,29),HØ(38,29),LC(38,29),
     6LD(38,29),LS(38,29),PHP(38,29),STR(38,29),GSL(38,29)
     7/BLK4/PEV(3,1,12),PPT(3,1,12)
      COMMON ADMS,AIN,AOUT,CDPH,CQIR,DX,DT,INN,IOT1,IOT2,L,L1,L2,
     1LYRO,M,M1,M2,NCL,NITX,NHY,NSL,NPR,NYR,RPPT,RTO,SCAL,
     2LYR,TLAM,EPS,FN,ISC1
      REAL MCSO,MESO
C
C
C     SECOND HALF-TIME STEP
C     IMPLICT IN Y-DIRECTION, EXPLICT IN X-DIRECTION
   55 SUM=0.0
C
C     SET COEFFICIENT ARRAYS.
      DO 28 I=1,L
      MBB=JBB(I)
      MDB=JDB(I)
      JB=JBG(I)
      JD=JND(I)
      JBP=JB+1
      JDM=JD-1
      DO 17 J=JBP,JDM
      A(J)=-TLAM/(2.*EPS)
      B(J)=1.+TLAM/EPS
   17 C(J)=A(J)
      IF(MBB.NE.3) GO TO 18
      B(JB)=1.+TLAM/(EPS*SP(I))
      C(JB)=-TLAM/(EPS*(1.+SP(I)))
      GO TO 19
   18 B(JB)=1.+TLAM/(EPS*QP(I))
      C(JB)=-TLAM/(EPS*(1.+QP(I)))
   19 IF(MDB.NE.4) GO TO 20
      A(JD)=-TLAM/(EPS*(1.+SP(I)))
      B(JD)=1.+TLAM/(EPS*SP(I))
      GO TO 21
   20 A(JD)=-TLAM/(EPS*(1.+QP(I)))
      B(JD)=1.+TLAM/(EPS*QP(I))
C
C     COMPUTE RIGHT-HAND SIDE VECTOR
   21 DO 26 J=JB,JD
      IB=IBG(J)
      ID=IND(J)
      DUMY=FI(I,J)
      FIT=DT*DUMY/(2.*EPS)
      IF(J.GT.JB) GO TO 23
      IF(MBB.NE.3) GO TO 22
      HSN1=HJ(I,1)
      HRS=(HI(2,J)+HØI(2,J))/2.
      IF(I.LT.ID) HRS=HØ(I+1,J)
      D1=TLAM*HSN1/(EPS*SP(I)*(1.+SP(I)))
      D2=TLAM*HRS/(EPS*RP(I)*(1.+RP(I)))
      D3=(1.-TLAM/(EPS*RP(I)))*HØ(I,J)
      D4=TLAM/(EPS*(1.+RP(I)))*HØ(I-1,J)
      D(J)=D1+D2+D3+D4+FIT
```

```
      GO TO 26
   22 HON1=HJ(I,1)
      HPS=(HI(1,J)+H0I(1,J))/2.
      IF(I.GT.IB) HPS=H0(I-1,J)
      D1=TLAM*HON1/(EPS*QP(I)*(1.+QP(I)))
      D2=TLAM*HPS/(EPS*PP(I)*(1.+PP(I)))
      D3=(1.-TLAM/(EPS*PP(I)))*H0(I,J)
      D4=TLAM/(EPS*(1.+PP(I)))*H0(I+1,J)
      D(J)=D1+D2+D3+D4+FIT
      GO TO 26
   23 IF(J.GE.JD) GO TO 24
      I6(I.LE.IB) GO TO 302
      IF(I.GE.ID) GO TO 303
      D(J)=TLAM*H0(I-1,J)/(2.*EPS)+(1.-TLAM/EPS)*H0(I,J)+TLAM*H0(I+1,J)/
     1(2.*EPS)+FIT
      GO TO 26
  302 D(J)=TLAM*H0I(1,J)/(2.*EPS)+(1.-TLAM/EPS)*H0(I,J)
     1+TLAM*H0(I+1,J)/(2.*EPS)+FIT
      GO TO 26
  303 D(J)=TLAM*H0(I-1,J)/(2.*EPS)+(1.-TLAM/EPS)*H0(I,J)
     1+TLAM*H0I(2,J)/(2.*EPS)+FIT
      GO TO 26
   24 IF(MOB.NE.4) GO TO 25
      HSN1=HJ(I,2)
      HRS=(HI(2,J)+H0I(2,J))/2.
      IF(I.LT.[illegible]) HRS=H0(I+1,J)
      D1=TLAM*HSN1/(EPS*SP(I)*(1.+SP(I)))
      D2=TLAM*HRS/(EPS*RP(I)*(1.+RP(I)))
      D3=(1.-TLAM/(EPS*RP(I)))*H0(I,J)
      D4=TLAM/(EPS*(1.+RP(I)))*H0(I-1,J)
      D(J)=D1+D2+D3+D4+FIT
      GO TO 26
   25 HON1=HJ(I,2)
      HPS=(HI(1,J)+H0I(1,J))/2.
      IF(I.GT.IB) HPS=H0(I-1,J)
      D1=TLAM*HON1/(EPS*QP(I)*(1.+QP(I)))
      D2=TLAM*HPS/(EPS*PP(I)*(1.+PP(I)))
      D3=(1.-TLAM/(EPS*PP(I)))*H0(I,J)
      D4=TLAM/(EPS*(1.+PP(I)))*H0(I+1,J)
      D(J)=D1+D2+D3+D4+FIT
   26 CONTINUE
      CALL TRID(JB,JD)
      DO 27 J=JB,JD
      H(I,J)=HS(J)
      IF(H(I,J).GT.GSL(I,J)) H(I,J)=GSL(I,J)
      SUM=SUM+(H(I,J)-H0(I,J))
   27 H0(I,J)=H(I,J)
C
   28 CONTINUE
C
      RETURN
      END
```

```
C     SUBROUTINE TO OUTPUT DATA LEVEL ARRAY
      SUBROUTINE OUTPUT(K,KK,KL)
      COMMON /BLK1/A(38),B(38),C(38),D(38),HS(38),JBB(38),JBG(38),
     1JDB(38),JND(38),PP(38),QP(38),RP(38),SP(38),HJ(38,2),HOJ(38,2),
     2H0J(38,2)/BLK2/IBB(29),IBG(29),IDB(29),IND(29),P(29),Q(29),R(29),
     3S(29),HI(2,29),HOI(2,29),H0I(2,29),CCR(4,12),CGW(12),CPH(12),
     4MCSO(4),MESO(4),PR(9),QIR(4,12),SIC(4),STRO(4)/BLK3/TPG(38,29),
     5DPH(38,29),FI(38,29),H(38,29),HO(38,29),H0(38,29),LC(38,29),
     6LD(38,29),LS(38,29),PMP(38,29),STR(38,29),GSL(38,29)
     7/BLK4/PEV(3,1,12),PPT(3,1,12)
      COMMON ADMS,AIN,AOUT,CDPH,CQIR,DX,DT,INN,IOT1,IOT2,L,L1,L2,
     1LYRO,M,M1,M2,NCL,NITX,NHY,NSL,NPR,NYR,RPPT,RTO,SCAL,
     2LYR,TLAM,EPS,FN,ISC1
      REAL MCSO,MESO
      DIMENSION ALAB(3)
      DATA ALAB(1),ALAB(2),ALAB(3)/4HINTL,4H 1ST,4H 2ND/
    1 WRITE(IOT1,200) LYR,KK,ALAB(KL),(III,III=1,10,ISC1)
  200 FORMAT(//5H YEARI5,5X5HMONTHI3,5XA4,15H HALF-TIME STEP /
     14H ROW4X1H010I7/)
      J=0
      WRITE(IOT1,201) J,(HJ(I,1),I=1,L,ISC1)
  201 FORMAT(1XI3,7X10F7.2/(11X10F7.2))
      DO 10 J=1,M
      IF(MOD(J,ISC1).NE.0) GO TO 10
      IB=IBG(J)
      ID=IND(J)
      WRITE(IOT1,601) J,HI(1,J),(H(I,J),I=IB,ID,ISC1),HI(2,J)
  601 FORMAT(1XI3,11F7.2/(11X10F7.2))
   10 CONTINUE
      J=M+1
      WRITE(IOT1,201) J,(HJ(I,2),I=1,L,ISC1)
      RETURN
      END
```

```
C     TRIDIAGONAL SIMULTANEOUS EQUATION SOLN SUBROUTINE
      SUBROUTINE TRIO(IFS,NS)
C     SOLVING A SYSTEM OF LINEAR SIMULTANEOUS EQUATIONS
C     HAVING A TRIDIAGONAL COEFFICIENT MATRIX.
      COMMON /BLK1/A(38),B(38),C(38),D(38),HS(38),JBB(38),JBG(38),
     1JDB(38),JND(38),PP(38),QP(38),RP(38),SP(38),HJ(38,2),HOJ(38,2),
     2HØJ(38,2)/BLK2/IBB(29),IBG(29),IDB(29),IND(29),P(29),Q(29),R(29),
     3S(29),HI(2,29),HOI(2,29),HØI(2,29),CCR(4,12),CGW(12),CPH(12),
     4MCSO(4),MESO(4),PR(9),QIR(4,12),SIC(4),STRO(4)/BLK3/TPG(38,29),
     5DPH(38,29),FI(38,29),H(38,29),HO(38,29),HØ(38,29),LC(38,29),
     6LD(38,29),LS(38,29),PMP(38,29),STR(38,29),GSL(38,29)
     7/BLK4/PEV(3,1,12),PPT(3,1,12)
      COMMON ADMS,AIN,AOUT,CDPH,CQIR,DX,DT,INN,IOT1,IOT2,L,L1,L2,
     1LYRO,M,M1,M2,NCL,NITX,NHY,NSL,NPR,NYR,RPPT,RTO,SCAL,
     2LYR,TLAM,EPS,FN,ISC1
      REAL MCSO,MESO
      DIMENSION BETA(38),GAMMA(38)
      BETA(IFS)=B(IFS)
C
      GAMMA(IFS)=D(IFS)/BETA(IF8)
      IFP1=IFS+1
      DO 77 IS=IFP1,NS
      BETA(IS)=B(IS)-A(IS)*C(IS-1)/BETA(IS-1)
   77 GAMMA(IS)=(D(IS)-A(IS)*GAMMA(IS-1))/BETA(IS)
      HS(NS)=GAMMA(NS)
      LAST=NS-IFS
      DO 88 KS=1,LAST
      IS=NS-KS
   88 HS(IS)=GAMMA(IS)-C(IS)*HS(IS+1)/BETA(IS)
      RETURN
      END
```

APPENDIX C:

DATA REQUIREMENTS

Input Data Characteristics

Note: Values in parenthesis were used in this report.

LYRO The year the study begins, (1960, 1963, etc).

NYR The number of years the program is to run for must correspond with the number of years for which precipitation and pan evaporation data are available. (1, 5, 7)

L Number of grid columns in study area (29).

M Number of grid rows in study area (38).

NSL Number of soil groups (4).

NCL Number of climatic stations used (3).

MHY Number of hydrologic areas (2).

NPR Number of parameters (9).

- PR(1) Return coefficient (0.20)
- PR(2) Minimum infiltration capacity (0.15)
- PR(3) Maximum infiltration capacity (0.30)
- PR(4) Runoff coefficient for the northern highlands (0.40) (This was set at 0.00 during part of Phase I).
- PR(5) Adjustment for consumptive use coefficient (1.00)
- PR(6) Threshold for runoff from northern highlands (0.00)
- PR(7) Transmissibility (12000.0)
- PR(8) Storage coefficient (0.18)
- PR(9) Adjustments for maximum infiltration capacity (2.0)

INN Number for computer input device (card reader = 5).

IOT1 Number for computer output device (printer = 6).

IOT2 Number for computer output device (printer = 6).

NITX Maximum number of reiterations (must be equal to or less than NYR).

N Number of interior points (648). Does not include boundary points.

AIN That part of the modeled area receiving runoff from the northern highland area (100 km^2).

AOUT Catchment of the northern highlands (207 km^2).

RPPT	Ratio of precipitation in northern highlands and that of Manati Station (1.10).
CCR	Crop consumptive-use coefficient (see Table 1).
QIR	Irrigation rates (see Table 1).
CPH	Phreatophyte consumptive use coefficient.
CGW	Groundwater consumptive use coefficient.
IBG(J)	Beginning interior point for row J (1, 2, 3, ... 24).
IBB(J)	Boundary type of the same point (1, 2) see Riley and Israelsen, June 1971, Appendix B, page 6.
P	See Wang and Riley (1971) page 12.
Q	See Wang and Riley (1971) page 12.
IND(J)	End interior point for row J (26, 27, ... 38).
IDB(J)	Boundary type for same point (3, 4) see Riley and Israelsen, June 1971, Appendix B, Page 6.
R	See Wang and Riley (1971) page 12.
S	See Wang and Riley (1971) page 12.
JBG(I)	Beginning interior point for column I (1).
JBB(I)	Boundary type for same point (1) see Riley and Israelsen, June 1971) Appendix B, Page 6.
PP	See Wang and Riley (1971) page 12.
QP	See Wang and Riley (1971) page 12.
JND(I)	End interior column I (9, 12, 20, 29, etc.).
JDB(I)	Boundary type for same point (2, 4) see Riley and Israelsen, June 1971, appendix B, Page 6.
RP	See Wang and Riley (1971) page 12.
SP	See Wang and Riley (1971) page 12.
GSL	Ground surface elevation to nearest tenth of a meter using 100.0 as sea level.
LS	Soil indicator, one of four soil groups (1, 2, 3, 4).

LC Climate indicator, one of three climatic stations (1, 2, 3).

LD Drainage indicator, is the grid affected by drainage from outside itself? (0, 1).

TPG Topographic parameter, water leaves (1), remains (0), or enters the grid square from one, two or three sides (-1, -2, -3).

DPH Phreatophyte density (0 to 100).

MCSO Soil moisture holding capacity, varies with type soil (30, 30, 30, 30) detailed data lacking.

MESO Critical soil moisture for potential evaporation, varies with type soil (20, 20, 20, 20) detailed data lacking.

SIC Initial soil moisture, varies with type soil and existing conditions (25, 25, 25, 25) detailed data lacking.

STRO Initial surface storage in swamps, varies with type soil and existing conditions (0, 30, 50, 70).

HO Initial groundwater elevation at grid points to nearest tenth of a meter using 100.0 as sea level.

HOI Initial groundwater elevation at boundary point in 1 direction to nearest tenth of a meter using 100.0 as sea level.

PPT Precipitation at each of the three climatic stations, measured in mm.

PEV Class A pan evaporation at each of three climatic stations, measured in mm.

L_1 Output control, $L_1 = 0$ suppresses printout of first half step, $L_1 = 1$ prints these values.

L_2 Output control, $L_2 = 0$ if M_1 or M_2 is used, $L_2 = 1$ prints 12 months of second half step data.

M_1 Output control, if L_1 and L_2 are zero, the number between 1 and 12 indicates which month data is to be printed out.

M_2 Same as M_1, program will print out the one or two months indicated by M_1 and M_2 (9, 1[illegible]

CDPH Adjustment for phreatophyte density, when $CDPH = 0$, all phreatophytes are eliminated (varied between 0.70 and 1.50).

CQIR Adjustment for irrigation (1.00).

ADMS Allowable error for soil moisture simulation (10).

DX Grid spacing (624m).

DT Time increment (10).

SCAL Scaling factor

ISC1 Output option indicating row multiple desired printed (1 = every row, 2 = every second rwo, 3 = every third row).

HI Boundary conditions, groundwater elevation to nearest tenth of a meter using 100.0 as sea level.

HJ Boundary conditions, groundwater elevation to nearest tenth of a meter using 100.0 as sea level.

PMP Pumping rates from groundwater (0.0).