Narrative for Module RCH1BD

This module calculates rates and volumes added to the aquifer by areally distributed recharge.

1. Clear the rate accumulators RATIN and RATOUT.

2. If cell-by-cell flow terms will be saved, clear the buffer (BUFF) in which they will be accumulated.

3. If the recharge option is one, the recharge goes into the top layer. Process the horizontal locations one at a time.

   (a) If the cell is external, do not calculate budget.

   (b) If cell-by-cell flow terms will be saved, add recharge to the buffer.

   (c) If the recharge is positive, add it to RATIN; otherwise, add it to RATOUT.

4. If the recharge option is two, recharge goes into the layer specified in indicator array (IRCH). Process the horizontal locations one at a time.

   (a) Get the cell layer from indicator array (IRCH).

   (b) If the cell is external, do not calculate budget.

   (c) If cell-by-cell flow terms will be saved, add the recharge to the buffer.

   (d) If the recharge is positive, add it to RATIN; otherwise, add it to RATOUT.

5. If the recharge option is three, the recharge goes into the top variable-head cell provided there is not a constant-head cell above it. Process the horizontal locations one at a time. Start with the top cell and work down.

(a) If the cell is inactive, there is no recharge into that cell; move down to the next one.

(b) If the cell is constant, there is no recharge at this horizontal location; move on to the next horizontal location.

(c) If cell-by-cell flow terms are to be saved, add the recharge to the buffer.

(d) If the recharge is positive, add it to RATIN; otherwise, add it to RATOUT.

6. If cell-by-cell flow terms will be saved, call module UBUDSV to write the buffer (BUFF) onto disk.

7. Move RATIN and RATOUT into the VBVL array for printing by BAS1OT.

8. Add RATOUT multiplied by the time-step length to the volume accumulators in VBVL for printing by BAS1OT.

9. Move the recharge budget-term labels to VBNM for printing by BAS1OT.

10. Increment the budget-term counter (MSUM).

11. RETURN.

Flow Chart for Module RCH1BD

RATIN is an accumulator to which all flows into the aquifer are added.

RATOUT is an accumulator to which all flows out of the aquifer are added.

BUFFER is an array in which values are stored as they are being gathered for printing or recording.

NRCHOP is the recharge option.

1 - Recharge is to the top layer.

2 - Recharge is to the layer specified by the user in the indicator array (IRCH).

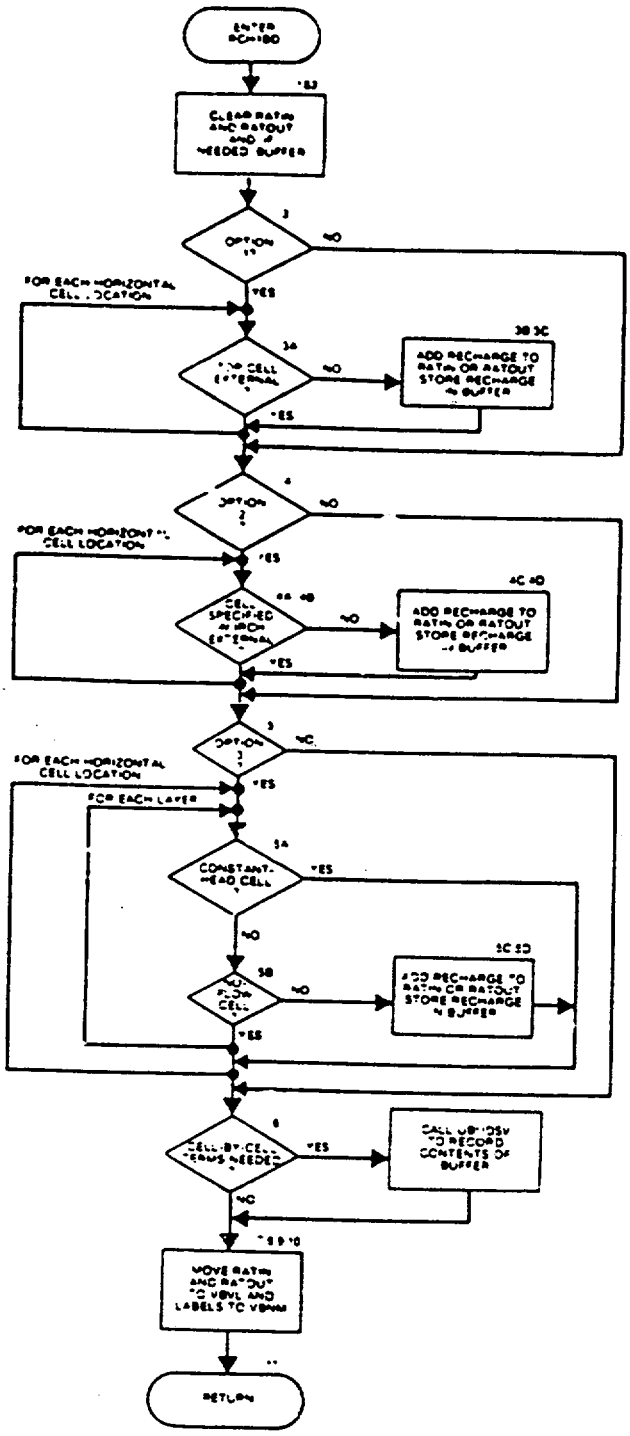
3 - Recharge is to the uppermost active cell.

IRCH is an array containing a recharge indicator for each horizontal cell. It is used only if the recharge option (NRCHOP) is equal to two.

VBVL is a table of budget entries calculated by component-of-flow packages for use in calculating the volumetric budget.

VBNM is a table of labels for budget terms.

EXTERNAL: a cell is external if it is either no flow (inactive) or constant head.



```
      SUBROUTINE RCH1BD(NRCHOP,IRCH,RECH,IBOUND,NROW,NCOL,NLAY,
     1    DELT,VBVL,VBNM,MSUM,KSTP,KPER,IRCHCB,ICBCFL,BUFF,IOUT)
C
C-----VERSION 1533 22DEC1982 RCH1BD
C     ******************************************************************
C     CALCULATE VOLUMETRIC BUDGET FOR RECHARGE
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DIMENSION IRCH(NCOL,NROW),RECH(NCOL,NROW),
     1          IBOUND(NCOL,NROW,NLAY),BUFF(NCOL,NROW,NLAY),
     2          VBVL(4,20),VBNM(4,20)
      DIMENSION TEXT(4)
      DATA TEXT(1),TEXT(2),TEXT(3),TEXT(4) /'    ','    ','RECH','ARGE'/
C     ------------------------------------------------------------------
C
C1------CLEAR THE RATE ACCUMULATORS.
      RATIN=0.
      RATOUT=0.
C
C2------IF CELL-BY-CELL FLOW TERMS WILL BE SAVED THEN CLEAR THE BUFFER.
      IBD=0
      IF(ICBCFL.EQ.0 .OR. IRCHCB.LE.0) GO TO 5
      IBD=1
      DO 2 IL=1,NLAY
      DO 2 IR=1,NROW
      DO 2 IC=1,NCOL
      BUFF(IC,IR,IL)=0.
    2 CONTINUE
C
C3------IF NRCHOP=1 RECH GOES INTO LAYER 1. PROCESS EACH HORIZONTAL
C3------CELL LOCATION.
    5 IF(NRCHOP.NE.1) GO TO 15
C
C       ---RECHARGE IS APPLIED TO TOP LAYER
      DO 10 IR=1,NROW
      DO 10 IC=1,NCOL
C
C3A-----IF CELL IS EXTERNAL THEN DO NOT DO BUDGET FOR IT.
      IF(IBOUND(IC,IR,1).LE.0)GO TO 10
      Q=RECH(IC,IR)
C
C3B-----IF CELL-BY-CELL FLOW TERMS WILL BE SAVED THEN ADD RECH TO BUFF
      IF(IBD.EQ.1) BUFF(IC,IR,1)=Q
C
C3C-----IF RECH POSITIVE ADD IT TO RATIN ELSE ADD IT TO RATOUT.
      IF(Q) 8,10,7
    7 RATIN=RATIN+Q
      GO TO 10
    8 RATOUT=RATOUT-Q
   10 CONTINUE
      GO TO 100
C
C4------IF NRCHOP=2 RECH IS IN LAYER SHOWN IN INDICATOR ARRAY(IRCH).
C4------PROCESS HORIZONTAL CELL LOCATIONS ONE AT A TIME.
   15 IF(NRCHOP.NE.2)GO TO 25
      DO 20 IR=1,NROW
      DO 20 IC=1,NCOL
C
C4A-----GET LAYER INDEX FROM INDICATOR ARRAY(IRCH).
      IL=IRCH(IC,IR)
C
C4B-----IF CELL IS EXTERNAL DO NOT CALCULATE BUDGET FOR IT.
      IF(IBOUND(IC,IR,IL).LE.0)GO TO 20
      Q=RECH(IC,IR)
```

```
C
C4C-----IF C-B-C FLOW TERMS WILL BE SAVED THEN ADD RECHARGE TO BUFFER.
      IF(IBD.EQ.1) BUFF(IC,IR,IL)=Q
C
C4D-----IF RECHARGE IS POSITIVE ADD TO RATIN ELSE ADD IT TO RATOUT.
      IF(Q) 18,20,17
   17 RATIN=RATIN+Q
      GO TO 20
   18 RATOUT=RATOUT-Q
   20 CONTINUE
      GO TO 100
C
C5------IF OPTION=3 RECHARGE IS INTO HIGHEST INTERNAL CELL. IT WILL NOT
C5------PASS THROUGH A CONSTANT HEAD CELL. PROCESS HORIZONTAL CELL
C5------LOCATIONS ONE AT A TIME.
   25 IF(NRCHOP.NE.3)GO TO 100
      DO 30 IR=1,NROW
      DO 30 IC=1,NCOL
      DO 28 IL=1,NLAY
C
C5A-----IF CELL IS CONSTANT HEAD MOVE ON TO NEXT HORIZONTAL LOCATION.
      IF(IBOUND(IC,IR,IL).LT.0) GO TO 30
C
C5B-----IF CELL IS INACTIVE MOVE DOWN TO NEXT CELL.
      IF (IBOUND(IC,IR,IL).EQ.0)GO TO 28
      Q=RECH(IC,IR)
C
C5C-----IF C-B-C FLOW TERMS TO BE SAVED THEN ADD RECHARGE TO BUFFER.
      IF(IBD.EQ.1) BUFF(IC,IR,IL)=Q
C
C5D-----IF RECH IS POSITIVE ADD IT TO RATIN ELSE ADD IT TO RATOUT.
      IF(Q) 27,30,26
   26 RATIN=RATIN+Q
      GO TO 30
   27 RATOUT=RATOUT-Q
      GO TO 30
   28 CONTINUE
   30 CONTINUE
C
  100 CONTINUE
C
C6------IF C-B-C FLOW TERMS TO BE SAVED CALL UBUDSV TO WRITE THEM.
      IF(IBD.EQ.1) CALL UBUDSV(KSTP,KPER,TEXT,IRCHCB,BUFF,NCOL,NROW,
     1                         NLAY,IOUT)
C
C7------MOVE TOTAL RECHARGE RATE INTO VBVL FOR PRINTING BY BAS1OT.
      VBVL(4,MSUM)=RATOUT
      VBVL(3,MSUM)=RATIN
C
C8------ADD RECHARGE FOR TIME STEP TO RECHARGE ACCUMULATOR IN VBVL.
      VBVL(2,MSUM)=VBVL(2,MSUM)+RATOUT*DELT
      VBVL(1,MSUM)=VBVL(1,MSUM)+RATIN*DELT
C
C9------MOVE BUDGET TERM LABELS TO VBNM FOR PRINT BY MODULE BAS_OT.
      VBNM(1,MSUM)=TEXT(1)
      VBNM(2,MSUM)=TEXT(2)
      VBNM(3,MSUM)=TEXT(3)
      VBNM(4,MSUM)=TEXT(4)
C
C10-----INCREMENT BUDGET TERM COUNTER.
      MSUM=MSUM+1
C
C11-----RETURN
      RETURN
      END
```

List of Variables for Module RCH1BD

Variable	Range	Definition
BUFF	Global	DIMENSION (NCOL,NROW,NLAY), Buffer used to accumulate information before printing or recording it.
DELT	Global	Length of the current time step.
IBD	Module	Flag. = 0, cell-by-cell flow terms for this package will not be recorded. ≠ 0, cell-by-cell flow terms for this package will be recorded.
IBOUND	Global	DIMENSION (NCOL,NROW,NLAY), Status of each cell. < 0, constant-head cell = 0, inactive cell > 0, variable-head cell
IC	Module	Index for columns.
ICBCFL	Global	Flag. = 0, cell-by-cell flow terms will not be recorded or printed for the current time step. ≠ 0, cell-by-cell flow terms will be recorded for the current time step.
IL	Module	Index for layers.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
IR	Module	Index for rows.
IRCH	Package	DIMENSION (NCOL,NROW), Layer number for each horizontal cell location to which recharge will be applied if the recharge option (NRCHOP) is equal to 2.
IRCHCB	Package	Flag. IRCHCB ≤ 0, cell-by-cell flow terms will not be recorded or printed. IRCHCB > 0 and ICBCFL ≠ 0, cell-by-cell flow terms for the RCH1 Package will be recorded on UNIT = IRCHCB.
KPER	Global	Stress period counter.
KSTP	Global	Time step counter. Reset at the start of each stress period.
MSUM	Global	Counter for budget entries and labels in VBVL and VBNM.
NCOL	Global	Number of columns in the grid.

List of Variables for Module RCH1BD (Continued)

Variable	Range	Definition
NLAY	Global	Number of layers in the grid.
NRCHOP	Package	Recharge option: = 1, recharge is to the top grid layer. = 2, recharge is to the grid layer specified in array IRCH. = 3, recharge is to the highest variable-head cell which is not below a constant-head cell.
NROW	Global	Number of rows in the grid.
Q	Module	Flow from recharge into a cell. (Reverse the sign to get flow out of the cell.)
RATIN	Module	Accumulator for the total flow into the flow field from recharge.
RATOUT	Module	Accumulator for the total flow out of the flow field to recharge.
RECH	Package	DIMENSION (NCOL,NROW), Recharge rate.
TEXT	Module	Label to be printed or recorded with the array data.
VBNM	Global	DIMENSION (4,20), Labels for entries in the volumetric budget.
VBVL	Global	DIMENSION (4,20), Entries for the volumetric budget. For flow component N, the values in VBVL are: (1,N), Rate for the current time step into the flow field. (2,N), Rate for the current time step out of the flow field. (3,N), Volume into the flow field during simulation. (4,N), Volume out of the flow field during simulation.

CHAPTER 8

WELL PACKAGE

Conceptualization and Implementation

A recharging well can be viewed as a source of water which is not affected by the head in the aquifer. A discharging well is a recharging well with a negative recharge rate. For the sake of this discussion, the well will be assumed to be screened in only a single cell. Thus for each cell containing a well, the recharge rate must be added to the right side of the finite-difference equation.

A list containing the location and rate for each well is maintained. The list contains four values for each entry: row, column, and layer of the cell, and the rate at which the well recharges the aquifer. At each iteration, for each variable-head cell i,j,k containing a pumping well, the well rate is added to the accumulator in which $RHS_{i,j,k}$ is formulated.

Well Package Input

Input for the Well (WEL) Package is read from the unit specified in IUNIT(2).

FOR EACH SIMULATION

WEL1AL

1. Data: MXWELL IWELCB
   Format: I10 I10

FOR EACH STRESS PERIOD

WEL1RP

2. Data: ITMP
   Format: I10

3. Data: Layer Row Column Q
   Format: I10 I10 I10 F10.0

   (Input item 3 normally consists of one record for each well. If ITMP is negative or zero, item 3 is not read.)

Explanation of Fields Used in Input Instructions

MXWELL--is the maximum number of wells used at any time.

IWELCB--is a flag and a unit number.

If IWELCB > 0, it is the unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL (see Output Control) is set.

If IWELCB = 0, cell-by-cell flow terms will not be printed or recorded.

If IWELCB < 0, well recharge will be printed whenever ICBCFL is set.

ITMP--is a flag and a counter.

If ITMP < 0, well data from the last stress period will be reused.

If ITMP $\geq$ 0, ITMP will be the number of wells active during the current stress period.

Layer--is the layer number of the model cell that contains the well.

Row--is the row number of the model cell that contains the well.

Column--is the column number of the model cell that contains the well.

Q--is the volumetric recharge rate. A positive value indicates recharge and a negative value indicates discharge.

SAMPLE INPUT TO THE WELL PACKAGE

DATA ITEM	EXPLANATION	INPUT RECORDS			
1	(MXWELL, IWELCB)	6	24		
2	STRESS PERIOD 1 (ITMP)	4			
3	FIRST WELL (Layer, Row, Column, Q	2	5	6	-.17
3	SECOND WELL (Layer, Row, Column, Q)	2	6	3	-.23
3	THIRD WELL (Layer, Row, Column, Q)	2	7	7	-.77
3	FOURTH WELL (Layer, Row, Column, Q)	2	9	2	-.32
2	STRESS PERIOD 2 (ITMP)	-1			
2	STRESS PERIOD 3 (ITMP)	-1			
2	STRESS PERIOD 4 (ITMP)	6			
3	FIRST WELL (Layer, Row, Column, Q)	2	6	5	-.73
3	SECOND WELL (Layer, Row, Column, Q)	2	9	4	-.32
3	THIRD WELL (Layer, Row, Column, Q	2	5	6	-.17
3	FOURTH WELL (Layer, Row, Column, Q)	2	6	3	-.43
3	FIFTH WELL (Layer, Row, Column, Q)	2	7	7	-.77
3	SIXTH WELL (Layer, Row, Column, Q)	2	9	2	-.32

Module Documentation for the Well Package

The Well Package (WEL1) consists of four modules, all of which are called by the MAIN program. The modules are:

WEL1AL — Allocates space for the list of wells (WELL).

WEL1RP — Reads location and recharge rate for all wells.
Note: Discharge rate is entered as a negative number.

WEL1FM — Subtracts the recharge rate from the term kHS for each cell containing pumping wells.

WEL1BD — Calculates the rates and accumulated volume of recharge to or discharge from the flow system by pumping wells.

Narrative for Module WELIAL

This module allocates space in the X array to store the list of wells. The X array is a pool of memory space from which space is allocated for tables, lists, and arrays.

1. Print a message identifying the package and initialize NWELLS (a counter containing the number of wells).

2. Read and print MXWELL (the maximum number of wells) and IWELBD (the unit number for cell-by-cell flow terms or a flag indicating that cell-by-cell flow terms should be printed).

3. Set LCWELL, which will point to the first element in the well list (WELL), equal to ISUM, which is currently pointing to the first unallocated element in the X array.

4. Calculate the amount of space needed for the well list (four values for each cell--row, column, layer, and rate) and add it to ISUM.

5. Print the number of elements in the X array used by the Well Package.

6. If the pointer to the lowest unallocated element in the X array (ISUM) is greater than the length of the X array (LENX), print a message warning that the X array will have to be enlarged.

7. RETURN.

Flow Chart for Module WELIAL

MXWELL is the maximum number of wells that will be active at any one time during the simulation.

IWELCB is a flag and a unit number.

If IWELCB > 0, it is the unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL is set.

If IWELCB = 0, cell-by-cell flow terms will not be printed or recorded.

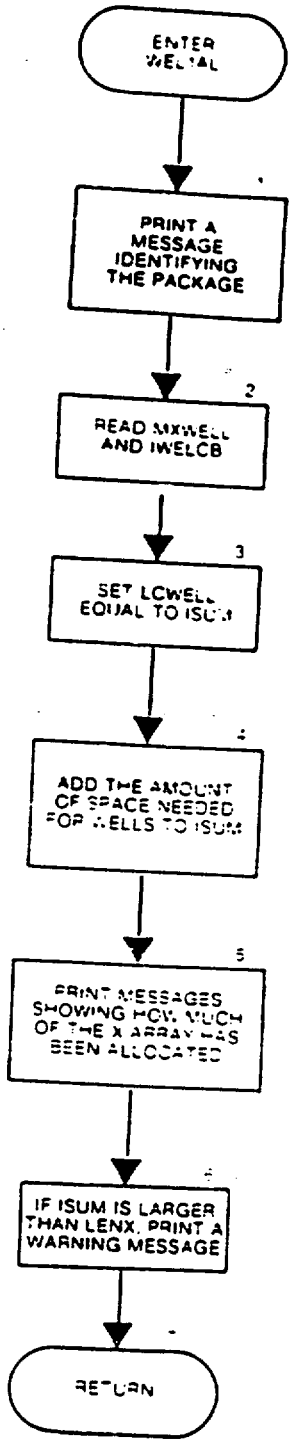
If IWELCB < 0, well recharge will be printed whenever ICBCFL is set.

LCWELL is a location pointer to the first storage location occupied by the well list.

ISUM is the location of the lowest unallocated storage location in the X array.

X array is the pool of memory space allocated for storing specific tables, arrays, and lists.

LENX is the size of the X array.



```
      SUBROUTINE WEL1AL(ISUM,LENX,LCWELL,MXWELL,NWELLS,IN,IOUT,
     1                  IWELCB)
C
C-----VERSION 0933 08DEC1983 WEL1AL
C     ******************************************************************
C     ALLOCATE ARRAY STORAGE FOR WELL PACKAGE
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
C     ------------------------------------------------------------------
C
C1------IDENTIFY PACKAGE AND INITIALIZE NWELLS
      WRITE(IOUT,1)IN
    1 FORMAT(1HO,'WEL1 -- WELL PACKAGE, VERSION 1, 12/08/83',
     2' INPUT READ FROM',I3)
      NWELLS=0
C
C2------READ MAX NUMBER OF WELLS AND
C2------UNIT OR FLAG FOR CELL-BY-CELL FLOW TERMS.
      READ(IN,2) MXWELL,IWELCB
    2 FORMAT(2I10)
      WRITE(IOUT,3) MXWELL
    3 FORMAT(1H ,'MAXIMUM OF',I5,' WELLS')
      IF(IWELCB.GT.0) WRITE(IOUT,9) IWELCB
    9 FORMAT(1X,'CELL-BY-CELL FLOWS WILL BE RECORDED ON UNIT',I3)
      IF(IWELCB.LT.0) WRITE(IOUT,8)
    8 FORMAT(1X,'CELL-BY-CELL FLOWS WILL BE PRINTED WHEN ICBCFL NOT 0')
C
C3------SET LCWELL EQUAL TO LOCATION OF WELL LIST IN X ARRAY.
      LCWELL=ISUM
C
C4------ADD AMOUNT OF SPACE USED BY WELL LIST TO ISUM.
      ISP=4*MXWELL
      ISUM=ISUM+ISP
C
C5------PRINT NUMBER OF SPACES IN X ARRAY USED BY WELL PACKAGE.
      WRITE(IOUT,4) ISP
    4 FORMAT(1X,I6,' ELEMENTS IN X ARRAY ARE USED FOR WELLS')
      ISUM1=ISUM-1
      WRITE(IOUT,5) ISUM1,LENX
    5 FORMAT(1X,I6,' ELEMENTS OF X ARRAY USED OUT OF',I7)
C
C6------IF THERE ISN'T ENOUGH SPACE IN THE X ARRAY THEN PRINT
C6------A WARNING MESSAGE.
      IF(ISUM1.GT.LENX) WRITE(IOUT,6)
    6 FORMAT(1X,'   ***X ARRAY MUST BE DIMENSIONED LARGER***')
C7------RETURN
      RETURN
      END
```

List of Variables for Module WEL1AL

Variable	Range	Definition
IN	Package	Primary unit number from which input for this package will be read.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
ISP	Module	Number of words in the X array allocated by this module.
ISUM	Global	Index number of the lowest element in the X array which has not yet been allocated. When space is allocated for an array, the size of the array is added to ISUM.
ISUM1	Module	ISUM-1.
IWELCB	Package	Flag and a unit number. > 0, unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL is set. = 0, cell-by-cell flow terms will not be printed or recorded. < 0, well recharge will be printed whenever ICBCFL is set.
LCWELL	Package	Location in the X array of the first element of array WELL.
LENX	Global	Length of the X array in words. This should always be equal to the dimension of X specified in the MAIN program.
MXWELL	Package	Maximum number of wells active at any one time.
NWELLS	Package	Number of wells active during the current stress period.

Narrative for Module WEL1RP

This module reads data to build the WELL list.

1. Read ITMP.

(a) If ITMP is less than zero, the well data read for the last stress period will be reused. Print a message to that effect and RETURN.

(b) If ITMP is greater than or equal to zero, it is equal to the number of wells (NWELLS) in the current stress period.

2. If the number of wells (NWELLS) in the current stress period is greater than the number specified as the maximum for the simulation (MXWELL), STOP.

3. Print the number of wells in the current stress period (NWELLS).

4. If there are no wells in the current stress period (NWELLS), bypass further well processing.

5. For each well, read and print the layer, row, column, and well recharge rate.

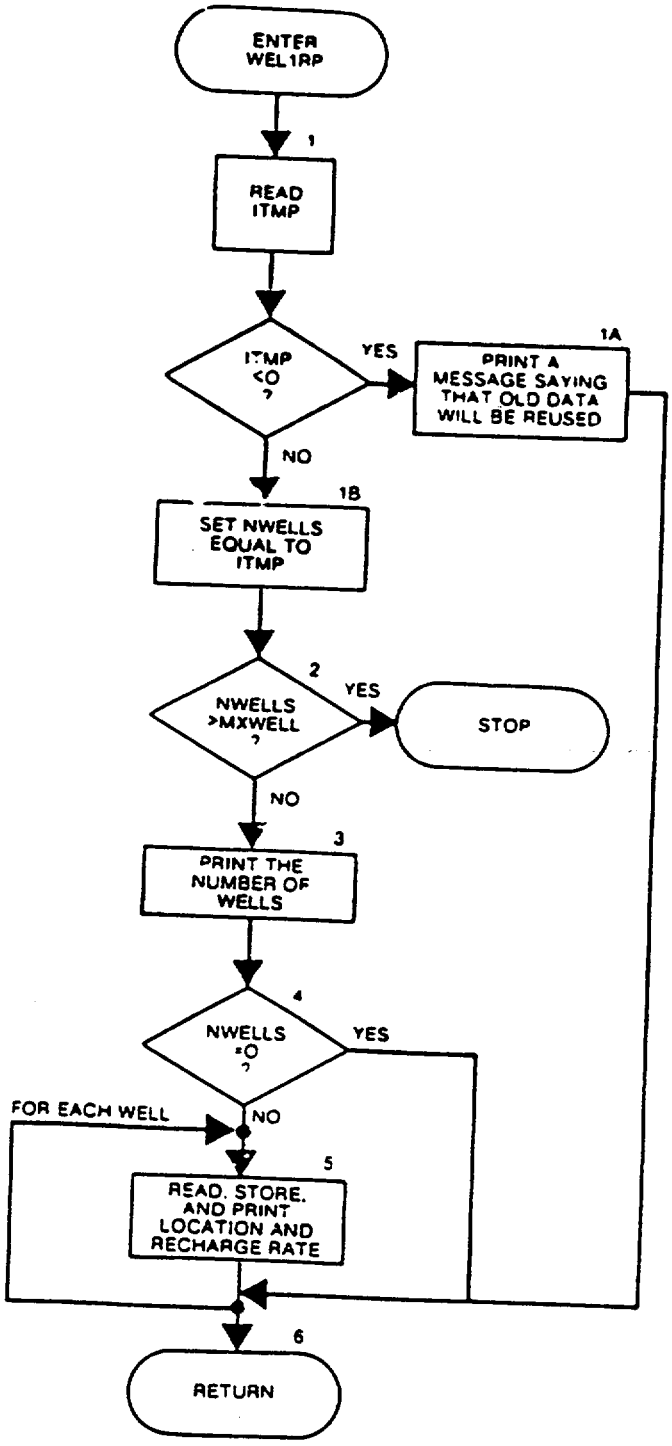
6. RETURN.

Flow Chart for Module WEL1RP

ITMP is a flag and/or the number of wells. If it is less than zero, it is a flag which indicates that the well data from the last stress period will be reused. If it is greater than or equal to zero, it is the number of wells active during the current stress period.

NWELLS is the number of wells active during the current stress period.

MXWELL is the maximum number of wells which will be active at any one time during the simulation.



```
      SUBROUTINE WELIRP(WELL,MWELLS,MXWELL,IN,IOUT)
C
C
C-----VERSION 1544 22DEC1982 WELIRP
C     ******************************************************************
C     READ NEW WELL LOCATIONS AND STRESS RATES
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DIMENSION WELL(4,MXWELL)
C     ------------------------------------------------------------------
C
C1------READ ITMP(NUMBER OF WELLS OR FLAG SAYING REUSE WELL DATA)
      READ (IN,1) ITMP
    1 FORMAT(I10)
      IF(ITMP.GE.0) GO TO 50
C
C1A-----IF ITMP LESS THAN ZERO REUSE DATA. PRINT MESSAGE AND RETURN.
      WRITE(IOUT,6)
    6 FORMAT(1HO,'REUSING WELLS FROM LAST STRESS PERIOD')
      RETURN
C
C1B-----ITMP=>0.  SET NWELLS EQUAL TO ITMP.
   50 NWELLS=ITMP
      IF(NWELLS.LE.MXWELL) GO TO 100
C
C2------NWELLS>MXWELL.  PRINT MESSAGE. STOP.
      WRITE(IOUT,99) NWELLS,MXWELL
   99 FORMAT(1HO,'NWELLS(',I4,') IS GREATER THAN MXWELL(',I4,')')
      STOP
C
C3------PRINT NUMBER OF WELLS IN CURRENT STRESS PERIOD.
  100 WRITE (IOUT,2) NWELLS
    2 FORMAT(1HO,I0X,I4,' WELLS')
C
C4------IF THERE ARE NO ACTIVE WELLS IN THIS STRESS PERIOD THEN RETURN
      IF(NWELLS.EQ.0) GO TO 260
C
C5------READ AND PRINT LAYER,ROW,COLUMN AND RECHARGE RATE.
      WRITE(IOUT,3)
    3 FORMAT('1H ',47X,'LAYER    ROW    COL    STRESS RATE   WELL NO.'/
     1,48X,45('-'))
      DO 250 II=1,NWELLS
      READ (IN,4) K,I,J,Q
    4 FORMAT(3I10,F10.0)
      WRITE (IOUT,5) K,I,J,Q,II
    5 FORMAT(48X,I3,I8,I7,G16.5,I8)
      WELL(1,II)=K
      WELL(2,II)=I
      WELL(3,II)=J
      WELL(4,II)=Q
  250 CONTINUE
C
C6------RETURN
  260 RETURN
      END
```

List of Variables for Module WELIRP

Variable	Range	Definition
I	Module	Row number of cell containing well.
II	Module	Index for wells.
IN	Package	Primary unit number from which input for this package will be read.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
ITMP	Module	Flag or number of wells. $\geq$ 0, number of wells active during the current stress period. < 0, same wells active during the last stress period will be active during the current stress period.
J	Module	Column number of cell containing well.
K	Module	Layer number of cell containing well.
MXWELL	Package	Maximum number of wells active at any one time.
NWELLS	Package	Number of wells active during the current stress period.
Q	Module	Rate at which the well recharges the aquifer.
WELL	Package	DIMENSION (4,MXWELL), For each well: layer, row, column, and recharge rate of the well.

Narrative for Module WEL1FM

This module adds terms representing well recharge to the accumulator in which the term RHS is formulated.

1. If NWELLS is less than or equal to zero in the current stress period, there are no wells. RETURN.

2. For each well in the WELL list:

   (a) If the cell containing the well is external (IBOUND (IC,IR,IL) $\leq$ 0), bypass processing on this well and go on to the next well.

   (b) If the cell containing the well is active, add the recharge rate to the accumulator RHS for that cell.

3. RETURN.

```
      SUBROUTINE WEL1FM(NWELLS,MXWELL,RHS,WELL,IBOUND,
     1           NCOL,NROW,NLAY,IOUT)
C
C-----VERSION 1001 26AUG1982 WEL1FM
C
C     ******************************************************************
C     ADD WELL FLOW TO SOURCE TERM
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DIMENSION RHS(NCOL,NROW,NLAY),WELL(4,MXWELL),
     1             IBOUND(NCOL,NROW,NLAY)
C     ------------------------------------------------------------------
C1------IF NUMBER OF WELLS <= 0 THEN RETURN.
      IF(NWELLS.LE.0) RETURN
C
C2------PROCESS EACH WELL IN THE WELL LIST.
      DO 100 L=1,NWELLS
      IR=WELL(2,L)
      IC=WELL(3,L)
      IL=WELL(1,L)
      Q=WELL(4,L)
C
C2A-----IF THE CELL IS INACTIVE THEN BYPASS PROCESSING.
      IF(IBOUND(IC,IR,IL).LE.0) GO TO 100
C
C2B-----IF THE CELL IS VARIABLE HEAD THEN ADD RECHARGE RATE
C       TO THE RHS ACCUMULATOR.
      RHS(IC,IR,IL)=RHS(IC,IR,IL)-Q
  100 CONTINUE
C
C3------RETURN
      RETURN
      END
```

List of Variables for Module WEL1FM

Variable	Range	Definition
IBOUND	Global	DIMENSION (NCOL,NROW,NLAY), Status of each cell. < 0, constant-head cell = 0, inactive cell > 0, variable-head cell
IC	Module	Index for columns.
IL	Module	Index for layers.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
IR	Module	Index for rows.
L	Module	Index for wells.
MXWELL	Package	Maximum number of wells active at any one time.
NCOL	Global	Number of columns in the grid.
NLAY	Global	Number of layers in the grid.
NROW	Global	Number of rows in the grid.
NWELLS	Package	Number of wells active during the current stress period.
Q	Module	Rate at which the well recharges the aquifer.
RHS	Global	DIMENSION (NCOL,NROW,NLAY), Right hand side of the finite-difference equation. RHS is an accumulation of terms from several different packages.
WELL	Package	DIMENSION (4,MXWELL), For each well: layer, row, column, and recharge rate of the well.

Narrative for Module WEL1BD

This module calculates rates and volumes transferred between the aquifer and wells.

1. Clear the rate accumulators RATIN and RATOUT and the flag (IBD) which indicates that cell-by-cell flow terms should be recorded on a disk.

2. If there are no wells, skip down to step 7.

3. Determine if the cell-by-cell flow terms for wells will be written on a disk. They will be if (1) this is the proper time step (ICBCFL is not equal to zero), (2) if the channel for well-budget terms (IWELCB) is greater than zero, and (3) if the number of wells (NWELLS) is greater than zero.

4. If budget terms are to be written on a disk, set IBD = 1 and clear the buffer (BUFF) in which they will be accumulated.

5. If the number of wells in the current stress period (NWELLS) is not equal to zero, then for each cell in the well list:

   (a) If the cell containing the well is external (IBOUND(I,J,K) $\leq$ 0), bypass further processing of the cell.

   (b) If the user has requested that cell-by-cell rates be printed (IWELCB < 0 and ICBCFL $\neq$ 0), print the rate (Q).

   (c) If the budget terms are to be saved on a disk, add the recharge rate (Q) to the buffer (BUFF).

   (d) If Q is positive, add it to RATIN.

   (e) If Q is negative, add it to RATOUT.

6. If the cell-by-cell flow terms are to be recorded, call module UBUDSV to write the contents of buffer (BUFF) onto the disk.

7. Move RATIN and RATOUT into the VBVL array for printing by BAS1OT.

8. Add RATIN and RATOUT multiplied by the time-step length to the volume accumulators in the VBVL array for printing by BAS1OT.

9. Move the well budget term labels to VBNM for printing by BAS1OT.

10. Increment the budget-term counter (MSUM).

11. RETURN.

Flow Chart for Module WEL1BD

RATIN is an accumulator to which all flows into the aquifer are added.

RATOUT is an accumulator to which all flows out of the aquifer are added.

IBD is a flag which, if set, causes cell-by-cell flow terms for river well flow to be recorded.

BUFFER is an array in which values are stored as they are being gathered for printing or recording.

EXTERNAL: a cell is said to be external if it is either no flow or constant head (i.e., an equation is not formulated for the cell).

RECHARGE is the rate at which the well recharges the aquifer. A discharging well is represented by a negative rate.

IWELCB is a flag and a unit number.

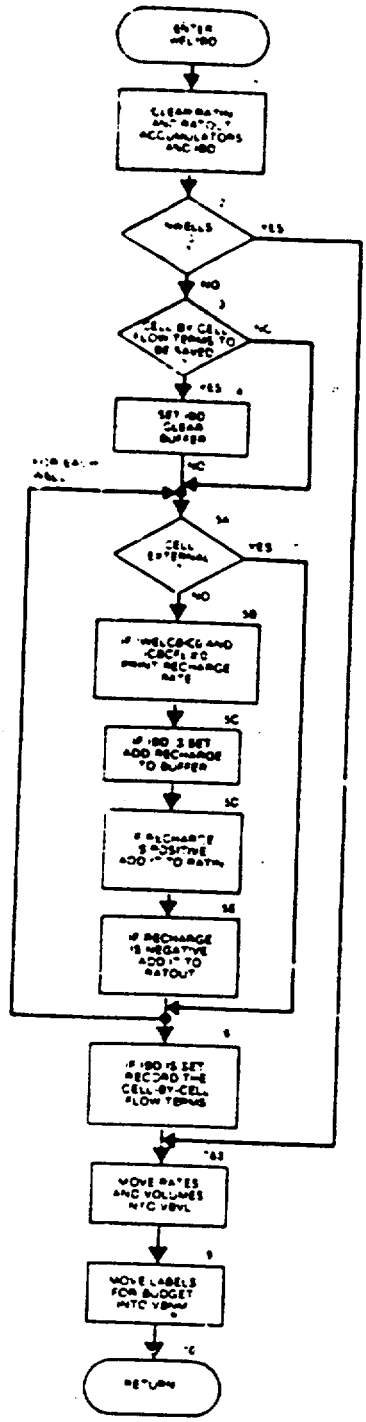
If IWELCB > 0, it is the unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL is set.

If IWELCB = 0, cell-by-cell flow terms will not be printed or recorded.

If IWELCB < 0, well recharge rate will be printed whenever ICBCFL is set.

ICBCFL is a flag.

If ICBCFL ≠ 0, cell-by-cell flow terms will be either printed or recorded (depending on IWELCB) for the current time step.



```
      SUBROUTINE WEL1BD(NWELLS,MXWELL,VBNM,VBVL,MSUM,WELL,IBOUND,DELT,
     1              NCOL,NROW,NLAY,KSTP,KPER,IWELCB,ICBCFL,BUFF,IOUT)
C
C-----VERSION 1449 20MAY1983 WEL1BD
C     ******************************************************************
C     CALCULATE VOLUMETRIC BUDGET FOR WELLS
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DIMENSION VBNM(4,MSUM),VBVL(4,MSUM),WELL(4,MXWELL),
     1          IBOUND(NCOL,NROW,NLAY),BUFF(NCOL,NROW,NLAY)
      DIMENSION TEXT(4)
C
      DATA TEXT(1),TEXT(2),TEXT(3),TEXT(4) /'    ','    ',' W','ELLS'/
C     ------------------------------------------------------------------
C
C1------CLEAR RATIN AND RATOUT ACCUMULATORS.
      RATIN=0.
      RATOUT=0.
      IBD=0
C
C2------IF THERE ARE NO WELLS DO NOT ACCUMULATE FLOW
      IF(NWELLS.EQ.0) GO TO 200
C
C3------TEST TO SEE IF CELL-BY-CELL FLOW TERMS WILL BE RECORDED.
      IF(ICBCFL.EQ.0 .OR. IWELCB.LE.0) GO TO 60
C
C4------IF CELL-BY-CELL FLOWS WILL BE SAVED THEN CLEAR THE BUFFER.
      IBD=1
      DO 50 IL=1,NLAY
      DO 50 IR=1,NROW
      DO 50 IC=1,NCOL
      BUFF(IC,IR,IL)=0.
   50 CONTINUE
C
C5------PROCESS WELLS ONE AT A TIME.
   60 DO 100 L=1,NWELLS
      IR=WELL(2,L)
      IC=WELL(3,L)
      IL=WELL(1,L)
      Q=WELL(4,L)
C
C5A-----IF THE CELL IS EXTERNAL IGNORE IT.
      IF(IBOUND(IC,IR,IL).LE.0)GO TO 100
C
C5B-----PRINT THE INDIVIDUAL RATES IF REQUESTED(IWELCB<0).
      IF(IWELCB.LT.0.AND.ICBCFL.NE.0) WRITE(IOUT,900) (TEXT(N),N=1,4),
     1    KPER,KSTP,L,IL,IR,IC,Q
  900 FORMAT(1HO,4A4,'   PERIOD',I3,'   STEP',I3,'   WELL',I4,
     1     '   LAYER',I3,'   ROW ',I4,'   COL',I4,'   RATE',G15.7)
C
C5C-----IF CELL-BY-CELL FLOWS ARE TO BE SAVED THEN ADD THEM TO BUFFER.
```

```
      IF(IBD.EQ.1) BUFF(IC,IR,IL)=BUFF(IC,IR,IL)+Q
      IF(Q) 90,100,80
C
C5D-----PUMPING RATE IS POSITIVE(RECHARGE). ADD IT TO RATIN.
   80 RATIN=RATIN+Q
      GO TO 100
C
C5E-----PUMPING RATE IS NEGATIVE(DISCHARGE). ADD IT TO RATOUT.
   90 RATOUT=RATOUT-Q
  100 CONTINUE
C
C6------IF CELL-BY-CELL FLOWS WILL BE SAVED CALL UBUDSV TO RECORD THEM
      IF(IBD.EQ.1) CALL UBUDSV(KSTP,KPER,TEXT,IWELCB,BUFF,NCOL,NROW,
     1                         NLAY,IOUT)
C
C7------MOVE RATES INTO VBVL FOR PRINTING BY MODULE BAS1OT.
  200 VBVL(3,MSUM)=RATIN
      VBVL(4,MSUM)=RATOUT
C
C8------MOVE RATES TIMES TIME STEP LENGTH INTO VBVL ACCUMULATORS.
      VBVL(1,MSUM)=VBVL(1,MSUM)+RATIN*DELT
      VBVL(2,MSUM)=VBVL(2,MSUM)+RATOUT*DELT
C
C9------MOVE BUDGET TERM LABELS INTO VBNM FOR PRINTING.
      VBNM(1,MSUM)=TEXT(1)
      VBNM(2,MSUM)=TEXT(2)
      VBNM(3,MSUM)=TEXT(3)
      VBNM(4,MSUM)=TEXT(4)
C
C10-----INCREMENT BUDGET TERM COUNTER(MSUM).
      MSUM=MSUM+1
C
C11-----RETURN
      RETURN
      END
```

List of Variables for Module WEL1BD

Variable	Range	Definition
BUFF	Global	DIMENSION (NCOL,NROW,NLAY), Buffer used to accumulate information before printing or recording it.
DELT	Global	Length of the current time step.
IBD	Module	Flag. = 0, cell-by-cell flow terms for this package will not be recorded. ≠ 0, cell-by-cell flow terms for this package will be recorded.
IBOUND	Global	DIMENSION (NCOL,NROW,NLAY), Status of each cell. < 0, constant-head cell = 0, inactive cell > 0, variable-head cell
IC	Module	Index for columns.
ICBCFL	Global	Flag. = 0, cell-by-cell flow terms will not be recorded or printed for the current time step. ≠ 0, cell-by-cell flow terms will be either printed or recorded (depending on IWELCB) for the current time step.
IL	Module	Index for layers.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
IR	Module	Index for rows.
IWELCB	Package	Flag and a unit number. > 0, unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL is set. = 0, cell-by-cell flow terms will not be printed or recorded. < 0, well recharge rate will be printed whenever ICBCFL is set.
KPER	Global	Stress period counter.
KSTP	Global	Time step counter. Reset at the start of each stress period.
L	Module	Index for wells.
MSUM	Global	Counter for budget entries and labels in VBVL and VBNM.
MXWELL	Package	Maximum number of wells active at any one time.

List of Variables for Module WELIBD (Continued)

Variable	Range	Definition
NCOL	Global	Number of columns in the grid.
NLAY	Global	Number of layers in the grid.
NROW	Global	Number of rows in the grid.
NWELLS	Package	Number of wells active during the current stress period.
Q	Module	Rate at which the well recharges the aquifer.
RATIN	Module	Accumulator for the total flow into the flow field from wells.
RATOUT	Module	Accumulator for the total flow out of the flow field into wells.
TEXT	Module	Label to be printed or recorded with the array data.
VBNM	Global	DIMENSION (4,20), Labels for entries in the volumetric budget.
VBVL	Global	DIMENSION (4,20), Entries for the volumetric budget. For flow component N, the values in VBVL are: (1,N) Rate for the current time step into the flow field. (2,N) Rate for the current time step out of the flow field. (3,N) Volume into the flow field during simulation. (4,N) Volume out of the flow field during simulation.
WELL	Package	DIMENSION (4,MXWELL), For each well: layer, row, column, and recharge rate of the well.

CHAPTER 9

DRAIN PACKAGE

Conceptualization and Implementation

The rate at which water seeps into a drain in the saturated zone of an aquifer is approximated in the model using the equation

$$QD_{i,j,k} = CD_{i,j,k}(h_{i,j,k}-d_{i,j,k}) = CD_{i,j,k}h_{i,j,k} - CD_{i,j,k}d_{i,j,k} \quad (65)$$

where

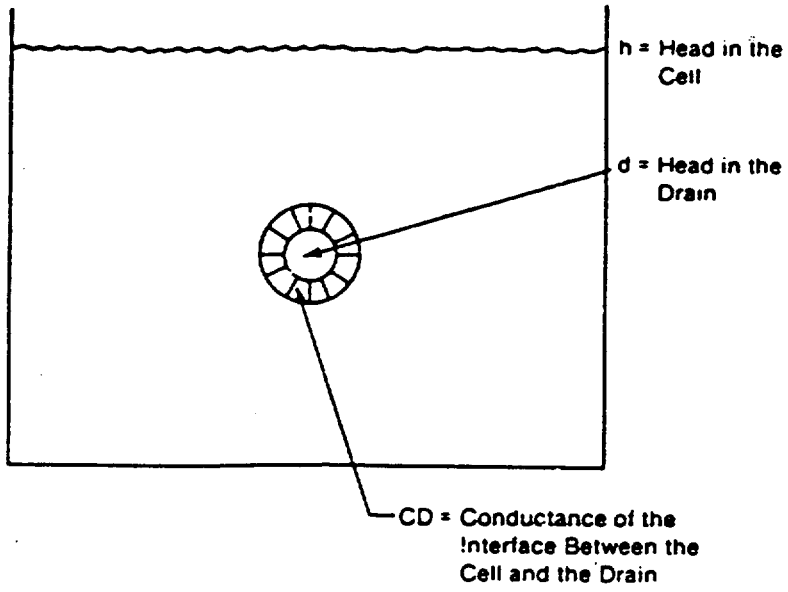
$QD_{i,j,k}$ is the rate water flows into the drain (L^3t^{-1});

$d_{i,j,k}$ is the head in the drain (L);

$h_{i,j,k}$ is the head in the aquifer near the drain (L); and

$CD_{i,j,k}$ is the conductance of the interface between the aquifer and the drain (L^2t^{-1}).

The coefficient $CD_{i,j,k}$ (fig. 39) is the conductance of the interface between the drain and the porous material. It may be affected by size and frequency of openings in a drain tile, chemical precipitation around a tile, difference in permeability between the aquifer material and the backfill around a tile, and a low permeability bed in an open drain or the converging area of flow as the drain is approached (fig. 40). The head in the drain is assumed to be the elevation of the drain. Thus the flow into the drain is assumed to be proportional to the head above the drain (fig. 41). This equation only holds when the head in the aquifer is greater than the head in the drain. When the elevation of the drain is greater than the head in the aquifer, the flow into the drain, $QD_{i,j,k}$, is equal to zero.



$$Q = CD\,(h-d)$$

Figure 39.—Flow into a drain as a function of head in the aquifer and the elevation of the drain.

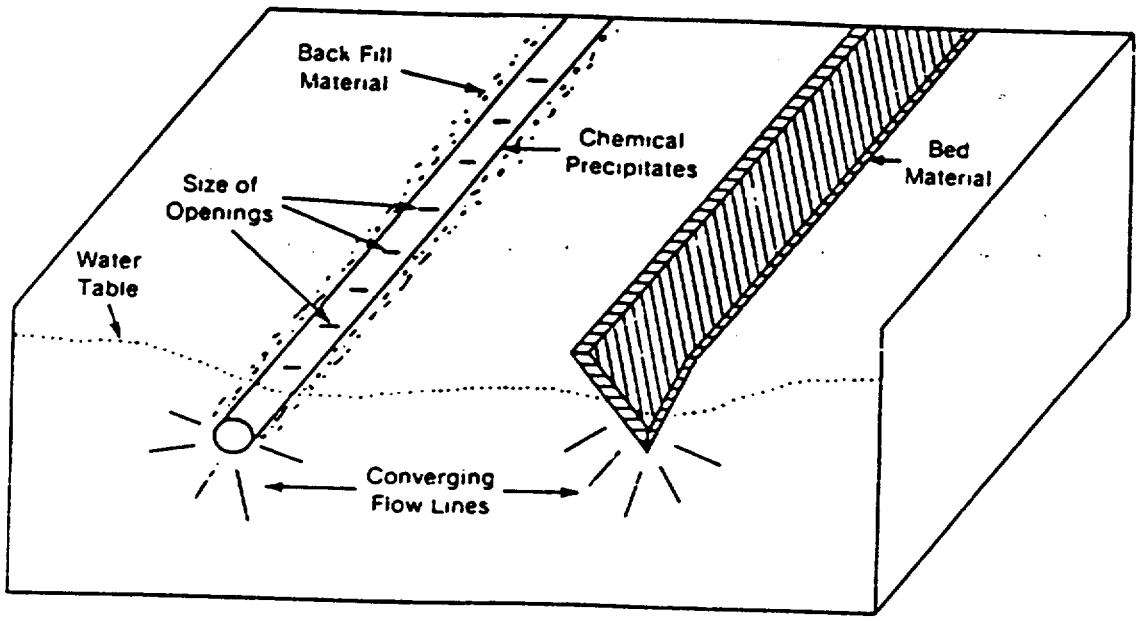


Figure 40.—Factors that may affect the conductance of the interface between an aquifer and a drain.

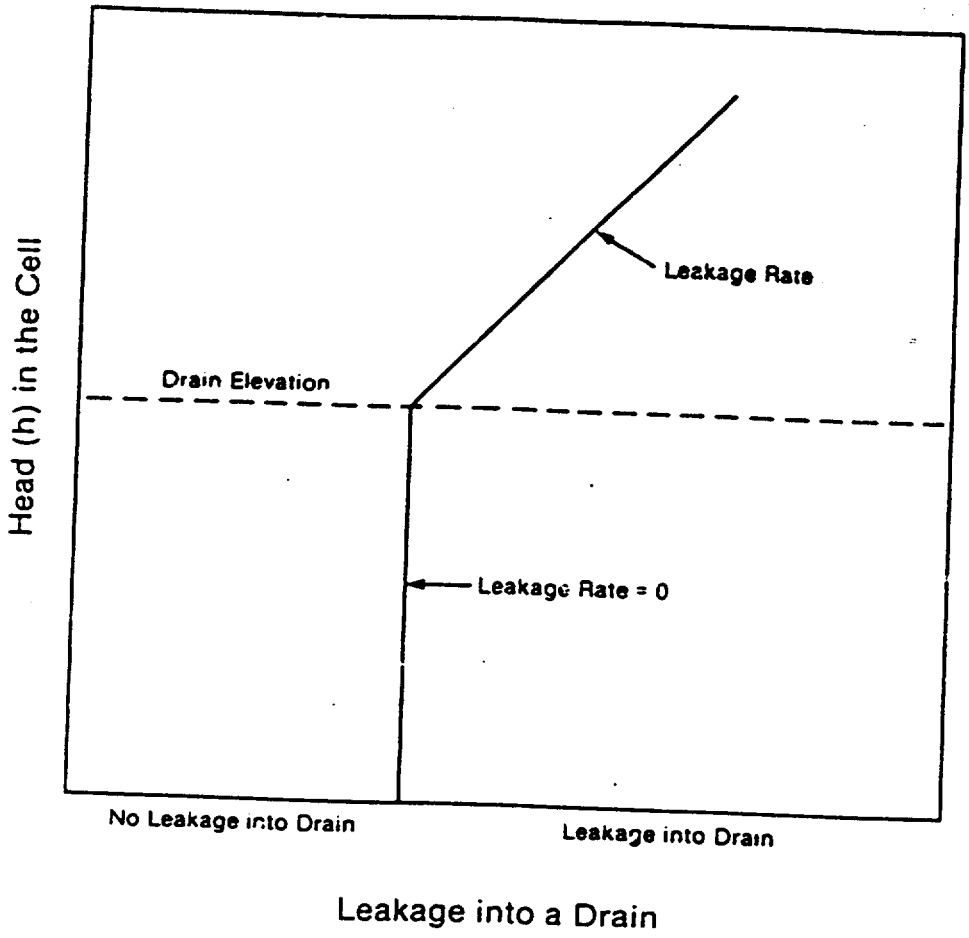


Figure 41.—Leakage into a drain as a function of head in the aquifer.

Data describing each drain is stored in a list. The contents of the list, which are specified by the user at the beginning of each stress period, consist of the row, column, layer, elevation, and conductance for each drain. During the formulation phase, the heads from the previous iteration are compared to the drain elevation. If the drain elevation is less than the head in the cell, the expressions $-CD_{i,j,k}$ and $-CD_{i,j,k}d_{i,j,k}$ are added to the accumulator $HCOF_{i,j,k}$ and $RHS_{i,j,k}$, respectively. If the drain elevation is greater than or equal to the head in the cell, nothing is added to $HCOF_{i,j,k}$ and $RHS_{i,j,k}$.

Drain Package Input

Input to the Drain (DRN) Package is read from the unit specified in IUNIT(3).

FOR EACH SIMULATION

DRN1AL

1. Data: MXDRN IDRNCB
   Format: I10 I10

FOR EACH STRESS PERIOD

DRN1RP

2. Data: ITMP
   Format: I10

3. Data: Layer Row Col Elevation Cond
   Format: I10 I10 I10 F10.0 F10.0

   (Input item 3 normally consists of one record for each drain. If ITMP is negative or zero, item 3 will not be read.)

Explanation of Fields Used in Input Instructions

MXDRN--is the maximum number of drain cells active at one time.

IDRNCB--is a flag and a unit number.

If IDRNCB > 0, it is the unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL (see Output Control) is set.

If IDRNCB = 0, cell-by-cell flow terms will not be printed or recorded.

If IDRNCB < 0, drain leakage for each cell will be printed whenever ICBCFL is set.

ITMP--is a flag and a counter.

If ITMP < 0, drain data from the last stress period will be reused.

If ITMP $\geq$ 0, ITMP will be the number of drains active during the current stress period.

Layer--is the layer number of the cell containing the drain.

Row--is the row number of the cell containing the drain.

Column--is the column number of the cell containing the drain.

Elevation--is elevation of the drain.

Cond--is the hydraulic conductance of the interface between the aquifer and the drain.

SAMPLE INPUT TO THE DRAIN PACKAGE

DATA ITEM	EXPLANATION	INPUT RECORDS			
1	(MXDRNR, IDRNCB)_____	3	55		
2	(ITMP) FOR FIRST STRESS PERIOD_____	3			
3	(LAYER, ROW, COLUMN, ELEVATION, COND) FOR FIRST DRAIN_____	2	6	4	220.
3	(LAYER, ROW, COLUMN, ELEVATION, COND) FOR SECOND DRAIN_____	2	7	4	225.
3	(LAYER, ROW, COLUMN, ELEVATION, COND) FOR THIRD DRAIN_____	2	5	4	210.
2	(ITMP) FOR SECOND STRESS PERIOD_____	-1			
2	(ITMP) FOR THIRD STRESS PERIOD_____	-1			
2	(ITMP) FOR FOURTH STRESS PERIOD_____	2			
3	(LAYER, ROW, COLUMN, ELEVATION, COND) FOR FIRST DRAIN_____	2	5	4	210.
3	(LAYER, ROW, COLUMN, ELEVATION, COND) FOR SECOND DRAIN_____	2	6	4	220.
2	(ITMP) FOR FIFTH STRESS PERIOD_____	0			
2	(ITMP) FOR SIXTH STRESS PERIOD_____	-1			

Module Documentation for the Drain Package

The Drain Package (DRN1) consists of four modules, all of which are called by the MAIN program. The modules are:

DRN1AL — Allocates space for an array that contains the drain list (DRA1).

DRN1RP — Reads location, drain elevation, and drain conductance of each cell containing a drain.

DRN1FM — Adds the terms $-CD_{i,j,k}$ and $-CD_{i,j,k}d_{i,j,k}$ to the accumulators $HCOF_{i,j,k}$ and $RHS_{i,j,k}$, respectively.

DRN1BD — Calculates the rates and accumulated volume of drainage from the flow system.

Narrative for Module DRN1AL

This module allocates space in the X array to store the list of drains.

1. Print a message identifying the package and initialize NDRAIN (number of drains).

2. Read and print MXDRAN (the maximum number of drains) and IDRNCB (the file number for saving cell-by-cell flow terms or a flag indicating that cell-by-cell flow terms should be printed).

3. Set LCDRAI (which will point to the first element in the drain list) equal to ISUM (which points to the first unallocated element in the X array.

4. Calculate the amount of space needed for the drain list (five values for each drain--row, column, layer, drain elevation, and drain conductance).

5. Print the number of elements in the X array used by the Drain Package.

6. RETURN.

Flow Chart for Module DRN1AL

NDRAIN is the number of drains being simulated at any given time.

MXDRN is the maximum number of drains simulated.

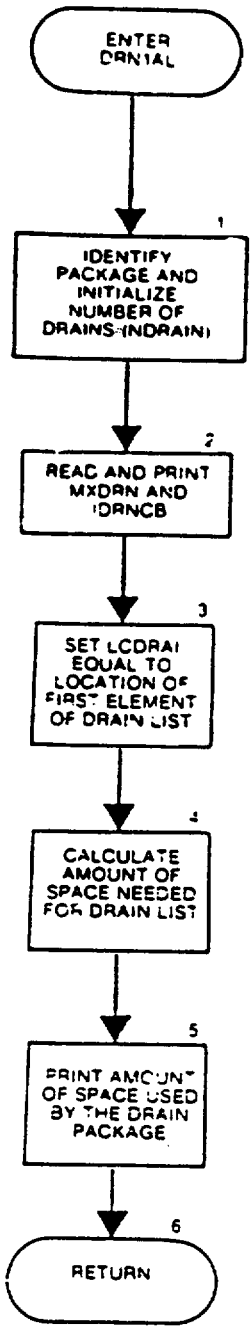
IDRNCB is a flag and a unit number.

If IDRNCB > 0, it is the unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL is set.

If IDRNCB = 0, cell-by-cell flow terms will not be printed or recorded.

If IDRNCB < 0, drain leakage for each drain will be printed whenever ICBCFL is set.

LCDRAI is the location, in the X array, of the list of drain data (DRAI).



```
      SUBROUTINE DRN1AL(ISUM,LENX,LCDRAI,NDRAIN,MXDRN,IN,IOUT,
     1                  IDRNCB)
C
C-----VERSION 0956 08DEC1983 DRN1AL
C     ******************************************************************
C     ALLOCATE ARRAY STORAGE FOR DRAIN PACKAGE
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
C     ------------------------------------------------------------------
C
C1------IDENTIFY PACKAGE AND INITIALIZE NDRAIN.
      WRITE(IOUT,1)IN
    1 FORMAT(1HO,'DRN1 -- DRAIN PACKAGE, VERSION 1, 12/08/83',
     2' INPUT READ FROM UNIT',I3)
      NDRAIN=0
C
C2------READ & PRINT MXDRN & IDRNCB(UNIT & FLAG FOR CELL-BY-CELL FLOW)
      READ(IN,2) MXDRN,IDRNCB
    2 FORMAT(2I10)
      WRITE(IOUT,3) MXDRN
    3 FORMAT(1H ,'MAXIMUM OF',I5,' DRAINS')
      IF(IDRNCB.GT.0) WRITE(IOUT,9) IDRNCB
    9 FORMAT(1X,'CELL-BY-CELL FLOWS WILL BE RECORDED ON UNIT',I3)
      IF(IDRNCB.LT.0) WRITE(IOUT,8)
    8 FORMAT(1X,'CELL-BY-CELL FLOWS WILL BE PRINTED WHEN ICBCFL NOT 0')
C
C3------SET LCDRAI EQUAL TO ADDRESS OF FIRST UNUSED SPACE IN X.
      LCDRAI=ISUM
C
C4------CALCULATE AMOUNT OF SPACE USED BY THE DRAIN PACKAGE.
      ISP=5*MXDRN
      ISUM=ISUM+ISP
C
C5------PRINT AMOUNT OF SPACE USED BY DRAIN PACKAGE.
      WRITE(IOUT,4) ISP
    4 FORMAT(1X,I6,' ELEMENTS IN X ARRAY ARE USED FOR DRAINS')
      ISUM1=ISUM-1
      WRITE(IOUT,5) ISUM1,LENX
    5 FORMAT(1X,I6,' ELEMENTS OF X ARRAY USED OUT OF',I7)
      IF(ISUM1.GT.LENX) WRITE(IOUT,6)
    6 FORMAT(1X,'   ***X ARRAY MUST BE DIMENSIONED LARGER***')
C
C6------RETURN
      RETURN
      END
```

List of Variables for Module DRN1AL

Variable	Range	Definition
IDRNCB	Package	Flag and a unit number. > 0, unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL is set. = 0, cell-by-cell flow terms will be neither printed nor recorded. < 0, leakage for each drain will be printed.
IN	Package	Primary unit number from which input for this package will be read.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
ISP	Module	Number of words in the X array allocated by this module.
ISUM	Global	Index number of the lowest element in the X array which has not yet been allocated. When space is allocated for an array, the size of the array is added to ISUM.
ISUM1	Module	ISUM - 1.
LCDRAI	Package	Location in the X array of the first element of array DRAI.
LENX	Global	Length of the X array in words. This should always be equal to the dimension of X specified in the MAIN Program.
MXDRN	Package	Maximum number of drains active at any one time.
NDRAIN	Package	Number of drains active during the current stress period.

Narrative for Module DRN1RP

This module reads data to build the drain list.

1. Read ITMP. ITMP is the number of drains or a flag indicating that drain data from the previous stress period should be reused.

2. Test ITMP. If ITMP is less than zero, the drain data read for the last stress period will be reused. Print a message to that effect and RETURN.

3. If ITMP is greater than or equal to zero, it is the number of drains for this stress period. Set the number of drains (NDRAIN) in the current stress period equal to ITMP.

4. Compare the number of drains (NDRAIN) in the current stress period to the number specified as the maximum for the simulation (MXDRN). If NDRAIN is greater than MXDRN, STOP.

5. Print the number of drains in the current stress period (NDRAIN).

6. See if there are any drains. If there are no drains in the current stress period (NDRAIN = 0), bypass further drain processing.

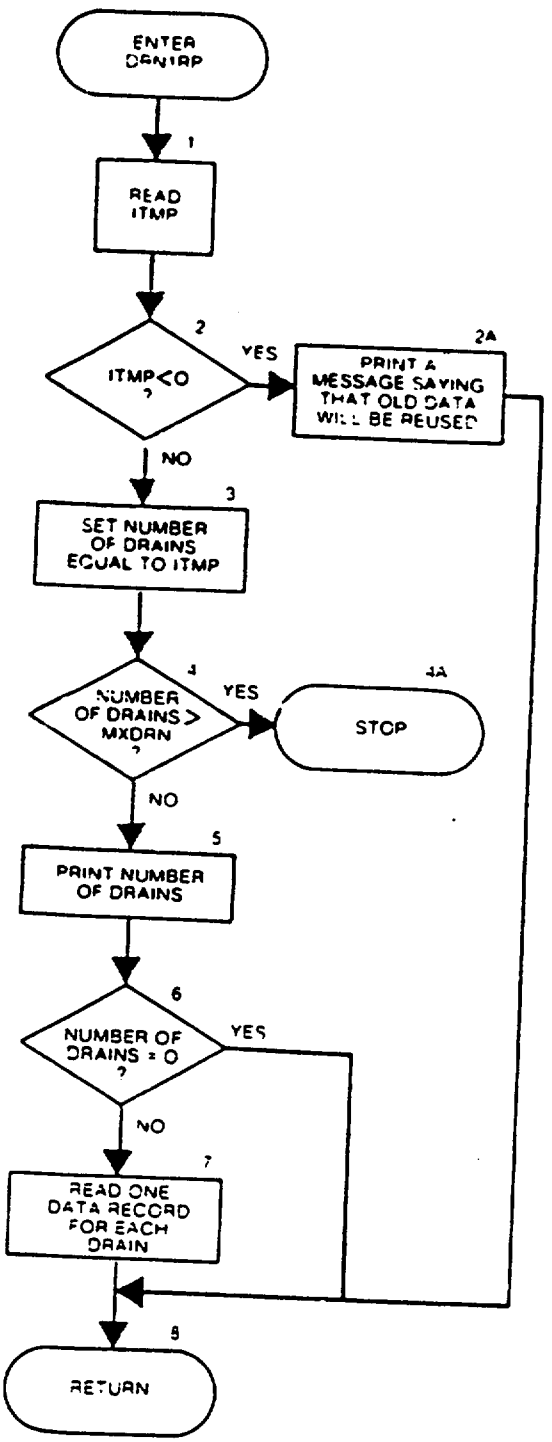
7. Read and print the layer, row, column, elevation, and conductance for each drain.

8. RETURN.

Flow Chart for Module DRN1RP

ITMP is both a flag and a counter. If it is greater than or equal to zero, it is the number of drains to be simulated during the current stress period. If it is less than zero, it indicates that the drains simulated in the last stress period should be simulated in the current stress period.

MXDRN is the maximum number of drains to be simulated.



```
      SUBROUTINE DRN1RP(DRAI,NDRAIN,MXDRN,IN,IOUT)
C
C
C-----VERSION 1603 25APR1983 DRN1RP
C     ******************************************************************
C     READ DRAIN LOCATIONS, ELEVATIONS, AND CONDUCTANCES
C     ******************************************************************
C
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DIMENSION DRAI(5,MXDRN)
C     ------------------------------------------------------------------
C
C1------READ ITMP(NUMBER OF DRAIN CELLS OR FLAG TO REUSE DATA)
      READ(IN,8) ITMP
    8 FORMAT(I10)
C
C2------TEST ITMP
      IF(ITMP.GE.0) GO TO 50
C
C2A-----IF ITMP<0 THEN REUSE DATA FROM LAST STRESS PERIOD.
      WRITE(IOUT,7)
    7 FORMAT(1HO,'REUSING DRAINS FROM LAST STRESS PERIOD')
      RETURN
C
C3------IF ITMP<>0 THEN IT IS THE NUMBER OF DRAINS.
   50 NDRAIN=ITMP
      IF(NDRAIN.LE.MXDRN) GO TO 100
C
C4------IF NDRAIN>MXDRN THEN STOP
      WRITE(IOUT,99) NDRAIN,MXDRN
   99 FORMAT(1HO,'NDRAIN(',I4,') IS GREATER THAN MXDRN(',I4,')')
      STOP
C
C5------PRINT NUMBER OF DRAINS IN THIS STRESS PERIOD.
  100 WRITE(IOUT,1) NDRAIN
    1 FORMAT(1HO,//1X,I5,' DRAINS')
C
C6------IF THERE ARE NO DRAINS THEN RETURN.
      IF(NDRAIN.EQ.0) GO TO 260
C
C7------READ AND PRINT DATA FOR EACH DRAIN.
      WRITE(IOUT,3)
    3 FORMAT(1HO,15X,'LAYER',5X,'ROW',5X
     1,'COL   ELEVATION   CONDUCTANCE   DRAIN NO.'/1X,15X,60('-'))
      DO 250 II=1,NDRAIN
      READ (IN,4) K,I,J,DRAI(4,II),DRAI(5,II)
    4 FORMAT(3I10,2F10.0)
      WRITE (IOUT,5) K,I,J,DRAI(4,II),DRAI(5,II),II
    5 FORMAT(1X,15X,I4,I9,I8,G13.4,G14.4,I8)
      DRAI(1,II)=K
      DRAI(2,II)=I
      DRAI(3,II)=J
  250 CONTINUE
C
C8------RETURN
  260 RETURN
C
      END
```

List of Variables for Module DRN1RP

Variable	Range	Definition
DRAI	Package	DIMENSION (5,MXDRN), For each drain: layer, row, column, head in drain, and conductance into drain.
I	Module	Index for rows.
II	Module	Index for drains.
IN	Package	Primary unit number from which input for this package will be read.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
ITMP	Module	Flag or number of drains. ≥ 0, number of drains active during the current stress period. < 0, same drains active during the last stress period will be active during the current stress period.
J	Module	Index for columns.
K	Module	Index for layers.
MXDRN	Package	Maximum number of drains active at any one time.
NDRAIN	Package	Number of drains active during the current stress period.

Narrative for Module DRN1FM

This module adds terms representing drain leakage to the accumulators HCOF and RHS.

1. If NDRAIN is less than or equal to zero in the current stress period, there are no drains. RETURN.

2. For each drain in the drain list, DO STEPS 3-7.

3. Determine the column (IC), row (IR), and layer (IL).

4. If the cell is external (IBOUND(IC, IR, IL) $\leq$ 0), bypass processing on this drain and go on to the next drain.

5. If the cell is internal, get the drain data (elevation and conductance).

6. If the head in the aquifer (HHNEW) is greater than the elevation of the drain, there is no drain leakage. RETURN.

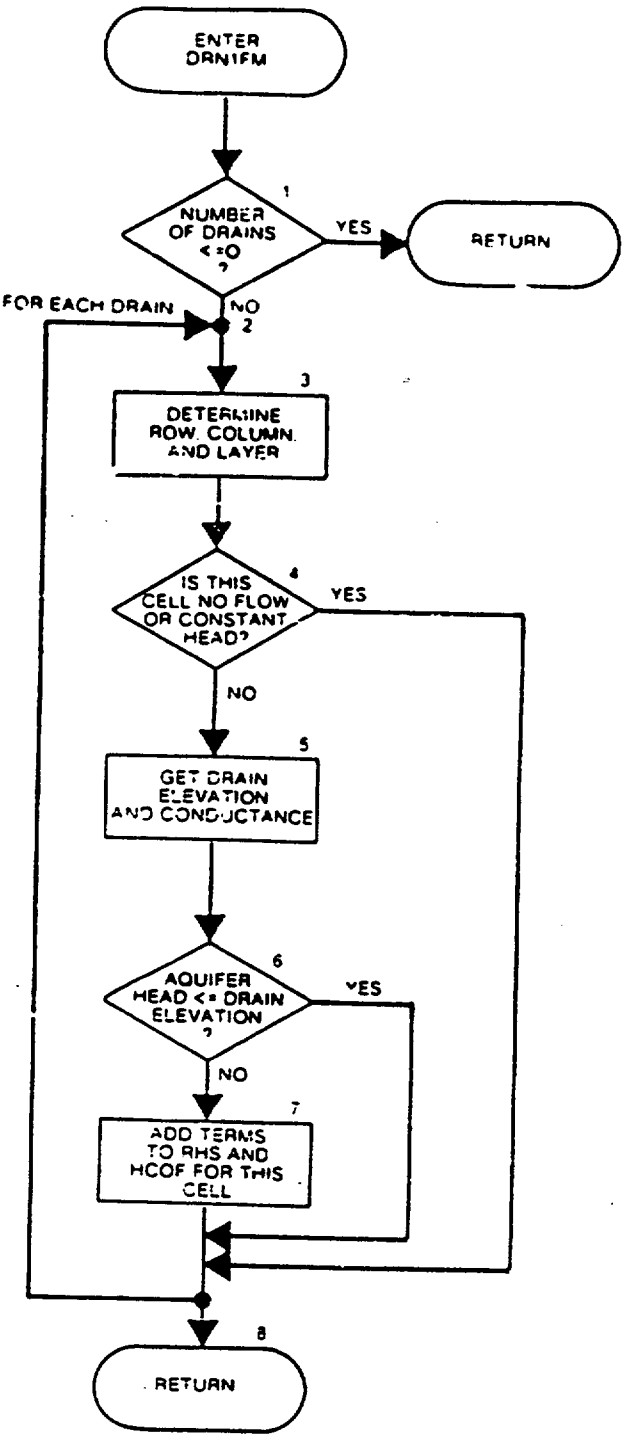
7. If the head in the aquifer (HHNEW) is greater than the elevation of the drain (EL), add the term -C*EL (C is the drain conductance) to the accumulator RHS and the term -C to the accumulator HCOF.

8. RETURN.

Flow Chart for Module DRN1FM

RHS is an accumulator in which the right hand side of the equation is formulated.

HCOF is an accumulator in which the coefficient of head in the cell is formulated.



```
      SUBROUTINE DRN1FM(NDRAIN,MXDRN,DRAI,HNEW,HCOF,RHS,IBOUND,
     1                  NCOL,NROW,NLAY,IOUT)
C
C-----VERSION 1638 25APR1983 DRN1FM
C
C     ******************************************************************
C     ADD DRAIN FLOW TO SOURCE TERM
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DOUBLE PRECISION HNEW
C
      DIMENSION DRAI(5,MXDRN),HNEW(NCOL,NROW,NLAY),
     1          RHS(NCOL,NROW,NLAY),IBOUND(NCOL,NROW,NLAY),
     1          HCOF(NCOL,NROW,NLAY)
C     ------------------------------------------------------------------
C
C1------IF NDRAIN<=0 THERE ARE NO DRAINS. RETURN
      IF(NDRAIN.LE.0) RETURN
C
C2------PROCESS EACH CELL IN THE DRAIN LIST
      DO 100 L=1,NDRAIN
C
C3------GET COLUMN, ROW AND LAYER OF CELL CONTAINING DRAIN.
      IL=DRAI(1,L)
      IR=DRAI(2,L)
      IC=DRAI(3,L)
C
C4-------IF THE CELL IS EXTERNAL SKIP IT.
      IF(IBOUND(IC,IR,IL).LE.0) GO TO 100
C
C5-------IF THE CELL IS INTERNAL GET THE DRAIN DATA.
      EL=DRAI(4,L)
      HHNEW=HNEW(IC,IR,IL)
C
C6------IF HEAD IS LOWER THAN DRAIN THEN SKIP THIS CELL.
      IF(HHNEW.LE.EL) GO TO 100
C
C7------HEAD IS HIGHER THAN DRAIN. ADD TERMS TO RHS AND HCOF.
      C=DRAI(5,L)
      HCOF(IC,IR,IL)=HCOF(IC,IR,IL)-C
      RHS(IC,IR,IL)=RHS(IC,IR,IL)-C*EL
  100 CONTINUE
C
C8------RETURN
      RETURN
      END
```

List of Variables for Module DRN1FM

Variable	Range	Definition
C	Module	Conductance into the drain.
DRAI	Package	DIMENSION (5,MXDRN). For each drain: layer, row, column, head in the drain and conductance into the drain.
EL	Module	Elevation of the drain (head in the drain).
HCOF	Global	DIMENSION (NCOL,NROW,NLAY). Coefficient of head in the cell (J,I,K) in the finite-difference equation.
HHNEW	Module	Head in the cell containing the drain.
HNEW	Global	DIMENSION (NCOL,NROW,NLAY). Most recent estimate of head in each cell. HNEW changes at each iteration.
IBOUND	Global	DIMENSION (NCOL,NROW,NLAY). Status of each cell. < 0, constant-head cell = 0, inactive cell > 0, variable-head cell
IC	Module	Index for columns.
IL	Module	Index for layers.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
IR	Module	Index for rows.
MXDRN	Package	Maximum number of drains active at any one time.
NCOL	Global	Number of columns in the grid.
NDRAIN	Package	Number of drains active during the current stress period.
NLAY	Global	Number of layers in the grid.
NROW	Global	Number of rows in the grid.
RHS	Global	DIMENSION (NCOL,NROW,NLAY). Right hand side of the finite-difference equation. RHS is an accumulation of terms from several different packages.

Narrative for Module DRN1BD

This module calculates rates and volumes transferred between the aquifer and drains.

1. Initialize the cell-by-cell flow-term flag (IBD) and the rate accumulator (RATOUT).

2. If there are no drains (NDRAIN $\leq$ 0), skip down to step 12 and put zeros into the budget terms for drains.

3. Test to see if cell-by-cell flow terms are to be saved on disk. They will not be saved if either of the following conditions hold: (1) this is not the proper time step (ICBCFL = 0) or (2) cell-by-cell flow terms are not needed for drains during this simulation (IDRNCB $\leq$ 0). If cell-by-cell flow terms will be saved for drains, set the cell-by-cell flow-term flag (IBD) and clear the buffer in which they will be accumulated (BUFF).

4. For each drain, do steps 3-11 accumulating flows into drains.

5. Determine the row, column, and layer of the cell containing the drain.

6. If the cell is external (IBOUND(I,J,K), $\leq$ 0), bypass further processing of this drain.

7. Get the drain parameters from the drain list.

8. If the head in the cell is less than the elevation of the drain, bypass further processing of this drain.

9. If the head in the cell is greater than the elevation of the drain, set "Q" equal to the conductance of the drain (C) times the drain elevation (EL) minus the head in the cell (HHNEW) (Q = C*(EL - HHNEW)). Add Q to the accumulator RATOUT to get the total flow from the aquifer into drains.

10. If the cell-by-cell flow terms are to be printed (IDRNCB < 0 and ICBCFL ≠ 0), print Q.

11. If the cell-by-cell flow terms for drains are to be saved, add Q to the buffer (BUFF).

12. See if the cell-by-cell flow terms are to be saved (IBD = 1). If they are, call module UBUDSV to record the buffer (BUFF) onto disk.

13. Move RATOUT into the VBVL array for printing by BAS1OT. Add RATOUT multiplied by the time-step length to the volume accumulator in VBVL for printing by BAS1OT. Move the drain budget-term labels to VBNM for print by BAS1OT.

14. Increment the budget-term counter (MSUM). See the section in the Basic Package for a detailed explanation of VBVL, VBNM, and MSUM.

15. RETURN.

Flow Chart for Module DRN1BD

IBD is a flag which, if set, causes cell-by-cell flow terms for drains to be recorded.

EXTERNAL: a cell is said to be external if it is either no flow or constant head (i.e., an equation is not formulated for the cell).

BUFFER is an array in which values are stored as they are being gathered for printing or recording.

RATOUT is an accumulator to which all flows out of the aquifer are added.

Q is the discharge to a drain.

EL is the elevation of the drain.

IDRNCB is a flag and a unit number.

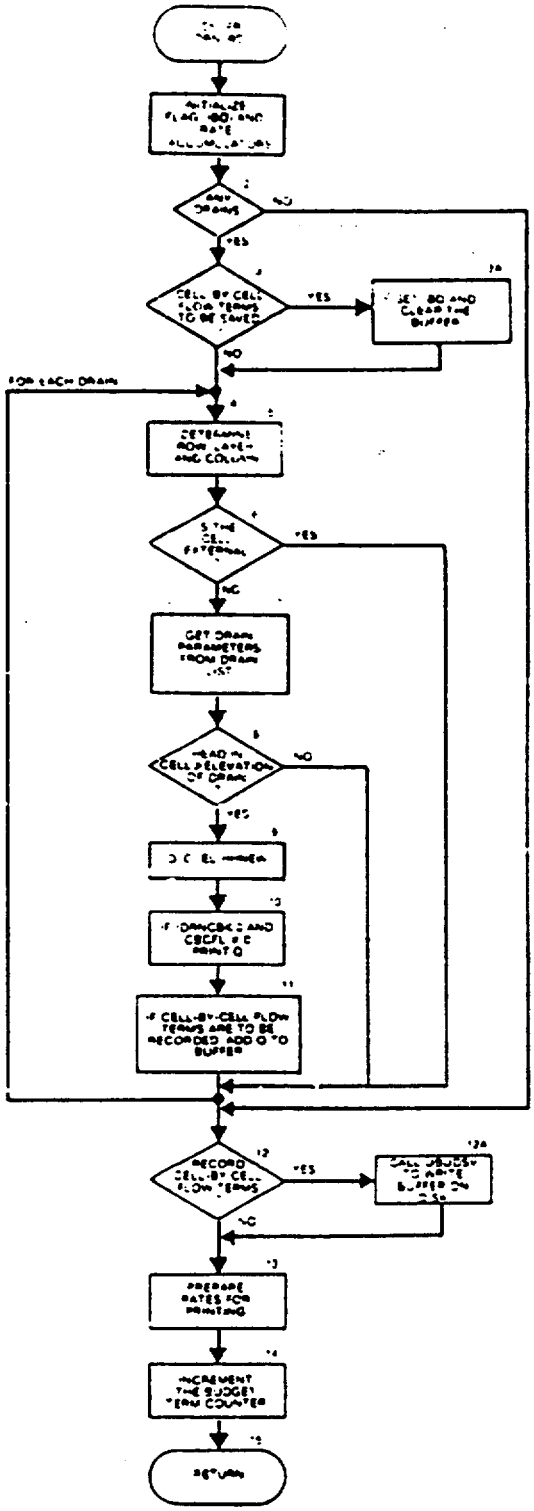
If IDRNCB > 0, it is the unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL is set.

If IDRNCB = 0, cell-by-cell flow terms will not be printed or recorded.

If IDRNCB < 0, drain leakage for each drain will be printed whenever ICBCFL is set.

ICBCFL is a flag.

If ICBCFL ≠ 0, cell-by-cell flow terms will be either printed or recorded for the current time step.



```
      SUBROUTINE DRN1BD(NDRAIN,MXDRN,VBNM,VBVL,MSUM,DRAI,DELT,HNEW,
     1        NCOL,NROW,NLAY,IBOUND,KSTP,KPER,IDRNCB,ICBCFL,BUFF,IOUT)
C
C-----VERSION 1301 28DEC1983 DRN1BD
C
C     ******************************************************************
C     CALCULATE VOLUMETRIC BUDGET FOR DRAINS
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DOUBLE PRECISION HNEW
C
      DIMENSION VBNM(4,MSUM),VBVL(4,MSUM),DRAI(5,MXDRN),
     1          HNEW(NCOL,NROW,NLAY),IBOUND(NCOL,NROW,NLAY),
     2          BUFF(NCOL,NROW,NLAY)
      DIMENSION TEXT(4)
C
      DATA TEXT(1),TEXT(2),TEXT(3),TEXT(4) /'    ','    ','  DR','AINS'/
C     ------------------------------------------------------------------
C
C1------INITIALIZE CELL-BY-CELL FLOW TERM FLAG (IBD) AND
C1------ACCUMULATORS (RATIN AND RATOUT).
      RATOUT=0.
      IBD=0
C
C2------IF THERE ARE NO DRAINS THEN DO NOT ACCUMULATE DRAIN FLOW
      IF(NDRAIN.LE.0) GO TO 200
C
C3------TEST TO SEE IF CELL-BY-CELL FLOW TERMS ARE NEEDED.
      IF(ICBCFL.EQ.0 .OR. IDRNCB.LE.0) GO TO 60
C
C3B-----CELL-BY-CELL FLOW TERMS ARE NEEDED SET IBD AND CLEAR BUFFER.
      IBD=1
      DO 50 IL=1,NLAY
      DO 50 IR=1,NROW
      DO 50 IC=1,NCOL
      BUFF(IC,IR,IL)=0.
   50 CONTINUE
C
C4------FOR EACH DRAIN ACCUMULATE DRAIN FLOW
   60 DO 100 L=1,NDRAIN
C
C5------GET LAYER, ROW & COLUMN OF CELL CONTAINING REACH.
      IL=DRAI(1,L)
      IR=DRAI(2,L)
      IC=DRAI(3,L)
C
C6------IF CELL IS EXTERNAL IGNORE IT.
      IF(IBOUND(IC,IR,IL).LE.0) GO TO 100
C
C7------GET DRAIN PARAMETERS FROM DRAIN LIST.
      EL=DRAI(4,L)
      C=DRAI(5,L)
```

```
      HHNEW=HNEW(IC,IR,IL)
C
C8------IF HEAD LOWER THAN DRAIN THEN FORGET THIS CELL.
      IF(HHNEW.LE.EL) GO TO 100
C
C9------HEAD HIGHER THAN DRAIN. CALCULATE Q=C*(EL-HHNEW) ADD Q TO RATOUT
      Q=C*(EL-HHNEW)
      RATOUT=RATOUT-Q
C
C10-----PRINT THE INDIVIDUAL RATES IF REQUESTED(IDRNCB<0).
      IF(IDRNCB.LT.0.AND.ICBCFL.NE.0) WRITE(IOUT,900) (TEXT(N),N=1,4),
     1    KPER,KSTP,L,IL,IR,IC,Q
  900 FORMAT(1H0,4A4,'   PERIOD',I3,'   STEP',I3,'   DRAIN',I4,
     1    '   LAYER',I3,'   ROW',I4,'   COL',I4,'   RATE',G15.7)
C
C11-----IF C-B-C FLOW TERMS ARE TO BE SAVED THEN ADD Q TO BUFFER.
      IF(IBD.EQ.1) BUFF(IC,IR,IL)=BUFF(IC,IR,IL)+Q
  100 CONTINUE
C
C12-----IF C-B-C FLOW TERMS WILL BE SAVED CALL UBUDSV TO RECORD THEM.
      IF(IBD.EQ.1) CALL UBUDSV(KSTP,KPER,TEXT,IDRNCB,BUFF,NCOL,NROW,
     1                         NLAY,IOUT)
C
C13-----MOVE RATES,VOLUMES & LABELS INTO ARRAYS FOR PRINTING.
  200 VBVL(3,MSUM)=0.
      VBVL(4,MSUM)=RATOUT
      VBVL(2,MSUM)=VBVL(2,MSUM)+RATOUT*DELT
      VBNM(1,MSUM)=TEXT(1)
      VBNM(2,MSUM)=TEXT(2)
      VBNM(3,MSUM)=TEXT(3)
      VBNM(4,MSUM)=TEXT(4)
C
C14-----INCREMENT BUDGET TERM COUNTER
      MSUM=MSUM+1
C
C15-----RETURN
      RETURN
      END
```

List of Variables for Module DRN1BD

Variable	Range	Definition
BUFF	Global	DIMENSION (NCOL,NROW,NLAY), Buffer used to accumulate information before printing or recording it.
C	Module	Conductance into drains.
DELT	Global	Length of the current time step.
DRAI	Package	DIMENSION (5,MXDRN), For each drain: layer, row, column, head in the drain and conductance into the drain.
EL	Module	Elevation of the drain (head in the drain).
HHNEW	Module	Head in the cell containing the drain.
HNEW	Global	DIMENSION (NCOL,NROW,NLAY), Most recent estimate of head in each cell. HNEW changes at each iteration.
IBD	Package	Flag. = 0, cell-by-cell flow terms for this package will not be recorded. ≠ 0, cell-by-cell flow terms for this package will be recorded.
IBOUND	Global	DIMENSION (NCOL,NROW,NLAY), Status of each cell. < 0, constant-head cell = 0, inactive cell > 0, variable-head cell
IC	Module	Index for columns.
ICBCFL	Global	Flag. = 0, cell-by-cell flow terms will not be recorded or printed for the current time step. ≠ 0, cell-by-cell flow terms will be recorded for the current time step.
IDRNCB	Package	Flag. > 0 and if ICBCFL ≠ 0, cell-by-cell flow terms for the DRN1 Package will be recorded on UNIT = IDRNCB.
IL	Module	Index for layers.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
IR	Module	Index for rows.
KPER	Global	Stress period counter.

List of Variables for Module DRN1BD (Continued)

Variable	Range	Definition
KSTP	Global	Time step counter. Reset at the start of each stress period.
L	Module	Index for drains.
MSUM	Global	Counter for budget entries and labels in VBVL and VBNM.
MXDRN	Package	Maximum number of drains active at any one time.
NCOL	Global	Number of columns in the grid.
NDRAIN	Package	Number of drains active during the current stress period.
NLAY	Global	Number of layers in the grid.
NROW	Global	Number of rows in the grid.
Q	Module	Flow from a drain into a cell. (Reverse the sign to get the flow into the drain.)
RATOUT	Module	Accumulator for the total flow out of the flow field into the drains.
TEXT	Module	Label to be printed or recorded with the array data.
VBNM	Global	DIMENSION (4,20), Labels for entries in the volumetric budget.
VBVL	Global	DIMENSION (4,20), Entries for the volumetric budget. For flow component N, the values in VBVL are: (1,N) Rate for the current time step into the flow field. (2,N) Rate for the current time step out of the flow field. (3,N) Volume into the flow field during simulation. (4,N) Volume out of the flow field during simulation.

CHAPTER 10

EVAPOTRANSPIRATION PACKAGE

Conceptualization and Implementation

Evapotranspiration (ET) is the mechanism whereby water is converted from the liquid phase to the vapor phase. This package simulates the effect of ET where the source of water is the saturated porous medium; therefore, it deals primarily with water removed by the roots of plants.

The ET rate determined by the ET Package depends on the position of the aquifer head relative to two given ET reference elevations--ET surface and ET extinction elevation (fig. 42). For a given model node, the ET rate decreases to zero as the aquifer head declines to the extinction elevation and is set to zero when the aquifer head drops below this elevation. The ET rate increases to a user-controlled maximum limit as the aquifer head rises above the extinction elevation to the given ET surface elevation. The ET rate is assumed to be proportional to the saturated thickness above the given ET extinction elevation. The ET rate is expressed in terms of flow into the aquifer as

$$Q = 0 \text{ when } h < EXEL \tag{70}$$

$$Q = EVTR\,(h - EXEL)/EXDP \text{ when } SURF \geq h \geq EXEL \tag{71}$$

$$Q = EVTR \text{ when } h > SURF \tag{72}$$

where

Q is the ET rate (L^3t^{-1});

h is the head in the aquifer (L);

EXEL is the extinction elevation (L);

SURF is the ET surface elevation (L);

EXDP is the extinction depth (SURF - EXEL) (L); and

EVTR is the maximum ET rate (L^3t^{-1}).

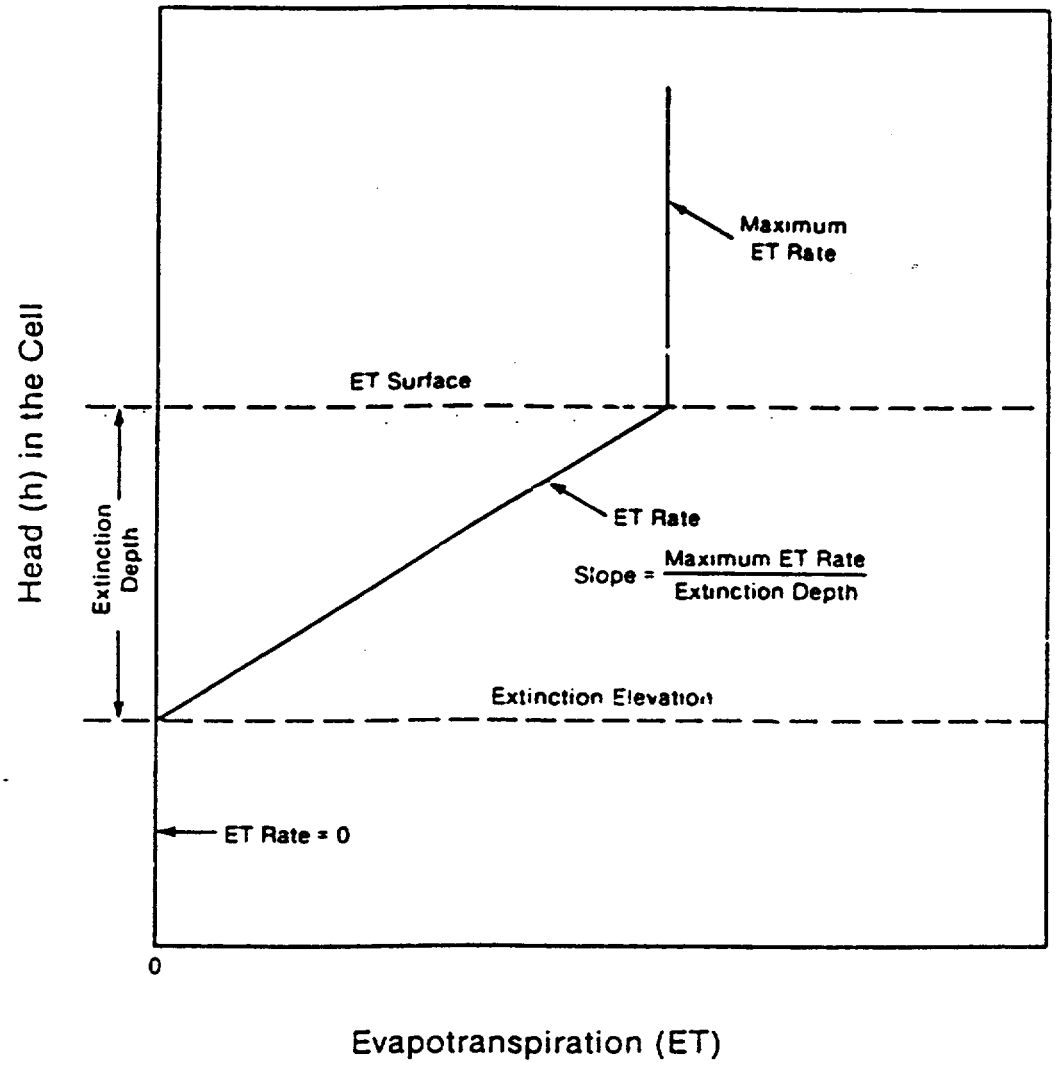


Figure 42.—Evapotranspiration as a function of head in the aquifer.

Replacing the term EXEL by the expression (SURF - EXDP) in equations 70, 71, and 72 yields

$$Q = 0 \text{ when } h < SURF - EXDP \tag{73}$$

$$Q = EVTR\,(h - (SURF - EXDP))/EXDP \text{ when } SURF \geq h \geq SURF - EXDP \tag{74}$$

$$Q = EVTR \text{ when } h > SURF. \tag{75}$$

To simulate the effect of ET on an aquifer, one of these expressions is added to the finite-difference equation for each cell. The finite-difference equation was written in the form

$$CV_{i,j,k-1/2}h^{m}_{i,j,k-1} + CC_{i-1/2,j,k}h^{m}_{i-1,j,k} + CR_{i,j-1/2,k}h^{m}_{i,j-1,k}$$

$$+(-CV_{i,j,k-1/2} - CC_{i-1/2,j,k} - CR_{i,j-1/2,k} - CR_{i,j+1/2,k}$$

$$- CC_{i+1/2,j,k} - CV_{i,j,k+1/2} + HCOF_{i,j,k})h^{m}_{i,j,k} + CR_{i,j+1/2,k}h^{m}_{i,j+1,k}$$

$$+ CC_{i+1/2,j,k}h^{m}_{i+1,j,k} + CV_{i,j,k+1/2}h^{m}_{i,j,k+1} = RHS_{i,j,k} \tag{76}$$

where

$RHS_{i,j,k}$ is composed of all terms independent of head at the end of the iteration; and

$HCOF_{i,j,k}$ is composed of all coefficients of $h_{i,j,k}$ other than conductances from adjacent cells.

As explained in chapter 2, an external source of water represented by an equation of the form

$$a_{i,j,k,n} = p_{i,j,k,n}h^{n}_{i,j,k} + q_{i,j,k,n} \tag{77}$$

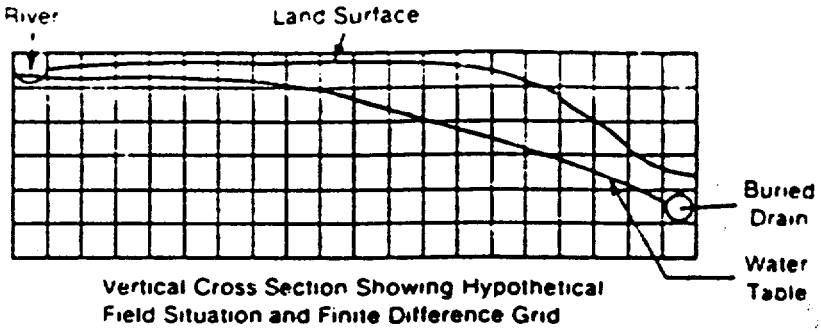
can be incorporated into equation 76 by adding $p_{i,j,k,n}$ to $HCOF_{i,j,k}$ and subtracting $q_{i,j,k,n}$ from $RHS_{i,j,k}$. The value of $p_{i,j,k,n}$ and $q_{i,j,k,n}$

depends on which of the three equations--73, 74, or 75 is selected. The values are shown in the following table.

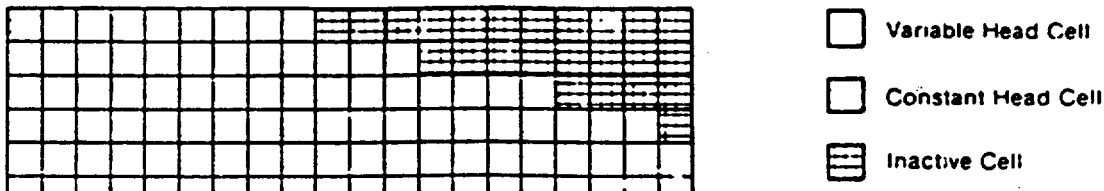
	Equation		
	73	74	75
$P_{i,j,k,n}$	0	-EVTR/EXDP	0
$q_{i,j,k,n}$	0	EVTR*(SURF-EXDP)/EXDP	-EVTR

The data needed to calculate the terms in this table are the three variables--maximum ET rate, ET surface elevation, and extinction depth. The three variables are stored in the three arrays--EVTR, SURF, and EXDP, each array having one value for each horizontal-cell location. The user must specify values for each variable at each horizontal-cell location.

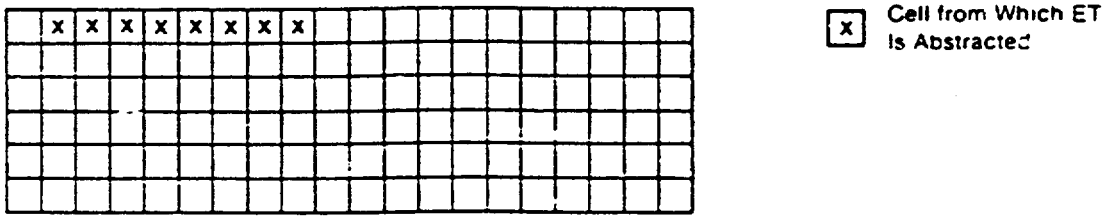
There are two options (fig. 43) for indicating from which layer ET is abstracted at a given horizontal-cell location. Under option 1, ET is taken from grid layer 1. Under option 2, ET is taken from the layer specified by the user in a special array called IEVT.



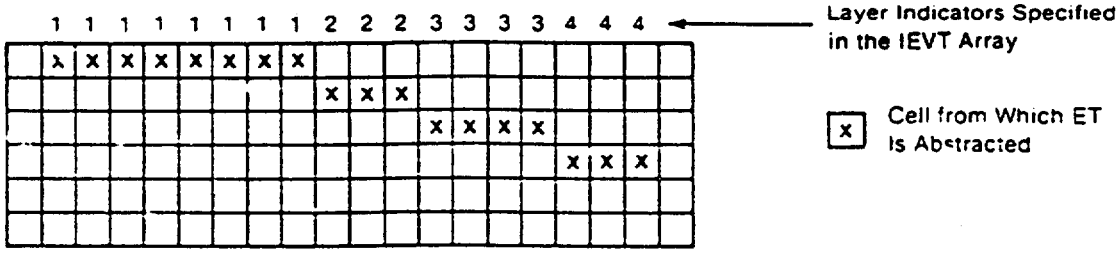
Vertical Cross Section Showing Hypothetical Field Situation and Finite Difference Grid



Status of Cells at End of Simulated Period



Cells from Which ET Is Abstracted Under Option 1



Cells from Which ET Is Abstracted Under Option 2

Figure 43.—Hypothetical problem showing from which cells ET will be abstracted under the two options available in the ET Package.

Evapotranspiration Package Input

Input to the Evapotranspiration (EVT) Package is read from the unit specified in IUNIT (5).

FOR EACH SIMULATION

EVT1AL

1. Data: NEVTOP IEVTCB
   Format: I10 I10

FOR EACH STRESS PERIOD

EVT1RP

2. Data: INSURF INEVTR INEXDP. INIEVT
   Format: I10 I10 I10 I10

3. Data: SURF
   Module: U2DREL

4. Data: EVTR
   Module: U2DREL

5. Data: EXDP
   Module: U2DREL

IF THE ET OPTION IS EQUAL TO TWO

6. Data: IEVT
   Module: U2DINT

Explanation of Fields Used in Input Instructions

NEVTOP--is the evapotranspiration (ET) option code. ET parameters (ET surface, maximum ET rate, and extinction depth) are specified in two-dimensional arrays, SURF, EVTR, and EXDP, with one value for each vertical column. Accordingly, ET is calculated for one cell in each vertical column. The option codes determine for which cell in the column ET will be calculated.

1 - ET is calculated only for cells in the top grid layer.

2 - The cell for each vertical column is specified by the user in array IEVT.

IEVTCB--is a flag and a unit number.

If IEVTCB > 0, it is the unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL (see Output Control) is set.

If IEVTCB $\leq$ 0, cell-by-cell flow terms will not be printed or recorded.

INSURF--is the ET surface (SURF) read flag.

If INSURF $\geq$ 0, an array containing the ET surface elevation will be read.

If INSURF < 0, the ET surface from the preceding stress period will be reused.

INEVTR--is the maximum ET rate (EVTR) read flag.

If INEVTR $\geq$ 0, an array containing the maximum ET rate will be read.

If INEVTR < 0, the maximum ET rate from the preceding stress period will be reused.

INEXDP--is the extinction depth (EXDP) read flag.

If INEXDP $\geq$ 0, an array containing the extinction depth (EXDP) will be read.

If INEXDP < 0, the extinction depth from the preceding stress period will be reused.

INIEVT--is the layer indicator (IEVT) read flag. It is used only if the ET option (NEVTOP) is equal to two.

If INIEVT $\geq$ 0, an array containing the layer indicators (IEVT) will be read.

If INIEVT < 0, layer indicators used during the preceding stress period will be reused.

SURF--is the elevation of the ET surface.

EVTR--is the maximum ET rate.

EXDP--is the ET extinction depth.

IEVT--is the layer indicator array. For each horizontal location, it indicates the layer from which ET is removed. It is needed only if the ET option is equal to two.

SAMPLE INPUT TO THE EVAPOTRANSPIRATION PACKAGE USING ET OPTION 1

DATA ITEM	EXPLANATION	INPUT RECORDS					
1	(NEVTOP, IEVTCB)	1	0				
2	Stress period 1--(INSURF, INEVTR, INEXDP, INIEVT)	1	1	1			
3	Control record for ET surface array	27	1.	(10F5.0)			4
	ET surface	710 715 720 725 730					
		715 720 725 730 735					
		720 725 730 735 740					
		725 730 735 740 745					
		730 735 740 745 750					
		735 740 745 750 755					
4	Control record for maximum ET rate	0	9.65E-7				
5	Control record for extinction depth array	0	10.				
2	Stress period 2--(INSURF, INEVTR, INEXDP, INIEVT)	-1	1	-1			
4	Control record for maximum ET rate	0	8.23E-7				
2	Stress period 3--(INSURF, INEVTR, INEXDP, INIEVT)	-1	1	-1			
4	Control record for maximum ET rate	27	9.65E-7	(10F4.0)			4
	max ET rate	1.2 1.2 1.2 1.2 1.3					
		1.2 1.2 1.2 1.3 1.4					
		1.2 1.2 1.3 1.4 1.4					
		1.0 1.0 1.0 1.1 1.1					
		1.2 1.3 1.3 1.4 1.4					
		1.3 1.3 1.4 1.4 1.4					

SAMPLE INPUT TO THE EVAPOTRANSPIRATION PACKAGE USING ET OPTION 2

DATA ITEM	EXPLANATION	INPUT RECORDS					
1	(NEVTOP, IEVTCB)	2	45				
2	Stress period 1--(INSURF, INEVTR, INEXDP, INIEVT)	1	1	1	1		
3	Control record for ET surface array	27	1.	(10F5.0)			4
	ET surface	710 715 720 725 730					
		715 720 725 730 735					
		720 725 730 735 740					
		725 730 735 740 745					
		730 735 740 745 750					
		735 740 745 750 755					
4	Control record for maximum ET rate	0	9.65E-7				
5	Control record for extinction depth array	0	10.				
6	Control record for layer indicator array	12	1	(2012)			3
	Layer numbers	1 2 2 2 3					
		1 2 2 2 2					
		1 1 2 2 2					
		1 1 1 1 2					
		1 1 1 1 1					
		1 1 1 1 1					
2	Stress period 2--(INSURF, INEVTR, INEXDP, INIEVT)	-1	1	-1	-1		
4	Control record for maximum ET rate	0	8.23E-7				

FIELDS IN ARRAY CONTROL RECORDS ARE---(LOCAT, CONST, FMTIN, IPRN)

Module Documentation for the Evapotranspiration Package

The Evapotranspiration Package (EVT1) consists of four modules, all of which are called by the MAIN program. The modules are:

EVT1AL — Allocates space for arrays to contain maximum ET rate (EVTR), surface elevation (SURF), extinction depth (EXDP), and, if option 2 is specified, the layer indicator (IEVT).

EVT1RP — Reads arrays containing the maximum ET rate (in terms of a volume per unit area), surface elevation, extinction depth, and, if option 2 is specified, the layer indicator. Maximum ET rates are multiplied by cell area to get the maximum ET for each node as a volumetric rate.

EVT1FM — Determines, for each horizontal location, which cell is at the surface. Determines if there is ET from that cell. If there is ET, add the appropriate terms to HCOF(I,J,K) and RHS(I,J,K).

EVT1BD — Calculates the rates and accumulated volume of ET out of the flow system.

Narrative for Module EVT1AL

This module allocates space in the X array to store data relating to evapotranspiration.

1. Print a message identifying the package.

2. Read and print the option indicator (NEVTOP) and the unit number for cell-by-cell flow terms (IEVTCB).

3. See if the ET option (NEVTOP) is legal. If NEVTOP is illegal (not 1 or 2), print a message saying the option is illegal. Do not allocate storage. STOP.

4. If NEVTOP is legal, print NEVTOP.

5. If the cell-by-cell flow terms are to be recorded, print the unit number (IEVTCB) where they will be recorded.

6. Allocate space for the maximum ET-rate array (EVTR), the extinction-depth array (EXDP), and the ET-surface array (SURF).

7. If the ET option (NEVTOP) is equal to two, allocate space for a layer-indicator array (IEVT).

8. Calculate and print the number of elements in the X array used by the ET package.

9. RETURN.

Flow Chart for Module EVT1AL

NEVTOP is the ET option.

If NEVTOP = 1, ET is from the top layer.

If NEVTOP = 2, ET is from the layer specified by the user in the indicator array (IEVT).

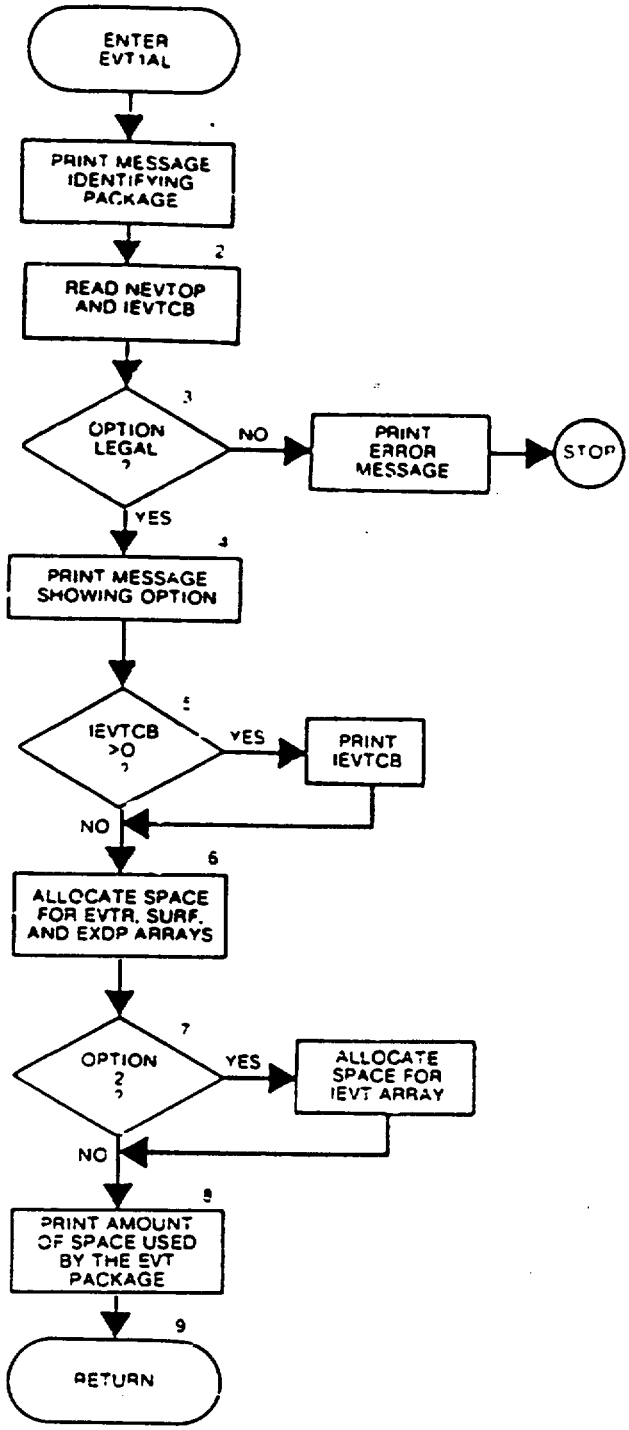
IEVTCB is the unit number on which cell-by-cell flow terms for ET will be written.

EVTR is an array which contains the maximum ET rate for each horizontal cell location.

SURF is an array which contains the elevation of the ET surface.

EXDP is an array which contains the extinction depth for ET.

IEVT is an array which contains the layer number from which ET is taken for each horizontal location. It is used only if option 2 has been specified.



```
      SUBROUTINE EVT1AL(ISUM,LENX,LCIEVT,LCEVTR,LCEXDP,LCSURF,
     1                  NCOL,NROW,NEVTOP,IN,IOUT,IEVTCB)
C
C-----VERSION 0943 08DEC1983 EVT1AL
C     ******************************************************************
C     ALLOCATE ARRAY STORAGE FOR EVAPOTRANSPIRATION
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
C     ------------------------------------------------------------------
C
C1------IDENTIFY PACKAGE.
      WRITE(IOUT,1)IN
    1 FORMAT(1H0,'EVT1 -- EVAPOTRANSPIRATION PACKAGE, VERSION 1,',
     1     ' 12/08/83',' INPUT READ FROM UNIT',I3)
C
C2------READ NEVTOP AND IEVTCB.
      READ(IN,3)NEVTOP,IEVTCB
    3 FORMAT(2I10)
C
C3------CHECK TO SEE THAT ET OPTION IS LEGAL.
      IF(NEVTOP.GE.1.AND.NEVTOP.LE.2)GO TO 200
C
C3A-----IF ILLEGAL PRINT A MESSAGE & ABORT SIMULATION.
      WRITE(IOUT,8)
    8 FORMAT(1X,'ILLEGAL ET OPTION CODE. SIMULATION ABORTING')
      STOP
C
C4------IF THE OPTION IS LEGAL THEN PRINT THE OPTION CODE.
  200 IF(NEVTOP.EQ.1) WRITE(IOUT,201)
  201 FORMAT(1X,'OPTION 1 -- EVAPOTRANSPIRATION FROM TOP LAYER')
      IF(NEVTOP.EQ.2) WRITE(IOUT,202)
  202 FORMAT(1X,'OPTION 2 -- EVAPOTRANSPIRATION FROM ONE SPECIFIED',
     1       ' NODE IN EACH VERTICAL COLUMN')
      IRK=ISUM
C
C5------IF CELL-BY-CELL TERMS TO BE SAVED THEN PRINT UNIT NUMBER.
      IF(IEVTCB.GT.0) WRITE(IOUT,203) IEVTCB
  203 FORMAT(1X,'CELL-BY-CELL FLOW TERMS WILL BE SAVED ON UNIT',I3)
C
C6------ALLOCATE SPACE FOR THE ARRAYS EVTR, EXDP AND SURF.
      LCEVTR=ISUM
      ISUM=ISUM+NCOL*NROW
      LCEXDP=ISUM
      ISUM=ISUM+NCOL*NROW
      LCSURF=ISUM
      ISUM=ISUM+NCOL*NROW
C
C7------IF OPTION 2 THEN ALLOCATE SPACE FOR THE INDICATOR ARRAY(IEVT)
      IF(NEVTOP.NE.2)GO TO 300
      LCIEVT=ISUM
      ISUM=ISUM+NCOL*NROW
C
C8------CALCULATE & PRINT AMOUNT OF SPACE USED BY ET PACKAGE.
  300 IRK=ISUM-IRK
      WRITE(IOUT,4)IRK
    4 FORMAT(1X,I6,' ELEMENTS OF X ARRAY USED FOR EVAPOTRANSPIRATION')
      ISUM1=ISUM-1
      WRITE(IOUT,5)ISUM1,LENX
    5 FORMAT(1X,I6,' ELEMENTS OF X ARRAY USED OUT OF',I7)
      IF(ISUM1.GT.LENX)WRITE(IOUT,6)
    6 FORMAT(1X,'  ***X ARRAY MUST BE MADE LARGER***')
C
C9------RETURN.
      RETURN
      END
```

List of Variables for Module EVT1AL

Variable	Range	Definition
IEVTCB	Package	Flag. If IEVTCB > 0 and ICBCFL ≠ 0, cell-by-cell flow terms for the EVT1 Package will be recorded on UNIT = IEVTCB.
IN	Package	Primary unit number from which input for this package will be read.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
IRK	Module	Before this module allocates space, IRK is set equal to ISUM. After allocation, IRK is subtracted from ISUM to get the amount of space in the X array allocated by this module.
ISUM	Global	Index number of the lowest element in the X array which has not yet been allocated. When space is allocated for an array, the size of the array is added to ISUM.
ISUM1	Module	Index number of the last element of the X array allocated by this module.
LCEVTR	Package	Location in the X array of the first element of array EVTR.
LCEXDP	Package	Location in the X array of the first element of array EXDP.
LCIEVT	Package	Location in the X array of the first element of array IEVT.
LCSURF	Package	Location in the X array of the first element of array SURF.
LENX	Global	Length of the X array in words. This should always be equal to the dimension of X specified in the MAIN program.
NCOL	Global	Number of columns in the grid.
NEVTOP	Package	ET option: = 1, ET is from the top layer. = 2, ET at each horizontal-cell location is from the layer-indicator array (IEVT).
NROW	Global	Number of rows in the grid.

Narrative for Module EVT1RP

This module reads data used to calculate the terms which represent evapotranspiration.

1. Read the values INSURF, INEXDP, INEVTR, and INIEVT which indicate whether the data contained in arrays SURF, EXDP, EVTR, and IEVT, respectively, used during the last stress period, are to be used for the current stress period.

2. Test INSURF to see where the ET-surface array (SURF) is coming from. If INSURF is less than zero, the ET-surface elevation used in the last stress period will be used again in this stress period. Print a message to that effect and GO TO 4.

3. INSURF is greater than or equal to zero. CALL U2DREL to read SURF.

4. Test INEVTR to see where the maximum ET rate (EVTR) is coming from. If INEVTR is less than zero, the maximum ET rate used in the last stress period will be used again in this stress period. Print a message to that effect and GO TO 7.

5. INEVTR is greater than or equal to zero. CALL U2DREL to read the maximum ET rate (EVTR).

6. Multiply the maximum ET rate by the area to get a volumetric rate.

7. Test INEXDP to see where the extinction rate is coming from. If INEXDP is less than zero, the extinction depth used in the last stress period will be used again in this stress period. Print a message to that effect and GO TO 9.

8. If INEXDP is greater than or equal to zero, CALL U2DREL to read the extinction depth.

9. If the ET option (NEVTOP) is equal to two, a layer-indicator array is needed.

10. Test INIEVT to see where the layer indicator is coming from. If INIEVT is less than zero, the indicator array used in the last stress period will be used again in this stress period. Print a message to that effect and GO TO 12.

11. If INIEVT is greater than or equal to zero, CALL U2DINT to read the IEVT array.

12. RETURN.

Flow Chart for Module EVTIPP

INEVTR is a flag which, when set, indicates that the maximum ET rate EVTR should be read for the current stress period. If it is clear (less than zero), maximum ET rates from the last stress period should be reused.

INIEVT, INSURF, and INEXDP are flags similar to INEVTR used for the layer indicator array (IEVT), the ET surface array (SURF), and the extinction depth array (EXDP), respectively.

EVTR is an array containing the maximum ET rate for every horizontal cell location.

SURF is an array containing the ET surface elevation for each horizontal cell location.

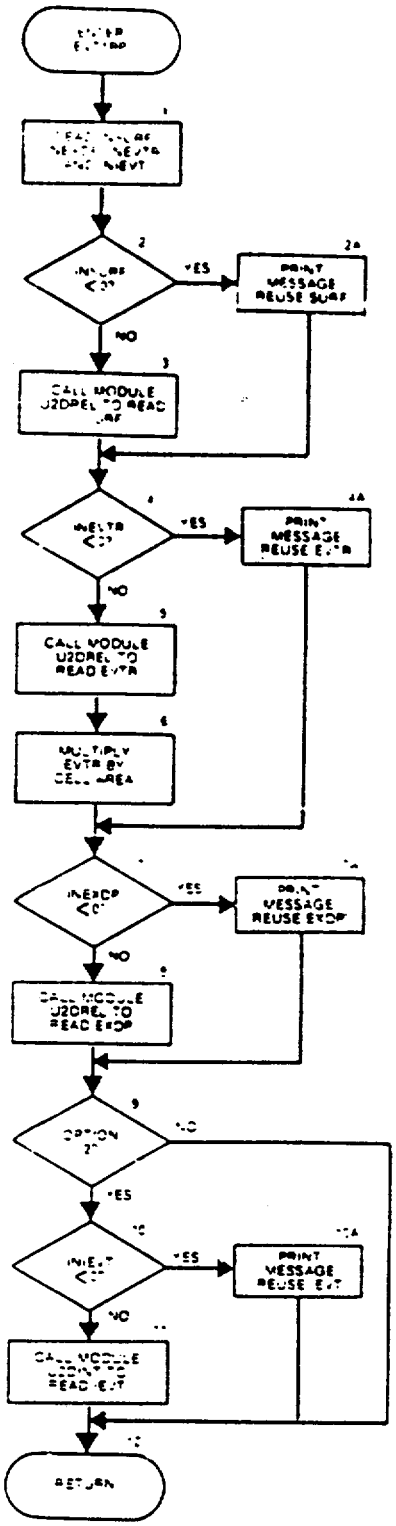
EXDP is an array containing the extinction depth for each horizontal cell location.

IEVT is an array containing a layer indicator for each horizontal cell location. For each horizontal cell location, it indicates the layer number of the cell at that location from which ET is taken. It is used only if the ET option (NEVTOP) is equal to two.

NEVTOP is the ET option.

If NEVTOP = 1, ET is from the top layer.

If NEVTOP = 2, ET is from the layer specified by the user in the indicator array (IEVT).



```
      SUBROUTINE EVTIRP(NEVTOP,IEVT,EVTR,EXDP,SURF,DELR,DELC,
     1                  NCOL,NROW,NLAY,IN,IOUT)
C
C-----VERSION 1631 08FEB1993 EVTIRP
C     ******************************************************************
C     READ EVAPOTRANSPIRATION DATA
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DIMENSION IEVT(NCOL,NROW),EVTR(NCOL,NROW),EXDP(NCOL,NROW),
     1          SURF(NCOL,NROW),ANAME(6,4),DELR(NCOL),DELC(NROW)
C
      DATA ANAME(1,1),ANAME(2,1),ANAME(3,1),ANAME(4,1),ANAME(5,1),
     1  ANAME(6,1) /'     ','     ','     ',' ET',' LAY','ER I','NDEX'/
      DATA ANAME(1,2),ANAME(2,2),ANAME(3,2),ANAME(4,2),ANAME(5,2),
     1  ANAME(6,2) /'     ','     ','     ','     ',' ET',' SUR','FACE'/
      DATA ANAME(1,3),ANAME(2,3),ANAME(3,3),ANAME(4,3),ANAME(5,3),
     1  ANAME(6,3) /' EVA','POTR','ANSP','IRAT','ION ','RATE'/
      DATA ANAME(1,4),ANAME(2,4),ANAME(3,4),ANAME(4,4),ANAME(5,4),
     1  ANAME(6,4) /'     ','     ','EXTI','NCTI','ON D','EPTH'/
C     ------------------------------------------------------------------
C
C1------READ FLAGS SHOWING WHETHER DATA IS TO BE REUSED.
      READ(IN,6)INSURF,INEVTR,INEXDP,INIEVT
    6 FORMAT(4I10)
C
C2------TEST INSURF TO SEE WHERE SURFACE ELEVATION COMES FROM.
      IF(INSURF.GE.0)GO TO 32
C
C2A-----IF INSURF<0 THEN REUSE SURFACE ARRAY FROM LAST STRESS PERIOD
      WRITE(IOUT,3)
    3 FORMAT(1HO,'REUSING SURF FROM LAST STRESS PERIOD')
      GO TO 35
C
C3------IF INSURF=>0 THEN CALL MODULE U2DREL TO READ SURFACE.
   32 CALL U2DREL(SURF,ANAME(1,2),NROW,NCOL,0,IN,IOUT)
C
C4------TEST INEVTR TO SEE WHERE MAX ET RATE COMES FROM.
   35 IF(INEVTR.GE.0)GO TO 37
C
C4A-----IF INEVTR<0 THEN REUSE MAX ET RATE.
      WRITE(IOUT,4)
    4 FORMAT(1HO,'REUSING EVTR FROM LAST STRESS PERIOD')
      GO TO 45
C
C5------IF INEVTR=>0 CALL MODULE U2DREL TO READ MAX ET RATE.
   37 CALL U2DREL(EVTR,ANAME(1,3),NROW,NCOL,0,IN,IOUT)
C
C6------MULTIPLY MAX ET RATE BY CELL AREA TO GET VOLUMETRIC RATE
      DO 40 IR=1,NROW
      DO 40 IC=1,NCOL
      EVTR(IC,IR)=EVTR(IC,IR)*DELR(IC)*DELC(IR)
   40 CONTINUE
C
C7------TEST INEXDP TO SEE WHERE EXTINCTION DEPTH COMES FROM
   45 IF(INEXDP.GE.0)GO TO 47
C
C7A-----IF INEXDP<0 REUSE EXTINCTION DEPTH FROM LAST STRESS PERIOD
      WRITE(IOUT,5)
    5 FORMAT(1HO,'REUSING EXDP FROM LAST STRESS PERIOD')
      GO TO 48
C
C8------IF INEXDP=>0 CALL MODULE U2DREL TO READ EXTINCTION DEPTH
   47 CALL U2DREL(EXDP,ANAME(1,4),NROW,NCOL,0,IN,IOUT)
C
C9------IF OPTION(NEVTOP) IS 2 THEN WE NEED AN INDICATOR ARRAY.
   48 IF(NEVTOP.NE.2)GO TO 50
C
C10-----IF INIEVT<0 THEN REUSE LAYER INDICATOR ARRAY.
      IF(INIEVT.GE.0)GO TO 49
      WRITE(IOUT,2)
    2 FORMAT(1HO,'REUSING IEVT FROM LAST STRESS PERIOD')
      GO TO 50
C
C11-----IF INIEVT=>0 THEN CALL MODULE U2DINT TO READ INDICATOR ARRAY.
   49 CALL U2DINT(IEVT,ANAME(1,1),NROW,NCOL,0,IN,IOUT)
C
C12-----RETURN
   50 RETURN
      END
```

List of Variables for Module EVTIRP

Variable	Range	Definition
ANAME	Module	Label for printout of the input array.
DELC	Global	DIMENSION (NROW), Cell dimension in the column direction. DELC(I) contains the width of row I.
DELR	Global	DIMENSION (NCOL), Cell dimension in the row direction. DELR(J) contains the width of column J.
EVTR	Package	DIMENSION (NCOL,NROW), Maximum ET rate.
EXDP	Package	DIMENSION (NCOL,NROW), Extinction depth.
IC	Module	Index for columns.
IEVT	Package	DIMENSION (NCOL,NROW), Layer number for each horizontal cell location from which ET will be taken if the ET option (NEVTOP) is equal to two.
IN	Package	Primary unit number from which input for this package will be read.
INEVTR	Module	Flag. $\geq$ 0, EVTR array will be read. < 0, EVTR array already in memory from the last stress period will be used.
INEXDP	Module	Flag. $\geq$ 0, EXDP array will be read. < 0, EXDP array already in memory from the last stress period will be used.
INIEVT	Module	Flag. $\geq$ 0, IEVT array will be read. < 0, IEVT array already in memory from the last stress period will be used.
INSURF	Module	Flag. $\geq$ 0, SURF array will be read. < 0, SURF array already in memory from the last stress period will be used.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
IR	Module	Index for rows.
NCOL	Global	Number of columns in the grid.
NEVTOP	Package	ET option. = 1, ET is from the top layer. = 2, ET at each horizontal-cell location is from the layer-indicator array (IEVT).
NLAY	Global	Number of layers in the grid.
NROW	Global	Number of rows in the grid.
SURF	Package	DIMENSION (NCOL,NROW), Elevation of the ET surface.

Narrative for Module EVT1FM

This module adds terms representing ET to the finite-difference equations.

1. For each horizontal-cell location, determine which layer ET comes from and add the appropriate terms to the equation for the cell. DO STEPS 1-7.

2. Set the layer index equal to one.

3. If option 2 was invoked, get the layer index from the indicator array (IEVT).

4. If the cell is external, move on to the next horizontal-cell location. SKIP STEPS 5-7.

5. If the head in the aquifer is greater than or equal to the ET-surface elevation, add EVTR to RHS and move on to the next horizontal-cell location. SKIP STEPS 6 AND 7.

6. If the head in the aquifer is less than the extinction elevation (ET surface minus extinction depth), no terms need to be added to the finite-difference equation. Move on to the next horizontal-cell location. SKIP STEP 7.

7. Add the term -EVTR/EXDP to HCOF and subtract the term -EVTR(EXDP - SURF)/EXDP from RHS.

8. RETURN.

Flow Chart for Module EVTIFM

IEVT is an array containing a layer indicator for each horizontal cell location. For each horizontal cell location, it indicates the layer number of the cell at that location from which ET is taken. It is used only if the ET option (NEVTOP) is equal to two.

SURF is an array containing the maximum ET rate for every horizontal cell location.

EVTR is an array containing the maximum ET rate for every horizontal cell location.

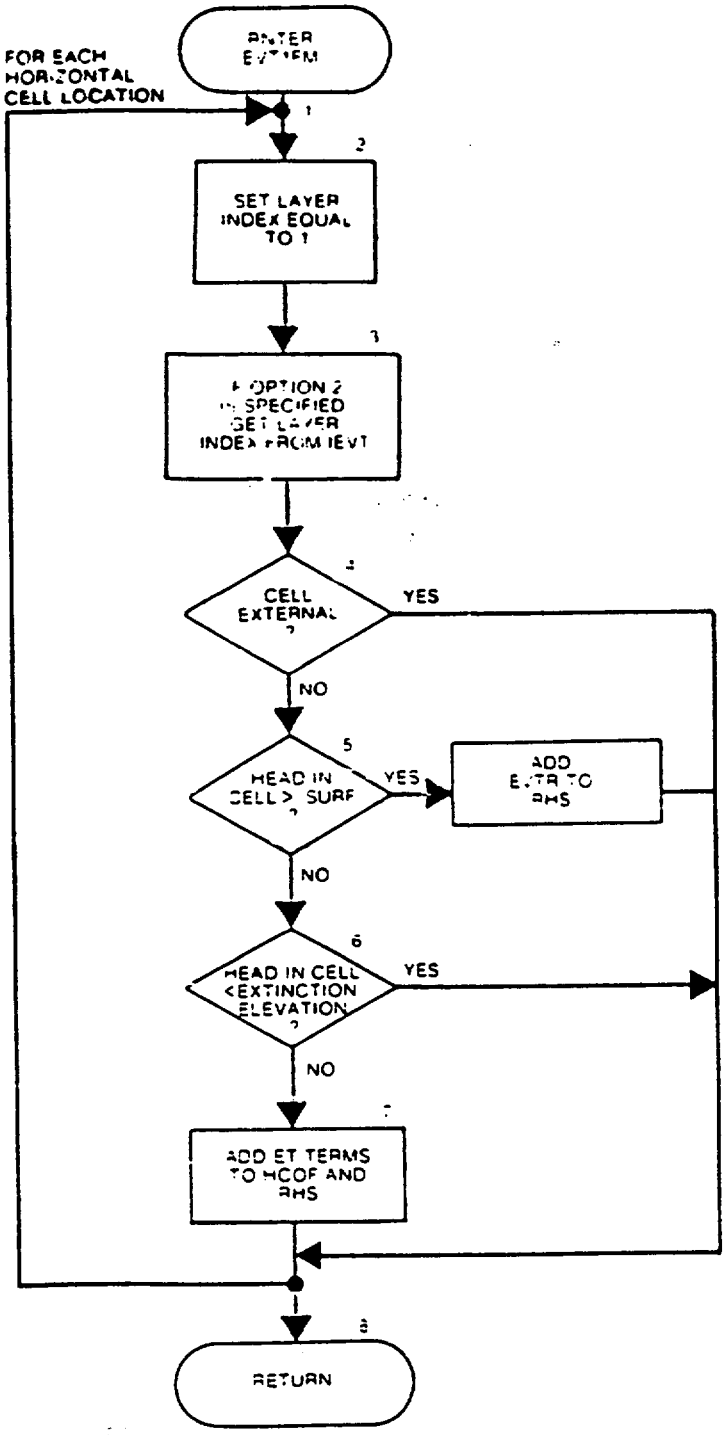
RHS is an accumulator in which the right hand side of the finite-difference equation is formulated.

HCOF is an accumulator in which a coefficient of head in the finite-difference equation is formulated.

NEVTOP is the ET option.

If NEVTOP = 1, ET is from the top layer.

If NEVTOP = 2, ET is from the layer specified by the user in the indicator array (IEVT).



```
      SUBROUTINE EVT1FM(NEVTOP,IEVT,EVTR,EXDP,SURF,RHS,HCOF,
     1                  IBOUND,HNEW,NCOL,NROW,NLAY,IOUT)
C
C-----VERSION 0835 10FEB1983 EVT1FM
C     ******************************************************************
C        ADD EVAPOTRANSPIRATION TO RHS AND HCOF
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DOUBLE PRECISION HNEW
      DIMENSION IEVT(NCOL,NROW),EVTR(NCOL,NROW),EXDP(NCOL,NROW),
     1          SURF(NCOL,NROW),RHS(NCOL,NROW,NLAY),
     2          HCOF(NCOL,NROW,NLAY),IBOUND(NCOL,NROW,NLAY),
     3          HNEW(NCOL,NROW,NLAY)
C     ------------------------------------------------------------------
C
C1------PROCESS EACH HORIZONTAL CELL LOCATION
      DO 10 IR=1,NROW
      DO 10 IC=1,NCOL
C
C2------SET THE LAYER INDEX EQUAL TO 1
      IL=1
C
C3------IF OPTION 2 IS SPECIFIED THEN GET LAYER INDEX FROM IEVT ARRAY
      IF(NEVTOP.EQ.2)IL=IEVT(IC,IR)
C
C4------IF THE CELL IS EXTERNAL IGNORE IT.
      IF(IBOUND(IC,IR,IL).LE.0)GO TO 10
      C=EVTR(IC,IR)
      S=SURF(IC,IR)
      H=HNEW(IC,IR,IL)
C
C5------IF AQUIFER HEAD IS GREATER THAN OR EQUAL TO SURF, ET IS CONSTANT
      IF(H.LT.S) GO TO 5
C
C5A-----SUBTRACT -EVTR FROM RHS
      RHS(IC,IR,IL)=RHS(IC,IR,IL) + C
      GO TO 10
C
C6------IF DEPTH TO WATER>=EXTINCTION DEPTH THEN ET IS 0
    5 D=S-H
      X=EXDP(IC,IR)
      IF(D.GE.X)GO TO 10
C
C7------LINEAR RANGE. ADD ET TERMS TO BOTH RHS AND HCOF.
      RHS(IC,IR,IL)=RHS(IC,IR,IL)+C-C*S/X
      HCOF(IC,IR,IL)=HCOF(IC,IR,IL)-C/X
   10 CONTINUE
C
C8------RETURN
      RETURN
      END
```

List of Variables for Module EVT1FM

Variable	Range	Definition
C	Module	Maximum ET rate.
D	Module	Depth to water.
EVTR	Package	DIMENSION (NCOL,NROW), Maximum ET rate.
EXDP	Package	DIMENSION (NCOL,NROW), Extinction depth.
H	Module	Head in the cell.
HCOF	Global	DIMENSION (NCOL,NROW,NLAY), Coefficient of head in the cell (J,I,K) in the finite-difference equation.
HNEW	Global	DIMENSION (NCOL,NROW,NLAY), Most recent estimate of head in each cell. HNEW changes at each iteration.
IBOUND	Global	DIMENSION (NCOL,NROW,NLAY), Status of each cell. < 0, constant-head cell = 0, inactive cell > 0, variable-head cell
IC	Module	Index for columns.
IEVT	Package	DIMENSION (NCOL,NROW), Layer number, for each horizontal-cell location, from which ET will be taken if the ET option (NEVTOP) is equal to two.
IL	Module	Index for layers.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
IR	Module	Index for rows.
NCOL	Global	Number of columns in the grid.
NEVTOP	Package	ET option. = 1, ET is from the top layer. = 2, ET at each horizontal cell location is from the layer-indicator array (IEVT).
NLAY	Global	Number of layers in the grid.
NROW	Global	Number of rows in the grid.
RHS	Global	DIMENSION (NCOL,NROW,NLAY), Right hand side of finite-difference equation. RHS is an accumulation of terms from several different packages.
S	Module	ET surface elevation for a cell.
SURF	Package	DIMENSION (NCOL,NROW), Elevation of the ET surface.
X	Module	Extinction depth for a cell.

Narrative for Module EVT1BD

This module calculates rates and volumes removed from the aquifer by evapotranspiration.

1. Clear the rate accumulator RATOUT.

2. If budget terms will be saved, clear the buffer (BUFF) in which they will be accumulated.

3. Process each horizontal-cell location one at a time calculating flow to evapotranspiration (STEPS 4-11).

4. Set the layer index (IL) equal to one.

5. If option 2 is in effect, get the layer index from the layer-indicator array (IEVT).

6. If the cell is external (IBOUND $\leq$ 0), bypass processing of the cell.

7. If the head in the aquifer is greater than the elevation of the ET surface, set the ET rate for the cell equal to the maximum ET rate. SKIP STEPS 8 AND 9.

8. If the depth to the water is greater than the extinction depth, bypass further processing of this cell. SKIP STEP 9.

9. Calculate the ET rate using the linear approximation.

10. Add the ET flow from the cell to the accumulator (RATOUT).

11. If the cell-by-cell flow terms are to be saved, add the ET rate to the buffer (BUFF).

12. If the cell-by-cell flow terms are to be saved, call module UBUDSV to write the buffer (BUFF) onto a disk.

13. Move RATOUT into the VBVL array for printing by BAS1OT.

14. Add RATOUT multiplied by the time-step length to the volume accumulators in VBVL for printing by BAS1OT.

15. Move the ET budget-term labels to VBNM for printing by BAS1OT.

16. Increment the budget-term counter (MSUM).

17. RETURN.

Flow Chart for Module EVT1BD

RATOUT is an accumulator to which all flows out of the aquifer are added.

BUFFER is an array in which values are stored as they are being gathered for printing or recording.

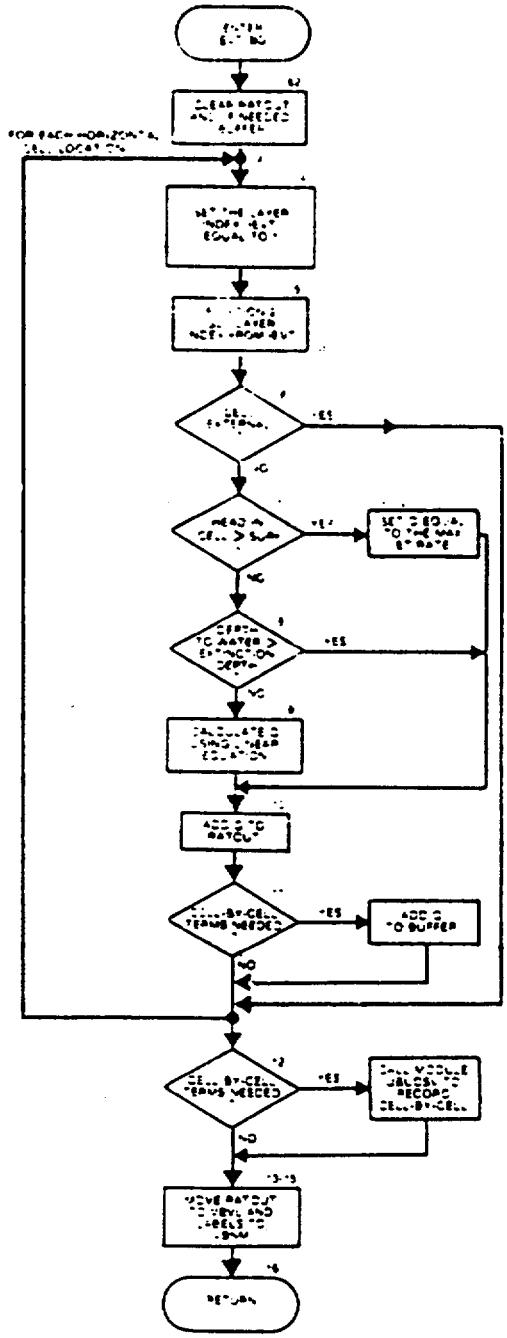
IEVT is an array containing a layer indicator for each horizontal cell location. For each horizontal cell location, it indicates the layer number of the cell at that location from which ET is taken. It is used only if NEVTOP is equal to two.

SURF is an array containing the ET surface elevation for each horizontal cell location.

Q is the flow to ET from an individual cell.

VBVL is a table of budget entries calculated by component-of-flow packages for use in calculating the volumetric budget.

VBNM is a table of labels for budget terms.



```
      SUBROUTINE EVT1BD(NEVTOP,IEVT,EVTR,EXDP,SURF,IBOUND,HNEW,
     1           NCOL,NROW,NLAY,DELT,VBVL,VBNM,MSUM,KSTP,KPER,
     2           IEVTCB,ICBCFL,BUFF,IOUT)
C-----VERSION 1405 10FEB1983 EVT1BD
C     ******************************************************************
C     CALCULATE VOLUMETRIC BUDGET FOR EVAPOTRANSPIRATION
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DOUBLE PRECISION HNEW
      DIMENSION IEVT(NCOL,NROW),EVTR(NCOL,NROW),EXDP(NCOL,NROW),
     1          SURF(NCOL,NROW),IBOUND(NCOL,NROW,NLAY),
     2          VBVL(4,20),VBNM(4,20),HNEW(NCOL,NROW,NLAY),
     3          BUFF(NCOL,NROW,NLAY)
      DIMENSION TEXT(4)
      DATA TEXT(1),TEXT(2),TEXT(3),TEXT(4) /'    ','    ','    ',' ET'/
C     ------------------------------------------------------------------
C
C1------CLEAR THE RATE ACCUMULATOR.
      RATOUT=0
C
C2------IF CELL-BY-CELL FLOW TERMS WILL BE SAVED THEN CLEAR THE BUFFER.
      IBD=0
      IF(IEVTCB.LE.0 .OR. ICBCFL.EQ.0) GO TO 5
      IBD=1
      DO 4 IL=1,NLAY
      DO 4 IR=1,NROW
      DO 4 IC=1,NCOL
      BUFF(IC,IR,IL)=0.
    4 CONTINUE
C
C3------PROCESS EACH HORIZONTAL CELL LOCATION
    5 DO 10 IR=1,NROW
      DO 10 IC=1,NCOL
C
C4------SET THE LAYER INDEX EQUAL TO 1
      IL=1
C
C5------IF OPTION 2 IS SPECIFIED THEN GET LAYER INDEX FROM IEVT ARRAY
      IF(NEVTOP.EQ.2)IL=IEVT(IC,IR)
C
C6------IF CELL IS EXTERNAL THEN IGNORE IT.
      IF(IBOUND(IC,IR,IL).LE.0)GO TO 10
      C=EVTR(IC,IR)
      S=SURF(IC,IR)
      H=HNEW(IC,IR,IL)
C
C7------IF AQUIFER HEAD => SURF,SET Q=MAX ET RATE
      IF(H.LT.S) GO TO 7
      Q=-C
      GO TO 9
C
C8------IF DEPTH=>EXTINCTION DEPTH, ET IS 0
```

```
    7 X=EXDP(IC,IR)
      D=S-H
      IF(D.GE.X)GO TO 10
C
C9------LINEAR RANGE . Q=-EVTR(H-EXEL)/EXDP
      Q=C*D/X-C
C
C10-----ACCUMULATE TOTAL FLOW RATE
    9 RATOUT=RATOUT-Q
C
C11-----IF CELL-BY-CELL FLOW TERMS TO BE SAVED THE ADD Q TO BUFFER.
      IF(IBD.EQ.1) BUFF(IC,IR,IL)=Q
   10 CONTINUE
C
C12-----IF C-B-C TO BE SAVED CALL MODULE UBUDSV TO RECORD THEM.
      IF(IBD.EQ.1) CALL UBUDSV(KSTP,KPER,TEXT,IEVTCB,BUFF,NCOL,NROW,
     1                         NLAY,IOUT)
C
C13-----MOVE TOTAL ET RATE INTO VBVL FOR PRINTING BY BAS1OT.
      VBVL(3,MSUM)=0.
      VBVL(4,MSUM)=RATOUT
C
C14-----ADD ET(ET RATE TIMES STEP LENGTH) TO VBVL
      VBVL(1,MSUM)=0.
      VBVL(2,MSUM)=VBVL(2,MSUM)+RATOUT*DELT
C
C15-----MOVE BUDGET TERM LABELS TO VBNM FOR PRINT BY MODULE BAS1OT
      VBNM(1,MSUM)=TEXT(1)
      VBNM(2,MSUM)=TEXT(2)
      VBNM(3,MSUM)=TEXT(3)
      VBNM(4,MSUM)=TEXT(4)
C
C16-----INCREMENT BUDGET TERM COUNTER
      MSUM=MSUM+1
C
C17-----RETURN
      RETURN
      END
```

List of Variables for Module EVT1BD

Variable	Range	Definition
BUFF	Global	DIMENSION (NCOL,NROW,NLAY), Buffer used to accumulate information before printing or recording it.
C	Module	Maximum ET rate at a cell.
D	Module	Depth to water below the ET surface.
DELT	Global	Length of the current time step.
EVTR	Package	DIMENSION (NCOL,NROW), Maximum ET rate.
EXDP	Package	DIMENSION (NCOL,NROW), Extinction depth.
H	Module	Head in the cell.
HNEW	Global	DIMENSION (NCOL,NROW,NLAY), Most recent estimate of head in each cell. HNEW changes at each iteration.
IBD	Module	Flag. = 0, cell-by-cell flow terms for this package will not be recorded. ≠ 0, cell-by-cell flow terms for this package will be recorded.
IBOUND	Global	DIMENSION (NCOL,NROW,NLAY), Status of each cell. < 0, constant-head cell = 0, inactive cell > 0, variable-head cell
IC	Module	Index for columns.
ICBCFL	Global	Flag. = 0, cell-by-cell flow terms will not be recorded or printed for the current time step. ≠ 0, cell-by-cell flow terms will be recorded for the current time step.
IEVT	Package	DIMENSION (NCOL,NROW), Layer number for each horizontal-cell location from which ET will be taken if the ET option (NEVTOP) is equal to two.
IEVTCB	Package	Flag. If IEVTCB > 0 and ICBCFL ≠ 0, cell-by-cell flow terms for the EVT1 Package will be recorded on UNIT = IEVTCB.
IL	Module	Index for layers.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
IP	Module	Index for rows.
KPER	Global	Stress period counter.
KSTP	Global	Time step counter. Reset at the start of each stress period.
MSUM	Global	Counter for budget entries and labels in VBVL and VBNM.
NCOL	Global	Number of columns in the grid.
NEVTOP	Package	ET option. = 1, ET is from the top layer. = 2, ET at each horizontal-cell location is from the layer-indicator array (IEVT).
NLAY	Global	Number of layers in the grid.
NROW	Global	Number of rows in the grid.
Q	Module	Flow from ET into the cell. (Reverse the sign to get the flow to ET.)

List of Variables for Module EVT1BD (Continued)

Variable	Range	Definition
RATOUT	Module	Accumulator for the total flow out of the flow field to ET.
S	Module	Elevation of the ET surface for a cell.
SURF	Package	DIMENSION (NCOL,NROW), Elevation of the ET surface.
TEXT	Module	Label to be printed or recorded with the array data.
VBNM	Global	DIMENSION (4,20), Labels for entries in the volumetric budget.
VBVL	Global	DIMENSION (4,20), Entries for the volumetric budget. For flow component N, the values in VBVL are: (1,N), Rate for the current time step into the flow field. (2,N), Rate for the current time step out of the flow field. (3,N), Volume into the flow field during simulation. (4,N), Volume out of the flow field during simulation.
X	Module	Extinction depth for a cell.

CHAPTER 11

GENERAL-HEAD BOUNDARY PACKAGE

Conceptualization and Implementation

A general-head boundary (GHB) consists of a source of water outside the modeled area which supplies water to a cell in the modeled area at a rate proportional to the head difference between the source and the cell. The rate at which water is supplied to cell i,j,k is given by the expression

$$Q_{i,j,k,m} = C_m(HB_m - h_{i,j,k}) \qquad (78)$$

where

$Q_{i,j,k,m}$ is the rate at which water is supplied to the cell from boundary m (L^3t^{-1});

C_m is the constant of proportionality for boundary m (L^2t^{-1});

HB_m is the head at the source boundary m (L); and

$h_{i,j,k}$ is the head in the cell (L).

The source of water could be a gaining river in which case the constant of proportionality is the conductance of the riverbed (fig. 44(a)). The source could be a buried drain (i.e., a negative source); then the constant is a function of the material around the drain and the size and spacing of openings in the skin of the drain (fig. 44(b)). It could also be the head in the aquifer outside the simulated area in which case the constant of proportionality is the hydraulic conductance of the material between the known head and boundary of the simulated area (fig. 44(c)). Although the GHB Package can be used to simulate the situations shown in figure 44, it should be done with great care. In the first two cases, the GHB Package, which deals with a single linear relationship (fig. 45), is more restrictive

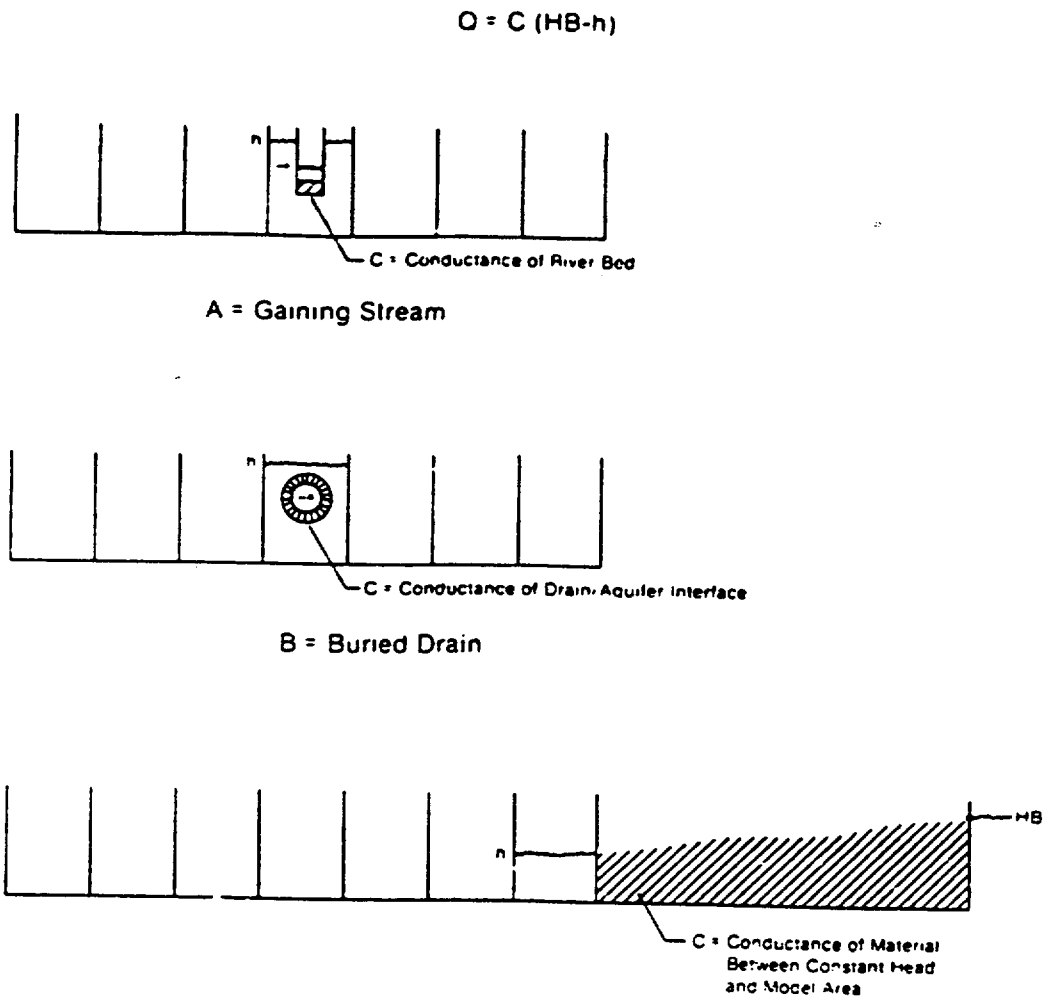
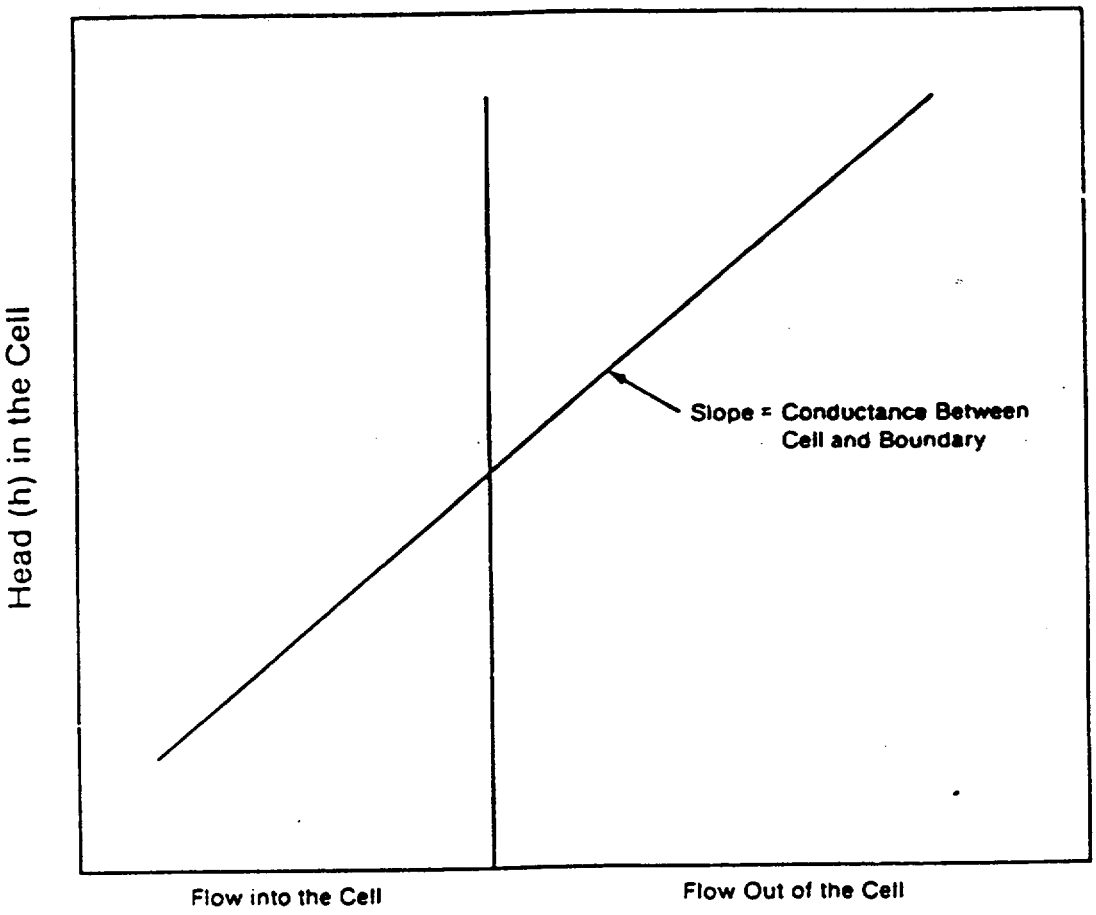


Figure 44.—Three situations which can be simulated using the General Head Boundary Package: (a) a gaining stream, (b) a buried drain, and (c) horizontal leakage.



Flow to a General Head Boundary

Figure 45.—Flow from a general-head boundary as a function of head in the aquifer.

than the River or Drain Packages, each of which deal with two linear relationships. In the third case, the GHB Package does not attempt to account for change in storage in the aquifer material between the boundary head and the simulated area.

Data describing each GHB, which is stored in a list, is specified by the user for each stress period. Input for each boundary consists of the location of the boundary cell--layer, row, and column--the boundary head, and the constant of proportionality. During the formulation phase of each iteration, the term -C*HB is added to the accumulator RHS and the term -C is added to the accumulator HCOF.

General-Head Boundary Package Input

Input for the General-Head Boundary (GHB) Package is read from the unit specified in IUNIT(7).

FOR EACH SIMULATION

GHB1AL

1. Data:	MXBND	IGHBCB	
Format:	I10	I10	

FOR EACH STRESS PERIOD

GHB1RP

2. Data:	ITMP					
Format:	I10					
					Boundary	
3. Data:	Layer	Row	Column		Head	Cond
Format:	I10	I10	I10		F10.0	F10.0

(Input item 3 normally consists of one record for each GHB. If ITMP is negative or zero, item 3 is not read.)

Explanation of Fields Used in Input Instructions

MXBND--is the maximum number of general-head boundary cells at one time.

IGHBCB--is a flag and a unit number.

If IGHBCB > 0, it is the unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL (see Output Control) is set.

If IGHBCB = 0, cell-by-cell flow terms will not be printed or recorded.

If IGHBCB < 0, boundary leakage for each cell will be printed whenever ICBCFL is set.

ITMP--is a flag and a counter.

If ITMP < 0, GHB data from the preceding stress period will be reused.

If ITMP $\geq$ 0, ITMP is the number of general-head boundaries during the current stress period.

Layer--is the layer number of the cell affected by the head-dependent boundary.

Row--is the row number of the cell affected by the head-dependent boundary.

Column--is the column number of the cell affected by the head-dependent boundary.

Boundary head--is the head on the boundary.

Cond--is the hydraulic conductance of the interface between the aquifer cell and the boundary.

SAMPLE INPUT TO THE GENERAL HEAD BOUNDARY PACKAGE

DATA ITEM	EXPLANATION	INPUT RECORDS				
1	[MXBND, IGHBCB]_____	6	24			
2	STRESS PERIOD 1 [ITMP]_____	4				
3	FIRST BOUNDARY [Layer, Row, Column, Head, Conductance_____	2	5	6	235.0	.0012
3	SECOND BOUNDARY [Layer, Row, Column, Head, Conductance_____	2	4	6	230.0	.0012
3	THIRD BOUNDARY [Layer, Row, Column, Head, Conductance_____	2	5	8	250.0	.0018
3	FOURTH BOUNDARY [Layer, Row, Column, Head, Conductance_____	2	7	6	235.0	.0012
2	STRESS PERIOD 2 [ITMP]_____	-1				
2	STRESS PERIOD 3 [ITMP]_____	-1				
2	STRESS PERIOD 4 [ITMP]_____	6				
3	FIRST BOUNDARY [Layer, Row, Column, Head, Conductance_____	2	5	6	235.0	.0012
3	SECOND BOUNDARY [Layer, Row, Column, Head, Conductance_____	2	4	6	230.0	.0012
3	THIRD BOUNDARY [Layer, Row, Column, Head, Conductance_____	2	5	8	250.0	.0018
3	FOURTH BOUNDARY [Layer, Row, Column, Head, Conductance_____	2	7	6	235.0	.0018
3	FIFTH BOUNDARY [Layer, Row, Column, Head, Conductance_____	2	9	6	255.0	.0012
3	SIXTH BOUNDARY [Layer, Row, Column, Head, Conductance _____	2	10	6	250.0	.0012

Module Documentation for the General-Head Boundary Package

The General-Head Boundary Package (GHB1) consists of four modules, all of which are called by the MAIN program. The modules are:

GHB1AL — Allocates space for an array that contains the general-head boundary list (BNDS).

GHB1RP — Reads location, boundary head, and boundary conductance (C_m) of each cell containing general-head boundary m.

GHB1FM — Adds the terms $-C_m$ and $-C_mHB_m$ to the accumulators $HCOF_{i,j,k}$ and $RHS_{i,j,k}$, respectively.

GHB1BD — Calculates the rates and accumulated volume of flow to and from general-head boundaries.

Narrative for Module GHB1AL

This module allocates space in the X array to store the list of general-head boundaries (GHB).

1. Print a message identifying the package and initialize NBOUND (number of general-head boundaries).

2. Read and print MXBND (the maximum number of general-head boundaries) and IGHBCB (the unit number for saving cell-by-cell flow terms or a flag indicating that cell-by-cell flow terms should be printed).

3. Set LCBNDS, which will point to the first element in the boundary list (BNDS), equal to ISUM which is currently pointing to the first unallocated element in the X array.

4. Calculate the amount of space needed for the boundary list (five values for each boundary--row, column, layer, head, and conductance) and add it to ISUM so that it continues to point to the first unallocated element in X.

5. Print the number of elements in the X array used by the GHB Package.

6. RETURN.

Flow Chart for Module GHB1AL

NBOUND is the number of general-head boundaries being simulated at any given time.

MXBND is the maximum number of general-head boundaries simulated.

IGHBCB is a flag and a unit number.

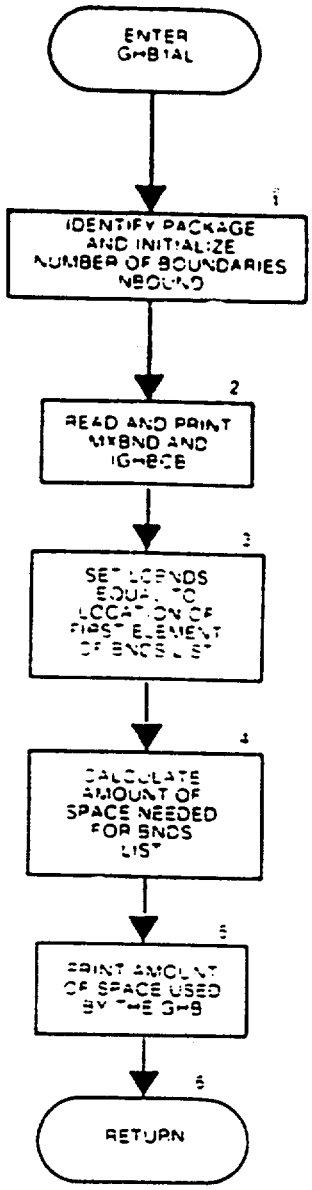
If IGHBCB > 0, it is the unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL is set.

If IGHBCB = 0, cell-by-cell flow terms will not be printed or recorded.

If IGHBCB < 0, the boundary leakage for each cell will be printed whenever ICBCFL is set.

LCBNDS is the location in the X array of the list of general-head boundaries data (BNDS).

BNDS is a table containing data for general-head boundaries.



```
      SUBROUTINE GHB1AL(ISUM,LENX,LCBNDS,NBOUND,MXBND,IN,IOUT,
     1                  IGHBCB)
C
C-----VERSION 0940 08DEC1983 GHB1AL
C     ******************************************************************
C     ALLOCATE ARRAY STORAGE FOR HEAD-DEPENDENT BOUNDARIES
C     ******************************************************************
C
C     SPECIFICATIONS:
C     ------------------------------------------------------------------
C     ------------------------------------------------------------------
C
C1------IDENTIFY PACKAGE AND INITIALIZE # OF GENERAL HEAD BOUNDS
      WRITE(IOUT,1)IN
    1 FORMAT(1HO,'GHB1 -- GHB PACKAGE, VERSION 1, 12/08/83',
     2' INPUT READ FROM UNIT',I3)
      NBOUND=0
C
C2------READ AND PRINT MXBND AND IGHBCB (MAX # OF BOUNDS AND UNIT
C2------FOR CELL-BY-CELL FLOW TERMS FOR GHB)
      READ(IN,2) MXBND,IGHBCB
    2 FORMAT(2I10)
      WRITE(IOUT,3) MXBND
    3 FORMAT(1H ,'MAXIMUM OF',I5,' HEAD-DEPENDENT BOUNDARY NODES')
      IF(IGHBCB.GT.0) WRITE(IOUT,9) IGHBCB
    9 FORMAT(1X,'CELL-BY-CELL FLOW WILL BE RECORDED ON UNIT',I3)
      IF(IGHBCB.LT.0) WRITE(IOUT,8)
    8 FORMAT(1X,'CELL-BY-CELL FLOW WILL BE PRINTED WHEN ICBCFL NOT 0')
C
C3------SET LCBNDS EQUAL TO ADDRESS OF FIRST UNUSED SPACE IN X.
      LCBNDS=ISUM
C
C4------CALCULATE AMOUNT OF SPACE USED BY THE GENERAL HEAD LIST.
      ISP=5*MXBND
      ISUM=ISUM+ISP
C
C5------PRINT AMOUNT OF SPACE USED BY THE GHB PACKAGE
      WRITE(IOUT,4) ISP
    4 FORMAT(1X,I6,' ELEMENTS IN X ARRAY ARE USED FOR HEAD',
     1       '-DEPENDENT BOUNDARIES')
      ISUM1=ISUM-1
      WRITE(IOUT,5) ISUM1,LENX
    5 FORMAT(1X,I6,' ELEMENTS OF X ARRAY USED OUT OF',I7)
      IF(ISUM1.GT.LENX) WRITE(IOUT,6)
    6 FORMAT(1X,'   ***X ARRAY MUST BE DIMENSIONED LARGER***')
C
C6------RETURN
      RETURN
      END
```

List of Variables for Module GHB1AL

Variable	Range	Definition
IGHBCB	Package	Flag and a unit number. > 0, unit number on which the cell-by-cell flow terms will be recorded whenever ICBCFL is set. = 0, cell-by-cell flow terms will not be printed or recorded. < 0, boundary leakage for each cell will be printed whenever IGHBFL is set.
IN	Package	Primary unit number from which input for this package will be read.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
ISP	Module	Number of words in the X array allocated by this module.
ISUM	Global	Index number of the lowest element in the X array which has not yet been allocated. When space is allocated for an array, the size of the array is added to ISUM.
ISUM1	Module	ISUM-1.
LCBNDS	Package	Location in the X array of the first element of array BNDS.
LENX	Global	Length of the X array in words. This should always be equal to the dimension of X specified in the MAIN program.
MXBND	Package	Maximum number of head boundaries active at any one time.
NBOUND	Package	Number of head boundaries active during the current stress period.

Narrative for Module GHB1RP

This module reads data to build the general-head boundary list.

1. Read ITMP. ITMP is the number of general-head boundaries or a flag indicating that data from the previous stress period should be reused.

2. Test ITMP. If ITMP is less than zero, the general-head boundary data read for the last stress period will be reused. Print a message to that effect and RETURN.

3. If ITMP is greater than or equal to zero, it is the number of general-head boundaries for this stress period. Set the number of general-head boundaries (NBOUND) in the current stress period equal to ITMP.

4. Compare the number of general-head boundaries (NBOUND) in the current stress period to the number specified as the maximum for the simulation (MXBND). If NBOUND is greater than MXBND, STOP.

5. Print the number of general-head boundaries in the current stress period (NBOUND).

6. See if there are any general-head boundaries. If there are none in the current stress period (NBOUND = 0), bypass further boundary processing (SKIP STEP 7).

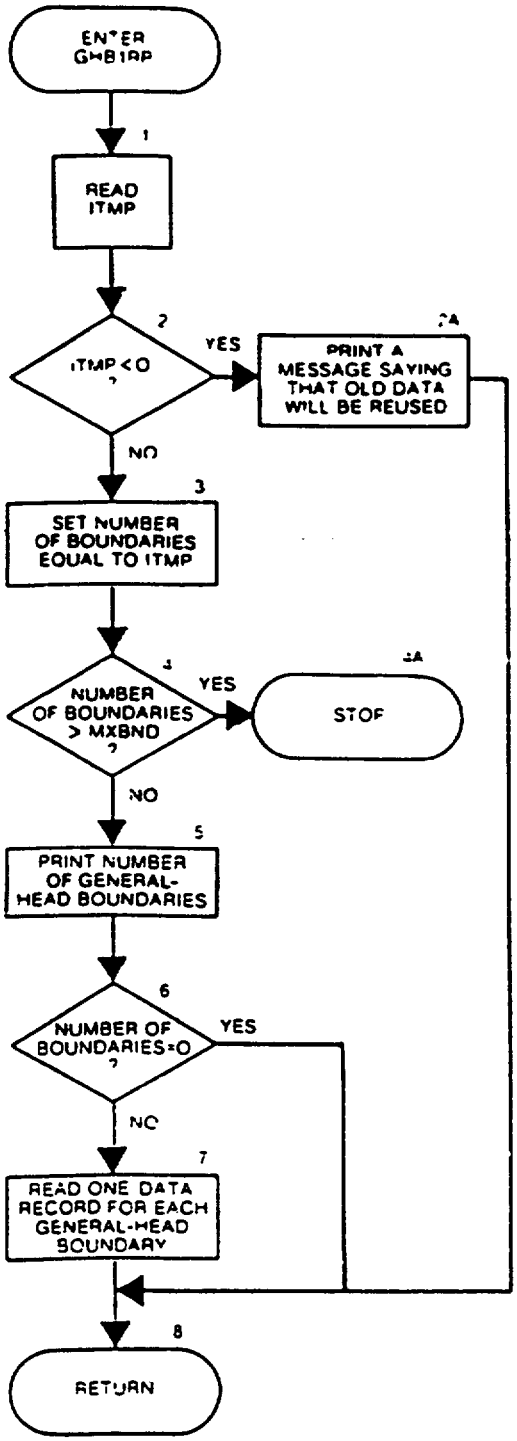
7. Read and print the layer, row, column, head, and conductance for each general-head boundary.

8. RETURN.

Flow Chart for Module GMBIRP

ITMP is both a flag and a counter. If it is greater than or equal to zero, it is the number of general-head boundaries to be simulated during the stress period. If it is less than zero, it indicates that the boundaries simulated in the last stress period should be simulated in the current stress period.

MXBND is the maximum number of general-head boundaries to be simulated.



```
      SUBROUTINE GHB1RP(BNDS,NBOUND,MXBND,IN,IOUT)
C
C
C-----VERSION 1651 02FEB1983 GHB1RP
C     ******************************************************************
C     READ DATA FOR GHB
C     ******************************************************************
C
C
C     SPECIFICATIONS:
C     ------------------------------------------------------------------
      DIMENSION BNDS(5,MXBND)
C     ------------------------------------------------------------------
C
C1------READ ITMP(# OF GENERAL HEAD BOUNDS OR FLAG TO REUSE DATA.)
      READ(IN,8) ITMP
    8 FORMAT(I10)
C
C2------TEST ITMP
      IF(ITMP.GE.0) GO TO 50
C
C2A-----IF ITMP<0 THEN REUSE DATA FROM LAST STRESS PERIOD
      WRITE(IOUT,7)
    7 FORMAT(1HO,'REUSING HEAD-DEPENDENT BOUNDS FROM LAST STRESS',
     1       ' PERIOD')
      GO TO 260
C
C3------IF ITMP=>0 THEN IT IS THE # OF GENERAL HEAD BOUNDS.
   50 NBOUND=ITMP
C
C4------IF MAX NUMBER OF BOUNDS IS EXCEEDED THEN STOP
      IF(NBOUND.LE.MXBND) GO TO 100
      WRITE(IOUT,99) NBOUND,MXBND
   99 FORMAT(1HO,'NBOUND(',I4,') IS GREATER THAN MXBND(',I4,')')
C
C4A-----ABNORMAL STOP
      STOP
C
C5------PRINT # OF GENERAL HEAD BOUNDS THIS STRESS PERIOD
  100 WRITE(IOUT,1) NBOUND
    1 FORMAT(1HO,//1X,I5,' HEAD-DEPENDENT BOUNDARY NODES')
C
C6------IF THERE ARE NO GENERAL HEAD BOUNDS THEN RETURN.
      IF(NBOUND.EQ.0) GO TO 260
C
C7------READ & PRINT DATA FOR EACH GENERAL HEAD BOUNDARY.
      WRITE(IOUT,3)
    3 FORMAT(1HO,15X,'LAYER',5X,'ROW',5X
     1,'COL   ELEVATION   CONDUCTANCE   BOUND NO.'/1X,15X,60('-'))
      DO 250 II=1,NBOUND
      READ (IN,4) K,I,J,BNDS(4,II),BNDS(5,II)
    4 FORMAT(3I10,2F10.0)
      WRITE (IOUT,5) K,I,J,BNDS(4,II),BNDS(5,II),II
    5 FORMAT(1X,15X,I4,I9,I8,G13.4,G14.4,I8)
      BNDS(1,II)=K
      BNDS(2,II)=I
      BNDS(3,II)=J
  250 CONTINUE
C
C8------RETURN
  260 RETURN
      END
```

List of Variables for Module GHB1RP

Variable	Range	Definition
BNDS	Package	DIMENSION (5,MXBND), Layer, row, column, head and conductance from boundary for each general-head boundary.
I	Module	Row number.
II	Module	Index for general-head boundaries.
IN	Package	Primary unit number from which input for this package will be read.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
ITMP	Module	Flag or number of boundaries. ≥ 0, number of bounds active during the current stress period. < 0, same bounds active during the last stress period will be active during the current stress period.
J	Module	Column number.
K	Module	Layer number.
MXBND	Package	Maximum number of head boundaries active at any one time.
NBOUND	Package	Number of head boundaries active during the current stress period.

Narrative for Module GHB1FM

This module adds terms representing riverhead boundaries to the accumulators HCOF and RHS.

1. If NBOUND is less than or equal to zero in the current stress period, there are no general-head boundaries. RETURN.

2. For each boundary in the BNDS list, DO STEPS 3-6.

3. Determine the column (IC), row (IR), and layer (IL).

4. If the cell is external (IBOUND(IC, IR, IL) $\leq$ 0), bypass processing on this boundary and go on to the next one.

5. If the cell is internal, get the boundary data (head and conductance).

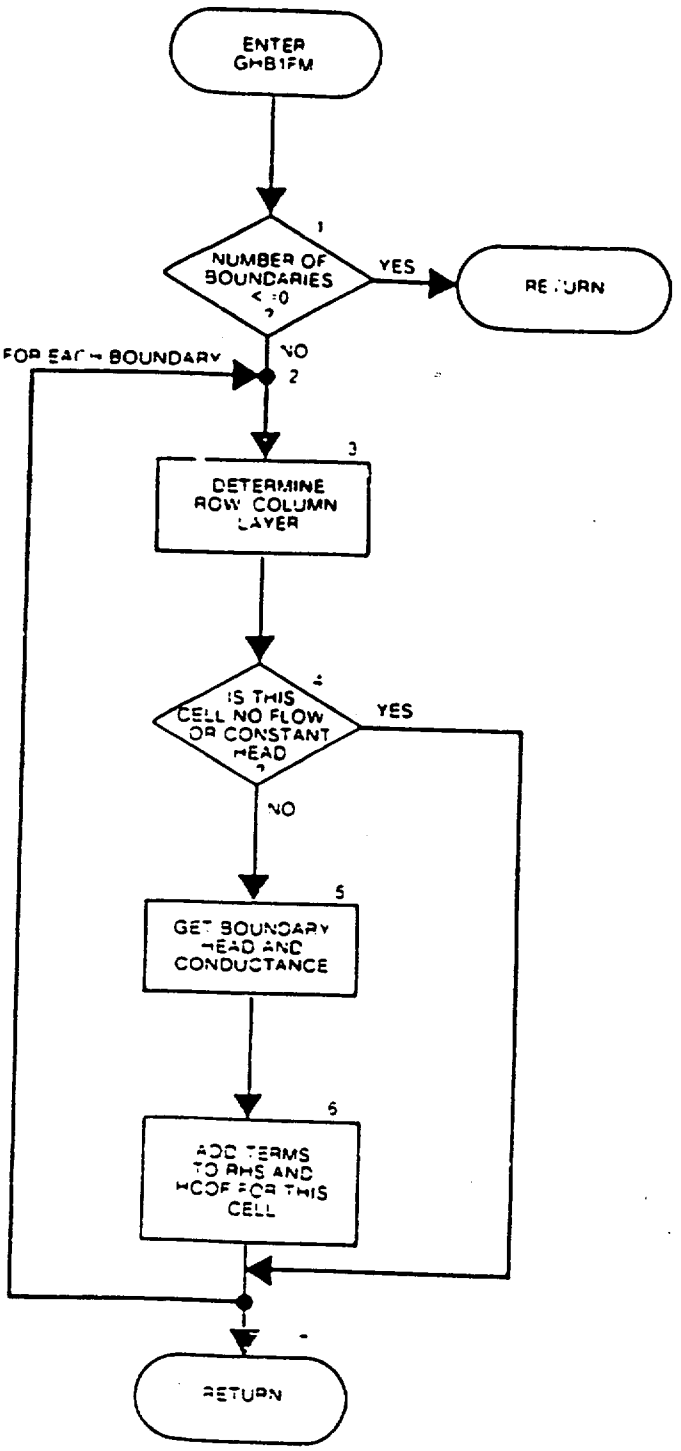
6. Add the -C*HB term (C is the conductance and HB is the boundary head) to the accumulator RHS and the term -C to the accumulator HCOF.

7. RETURN.

Flow Chart for Module GHB1FM

RHS is an accumulator in which the right hand side of the equation is formulated.

HCOF is an accumulator in which the coefficient of head in the cell is formulated.



```
      SUBROUTINE GHB1FM(NBOUND,MXBND,BNDS,HCOF,RHS,IBOUND,
     1                  NCOL,NROW,NLAY,IOUT)
C
C-----VERSION 1605 02FEB1983 GHB1FM
C     ******************************************************************
C     ADD GHB TERMS TO RHS AND HCOF
C     ******************************************************************
C
C     SPECIFICATIONS:
C     ------------------------------------------------------------------
      DIMENSION BNDS(5,MXBND),HCOF(NCOL,NROW,NLAY),
     1          RHS(NCOL,NROW,NLAY),IBOUND(NCOL,NROW,NLAY)
C     ------------------------------------------------------------------
C
C1------IF NBOUND<=0 THEN THERE ARE NO GENERAL HEAD BOUNDS. RETURN.
      IF(NBOUND.LE.0) RETURN
C
C2------PROCESS EACH ENTRY IN THE GENERAL HEAD BOUND LIST (BNDS)
      DO 100 L=1,NBOUND
C
C3------GET COLUMN, ROW AND LAYER OF CELL CONTAINING BOUNDARY
      IL=BNDS(1,L)
      IR=BNDS(2,L)
      IC=BNDS(3,L)
C
C4------IF THE CELL IS EXTERNAL THEN SKIP IT.
      IF(IBOUND(IC,IR,IL).LE.0) GO TO 100
C
C5------SINCE THE CELL IS INTERNAL GET THE BOUNDARY DATA.
      HB=BNDS(4,L)
      C=BNDS(5,L)
C
C6------ADD TERMS TO RHS AND HCOF
      HCOF(IC,IR,IL)=HCOF(IC,IR,IL)-C
      RHS(IC,IR,IL)=RHS(IC,IR,IL)-C*HB
  100 CONTINUE
C
C7------RETURN
      RETURN
      END
```

List of Variables for Module GHB1FM

Variable	Range	Definition
BNDS	Package	DIMENSION (5,MXBND), Layer, row, column, head and conductance from boundary for each general-head boundary.
C	Module	Conductance from the external boundary.
HB	Module	Head on boundary.
HCOF	Global	DIMENSION (NCOL,NROW,NLAY), Coefficient of head in the cell (J,I,K) in the finite-difference equation.
IBOUND	Global	DIMENSION (NCOL,NROW,NLAY). Status of each cell. < 0, constant-head cell = 0, inactive cell > 0, variable-head cell
IC	Module	Index for columns.
IL	Module	Index for layers.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
IR	Module	Index for rows.
L	Module	Index for boundaries.
MXBND	Package	Maximum number of head boundaries active at any one time.
NBOUND	Package	Number of head boundaries active during the current stress period.
NCOL	Global	Number of columns in the grid.
NLAY	Global	Number of layers in the grid.
NROW	Global	Number of rows in the grid.
RHS	Global	DIMENSION (NCOL,NROW,NLAY), Right hand side of the finite-difference equation. RHS is an accumulation of terms from several different packages.

Narrative for Module GHB1BD

This module calculates rates and volumes transferred between the aquifer and general-head boundaries.

1. Initialize the cell-by-cell flow-term flag (IBD) and the rate accumulator (RATOUT).

2. If there are no general-head boundaries (NBOUND = 0), skip down to step 13 and put zeros into the budget terms for general-head boundaries.

3. Test to see if cell-by-cell flow terms are to be saved on disk. They will not be saved if either of the following conditions hold: (1) this is not the proper time step (ICBCFL = 0) or (2) cell-by-cell flow terms are not needed for general-head boundaries during this simulation (IGHBCB $\leq$ 0). If cell-by-cell flow terms will be saved for this package, clear the buffer in which they will be accumulated (BUFF) and set the cell-by-cell flow-term flag (IBD).

4. For each general-head boundary, DO STEPS 5-13 accumulating flows from or into the general-head boundary.

5. Determine the row, column, and layer of the cell containing the general-head boundary.

6. If the cell is external (IBOUND(I,J,K) $\leq$ 0), bypass further processing of this boundary.

7. Get the boundary parameters from the boundary list (BNDS).

8. Set RATE equal to the boundary conductance times the boundary head minus the head in the cell (RATE = C*(HB - HHNEW)).

9. If cell-by-cell flow terms are to be printed (IGHBCB < 0 and ICBCFL ≠ 0), print RATE.

10. If budget terms for individual cells are to be saved, add the RATE to the buffer (BUFF).

11. Check to see whether flow is into or out of the aquifer.

12. If RATE is negative, add it to RATOUT.

13. If RATE is positive, add it to RATIN.

14. See if cell-by-cell flow terms for individual cells are to be saved (IBD = 1). If they are, call module UBUDSV to record the buffer (BUFF) onto disk.

15. Move RATIN and RATOUT into the VBVL array for printing by BAS1OT. Add RATIN and RATOUT multiplied by the time-step length to the volume accumulators in VBVL for printing by BAS1OT. Move the general-head boundary budget-term labels to VBNM for printing by BAS1OT.

16. Increment the budget-term counter (MSUM). See the section in the Basic Package for a detailed explanation of VBVL, VBNM, and MSUM.

17. RETURN.

Flow Chart for Module GHB1BD

IBD is a flag which, if set, causes cell-by-cell flow terms for general-head boundary to be recorded.

EXTERNAL: a cell is said to be external if it is either no flow or constant head (i.e., an equation is not formulated for the cell).

RATE is the leakage rate into the aquifer from the boundary in a cell.

BUFFER is an array in which values are stored as they are being gathered for printing or recording.

RATOUT is an accumulator to which all flows out of the aquifer are added.

RATIN is an accumulator to which all flows into the aquifer are added.

C is the conductance between the boundary and the cell.

HB is the boundary head.

HHNEW is the head in the cell.

IGHBCB is a flag and a unit number.

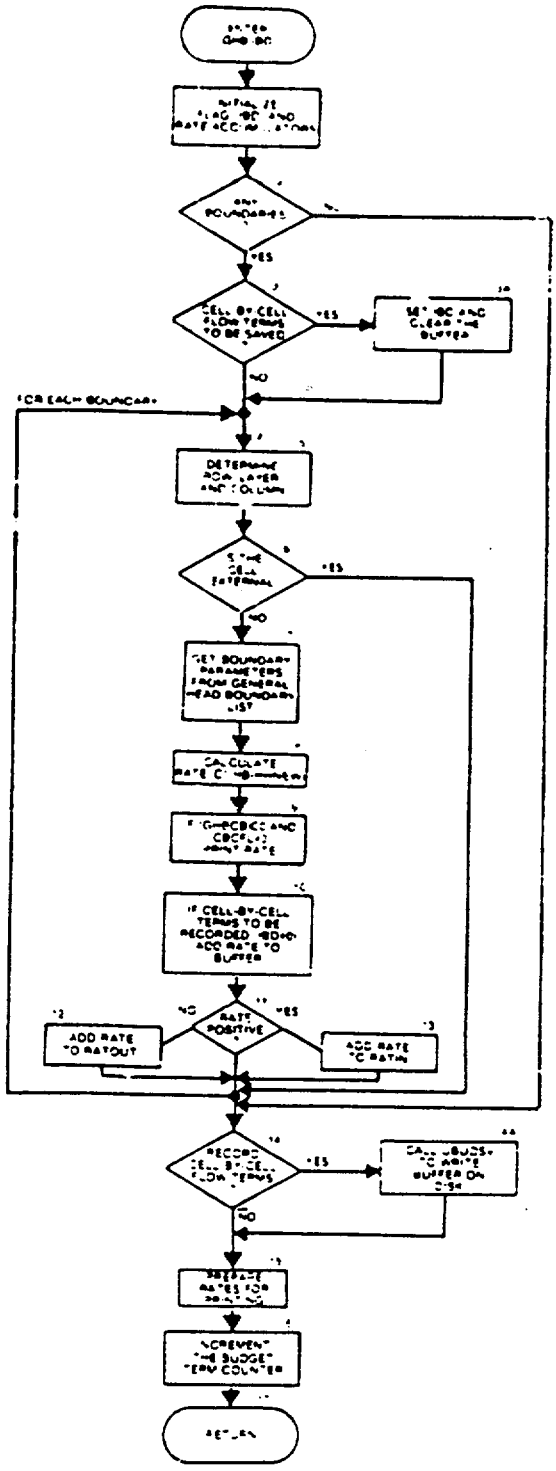
If IGHBCB > 0, it is the unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL is set.

If IGHBCB = 0, cell-by-cell flow terms will not be printed or recorded.

If IGHBCB < 0, boundary leakage for each cell will be printed whenever ICBCFL is set.

ICBCFL is a flag.

If ICBCFL ≠ 0, cell-by-cell flow terms will be either recorded or printed depending on IGHBCB for the current time step.



```
      SUBROUTINE GHB1BD(NBOUND,MXBND,VBNM,VBVL,MSUM,BNDS,DELT,HNEW,
     1   NCOL,NROW,NLAY,IBOUND,KSTP,KPER,IGHBCB,ICBCFL,BUFF,IOUT)
C
C-----VERSION 1152 20MAY1983 GHB1BD
C     ******************************************************************
C     CALCULATE VOLUMETRIC BUDGET FOR GHB
C     ******************************************************************
C
C     SPECIFICATIONS:
C     ------------------------------------------------------------------
      DOUBLE PRECISION HNEW
      DIMENSION VBNM(4,MSUM),VBVL(4,MSUM),BNDS(5,MXBND),
     1          HNEW(NCOL,NROW,NLAY),IBOUND(NCOL,NROW,NLAY),
     2          BUFF(NCOL,NROW,NLAY)
      DIMENSION TEXT(4)
      DATA TEXT(1),TEXT(2),TEXT(3),TEXT(4) /' HEA','D DE','P BO','UNDS'/
C     ------------------------------------------------------------------
C
C1------INITIALIZE CELL-BY-CELL FLOW TERM FLAG (IBD) AND
C1------ACCUMULATORS (RATIN AND RATOUT)
      IBD=0
      RATOUT=0.
      RATIN=0.
C
C2------IF NO BOUNDARIES THEN KEEP ZEROES IN ACCUMULATORS.
      IF(NBOUND.EQ.0) GO TO 200
C
C3------TEST TO SEE IF CELL-BY-CELL FLOW TERMS ARE NEEDED.
      IF(ICBCFL.EQ.0 .OR. IGHBCB.LE.0) GO TO 10
C
C3A-----SINCE CELL-BY-CELL FLOW TERMS ARE NEEDED CLEAR BUFFER & SET
C3A-----THE FLAG IBD.
      IBD=1
      DO 5 IL=1,NLAY
      DO 5 IR=1,NROW
      DO 5 IC=1,NCOL
      BUFF(IC,IR,IL)=0.
    5 CONTINUE
C
C4------FOR EACH GENERAL HEAD BOUND ACCUMULATE FLOW INTO AQUIFER
   10 DO 100 L=1,NBOUND
C
C5------GET LAYER, ROW AND COLUMN OF EACH GENERAL HEAD BOUNDARY.
      IL=BNDS(1,L)
      IR=BNDS(2,L)
      IC=BNDS(3,L)
C
C6------IF CELL IS EXTERNAL THEN IGNORE IT.
      IF(IBOUND(IC,IR,IL).LE.0) GO TO 100
C
C7------GET PARAMETERS FROM BOUNDARY LIST.
      HHNEW=HNEW(IC,IR,IL)
      HB=BNDS(4,L)
      C=BNDS(5,L)
```

```
C
C8------CALCULATE THE FOW RATE INTO THE CELL
      RATE=C*(HB-HHNEW)
C
C9------PRINT THE INDIVIDUAL RATES IF REQUESTED(IGHBCB<0).
      IF(IGHBCB.LT.0.AND.ICBCFL.NE.0) WRITE(IOUT,900) (TEXT(N),N=1,4),
     1    KPER,KSTP,L,IL,IR,IC,RATE
  900 FORMAT(1HO,4A4,'   PERIOD',I3,'   STEP',I3,'   BOUNDARY',I4,
     1     '   LAYER',I3,'   ROW',I4,'   COL',I4,'   RATE',G15.7)
C
C10-----IF CELL-BY-CELL TERMS ARE TO BE SAVED THEN PUT RATE IN BUFFER
      IF(IBD.EQ.1) BUFF(IC,IR,IL)=BUFF(IC,IR,IL)+RATE
C
C11-----SEE IF FLOW IS INTO AQUIFER OR OUT OF AQUIFER.
      IF(RATE)94,100,96
C
C12------FLOW IS OUT OF AQUIFER SUBTRACT RATE FROM RATOUT
   94 RATOUT=RATOUT-RATE
      GO TO 100
C
C13-----FLOW IS INTO AQIFER ADD RATE TO RATIN
   96 RATIN=RATIN+RATE
  100 CONTINUE
C
C14-----IF CELL-BY-CELL TERMS ARE TO BE SAVED THEN CALL
C14-----UTILITY MODULE UBUDSV
      IF(IBD.EQ.1) CALL UBUDSV(KSTP,KPER,TEXT,IGHBCB,BUFF,NCOL,NROW,
     1                         NLAY,IOUT)
C
C15-----MOVE RATES, VOLUMES AND LABELS INTO ARRAYS FOR PRINTING
  200 VBVL(3,MSUM)=RATIN
      VBVL(1,MSUM)=VBVL(1,MSUM)+RATIN*DELT
      VBVL(4,MSUM)=RATOUT
      VBVL(2,MSUM)=VBVL(2,MSUM)+RATOUT*DELT
      VBNM(1,MSUM)=TEXT(1)
      VBNM(2,MSUM)=TEXT(2)
      VBNM(3,MSUM)=TEXT(3)
      VBNM(4,MSUM)=TEXT(4)
C
C16-----INCREMENT THE BUDGET TERM COUNTER
      MSUM=MSUM+1
C
C17-----RETURN
      RETURN
      END
```

List of Variables for Module GHB1BD

Variable	Range	Definition
BNDS	Package	DIMENSION (5,MXBND), Layer, row, column, head and conductance from the boundary for each general-head boundary.
BUFF	Global	DIMENSION (NCOL,NROW,NLAY), Buffer used to accumulate information before printing or recording it.
C	Module	Conductance from the external boundary.
DELT	Global	Length of the current time step.
HB	Module	Head on boundary.
HHNEW	Module	HNEW (J,I,K), Single precision.
HNEW	Global	DIMENSION (NCOL,NROW,NLAY), Most recent estimate of head in each cell. HNEW changes at each iteration.
IBD	Package	Flag. = 0, cell-by-cell flow terms for this package will not be recorded ≠ 0, cell-by-cell flow terms for this package will be recorded.
IBOUND	Global	DIMENSION (NCOL,NROW,NLAY), Status of each cell. < 0, constant-head cell = 0, inactive cell > 0, variable-head cell
IC	Module	Index for columns.
IGHBCB	Package	Flag and a unit number. > 0, unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL is set. = 0, cell-by-cell flow terms will not be printed or recorded. < 0, boundary leakage for each cell will be printed whenever ICBCFL is set.
ICBCFL	Global	Flag. = 0, cell-by-cell flow terms will not be recorded or printed for the current time step. ≠ 0, cell-by-cell flow terms will be either printed or recorded (depending on IGHBCB) for the current time step.
IL	Module	Index for layers.
IOUT	Global	Primary unit number for all printed output. IOUT = 6.
IR	Module	Index for rows.
KPER	Global	Stress period counter.
KSTP	Global	Time step counter. Reset at the start of each stress period.
L	Module	Index for general-head boundaries.
MSUM	Global	Counter for budget entries and labels in VBVL and VBNM.
MXBND	Package	Maximum number of head boundaries active at any one time.
NBOUND	Package	Number of head boundaries active during the current stress period.
NCOL	Global	Number of columns in the grid.
NLAY	Global	Number of layers in the grid.
NROW	Global	Number of rows in the grid.

List of Variables for Module GHB1BD (Continued)

Variable	Range	Definition
RATE	Module	Flow from a bound into a cell. (Reverse the sign to get flow into the bound.)
RATIN	Module	Accumulator for the total flow into the flow field out of the bounds.
RATOUT	Module	Accumulator for the total flow out of the flow field into the bounds.
TEXT	Module	Label to be printed or recorded with the array data.
VBNM	Global	DIMENSION (4,20), Labels for entries in the volumetric budget.
VBVL	Global	DIMENSION (4,20), Entries for the volumetric budget. For flow component N, the values in VBVL are: (1,N), Rate for the current time step into the flow field. (2,N), Rate for the current time step out of the flow field. (3,N), Volume into the flow field during simulation. (4,N), Volume out of the flow field during simulation.

CHAPTER 12

STRONGLY IMPLICIT PROCEDURE PACKAGE

Conceptualization and Implementation

The Strongly Implicit Procedure (SIP) is a method for iteratively solving a large system of simultaneous linear equations.

For cell i,j,k, the finite-difference equation was shown to be of the form

$$CV_{i,j,k-1/2}h_{i,j,k-1} + CC_{i-1/2,j,k}h_{i-1,j,k} + CR_{i,j-1/2,k}h_{i,j-1,k}$$
$$+ (-CV_{i,j,k-1/2} - CC_{i-1/2,j,k} - CR_{i,j-1/2,k}$$
$$- CR_{i,j+1/2,k} - CC_{i+1/2,j,k} - CV_{i,j,k+1/2} + HCOF_{i,j,k})h_{i,j,k}$$
$$+ CR_{i,j+1/2,k}h_{i,j+1,k} + CC_{i+1/2,j,k}h_{i+1,j,k}$$
$$+ CV_{i,j,k+1/2}h_{i,j,k+1} = RHS_{i,j,k}. \qquad (79)$$

One equation of this form is written for each cell in the finite-difference grid. It expresses the relationship among the heads at node i,j,k and at each of the six adjacent nodes at the end of a time step. Because the head at any node appears in the equation for that node and in the equation for the adjoining cells, the equations must be solved simultaneously. The solution of all of the equations consists of the head for each node. The notation used in equation 79 is used to illustrate the role of conductances between nodes. It is convenient to rewrite the equation in a notation that permits easier identification of coefficients to a given equation. In the new notation, based on that of Weinstein, Stone, and Kwan (1969), the developers of SIP, equation 79 can be written

$$Z_{i,j,k}h_{i,j,k-1} + B_{i,j,k}h_{i-1,j,k} + D_{i,j,k}h_{i,j-1,k} + E_{i,j,k}h_{i,j,k}$$
$$+ F_{i,j,k}h_{i,j+1,k} + H_{i,j,k}h_{i+1,j,k} + S_{i,j,k}h_{i,j,k+1} = Q_{i,j,k}. \qquad (80)$$

Notation can be simplified by writing the system of equations in matrix form

$$\bar{\bar{A}}\bar{h} = \bar{q}. \tag{81}$$

The two bars over the $\bar{\bar{A}}$ indicate that it is a square matrix. The single bars over the $\bar{h}$ and the $\bar{q}$ indicate that they are vectors. Figure 46 shows the elements of the coefficient matrix and the two vectors. Notice that there are very few nonzero elements (the matrix is sparse) and that they are on just seven diagonals (fig. 47).

The coefficients in equation 80 all have the index i,j,k to show that they belong to the equations for node i,j,k. Furthermore, the Z coefficient for the equation at node i,j,k ($Z_{i,j,k}$), is equal to $CL_{i,j,k-1/2}$ which is the same as the S coefficient for the equation at node i,j,k-1 ($S_{i,j,k-1}$), or more succinctly,

$$Z_{i,j,k} = S_{i,j,k-1}. \tag{82}$$

Similarly,

$$B_{i,j,k} = H_{i-1,j,k} \tag{83}$$

and

$$D_{i,j,k} = F_{i,j-1,k}. \tag{84}$$

Thus the coefficient matrix, $\bar{\bar{A}}$, is symmetric (fig. 48).

Direct methods for solution of systems of simultaneous equations factor the coefficient equation, $\bar{\bar{A}}$, into two matrices, $\bar{\bar{L}}$ and $\bar{\bar{U}}$, such that in $\bar{\bar{L}}$, all of the nonzero elements are on or below the main diagonal; and in $\bar{\bar{U}}$, all of the nonzero elements are above the main diagonal (fig. 49). After factoring $\bar{\bar{A}}$, equation 81 can be solved using a method called "backward and forward

$$\bar{\bar{A}} =$$

$$\begin{bmatrix}
E_1 & F_1 & 0 & 0 & H_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
D_2 & E_2 & F_2 & 0 & 0 & H_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & D_3 & E_3 & F_3 & 0 & 0 & H_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & D_4 & E_4 & 0 & 0 & 0 & H_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
B_5 & 0 & 0 & 0 & E_5 & F_5 & 0 & 0 & H_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & B_6 & 0 & 0 & D_6 & E_6 & F_6 & 0 & 0 & H_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_6 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & B_7 & 0 & 0 & D_7 & E_7 & F_7 & 0 & 0 & H_7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_7 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & B_8 & 0 & 0 & D_8 & E_8 & 0 & 0 & 0 & H_8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_8 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & B_9 & 0 & 0 & 0 & E_9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_9 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & B_{10} & 0 & 0 & D_{10} & E_{10} & F_{10} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{10} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & B_{11} & 0 & 0 & D_{11} & E_{11} & F_{11} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{11} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{12} & 0 & 0 & D_{12} & E_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & S_{12} \\
Z_{13} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & E_{13} & F_{13} & 0 & 0 & H_{13} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & Z_{14} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & D_{14} & E_{14} & F_{14} & 0 & 0 & H_{14} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & Z_{15} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & D_{15} & E_{15} & F_{15} & 0 & 0 & H_{15} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & Z_{16} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & D_{16} & E_{16} & 0 & 0 & 0 & H_{16} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & Z_{17} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{17} & 0 & 0 & 0 & E_{17} & F_{17} & 0 & 0 & H_{17} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & Z_{18} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{18} & 0 & 0 & D_{18} & E_{18} & F_{18} & 0 & 0 & H_{18} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & Z_{19} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{19} & 0 & 0 & D_{19} & E_{19} & F_{19} & 0 & 0 & H_{19} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & Z_{20} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{20} & 0 & 0 & D_{20} & E_{20} & 0 & 0 & 0 & H_{20} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & Z_{21} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{21} & 0 & 0 & 0 & E_{21} & F_{21} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & Z_{22} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{22} & 0 & 0 & D_{22} & E_{22} & F_{22} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & Z_{23} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{23} & 0 & 0 & D_{23} & E_{23} & F_{23} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & Z_{24} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_{24} & 0 & 0 & D_{24} & E_{24}
\end{bmatrix}$$

Figure 46.—Correspondence between the finite-difference equations and the matrix equation for a grid of three rows, four columns, and two layers.

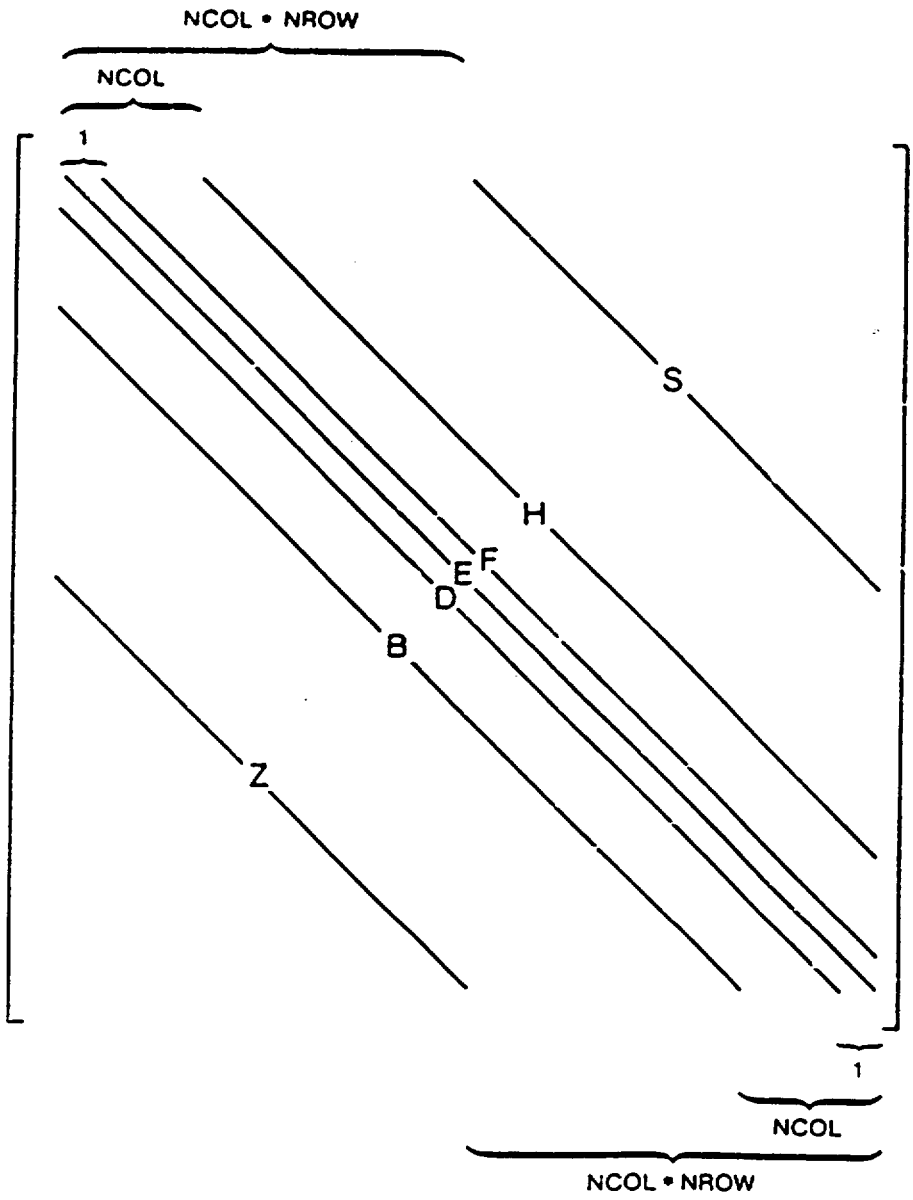


Figure 47.—Structure of coefficient matrix showing nonzero diagonals.

$E_{1,1,1}$	$F_{1,1,1}$	0	$H_{1,1,1}$	0	0	$S_{1,1,1}$	0	0	0	0	0
$F_{1,1,1}$	$E_{1,2,1}$	$F_{1,2,1}$	0	$H_{1,2,1}$	0	0	$S_{1,2,1}$	0	0	0	0
0	$F_{1,2,1}$	$E_{1,3,1}$	0	0	$H_{1,3,1}$	0	0	$S_{1,3,1}$	0	0	0
$H_{1,1,1}$	0	0	$E_{2,1,1}$	$F_{2,1,1}$	0	0	0	0	$S_{2,1,1}$	0	0
0	$H_{1,2,1}$	0	$F_{2,1,1}$	$E_{2,2,1}$	$F_{2,2,1}$	0	0	0	0	$S_{2,2,1}$	0
0	0	$H_{1,3,1}$	0	$F_{2,2,1}$	$E_{2,3,1}$	0	0	0	0	0	$S_{2,3,1}$
$S_{1,1,1}$	0	0	0	0	0	$E_{1,1,2}$	$F_{1,1,2}$	0	$H_{1,1,2}$	0	0
0	$S_{1,2,1}$	0	0	0	0	$F_{1,1,2}$	$E_{1,2,2}$	$F_{1,2,2}$	0	$H_{1,2,2}$	0
0	0	$S_{1,3,1}$	0	0	0	0	$F_{1,2,2}$	$E_{1,3,2}$	0	0	$H_{1,3,2}$
0	0	0	$S_{2,1,1}$	0	0	$H_{1,1,2}$	0	0	$E_{2,1,2}$	$F_{2,1,2}$	0
0	0	0	0	$S_{2,2,1}$	0	0	$H_{1,2,2}$	0	$F_{2,1,2}$	$E_{2,2,2}$	$F_{2,2,2}$
0	0	0	0	0	$S_{2,3,1}$	0	0	$H_{1,3,2}$	0	$F_{2,2,2}$	$E_{2,3,2}$

Figure 48.—Symmetric coefficient matrix for a grid containing two rows, three columns, and two layers.

$$\underline{\underline{A}} \qquad \bar{h} \qquad \bar{q}$$

$$\begin{bmatrix} 1 & 2 & 1 \\ -1 & 1 & 2 \\ 3 & 2 & -2 \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ h_3 \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \\ -3 \end{bmatrix}$$

$$\underline{\underline{L}} \qquad \underline{\underline{U}} \qquad \bar{h} \qquad \bar{q}$$

$$\begin{bmatrix} 1 & 0 & 0 \\ -1 & 3 & 0 \\ 3 & -4 & -1 \end{bmatrix} \begin{bmatrix} 1 & 2 & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ h_3 \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \\ -3 \end{bmatrix}$$

Figure 49.—Decomposition of a coefficient matrix into lower and upper triangular matrices.

substitution." Unfortunately, even though $\bar{\bar{A}}$ is sparse, $\bar{\bar{L}}$ and $\bar{\bar{U}}$ are not sparse: a lot of computer memory and time is needed to calculate all of the nonzero elements in $\bar{\bar{L}}$ and $\bar{\bar{U}}$. Furthermore, roundoff errors may become unacceptably large.

SIP tries to take advantage of the fact that the coefficient matrix is sparse. An attempt is made to find a matrix $\bar{\bar{B}}$ such that $\overline{\overline{A+B}}$ is "close" to $\bar{\bar{A}}$, and $\overline{\overline{A+B}}$ can be factored easily into sparse matrices $\bar{\bar{L}}$ and $\bar{\bar{U}}$. Once a matrix $\bar{\bar{B}}$ is constructed and $\bar{\bar{B}}\bar{h}$ is added to both sides of equation 81, the equation obtained is

$$(\overline{\overline{A+B}})\bar{h} = \bar{q} + \bar{\bar{B}}\bar{h}. \tag{85}$$

A vector $\bar{h}$ which is a solution to equation 85 is also a solution to equation 81. If we knew the value of the right side of equation 85, we could easily solve the equation by factoring $\overline{\overline{A+B}}$ into $\bar{\bar{L}}$ and $\bar{\bar{U}}$ and using backward and forward substitution. Of course, we do not know the value $\bar{\bar{B}}\bar{h}$. However, we could approximate it using our best estimate of $\bar{h}$. That would give rise to the iterative equation

$$(\overline{\overline{A+B}})\bar{h}^m = \bar{q} + \bar{\bar{B}}\bar{h}^{m-1}. \tag{86}$$

The vector $\bar{h}^m$ is the m-th estimate of the vector $\bar{h}$. On the first iteration ($m = 1$), the vector $\bar{h}^{m-1}$ would be the heads at the start of the time step. On subsequent iterations, $\bar{h}^{m-1}$ would be the head vector calculated at the previous iteration. The solution of equation 81 has been transformed to the problem of finding a matrix $\bar{\bar{B}}$ such that $\overline{\overline{A+B}}$ is close to $\bar{\bar{A}}$ and easily factored into lower and upper matrices $\bar{\bar{L}}$ and $\bar{\bar{U}}$, where $\bar{\bar{L}}$ and $\bar{\bar{U}}$ are sparse.

It is convenient to specify that $\bar{\bar{L}}$ and $\bar{\bar{U}}$ will not only be sparse but that each will have only four nonzero diagonals (fig. 50). Multiplication of $\bar{\bar{L}}$ and $\bar{\bar{U}}$ gives the form of $\overline{\overline{A+B}}$. There are six nonzero diagonals in $\overline{\overline{A+B}}$ that were not in $\bar{\bar{A}}$ (fig. 51). The relationship between elements in $\bar{\bar{L}}$ and $\bar{\bar{U}}$ and elements in $\overline{\overline{A+B}}$ are given by the following equations

$$Z'_{i,j,k} = a_{i,j,k} \tag{87-a}$$

$$A'_{i,j,k} = a_{i,j,k}e_{i,j,k-1} \tag{87-b}$$

$$T'_{i,j,k} = a_{i,j,k}f_{i,j,k-1} \tag{87-c}$$

$$B'_{i,j,k} = b_{i,j,k} \tag{87-d}$$

$$C'_{i,j,k} = e_{i-1,j,k}b_{i,j,k} \tag{87-e}$$

$$D'_{i,j,k} = c_{i,j,k} \tag{87-f}$$

$$E'_{i,j,k} = a_{i,j,k}g_{i,j,k-1} + b_{i,j,k}f_{i-1,j,k} + e_{i,j-1,k}c_{i,j,k}+d_{i,j,k} \tag{87-g}$$

$$F'_{i,j,k} = d_{i,j,k}e_{i,j,k} \tag{87-h}$$

$$G'_{i,j,k} = f_{i,j-1,k}c_{i,j,k} \tag{87-i}$$

$$H'_{i,j,k} = f_{i,j,k}d_{i,j,k} \tag{87-j}$$

$$U'_{i,j,k} = b_{i,j,k}g_{i-1,j,k} \tag{87-k}$$

$$R'_{i,j,k} = g_{i,j-1,k}c_{i,j,k} \tag{87-l}$$

$$S'_{i,j,k} = g_{i,j,k}d_{i,j,k} \tag{87-m}$$

If the subscript of an element in equations 87(a-m) places the element outside of the grid boundary, the element is assumed to be equal to zero. The 13 equations contain 20 unknown values, the elements of $\bar{\bar{L}}$, $\bar{\bar{U}}$, and $\overline{\overline{A+B}}$. Thus there are many matrices $\bar{\bar{B}}$ which can be added to $\bar{\bar{A}}$ so that the sum can by factored into upper and lower triangular matrices of the form of $\bar{\bar{L}}$ and $\bar{\bar{U}}$.

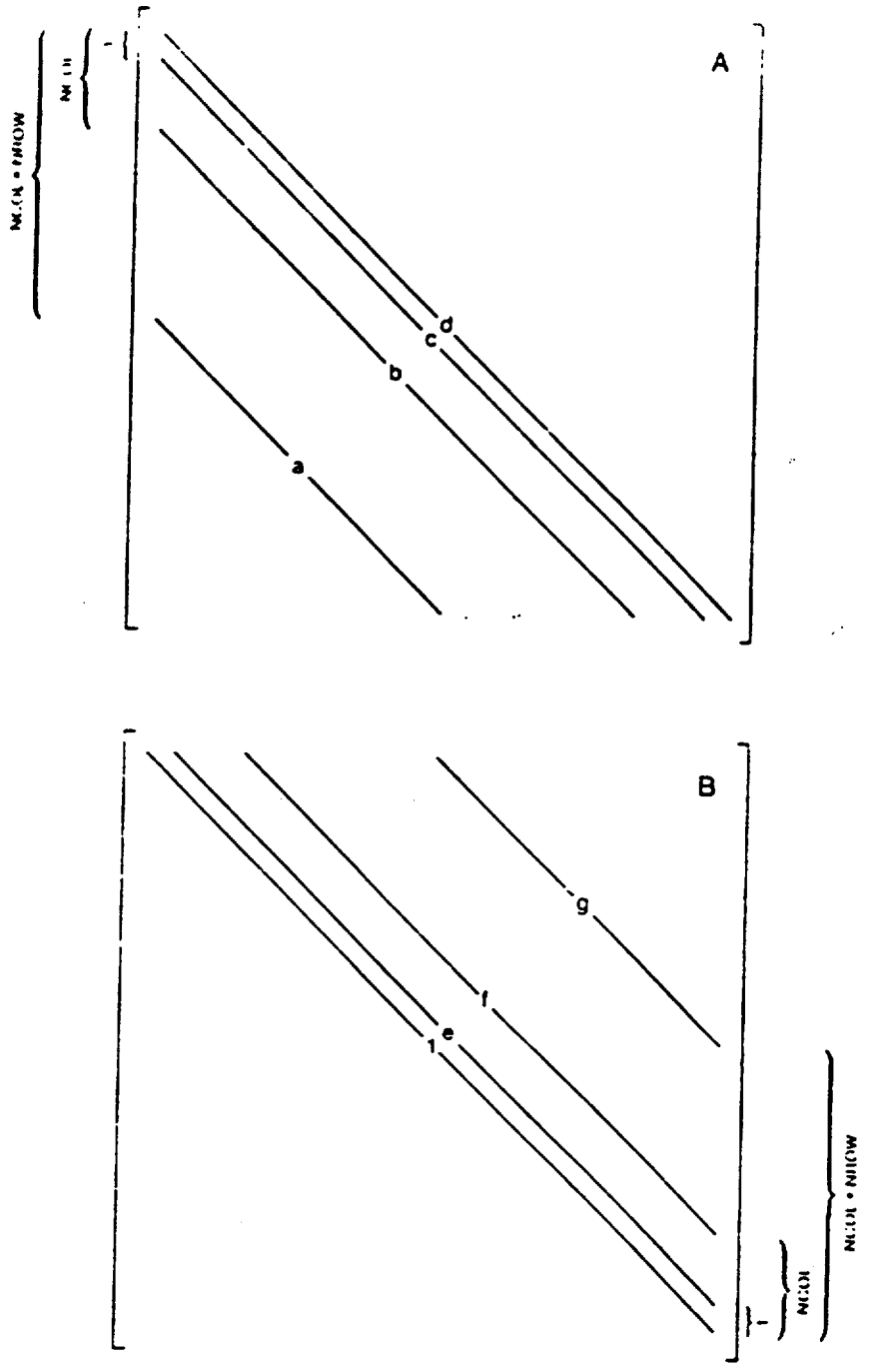


Figure 50.—Desired structure, showing nonzero diagonals, of (a) the lower triangular factor $\bar{L}$ of $\overline{A+B}$, and (b) the upper triangular factor $\bar{U}$ of $\overline{A+B}$.

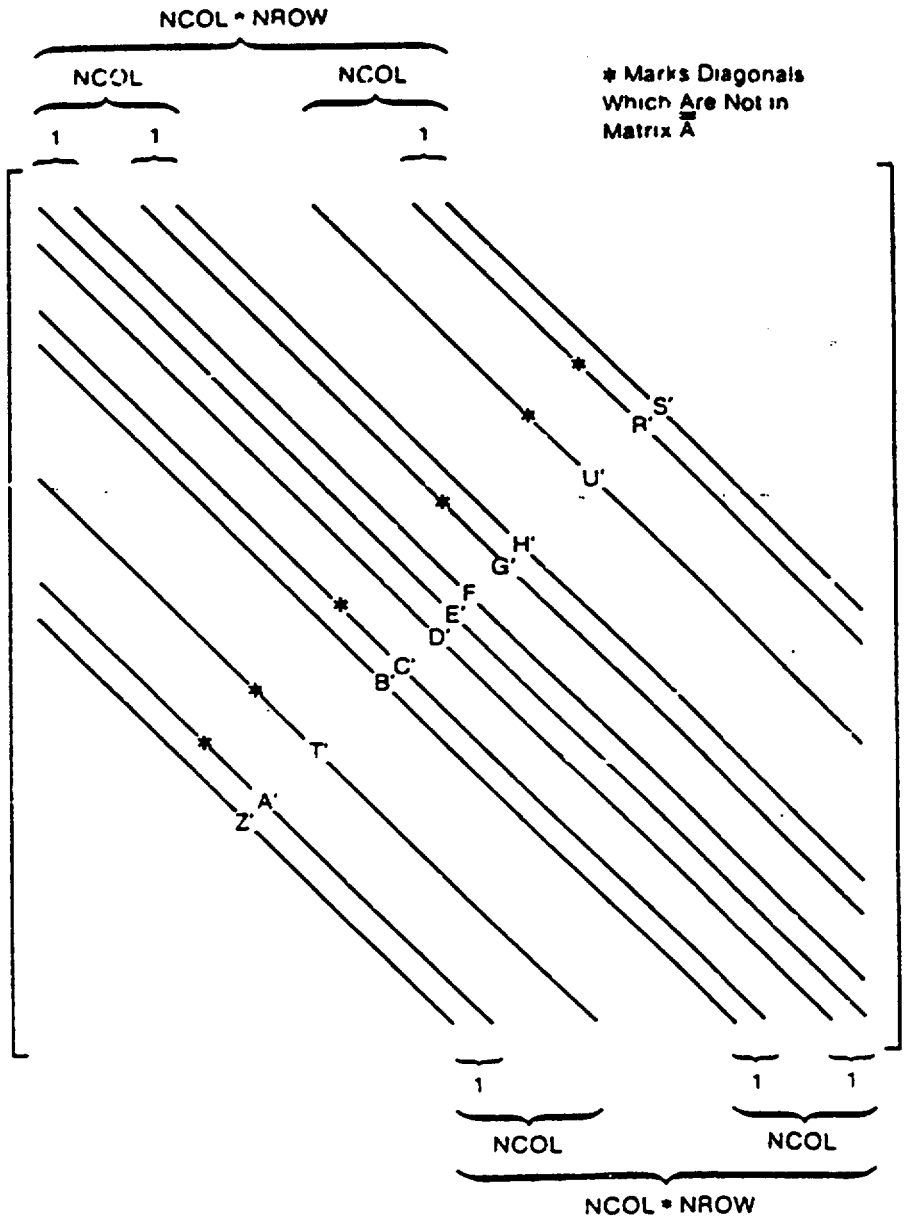


Figure 51.—Structure of matrix $\overline{A+B}$ showing nonzero diagonals.

The requirement that $\overline{\overline{A-B}}$ is "close" to $\bar{\bar{A}}$ has not been used. The term "close" can be defined by the relation

$$\bar{\bar{A}}\bar{h} = (\overline{\overline{A+B}})\bar{n}. \tag{88}$$

In terms of a single equation in the system of equations, $\overline{\overline{A+B}}$ is close to $\bar{\bar{A}}$ means that

$$\begin{aligned}
&Z'_{i,j,k}h_{i,j,k-1} + A'_{i,j,k}h_{i,j+1,k-1} + T'_{i,j,k}h_{i+1,j,k-1} \\
&+ B'_{i,j,k}h_{i-1,j,k} + C'_{i,j,k}h_{i-1,j+1,k} + D'_{i,j,k}h_{i,j-1,k} \\
&+ E'_{i,j,k}h_{i,j,k} + F'_{i,j,k}h_{i,j+1,k} + G'_{i,j,k}h_{i+1,j-1,k} \\
&+ H'_{i,j,k}h_{i+1,j,k} + U'_{i,j,k}h_{i-1,j,k+1} + R'_{i,j,k}h_{i,j-1,k+1} \\
&+ S'_{i,j,k}h_{i,j,k+1} = Z_{i,j,k}h_{i,j,k-1} + B_{i,j,k}h_{i-1,j,k} \\
&+ D_{i,j,k}h_{i,j-1,k} + E_{i,j,k}h_{i,j,k} + F_{i,j,k}h_{i,j+1,k} + H_{i,j,k}h_{i+1,j,k} \\
&+ S_{i,j,k}h_{i,j,k+1}.
\end{aligned} \tag{89}$$

Equation 89 can be rearranged so that the extra terms are on the right side and the changes in the existing terms are on the left side.

$$\begin{aligned}
&(Z_{i,j,k}-Z'_{i,j,k})h_{i,j,k-1} + (B_{i,j,k}-B'_{i,j,k})h_{i-1,j,k} \\
&+ (D_{i,j,k}-D'_{i,j,k})h_{i,j-1,k} + (E_{i,j,k}-E'_{i,j,k})h_{i,j,k} \\
&+ (F_{i,j,k}-F'_{i,j,k})h_{i,j+1,k} + (H_{i,j,k}-H'_{i,j,k})h_{i+1,j,k} \\
&+ (S_{i,j,k}-S'_{i,j,k})h_{i,j,k+1} = A'_{i,j,k}h_{i,j+1,k-1} \\
&+ T'_{i,j,k}h_{i+1,j,k-1} + C'_{i,j,k}h_{i-1,j+1,k} + G'_{i,j,k}h_{i+1,j-1,k} \\
&+ U'_{i,j,k}h_{i-1,j,k+1} + R'_{i,j,k}h_{i,j-1,k+1}
\end{aligned} \tag{90}$$

To partially cancel the effect of terms which contain head in cells not adjacent to cell i,j,k, the terms on the right side of equation 90 are multiplied by three "iteration parameters," α, β, and γ between zero and one.

$$(Z_{i,j,k}-Z'_{i,j,k})h_{i,j,k-1} + (B_{i,j,k}-B'_{i,j,k})h_{i-1,j,k}$$
$$+ (D_{i,j,k}-D'_{i,j,k})h_{i,j-1,k} + (E_{i,j,k}-E'_{i,j,k})h_{i,j,k}$$
$$+ (F_{i,j,k}-F'_{i,j,k})h_{i,j+1,k} + (H_{i,j,k}-H'_{i,j,k})h_{i+1,j,k}$$
$$+ (S_{i,j,k}-S'_{i,j,k})h_{i,j,k+1} = \alpha A'_{i,j,k}h_{i,j+1,k-1}$$
$$+ \beta T'_{i,j,k}h_{i+1,j,k-1} + \gamma C'_{i,j,k}h_{i-1,j+1,k} + \gamma G'_{i,j,k}h_{i+1,j-1,k}$$
$$+ \beta U'_{i,j,k}h_{i-1,j,k+1} + \alpha R'_{i,j,k}h_{i,j-1,k+1} \qquad (91)$$

The right side of equation 91 consists of terms which involve head in cells that are not adjacent to cell i,j,k. One such term is $\alpha A'_{i,j,k}h_{i,j+1,k-1}$. Node i,j+1,k-1 is at a corner of a rectangle; the other three corners of which i,j,k-1, i,j+1,k, and i,j,k are represented on the left side of equation 91. The head of one corner can be approximated by the sum of the heads at the adjacent corner minus the head at the opposite corner (fig. 52). Therefore,

$$h_{i,j+1,k-1} = h_{i,j+1,k} + h_{i,j,k-1} - h_{i,j,k}. \qquad (92a)$$

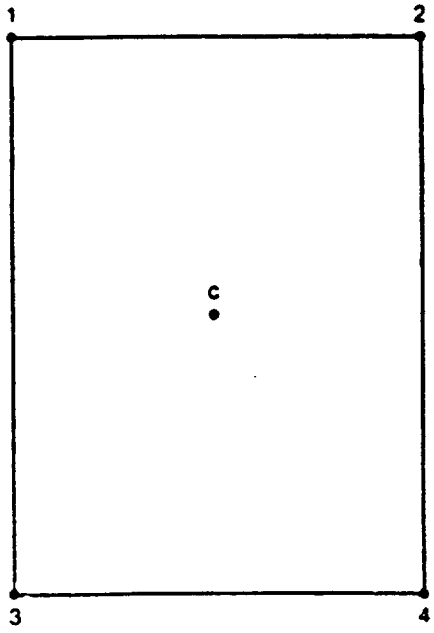
Similarly,

$$h_{i+1,j,k-1} = h_{i,j,k-1} + h_{i+1,j,k} - h_{i,j,k} \qquad (92b)$$
$$h_{i-1,j+1,k} = h_{i-1,j,k} + h_{i,j+1,k} - h_{i,j,k} \qquad (92c)$$
$$h_{i+1,j-1,k} = h_{i+1,j,k} + h_{i,j-1,k} - h_{i,j,k} \qquad (92d)$$
$$h_{i-1,j,k+1} = h_{i,j,k+1} + h_{i-1,j,k} - h_{i,j,k} \qquad (92e)$$
$$h_{i,j-1,k+1} = h_{i,j,k+1} + h_{i,j-1,k} - h_{i,j,k}. \qquad (92f)$$

Substituting equations 92(a-f) into equation 91 and reorganizing gives

$$(Z'_{i,j,k} - Z_{i,j,k} + \alpha A'_{i,j,k} + \beta T'_{i,j,k})h_{i,j,k-1}$$
$$+ (B'_{i,j,k} - B_{i,j,k} + \gamma C'_{i,j,k} + \beta U'_{i,j,k})h_{i-1,j,k}$$
$$+ (D'_{i,j,k} - D_{i,j,k} + \gamma G'_{i,j,k} + \alpha R'_{i,j,k})h_{i,j-1,k}$$
$$+ (E'_{i,j,k} - E_{i,j,k} - \alpha A'_{i,j,k} - \beta T'_{i,j,k} - \gamma C'_{i,j,k}$$
$$- \gamma G'_{i,j,k} - \beta U'_{i,j,k} - \alpha R'_{i,j,k})h_{i,j,k}$$
$$+ (F'_{i,j,k} - F_{i,j,k} + \alpha A'_{i,j,k} + \gamma C'_{i,j,k})h_{i,j+1,k}$$
$$+ (H'_{i,j,k} - H_{i,j,k} + \beta T'_{i,j,k} + \gamma G'_{i,j,k})h_{i+1,j,k}$$
$$+ (S'_{i,j,k} - S_{i,j,k} + \beta U'_{i,j,k} + \alpha R'_{i,j,k})h_{i,j,k+1} = 0. \qquad (93)$$

Suppose the Function f Is Known at 2, 3 and 4



By Simple Interpolation the Function at the Center Can Be Approximated by

$$f_1(c) \approx \frac{f(2) + f(3)}{2}$$

and

$$f_2(c) \approx \frac{f(1) + f(4)}{2}$$

Suppose

$$f_1(c) \approx f_2(c)$$

Then

$$\frac{f(2) + f(3)}{2} \approx \frac{f(1) + f(4)}{2}$$

Therefore

$$f(1) \approx f(2) + f(3) - f(4)$$

Figure 52.—Estimation of a function at one corner of a rectangle in terms of the function at the other three corners.

The relation in equation 93 holds only if each coefficient is approximately equal to zero. Setting them equal to zero yields the equations

$$Z'_{i,j,k} - Z_{i,j,k} + \alpha A'_{i,j,k} + \beta T'_{i,j,k} = 0 \tag{94a}$$

$$B'_{i,j,k} - B_{i,j,k} + \gamma C'_{i,j,k} + \beta U'_{i,j,k} = 0 \tag{94b}$$

$$D'_{i,j,k} - D_{i,j,k} + \gamma G'_{i,j,k} + \alpha R'_{i,j,k} = 0 \tag{94c}$$

$$\begin{aligned} E'_{i,j,k} - E_{i,j,k} &- \alpha A'_{i,j,k} - \beta T'_{i,j,k} \\ &- \gamma C'_{i,j,k} - \gamma G'_{i,j,k} \\ &- \beta U'_{i,j,k} - \alpha R'_{i,j,k} = 0 \end{aligned} \tag{94d}$$

$$F'_{i,j,k} - F_{i,j,k} + \alpha A'_{i,j,k} + \gamma C'_{i,j,k} = 0 \tag{94e}$$

$$H'_{i,j,k} - H_{i,j,k} + \beta T'_{i,j,k} + \gamma G'_{i,j,k} = 0 \tag{94f}$$

$$S'_{i,j,k} - S_{i,j,k} + \beta U'_{i,j,k} + \alpha R'_{i,j,k} = 0 \tag{94g}$$

Equations 94(a-g) and 87(a-m) form a system of 20 equations in 20 unknowns which when solved, will yield the entries of $\overline{\overline{A+B}}$, $\overline{\overline{L}}$, and $\overline{\overline{U}}$. For example, substituting equations 87-a, b, and c into equation 94(a) and rearranging yields

$$a_{i,j,k} = Z_{i,j,k}/(1 + \alpha e_{i,j,k-1} + \beta f_{i,j,k-1}). \tag{95a}$$

Similarly,

$$b_{i,j,k} = B_{i,j,k}/(1 + \gamma e_{i-1,j,k} + \beta g_{i-1,j,k}) \tag{95b}$$

$$c_{i,j,k} = D_{i,j,k}/(1 + \gamma f_{i,j-1,k} + \alpha g_{i,j-1,k}) \tag{95c}$$

$$A'_{i,j,k} = a_{i,j,k} e_{i,j,k-1} \tag{95d}$$

$$C'_{i,j,k} = e_{i-1,j,k} b_{i,j,k} \tag{95e}$$

$$G'_{i,j,k} = f_{i,j-1,k} c_{i,j,k} \tag{95f}$$

$$R'_{i,j,k} = g_{i,j-1,k} c_{i,j,k} \tag{95g}$$

$$T'_{i,j,k} = a_{i,j,k} f_{i,j,k-1} \tag{95h}$$

$$U'_{i,j,k} = b_{i,j,k} g_{i-1,j,k} \tag{95i}$$

$$d_{i,j,k} = E_{i,j,k} + \alpha A'_{i,j,k} + \beta T'_{i,j,k} + \gamma C'_{i,j,k} + \gamma G'_{i,j,k} + \beta U'_{i,j,k} + \alpha R'_{i,j,k} - a_{i,j,k} g_{i,j,k-1} - b_{i,j,k} f_{i-1,j,k} - e_{i,j-1,k} c_{i,j,k} \tag{95j}$$

$$e_{i,j,k} = (F_{i,j,k} - \alpha A'_{i,j,k} - \gamma C'_{i,j,k})/d_{i,j,k} \tag{95k}$$

$$f_{i,j,k} = (H_{i,j,k} - \beta T'_{i,j,k} - \gamma G'_{i,j,k})/d_{i,j,k} \tag{95l}$$

$$g_{i,j,k} = (S_{i,j,k} - \alpha R'_{i,j,k} - \beta U'_{i,j,k})/d_{i,j,k} \tag{95m}$$

Recall that the goal was to find a matrix $\bar{\bar{B}}$ such that $\overline{\overline{A+B}}$ is close to $\bar{\bar{A}}$, and $\overline{\overline{A+B}}$ can be factored into sparse lower and upper matrices $\bar{\bar{L}}$ and $\bar{\bar{U}}$. The matrix $\bar{\bar{B}}$ could then be used to solve the iterative equation

$$(\overline{\overline{A+B}})\bar{h}^m = \bar{q} + \bar{\bar{B}}\bar{h}^{m-1}. \tag{96}$$

To reduce rounding errors, equation 96 can be reformulated. Subtracting the term $(\overline{\overline{A+B}})h^{m-1}$ from both sides yields

$$(\overline{\overline{A+B}})(\bar{h}^m - \bar{h}^{m-1}) = \bar{q} - \bar{\bar{A}}\bar{h}^{m-1}. \tag{97}$$

Replacing the matrix $\overline{\overline{A+B}}$ with the product $\overline{\overline{LU}}$ yields

$$\overline{\overline{LU}}(\bar{h}^m - \bar{h}^{m-1}) = \bar{q} - \bar{\bar{A}}\bar{h}^{m-1}. \tag{98}$$

The vector $\overline{RES}^m$ can be defined by the equation

$$\overline{RES}^m = \bar{q} - \bar{\bar{A}}\bar{h}^{m-1}. \tag{99}$$

Then equation 96 can be written

$$\overline{\overline{LU}}(\bar{h}^m - \bar{h}^{m-1}) = \overline{RES}^m. \tag{100}$$

The problem of solving the equation

$$\bar{\bar{A}}\bar{h} = \bar{q} \tag{101}$$

for the head distribution $\bar{h}$ has been converted to iteratively solving equation 100. Matrices $\bar{\bar{L}}$ and $\bar{\bar{U}}$ can be derived from equations 95(a-m). Vector $\overline{RES}^m$ can be calculated from the vectors $\bar{q}$, $\bar{h}^{m-1}$ (head calculated at the previous iteration) and the coefficient matrix $\bar{\bar{A}}$. Equation 100 can be solved using first "forward" and then "back" substitution.

The first step is to perform forward substitution on the matrix equation

$$\bar{\bar{L}}\bar{v} = \overline{RES}^m \tag{102}$$

solving for $\bar{v}$, where $\bar{v} = \bar{\bar{U}}(\bar{h}^m - \bar{h}^{m-1})$. Then perform back substitution on the equation

$$\bar{\bar{U}}(\bar{h}^m - \bar{h}^{m-1}) = \bar{v} \tag{103}$$

solving for $(\bar{h}^m - \bar{h}^{m-1})$. In earlier discussions, the coefficients of the equations and hence the elements of the matrices are identified by the indices of the cells. At this point, it is convenient to renumber the equations sequentially starting with one (fig. 53).

Because all elements in $\bar{\bar{L}}$ to the right of the main diagonal (fig. 50(a)) are equal to zero, the first linear equation represented by matrix equation 102 is

$$d_1 v_1 = RES_1^m. \tag{104}$$

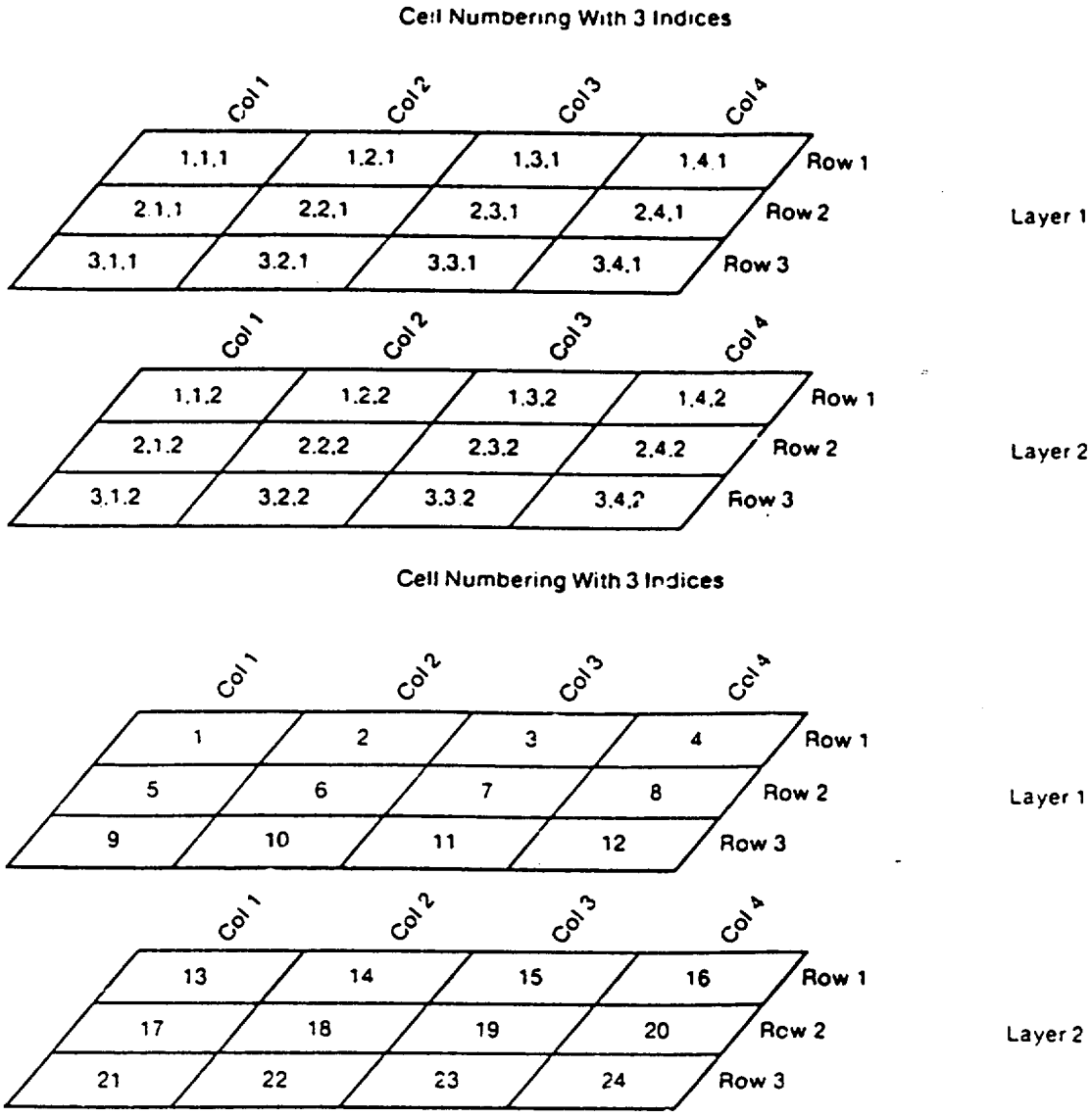


Figure 53.—Cell numbering schemes for a grid using three indices and using one index.

The only unknown is v_1. Dividing both sides of equation 104 by d_1 gives the value of v_1. The second linear equation represented by matrix equation 102 is

$$c_2 v_1 + d_2 v_2 = RES_2^m . \tag{105}$$

The value of v_1 was calculated using the first equation; the only unknown is v_2--it too can be found by simple algebra. Similarly, all of the other elements of the vector $\bar{v}$ can be calculated using the general equation

$$v_n = (\overline{RES}_n^m - a_n v_n - NRC - b_n v_n - NCOL - c_n v_{n-1})/d_n. \tag{106}$$

The reason equation 93 can be solved so easily is because the matrix $\bar{\bar{L}}$ has nothing but zeros to the right of the main diagonal--it is lower triangular. Thus starting at the top, each linear equation contains only one value in $\bar{v}$ that was not calculated in an earlier equation. The technique used here to solve equation 102 for $\bar{v}$ is called forward substitution.

Back substitution is similar to forward substitution. Since $\bar{\bar{U}}$ is upper triangular, however, the order of solution is reversed. The result of back substitution applied to equation 103 is the vector $(\bar{h}^m - \bar{h}^{m-1})$. That vector can be added to the vector $\bar{h}^{m-1}$ to get the vector $\bar{h}^m$. The vector $\bar{h}^m$ is the m-th estimate of the head distribution $\bar{h}$ which is, in turn, a solution to the equation

$$\bar{\bar{A}}\bar{h} = \bar{q}. \tag{107}$$

In summary, SIP is an iterative procedure which calculates a sequence of head distributions $\bar{h}^1$, $\bar{h}^2$..., $\bar{h}^m$ which converge to $\bar{h}$, the solution of $\bar{\bar{A}}\bar{h} = \bar{q}$. Each head distribution consists of a value of head for each active cell. A head distribution $\bar{h}^m$ is obtained by calculating a lower triangular

matrix $\bar{\bar{L}}$ and an upper triangular matrix $\bar{\bar{U}}$ such that $\overline{\overline{LU}}$ is "close" to $\bar{\bar{A}}$. Then the equation

$$\overline{\overline{LU}}(h^m - h^{m-1}) = q - Ah^{m-1} \qquad (108)$$

is solved for the head difference, $\bar{h}^m - \bar{h}^{m-1}$, using first forward and then back substitution. The head difference is added to $\bar{h}^{m-1}$ to get $\bar{h}^m$.

Two further modifications of the procedure must be described. There are times when the method consistently overestimates the vector $\bar{h}^m - \bar{h}^{m-1}$. That overestimation may prevent convergence to $\bar{h}$. An acceleration parameter (ACCL) between zero and one has been introduced which multiplies the right side of equation 108. It provides the user with a means of dampening the overestimation.

Experience has shown that if the finite-difference equations are solved in two different orders on alternate iterations, the number of iterations needed to converge to a solution is lower than it would be if just one order were used. The order used in the discussion, so far, for solving the equations, has been to start at the first column, the first row, and the first layer and to proceed in ascending column order, ascending row order, and ascending layer order. An alternative is to start at the first column, the last row, and the last layer and to proceed in ascending column order, descending row order, and descending layer order. Using the same ordering of diagonal names used in figure 51, equations similar to equations 97(a-m) can be developed. They are

$$a_{i,j,k} = Z_{i,j,k}/(1+\alpha e_{i,j,k+1} + \beta f_{i,j,k+1}) \quad (109a)$$

$$b_{i,j,k} = B_{i,j,k}/(1+\gamma e_{i+1,j,k} + \beta g_{i+1,j,k}) \quad (109b)$$

$$c_{i,j,k} = D_{i,j,k}/(1+\gamma f_{i,j-1,k} + \alpha g_{i,j-1,k}) \quad (109c)$$

$$A'_{i,j,k} = a_{i,j,k} e_{i,j,k+1} \quad (109d)$$

$$C'_{i,j,k} = e_{i+1,j,k} b_{i,j,k} \quad (109e)$$

$$G'_{i,j,k} = f_{i,j-1,k} c_{i,j,k} \quad (109f)$$

$$R'_{i,j,k} = g_{i,j-1,k} c_{i,j,k} \quad (109g)$$

$$T'_{i,j,k} = a_{i,j,k} f_{i,j,k+1} \quad (109h)$$

$$U'_{i,j,k} = b_{i,j,k} g_{i+1,j,k} \quad (109i)$$

$$\begin{aligned} d_{i,j,k} = {} & E_{i,j,k} + \alpha A'_{i,j,k} + \beta T'_{i,j,k} \\ & + \gamma C'_{i,j,k} + \gamma G'_{i,j,k} + \beta U'_{i,j,k} \\ & + \alpha R'_{i,j,k} - a_{i,j,k} g_{i,j,k+1} - b_{i,j,k} f_{i+1,j,k} \\ & - e_{i,j-1,k} c_{i,j,k} \end{aligned} \quad (109j)$$

$$e_{i,j,k} = (F_{i,j,k} - \alpha A'_{i,j,k} - \gamma C'_{i,j,k})/d_{i,j,k} \quad (109k)$$

$$f_{i,j,k} = (H_{i,j,k} - \beta T'_{i,j,k} - \gamma G'_{i,j,k})/d_{i,j,k} \quad (109l)$$

$$g_{i,j,k} = (S_{i,j,k} - \alpha R'_{i,j,k} - \beta U'_{i,j,k})/d_{i,j,k} \quad (109m)$$

Implementation of the concepts presented in the previous section entails setting up and solving either equations 95(a-m) or 109(a-m) to get the elements of matrices $\bar{\bar{L}}$ and $\bar{\bar{U}}$, solving for the vertors $\bar{v}$ and $(\bar{h}^m - \bar{F}^{m-1})$, and finally calculating the vector $\bar{h}^m$.

The first step is to select the three sequences of iteration parameters α, β, and γ. Selection of those parameters is based primarily on experience. Selection of the iteration parameters does not alter the value of the solution, only the efficiency of the solution method. It has been observed that all three sequences can be set equal to each other. Thus we will use a single sequence designated ω.

Although iteration parameters are an important part of the SIP solution process, how to select the parameters is not well understood. The number of parameters, their values, and the order of cycling through them must be chosen. Weinstein, Stone, and Kwan (1969) use the same set of parameters for all three planes and use from 4 to 10 parameters. Numerous methods of cycling the parameters have been used. Trescott, Pinder, and Larson (1976) tested different parameter ordering in two-dimensional problems and found that repeated cycling through the parameters in the order of smallest to largest worked well for a variety of problems. That method of cycling is used in this program.

The selection of the iteration parameters themselves is the most critical for the efficient operation of SIP. It has been customary to base the selection of parameters on one minus the maximum parameter, called the "seed" in this report. The equation for the iteration parameters is

$$\omega(\ell) = 1-SEED^{\ell-1/L-1} \qquad \ell = 1,2,\ldots NPARM \qquad (110)$$

where

ℓ is an index going from 1 to the number of iteration parameters;

$\omega(\ell)$ is the ℓth iteration parameter;

NPARM is the number of iteration parameters; and

L is the number of iteration parameters.

Using this equation leaves only the seed to be specified. This choice is not straightforward and, accordingly, the user is given the choice of specifying the seed or permitting the model to calculate it.

The equation used to calculate the seed in the model is based on the equation developed to define the minimum iteration parameter for the Alternating Direction Implicit Procedure (ADIP) solution process. That the ADIP equation has any value for use with SIP is simply an empirical result (Weinstein, Stone, and Kwan, 1969). The equation is

$$\text{SEED} = \underset{\text{of}}{\text{minimum}} \left[2\text{NCOL}^2\frac{\pi^2}{2}(1+\rho 1),\ 2\text{NROW}^2\frac{\pi^2}{2}(1+\rho 2),\ 2\text{NLAY}^2\frac{\pi^2}{2}(1+\rho 3)\right], \tag{111}$$

$$\text{where } \rho 1 = \frac{\text{KC DELR}^2}{\text{KR DELC}^2} + \frac{\text{KV DELC}^2}{\text{KR DELV}^2} \tag{112}$$

$$\rho 2 = \frac{\text{KR DELC}^2}{\text{KC DELR}^2} + \frac{\text{KV DELC}^2}{\text{KC DELV}^2} \tag{113}$$

$$\rho 3 = \frac{\text{KR DELV}^2}{\text{KV DELR}^2} + \frac{\text{KC DELV}^2}{\text{KV DELC}^2} \tag{114}$$

where

NCOL is the number of columns in the model grid;

NROW is the number of rows in the model grid;

NLAY is the number of layers in the model grid;

KC is the hydraulic conductivity in the column direction;

KR is the hydraulic conductivity in the row direction;

KV is the hydraulic conductivity in the vertical direction;

DELC is the cell width in the column direction;

DELR is the cell width in the row direction; and

DELV is the cell width in the vertical direction.

The ADIP equation was developed assuming a uniform grid and homogeneous medium; that is, KC, KR, KV, DELR, DELC, and DELV were assumed constant. For non-uniform grids or nonhomogeneous mediums, Weinstein, Stone, and Kwan (1969) calculate equation 33 at every cell and take the overall minimum. In this

program, an average of the values calculated by applying equation 111 to every cell is used. Using the average prevents a single cell with unusual properties from dominating the calculation.

The $\rho 1$, $\rho 2$, and $\rho 3$ terms are modified to use conductance producing

$$\rho 1 = \frac{CC + CV}{CR} \tag{115}$$

$$\rho 2 = \frac{CR + CV}{CC} \tag{116}$$

$$\rho 3 = \frac{CR + CC}{CV} \tag{117}$$

where

CC is the cell conductance in the column direction;

CR is the cell conductance in the row direction; and

CV is the cell conductance in the vertical direction.

Equations 115-117 require conductances at a cell; however, these values are not known to the model program. Only conductances between nodes are defined. Therefore, equations 115-117 are rewritten in terms of conductances between nodes. Wherever a value of cell conductance is required in equations 115-117, one of the two values of conductance between the two neighboring nodes in the required direction is selected so that the resulting seed is minimized. The resulting equations defining $\rho 1$, $\rho 2$, and $\rho 3$ are

$$\rho 1 = \frac{MAX(B,H) + MAX(Z,S)}{MIN(D,F)} \tag{118}$$

$$\rho 2 = \frac{MAX(D,F) + MAX(Z,S)}{MIN(B,H)} \tag{119}$$

$$\rho 3 = \frac{MAX(D,F) + MAX(B,H)}{MIN(Z,S)} \tag{120}$$

where

MAX is a mathematical function specifying the maximum of the values in parentheses;

MIN is a similar function specifying the minimum of values; and

B, H, Z, S, D, and F are the conductances as used in equation 80.

Experience has shown that setting the acceleration parameter (ACCL) to one and using the calculated value of the seed often results in inefficient convergence. Optimum convergence occurs when the convergence criterion is met with the least number of iterations. Convergence deviates from the optimum if the absolute value of head change each iteration is consistently either too small or too large. When head change is consistently too large, head overshoots the correct value and oscillations of head occurs. The sign of the head change repeatedly reverses in order to compensate for the overshoot. Severe overshoot causes divergence while moderate overshoot simply slows down convergence. When head change is consistently too small, the opposite problem occurs; head approaches the correct value slowly. In severe situations, the head-change criterion for convergence may be met, but the head will be far from the correct value. In such situations, a significant volumetric budget imbalance will occur.

Weinstein, Stone, and Kwan (1969) suggest that a trial and error method be used to improve the choice of the seed. Thus provisions have been made to permit the user to specify the seed. By observing the rate of convergence for several different seeds, an optimal seed can be selected.

The similarity between equations 95(a-m) and 109(a-m) was used to produce a system of equations with single indices taking on different values to

reflect the ordering of the equations. Since element v_n of the v vector can be calculated as soon as the n-th row of the $\underset{\sim}{L}$ matrix and $\underset{\sim}{U}$ matrix has been calculated, we can include the equation for $\bar{v}_n$ as the last equation in the list. The index nll refers to the cell in the last layer to be calculated which is in the same row and column as cell n. The indices nrl and ncl are defined analogously. The equations are

$$a_n = Z_n/(1 + \omega(e_{nll} + f_{nll})) \tag{121a}$$

$$b_n = B_n/(1 + \omega(e_{nrl} + g_{nrl})) \tag{121b}$$

$$c_n = D_n/(1 + \omega(f_{ncl} + g_{ncl})) \tag{121c}$$

$$A'_n = a_n e_{nll} \tag{121d}$$

$$C'_n = b_n e_{nrl} \tag{121e}$$

$$G'_n = c_n f_{ncl} \tag{121f}$$

$$R'_n = c_n g_{ncl} \tag{121g}$$

$$T'_n = a_n f_{nll} \tag{121h}$$

$$U'_n = b_n g_{nrl} \tag{121i}$$

$$d_n = E_n + \omega(A'_n + T'_n + C'_n + G'_n + U'_n + R'_n) - a_n g_{nll} - b_n f_{nrl} - c_n e_{ncl} \tag{121j}$$

$$e_n = (F_n - \omega(A'_n + C'_n))/d_n \tag{121k}$$

$$f_n = (H_n - \omega(T'_n + G'_n))/d_n \tag{121l}$$

$$g_n = (S_n - \omega(R'_n + U'_n))/c_n \tag{121m}$$

$$v_n = (RES_n - a_n v_{nll} - b_n v_{nrl} - c_n v_{ncl})/d_n \tag{121n}$$

Since the backward substitution requires all values of e_n, f_n, g_n, and v_n, space will have to be allocated in the SIP Package for four arrays to store those values. Each array has as many elements as there are cells in the grid.

The coefficient matrix $\bar{\bar{A}}$ is sparse with only seven nonzero diagonals. Rather than passing an entire matrix to the SIP Package, only the nonzero diagonals are passed. Because of symmetry of the matrix, only the main diagonal and the three lower diagonals are needed. The three lower diagonals correspond to the conductance arrays CC, CR, and CV. The main diagonal is formed from the three conductance arrays and the array HCOF described in chapter 2. The right hand side of the matrix equation, $\bar{q}$, corresponds to the array RHS described in chapter 2. The latest estimate of the head distribution, $\bar{h}^{m-1}$, corresponds to the array HNEW As new estimates of head are calculated by SIP, they are stored in HNEW replacing the previous estimates. Thus input to SIP consists of the following arrays: CC, CR, CV, RHS, HCOF, and HNEW. Output from SIP consists of a new HNEW. As explained in chapter 3, the Formulate Procedure is inside the iteration loop; therefore, the input arrays may be modified at each iteration.

Strongly Implicit Procedure Package Input

Input to the Strongly Implicit Procedure (SIP) Package is read from the unit specified in IUNIT(9).

FOR EACH SIMULATION

SIP1AL

1.	Data:	MXITER	NPARM
	Format:	I10	I10

SIP1RP

2.	Data:	ACCL	HCLOSE	IPCALC	WSEED	IPRSIP
	Format:	F10.0	F10.0	I10	F10.0	I10

Explanation of Fields Used in Input Instructions

MXITER--is the maximum number of times through the iteration loop in one time step in an attempt to solve the system of finite-difference equations. Fifty iterations are generally sufficient.

NPARM--is the number of iteration parameters to be used. Five parameters are generally sufficient.

ACCL--is the acceleration parameter. It must be greater than zero and is generally equal to one. If a zero is entered, it is changed to one.

HCLOSE--is the head change criterion for convergence. When the maximum absolute value of head change from all nodes during an iteration is less than or equal to HCLOSE, iteration stops.

IPCALC--is a flag indicating where the iteration parameter seed will come from.

0 - the seed will be entered by the user.

1 - the seed will be calculated at the start of the simulation from problem parameters.

WSEED--is the seed for calculating iteration parameters. It is only specified if IPCALC is equal to zero.

IPRSIP--is the printout interval for SIP. If IPRSIP is equal to zero, it is changed to 999. The maximum head change (positive or negative) is printed for each iteration of a time step whenever the time step is an even multiple of IPRSIP. This printout also occurs at the end of each stress period regardless of the value of IPRSIP.

SAMPLE INPUT TO THE SIP PACKAGE(USER SPECIFIES THE SEED)

DATA ITEM	EXPLANATION	INPUT RECORDS				
1	(MXITER, NPARM)	50	5			
2	(ACCL, HCLOSE, IPCALC, WSEED, IPRSIP)	.5	.01	0	.98	1

SAMPLE INPUT TO THE SIP PACKAGE(PROGRAM CALCULATES THE SEED)

DATA ITEM	EXPLANATION	INPUT RECORDS				
1	(MXITER, NPARM)	100	6			
2	(ACCL, HCLOSE, IPCALC, WSEED, IPRSIP)	1.	.01	1		

Module Documentation for the Strongly Implicit Procedure Package

The Stongly Implicit Procedure Package (SIP1) consists of three primary modules and two submodules. They are:

Primary Modules

SIP1AL	Allocates space for SIP work arrays.
SIP1RP	Reads control information needed by the SIP Package and calculates iteration parameters if the seed is specified by the user.
SIP1AP	Performs one iteration of the strongly implicit procedure.

Submodules

SSIP1P	Prints the largest head change for each iteration.
SSIP1I	Calculates iteration parameters when the seed is calculated by the program.

Narrative for Module SIP1AL

Module SIP1AL allocates space in the X array for SIP arrays. The four arrays, EL, FL, GL, and V hold intermediate results during the solution process. Each of these contains one element for each model cell. Additionally, three arrays, HDCG, LRCH, and W are required. HDCG holds the maximum head change each iteration and LRCH holds the cell location at which the maximum occurred. HDCG contains MXITER elements and LRCH contains three times MXITER elements, where MXITER--the maximum number of iterations allowed in a time step--is specified by the user. Array W holds iteration parameters. One element in W is used for each of the NPARM iteration parameters. (NPARM is specified by the user.)

Module SIP1AL performs its functions in the following order:

1. Print a message identifying the SIP Package.

2. Read and print MXITER and NPARM.

3. Allocate the required space in the X array. The X-array location pointer (ISUM) is saved in variable ISOLD prior to allocation so that the space required for SIP can be calculated in step 4.

4. Calculate and print the space used in the X array. The space used by SIP is ISUM - ISOLD. The total space allocated by all packages so far is ISUM - 1.

5. RETURN.