7-1-1981

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James A. Ferguson
University of Arkansas, Fayetteville

John T. Gilmour
Unversity of Arkansas, Fayetteville

Citation

Ferguson, James A. and Gilmour, John T.. 1981. A Hydrologic Carbonate Chemistry Model of Flooded Rice Fields. Arkansas Water Resources Center, Fayetteville, AR. PUB078. 32
https://scholarworks.uark.edu/awrctr/273

Arkansas Water Resources Center

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By

James A. Ferguson, Arkansas Water Resources Research Center, John T. Gilmour,
Arkansas Agricultural Experiment Station, University of Arkansas, Fayetteville,
Arkansas 72701

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Publication No. PUB-78

Arkansas Water Resources Center
112 Ozark Hall
University of Arkansas
Fayetteville, Arkansas 72701

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James A. Ferguson

and

John T. Gilmour

Water Resources Research Center
University of Arkansas
Fayetteville, Arkansas

and

Arkansas Agricultural Experiment Station
University of Arkansas
Fayetteville, Arkansas

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James A. Ferguson and John T. Gilmour

INTRODUCTION

Many flooded rice fields in Arkansas are irrigated with subterranean waters saturated or supersaturated with respect to calcium carbonate. Deposition of calcium carbonate from these waters largely occurs near field inlets and in flow areas (1). When sufficient amounts of calcium carbonate accumulate, soil pH rises and zinc deficiency occurs in rice seedlings grown on the affected soil (2). The use of zinc fertilizers has provided a short-term solution to the problem (3), but does not provide a water management alternative which would slow, stop or reverse the localized accumulation of calcium carbonate and concomitant soil pH increase.

A more detailed description of the calcium carbonate precipitation reaction shows that when the water is pumped onto a rice field, warming occurs, pH increases as carbon dioxide diffuses from the water and insoluble calcium carbonate begins to form. The reaction continues until the floodwater contains calcium and bicarbonate concentrations which are in equilibrium with the calcium carbonate precipitate. When this reaction occurs in a small containment area, water fluxes can be ignored and a knowledge of the kinetics of the calcium carbonate precipitation reaction will suffice in an evaluation of the spatial and/or temporal distribution of the precipitate. However, when such a description is desired for all or a portion of a rice field, the situation becomes more complex because irrigation water hydrology is superimposed upon the chemical reaction kinetics.

The major objectives of this study were: (1) to provide a description of the distribution of the calcium carbonate precipitate in a flooded rice field by developing a computer model which interfaced rice floodwater hydrology with the calcium carbonate precipitation reaction, and (2) to use the computer model to evaluate water management alternatives which minimize or reverse localized accumulations of calcium carbonate and attendant pH increases.

MODEL DESCRIPTION

The basic role of the mathematical model is to describe adequately the hydrologic and carbonate chemistry relations on a relatively short time scale. Every attempt was made to create a deterministic model primarily from a mass balance point of view.

Input data necessary are:

1. NLEVEE - number of levee areas in the field to be modeled (up to a macimum of 12).
2. A(NLEVEE) - vector of length "NLEVEE" containing area in each levee area in acres.
3. DYFIRST, DYLAST - starting and ending day of the simulation in Julian days.
4. PUMP - flow rate of irrigation system in cubic feet per second
5. DGATE - height of levee gates above ground surface in inches
6. CQ(1,0) - calcium concentration in irrigation water in meg per liter.
7. MG(1,0) - magnesium concentration in irrigation water in meg per liter.
8. SEEP - Downward percolation rate of water into the soil in inches per day.
9. Climatologic Array - four arrays of dimension 7 x 112 consisting of pan evaporation in inches per day, rainfall in inches perday, maximum daily temperature and minimum daily temperature in degrees Farenheit. The years chosen for our study were 1964 to 1970 and the days were day 151 to 262.

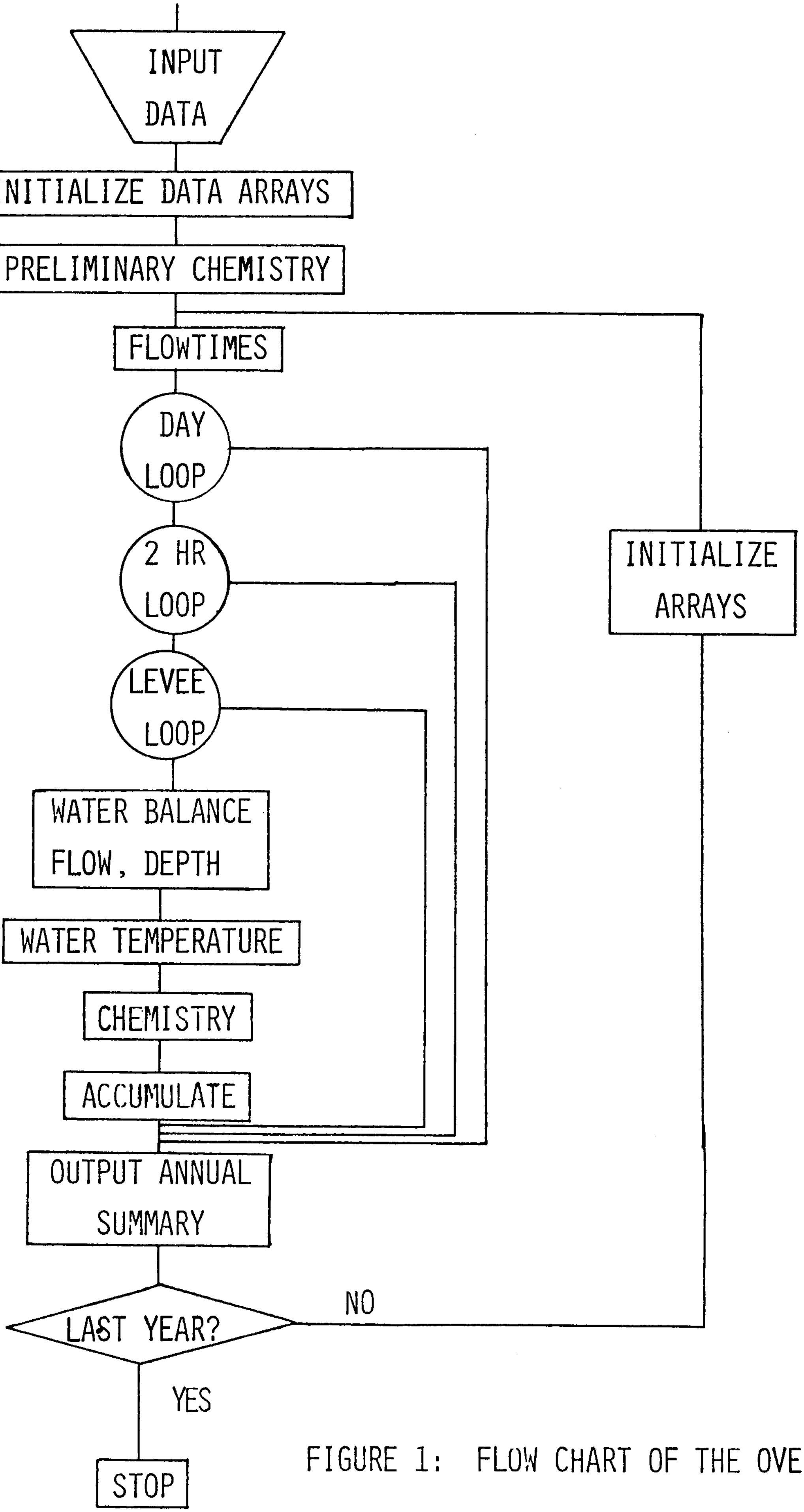

FIGURE 1: FLOW CHART OF THE OVERALL MODEL

The input data 1 through 8 are read from a file named RICESET in a list format. The climatological arrays are read in from a file named WEATHER in a list format one day at a time.

The unit of simulation is the area between two levees. The time step was two hours. This time step was chosen by the authors as being the maximum time period over which linearity in change in depth, flow rates, and carbonate precipitate rate could be assumed.

Figure 1 is a general flow chart of the overall mode. Each of the major blocks in the general flow chart will be discussed in detail. The levee loop interacts from levee 1 to NLEVEE: the two hour loop from 1 to 12: and the day loop from DYFIRST to DYLAST.

FLOWTIME: The flowtime within each levee is determined as a function of pumpage rate and distance between levees.

Distance is calculated as:

$$DX = (43560)^{*}\ A/W \tag{1}$$

where DX = distance across levee in feet

A = area in levee in acres

W = width of field in feet

Thomas (4) has shown that mean residence time can be represented by:

$$FT = (0.083/PUMP - 0.03)\ DX^{1.5} \tag{2}$$

combining formulas (1) and (2) gives the following which is used in the model:

$$FT = (0.083/PUMP - 0.03)\ (43560{*}A/W)^{1.5} \tag{3}$$

A flowtime is calculated once for each levee and retained throughout any given simulation.

WATER BALANCE: This segment of the model determines water depth in each levee, flow rate at each levee gate, resident water volume and transient water volume. It also determines if the irrigation system should be turned on or turned off. A flow chart of the water balance segment of the model is in Figure 2.

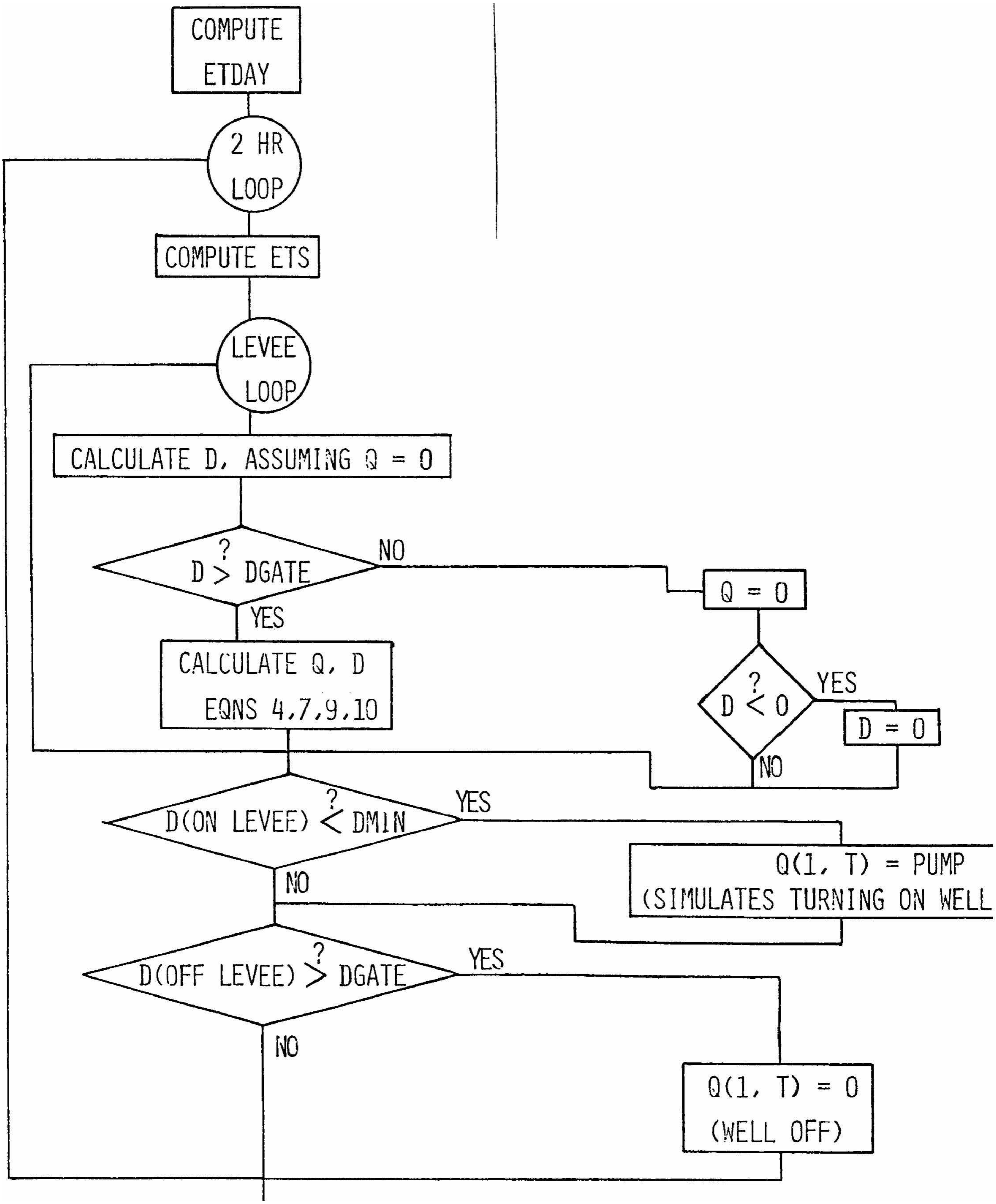

FIGURE 2: FLOW CHART OF THE WATER BALANCE SECTION OF THE MODEL

The fundamental relationship within a levee is as follows:

$$D_2 = D_1 - \mathrm{ETS} + \mathrm{PPT} + (\mathrm{QUIN}*2\mathrm{HRS} - \mathrm{QOUT}*2\mathrm{HRS})/\mathrm{AREA} \qquad (4)$$

where D_2 = water depth at end of two-hour period in inches

D_1 = water depth at beginning of period in inches

ETS = evapotranspiration and seepage during the two-hour period in inches

PPT = rainfall during the period in inches

QIN = mean flowrate into levee during the period in acre inches per hour

QOUT = mean flowrate out of levee during the period in acre inches per hour

AREA = levee area in acres

ETS is determined in a two step algorithm. At the start of each day, the total evapotranspiration and seepage is calculated as

$$\mathrm{ETDAY} = \mathrm{PE}*\ \mathrm{ETK} + \mathrm{SEEP} \qquad (5)$$

where ETDAY = total evapotranspiration and seepage for the day in inches

EP = pan evaporation in inches per day

SEEP = Seepage losses in inches per day

ETK = a water use parameter depending on crop age as shown by Ferguson (5). Values used for ETK are as given in Table 1.

Table 1. Crop Water Use Factor

Crop Age (Julian Days)	ETK
150 to 175	0.60
176 to 200	0.84
201 to 220	0.99
221 to 250	0.95
251 to 280	0.68

Bihourly evapotranspiration and seepage is then calculated as a proportion of daily evapotranspiration and seepage using the factors as shown on Table 2 where:

$$ETS = ETDAY*ETFACT \tag{6}$$

Table 2. Bihourly Evapotranspiration Factors

Time Period	Time	ETFACT	TIMEX
1	0000 - 0200	0.04	0.2
2	0200 - 0400	0.04	0.1
3	0400 - 0600	0.04	0.0
4	0600 - 0800	0.04	0.1
5	0800 - 1000	0.05	0.3
6	1000 - 1200	0.10	0.5
7	1200 - 1400	0.15	0.7
8	1400 - 1600	0.19	0.9
9	1600 - 1800	0.15	1.0
10	1800 - 2000	0.09	0.9
11	2000 - 2200	0.07	0.8
12	2200 - 0000	0.04	0.5

Since no time distribution of rainfall within the day was available, all rainfall within a day was arbitrarily assigned to the eighth two-hour time step or between 2 p.m. and 4 p.m.

Flow rate into the levee is determined by conditions in the levee above or by the irrigation pump in the case of the top levee. These then are known at the time equation (4) is solved and it is assumed that the mean flow rate is:

$$QIN = (Q\ (levee,\ T) + Q(levee,\ T-1))/2 \tag{7}$$

where Q(L,t) = flow into levee L in acre inches per hour.

Flow rate out of the levee is determined by the depth of water above gate depth as expressed by the weir equation:

$$Q(L+1,T) = 2.5*L*\ (D2-DGATE)\ **1.5 \tag{8}$$

where all variables as previously defined except L = length of levee gate in feet (assumed 6 feet).

An equation similar to equation (6) is written for outflow:

$$QOUT = (Q(L+1,T-1) + Q(L+1,T))/2 \tag{9}$$

Combining equations 9, 8 and 7 with equation 4, however leads to an equation for D2 that cannot be solved analytically. An iterative, trial and error solution was first attempted but difficulties were experienced because of oscillations and computer time. A quadratic equation that gives a reasonable approximation to the weir equation over the range of head that exists in a rice field was developed:

$$Q(L+1,T) = 0.311\ (D2-DGATE) + 0.084\ (D2-DGATE)^{**2.0} \tag{10}$$

This relationship gave values within 10% of the weir equation as (D2-DGATE) varied from 0 to 6 inches.

Equation 10, 9, and 7 were then combined with equation 4 and solved for D2 using the quadratic formula. Having determined D and Q for a given levee, D and Q the next lower levee is solved in a like manner.

After solution of all levees for the time period, depths in ONLEVEE and OFFLEVEE are compared with the specified criteria and the well is turned on or off if necessary. A flow diagram of the water balance section is shown in Figure 2.

This section of the model thus gives for each day, the arrays Q(L,T) and D(L,T).

TEMPERATURE SECTION: Based on previous studies the water temperature was found to be dependent upon air temperature, water depth and crop stage. Minimum daily water temperature was found to approximate the minimum air temperature early in the season but increasing to 4 degrees warmer at the end of the season.

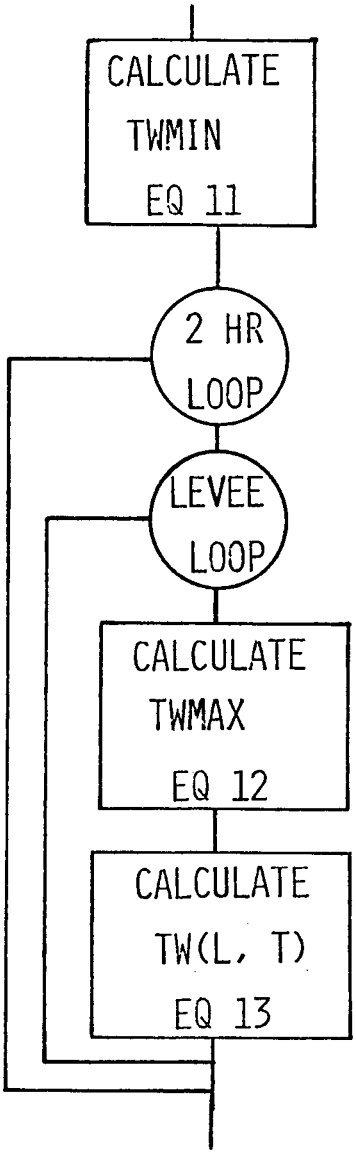

FIGURE 3: FLOW CHART FOR THE TEMPERATURE SECTION OF THE MODEL

Thus:

$$TWMIN = TMIN + (Day - DYFIRST)/100*4 \qquad (11)$$

Where $TWMIN$ = daily minimum water temperature °C

Day = day of year, Julian days

$TMIN$ = daily minimum air temperature, °C

Maximum daily water temperature is expressed as:

$$TWMAX = 5.1 + 0.58TMAX + TFACT*(14+(2.6*COS(0.16*2.54*D))) \qquad (12)$$

where $TWMAX$ = daily maximum water temperature, °C

$TMAX$ = daily maximum air temperature, °C

D = depth of water

$TFACT$ = a temperature factor between 1 and 0.2

$$TFACT = MAXIMUM\ \left(1 - \frac{DAY - DYFIRST}{100}\ , 0.2\right)$$

Bihourly water temperature is then determined by:

$$TW = TWMIN + TIMEX * (TW,AX - TWMIN) \qquad (13)$$

where TW = water temperatures for the particular time period, °C

$TIMEX$ = sinusoidal wave factor from 0 to 1 as shown in Table 2.

This section then generates the array $TW(L,T)$.

VOLUMES: In order to connect the hydraulic and chemistry phases of the model, three volumes of water were calculated for each levee area, thus:

$$VS(L,T) = MIN(D(L,T),D(L,T-1))*A \qquad (14)$$

where $VS(L,T)$ = static volume of water resident in Levee L at time T, acre inches

The gain volume (which may be positive or negative), VG, as defined as the difference between influx volume and outflow volume, thus:

$$VG(L,T) = \frac{Q(L,T) + Q(L,T-1) - Q(L+1+,T) + Q(L+1,T-1)}{2} * 2\ HRS \qquad (15)$$

or

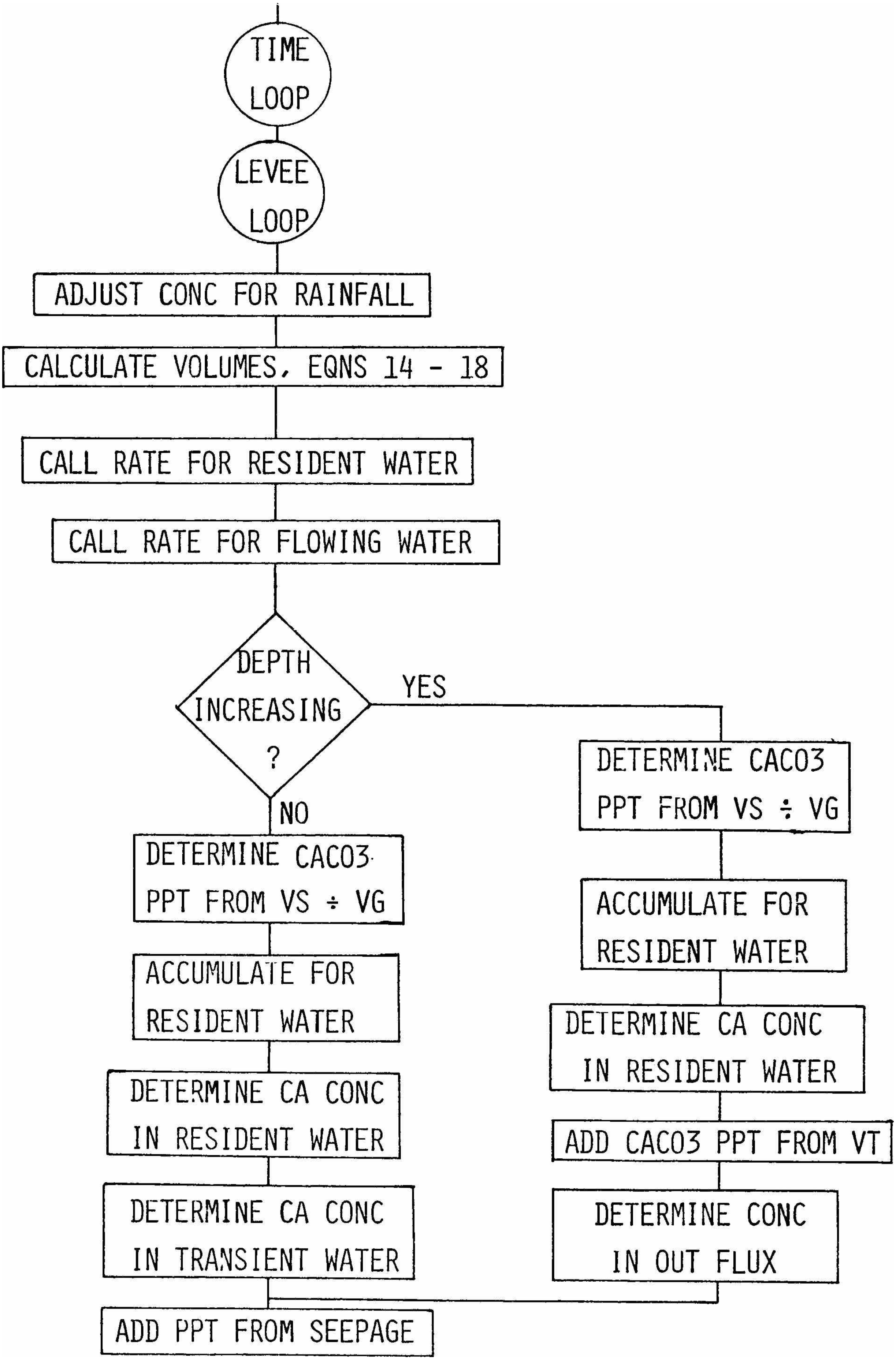

FIGURE 4: FLOW CHART FOR WATER VOLUME AND PRECIPITATE SECTION OF THE MODEL

$$VG(L,T) = Q(L,T) + Q(L,T-1) - Q(L+1,T) - Q(L+1,T-1) \qquad (16)$$

where VG(L,T) = Volume of water gained by levee L in time period T-1 to T in acre inches.

The transient volume, VT, was defined as the volume of water that moved through the levee area. Thus:

$$VT(L,T) = \frac{MIN(Q(L,T),\ Q(L+1,T))+MIN\ (Q(L,T-1),\ Q(L+1,T-1)}{2} * 2\ HRS \qquad (17)$$

or

$$VT(L,T) = MIN(Q(L,T),Q(L1+1,T) + MIN\ (Q(L,T-1),\ Q(L+1,T-1) \qquad (18)$$

where VT(L,T) = Volume of water that moved through levee L over time period T-1 to T in acre inches.

CHEMICAL MODEL: Two subroutines are called to make chemical computations. The first, PRECHEM, is used to compute that portion of the precipitation rate constant which is dependent upon initial solution parameters, and to establish the equilibrium calcium concentration. The second, RATE, is used to calculate the precipitation rate corrected for temperature effects.

The first function of PRECHEM is to compute X_2 and X_3, components of the precipitation rate constant (6), as shown below:

$$X_2 + 0.157 = 0.127*CAI \qquad (19)$$

$$X_3 = EXP(-0.016 + 0.23*MGI) \qquad (20)$$

where CAI = initial irrigation water calcium bicarbonate concentration in meg/l

MGI = initial irrigation water magnesium bicarbonate concentration in meg/l

Next, an iterative procedure (Figure 5) is used to compute the equilibrium value of calcium in the irrigation water as follows. First, water temperature is assumed to be 27°C yielding a solubility product, PKSP, of 8.46 for calcium carbonate (7). Second, calcium and bicarbonate concentrations are decreased by

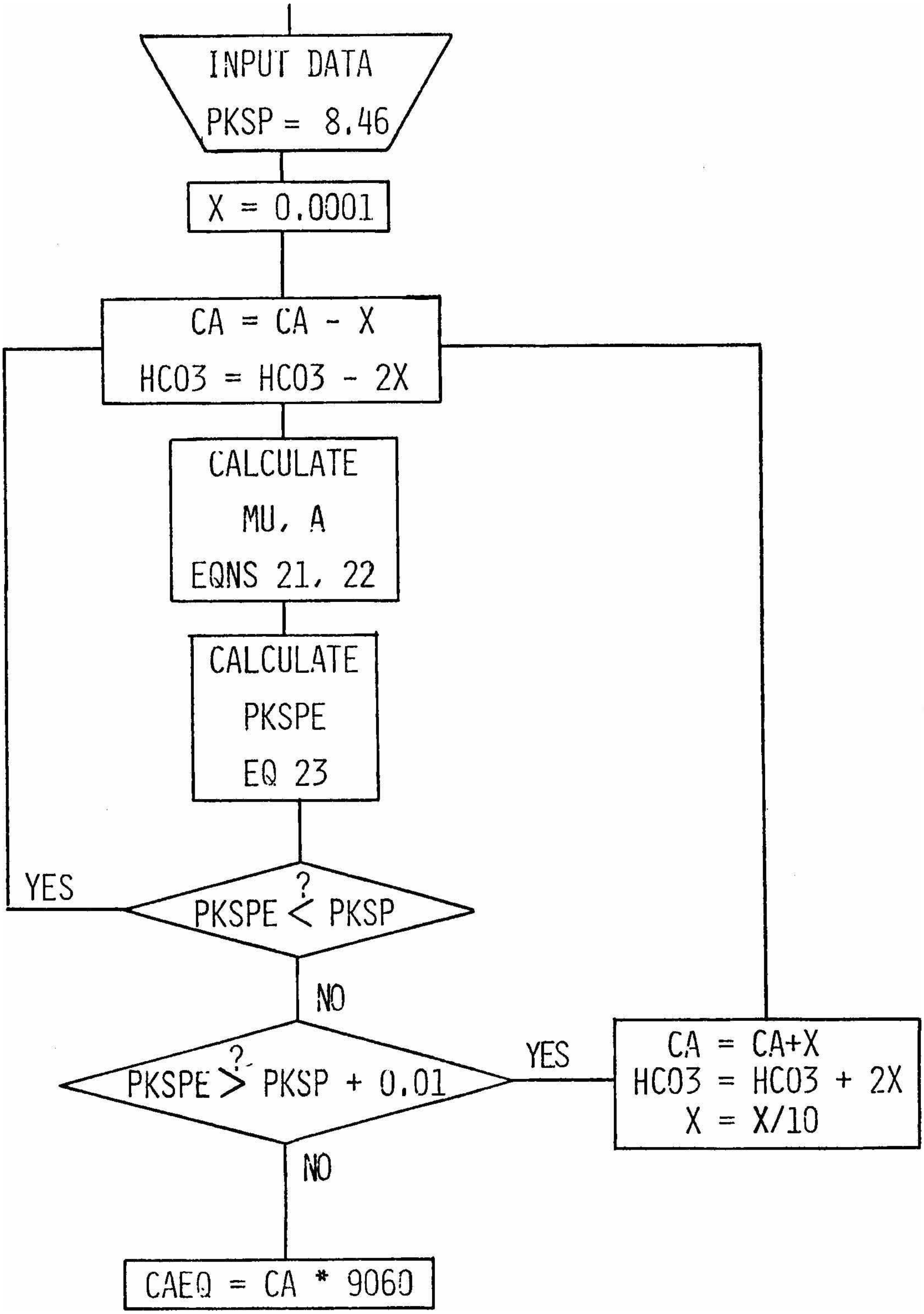

FIGURE 5: CHEMICAL SECTION OF THE MODEL

a given amount which simulates concentration changes due to calcium carbonate precipitation. Third, an ionic strength calculation is made (8).

$$\mathrm{MU = 2{*}CA + 2{*}MGI + HCO3/2 + 1.25x10^{-3}} \tag{21}$$

where: MU = ionic strength

CA = adjusted calcium concentration in $\underline{M}$.

MGI = initial magnesium concentration in $\underline{M}$.

HCO3 = adjusted bicarbonate concentration in $\underline{M}$.

The constant $1.25X10^{-3}$ in Equation 21 is the contribution of NA,U and SO_4 at 1,0.5 and 0.5 meg/l, respectively, to MU. Fourth, a term A. is calculated which is equivalent to the sum of the negative logarithms of mono and dualent activity coefficients from the Davies equation (9).

$$\mathrm{A = 2.545{*}(SQRT(MU)/(1{+}SQRT(MU) - 0.2{*}MU)} \tag{22}$$

Fifth, a solubility product estimate, PKSPE, is made for the irrigation water as shown below:

$$\mathrm{PKSPE = -LOG10(CA){-}LOG10(HCO3(+ A + 2.38)} \tag{23}$$

Equation 23 assumes that irrigation water pH is 8.00 and that negative log of the second dissociation constant of carbonic acid is 10.38 at 27°C (10). The value of PKSPE is then compared to PKSP and the iteration continued until PKSPE nears PKSP as shown in Figure 5. At that point, CAEQ is assigned the value of CA and converted to lbs. calcium per acre inch.

When X_2, X_3, and CAEQ are known the calcium carbonate precipitation rate, PRATE, can be computed with the first order rate equation as reported by Gilmour *et al* (10). The subroutine, RATE, is called and the following calculations made. First, the effect of temperature on the rate constant is evaluated through X_1 shown below.

$$X_1 = \mathrm{EXP\ (-5955/(TW + 273) + 17.96)} \tag{24}$$

where: TW = irrigation water temperature in °C.

Second, the rate constant, SLOPE, is computed.

$$\text{SLOPE} = X_1 * X_2 * X_3 \tag{25}$$

And third, the rate of calcium loss from solution as calcium carbonate is estimated.

$$\text{PRATE} = \text{SLOPE}*(\text{CONC} - \text{CAEQ}) \tag{26}$$

where: PRATE = rate of calcium loss from solution in lbs. calcium/acre inch

CONC = irrigation water calcium concentration in lbs. calcium/acre inch.

The value of PRATE is then used in the main program to calculate the amount of calcium precipitated from the floodwater in a 2 hour period.

FIELD VERIFICATION OF THE MODEL

Three production fields in Prairie and Arkansas counties were selected to use to validate the accuracy of the model. The criteria for selection of fields were:

1. The field has an electric-powered well as the only water source for the field.
2. The field must be watered from only one inlet.
3. The well must serve only that field.

The physical characteristics of the field were as given in Table 3. Water stage recorders were installed in the first and last interlevee area in each field. These were mounted on stilling wells staked in the field and gave a 2:1 amplification of water level changes on a seven day chart. The chart in the first interlevee area allowed accurate (± 1 hr) determination of time when the well was turned on or turned off. The recorder in the last interlevee area was used to verify model accuracy. Rain gages were installed at each site and read once each week and the water stage recorder from the first interlevee area used to assign times and amounts throughout the week.

Figure 8: Plot of computer predicted flood depth (-) and observed flood depth (X) in field SE.

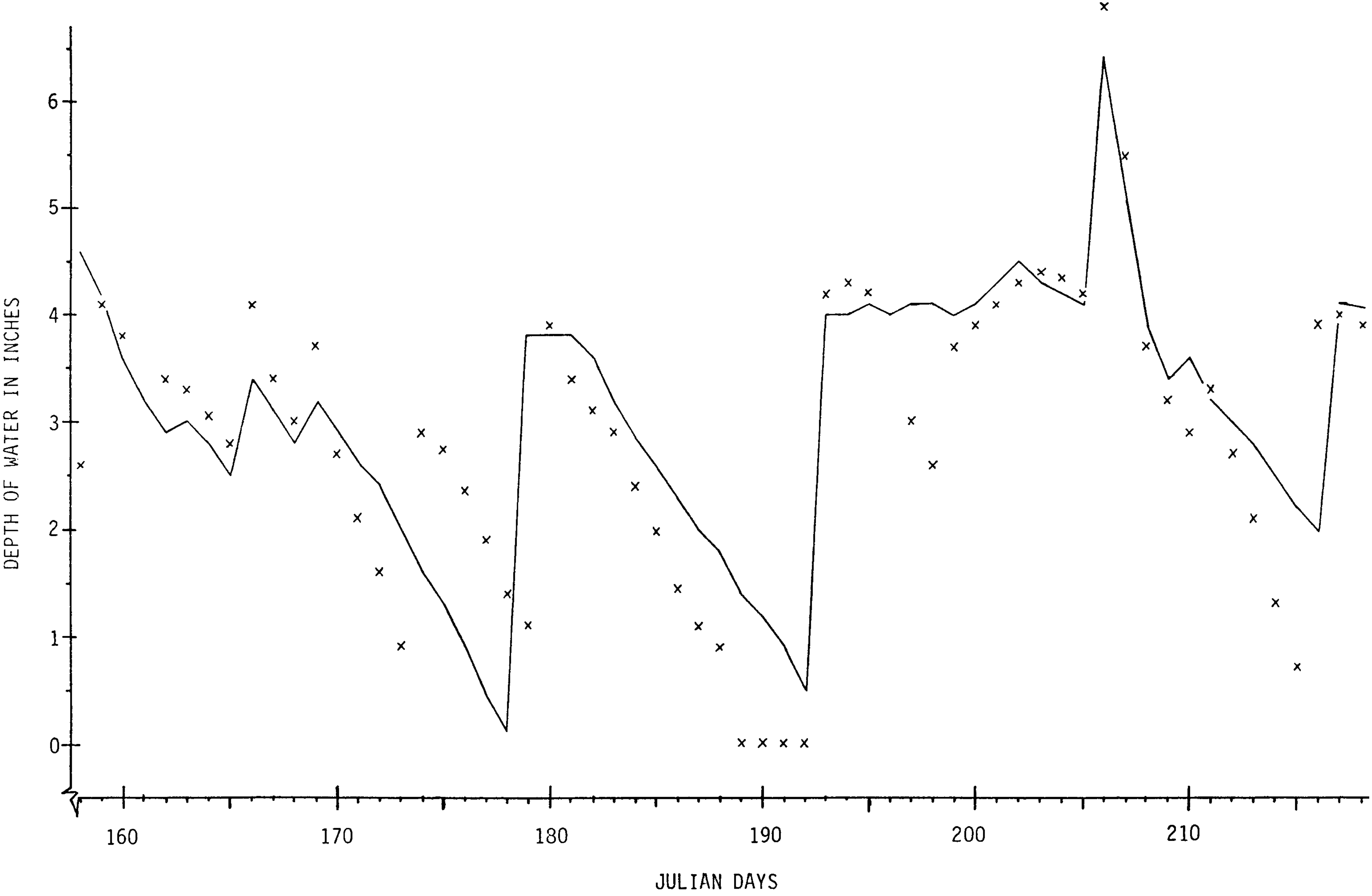

Figure 6: Plot of computer predicted depth (-) and observed depth (X) in the last levee of field EN.

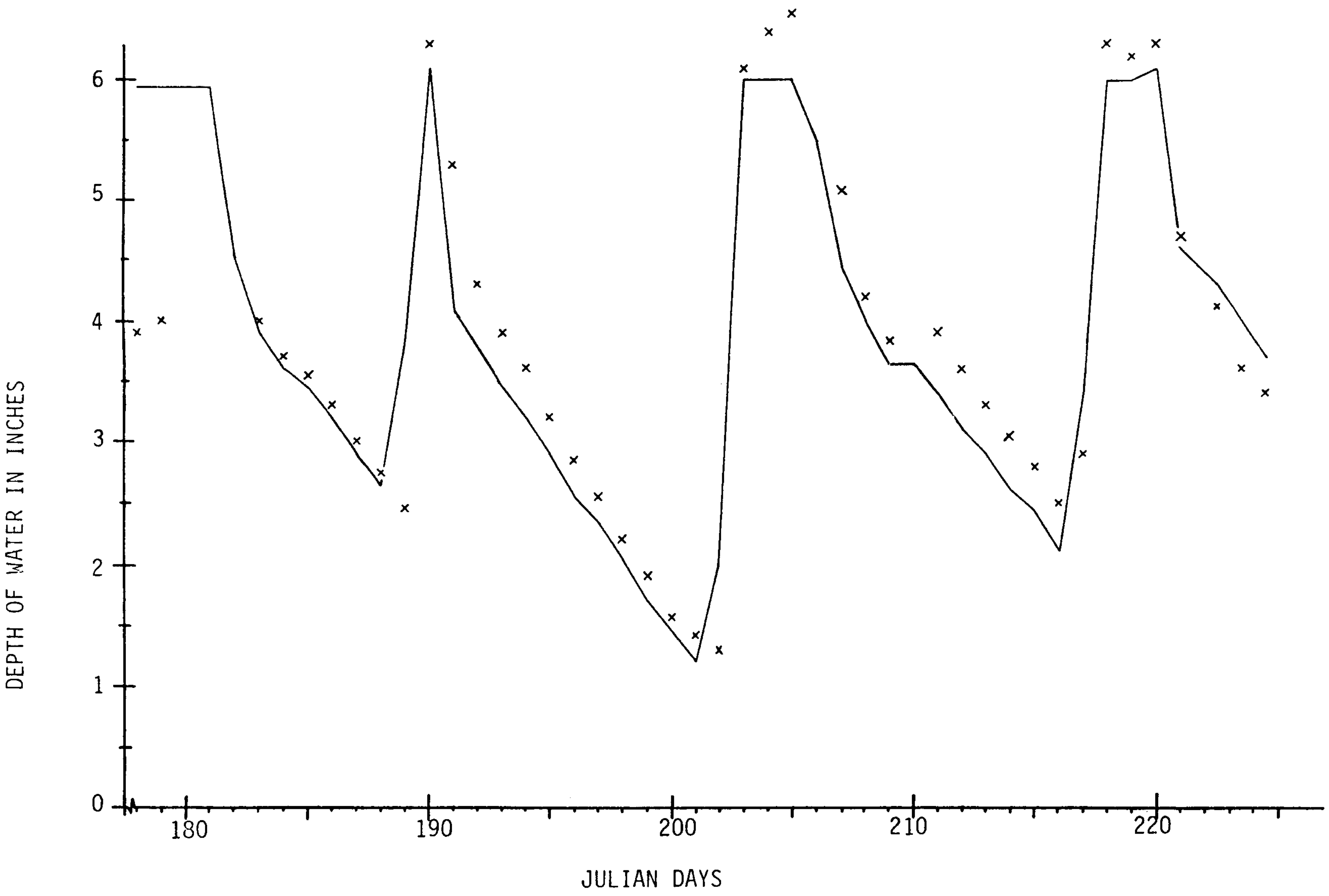

Figure 7: Plot of computer predicted flood depth (-) and observed depth (X) in field SK.

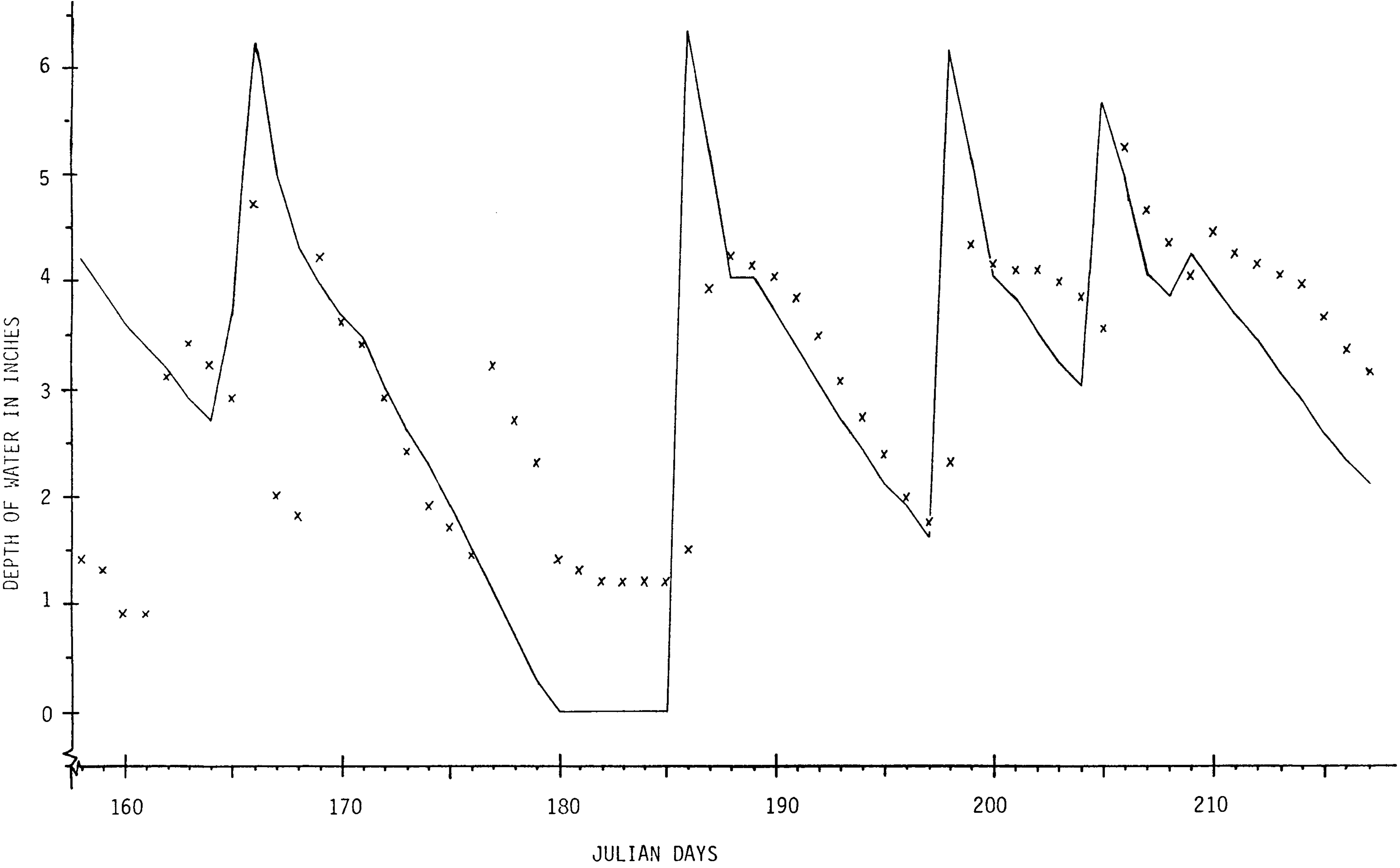

Table 3. Summary of Characteristics of Verification Fields

Field Designation	Soil Type	Area Acres	Well Flow Rate, GPM	Length/Width Ratio	Number of Levees
EN	Siltloam	55	680	3	18
SK	Siltloam	40	800	4	15
SE	Siltloam	40	600	1	7

At the end of the season the rainfall, pan evaporation from the Rice Research and Extension center near Stuttgart, and the time of turning on and turning off the well were used in the model and water depth in the final interlevee area was projected. The data from the computer projection and the observation are plotted in figures 6, 7, and 8.

The excellent prediction of water depth is apparent from the plots. Absolute values are occasionally somewhat different due to the land owner changing gate depths without informing the researchers, but relative changes in depth are predicted with extreme sensitivity and accuracy. While only one observation per day is plotted, analysis of time periods verifies that time of abrupt flood depth change is always predicted within one time unit (2 hours).

The conclusion drawn from the field study was that the model predicted the hydrologic occurrences within a field with accuracy greater than our ability to sense them.

EXAMPLE OF USE OF THE MODEL

Once the model was verified, it was used to establish prediction equations for calcium carbonate depositions with varying water quality and water management. The following acreage and flow combinations were used: 40 acre 400 gpm, 40 acre 800 gpm, 80 acre 800 gpm, and 40 acre 1200 gpm. Calcium concentrations of 2,3,4,5, and 6 milliequivalents per liter were used on all acreage-flow combinations. Ten levees were simulated and weather conditions in 1969 used. The

TABLE 4 - CALCIUM DISTRIBUTION IN A HYPOTHETICAL 40 ACRE FIELD

Calcium Precipitate, Pounds Per Acre

Acres	Q GPM	Irr Inch	Ca Me/l	Levee Number 1	2	3	4	5	6	7	8	9	10
40	400	20.4	2	326	274	168	118	112	91	73	64	57	46
		20.4	3	648	527	364	218	176	133	100	83	69	50
		20.4	4	1042	818	579	301	225	163	119	97	78	53
		20.4	5	1510	1138	803	368	260	185	132	107	84	55
		20.4	6	2049	1979	1029	420	285	199	142	114	89	56
40	800	23.4	2	329	264	177	148	140	114	74	48	47	45
		23.4	3	594	486	390	301	252	196	107	49	48	47
		23.4	4	880	723	621	454	356	270	135	49	49	48
		23.4	5	1186	974	866	600	453	336	160	50	49	48
		23.4	6	1512	1239	1124	740	537	393	181	50	49	48
40	1200	23.5	2	342	262	175	161	156	99	54	52	50	45
			3	602	479	379	345	313	171	56	53	52	46
			4	864	697	585	532	474	246	58	54	52	47
			5	1126	917	793	719	635	322	61	55	52	47
			6	1391	1138	1002	906	794	398	63	55	52	47

TABLE 5 - CALCIUM DISTRIBUTION IN A HYPOTHETICAL 80 ACRE FIELD

Calcium Precipitate, Pounds Per Acre

Acres	Q GPM	Irr Inch	Ca Me/l	Levee Number 1	2	3	4	5	6	7	8	9	10
800	800	23.7	2	231	204	167	122	98	84	70	56	47	32
			3	473	416	384	256	185	154	126	95	75	46
			4	755	657	631	384	257	211	170	126	97	55
			5	1073	922	902	502	318	256	204	151	114	62
			6	1430	1209	1195	606	367	293	231	171	128	68
800	1600	25.6	2	250	203	147	140	139	107	57	27	25	25
			3	455	387	306	317	327	261	119	27	26	25
			4	644	559	455	493	537	446	201	28	26	25
			5	818	717	587	667	759	654	303	29	26	26
			6	977	861	703	836	993	885	426	30	26	26
800	2400	24.8	2	248	189	139	160	166	88	30	29	27	27
			3	451	370	305	381	415	203	32	29	27	27
			4	623	524	440	602	709	358	35	29	27	27
			5	764	648	542	816	1053	564	41	29	28	27
			6	873	743	606	1013	1451	838	51	29	28	27

rice season of 1969 was the nearest to an average year that was available. With this simulation, rainfall was 9.97 inches, and total evapotranspiration was 25.05 inches. The calcium precipitate is as shown in table 4.

Since the most severe damage from calcium carbonate occurs in the upper portion of the field, the calcium carbonate precipitate in the upper 10% of the field was regressed on flow and quality resulting in the following relationship:

$$ACO3_{(10)} = (-0.394Q + 1050)\ CA + (0.950)Q - 1530 \qquad (27)$$

where: $CACO3_{(10)}$ = calcium carbonate precipitated in the upper 10% of the field in pounds per acre;

Q = well flow rate in gallons per minute; and

CA = calcium carbonate concentrate in the water, milliequivalent per liter.

The hydrologic portion of the model has been used to analyze the effect of power interruptions on rice irrigation (Ferguson, 1979) and gave results that were very effective in allowing power producers to show peak loading without detrimental effects on rice production.

APPENDIX

```
RICEWAT: PROC OPTIONS(MAIN);
  /* *********************************************************
                        PROGRAM DESCRIPTION
INPUT DATA NEEDED:
  INITIAL DATA(ONE TIME ONLY):
    1. CHARACTER STRING OF LENGTH 40 NAMING THE FIELD TO BE MODELED
    2. NUMBER OF INTERLEVEE AREAS IN THE FIELD (NLEVEE) (12 OR LESS)
    3. A VECTOR OF LENGTH 'NLEVEE' LISTING THE INTER LEVEE AREAS IN ACRES
    5. STARTING AND ENDING DAYS IN JULIAN DAYS
    6. IRRIGATION FLOW RATE IN CFS
    7. HEIGHT OF LEVEE GATE ABOVE GROUND SURFACE IN INCHS
   10. CALCIUM CONCENTRATION IN IRRIGATION WATER IN POUNDS OF
           CALCIUM PER ACRE INCH (4.53 * MEQ/L)
  DAILY DATA (STARTING WITH STARTING DAY:
   1. DAILY PAN EVAPORATION
   2. DAILY MAXIMUM TEMPERATURE DEGREES F
   3. DAILY MINIMUM TEMPERATURE DEGREES F
   4. DAILY RAINFALL INCHES
  *********************************************************** */
DECLARE NAME CHAR(40),(NLEVEE,DYFIRST,DYLAST,T,DAY) FIXED(3,0);
DECLARE A(12);
DECLARE ETS (0:12), PPT(0:12), Q(16,0:12), D(16,0:12);
DECLARE ETCFACT (0:12);;
DECLARE NGATE(16);
DECLARE (C,CPPT,CQ)(16,0:12),(CPPTTOT,FT,STOT,ST,TOTAL)(16);
DECLARE TIMEX(0:12) FLOAT;
DECLARE (PE,RAIN,TMAX,TMIN)(64:70,151:253) FLOAT;
DECLARE TW(16,0:12) FLOAT;
DECLARE (VS,VG,VT,STAG)(16,0:12);
DECLARE ETK(150:280) FLOAT;
DECLARE F(16) FLOAT;
DECLARE PUMP FLOAT;
```

A. Program listing

```
  /* ******************************************************* */
  /*          THIS SECTION GETS INITIAL DATA                 */
  /* ******************************************************* */
OPEN FILE(WALL) INPUT;
DO YEAR = 64 TO 70;  DO DAY = 151 TO 262;
GET FILE(WALL) LIST(PE(YEAR,DAY),RAIN(YEAR,DAY),TMAX(YEAR,DAY),TMIN(YEAR,DAY));
TMAX(YEAR,DAY) = (TMAX(YEAR,DAY)-32)*0.5555;
TMIN(YEAR,DAY) = (TMIN(YEAR,DAY) - 32.0)* 0.5555;
END;  END; CLOSE FILE(WALL);
OPEN FILE(RICESET) INPUT;  GET FILE(RICESET) EDIT(NAME)(A(40));
GET  FILE(RICESET) LIST(NLEVEE,(A(I) DO I = 1 TO NLEVEE),DYFIRST,DYLAST,
DGATE,SEEP, DCRIT,DGATE,DMIN,
CAEQ,ONLEVEE,OFFLEVEE);
CLOSE FILE(RICESET);
DO I = 150 TO 175;  ETK(I) = 0.60;       END;
DO I = 176 TO 200;  ETK(I) = 0.84;       END;
DO I = 201 TO 220;  ETK(I) = 0.99;       END;
DO I = 221 TO 250;  ETK(I) = 0.95;       END;
DO I = 251 TO 280;  ETK(I) = 0.68;       END;
ET[FACT(1) = 0.04;  ET[FACT(2) = 0.04;  ET[FACT(3) = 0.04;
ET[FACT(4) = 0.04;  ET[FACT(5) = 0.05;  ET[FACT(6) = 0.10;
ET[FACT(7) = 0.15;  ET[FACT(8) = 0.19;  ET[FACT(9) = 0.15;
ET[FACT(10) = 0.09;  ET[FACT(11) = 0.07;  ET[FACT(12) = 0.04;
TIMEX(0) = 0.5;  TIMEX(1) = 0.2;  TIMEX(2) = 0.1;  TIMEX(3) = 0.0;
TIMEX(4) = 0.1;  TIMEX(5) = 0.3;  TIMEX(6) = 0.5;
TIMEX(7) = 0.7;  TIMEX(8) = 0.9;  TIMEX(9) = 1.0;
TIMEX(10) = 0.9;  TIMEX(11) = 0.8;  TIMEX(12) = 0.5;
  /* ******************************************************* */
  /*          THIS SECTION SETS PRELIMINARY DATA VALUES      */
  /* ******************************************************* */
DOFF = DGATE;
DO I = 1 TO NLEVEE;  AREA = AREA + A(I);  END;
YEAR = 69;
DO IJK = 2 TO 6;  DO KJI = 2 TO 6;
ZZ = (IJK);
PUMP = ZZ*400/450;
CQ(1,0) = 4.53 * KJI;
DO I = 1 TO 12; CQ(1,I) = CQ(1,0); END;
DO III = 1 TO 10 ;
FT(III) = (((0.083/PUMP)-0.03)*((A(III)*66.0)**1.5))/60.0;  END;
C = 0;  CPPT = 0.0;  CPPTTOT = 0.0;    D = 0.0;  Q = 0.0;TOTAL = 0.0;
GPMA=PUMP*450/AREA;  IF GPMA<16 THEN DO; IF GPMA<11 THEN OFFLEVEE=10;
ELSE OFFLEVEE=8; END; ELSE DO; IF GPMA<26 THEN OFFLEVEE=7;
ELSE OFFLEVEE=6; END;
OFFLEVEE = 10;
STOT = 0.0;
PPTTOT = 0.0;  ETTOT = 0.0;  NHRIRR = 0.0;
DAY = DYFIRST;
DAILY:
PPT(8) = RAIN(YEAR,DAY);
PPTTOT = PPTTOT + PPT(8);
ETDAY = PE(YEAR,DAY) * ETK(DAY) + SEEP;
ETTOT = ETTOT + ETDAY;
DO I = 1 TO 12;  ETS(I) = ETDAY * ET[FACT(I);  END;
```

A. Program listing, con't.

```
  /* ************************************************ */
  /*      THIS SECTION CALCULATES FLOWS AND DEPTHS         */
  /* ************************************************ */
SET: DO T = 1 TO 12;  DO LEVEE = 1 TO NLEVEE;
D(LEVEE,T) = ((Q(LEVEE,T) + Q(LEVEE,T-1) -Q(LEVEE+1,T-1)) / (A(LEVEE)))
 - ETS(T) + PPT(T) + D(LEVEE,T-1);
Q(LEVEE + 1,T) = 0.0;  IF D(LEVEE,T) < 0.0 THEN D(LEVEE,T) = 0.0;
IF D(LEVEE,T) > DGATE THEN DO;
Z = D(LEVEE,T-1) + (Q(LEVEE,T-1) + Q(LEVEE,T) -Q(LEVEE+1,T-1))/A(LEVEE) -ETS(T)
 + PPT(T);
D(LEVEE,T) =( -.311 -A(LEVEE) +((.311+A(LEVEE))**2 + 4*A(LEVEE)*.084*(Z-DGATE))
 **.5)/.168 + DGATE;
Q(LEVEE+1,T) = 0.311* (D(LEVEE,T)-DGATE) + .084*((D(LEVEE,T)-DGATE)**2);
END;  END;
IF D(ONLEVEE,T) < DMIN & Q(1,T) = 0 THEN DO;  DO I = T TO 12;  Q(1,I)= PUMP;
 END; GO TO QSET; END;
IF D(OFFLEVEE,T) > DOFF & Q(1,T) ]= 0 THEN DO;  DO I = T 10 12;  Q(1,I) = 0.0;
 END; GO TO QSET; END;
QSET:  END;
  /* ************************************************* */
 /*  TEMPERATURE SECTION     */
 /* ************************************************* */
TFACT = 5.1 + 0.58 * (TMAX(YEAR,DAY));  XTFACT = MAX(1 - (DAY - DYFIRST)/100, 0.2);
TWMIN = TMIN(YEAR,DAY) + ((DAY - DYFIRST)/100)* 4.0;
DO T = 1 TO 12;  DO L = 1 TO NLEVEE;
TWMAX = TFACT + XTFACT*(14 + (2.6 * (COS(D(L,T)*0.16*2.54))));
TW(L,T) = TWMIN + (TIMEX(T) * (TWMAX - TWMIN));
END;
END;
  /* ************************************************ */
  /*  THIS SECTION CALCULATES WATER VOLUMES AND CAL PPT RATES */
  /* ************************************************ */
DO IT = 1 TO 12;  DO IL = 1 TO NLEVEE;
IF PPT(IT) ]= 0.0 THEN C(IL,IT-1) = C(IL,IT-1) * (D(IL,IT-1) / (D(IL,IT-1)
+ PPT(IT)));
VS(IL,IT) = MIN(D(IL,IT),D(IL,IT-1)) * A(IL);
VG(IL,IT) = (Q(IL,IT) + Q(IL,IT-1) - Q(IL + 1,IT) - Q(IL + 1,IT - 1)) ;
VT(IL,IT) = (MIN(Q(IL,IT),Q(IL+1,IT)) + MIN(Q(IL,IT-1),Q(IL+1,IT-1)));
CALL RATE(C(IL,IT-1),CPRS);
CONC = (CQ(IL,IT) + CQ(IL,IT-1)) / 2.0;
CALL RATE(CONC,CPRQ);
```

A. Program listing, con't.

```
1200   /* ******************************************************** */
1210   /* THIS SECTION CALCULATES CONCENTRATION AND CAL PPT AMOUNT */
1220   /* ******************************************************** */
1230 IF VG(IL,IT)>= 0.0 THEN DO;
1240 CPPT(IL,IT) = VS(IL,IT) * CPRS * 2.0 + VG(IL,IT) * CPRQ ;
1250 STAG(IL,IT) = CPPT(IL,IT);
1260 STOT(IL) = STOT(IL) + CPPT(IL,IT);
1270 IF D(IL,IT) = 0 THEN C(IL,IT) = 0;
1280 ELSE C(IL,IT) = (C(IL,IT-1) * VS(IL,IT) + VG(IL,IT) * ((CQ(IL,IT)
1290 + CQ(IL,IT-1))
1300   / 2.0)  - CPPT(IL,IT)) / (D(IL,IT) * A(IL));
1310 CPPT(IL,IT) = CPPT(IL,IT) + (VT(IL,IT) * CPRQ * MIN(FT(IL),2.0));
1320 IF Q(IL+1,IT) = 0 THEN CQ(IL+1,IT) = 0;
1330 ELSE CQ(IL+1,IT) = CQ(IL,IT) - (CPRQ * (MIN(FT(IL),2.0)));  END;
1340 ELSE DO;
1350 CPPT(IL,IT) = VS(IL,IT) * CPRS * 2.0 - (VG(IL,IT) * CPRS ) + (VT(IL,IT)
1360 * CPRQ * MIN(FT(IL),2.0));
1370 STAG(IL,IT) = VS(IL,IT) * CPRS * 2.0 - (VG(IL,IT) * CPRS);
1380 STOT(IL) = STOT(IL) + STAG(IL,IT);
1390 IF D(IL,IT) = 0 THEN C(IL,IT) = 0;
1400 ELSE C(IL,IT) = ((C(IL,IT-1) - (CPRS * 2.0)) * VS(IL,IT)) / (D(IL,IT)
1410 * A(IL));
1420 IF Q(IL+1,IT) = 0.0 THEN CQ(IL+1,IT) = 0.0;  ELSE
1430 CQ(IL+1,IT) = ((-VG(IL,IT) / (-VG(IL,IT) + VT(IL,IT))) * C(IL,IT))
1440 + (VT(IL,IT) / (-VG(IL,IT) + VT(IL,IT)))
1450   *(CQ(IL,IT) - (CPRQ * (MIN(FT(IL),2.0))));
1460 END;
1465 CPPT(IL,IT) = CPPT(IL,IT) + SEEP * C(IL,IT);
1470 CPPTTOT(IL) = CPPTTOT(IL) + CPPT(IL,IT);
1480 ST(IL) = ST(IL) + STAG(IL,IT);
1490 END;  END;
1500 DO I = 1 TO NLEVEE;  TOTAL(I) = TOTAL(I) + CPPTTOT(I);  END;
1510   /* ******************************************************** */
1520   /*                    OUTPUT SECTION                      */
1530   /* ******************************************************** */
```

A. Program listing, con't.

```
  /* ********************************************************* */
  /*                DAILY RESET SECTION                        */
  /* ********************************************************* */
DAY = DAY + 1;
DO I = 1 TO NLEVEE;  TW(I,0) = TW(I,12);
Q(I,0) = Q(I,12);  D(I,0) = D(I,12);  C(I,0) = C(I,12);
CPPT(I,0) = CPPT(I,12);  CQ(I,0) = CQ(I,12);
CPPTTOT(I) = 0.0;
ST(I) = 0.0; END;
DO I = 1 TO 12;  IF Q(1,I) ]= 0.0 THEN NHRIRR = NHRIRR + 1;  END;
Q(1,*) = Q(1,12);
  GO TO DAILY;
  /* ********************************************************* */
  /*                   SUBROUTINE SECTION                      */
  /* ********************************************************* */
RATE: PROCEDURE(CONC,PRATE);
X1 = EXP(-5955/(TW(IL,IT) + 273) + 17.96);
X2 = 0.157 + (0.127 * (CONC / 4.53));
X3 = EXP(-0.016 + (0.231 * MG));
SLOPE = X1 * X2 * X3;
IF CONC < CAEQ THEN PRATE = 0;
ELSE PRATE = -(SLOPE * CAEQ) + (SLOPE * CONC);
DONE:  END RATE;
  /* ********************************************************* */
  /*             END OF SUBROUTINE SECTION                     */
  /* ********************************************************* */
TERMINUS: PUT SKIP;  PUT SKIP;  PUT SKIP;  PUT SKIP;  PUT SKIP; END;
END ;  END;
```

A. Program listing, con't.

```
1540 IF DAY = DYLAST THEN DO;
1550 PUT SKIP EDIT('SEASON CALCIUM PRECIPITATE FOR 19',YEAR)(X(20),A,F(2,0));
1560 PUT SKIP;
1565 ZZ = PUMP * 450.0 ;
1570 PUT SKIP EDIT('AREA =  ',AREA,' ACRES AND PUMPAGE RATE = ',ZZ,' GALLONS PER MINUTE ')
1580 (X(2),A,F(2),A,F(4),A);
1590 PUT SKIP;
1600 XIRR = 2.0*NHRIRR*PUMP/AREA;
1610 PUT SKIP EDIT('SEASONAL RAINFALL = ',PPTTOT,' TOTAL EVAPOTRANSPIRATION = ',ETTOT,
1620 'TOTAL IRRIGATION = ',XIRR)(A,F(5,2),A,F(5,2),A,F(5,2));
1630 PUT SKIP EDIT('CALCIUM CONCENTRATION IN IRRIGATION WATER = ',CQ(1,0),' LBS CA PER ACRE INCH')
1631 (A,F(5,1),A);
1640 PUT SKIP EDIT('THIS ANALYSIS USES ',CAEQ,' POUNDS PER ACRE INCH AS AN EQUIL. CAL. CONCENTRATION
')
1650 (X(2),A,F(5,3),A);
1651 PUT SKIP;  PUT SKIP EDIT('TOTAL CALCIUM PRECIPITATE')(X(20),A);
1660 PUT SKIP;
1670 PUT SKIP EDIT('LEVEE',(I DO I = 1 TO NLEVEE))(A,X(5),(NLEVEE)(F(2),X(4)));
1680 PUT SKIP;  PUT SKIP EDIT('CALCIUM PRECIPITATE FROM RESIDENT WATER')(X(20),A);
1690 PUT SKIP;
1700 PUT SKIP EDIT('POUNDS',(STOT(J) DO J = 1 TO NLEVEE))(A,(NLEVEE)(F(10)));
1710 PUT SKIP EDIT('LB/AC.',(STOT(J)/A(J) DO J = 1 TO NLEVEE))(A,(NLEVEE)(F(10)));
1720 PUT SKIP;
1730 PUT SKIP EDIT('CALCIUM PRECIPITATE FROM FLOWING WATER')(X(20),A);
1740 PUT SKIP;
1750 PUT SKIP EDIT('POUNDS',(TOTAL(J)-STOT(J) DO J = 1 TO NLEVEE))(A,(NLEVEE)(F(10)));
1760 PUT SKIP EDIT('LB/AC.',(TOTAL(J)/A(J)-STOT(J)/A(J) DO J = 1 TO NLEVEE))(A,(NLEVEE)(F(10)));
1780 PUT SKIP;
1790 PUT SKIP EDIT('POUNDS ',(TOTAL(J) DO J = 1 TO NLEVEE))(A,(NLEVEE)(F(6)));
1800 PUT SKIP EDIT('LB/AC .',(TOTAL(J)/A(J) DO J = 1 TO NLEVEE))(A,(NLEVEE)(F(6)));
1801 PUT SKIP EDIT('PERCENT',((TOTAL(J)*100/(SUM(TOTAL(*)))) DO J = 1 TO NLEVEE))
1802 (A,(NLEVEE)(F(6,1)));
1803 PUT SKIP EDIT('CUM PER')(A);  XPER = 0.0;
1804 DO J = 1 TO NLEVEE;
1805 XPER = XPER + TOTAL(J);
1806 PUT EDIT(XPER*100/SUM(TOTAL(*)))(F(6,1));
1807 END;
1810 GO TO TERMINUS;
1820 END:
```

B. Output type 1 listing

```
1510   /* ****************************************************** */
1520   /*                      OUTPUT SECTION                    */
1530   /* ****************************************************** */
1540 IF DAY = DYLAST THEN DO;
1550 PUT SKIP EDIT('SEASON CALCIUM PRECIPITATE FOR 19',YEAR)(X(20),A,F(2,0));
1560 PUT SKIP;
1565 ZZ = PUMP * 450.0 ;
1570 PUT SKIP EDIT('AREA =  ',AREA,' ACRES AND PUMPAGE RATE = ',ZZ,' GALLONS PER
 MINUTE ')
1580 (X(2),A,F(2),A,F(4),A);
1590 PUT SKIP;
1600 XIRR = 2.0*NHRIRR*PUMP/AREA;
1610 PUT SKIP EDIT('SEASONAL RAINFALL = ',PPTTOT,' TOTAL EVAPOTRANSPIRATION = ',
ETTOT,
1620 'TOTAL IRRIGATION = ',XIRR)(A,F(5,2),A,F(5,2),A,F(5,2));
1630 PUT SKIP EDIT('CALCIUM CONCENTRATION IN IRRIGATION WATER = ',CQ(1,0),' LBS
CA PER ACRE INCH')
1631 (A,F(5,1),A);
1640 PUT SKIP EDIT('THIS ANALYSIS USES ',CAEQ,' POUNDS PER ACRE INCH AS AN EQUIL
. CAL. CONCENTRATION')
1650 (X(2),A,F(5,3),A);
1651 PUT SKIP;  PUT SKIP EDIT('TOTAL CALCIUM PRECIPITATE')(X(20),A);
1660 PUT SKIP;
1670 PUT SKIP EDIT('LEVEE',(I DO I = 1 TO NLEVEE))(A,X(5),(NLEVEE)(F(2),X(4)));
1680 PUT SKIP;  PUT SKIP EDIT('CALCIUM PRECIPITATE FROM RESIDENT WATER')(X(20),A
);
1690 PUT SKIP;
1700 PUT SKIP EDIT('POUNDS',(STOT(J) DO J = 1 TO NLEVEE))(A,(NLEVEE)(F(10)));
1710 PUT SKIP EDIT('LB/AC.',(STOT(J)/A(J) DO J = 1 TO NLEVEE))(A,(NLEVEE)(F(10))
);
1720 PUT SKIP;
1730 PUT SKIP EDIT('CALCIUM PRECIPITATE FROM FLOWING WATER')(X(20),A);
1740 PUT SKIP;
1750 PUT SKIP EDIT('POUNDS',(TOTAL(J)-STOT(J) DO J = 1 TO NLEVEE))(A,(NLEVEE)(F(
10)));
1760 PUT SKIP EDIT('LB/AC.',(TOTAL(J)/A(J)-STOT(J)/A(J) DO J = 1 TO NLEVEE))(A,(
NLEVEE)(F(10)));
1780 PUT SKIP;
1790 PUT SKIP EDIT('POUNDS ',(TOTAL(J) DO J = 1 TO NLEVEE))(A,(NLEVEE)(F(6)));
1800 PUT SKIP EDIT('LB/AC .',(TOTAL(J)/A(J) DO J = 1 TO NLEVEE))(A,(NLEVEE)(F(6)
));
1801 PUT SKIP EDIT('PERCENT',((TOTAL(J)*100/(SUM(TOTAL(*)))) DO J = 1 TO NLEVEE)
)
1802 (A,(NLEVEE)(F(6,1)));
1803 PUT SKIP EDIT('CUM PER')(A);  XPER = 0.0;
1804 DO J = 1 TO NLEVEE;
1805 XPER = XPER + TOTAL(J);
```

B. output type 2 listing