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Identification of Critical Water Levels in Flooded Rice Fields

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Technical Completion Report Research Project G-829-02

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ABSTRACT

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A mathematical model was developed to simulate the transient hydrology of a flooded rice field. With the model, users can determine the critical interlevee areas in which to monitor the water levels so that the irrigation well can be turned on at the critical low water level, and turned off at the critical high water level, in order to maximize water application efficiency. Sensitivity analysis performed with the model showed that it will be necessary to calibrate the model for each specific field. A calibration procedure has been developed.

Carl L. Griffis

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KEYWORDS: Mathematical Modelling / Irrigation / Rice / Microcomputer

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

One of the principal limiting factors in the production of rice is the need for irrigation. The area of land used for rice production is frequently limited by the amount of water available (Ferguson, 1979). In addition, in many agricultural areas of the United States, the amount of water available for irrigation is steadily decreasing. Thus, the careful use of the water available is of vital importance to the producer and to the rest of society.

The production of rice requires large quantities of water. In Arkansas, on the silt-loam soils of the Grand Prairie, a producer may have to add an average of 24 inches of water through irrigation in the average year (Engler, 1945). Many producers attempt to maximize the acreage supported by each well by irrigating at the practical limit, 10 gallons per minute per acre (Ferguson, 1979). One consequence of this effort to maximize production is the fact that long time intervals exist between the moment when a well is started, and the moment at which water has been applied successfully to the entire field. For example, if one wished to apply a flood of 4 inches of water to a 40-acre field, with a well producing 400 gallons per minute, a period of more than 7.5 days would be required. The consequences of such long time periods include major difficulties in controlling the application of water in order to minimize losses.

Rates of loss through infiltration are related to the depth of the flood. Thus, the producer has an incentive to maintain only as much water on his field as is required to insure that there are no dry spots in any of the interlevee areas. In addition, it will be to his advantage to wait as long as possible before adding additional water. There is a risk, however, in waiting too long. If any part of the field becomes dry, there can be substantial losses in production of rice (Ferguson, 1979, Bhuiyan, 1978). Thus, the producer needs a method of determining the critical moment at which to start his well so that water will reach every part of his field just before any part is dry.

Another problem of timing exists when the well is in operation. Water which is pumped into the uppermost area of the field fills the volume enclosed by the first levee until it rises above the <u>gate</u> installed in the levee. Then it flows into the next lower area. The water in the upper area must rise well above the gate in order to flow into the next. Thus, if the well were suddenly cut off, there would be some <u>in-transit</u> water that would continue to flow. Each interlevee area overflows in the same way into the next lower area. Thus, in a large field there can be sizeable quantities of in-transit water. For example, if the flow rate produced by the well is 1000 gallons per minute, and the gate is four feet wide, then according to the <u>rectangular weir equation</u>, (Roth, et al, 1975), the water would have to rise to a level of almost 4 inches above the gate. In a 40-acre field, the in-transit water would amount to almost 4 million gallons.

One of the simplest methods of determining the time at which to turn off the pump is to simply wait until water is flowing over the last of the gates at the lowest elevation in the field. This technique, while simple, is extremely wasteful, since much of the in-transit water is lost. Careful producers have already learned to allow for the in-transit water, and turn off the pump well before water begins to flow over the last gate. The determination of the critical water level in the field at which the pump should be stopped, however, is not a simple problem, and has frequently been based upon trial and error.

A. Purpose and Objectives

The objectives of this study were:

1. To develop a new mathematical model of the transient flow of flood water in a rice field. The model must satisfy the following requirements:
    a) The computer program must be executable on the IBM personal computer and IBM-compatible computers. In addition, the program must be executable on as many other microcomputers as possible.
    b) The computer program must be written in a language which is common to as many microcomputers as possible.

2. To apply the model to discover a general method for determining the following.
   a) The critical high water level at which to turn off the pump.
   b) The critical interlevee area in which to measure the high water level.
3. To apply the model to discover a general method for determining the following.
   a) The critical low water level at which to turn on the pump.
   b) The critical interlevee area in which to measure the low water level.
4. To test the assumptions in the model by gathering field data from a production rice field and comparing the data to a simulation of the field.

B. Related Research or Activities

The techniques of mathematical modeling have been applied to various aspects of rice production. McMennamy (1980) developed a simple plant population model which responds to daily weather parameters. Hagan and Wang (1977) developed improved formulas for calculating canal and pump capacities for rice irrigation. Their methods result in improved system efficiencies. Wu (1980) also developed improved methods of designing water conveyance systems, leading to higher utilization efficiency. Clark and Bramley

(1982) studied water requirements during the presaturation phase of flood irrigation. None of these investigators, however, modelled mathematically the hydrology of flooded rice fields.

Ferguson and Gilmour (1981) developed a computer simulation of the hydrology of flooded rice fields. Their purpose was to combine this model with a solute mass-balance so that they could study the long-term effects of the solutes in the irrigation water. Their model included a dynamic simulation of transient hydrology similar to the one developed in this study. Their model, however, was written in PL/I, a language which is not commonly used on microcomputers. In addition, the model used an empirical equation to solve for the depth of water in an interlevee area when flow was occurring over the gate into the next area. Finally, their model was based upon a time increment of 2 hours which appears too long for precise water management.

Ferguson (1979) developed a technique for quantifying the moisture stress which may occur in an irrigated rice field in which one or more of the interlevee areas may become dry through imperfect water management. He defined a dryness parameter as shown below.

$$DP = \sum_{i} \sum_{t} (N_{i,t}^{2} * PF_{t}) / 10^{6} \qquad 1$$

Where DP is the dryness parameter
$N_{i,t}$ is the number of continuous 2-hr intervals during which the water level of area i is less than 1 inch.
and PF_t is a factor which adjusts for the severity of the damage done to the crop by dryness. The severity is a function of time, t.

METHODS AND PROCEDURES

The mathematical development of the model will be described first, and then the details of the program written to implement the mathematical principles. The model is a combination of general mathematical principles, specific field geometry, and hydrological principles.

General Mathematical Principles

Transient responses of the volume of water in an interlevee area can be described mathematically by the General Accounting Equation:

$$\text{Rate of Accumulation} = \text{Input Rate} - \text{Output Rate} + \text{Source Rate} - \text{Sink Rate} \qquad (2)$$

Since we will be interested in the height of the water in the interlevee area, it will be desirable to relate the volume of the water to the height. There are three possible situations which occur during the filling and depletion of the water in each area.

1. Since there is a difference in elevation from one levee to another, the bottom of the interlevee area is not level. The

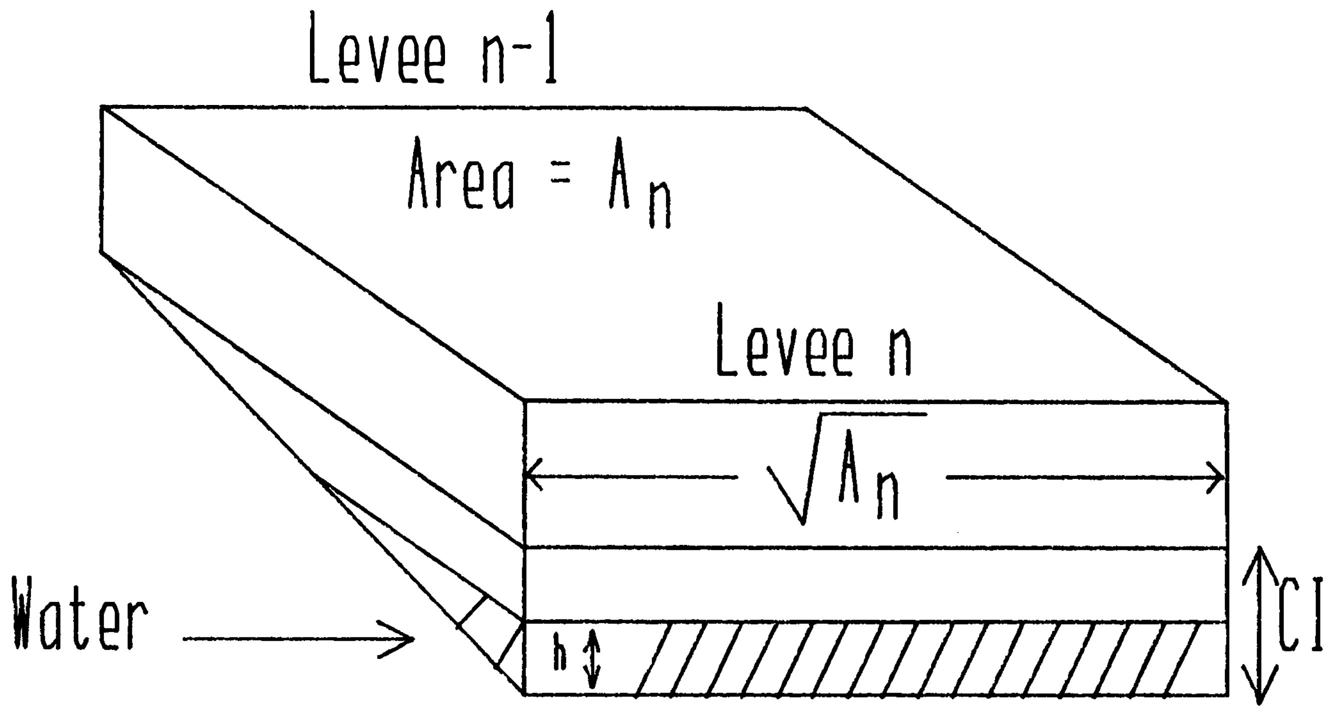

Figure 1. Idealized Interlevee Area

volume occupied by the water will have a shape similar to the one in Figure 1. The area of the surface of the water will be a function of the shape of the interlevee area. The simplest approach is to assume a rectangular area. Another complication arises when the field is being flooded for the first time in a season.

Some of the water is required to wet the soil, and does not contribute to the height of water in the area. This is called the soil water deficit. If the area is assumed square, the relationship between volume and height during the period of initial wetting can be expressed as follows.

$$V = h/2 * h/CI * A_n + h_{def} \qquad 3$$

Where V is the volume of water in an area in cubic feet,
h is the height of the water above the soil measured at the upstream side of the gate, in feet,
h_{def} is the soil water deficit, in feet,
CI is the contour interval in feet,
and A_n is the area contained within interlevee area n in square feet.

For the purpose of a dynamic simulation, one is more interested in the rate at which the level of water changes with changes in volume. Such a relationship can be found by differentiating Equation 3 with respect to time.

$$dV/dt = h * A_n/CI * dh/dt \qquad 4$$

For the first interlevee area, the input rate has only one of two values, zero if the well is off, or the well output rate if the well is on. For interlevee areas after the first, the input rate of an area is the same as the flow rate over the gate of the previous area. The output rate from an area consists of the flow over the gate into the next area, plus the losses from infiltration and evapotranspiration (ET).

For simplicity, losses from infiltration can be set at a constant value per hour, depending upon the soil. Evapotranspiration, however, is a strong function of time-of-day, rising to a peak during daylight hours, and dropping to a minimum at night. Following Ferguson (1979) the rate of loss due to ET and infiltration can be expressed as a fraction of the total daily loss. The first 2-hour period is from midnight until 2 am.

EVAPOTRANSPIRATION FACTORS

2-hr Period	Fraction Of Total
1	0.04
2	0.04
3	0.04
4	0.04
5	0.05
6	0.10
7	0.15
8	0.19
9	0.15
10	0.09
11	0.07
12	0.04

Equation 2 can be rewritten as follows:

$$h * A_n/CI * dh/dt = Q_{n-1} - Q_n - WL \qquad 5$$

Where Q_n is the flow rate of water out of an area n into area n+1
and WL is the water loss rate from infiltration and evapotranspiration.

Equation 5 can be solved (approximately) for the rate of change of the height of water within an area as follows:

$$h_{n2} = h_{n1} + \Delta t * CI * [Q_{n-1} - Q_n - WL]/(A_n * h_{n1}) \qquad 6$$

Where Δt is the time increment over which the changes are to be projected
h_{n1} is the current value of h_n
h_{n2} is the projected value of h_n

The appearance of h_{n1} in the denominator in Equation 6 is the source of another complication. If the area is dry at the start of the simulation, h_{n1} is zero, and Equation 6 cannot be used without modification. Thus, an alternative procedure must be used to determine the relationship between the volume of water added to an area and the corresponding height within the area. No change in height is permitted until sufficient water has been added to satisfy all of the deficit. Then, the initial increase in height from the starting value of zero is calculated as follows:

$$h_n = (2 * Q_{n-1} * \Delta t * CI/A_n)^{0.5} \qquad 7$$

Equation 7 is used only once in each interlevee area, then Equation 6 is used until the water level in the area reaches the contour interval, as described below.

2. The second possibility is that the water may have risen until the entire cross section of the interlevee area has been covered. Thus, the water level in the area will be numerically equal to the contour interval. In this case there is a new relationship between the rate of change of volume and the rate of change of height.

$$dV/dt = A_n * dh/dt \qquad 8$$

Again, this equation can be substituted into Equation 2 with the result shown below.

$$dh/dt = [Q_{n-1} - Q_n - WL_t]/A_n \qquad 9$$

This equation can be solved for the height of water within an area as follows, assuming that Q_n is zero.

$$h_{n2} = h_{n1} + \Delta t * [Q_{n-1} - WL_t]/A_n \qquad 10$$

3. Finally, there is the possibility that the water level may rise to the point at which flow over the gate into the next lower interlevee area begins. Then, the rate of change of volume within the area under consideration is a function not only of the quantity flowing into the area but of the quan-

tity flowing out. The quantity flowing out is related to the height of the water within the interlevee area by the rectangular weir equation.

$$Q_n = 3.33 * [L - 0.2 * h_n] \, h_n^{1.5} \qquad 11$$

Where Q_n is the flow rate of water across the nth weir, in CFS
L is the width of the gate in feet,
and h_n is the height of the water surface above the soil at the base of the nth gate on the upstream side in feet.

It is, thus, possible to solve for the height of water in an area from which there is an overflow by substituting Equation 11 into Equation 9.

$$h_{n2} = h_{n1} + \Delta t * [Q_{n-1} - WL_t - 3.33 * (L - 0.2 * h_{n2}) * h_{n2}^{1.5} \qquad 12$$

Equation 12 must, of necessity, be solved by an iterative process, since, h_{n2} appears on both sides of the equation.

Application of the Principles

The following procedure was used to simulate the changes which occur in the water levels h in each area of the field.

1. The projected value of h in each area was calculated from the previous value, the mathematical principles described above, and the assumed time increment.

2. If the previous value of h in an area was less than the contour interval, CI, then Equation 4 was used to project into the future.
3. If the previous value of h in an area was greater than or equal to CI, but less than the gate height, then Equation 8 was used to project into the future.
4. If the previous value of h in an area was greater than the gate height, Z, then Equation 12 was used to project into the future. An iterative procedure must be used, since h appears on both sides.
5. The time increment to be used for the simulation was chosen by sensitivity testing. The equations used in the simulation are approximations to the differential equations derived above. The approximations are more reliable when very short time intervals are used for Δt. Short time intervals, however, result in long calculation times, leading one to attempt to use time increments which are as long as possible. Since the simulation method is a projection into the future, it is important to minimize the cumulative errors which might result from such long increments. The strategy was to simulate particular field conditions with successively shorter time increments until no further changes resulted from reducing the increment. An increment of 2 hours was tested first. Then increments of 1 hour, 0.1 hours, and 0.01 hours.

The model was used to predict the time at which water would flow over the last gate in a 50-acre field with 10 levees enclosing 5 acres each. The assumed well capacity was 600 gallons per minute.

Calculated Time to Flow Over Last Gate

Time Increment (hours)	Elapsed Time (hr)
2	476
1	479
0.1	480
0.01	480

6. The effects of assumptions about water deficits and loss rates were investigated through sensitivity testing, also. These two assumptions have a great impact on the calculation of the time which passes between the moment at which the well is turned on and the moment at which water begins to flow over each gate. Thus, a series of runs were made with the mathematical model to predict the time at which water began to flow over the last gate in a simulated field with different values for initial water deficits and infiltration rates. The results are shown below for a 50 acre field with 10 levees and a pump which produces 600 gallons per minute.

Sensitivity Testing of Soil Water Deficit

Assumed Deficit Feet	Calculated Time at which Water Tops The Last Gate (Hours)
0.045	477
0.050	480
0.055	482

Sensitivity Testing of Water Loss Rate

Overall Water Loss Inches per Day	Calculated Time until Water Tops The Last Gate (Hours)
0.324	457
0.360	480
0.396	507

7. It has, thus, been shown that it will not be possible to use the model to simulate a general rice field, unless one has very precise information about certain soil physical properties. If the estimate of the soil water deficit is in error by as little as 10%, the estimated time at which flow would begin across the last gate can be in error by as much as three hours. If the estimated daily loss rate is in error by as little as 10%, the estimated time at which flow over the last gate would begin can be in error by as much as 27 hours. It is unlikely that a producer will have information about his soil that is accurate enough to use in the model with any degree of confidence. It will, thus, be necessary to calibrate the model to each field.

A calibration procedure which can be used is as follows:

1. First, make a record of the exact time at which the well is started.
2. Next, make sure that the flow rate produced by the well is known, measuring it if necessary.
3. Make sure that the area of the field above the first gate is known to a high degree of accuracy.
4. Determine the exact time at which flow begins over the first gate.
5. At this point, there are three parameters to be adjusted, the moisture deficit, the infiltration rate, and the evapotranspiration rate.
6. After the field has been flooded for the first time, and the well has been stopped, the combined infiltration rate and evapotranspiration rate can be estimated by monitoring the declining water level in one of the areas.
7. When it is time to start the well again, the starting water deficit can be estimated by a comparison of the time required to fill the first area with the initial filling time.

PRINCIPAL FINDINGS AND SIGNIFICANCE

A computer model has been developed to simulate the hydrology of flood water in an irrigated rice field. The model has been written in M-BASIC, the version of BASIC developed by Microsoft.

This version of BASIC has become the defacto standard for micro-computers. The program has been executed on three types of computers to test its machine independence. It has been successfully executed on an Osborne 1, on an IBM PC, and on a Columbia VP. Results have been equivalent on all three machines.

The maximum time increment that can be used for Δt in the simulation was found to be 0.1 hours, or 0.004167 days. Assuming the model can be properly calibrated for a particular field, its advice to the user about the appropriate time for taking action with respect to the well should be within an hour of the optimum time.

In the development of the model, two assumptions were made which necessitate calibration of the model for each field where it is to be used. The first assumption is the rate at which infiltration and evapotranspiration will take place in the field. The second assumption is the volume of water required to saturate the soil when water is first added to the field. Each of these parameters has a significant effect upon the timing required in controlling the well, as shown by sensitivity testing.

The model calculates and displays some parameters which help the user to optimize water management in the field simulated. The first of these, of course, are the calculated water levels in each interlevee area, at the end of each hour. Another parameter is the amount of water which the model estimates would be lost by following the management strategy simulated. Typically, the model can be used to simulate the entire growing season, indicating the appropriate times for starting and stopping the well, based upon the criteria supplied by the user.

CONCLUSIONS

Most of the objectives outlined at the beginning of this study have been achieved.

1. The computer program developed predicts water levels which change in a way that is consistent with reality.
2. Sensitivity analysis has demonstrated that the time increments used in some previous models may have been too long for precise water management.
3. Further sensitivity analyses have shown that certain soil physical property data must be known with an error of less than 10% before the model can be used to aid the user in achieving optimum water management. These properties are:
   a) The initial water deficit.
   b) The rate of infiltration.
4. Further work must be done with the model to test the calibration procedure described. Work will continue during the next year, including the development of a sensing device which will signal to the operator when the critical high and low water levels have been reached.

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APPENDIX A

COMPUTER PROGRAM

```
10 DEFDBL A-Z
20 DIM A(30), H(30), XDEF(30), Q(31), WL(12)
30 REM ZN IS THE GATE HEIGHT
40 REM XDEF(I) IS THE MOISTURE DEFICIT REMAINING IN AREA I
50 REM ZWETN IS THE VARIABLE USED FOR DEFICITS IN THE ITERATIONS
60 HOUR = 0
70 DAY% = 0
80 CI=.2
90 ZN = .6
100 PRINT "HOW MANY DAYS TO SIMULATE ";
110 INPUT NDAYS
120 WLOSS=0
130 REM WL IS THE WATER LOSS RATE DUE TO INFILTRATION AND
      EVAPOTRANSPIRATION
140 WL(1)=.0144: WL(2)=.0144: WL(3)=.0144: WL(4)=.0144: WL(5)=.018
150 WL(6)=.036: WL(7)=.054: WL(8)=.0684: WL(9)=.054
160 WL(10)=.0324: WL(11)=.0252: WL(12)=.0144
170 INPUT "HOW MANY LEVEES?";N%
180 LPRINT "THERE ARE",N%;" LEVEES"
190 REM DELT ESTABLISHED BY SENSITIVITY
200 DELT = .004167
210 TENTH=0
220 DELT = .004167
230 ZWETN=.05
240 FOR I% = 1 TO N%
250 XDEF(I%) = ZWETN
260 PRINT "Area of levee";I%;"in acres?";
270 INPUT A(I%)
280 LPRINT "LEVEE ";I%;" ENCLOSES ";A(I%);" ACRES
290 A(I%)=A(I%)*43560!
300 NEXT I%
310 INPUT "Well discharge in gpm?";Q(1)
320 LPRINT "THE WELL DISCHARGES ";Q(1);" GPM"
330 LPRINT "THE GATE HEIGHT IS ",ZN;" FEET"
340 Q(1) = Q(1)*192.51
350 WELL = Q(1)
360 INPUT "CRITICAL TURN OFF LEVEE ";L%
370 INPUT "CRITICAL HEIGHT ";HT
380 LPRINT "TURN-OFF LEVEE IS ";L%;" AT HEIGHT OF ";HT
390 INPUT "CRITICAL TURN ON LEVEE ";L2%
400 INPUT "CRITICAL HEIGHT ";HT2
```

```
410 LPRINT "TURN-ON LEVEE IS ";L2%;" AT HEIGHT OF ";HT2
420 LPRINT
430 LPRINT "HR   H1    H2     H3     H4     H5     H6
      H7    H8     H9     H10"
440 FOR I% = 1 TO N%
450 QN = Q(I%)
460 AN = A(I%)
470 HN = H(I%)
480 ZWETN=XDEF(I%)
490 GOSUB 920
500 IF HOUR<2 THEN J%=1: GOTO 620
510 IF HOUR<4 THEN J%=2: GOTO 620
520 IF HOUR<6 THEN J%=3: GOTO 620
530 IF HOUR<8 THEN J%=4: GOTO 620
540 IF HOUR<10 THEN J%=5: GOTO 620
550 IF HOUR<12 THEN J%=6: GOTO 620
560 IF HOUR<14 THEN J%=7: GOTO 620
570 IF HOUR<16 THEN J%=8: GOTO 620
580 IF HOUR<18 THEN J%=9: GOTO 620
590 IF HOUR<20 THEN J%=10: GOTO 620
600 IF HOUR<22 THEN J%=11: GOTO 620
610 J%=12
620 H(I%) = HN - DELT*WL(J%)
630 IF H(I%)<0 THEN H(I%)=0
640 Q(I%+1)=QNEXT
650 XDEF(I%)=ZWETN
660 NEXT I%
670 WLOSS = WLOSS + QNEXT*DELT
680 IF H(L%) > HT THEN Q(1) = 0
690 IF H(L2%) < HT2 THEN Q(1) = WELL
700 TENTH=TENTH+1
710 IF TENTH < 10 THEN GOTO 440
720 TENTH=0
730 HOUR=HOUR+1
740 LPRINT HOUR;
750 FOR I%=1 TO N%
760 LPRINT USING "#.###  ";H(I%);
770 NEXT I%
780 LPRINT
790 IF HOUR < 24 THEN GOTO 440
800 HOUR = 0
810 DAY% = DAY% + 1
820 LPRINT "DAY";DAY%;
830 PRINT "DAY";DAY%;
840 FOR I% = 1 TO N%
850 LPRINT USING "#.###  ";H(I%);
860 PRINT H(I%);
```

```
870 NEXT I%
880 LPRINT
890 IF DAY%=NDAYS THEN LPRINT "LOSS IS ";WLOSS;: END
900 PRINT
910 GOTO 440
920 REM subroutine to determine height in interlevee area
930 QNEXT=0
940 IF HN>0 THEN GOTO 1020
950 IF ZWETN <= 0 THEN GOTO 980
960 ZWETN = ZWETN - QN*DELT/AN
970 IF ZWETN>0 THEN RETURN
980 ZZN# = 2*QN*DELT*CI/AN
990 REM LPRINT TIME
1000 HN = SQR(ZZN#)
1010 RETURN
1020 IF HN>CI THEN GOTO 1080
1030 H3=HN:H2=HN
1040 H2 = HN + DELT*CI*QN/((HN+H2)/2*AN)
1050 IF ABS(H3-H2)>.001*H2 THEN H3=H2: GOTO 1040
1060 HN=H2
1070 RETURN
1080 IF HN > ZN THEN GOTO 1110
1090 HN=HN +DELT*QN/AN
1100 RETURN
1110 H3=HN:H2=HN
1120 H2=HN + DELT*(QN-QNEXT)/AN
1130 QNEXT = 86400!*13.33*((HN+H2)/2-ZN)^1.5
1140 IF ABS(H3-H2)>.0001*H2 THEN H3=H2:GOTO 1120
1150 HN=H2
1160 RETURN
1170 END
```