APPLICATION OF COMPUTER TECHNIQUES FOR LONG RANGE REGIONAL GROUNDWATER RESOURCES MANAGEMENT

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SYNOPSIS

South Florida, during the past three decades has experienced phenomenal, rapid and generally uncontrolled growth. As a consequence, there has been a drastic increase in the use of ground water. Presently more than 2.5 million people reside in this area. The sole source of fresh water supply for this area comes from a highly permeable water table aquifer known locally as the Biscayne aquifer. This aquifer consists of limestone which is porous and permeable, having transmissivity values in excess of 3.5 million gallons per day per foot of drawdown. Natural rainfall and a man-made network of canals recharges this aquifer system.

In south Florida most municipal wellfields are located in close proximity to population centers which in turn are concentrated along the Atlantic Ocean. Over the past several years many of the wellfields have begun to show early signs of salt water intrusion. This has occurred essentially as a result of dramatic and largely uncontrolled growth and the consequent increases in fresh water demand.

In the past, no scientific attempt was made to quantify the amount of fresh water that could be safely withdrawn from these wellfields without causing adverse ground water or environmental impact.

In order to study the existing complex system of wellfields, and their impact on the delicate ecosystem, salt water intrusion and the ultimate safe yield of the ground water system under various hydrologic conditions, a hybrid computer modeling technique was developed in-house. The model is used to study the interrelationship between hydrologic and hydrogeologic variables and to synthesize the behavior of the aquifer system in response to naturally occurring (ET) as well as applied stress (pumpage) by man.

The objective of this study was to quantify the following:

1. What is the safe sustained yield of the presently existing aquifer systems?
2. Can additional wellfields be developed west of the present wellfields to meet the short range water requirements of the area?
3. What is the ultimate capacity that can be safely withdrawn from this aquifer system on a long term average annual basis?
4. What are the consequences in terms of environmental impact?

Preliminary computer results show that during normal years (60 inches of rainfall) an average of approximately 320 million gallons of water per day can be safely withdrawn from the existing wellfields. The results further show that additional wellfields can be developed along the western portion of the area to increase the sustained yield to a maximum of 720 million gallons per day with 375 gallons per day of canal flow recharging the aquifer.

However, during critical years such as 1970-71 when only 38 inches of rain fell on the ground (U. S. Geological Survey estimates the recurrence interval of the 1970-71 drought event to be in excess of 1 in 100 years), the sustained yield from the existing wellfields would decrease to 310 million gallons per day, without causing any environmental impact. In this computer run no canal recharge was allowed to take place.

Introduction

The influx of population in south Florida during the past three decades has been phenomenal. The total number of people residing in the region increased from approximately 693,000 to more than 2.5 million. To accomodate such growth, land use changes took place with regard to environmental constraints or to the availability of supportive natural resources (Figure 1). There is no indication that this population expansion trend is diminishing.

In south Florida 95% of the water for public water supply comes from shallow aquifers. Most of the wellfields which supply water for public uses are located along the coastal areas, as are the centers of population (Figure 2). Due to their proximity to the coast, the safe sustained yields from these wellfields are limited. In the past, no scientific attempt was made to quantify the amount of freshwater that could be safely withdrawn from these coastal wellfields. Due to dramatic and largely uncontrolled growth, pumpage was increased beyond safe sustained yields to meet the freshwater demand of the region, and many of the wellfields have begun to show signs of saltwater intrusion.

To further intensify the water supply problem, south Florida suffered one of its most extreme drought events in history during 1970-71. The U. S. Geological Survey estimated the severity of this drought to be in excess of a 1 in 100 year event. As a consequence, public water suppliers had to reduce pumpage by as much as 30% to prevent the saltwater from intruding inland.

Realizing that the natural resources of the region were being stressed to a critical state and some form of management was urgently needed, the Florida State Legislature passed the Water Resources Act of 1972. Five water management districts (2 of which were already in existence) were formed and were delegated total water management authority for their respective regions. Under the statute, each of the 5 districts had to develop a water resources policy for their region, which later were to be

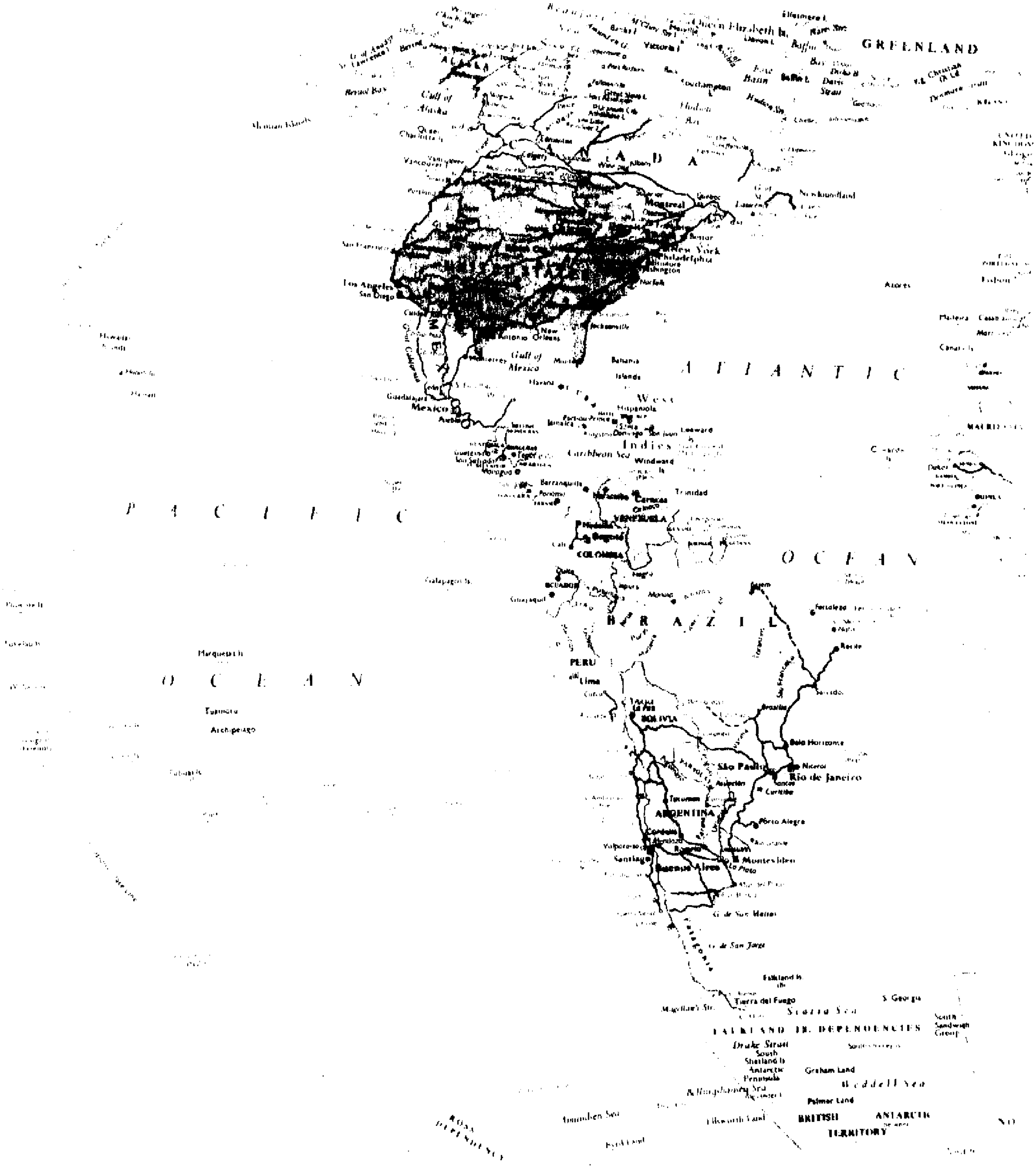

Figure 1a. GEOGRAPHIC LOCATION

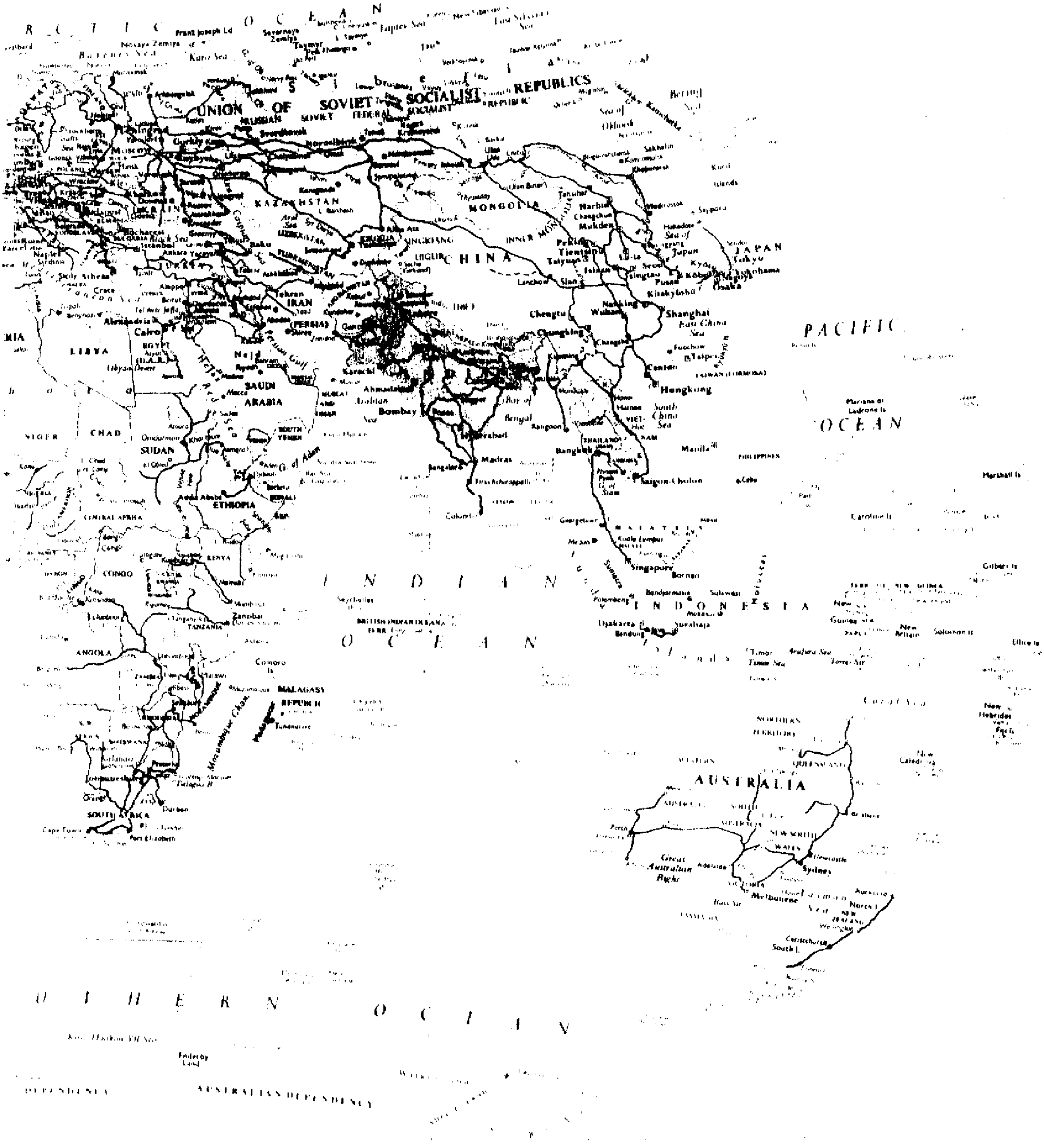

Figure 1b GEOGRAPHIC LOCATION

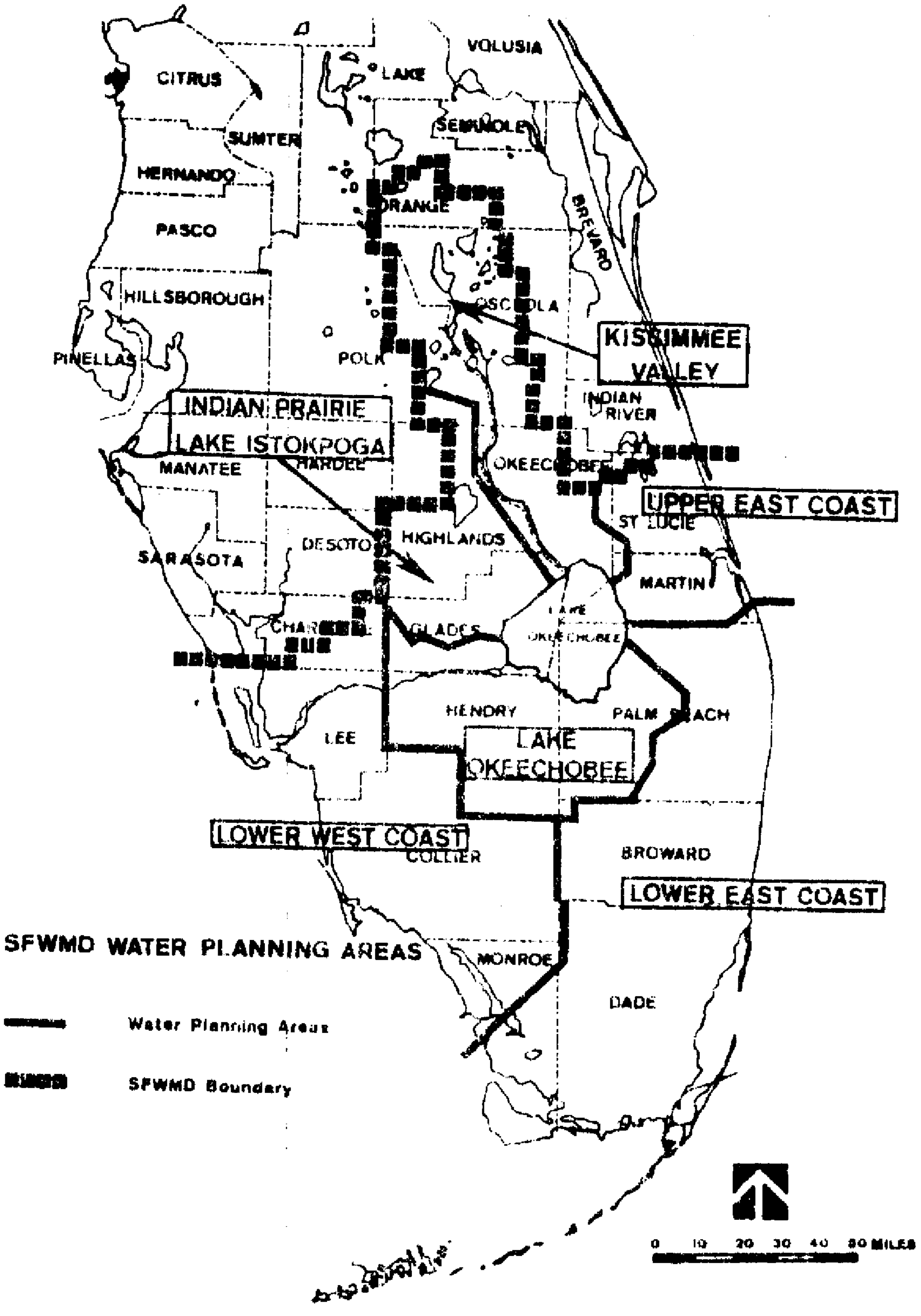

Figure 1c WATER PLANNING AREAS

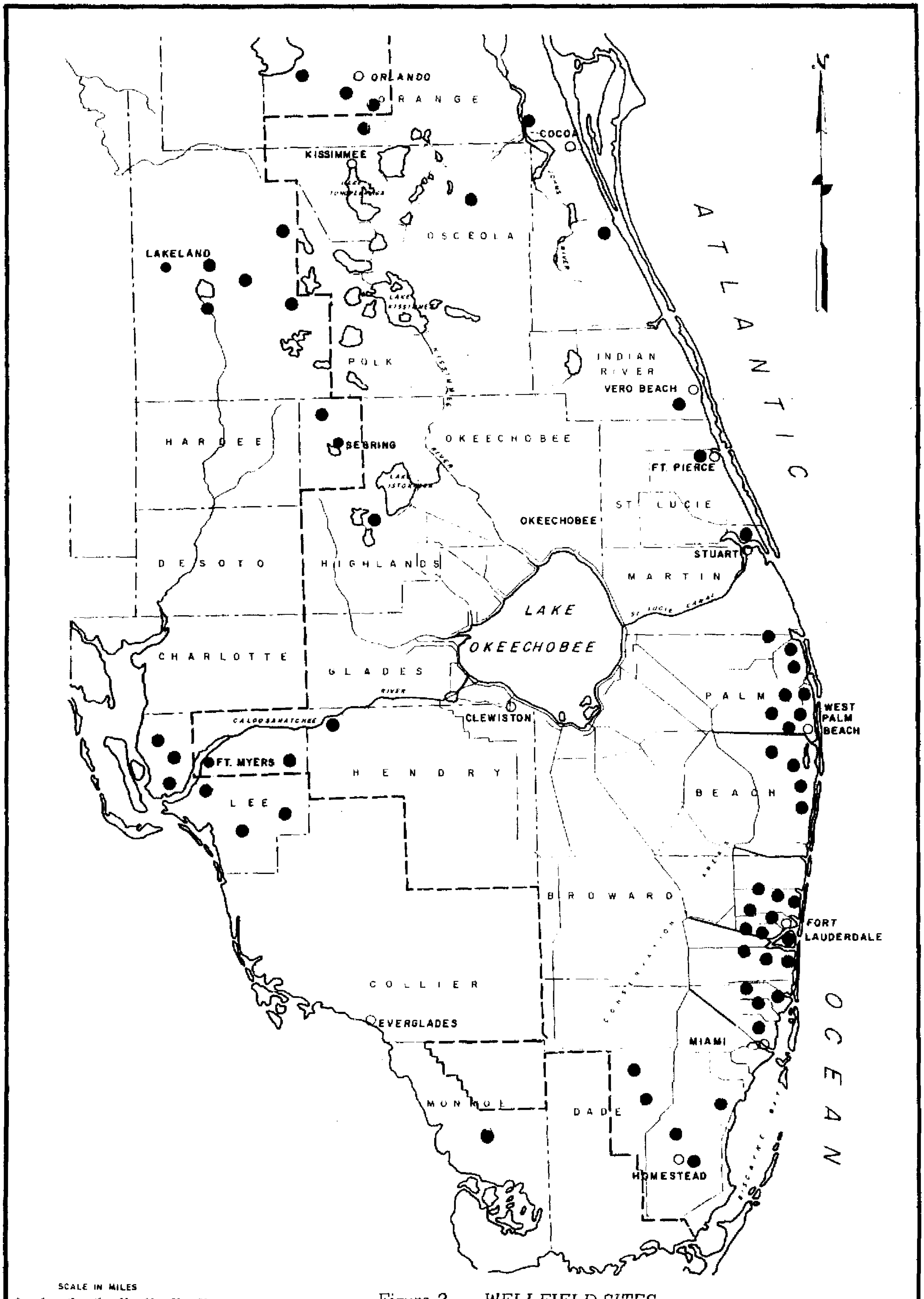

Figure 2 WELLFIELD SITES

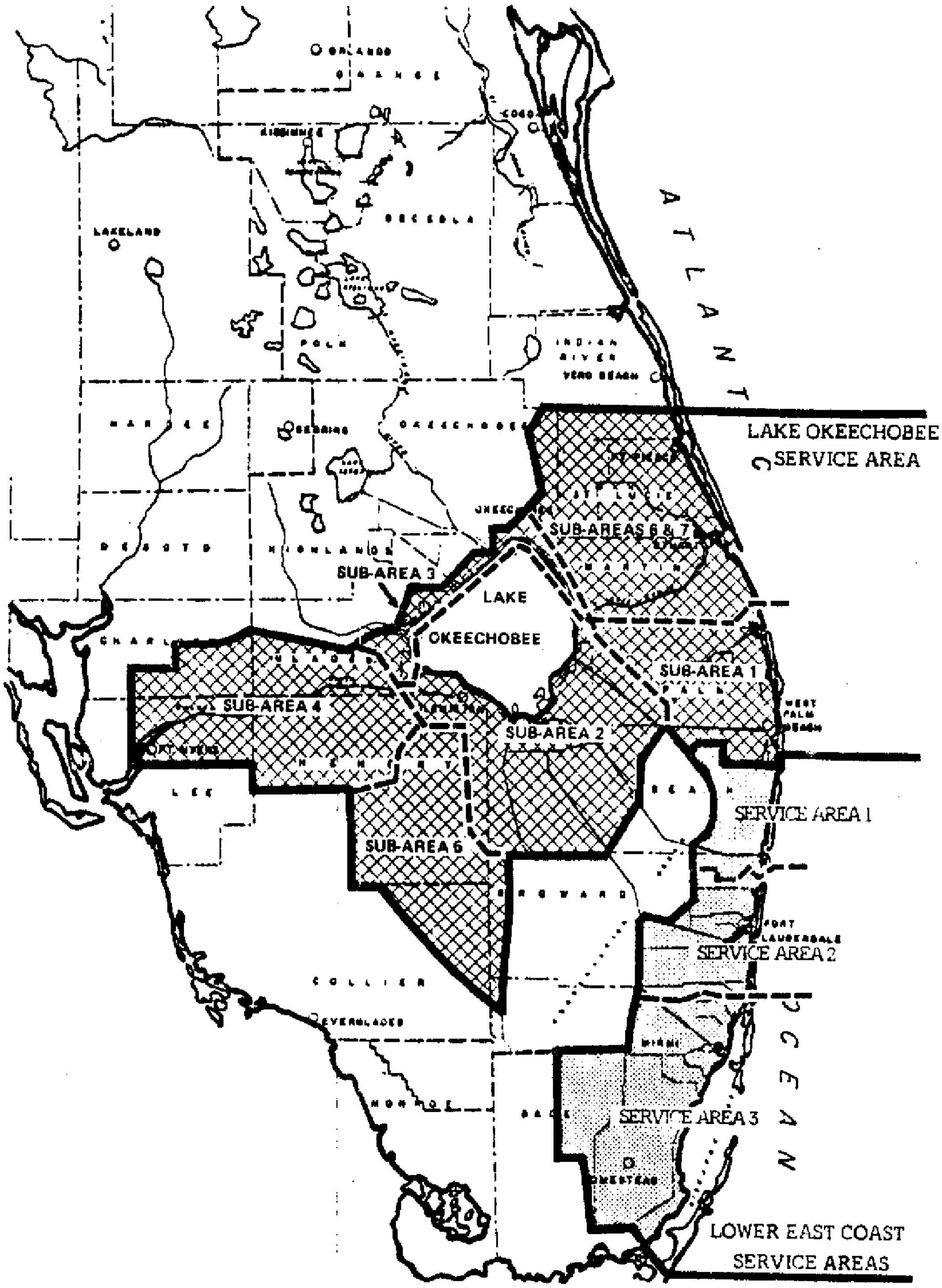

Figure 3 *SERVICE AREAS WITHIN THE LOWER EAST COAST AND LAKE OKEECHOBEE AREAS (CONSIDERED IN THE CURRENT DRAFT PLANS)*

combined and put together as the State's Water Resources Plan.

To comply with the Act, the South Florida Water Management District (which was formerly a flood control district) undertook the task for preparing water use and supply development plans under a wide variety of growth conditions for the area (16,000 square miles). The District area was divided to six planning areas. The Lower East Coast Planning Area (Dade, Broward and the southerly portion of Palm Beach Counties) and the Lake Okeechobee Planning Area were choosen to be the two planning areas to be studied first (Figure 3).

The Water Use Plan in draft form for these two areas is completed. The plan addresses 14 different alternatives to meet future water requirements of the region, under a wide variety of growth conditions. The alternatives that were studied are:

1. Water Conservation
2. Regulation
3. Wellfield Development
4. Bakcpumping of Stormwater
5. Forward Pumping
6. Additional Water Storage in Lake Okeechobee
7. Desalination of Brackish Water
8. Deep Aquifer Storage
9. Reuse of Renovated Wastewater for Non-Body Contact Type of Usage
10. Weather Modification
11. Desalination of Seawater
12. Additional Surface Water Storage Areas
13. Evaporation Supression
14. Water Importation

Because the theme of this paper is the application of computer modeling to groundwater resource management, attention will now focus on this subject. Since 1970, the South Florida Water Management District (SFWMD) has been utilizing analog, digital and hybrid-computers as tools to study the groundwater resources of the region. Presently, the above stated computer techniques are selectively utilized to solve groundwater problems.

Groundwater Flow Equations

The basic partial differential equation governing the two-dimensional non-steady state flow of groundwater (Jacob, 1950) can be written as:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{T}\frac{\partial h}{\partial t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1$$

Where,

S = storage coefficient (dimensionless)

T = transmissivity of the aquifer (gallons/day/ft.) This is defined as the flow of water in gallons/day/ft. through a vertical cross section having a width of 1 ft. and a depth equal to the aquifer thickness, under the influence of a hydraulic gradient of 1 ft.

x,y = space coordinates (ft.)

h = head of water (ft.)

t = time (days)

The storage coefficient (S) is the product of the specific storage coefficient S_0 and the aquifer thickness b, or $S = S_0 b$. The aquifer transmissivity (T) is the product of the aquifer's hydraulic conductivity K and aquifer thickness b, or $T = K \cdot b$.

Analytical Tools to Solve the Groundwater Flow Equations

The modern-day groundwater hydrologist can utilize the following analytical tools to solve the two-dimensional groundwater flow equation as written earlier.

1. Digital Computers.
2. Electric Analog Simulators, involving electronic analyzers coupled to an array of resistors and capacitors simulating a scaled down version of the aquifer system.
3. Analog-Digital combinations forming a hybrid computer.

Under suitable circumstances, each type of analytical tool has its own merit in studying the response of the aquifer system to the applied stresses (recharge and discharge). Each of these analytical tools will be described in detail.

Digital Simulation Techniques

No general solution exists to equation 1; however, a numerical solution to the equation can be obtained through 1) finite difference, and 2) finite element approaches. The finite difference approach first involves replacing the continuous aquifer system parameters by an equivalent set of discrete elements. Secondly, the equations governing the flow of groundwater in the discretized model are written in finite difference form. Finally, the resulting set of finite difference equations are solved numerically with the aid of a digital computer.

A generalized digital computer program as advanced by T. Prickett and C. Lonnquist (14) is presented. This program can simulate two-dimensional flow of groundwater in non-isotropic aquifers under non-leaky and/or leaky artesian conditions. A special feature of the program is that a large simulation (up to an estimated 10,000 node problem) can be accomplished on a disk supported small computer with only 4,000 words (32 bites per word) of core storage.

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ILLINOIS STATE WATER SURVEY
AQUIFER SIMULATION MODEL FOR DISK
SUPPORTED COMPUTERS WITH LESS
THAN 8K WORDS OF CORE STORAGE


DEFINITION OF VARIABLES

AA,BB,CC,DD---COEFFICIENTS IN WATER
              BALANCE EQUATIONS
G-------------PEACEMAN-RACHFORD G ARRAY
B-------------PEACEMAN-RACHFORD B ARRAY
I-------------FOR ROW CALCULATIONS THIS
              IS THE COLUMN NUMBER.  FOR
              COLUMN CALCULATIONS THIS IS
              THE ROW NUMBER
J-------------FOR COLUMN CALCULATIONS THIS
              IS THE ROW NUMBER.
              FOR ROW CALCULATIONS THIS
              IS THE COLUMN NUMBER.
HH,SI,QQ,TT---EXAMPLE MODEL
              DEFAULT VALUES
NC------------NUMBER OF COLUMNS OF MODEL
NR------------NUMBER OF ROWS OF MODEL
DELTA---------TIME INCREMENTS, IN DAYS
NSTEP---------NUMBER OF TIME INCREMENTS
ITER----------NUMBER OF PROGRAM ITERATIONS
ERROR---------CRITERIA FOR SOLUTION
              CONVERGENCE, IN FT
COLM----------ROW CALCULATIONS WHEN
              COLM=0, COLUMN CALCULATIONS
              WHEN COLM=1
S(10,50,3)----CORE STORAGE ARRAY FOR
  *  *  *     NODE DATA OF THREE ROWS
  *  *  *     OR COLUMNS OF MODEL
  *  *  ******FOR ROW CALCULATIONS,
  *  *        J1=NODE DATA FROM ADJACENT ROW.
  *  *        J2=NODE DATA FROM ROW ALONG
  *  *        WHICH HEADS WILL BE CALCULATED.
  *  *        J3=NODE DATA FROM OTHER
  *  *        ADJACENT ROW.
  *  *        FOR COLUMN CALCULATIONS,
  *  *        J1=NODE DATA FROM ADJACENT COLUMN.
  *  *        J2=NODE DATA FROM COLUMN ALONG
  *  *        WHICH HEADS WILL BE CALCULATED.
  *  *********FOR ROW CALCULATIONS,
  *           THIS IS THE COLUMN NUMBER.
  *           FOR COLUMN CALCULATIONS,
  *           THIS IS A ROW NUMBER.
  ************CORE STORAGE LOCATIONS
              FOR NODE DATA AS FOLLOWS:
              1---HEAD, H, AT END OF
              TIME INCREMENT, IN FT
              2---HEAD, HO, AT BEGINNING
              OF TIME INCREMENT, IN FT
              3---DIFFERENCE IN HEADS, D,
              AS DEFINED IN PREDICTOR SECTION
              4---AQUIFER TRANSMISSIVITY, T1
              BETWEEN I,J AND I,J+1
              IN GPD/FT
              5---AQUIFER TRANSMISSIVITY, T2
              BETWEEN I,J AND I+1,J
              IN GPD/FT
              6---STORAGE FACTOR, SF1,
              IN GAL/FT
              7---NET WITHDRAWAL RATE,
              Q, IN GPD
              8---RECHARGE FACTOR, R,
              IN GPD/FT
              9---ELEVATION OF STREAM OR
              LAND SURFACE, RH, IN FT
              10--ELEVATION OF STREAMBED
              BOTTOM, ELEVATION BELOW
              WHICH EVAPOTRANSPIRATION
              CEASES, OR ELEVATION OF
              TOP OF AQUIFER, RD, IN FT
ISP-----------TIME STEPS BEFORE NET
              WITHDRAWAL RATES ARE CHANGED
IP------------I COORDINATE WHERE NET
              WITHDRAWAL TAKES PLACE
JP------------J COORDINATE WHERE NET
              WITHDRAWAL TAKES PLACE


DIMENSION S(10,50,3),G(50),B(50)

DEFINE STRUCTURE OF DISK STORAGE

DEFINE FILE 1(2500,20,U,ID1)


DEFINE INPUT-OUTPUT DEVICE NUMBERS.
FOR SOME IBM 1130 COMPUTERS IN=2
AND OUT=3.

IN=5
IOUT=6
```

```
C       SET VARIABLE PUMPAGE INDEX
        ISP=-1
C       CALL SUBROUTINE TO READ
C       THE PARAMETER AND DEFAULT
C       VALUE CARDS AND FILL
C       DISK STORAGE ARRAYS
C
        CALL PARM(NSTEP,DELTA,ERROR,NC,NR,IN)
C
C       CALL SUBROUTINE TO READ NODE CARDS
C       AND REPLACE VALUES IN APPROPRIATE
C       LOCATIONS ON DISK STORAGE
C
        CALL NODE(NC,NR,IN)
C
C       START OF SIMULATION
C
40      TIME=0.0
        DEL=DELTA
50      DO 370 ISTEP=1,NSTEP
        ITER=0
        TIME=TIME+DELTA
60      E=0.0
        ITER=ITER+1
C
C       TRANSFER FIRST THREE ROWS OF DATA FROM
C       DISK PACK TO CORE STORAGE FOR ROW
C       CALCULATIONS
C
70      ID1=1
        READ(1'ID1)(((S(L,I,K),L=1,10),
       1I=1,NC),K=1,3)
        M1=4
        M2=5
        COLM=0.
        N=NC-1
        NL=NR-1
        GO TO 100
C
C       TRANSFER FIRST THREE COLUMNS OF DATA
C       FROM DISK PACK TO CORE STORAGE FOR
C       COLUMN CALCULATIONS
C
80      DO 90 I=1,NR
        ID1=(I-1)*NC+1
90      READ(1'ID1)((S(L,I,K),L=1,10),K=1,3)
        M1=5
        M2=4
        COLM=1.0
        N=NR-1
        NL=NC-1
C
C       SET CORE STORAGE INDICES
C
100     J1=1
        J2=2
        J3=3
        J=2
C
C       ZERO OUT FIRST G AND B VALUES
C
        G(1)=0.0
        B(1)=0.0
C
C       CALCULATE HEADS BY IADI METHOD
C
110     DO 150 I=2,N
        IF(S(1,I,J2)-S(10,I,J2))130,130,120
120     RE=S(9,I,J2)*S(8,I,J2)
        RB=1.0
        GO TO 140
130     RE=(S(9,I,J2)-S(10,I,J2))*S(8,I,J2)
        RB=0.0
140     DD=S(2,I,J2)*S(6,I,J2)/DELTA-S(7,I,J2)+
       1RE+S(1,I,J1)*S(M1,I,J1)+S(1,I,J3)*S(M1,I,J2)
        BB=S(6,I,J2)/DELTA+S(8,I,J2)*RB+S(M1,I,J1)+
       1S(M1,I,J2)+S(M2,I-1,J2)+S(M2,I,J2)
        AA=-S(M2,I-1,J2)
        CC=-S(M2,I,J2)
        W=BB-AA*B(I-1)
        B(I)=CC/W
        G(I)=(DD-AA*G(I-1))/W
150     CONTINUE
        K=N
160     HA=G(K)-B(K)*S(1,K+1,J2)
        E=E+ABS(S(1,K,J2)-HA)
        S(1,K,J2)=HA
        K=K-1
        IF(K-1)170,170,160
170     CONTINUE
        IF(J-NL)180,230,230
C
C       PUT BACK ON DISK THE
C       UNNECESSARY ROW OF DATA
C
180     IF(COLM)200,190,200
190     ID1=(J-2)*NC+1
        WRITE(1'ID1)((S(K,I,J1),K=1,10),I=1,NC)
```

Figure 4   Aquifer simulation model for disk supported computer

```
C       READ INTO CORE THE NEXT
C       ROW OF DATA
C
        IDI=(J+1)*NC+1
        READ(1'IDI)((S(K,I,J1),K=1,10),I=1,NC)
        GO TO 220
C
C       PUT BACK ON DISK THE
C       UNNECESSARY COLUMN OF DATA
C
200     DO 210 I=1,NR
        IDI=(I-1)*NC+J-1
        WRITE(1'IDI)(S(K,I,J1),K=1,10)
C
C       READ INTO CORE THE NEXT
C       COLUMN OF DATA
        IDI=IDI+2
210     READ(1'IDI)(S(K,I,J1),K=1,10)
C
C       SYNCHRONOUS REVOLVING
C       SUBSCRIPT SPECIFICATION
C
220     K=J1
        J1=J2
        J2=J3
        J3=K
        J=J+1
        GO TO 110
C
C       ROW OR COLUMN CALCULATIONS
C       COMPLETED AND CORE STORAGE PURGED
C
230     IF(COLM)250,240,250
240     IDI=(J-2)*NC+1
        WRITE(1'IDI)((S(K,I,J1),K=1,10),I=1,NC),
       1((S(K,I,J2),K=1,10),I=1,NC)
        GO TO 80
250     DO 260 I=1,NR
        IDI=I*NC-2
260     WRITE(1'IDI)(S(K,I,J1),K=1,10),
       1(S(K,I,J2),K=1,10)
        COLM=0.0
        N=NC-1
        NL=NR-1
C
C       TEST FOR CONVERGENCE
C       AND LIMIT ITERATIONS TO 20
C
270     IF(E-ERROR)280,280,275
275     IF(ITER-20)60,280,280
C
C       CALL SUBROUTINE TO PRINT
C       RESULTS AND PREPARE FOR
C       NEXT TIME STEP
C
280     CALL OUTIS(ISP,ISTEP,TIME,E,ITER,NC,
       1NR,IN,IOUT,RESET)
C
        DELTA=DELTA*1.2
        IF(RESET)370,370,385
385     DELTA=DEL
370     CONTINUE
        END
C       ********************************************
C       THIS SUBROUTINE READS THE PARAMETER AND
C       DEFAULT VALUE CARD AND FILLS THE
C       DISK STORAGE AARAYS
C       ********************************************
C
        SUBROUTINE PARM(NSTEP,DELTA,ERROR,NC,NR,IN)
C
        DEFINE FILE 1(2500,20,U,IDI)
C
C       READ DEFAULT VALUE CARD
C
5       READ(IN,10)NSTEP,DELTA,ERROR,NC,NR,
       1TT,S1,HH,QQ,RR,RRH,RRD
10      FORMAT(I6,2F6.0/2I6,7F6.0)
C
C       CONSTRUCT FRAME AROUND MODEL
C
        NC=NC+2
        NR=NR+2
C
C
C       STORE DEFAULT VALUES ON DISK PACK
C
        NA=(NC+1)*10
        Z=0.0
        IDI=1
        WRITE(1'IDI)(Z,I=1,NA),((HH,HH,Z,TT,
       1TT,S1,QQ,RR,RRH,RRD,I=4,NC),HH,HH,
       2Z,TT,Z,S1,QQ,RR,RRH,RRD,(Z,I=1,20),
       3J=4,NR),(HH,HH,Z,Z,TT,S1,QQ,RR,RRH,RRD,
       4I=4,NC),HH,HH,Z,Z,Z,S1,QQ,RR,RRH,RRD,
       5(Z,I=1,NA)
        RETURN
        END
```

```
C       ********************************************
C       THIS SUBROUTINE READS THE NODE CARDS
C       AND PLACES THEIR VALUES IN THE
C       APPROPRIATE LOCATIONS ON THE DISK
C       ********************************************
C
        SUBROUTINE NODE(NC,NR,IN)
        DEFINE FILE 1(2500,20,U,IDI)
C
C       READ NODE CARDS
C
20      READ(IN,30)I,J,T1,T2,SF1,H,
       1Q,R,RH,RD
30      FORMAT(2I3,2F6.0,2F4.0,4F6.0)
C
C       SET ZERO TRANSMISSIVITIES
C       IN MODEL FRAME
        IF(I)29,40,29
29      IF(I-NC+2)32,31,32
31      T2=0.0
32      IF(J-NR+2)34,33,34
33      T1=0.0
C
C       STORE NODE DATA ON DISK PACK
C
34      IDI=J*NC+I+1
        Z=0.0
        WRITE(1'IDI)H,H,Z,T1,T2,SF1,Q,
       1R,RH,RD
        GO TO 20
40      RETURN
        END
C
C       ********************************************
C       THIS SUBROUTINE PRINTS HEADS, PREDICTS
C       FUTURE HEADS, AND CHANGES NET
C       WITHDRAWAL RATES IF NECESSARY.
C       ********************************************
C
        SUBROUTINE OUTIS(ISP,ISTEP,TIME,E,ITER,
       1NC,NR,IN,IOUT,RESET)
C
        DEFINE FILE 1(2500,20,U,IDI)
        DIMENSION S(10,50,3)
C
C       MAIN OUTPUT SECTION, UPDATE CALCULATED
C       HEADS, AND PREDICT HEADS FOR NEXT
C       TIME INCREMENT
C
        RESET=0
280     WRITE(IOUT,285)TIME,E,ITER
285     FORMAT(6H2TIME=,F6.2///,E20.7,I5)
        JJ=NR-1
        II=NC-1
        DO 360 J=2,JJ
        IDI=(J-1)*NC+1
        READ(1'IDI)((S(K,I,1),K=1,10),I=1,NC)
C
C       PREDICT HEADS FOR NEXT
C       TIME INCREMENT (SEE PAGES
C       11 AND 12 IN BULLETIN 551.
C
        DO 350 I=2,II
        D=S(1,I,1)-S(2,I,1)
        S(2,I,1)=S(1,I,1)
        F=1.0
        IF(S(3,I,1))290,340,290
290     F=D/S(3,I,1)
300     IF(F-5.0)320,320,310
310     F=5.0
320     IF(F)330,340,340
330     F=0.0
340     S(3,I,1)=D
350     S(1,I,1)=S(1,I,1)+D*F
C
C       CHANGE NET WITHDRAWAL RATES
C
        K=J-1
349     IF(ISP)351,356,353
351     READ(IN,352)ISP,IP,JP,QQ
352     FORMAT(3I3,F11.0)
        GO TO 349
353     IF(ISP-ISTEP)351,354,356
354     IF(JP+1-J)356,357,356
357     S(7,IP+1,1)=QQ
        RESET=1
        GO TO 351
356     CONTINUE
C
C       PRINT RESULTS
C
        WRITE(IOUT,355)K,(S(2,I,1),I=2,II)
355     FORMAT(I5,5X,10F10.4/(12X,10F10.4))
C
C       RETURN INFORMATION TO DISK PACK
C
        IDI=(J-1)*NC+1
360     WRITE(1'IDI)((S(K,I,1),K=1,10),I=1,NC)
        RETURN
        END
```

Figure 5 (Concluded)

The computer can handle time varying pumpage from wells, natural or artificial recharge rate, the relationships of water exchange between surface water and the groundwater reservoir, the process of evapotranspiration, and the mechanism of flow from springs.

Finite element approach to solving partial differential equations is a relatively recent development. The basic difference between the finite element and the finite difference methods to solve partial differential equations (such as equation 1), is the concept of discretization.

In the finite element method the basis functions adopted are polynomials which are piecewise and continuous over sub-domains called finite elements. Nodes are located along boundaries of each sub-domain and each basis function is identified with a specific node (see Pinder (10) for details).

Analog Simulation Techniques

An equation that describes the current flow in an electrical system is written as follows:

$$\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} = \frac{\partial v}{\partial t} \cdot \frac{c}{\rho} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2$$

Where,

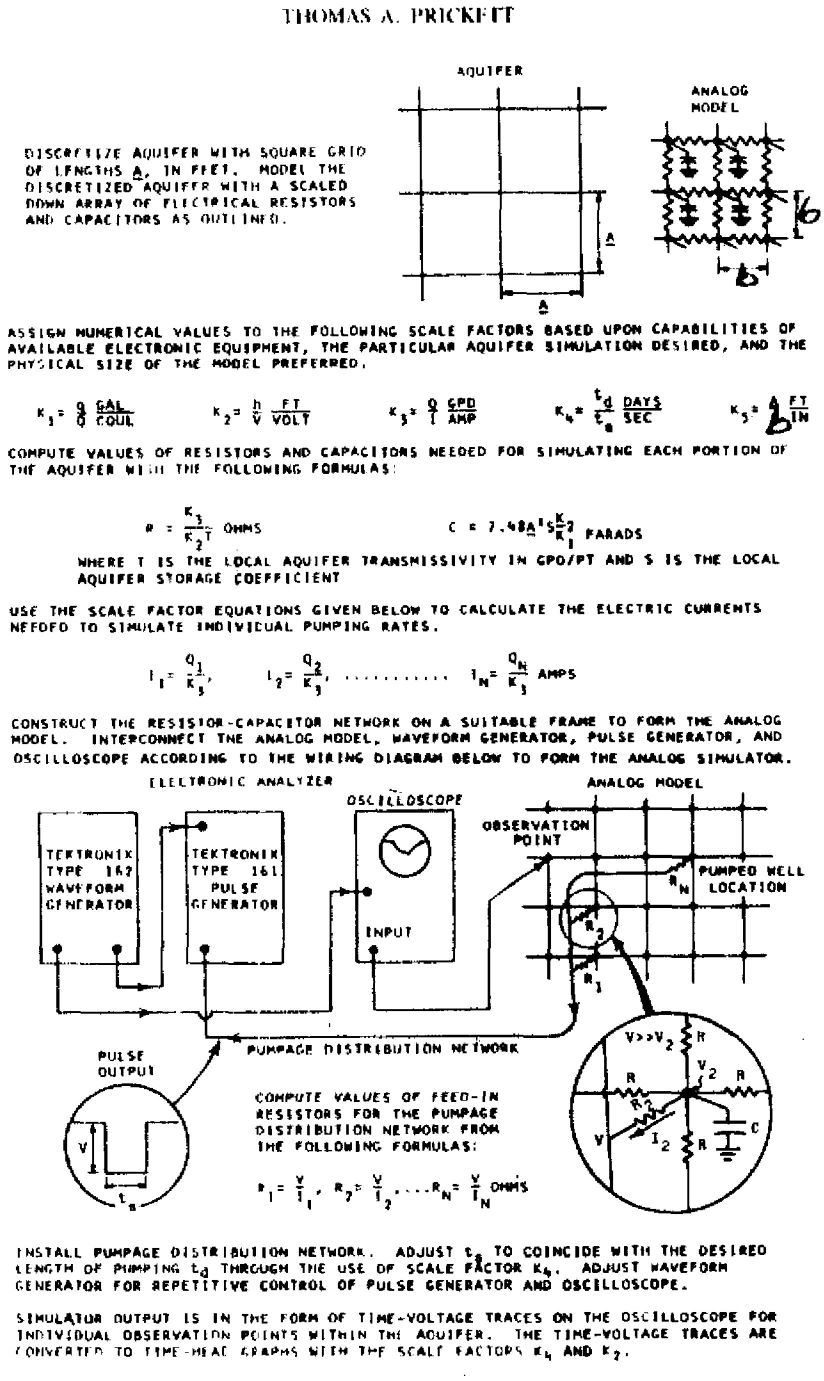
v = the electrical potential (volts)

c = the electrical capacitance (Farads/ft.^{3})

ρ = the electrical conductance (mho/ft.)

= $\frac{1}{R}$; R is resistance in (ohm/ft.)

If one compares equations 1 and 2, a relationship can be recognized. These two systems (groundwater flow and electrical flow) are said to be "analogs" of one another.



THOMAS A. PRICKETT

DISCRETIZE AQUIFER WITH SQUARE GRID OF LENGTHS $\underline{A}$, IN FEET. MODEL THE DISCRETIZED AQUIFER WITH A SCALED DOWN ARRAY OF ELECTRICAL RESISTORS AND CAPACITORS AS OUTLINED.

ASSIGN NUMERICAL VALUES TO THE FOLLOWING SCALE FACTORS BASED UPON CAPABILITIES OF AVAILABLE ELECTRONIC EQUIPMENT, THE PARTICULAR AQUIFER SIMULATION DESIRED, AND THE PHYSICAL SIZE OF THE MODEL PREFERRED.

$K_1 = \frac{q}{Q}\ \frac{\text{GAL}}{\text{COUL}}$ $\quad K_2 = \frac{h}{V}\ \frac{\text{FT}}{\text{VOLT}}$ $\quad K_3 = \frac{Q}{I}\ \frac{\text{GPD}}{\text{AMP}}$ $\quad K_4 = \frac{t_d}{t_a}\ \frac{\text{DAYS}}{\text{SEC}}$ $\quad K_5 = \frac{\underline{A}}{b}\ \frac{\text{FT}}{\text{IN}}$

COMPUTE VALUES OF RESISTORS AND CAPACITORS NEEDED FOR SIMULATING EACH PORTION OF THE AQUIFER WITH THE FOLLOWING FORMULAS:

$$R = \frac{K_3}{K_2 T}\ \text{OHMS} \qquad C = 7.48\underline{A}^2 S \frac{K_2}{K_1}\ \text{FARADS}$$

WHERE T IS THE LOCAL AQUIFER TRANSMISSIVITY IN GPD/FT AND S IS THE LOCAL AQUIFER STORAGE COEFFICIENT

USE THE SCALE FACTOR EQUATIONS GIVEN BELOW TO CALCULATE THE ELECTRIC CURRENTS NEEDED TO SIMULATE INDIVIDUAL PUMPING RATES.

$$I_1 = \frac{Q_1}{K_3}, \quad I_2 = \frac{Q_2}{K_3}, \ \ldots\ldots\ldots\ldots \ I_N = \frac{Q_N}{K_3}\ \text{AMPS}$$

CONSTRUCT THE RESISTOR-CAPACITOR NETWORK ON A SUITABLE FRAME TO FORM THE ANALOG MODEL. INTERCONNECT THE ANALOG MODEL, WAVEFORM GENERATOR, PULSE GENERATOR, AND OSCILLOSCOPE ACCORDING TO THE WIRING DIAGRAM BELOW TO FORM THE ANALOG SIMULATOR.

COMPUTE VALUES OF FEED-IN RESISTORS FOR THE PUMPAGE DISTRIBUTION NETWORK FROM THE FOLLOWING FORMULAS:

$$R_1 = \frac{V}{I_1}, \quad R_2 = \frac{V}{I_2}, \ldots R_N = \frac{V}{I_N}\ \text{OHMS}$$

INSTALL PUMPAGE DISTRIBUTION NETWORK. ADJUST t_a TO COINCIDE WITH THE DESIRED LENGTH OF PUMPING t_d THROUGH THE USE OF SCALE FACTOR K_4. ADJUST WAVEFORM GENERATOR FOR REPETITIVE CONTROL OF PULSE GENERATOR AND OSCILLOSCOPE.

SIMULATOR OUTPUT IS IN THE FORM OF TIME-VOLTAGE TRACES ON THE OSCILLOSCOPE FOR INDIVIDUAL OBSERVATION POINTS WITHIN THE AQUIFER. THE TIME-VOLTAGE TRACES ARE CONVERTED TO TIME-HEAD GRAPHS WITH THE SCALE FACTORS K_4 AND K_2.

Figure 6 EXAMPLE DESIGN OF A RESISTANCE-CAPACITANCE NETWORK MODEL (FROM PRICKETT AND LONNQUIST, 1968)

The basic design of commonly used analog simulators used in evaluating aquifers under artesian, non-steady state and two dimensional flow conditions is presented in Figure 6. This analog simulator is of the discrete space, continuous time type, and is made up of an electric analyzer coupled to an analog model.

The conversion between equations 1 and 2 is made by the following scaling factors:

$$K1 = \frac{\text{volume of water (gallons)}}{\text{quantity of electrons (columb)}}$$

$$K2 = \frac{\text{water head (feet)}}{\text{electrical current rate (volts)}}$$

$$K3 = \frac{\text{water flow rate (gallons/day)}}{\text{electrical current rate (ampere)}}$$

$$K4 = \frac{\text{aquifer system response time (days)}}{\text{electrical system response time (seconds)}}$$

$K1 = K3 \times K4$ as volume of water equals flow rate X time.

The electrical system properties are related to aquifer system properties by

$$R = \frac{K3}{K2T}$$

$$C = 7.48 \; a^2 \; S \; \frac{K2}{K1}$$

Where,

7.48 is a conversion factor from cubic feet to gallons.

$a^2 = \Delta x \times \Delta y$, nodal spacing.

Analog/Digital Combinations (Hybrid Computer)

When a digital data processer is used to control the input to and output from the analog simulator, the system becomes a hybrid system (Figure 7). The input to the simulator is through a custom designed D/A converter. The A/D (analog/digital) measurement system is the digital computer used for digitizing analog data and storing it for later analyses. Analog simulation of the distributed system is

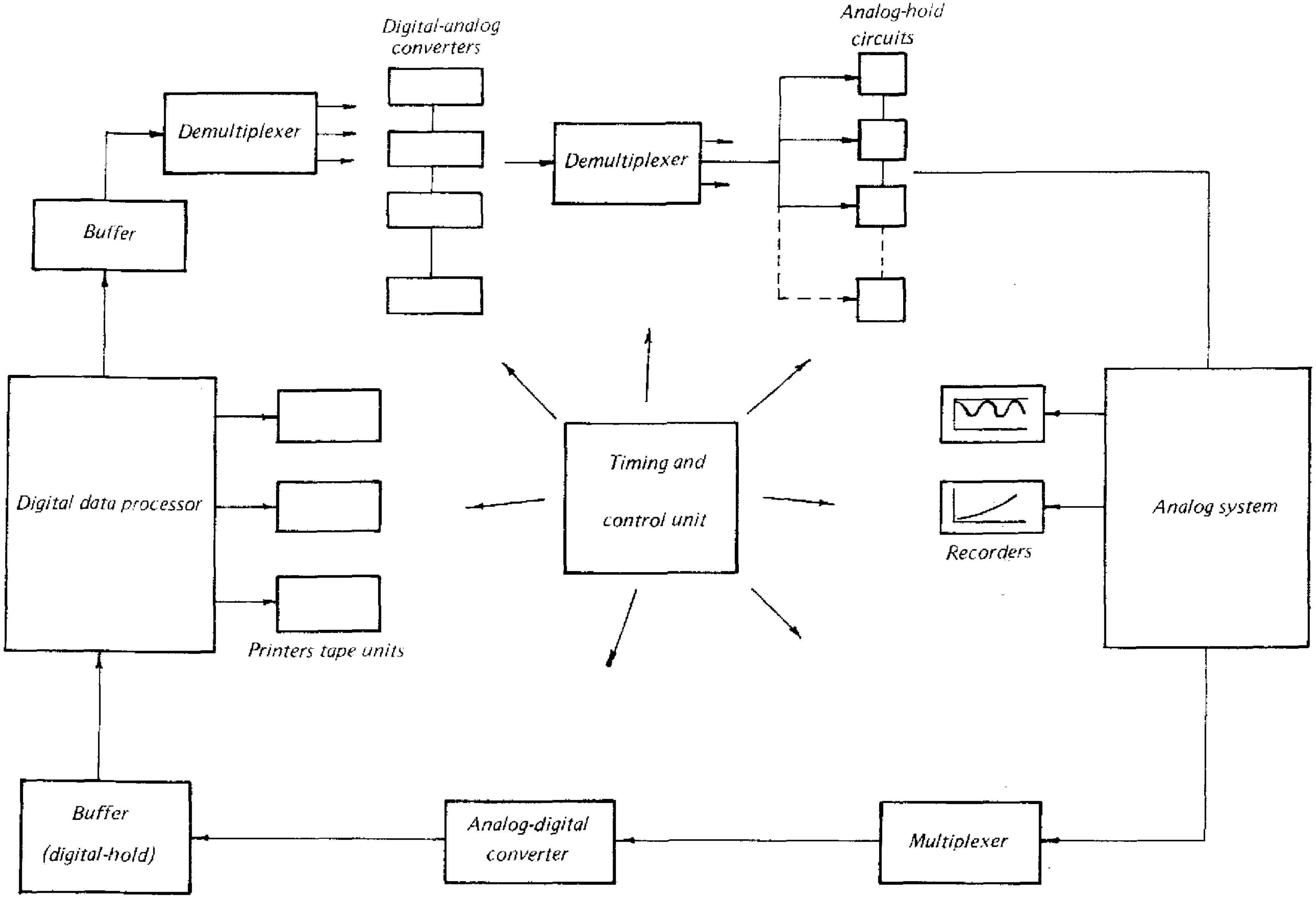


Figure 7 MAJOR COMPONENTS OF HYBRID COMPUTER SYSTEM (15)

different from the digital simulation in that it can process space points simultaneously. This parallel operation in real time, however, requires that all inputs be applied to the model at the same time. The function is achieved by a hybrid computer system as depicted in Figure 7.

The main advantages and disadvantages of the digital and analog models are as follows:

1. A digital computer operates with numbers expressed directly as digits. The digital computer gives a discrete solution of the problem at discrete points. Digital computer techniques do not require as much time for model construction and data read-out. However, they are limited by the core size. Even present day computers have core limitations. Additionally, a digital computer model made up of decks of keypunched cards, bears no physical resemblance to the problem under study.

2. Analog computers work with voltage and current, therefore it measures a magnitude. Additionally, the analog computer provides a continuous solution capability providing answers to questions at various points simultaneously. No iteration problem is involved in analog simulation.

   The main advantage of the analog computer is that it can be used for regional groundwater resources evaluation as no core size limitation exists. The analog computer also offers advantages when it is desired to solve problems requiring a direct insight into the behavoir of the physical system. The analog model, with its simplicity in principle also offers a reasonable starting point in cases where data is scarce.

3. A hybrid computer is a combination for the two types to take advantage of the best features of both methods. The digital component is utilized for its input and output convenience and flexibility and for its data manipulation capability. The analog contributes its parallelism and continuous function capabilities.

Any of the above described computer applications requires hydrologic, hydrogeologic and meterological parameters as input to the model.

Hydrologic Setting of South Florida

The hydrologic system of the lower east coast area of Florida consists of the Biscayne aquifer (named after Biscayne Bay), a system of levees and canals, and the associated water-control facilities. Major and secondary canals have been cut into the upper part of the aquifer for draining excess storm water, the canals and the aquifer thus form a hydraulically connected system (Figure 8). Manipulation of water control facilities to change canal stages affect water levels in the aquifer. Conversely, if stress is applied in the aquifer (pumpage) it has direct affect on canal stages.

The Biscayne aquifer is one of the most permeable aquifers in the world. It is the sole source of freshwater supply in those areas where it is situated. The aquifer is comprised mainly of limestone and shell beds. Depending upon locations, the aquifer is also found to have marl, silt and clay layers.

The transmissivity of the aquifer system varies from 1.0 to 8.0 mgd/ft. except for the extreme western parts. The U. S. Geological Survey (1) has prepared a transmissivity contour map of the area. The transmissivity values were derived from aquifer pumping tests, tests of specific capacity of wells, flow net analysis of water-level contours around major wellfields, and analysis of aquifer water-level fluctuations in response to cyclic changes in Bay level or canal stage. Figure 9 shows the aerial variation of transmissivity.

The storage coefficient (Parker, et. al. (9) and Schroeder, et. al (1)) of this aquifer ranges from .10 to .35, and averages around .20. Due to the lack of specific point data, a value of .20 has been used consistently in all groundwater studies.

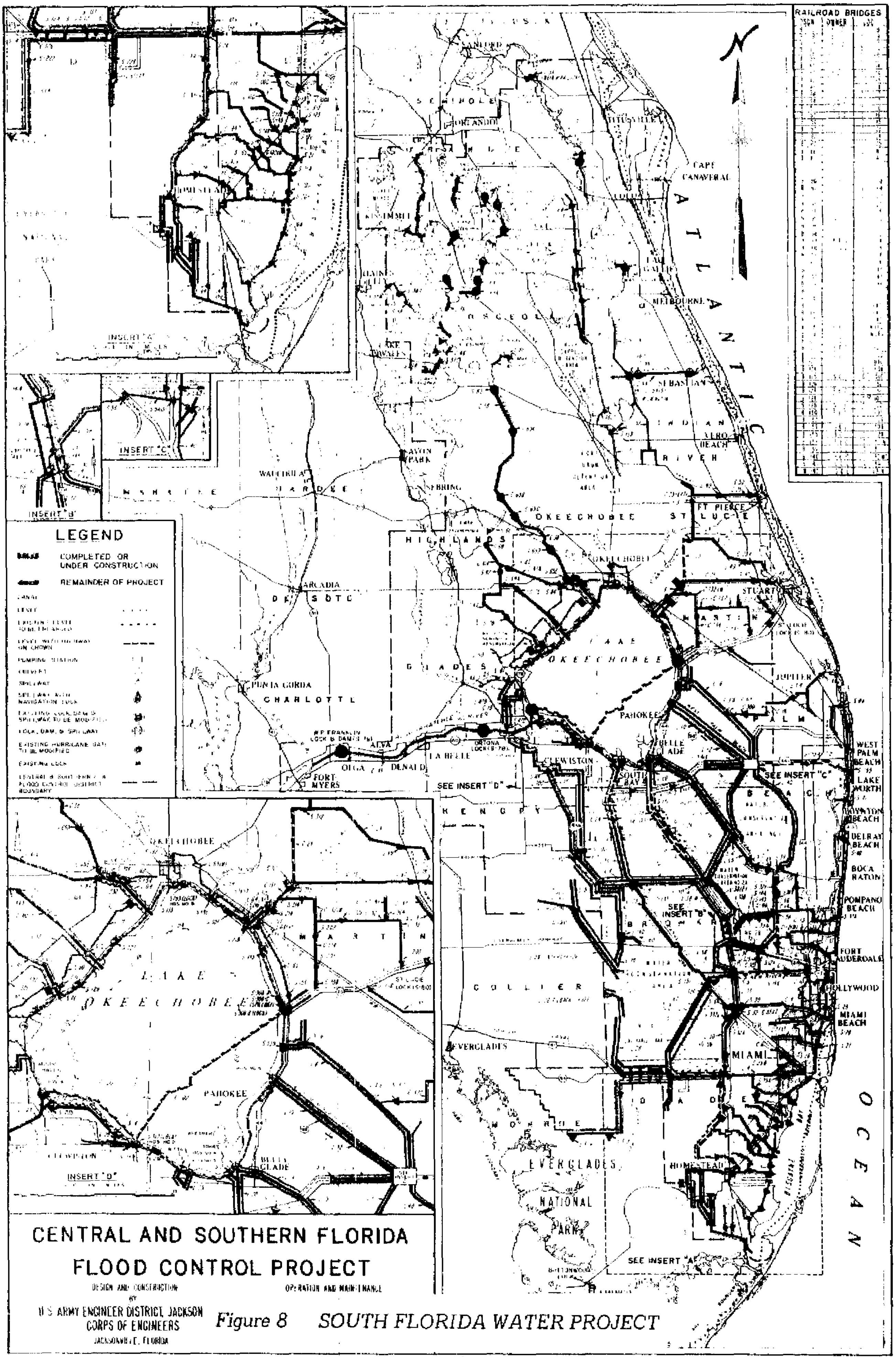


Figure 8 SOUTH FLORIDA WATER PROJECT

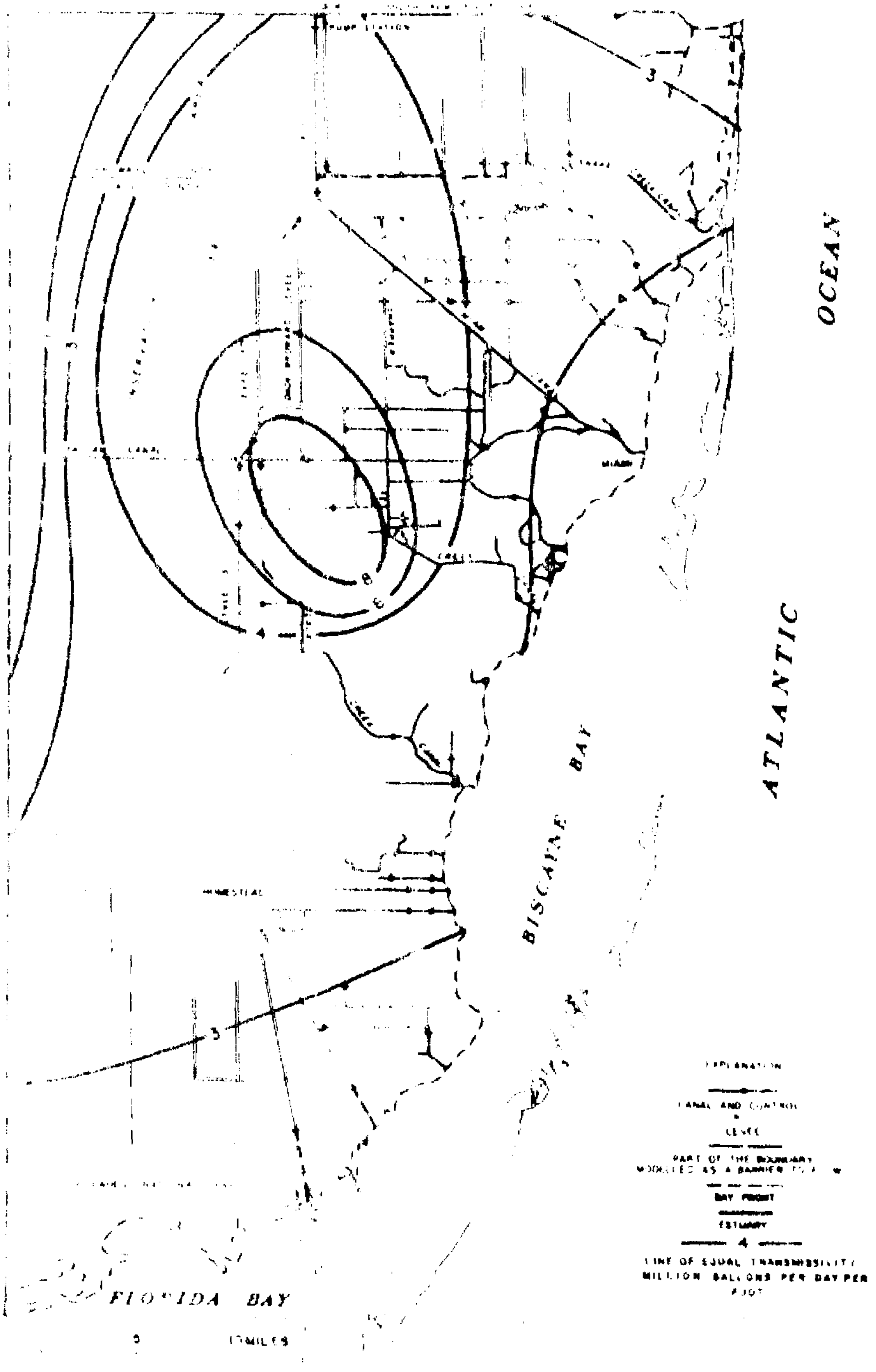


Figure 9 AQUIFER TRANSMISSIVITY

Canal infiltration was measured along with Miami Canal by the U. S. Geological Survey (8), where the infiltration was estimated to be approximately 10 cfs/mile of canal per foot of head differential. Due to canal siltation, however, the infiltration value has been observed to decrease with time.

The aquifer is recharged by rainfall and the import of water via canals. A USGS (1) report cites the average annual rainfall of the area to be approximately 60 inches.

Presented below in Tabular form are the average monthly rainfall and the critical rainfall per month for the year 1970-71 (18).

TABLE 1 - AVERAGE AND CRITICAL MONTHLY RAINFALL VALUES

MONTH	*AVERAGE INCHES	**CRITICAL INCHES
January	2.70	.09
February	2.00	.17
March	2.40	.51
April	2.20	.80
May	2.10	.40
June	2.50	.07
July	7.00	4.13
August	10.50	11.65
September	6.00	4.72
October	6.60	6.02
November	9.00	9.63
December	7.30	7.48
	60.30	45.67

*27 years of record
**1970-71

Aquifer recharge and pumpage variation for the aquifer system, on a monthly basis, has been estimated by the District (18). They are presented in Table 2.

TABLE 2 - MONTHLY AQUIFER RECHARGE AND PUMPAGE COEFFICIENTS (PERCENTAGE)

MONTH	RECHARGE COEFFICIENT	PUMPAGE COEFFICIENT
January	.10	.99
February	.10	1.06
March	.20	.89
April	.20	.88
May	.20	1.13
June	.20	1.29
July	.20	1.11
August	.20	.78
September	.10	1.04
October	.10	1.05
November	.40	.88
December	.40	.90

Groundwater levels vary from 1.0 ft. msl to around 12.0 ft. near the Conservation Areas. The difference between annual high and low groundwater levels is 5 ft. or less (1).

Canal Inflow

Several primary and secondary canals exist in the area. The total flows from these canals to the ocean in an average year, and the critical year (1970-71), are presented below in Table 3.

TABLE 3 - CANAL INFLOWS - AVERAGE AND CRITICAL YEAR MONTHLY FLOWS

MONTH	CRITICAL YEAR FLOW (MGD)	AVERAGE YEAR FLOW (MGD)
January	580	389
February	617	364
March	445	332
April	530	345
May	688	393
June	894	371
July	668	318
August	360	385
September	597	465
October	605	399
November	465	388
December	455	340

As can be seen during critical years, more water is imported from the conservation areas and Lake Okeechobee to meet downstream demands to maintain optimal canal levels for preventing saltwater intrusion.

Water Requirements

Agricultural, municipal, industrial and commercial water requirements for the area have been estimated by the District (4) for the year 1985, 2,000 and 2,020.

Table 4 below presents the 1973 and 2020 population (saturated) with the presently pumped groundwater usage and the anticipated requirements (4).

TABLE 4 - 1973 AND 2020 POPULATION AND WATER USE ESTIMATES

COUNTY	POPULATION 1973	POPULATION 2020	(MGD) WATER PUMPED 1973	(MGD) EST. REQUIREMENTS 2020
Dade	1,300,000	2,165,800	240.75	385.00
Broward	802,000	1,504,300	147.29	378.30
Palm Beach	262,000	928,800	71.50	566.00

All of the data presented above describes in summary form the physical, hydrologic and hydrogeologic setting of the area. These data together with the specific bound conditions constitutes the basic input data to those studies cited below.

Case Studies

In order to familiarize the readers with the analytical tools now available to hydrologists, three case studies in which the District actively took part will be cited. The first case is an example of the application of the analog model on a county scale. The second example deals with digital computer modeling of a wellfield. The third example will show the application of hybrid computer techniques to manage the groundwater resources on a regional level.

Analog Simulation Model

One of the first simulation models that was applied in the area was an analog model developed by the USGS in cooperation with the District (1). The model covered approximately 1,600 square miles in area. The objective of the model was to determine the quantities of canal flows required to satisfy the anticipated pumpage requirements of Dade County by the year 2020, maintaining optimal aquifer and canal levels. The test period used for this simulation was November through May (dry months).

It was determined from the analog model that approximately 1,150 cfs of flow had to be released either from Lake Okeechobee or the conservation areas to meet the 2020 demand of Dade County to maintain optimal canal and aquifer levels without rainfall recharge.

The conveyance canal which is designed to convey this water to south Dade is presently under construction.

Digital Computer Modeling

The digital computer model as described earlier (14) was applied to determine whether the annual pumpage from a wellfield could be increased by 20% without causing significant movement of a freshwater-saltwater interface known to threaten the wellfield. The project area was discretized to a 38 X 43 array. Values were assumed for the static groundwater head at each node; rates of induced infiltration from the Pompano, Cypress Creek, Middle River and Feeder Canal, and the Florida Turnpike drainage ditches (Figure 10).

The digital model was calibrated against the 1975 groundwater contour map prepared by the U. S. Geological Survey. Values of transmissivity and recharge rates from canals were varied until a reasonable calibration was achieved. No rainfall recharge was included in the model in order to simulate the dry season conditions.

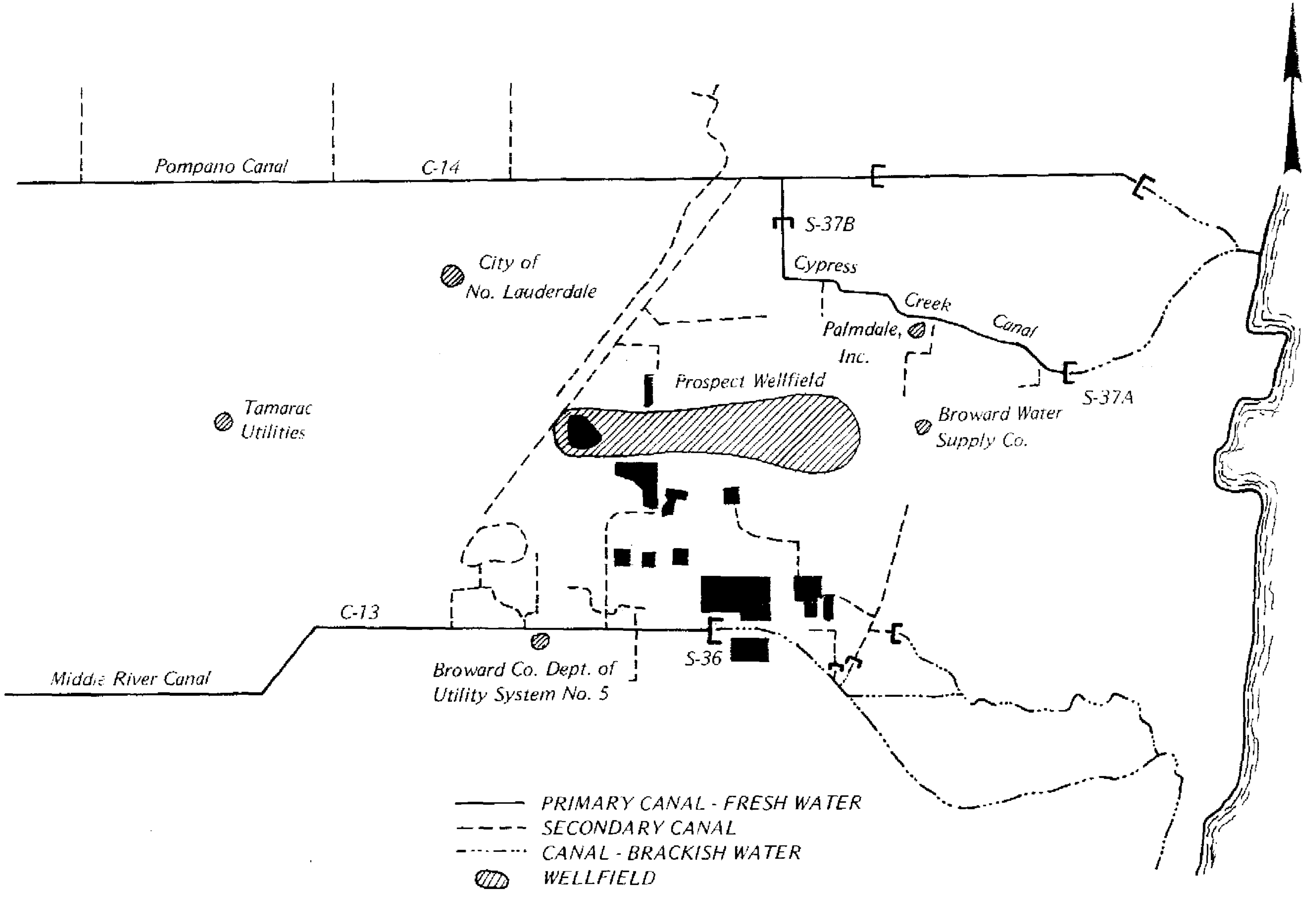


Figure 10 MAP SHOWING PROSPECT WELLFIELD, NEIGHBORING GROUNDWATER USERS AND SURFACE WATER COURSES.

Results of the modeling effort revealed the following:

1. Recharge rates from all canals and ditches are high relative to those measured in other parts of southern Florida. The rates appear to be close to 10 gallons per day/square ft./ft. of head.
2. The effective transmissivity appears to be about 600,000 gallons per day/ft. in contrast to much higher transmissivities determined by aquifer tests. This discrepancy is believed to be attributable to the fact that wells of the Prospect Wellfield do not fully penetrate the aquifer as did the wells used in aquifer tests.
3. Equilibrium (no further drawdowns) became effective after about 180 days of pumping at a rate of 34 mgd (includes increment of 20%).
4. At equilibrium, water was being drawn from the canals approximately as follows: Pompano and Cypress Creek Canals, 5 mgd; Middle River Canal, 3 mgd; Turnpike ditches, 9 mgd; Feeder Canal, 10 mgd.
5. Groundwater levels between the wellfield and the Intracoastal Waterway were reduced to less than 1 ft. msl at equilibrium.
6. Simulation at a higher pumping rate (50 mgd) approached equilibrium after pumping for 90 days following 234 days at 34 mgd. Groundwater levels between the wells and the Intracoastal Waterway were further reduced but not below zero ft. msl.

Based on the computer modeling analysis, it was determined that annual pumpage from the prospect wellfield could be increased by 20% without causing detrimental saltwater intrusion.

Hybrid Computer Model

A hybrid computer model was developed in-house under the direction of Dr. G. Shih (15). The objective of this model study was to quantify the following:

1. The safe sustained yield of the presently existing aquifer system.

2. The potential for the development of additional wellfields west of the present wellfields to meet the short range water requirements of the area.
3. The ultimate capacity that can be safely withdrawn from this aquifer system, on a long term average annual basis.
4. The consequences in terms of environmental impact.

The heart of this model is an analog model similar to the previously described system; however, enlarged to cover a greater area. The input and output is through a digital model.

A rectangular grid size of 1 square mile was used in the model. In total there were 6,000 nodes. The same resistors and capacitor (4 resistors and one capacitor) represented the square grid system. The values in the resistor-capacitor (R-C) network were computed using equations $R = \frac{K3}{K2 \cdot T}$ and $C = 7.48\, a^2\, S\, \frac{K2}{K1}$.

The scaling factors used were:

a = 1 square mile

K1 = 10^{14} i.e. 1 columb = 10^{14} gallons

K2 = 2.5 ft./volt i.e. 1 volt = 2.5 ft.

K3 = 10^{11} gpd/amp i.e. 1 amp = 10^{11} gpd

K4 = 10^{3}day/sec. i.e. 1 sec. in the simulator = 1000 days in the aquifer

The model was calibrated by use of the U. S. Geological Survey's water table map for the area, for the year 1971.

Case Studies

A series of simulations have been made to evaluate the aquifer capacity. However, due to lack of space, only the average year and the critical year case studies will be explained.

The critical year (1970-71) rainfall has been defined as the critical condition. Local capacity of the aquifer during this period is limited to rainfall and seepage from the conservation area and levees. No canal inflow is released. Based on this study, 7 wellfields which are east of the critical lines (0' stage) would have to be abandoned. The remaining wellfields could pump around 310 mgd. This was determined to be the local groundwater resources of the area under critical year conditions.

Average Year Conditions

When the region receives 60 inches of rainfall, 13.9 inches fall during the six critical dry months. Under these conditions, without causing any saltwater intrusion, the maximum pumpage from the existing wellfield could be up to 550 mgd.

Future Wellfield Development

If new wellfields are developed along the western portion of the present day wellfields, then without any canal water recharging the aquifer, the safe allowable yield under average conditions will be 410 mgd.

If 375 mgd of canal flow water is used to recharge the aquifer, the maximum quantity of water that can be withdrawn from the existing and the planned wellfields (up to 1985) would be 720 mgd. However, if more water can be released from the canals (say 915 mgd), the pumpage from the aquifer can be as high as 1270 mgd.

Summary

This paper demonstrates the application of three computer techniques to solve the groundwater resources problem of a region. Two of the techniques, namely the digital computer modeling and the hybrid computer modeling techniques were used directly by the District staff. The analog model study was undertaken by the U. S. Geological Survey in cooperation with the South Florida Water Management

District (formerly the Central and Southern Florida Flood Control District).

The analog and the hybrid computer models were used in the regional study due to: a) unavailability of a large digital computer to model the entire region, and b) scarcity of adequate data to get direct insight into the behavior of the physical system. The digital model was used to evaluate a public water supply wellfield for water use permitting.

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