DOCUMENTATION OF A COMPUTER PROGRAM TO SIMULATE HORIZONTAL-FLOW BARRIERS USING THE U.S. GEOLOGICAL SURVEY'S MODULAR THREE-DIMENSIONAL FINITE-DIFFERENCE GROUND-WATER FLOW MODEL

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PREFACE

This report presents a computer program for simulating horizontal-flow barriers in the Modular Three-Dimensional Finite-Difference Ground-Water Flow Model (MODFLOW) developed by the U.S. Geological Survey. Users of the report are encouraged to notify the originating office of any errors found in the report or in the computer program. Updates may be made occasionally to both the report and computer program. Users who wish to be added to the mailing list to receive updates, if any, may send a request to:

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Definitions

Executable program: An organized set of instructions that directs a computer in solving a particular problem or performing a designated task. This is the program that "runs" on the computer.
MAIN program: The controlling program unit at which program execution begins. It controls the order in which the primary modules are executed and it serves as a switching system for information.
Module: A collection of related source-code instructions to perform a functional task.
Package or PACKAGE: A collection of related modules (includes submodules).
Primary Module: A module that is called directly by the MAIN program.
Source code: The collection of programming language instructions, Fortran in this report, written by a programmer.
Submodule: A module that is called by other modules.
Subroutine: For this report, synonymous with module or submodule.

Notes

1. The source code used for the subroutines contained in this report is written in the Fortran computer programming language and conforms to the Fortran 66 standard (American National Standards Institute, 1966). The only exception to the Fortran 66 standard is that character strings in FORMAT statements are in single quotes rather than Hollerith constants. Most Fortran 66 compilers include this capability. The modified MAIN program in this report includes conversions by McDonald and Harbaugh (1988) to conform to the Fortran 77 standard (American National Standards Institute, 1978).
2. Rather than writing out a complete logical IF statement as it appears in the source code, the authors simply refer to it, when it is used in the text, as an IF statement or an 'IF...CALL...' statement (quotation marks included).
3. Fortran allows for a program identification/sequence alphanumeric to be placed in columns 73 through 80 of a statement field. In the source-code listing for MAIN found in the text, those columns that contain *HFB* identify code produced for this report.
4. In the text, the word 'CALL', written in capitals, refers to the Fortran keyword CALL and is sometimes used as a verb as in 'CALLed' or a plural as in 'CALLs'.

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Abstract

As an addition to the U.S. Geological Survey's Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, the Horizontal-Flow-Barrier (HFB) Package simulates thin, vertical low-permeability geologic features that impede the horizontal flow of ground water. These geologic features are approximated as a series of horizontal-flow barriers conceptually situated on the boundaries between pairs of adjacent cells in the finite-difference grid. The key assumption underlying the HFB Package is that the width of the barrier is negligibly small in comparison with the horizontal dimensions of the cells in the grid. Barrier width is not explicitly considered in the Package, but is included implicitly in a hydraulic characteristic defined as either (1) barrier transmissivity divided by barrier width, if the barrier is in a constant-transmissivity layer, or (2) barrier hydraulic conductivity divided by barrier width, if the barrier is in a variable-transmissivity layer. Furthermore, the barrier is assumed to have zero storage capacity. Its sole function is to lower the horizontal branch conductance between the two cells that it separates.

Documentation of the HFB Package includes data-input instructions, narratives, flowcharts, program listings, and variables lists for the three primary modules and one submodule in the Package.

INTRODUCTION

In some aquifers there may exist thin, vertical low-permeability geologic features, such as vertical faults, that act as barriers to the horizontal flow of water. These features can be simulated in the model developed by McDonald and Harbaugh (1988) by reducing model grid spacing appropriately or by using variable grid spacing in the region of the features to be modeled. However, reduced grid spacing may result in an excessive number of model cells, and variable grid spacing is efficient (in terms of number of model cells used for a feature) only if all the features to be modeled are parallel to either the row or column direction of the model. In addition, the abruptness with which changing hydraulic properties are modeled must be considered in order to avoid possible numerical difficulties. The Horizontal-Flow-Barrier (HFB) Package, documented in this report, allows these features to be modeled without increasing the number of model cells or using variable grid spacing; thus, the HFB Package may enhance model efficiency.

The Horizontal-Flow-Barrier (HFB) Package consists of three primary modules and one submodule. The documentation includes data-input instructions, narratives, flowcharts, program listings, and variables lists for the three primary modules and one submodule.

PROGRAM DESIGN

The HFB Package is designed to be totally compatible with the standard version of the Modular Three-Dimensional Finite-Difference Ground-Water Flow Model (McDonald and Harbaugh, 1988), which commonly is referred to as MODFLOW. The HFB Package can be incorporated into MODFLOW by (1) designating an unused and unreserved element of the IUNIT array to serve as a flag for invoking the Package, (2) inserting into the MAIN program of MODFLOW three IF statements which, when true, invoke CALLs to HFB subroutine modules, (3) adding the source codes of four HFB modules (three primary modules and one submodule) to the MODFLOW source code, and (4) for a typical computer system, compiling and linking the code into an executable program. In the present case, IUNIT(16) is chosen to be the flag for invoking the Package.

ADDITIONS TO THE MAIN PROGRAM

The three IF statements added to the MAIN program of MODFLOW are enclosed by boxes in the listing of the modified MAIN program on pages 3-6 of this report. These statements cause execution of CALLs to the three primary modules (HFB1AL, HFB1RP, and HFB1FM) of the HFB Package when the Package is invoked. The IF statement resulting in the CALL to module (subroutine) HFB1AL can be placed anywhere within the "allocate space" procedure of the MAIN program (McDonald and Harbaugh, 1988, chap. 3, p. 1-2). However, the IF statement that results in a CALL to module HFB1RP should be placed after the 'IF...CALL...' to module BCF1RP, and the IF statement that results in a CALL to module HFB1FM should be placed after the 'IF...CALL...' to module BCF1FM. In the event that the user is using an alternative package to the Block-Centered Flow Package, then the IF statements resulting in CALLs to the HFB1RP and HFB1FM modules should be placed after the statements that replace the 'IF...CALL...' to BCF1RP and BCF1FM, respectively. The relations among the primary modules, submodule, and MAIN program are shown in figure 1.

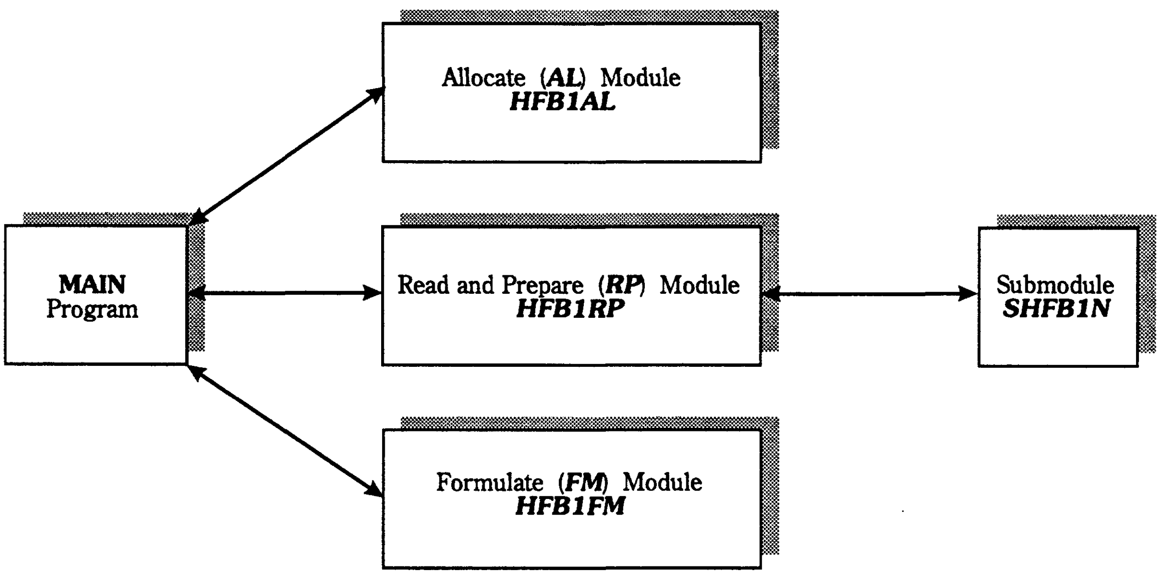


Figure 1. Relations among the primary modules, submodule, and MAIN program in the Horizontal-Flow-Barrier Package.

INVOKING THE HORIZONTAL-FLOW-BARRIER PACKAGE

As described in this report, the HFB Package is invoked by assigning a nonzero input unit number to IUNIT(16) of the Basic Package input (McDonald and Harbaugh, 1988, chap. 4, p. 9). The Package is invoked by entering a nonzero input unit number in columns 46 to 48 of data-item 4 of the Basic Package input.

PROGRAM LISTING FOR MODIFIED MAIN PROGRAM OF THE MODULAR MODEL (WITH THREE IF..CALL STATEMENTS INSERTED TO INVOKE HFB)

```
C ********************************************************************
C     MAIN CODE FOR MODULAR MODEL --     9/1/87
C          BY MICHAEL G. MCDONALD AND ARLEN W. HARBAUGH
C-----VERSION 1638 24 JUL 1987 MAIN1 MODIFIED TO INCLUDE HORIZONTAL-FLOW-
C     BARRIER (HFB) PACKAGE
C     ****************************************************************
C
C        SPECIFICATIONS:
C     ----------------------------------------------------------------
      COMMON X(30000)
      COMMON /FLWCOM/LAYCON(80)
      CHARACTER*4 HEADNG,VBNM
      DIMENSION HEADNG(32),VBNM(4,20),VBVL(4,20),IUNIT(24)
      DOUBLE PRECISION DUMMY
      EQUIVALENCE (DUMMY,X(1))
C     ----------------------------------------------------------------
C
C1------SET SIZE OF X ARRAY. REMEMBER TO REDIMENSION X.
      LENX=30000
C
C2------ASSIGN BASIC INPUT UNIT AND PRINTER UNIT.
      INBAS=1
      IOUT=6
C
C3------DEFINE PROBLEM__ROWS,COLUMNS,LAYERS,STRESS PERIODS,PACKAGES
      CALL BAS1DF(ISUM,HEADNG,NPER,ITMUNI,TOTIM,NCOL,NROW,NLAY,
     1             NODES,INBAS,IOUT,IUNIT)
C
C4------ALLOCATE SPACE IN "X" ARRAY.
      CALL BAS1AL(ISUM,LENX,LCHNEW,LCHOLD,LCIBOU,LCCR,LCCC,LCCV,
     1              LCHCOF,LCRHS,LCDELR,LCDELC,LCSTRT,LCBUFF,LCIOFL,
     2              INBAS,ISTRT,NCOL,NROW,NLAY,IOUT)
      IF(IUNIT(1).GT.0) CALL BCF1AL(ISUM,LENX,LCSC1,LCHY,
     1     LCBOT,LCTOP,LCSC2,LCTRPY,IUNIT(1),ISS,
     2     NCOL,NROW,NLAY,IOUT,IBCFCB)
      IF(IUNIT(2).GT.0) CALL WEL1AL(ISUM,LENX,LCWELL,MXWELL,NWELLS,
     1                   IUNIT(2),IOUT,IWELCB)
      IF(IUNIT(3).GT.0) CALL DRN1AL(ISUM,LENX,LCDRAI,NDRAIN,MXDRN,
     1                   IUNIT(3),IOUT,IDRNCB)
      IF(IUNIT(8).GT.0) CALL RCH1AL(ISUM,LENX,LCIRCH,LCRECH,NRCHOP,
     1             NCOL,NROW,IUNIT(8),IOUT,IRCHCB)
      IF(IUNIT(5).GT.0) CALL EVT1AL(ISUM,LENX,LCIEVT,LCEVTR,LCEXDP,
     1             LCSURF,NCOL,NROW,NEVTOP,IUNIT(5),IOUT,IEVTCB)
      IF(IUNIT(4).GT.0) CALL RIV1AL(ISUM,LENX,LCRIVR,MXRIVR,NRIVER,
     1             IUNIT(4),IOUT,IRIVCB)
      IF(IUNIT(7).GT.0) CALL GHB1AL(ISUM,LENX,LCBNDS,NBOUND,MXBND,
     1             IUNIT(7),IOUT,IGHBCB)
      IF(IUNIT(9).GT.0) CALL SIP1AL(ISUM,LENX,LCEL,LCFL,LCGL,LCV,
     1           LCHDCG,LCLRCH,LCW,MXITER,NPARM,NCOL,NROW,NLAY,
     2           IUNIT(9),IOUT)
      IF(IUNIT(11).GT.0) CALL SOR1AL(ISUM,LENX,LCA,LCRES,LCHDCG,LCLRCH,
     1            LCIEQP,MXITER,NCOL,NLAY,NSLICE,MBW,IUNIT(11),IOUT)
```

```
      IF(IUNIT(16).GT.0) CALL HFB1AL(ISUM,LENX,LCHFBR,NHFB,IUNIT(16),     *HFB*
     1             IOUT)                                                   *HFB*
C
C5------IF THE "X" ARRAY IS NOT BIG ENOUGH THEN STOP.
      IF(ISUM-1.GT.LENX) STOPC
C6------READ AND PREPARE INFORMATION FOR ENTIRE SIMULATION.
      CALL BAS1RP(X(LCIBOU),X(LCHNEW),X(LCSTRT),X(LCHOLD),
     1       ISTRT,INBAS,HEADNG,NCOL,NROW,NLAY,NODES,VBVL,X(LCIOFL),
     2       IUNIT(12),IHEDFM,IDDNFM,IHEDUN,IDDNUN,IOUT)
      IF(IUNIT(1).GT.0) CALL BCF1RP(X(LCIBOU),X(LCHNEW),X(LCSC1),
     1          X(LCHY),X(LCCR),X(LCCC),X(LCCV),X(LCDELR),
     2           X(LCDELC),X(LCBOT),X(LCTOP),X(LCSC2),X(LCTRPY),
     3           IUNIT(1),ISS,NCOL,NROW,NLAY,NODES,IOUT)
      IF(IUNIT(16).GT.0) CALL HFB1RP(X(LCCR),X(LCCC),X(LCDELR),           *HFB*
     1         X(LCDELC),X(LCHFBR),IUNIT(16),NCOL,NROW,NLAY,NODES,         *HFB*
     2         NHFB,IOUT)                                                  *HFB*
      IF(IUNIT(9).GT.0) CALL SIP1RP(NPARM,MXITER,ACCL,HCLOSE,X(LCW),
     1          IUNIT(9),IPCALC,IPRSIP,IOUT)
      IF(IUNIT(11).GT.0) CALL SOR1RP(MXITER,ACCL,HCLOSE,IUNIT(11),
     1         IPRSOR,IOUT)
C
C7------SIMULATE EACH STRESS PERIOD.
      DO 300 KPER=1,NPER
      KKPER=KPER
C
C7A-----READ STRESS PERIOD TIMING INFORMATION.
      CALL BAS1ST(NSTP,DELT,TSMULT,PERTIM,KKPER,INBAS,IOUT)
C
C7B-----READ AND PREPARE INFORMATION FOR STRESS PERIOD.
      IF(IUNIT(2).GT.0) CALL WEL1RP(X(LCWELL),NWELLS,MXWELL,IUNIT(2),
     1             IOUT)
      IF(IUNIT(3).GT.0) CALL DRN1RP(X(LCDRAI),NDRAIN,MXDRN,IUNIT(3),
     1                 IOUT)
      IF(IUNIT(8).GT.0) CALL RCH1RP(NRCHOP,X(LCIRCH),X(LCRECH),
     1            X(LCDELR),X(LCDELC),NROW,NCOL,IUNIT(8),IOUT)
      IF(IUNIT(5).GT.0) CALL EVT1RP(NEVTOP,X(LCIEVT),X(LCEVTR),
     1            X(LCEXDP),X(LCSURF),X(LCDELR),X(LCDELC),NCOL,NROW,
     1            IUNIT(5),IOUT)
      IF(IUNIT(4).GT.0) CALL RIV1RP(X(LCRIVR),NRIVER,MXRIVR,IUNIT(4),
     1            IOUT)
      IF(IUNIT(7).GT.0) CALL GHB1RP(X(LCBNDS),NBOUND,MXBND,IUNIT(7),
     1              IOUT)
C
C7C-----SIMULATE EACH TIME STEP.
      DO 200 KSTP=1,NSTP
      KKSTP=KSTP
C
C7C1----CALCULATE TIME STEP LENGTH. SET HOLD=HNEW.
      CALL BAS1AD(DELT,TSMULT,TOTIM,PERTIM,X(LCHNEW),X(LCHOLD),KKSTP,
     1             NCOL,NROW,NLAY)
C
```

```
C7C2----ITERATIVELY FORMULATE AND SOLVE THE EQUATIONS.
      DO 100 KITER=1,MXITER
      KKITER=KITER
C
C7C2A---FORMULATE THE FINITE DIFFERENCE EQUATIONS.
      CALL BAS1FM(X(LCHCOF),X(LCRHS),NODES)
      IF(IUNIT(1).GT.0) CALL BCF1FM(X(LCHCOF),X(LCRHS),X(LCHOLD),
     1          X(LCSC1),X(LCHNEW),X(LCIBOU),X(LCCR),X(LCCC),X(LCCV),
     2          X(LCHY),X(LCTRPY),X(LCBOT),X(LCTOP),X(LCSC2),
     3          X(LCDELR),X(LCDELC),DELT,ISS,KKITER,KKSTP,KKPER,NCOL,
     4          NROW,NLAY,IOUT)
      IF(IUNIT(16).GT.0) CALL HFB1FM(X(LCHNEW),X(LCCR),X(LCCC),        *HFB*
     1          X(LCBOT),X(LCTOP),X(LCDELR),X(LCDELC),X(LCHFBR),       *HFB*
     2          NCOL,NROW,NLAY,NHFB)                                   *HFB*
      IF(IUNIT(2).GT.0) CALL WEL1FM(NWELLS,MXWELL,X(LCRHS),X(LCWELL),
     1           X(LCIBOU),NCOL,NROW,NLAY)
      IF(IUNIT(3).GT.0) CALL DRN1FM(NDRAIN,MXDRN,X(LCDRAI),X(LCHNEW),
     1         X(LCHCOF),X(LCRHS),X(LCIBOU),NCOL,NROW,NLAY)
      IF(IUNIT(8).GT.0) CALL RCH1FM(NRCHOP,X(LCIRCH),X(LCRECH),
     1            X(LCRHS),X(LCIBOU),NCOL,NROW,NLAY)
      IF(IUNIT(5).GT.0) CALL EVT1FM(NEVTOP,X(LCIEVT),X(LCEVTR),
     1            X(LCEXDP),X(LCSURF),X(LCRHS),X(LCHCOF),X(LCIBOU),
     1            X(LCHNEW),NCOL,NROW,NLAY)
      IF(IUNIT(4).GT.0) CALL RIV1FM(NRIVER,MXRIVR,X(LCRIVR),X(LCHNEW),
     1            X(LCHCOF),X(LCRHS),X(LCIBOU),NCOL,NROW,NLAY)
      IF(IUNIT(7).GT.0) CALL GHB1FM(NBOUND,MXBND,X(LCBNDS),X(LCHCOF),
     1            X(LCRHS),X(LCIBOU),NCOL,NROW,NLAY)
C
C7C2B---MAKE ONE CUT AT AN APPROXIMATE SOLUTION.
      IF(IUNIT(9).GT.0) CALL SIP1AP(X(LCHNEW),X(LCIBOU),X(LCCR),X(LCCC),
     1     X(LCCV),X(LCHCOF),X(LCRHS),X(LCEL),X(LCFL),X(LCGL),X(LCV),
     2     X(LCW),X(LCHDCG),X(LCLRCH),NPARM,KKITER,HCLOSE,ACCL,ICNVG,
     3     KKSTP,KKPER,IPCALC,IPRSIP,MXITER,NSTP,NCOL,NROW,NLAY,NODES,
     4     IOUT)
      IF(IUNIT(11).GT.0) CALL SOR1AP(X(LCHNEW),X(LCIBOU),X(LCCR),
     1     X(LCCC),X(LCCV),X(LCHCOF),X(LCRHS),X(LCA),X(LCRES),X(LCIEQP),
     2     X(LCHDCG),X(LCLRCH),KKITER,HCLOSE,ACCL,ICNVG,KKSTP,KKPER,
     3     IPRSOR,MXITER,NSTP,NCOL,NROW,NLAY,NSLICE,MBW,IOUT)
C
C7C2C---IF CONVERGENCE CRITERION HAS BEEN MET STOP ITERATING.
      IF(ICNVG.EQ.1) GO TO 110
  100 CONTINUE
      KITER=MXITER
  110 CONTINUE
C
C7C3----DETERMINE WHICH OUTPUT IS NEEDED.
      CALL BAS1OC(NSTP,KKSTP,ICNVG,X(LCIOFL),NLAY,
     1  IBUDFL,ICBCFL,IHDDFL,IUNIT(12),IOUT)
C
C7C4----CALCULATE BUDGET TERMS. SAVE CELL-BY-CELL FLOW TERMS.
      MSUM=1
      IF(IUNIT(1).GT.0) CALL BCF1BD(VBNM,VBVL,MSUM,X(LCHNEW),
     1     X(LCIBOU),X(LCHOLD),X(LCSC1),X(LCCR),X(LCCC),X(LCCV),
```

```
     2      X(LCTOP),X(LCSC2),DELT,ISS,NCOL,NROW,NLAY,KKSTP,KKPER,
     3      IBCFCB,ICBCFL,X(LCBUFF),IOUT)
      IF(IUNIT(2).GT.0) CALL WEL1BD(NWELLS,MXWELL,VBNM,VBVL,MSUM,
     1      X(LCWELL),X(LCIBOU),DELT,NCOL,NROW,NLAY,KKSTP,KKPER,IWELCB,
     1      ICBCFL,X(LCBUFF),IOUT)
      IF(IUNIT(3).GT.0) CALL DRN1BD(NDRAIN,MXDRN,VBNM,VBVL,MSUM,
     1      X(LCDRAI),DELT,X(LCHNEW),NCOL,NROW,NLAY,X(LCIBOU),KKSTP,
     2      KKPER,IDRNCB,ICBCFL,X(LCBUFF),IOUT)
      IF(IUNIT(8).GT.0) CALL RCH1BD(NRCHOP,X(LCIRCH),X(LCRECH),
     1      X(LCIBOU),NROW,NCOL,NLAY,DELT,VBVL,VBNM,MSUM,KKSTP,KKPER,
     2      IRCHCB,ICBCFL,X(LCBUFF),IOUT)
      IF(IUNIT(5).GT.0) CALL EVT1BD(NEVTOP,X(LCIEVT),X(LCEVTR),
     1      X(LCEXDP),X(LCSURF),X(LCIBOU),X(LCHNEW),NCOL,NROW,NLAY,
     2      DELT,VBVL,VBNM,MSUM,KKSTP,KKPER,IEVTCB,ICBCFL,X(LCBUFF),IOUT)
      IF(IUNIT(4).GT.0) CALL RIV1BD(NRIVER,MXRIVR,X(LCRIVR),X(LCIBOU),
     1      X(LCHNEW),NCOL,NROW,NLAY,DELT,VBVL,VBNM,MSUM,
     2      KKSTP,KKPER,IRIVCB,ICBCFL,X(LCBUFF),IOUT)
      IF(IUNIT(7).GT.0) CALL GHB1BD(NBOUND,MXBND,VBNM,VBVL,MSUM,
     1      X(LCBNDS),DELT,X(LCHNEW),NCOL,NROW,NLAY,X(LCIBOU),KKSTP,
     2      KKPER,IGHBCB,ICBCFL,X(LCBUFF),IOUT)
C
C7C5---PRINT AND OR SAVE HEADS AND DRAWDOWNS. PRINT OVERALL BUDGET.
      CALL BAS1OT(X(LCHNEW),X(LCSTRT),ISTRT,X(LCBUFF),X(LCIOFL),
     1         MSUM,X(LCIBOU),VBNM,VBVL,KKSTP,KKPER,DELT,
     2         PERTIM,TOTIM,ITMUNI,NCOL,NROW,NLAY,ICNVG,
     3      IHDDFL,IBUDFL,IHEDFM,IHEDUN,IDDNFM,IDDNUN,IOUT)
C
C7C6----IF ITERATION FAILED TO CONVERGE THEN STOP.
      IF(ICNVG.EQ.0) STOP
  200 CONTINUE
  300 CONTINUE
C
C8------END PROGRAM
      STOP
C
      END
```

DESCRIPTION OF HORIZONTAL-FLOW-BARRIER PACKAGE

CONCEPTUALIZATION AND IMPLEMENTATION

A plan view of a model layer containing a thin, vertical low-permeability geologic feature is shown in figure 2*A*. This geologic feature is approximated, in figure 2*B*, as a series of horizontal-flow barriers conceptually situated on the boundary between pairs of adjacent cells in the finite-difference grid. Note that each segment of the geologic feature lying between two adjacent cells is defined as a horizontal-flow barrier. Thus, geologically speaking, figure 2*A* shows a single low-permeability feature in the model layer. However, in the finite-difference grid (fig. 2*B*), this feature is treated as six horizontal-flow barriers in the model layer.

The key assumption underlying the Horizontal-Flow-Barrier Package is that the width of the barrier (that is, the shortest distance through the barrier) is negligibly small in comparison with the horizontal dimensions of the cells in the finite-difference grid. Thus, the barrier width is not explicitly considered in the Package, but it is included implicitly in a hydraulic characteristic defined as either (1) barrier transmissivity divided by barrier width, if it is in a constant-transmissivity layer, or (2) barrier hydraulic conductivity divided by barrier width, if it is in a variable-transmissivity layer. Furthermore, the barrier is assumed to have zero storage capacity. Its sole function is to lower the horizontal branch conductance between the two cells that it separates.

Shown in figure 3*A* is a horizontal-flow barrier situated between cell i,j,k, and cell $i,j+1,k$--that is, two adjacent cells in the same row in a model layer. The branch conductance in the row direction between the two cells can be determined as shown by McDonald and Harbaugh (1988, chap. 5, p. 6, eq. 38, and p. 7, fig. 25):

$$\frac{1}{CR_{i,j+1/2,k}} = \frac{1}{\dfrac{TR_{i,j,k}DELC_i}{\dfrac{DELR_j}{2}}} + \frac{1}{TDW_{i,j+1/2,k}DELC_i} + \frac{1}{\dfrac{TR_{i,j+1,k}DELC_i}{\dfrac{DELR_{j+1}}{2}}}, \qquad (1)$$

where

$CR_{i,j+1/2,k}$ is the branch conductance in the row direction between nodes i, j, k and $i,j+1,k$ $[L^2T^{-1}]$;
$TR_{i,j,k}$ is the transmissivity in the row direction of cell i,j,k $[L^2T^{-1}]$;
$TR_{i,j+1,k}$ is the transmissivity in the row direction of cell $i,j+1,k$ $[L^2T^{-1}]$;
$DELR_j$ is the grid width in the row direction of column j [L];
$DELR_{j+1}$ is the grid width in the row direction of column $j+1$ [L];
$DELC_i$ is the grid width in the column direction of row i [L]; and
$TDW_{i,j+1/2,k}$ is the barrier transmissivity divided by the width of the barrier between cell i,j,k and cell $i,j+1,k$ $[LT^{-1}]$.

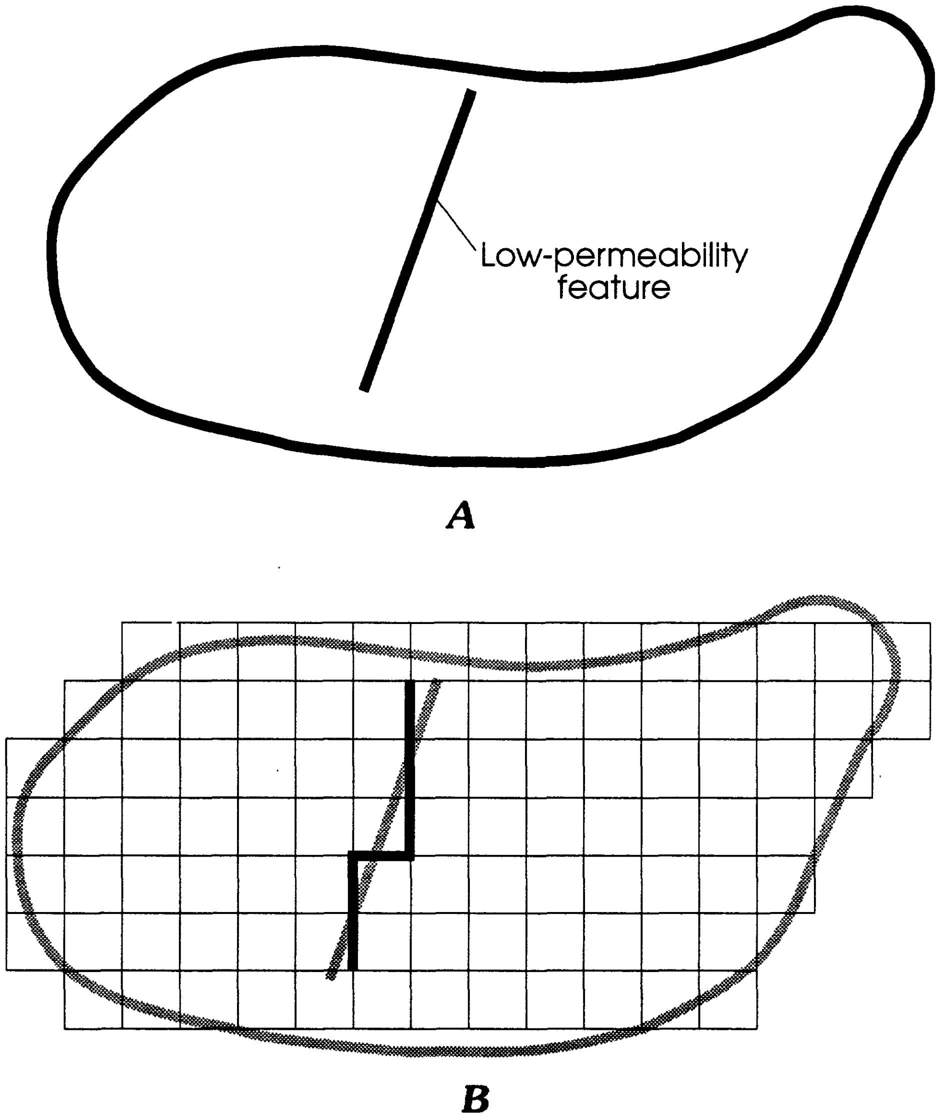


Figure 2. Schematic representation of model layer (***A***) and grid (***B***) with a low-permeability feature and its representation in the grid as a series of six horizontal-flow barriers.

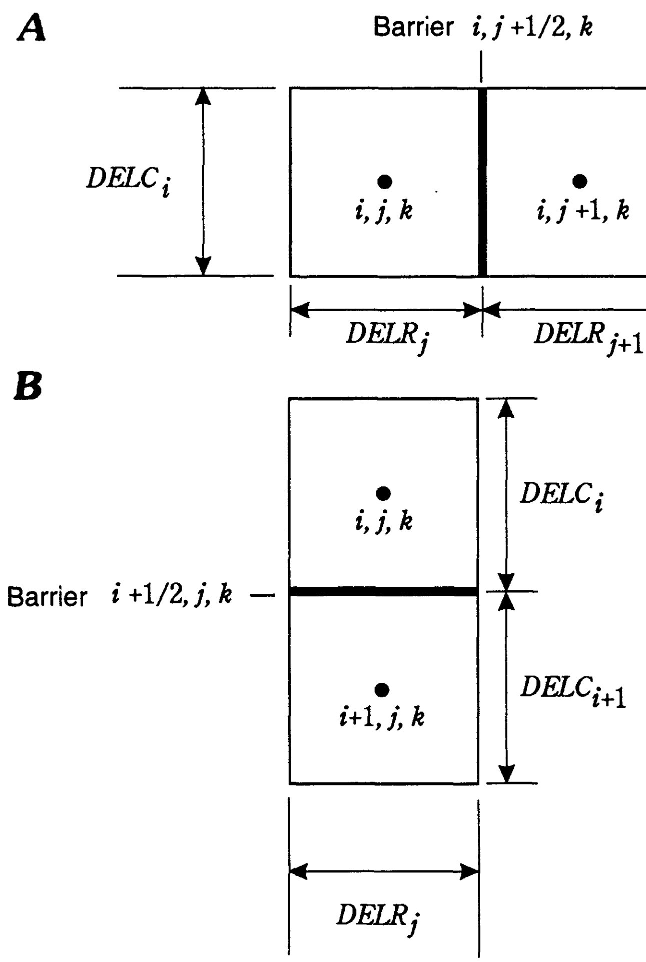


Figure 3. Schematic representation of a horizontal-flow barrier separating two adjacent model cells in the same row (***A***) and two adjacent model cells in the same column (***B***).

Combining the first and third terms on the right side of equation 1 gives

$$\frac{1}{CR_{i,j+1/2,k}} = \frac{1}{CR^*_{i,j+1/2,k}} + \frac{1}{TDW_{i,j+1/2,k}DELC_i}, \tag{2}$$

where $CR^*_{i,j+1/2,k}$ is the branch conductance if the barrier did not exist, and is given by

$$CR^*_{i,j+1/2,k} = 2\ DELC_i \frac{TR_{i,j,k}TR_{i,j+1,k}}{TR_{i,j,k}DELR_{j+1} + TR_{i,j+1,k}DELR_j}. \tag{3}$$

Solving for $CR_{i,j+1/2,k}$ in equation 2 yields

$$CR_{i,j+1/2,k} = \frac{CR^*_{i,j+1/2,k}TDW_{i,j+1/2,k}DELC_i}{CR^*_{i,j+1/2,k} + TDW_{i,j+1/2,k}DELC_i}. \tag{4}$$

The same process can be applied when the horizontal-flow barrier is situated between two cells on the same column in a layer (fig. 3*B*). In this case, the branch conductance in the column direction between nodes i,j,k and nodes $i+1,j,k$ is

$$CC_{i+1/2,j,k} = \frac{CC^*_{i+1/2,j,k} TDW_{i+1/2,j,k} DELR_j}{CC^*_{i+1/2,j,k} + TDW_{i+1/2,j,k} DELR_j}, \quad (5)$$

where $CC^*_{i+1/2,j,k}$ is the branch conductance if the barrier did not exist, and is given by

$$CC^*_{i+1/2,j,k} = 2\ DELR_j \frac{TC_{i,j,k} TC_{i+1,j,k}}{TC_{i,j,k} DELC_{i+1} + TC_{i+1,j,k} DELC_i}, \quad (6)$$

and

$TC_{i,j,k}$ is the transmissivity in the column direction of cell i,j,k [L^2T^{-1}]; and
$TC_{i+1,j,k}$ is the transmissivity in the column direction of cell $i+1,j,k$ [L^2T^{-1}].

In the computer program, the horizontal branch conductances are computed in two steps. First, the horizontal-flow barriers are neglected and the branch conductances CC^* and CR^* are computed by the standard method (for example, eqs. 3 and 6; see also McDonald and Harbaugh, 1988, chap. 5, p. 6-10). Next, the effects of the barriers are taken into account by means of equations 4 and 5.

In a model layer that is confined, TDW (in this case, barrier transmissivity divided by barrier width) of a barrier will be constant for the simulation. If a layer is potentially unconfined, new values of TDW must be calculated as the head fluctuates. This is done at the start of each iteration. In this case, TDW is obtained by multiplying the average saturated thickness of the two cells on either side of the barrier by the barrier hydraulic conductivity divided by the width of the barrier.

INPUT FOR HORIZONTAL-FLOW-BARRIER PACKAGE

FOR EACH SIMULATION

```
                                      HFB1AL
1.   Data:     NHFB
     Format:   I10

                                      HFB1RP
```

The following input data are read one layer at a time; that is, all the data for layer 1 are read first, then all the data for layer 2, and so forth.

FOR EACH LAYER

```
2.   Data:     NBRLAY
     Format:   I10

3.   Data:     IROW1     ICOL1     IROW2     ICOL2     HYDCHR
     Format:   I10       I10       I10       I10       F10.0
     (Input item 3 consists of one record for each horizontal-flow barrier.
     If NBRLAY is zero, item 3 will not be read.)
```

EXPLANATION OF FIELDS USED IN INPUT INSTRUCTIONS

NHFB--is the total number of horizontal-flow barriers in the finite-difference grid.

NBRLAY--is the number of horizontal-flow barriers in a layer.

NOTE: Within a layer, the location of a horizontal-flow barrier is identified by the two cells on either side of the barrier. The row and column numbers of these two cells are IROW1, ICOL1, and IROW2, ICOL2, respectively. There is no requirement regarding the order in which the cells are identified.

IROW1--is the row number of the cell on one side of the horizontal-flow barrier.

ICOL1--is the column number of the cell on one side of the horizontal-flow barrier.

IROW2--is the row number of the cell on the other side of the horizontal-flow barrier.

ICOL2--is the column number of the cell on the other side of the horizontal-flow barrier.

HYDCHR--is a hydraulic characteristic of the horizontal-flow barrier. If the layer type is 0 or 2, it is the barrier transmissivity divided by the width of the horizontal-flow barrier. If the layer type is 1 or 3, it is the barrier hydraulic conductivity divided by the width of the horizontal-flow barrier.

SAMPLE INPUT FOR THE HORIZONTAL-FLOW-BARRIER PACKAGE

The following example illustrates input for the HFB Package. There are three simulated layers, as shown in figure 4. In layer 1, a low-permeability feature is represented by four horizontal-flow barriers. The hydraulic characteristic (HYDCHR) of this feature is nonuniform, as reflected by nonuniform values of HYDCHR in the input data. Layer 2 does not have any horizontal-flow barriers. In layer 3, a low-permeability feature is represented by three horizontal-flow barriers. The hydraulic characteristic of this feature is uniform, as reflected by uniform values of HYDCHR in the input data.

Data item	Explanation	Input record				
1	{NHBF}	7				
2	{NBRLAY} FOR LAYER 1	4				
3	{IROW1, ICOL1, IROW2, ICOL2, HYDCHR}	3	4	3	5	0.00025
3	{IROW1, ICOL1, IROW2, ICOL2, HYDCHR}	3	4	4	4	.00025
3	{IROW1, ICOL1, IROW2, ICOL2, HYDCHR}	4	3	4	4	.00041
3	{IROW1, ICOL1, IROW2, ICOL2, HYDCHR}	5	3	5	4	.00054
2	{NBRLAY} FOR LAYER 2	0				
2	{NBRLAY} FOR LAYER 3	3				
3	{IROW1, ICOL1, IROW2, ICOL2, HYDCHR}	2	4	3	4	.00013
3	{IROW1, ICOL1, IROW2, ICOL2, HYDCHR}	3	3	3	4	.00013
3	{IROW1, ICOL1, IROW2, ICOL2, HYDCHR}	3	3	4	3	.00013

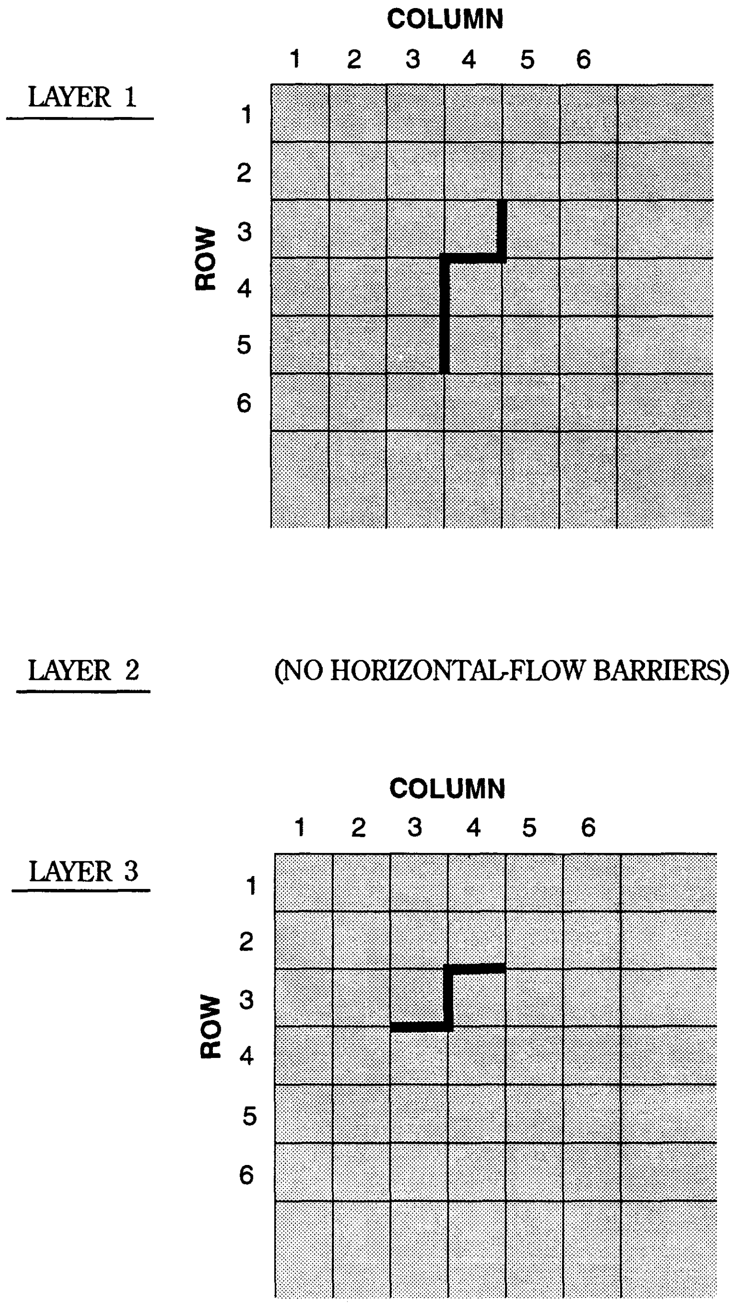


Figure 4. Schematic representation of model grid locations of horizontal-flow barriers (heavy lines) in layers 1 and 3.

MODULE DOCUMENTATION FOR THE HORIZONTAL-FLOW-BARRIER PACKAGE

The Horizontal-Flow-Barrier Package (HFB1) has three primary modules and one submodule. The primary modules HFB1AL, HFB1RP, and HFB1FM are called in the MAIN program; the submodule SHFB1N is called in the primary module HFB1RP. Following is an overview of the modules.

HFB1AL Allocates space for data array. A narrative, flowchart, program listing, and variables list for this module are included in this report on pages 13-16.

HFB1RP Reads all data needed by the package and invokes SHFB1N, which checks input data and modifies horizontal branch conductances in constant-transmissivity layers to account for horizontal-flow barriers. A narrative, flowchart, program listing, and variables list for this module are included in this report on pages 16-20.

HFB1FM Modifies horizontal branch conductances in variable-transmissivity layers to account for horizontal-flow barriers. A narrative, flowchart, program listing, and variables list for this module are included in this report on pages 21-26.

SHFB1N Checks input data and modifies horizontal branch conductances in constant-transmissivity layers to account for horizontal-flow barriers. A narrative, flowchart, program listing, and variables list for this module are included in this report on pages 27-31.

PRIMARY MODULES

HFB1AL

Narrative for module HFB1AL.--This module allocates space in the X array to store the locations of the horizontal-flow barriers and their hydraulic characteristics. The order of execution is:

1. Print a message identifying the package.

2. Read and print NHFB (number of horizontal-flow barriers in the finite-difference grid).

3. Set LCHFBR, which will point to the first element in the horizontal-flow-barrier data list (HFBR), equal to ISUM, which, in turn, currently is pointing to the first unallocated element in the X array.

4. Calculate the amount of space needed for the horizontal-flow-barrier data list (five values for each barrier--IROW1, ICOL1, IROW2, ICOL2, and hydraulic characteristic HYDCHR) and add it to ISUM.

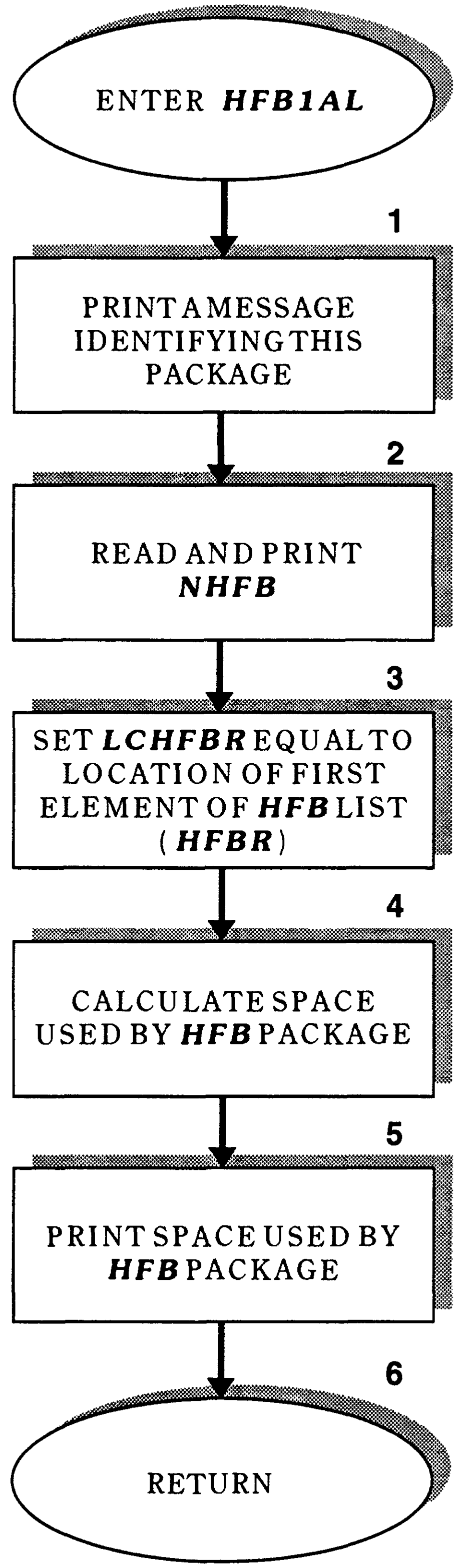
5. Print the number of elements in the X array used by the HFB Package.

6. Return.

Flowchart for module HFB1AL.--

NHFB is the number of horizontal-flow barriers in the finite-difference grid.

LCHFBR is the location in the X array of the list of horizontal-flow-barrier data (HFBR).



Program listing for module HFB1AL.--

```
      SUBROUTINE HFB1AL(ISUM,LENX,LCHFBR,NHFB,IN,IOUT)
C
C-------VERSION 0001 13JUNE1986 HFB1AL
C
C     ******************************************************************
C     ALLOCATE ARRAY STORAGE FOR HORIZONTAL-FLOW-BARRIER PACKAGE
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      COMMON/HFBCOM/NBRLAY(80)
C     ------------------------------------------------------------------
C
C1------IDENTIFY PACKAGE.
      WRITE(IOUT,1)IN
    1 FORMAT(1H0,'HFB1 -- HORIZONTAL-FLOW-BARRIER PACKAGE, VERSION 1',
     1', 06/13/86',' INPUT READ FROM UNIT',I3)
C
C2------READ AND PRINT NHFB (TOTAL NUMBER OF HORIZONTAL-FLOW BARRIERS).
      READ(IN,2) NHFB
    2 FORMAT(I10)
      WRITE(IOUT,3)NHFB
    3 FORMAT(1H0,'A TOTAL OF',I5,' HORIZONTAL-FLOW BARRIERS')
C
C3------SET LCHFBR EQUAL TO ADDRESS OF FIRST UNUSED SPACE IN THE X ARRAY.
      LCHFBR=ISUM
C
C4------CALCULATE AMOUNT OF SPACE USED BY HFB PACKAGE.
      ISP=5*NHFB
      ISUM=ISUM+ISP
C
C5------PRINT AMOUNT OF SPACE USED BY HFB PACKAGE.
      WRITE(IOUT,4)ISP
    4 FORMAT(1X,I6,' ELEMENTS IN X ARRAY ARE USED FOR HORIZONTAL-FLOW'
     1,' BARRIERS')
      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 HFB1AL.--

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 is set to be 6 in MAIN.
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 that has not yet been allocated. When space is allocated for an array, this size of the array is added to ISUM.
ISUM1	Module	ISUM-1.
LCHFBR	Package	Location in the X array of the first element of array HFBR.
LENX	Global	Length of X array in words. This always should be equal to the dimension of X specified in the MAIN program.
NHFB	Package	Number of horizontal-flow barriers in the finite-difference grid.

HFB1RP

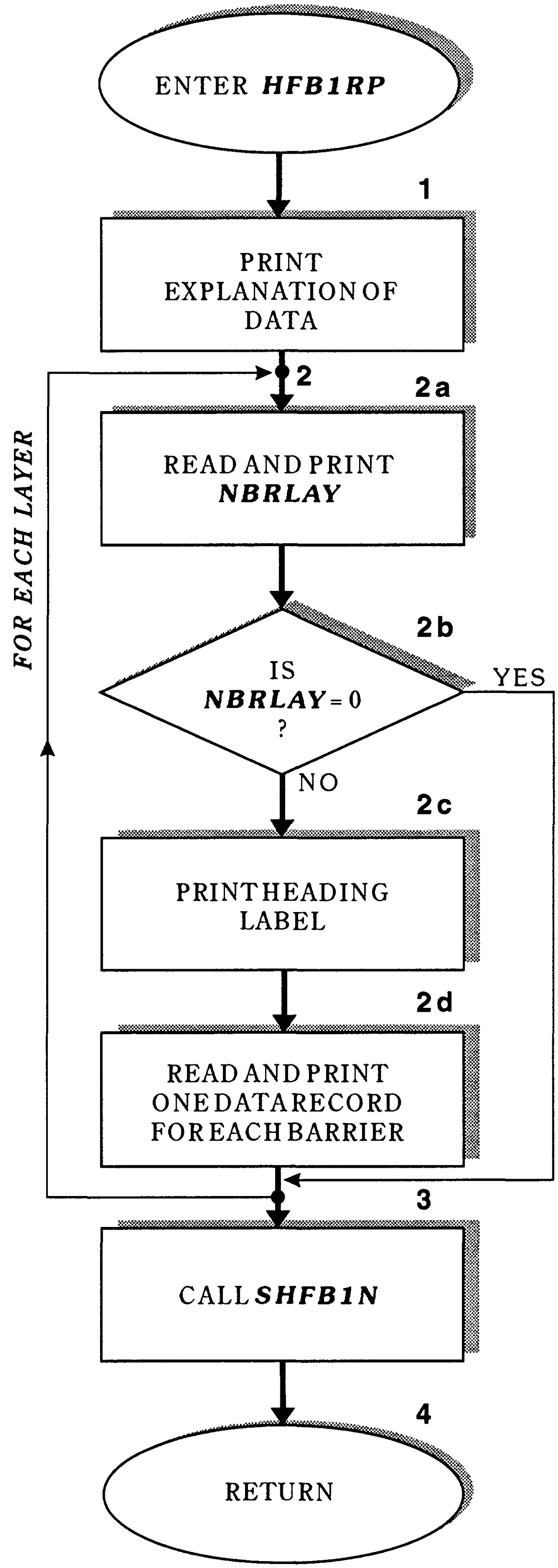
Narrative for module HFB1RP.--This module reads data to build the horizontal-flow-barrier data list one layer at a time. Within a layer, the location of a horizontal-flow barrier is identified by the two cells on either side of the barrier. The row and column numbers of the two cells are respectively IROW1, ICOL1, and IROW2, ICOL2. Thus, for each barrier, the horizontal-flow-barrier data list consists of five items: IROW1, ICOL1, IROW2, ICOL2, and HYDCHR (hydraulic characteristic of the barrier). After all data are read, the module calls the submodule SHFB1N to check the input data and to modify horizontal branch conductances in constant-transmissivity layers to account for the horizontal-flow barriers. The order of execution is:

1. Print explanation of data.
2. For each layer, read and print input data.
   (a) Read and print NBRLAY (number of horizontal-flow barriers in the layer).
   (b) If there are no horizontal-flow barriers in the layer (NBRLAY = 0), then go to the next layer.
   (c) Print heading label of horizontal-flow-barrier data list. For constant-transmissivity layer (LAYCON = 0 or 2), HYDCHR is read as the barrier transmissivity divided by the width of the barrier. For variable-transmissivity layer (LAYCON = 1 or 3), HYDCHR is read as the barrier hydraulic conductivity divided by the width of the barrier.
   (d) For each horizontal-flow barrier, read and print IROW1, ICOL1, IROW2, ICOL2, and HYDCHR.
3. Call submodule SHFB1N to check data and modify horizontal branch conductances in constant-transmissivity layers to account for horizontal-flow barriers.
4. Return.

Flowchart for module HFB1RP.--

NBRLAY is the number of horizontal-flow barriers in a layer.

SHFB1N is the submodule called to check data and modify horizontal branch conductances in constant transmissivity layers.



Program listing for module HFB1RP.--

```
      SUBROUTINE HFB1RP(CR,CC,DELR,DELC,HFBR,IN,NCOL,NROW,NLAY,NODES,
     1        NHFB,IOUT)
C
C-----VERSION 0001 13JUNE1986 HFB1RP
C
C     ******************************************************************
C     READ AND INITIALIZE DATA FOR HORIZONTAL-FLOW-BARRIER PACKAGE
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DIMENSION CR(NODES),CC(NODES),DELR(NCOL),DELC(NROW),HFBR(5,NHFB)
C
      COMMON/HFBCOM/NBRLAY(80)
      COMMON/FLWCOM/LAYCON(80)
C     ------------------------------------------------------------------
C1------PRINT EXPLANATION OF DATA.
      WRITE(IOUT,8)
    8 FORMAT(///1X,'HORIZONTAL-FLOW BARRIERS -- LISTED BY ',
     1'LAYERS.  WITHIN EACH LAYER, THE LOCATION OF A BARRIER IS ',
     2'IDENTIFIED BY'/1X,'THE 2 CELLS ON EITHER SIDE OF THE BARRIER.  ',
     3'THE ROW AND COLUMN NUMBER OF THE TWO CELLS ARE RESPECTIVELY '/1X,
     4'IROW1, ICOL1, AND IROW2, ICOL2.')
C
C2------FOR EACH LAYER, READ AND PRINT INPUT DATA.
      II=0
      DO 100 K=1,NLAY
C
C2A-----READ AND PRINT NUMBER OF HORIZONTAL-FLOW BARRIERS IN LAYER K.
      READ(IN,1) NBRLAY(K)
    1 FORMAT(I10)
      WRITE(IOUT,2) NBRLAY(K),K
    2 FORMAT(1H0,I5,' HORIZONTAL-FLOW BARRIERS IN LAYER',I3)
C
C2B-----IF NO BARRIERS, THEN GO TO NEXT LAYER.
      IF(NBRLAY(K).EQ.0) GOTO 100
C
C2C------PRINT HEADING LABEL.
      IF (LAYCON(K).EQ.0 .OR. LAYCON(K).EQ.2) WRITE(IOUT,3)
    3 FORMAT(1X,20X,'IROW1',5X,'ICOL1',5X,'IROW2',5X,'ICOL2',3X,
     1'TRANSMIS./WIDTH',3X,'BARRIER NO.'/1X,20X,71('-'))
      IF (LAYCON(K).EQ.1 .OR. LAYCON(K).EQ.3) WRITE(IOUT,4)
    4 FORMAT(1X,20X,'IROW1',5X,'ICOL1',5X,'IROW2',5X,'ICOL2',2X,
     1'HYD. COND./WIDTH',2X,'BARRIER NO.'/1X,20X,71('-'))
C
C2D-----FOR EACH HORIZONTAL-FLOW BARRIER IN LAYER, READ AND PRINT BARRIER
C2D-----LOCATION AND HYDRAULIC CHARACTERISTIC.
      DO 90 JJ=1,NBRLAY(K)
      II=II+1
      READ(IN,5)IROW1,ICOL1,IROW2,ICOL2,HYDCHR
    5 FORMAT(4I10,F10.0)
      WRITE(IOUT,6)IROW1,ICOL1,IROW2,ICOL2,HYDCHR,II
```

```
    6 FORMAT(1X,19X,I5,3I10,5X,G12.4,I11)
      HFBR(1,II)=IROW1
      HFBR(2,II)=ICOL1
      HFBR(3,II)=IROW2
      HFBR(4,II)=ICOL2
      HFBR(5,II)=HYDCHR
   90 CONTINUE
  100 CONTINUE
C
C3------CHECK HFB DATA AND MODIFY HORIZONTAL BRANCH CONDUCTANCES FOR
C3------CONSTANT TRANSMISSIVITY LAYERS.
      CALL SHFB1N(CR,CC,DELR,DELC,HFBR,NCOL,NROW,NLAY,NHFB,IOUT)
C
C4------RETURN
      RETURN
      END
```

List of variables for module HFB1RP.--

Variable	Range	Definition
CC	Global	DIMENSION (NCOL, NROW, NLAY), Conductance in the column direction. CC(J,I,K) contains conductance between nodes (J,I,K) and (J,I+1,K).
CR	Global	DIMENSION (NCOL, NROW, NLAY), Conductance in the row direction. CR(J,I,K) contains conductance between nodes (J,I,K) and (J+1,I,K).
DELC	Global	DIMENSION (NROW), Cell dimension in the column direction. DELC(I) contains width of row I.
DELR	Global	DIMENSION (NCOL), Cell dimension in the row direction. DELR(J) contains width of column J.
HFBR	Package	DIMENSION (5,NHFB), For each horizontal-flow barrier: IROW1, ICOL1, IROW2, ICOL2, and HYDCHR.
HYDCHR	Module	Hydraulic characteristic of the horizontal-flow barrier. If LAYCON = 0 or 2, HYDCHR is the barrier transmissivity divided by the width of the barrier. If LAYCON = 1 or 3, HYDCHR is the barrier hydraulic conductivity divided by the width of the barrier.
ICOL1	Module	Column number of cell on one side of horizontal-flow barrier.
ICOL2	Module	Column number of cell on other side of horizontal-flow barrier.
II	Module	Index for horizontal-flow barriers.
IN	Package	Primary unit number from which input for this package will be read.
IOUT	Global	Primary unit number for all printed output. IOUT is set to be 6 in MAIN.
IROW1	Module	Row number of cell on one side of horizontal-flow barrier.
IROW2	Module	Row number of cell on other side of horizontal-flow barrier.
JJ	Module	Index for horizontal-flow barriers within a layer.
K	Module	Index for layer.
LAYCON	Package	DIMENSION (80) Layer type code: 0 - Layer strictly confined. 1 - Layer strictly unconfined. 2 - Layer confined/unconfined (transmissivity is constant). 3 - Layer confined/unconfined (transmissivity varies).
NBRLAY	Package	DIMENSION (80), Number of horizontal-flow barriers in each layer. NBRLAY(K) is the number of horizontal-flow barriers in layer K.
NCOL	Global	Number of columns in the grid.
NHFB	Package	Number of horizontal-flow barriers in the grid.
NLAY	Global	Number of cells (nodes) in the grid.
NROW	Global	Number of rows in the grid.

Narrative for module HFB1FM.--This module modifies the horizontal branch conductance in variable-transmissivity layers to account for the horizontal-flow barriers. Upon entry of the module, the arrays CR and CC must contain horizontal branch conductance values computed for the case of no horizontal-flow barriers in the variable-transmissivity layers. The following steps are executed:

1. For each layer, modify horizontal branch conductance if transmissivity varies.
   (a) If layer type is not 1 or 3, go to the next layer.
   (b) If zero barriers in the layer, go the next layer.
   (c) For each barrier in the layer, modify horizontal branch conductances.
      (1) Determine I1 and J1, which are the row and column numbers of the cell whose horizontal branch conductances are to be modified.
      (2) Determine I2 and J2, which are the row and column numbers of the cell that is separated from cell (J1, I1, K) by the barrier.
      (3) If I1≠I2, then horizontal branch conductance along row direction is not modified. Otherwise, go to step (4).
      (4) If CR(J1,I1,K) is zero, then go to the next barrier.
      (5) Determine the average saturated thickness between cells (J1,I1,K) and (J2,I2,K).
      (6) Modify CR(J1,I1,K) to account for barrier and go to next barrier.
      (7) Case of J1=J2. Horizontal branch conductance along column direction to be modified.
      (8) If CC(J1,I1,K) is zero, then go to the next barrier.
      (9) Determine the average saturated thickness between cells (J1,I1,K) and (J2,I2,K).
      (10) Modify CC(J1,I1,K) to account for barrier and go to next barrier.
2. Return.

Flowchart for module HFB1FM.--

LAYCON is a layer-type code (one for each layer).
- 0-confined
- 1-unconfined
- 2-confined/unconfined but transmissivity is constant
- 3-confined/unconfined

NBRLAY is the number of horizontal-flow barriers in a layer.

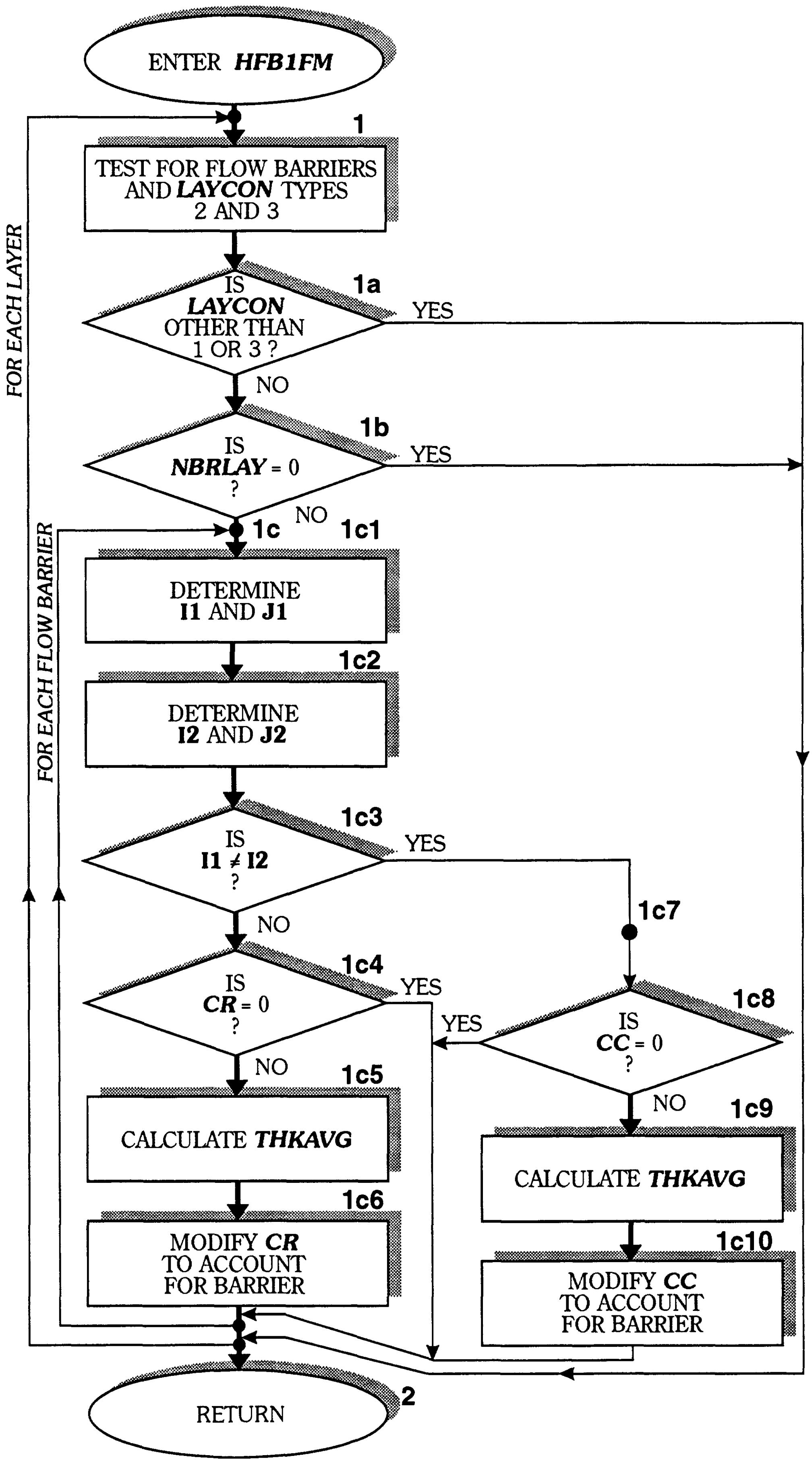
I1 and I2 are the row numbers of the two cells separated by the horizontal-flow barrier.

J1 and J2 are the column numbers of the two cells separated by the horizontal-flow barrier.

CR is the conductance in the row direction.

CC is the conductance in the column direction.

THKAVG is the average saturated thickness of the two cells separated by the horizontal-flow barrier.



Program listing for module HFB1FM.--

```
      SUBROUTINE HFB1FM(HNEW,CR,CC,BOT,TOP,DELR,DELC,HFBR,NCOL,NROW,
     1      NLAY,NHFB)
C
C-----VERSION 0001 13JUNE1986 HFB1FM
C
C     ******************************************************************
C     MODIFY HORIZONTAL BRANCH CONDUCTANCES IN VARIABLE-TRANSMISSIVITY
C     LAYERS TO ACCOUNT FOR HORIZONTAL-FLOW BARRIERS.
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DOUBLE PRECISION HNEW
C
      DIMENSION HNEW(NCOL,NROW,NLAY),CR(NCOL,NROW,NLAY),
     1    CC(NCOL,NROW,NLAY),BOT(NCOL,NROW,NLAY),TOP(NCOL,NROW,NLAY),
     2    DELR(NCOL),DELC(NROW),HFBR(5,NHFB)
C
      COMMON/HFBCOM/NBRLAY(80)
      COMMON/FLWCOM/LAYCON(80)
C     ------------------------------------------------------------------
      KB=0
      KT=0
      II2=0
C
C1------FOR EACH LAYER: CHECK IF TRANSMISSIVITY VARIES.
      DO 100 K=1,NLAY
      IF (NBRLAY(K).EQ.0) GO TO 5
      II1=II2+1
      II2=II2+NBRLAY(K)
    5 IF (LAYCON(K).EQ.3 .OR. LAYCON(K).EQ.2) KT=KT+1
C
C1A-----IF LAYER TYPE IS NOT 1 OR 3, THEN SKIP THIS LAYER.
      IF (LAYCON(K).NE.3 .AND. LAYCON(K).NE.1) GO TO 100
      KB=KB+1
C
C1B-----IF NO BARRIER IN THE LAYER, GO TO NEXT LAYER.
      IF (NBRLAY(K).EQ.0) GO TO 100
C
C1C-----FOR EACH BARRIER IN THE LAYER, MODIFY HORIZONTAL BRANCH
C1C-----CONDUCTANCES
      DO 90 II=II1,II2
C1C1----CELL (J1,I1,K) IS THE ONE WHOSE HORIZONTAL BRANCH
C1C1----CONDUCTANCES ARE TO BE MODIFIED.
      I1=HFBR(1,II)
      J1=HFBR(2,II)
C1C2----CELL (J2,I2,K) IS THE CELL NEXT TO CELL (J1,I1,K) AND SEPARATED
C1C2----FROM IT BY THE BARRIER.
      I2=HFBR(3,II)
      J2=HFBR(4,II)
      HCDW=HFBR(5,II)
C
C1C3----IF I1=I2, THEN MODIFY HORIZONTAL BRANCH CONDUCTANCES ALONG ROW
C1C3----DIRECTION.
```

```
      IF (I1.NE.I2) GOTO 20
C
C1C4----IF CR(J1,I1,K)=0, THEN GO TO NEXT BARRIER
      IF (CR(J1,I1,K).EQ.0.) GO TO 90
C
C1C5----CALCULATE AVERAGE SATURATED THICKNESS BETWEEN CELLS (J1,I1,K)
C1C5----AND (J2,I2,K).  NOTE: NEGATIVE SATURATED THICKNESS DOES NOT
C1C5----OCCUR; OTHERWISE, CR(J1,I1,K) WOULD BE ZERO AND THE FOLLOWING
C1C5----CALCULATION FOR SATURATED THICKNESS WOULD BE SKIPPED.
      HD1=HNEW(J1,I1,K)
      HD2=HNEW(J2,I2,K)
      IF (LAYCON(K).EQ.1) GO TO 10
      IF (HD1.GT.TOP(J1,I1,KT)) HD1=TOP(J1,I1,KT)
      IF (HD2.GT.TOP(J2,I2,KT)) HD2=TOP(J2,I2,KT)
   10 THKAVG=((HD1-BOT(J1,I1,KB))+(HD2-BOT(J2,I2,KB)))/2.
C
C1C6----MODIFY CR(J1,I1,K) TO ACCOUNT FOR BARRIER.
      TDW=THKAVG*HCDW
      CR(J1,I1,K)=TDW*CR(J1,I1,K)*DELC(I1)/(TDW*DELC(I1)+CR(J1,I1,K))
      GOTO 90
C
C1C7----CASE OF J1=J2. MODIFY HORIZONTAL BRANCH CONDUCTANCES ALONG
C1C7----COLUMN DIRECTION.
   20 CONTINUE
C
C1C8----IF CC(J1,I1,K)=0, THEN GO TO NEXT BARRIER.
      IF (CC(J1,I1,K).EQ.0.) GO TO 90
C
C1C9----CALCULATE AVERAGE SATURATED THICKNESS BETWEEN CELLS (J1,I1,K)
C1C9----AND (J2,I2,K).  NEGATIVE SATURATED THICKNESS DOES NOT OCCUR
C1C9----FOR THE SAME REASON AS DESCRIBED ABOVE.
      HD1=HNEW(J1,I1,K)
      HD2=HNEW(J2,I2,K)
      IF (LAYCON(K).EQ.1) GO TO 30
      IF (HD1.GT.TOP(J1,I1,KT)) HD1=TOP(J1,I1,KT)
      IF (HD2.GT.TOP(J2,I2,KT)) HD2=TOP(J2,I2,KT)
   30 THKAVG=((HD1-BOT(J1,I1,KB))+(HD2-BOT(J2,I2,KB)))/2.
C
C1C10---MODIFY CC(J1,I1,K) TO ACCOUNT FOR BARRIER.
      TDW=THKAVG*HCDW
      CC(J1,I1,K)=TDW*CC(J1,I1,K)*DELR(J1)/(TDW*DELR(J1)+CC(J1,I1,K))
   90 CONTINUE
  100 CONTINUE
C
C2------RETURN
      RETURN
      END
```

List of variables for module HFB1FM.--

Variable	Range	Definition
BOT	Package	DIMENSION (NCOL,NROW,NBOT), Elevation of bottom of each layer. (NBOT is the number of layers for which LAYCON = 1 or 3.)
CC	Global	DIMENSION (NCOL,NROW,NLAY) Conductance in the column direction. CC(J,I,K) contains conductance between nodes (J,I,K) and (J,I+1,K).
CR	Global	DIMENSION (NCOL,NROW,NLAY), Conductance in the row direction. CR(J,I,K) contains conductance between nodes (J,I,K) and (J+1,I,K).
DELC	Global	DIMENSION (NROW), Cell dimension in the column direction. DELC(I) contains width of row I.
DELR	Global	DIMENSION (NCOL), Cell dimension in the row direction. DELR(J) contains width of column J.
HCDW	Module	Hydraulic conductivity divided by the width of the horizontal-flow barrier.
HD1	Module	Temporary label of HNEW(J1,I1,K).
HD2	Module	Temporary label of HNEW(J2,I2,K).
HFBR	Package	DIMENSION (5,NHFB), Horizontal-flow barrier list. Contains row and column numbers of the two cells on either side of the barrier and the hydraulic characteristic of the barrier.
HNEW	Global	DIMENSION (NCOL,NROW,NLAY), Most recent estimation of head in each cell. HNEW changes at each iteration.
I1	Module	Row number of cell whose horizontal branch conductances are to be modified.
I2	Module	Row number of the cell next to cell (J1,I1,K) and separated from it by the horizontal-flow barrier.
II	Module	Counter for horizontal-flow barriers.
II1	Module	Lower limit of II in DO loop.
II2	Module	Upper limit of II in DO loop.
IN	Package	Primary unit number from which input for this package will be read.
IOUT	Global	Primary unit number for all printed output. IOUT is set to be 6 in MAIN.
J1	Module	Column number of cell whose horizontal branch conductances are to be modified.
J2	Module	Column number of the cell next to cell (J1,I1,K) and separated from it by the horizontal-flow barrier.

K	Module	Index for layers.
KB	Module	Counter for layers for which bottom elevation is needed.
KT	Module	Counter for layers for which top elevation is needed.
LAYCON	Package	DIMENSION (80) Layer type code: 0 - Layer strictly confined. 1 - Layer strictly unconfined. 2 - Layer confined/unconfined (transmissivity is constant.) 3 - Layer confined/unconfined (transmissivity varies).
NBRLAY	Package	DIMENSION (80), Number of horizontal-flow barriers in each layer. NBRLAY(K) is the number of horizontal-flow barriers in layer K.
NCOL	Global	Number of columns in the grid.
NHFB	Package	Number of horizontal-flow barriers in the grid.
NLAY	Global	Number of layers in the grid.
NROW	Global	Number of rows in the grid.
THKAVG	Module	Average saturated thickness of the cells (J1,I1,K) and (J2,I2,K).
TOP	Package	DIMENSION (NCOL,NROW,NTOP), Elevation of top of layer. (NTOP is the number of layers for which LAYCON = 2 or 3.)

Submodule SHFB1N

Narrative for submodule SHFB1N.--This submodule checks the input data read by the primary module HFB1RP and modifies the horizontal branch conductances in the constant-transmissivity layers to account for horizontal-flow barriers. Upon entry of the submodule, the arrays CR and CC must contain the horizontal branch conductance values of the constant-transmissivity layers computed for the case of no horizontal-flow barriers. The following steps are executed in the submodule:

1. Initialize the error flag to zero.
2. Check input data one layer at a time.
   - (a) If no barriers in layer, then go to next layer.
   - (b) Check input data for each barrier in the layer.
     - (1) Find row and column number of the two cells on either side of the barrier, and rearrange HFBR array so that HFBR(1,II) and HFBR(2,II) contain the row and column number of the cell whose horizontal branch conductances are to be modified to account for the presence of barrier no. II. This cell is denoted by (J1,I1,K).
     - (2) Check if the two cells are on different rows. If true, then go to step (7).
     - (3) Check if the two cells are on non-adjacent columns. If true, then print error message, set error flag to 1 (2b12), and go to next barrier.
     - (4) If layer type is 1 or 3, then go to next barrier.
     - (5) If CR(J1,I1,K) is zero, then go to next barrier.
     - (6) Modify CR(J1,I1,K) to account for barrier and go to next barrier.
     - (7) Check if the two cells are on different columns. If true, then print error message, set error flag to 1 (2b12), and go to next barrier.
     - (8) Check if the two cells are on nonadjacent rows. If true, then print error message, set error flag to 1 (2b12), and go to next barrier.
     - (9) If layer type is 1 or 3, then go to next barrier.
     - (10) If CC(J1,I1,K) is zero, then go to next barrier.
     - (11) Modify CC(J1,I1,K) to account for barrier and go to next barrier.
     - (12) Print an error message if (3) or (7) or (8) is true.
3. If error flag is 1, stop execution.
4. Return.

Flowchart for sub-module SHFB1N.--

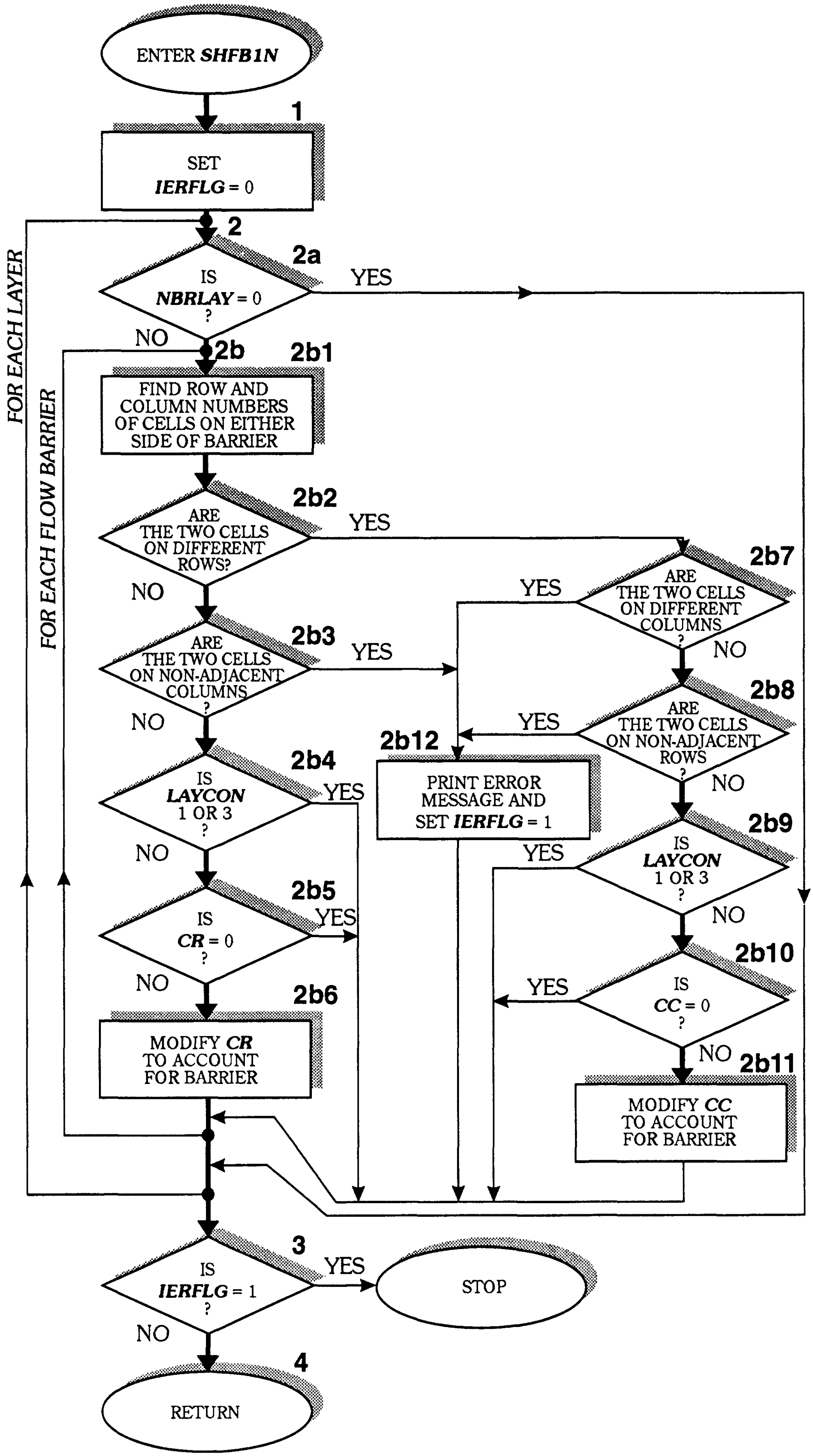
IERFLG is an error flag.
0-no error detected
1-error detected

NBRLAY is the number of horizontal-flow barriers in a layer.

LAYCON is a layer-type code (one for each layer).
0-confined
1-unconfined
2-confined/ unconfined but transmissivity is constant
3-confined/ unconfined

CR is the conductance in the row direction.

CC is the conductance in the column direction.



Program listing for submodule SHFB1N.--

```
      SUBROUTINE SHFB1N(CR,CC,DELR,DELC,HFBR,NCOL,NROW,NLAY,NHFB,IOUT)
C
C-----VERSION 0001 13JUNE1986 SHFB1N
C
C     ******************************************************************
      CHECK HFB DATA AND MODIFY HORIZONTAL CONDUCTANCES (CR AND CC)
C     FOR CONSTANT TRANSMISSIVITY LAYERS TO ACCOUNT FOR HORIZONTAL-FLOW
C     BARRIERS.
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DIMENSION CR(NCOL,NROW,NLAY),CC(NCOL,NROW,NLAY),DELR(NCOL),
     1     DELC(NROW),HFBR(5,NHFB)
C
      COMMON/HFBCOM/NBRLAY(80)
      COMMON/FLWCOM/LAYCON(80)
C     ------------------------------------------------------------------
C
C1------INITIALIZE ERROR FLAG TO ZERO.
      IERFLG=0
C
C2------CHECK HFB DATA ONE LAYER AT A TIME.
      II=0
      DO 100 K=1,NLAY
C
C2A-----IF ZERO BARRIER IN LAYER, THEN GO TO NEXT LAYER.
      IF (NBRLAY(K).EQ.0) GOTO 100
C
C2B-----CHECK EACH BARRIER IN LAYER K.
      DO 90 JJ=1,NBRLAY(K)
      II=II+1
      TDW=HFBR(5,II)
C
C2B1----FIND ROW AND COLUMN NUMBERS OF THE TWO CELLS ON EITHER SIDE
C2B1----OF THE BARRIER AND REARRANGE HFBR ARRAY.
      I1=MIN(HFBR(1,II),HFBR(3,II))
      J1=MIN(HFBR(2,II),HFBR(4,II))
      I2=MAX(HFBR(1,II),HFBR(3,II))
      J2=MAX(HFBR(2,II),HFBR(4,II))
      HFBR(1,II)=I1
      HFBR(2,II)=J1
      HFBR(3,II)=I2
      HFBR(4,II)=J2
C
C2B2----IF I1=I2, BARRIER IS BETWEEN TWO CELLS ON THE SAME ROW.
      IF (I1.NE.I2) GOTO 10
C
C2B3----IF J2-J1=1, THE TWO CELLS ARE NEXT TO ONE ANOTHER (DATA OK).
C2B3----OTHERWISE, PRINT ERROR MESSAGE AND SET ERROR FLAG TO 1.
      IF ((J2-J1).NE.1) GOTO 80
C
C2B4----IF LAYER TYPE IS 1 OR 3, THEN GO TO NEXT BARRIER.
      IF (LAYCON(K).EQ.1 .OR. LAYCON(K).EQ.3) GOTO 90
```

```
C
C2B5-----IF CR(J1,I1,K)=0 THEN GO TO NEXT BARRIER.
      IF (CR(J1,I1,K).EQ.0.) GO TO 90
C
C2B6----MODIFY CR(J1,I1,K) TO ACCOUNT FOR BARRIER.
      CR(J1,I1,K)=TDW*CR(J1,I1,K)*DELC(I1)/(TDW*DELC(I1)+CR(J1,I1,K))
      GOTO 90
C
C2B7----IF J1=J2, BARRIER IS BETWEEN TWO CELLS ON THE SAME COLUMN.
C2B7----OTHERWISE, PRINT ERROR MESSAGE AND SET ERROR FLAG TO 1.
   10 IF (J1.NE.J2) GOTO 80
C
C2B8----IF I2-I1=1, THE TWO CELLS ARE NEXT TO ONE ANOTHER (DATA OK).
C2B8----OTHERWISE, PRINT ERROR MESSAGE AND SET ERROR FLAG TO 1.
      IF ((I2-I1).NE.1) GOTO 80
C
C2B9----IF LAYER TYPE IS 1 OR 3, THEN GO TO NEXT BARRIER.
      IF (LAYCON(K).EQ.1 .OR. LAYCON(K).EQ.3) GOTO 90
C
C2B10---IF CC(J1,I1,K)=0, THEN GO TO NEXT BARRIER.
      IF (CC(J1,I1,K).EQ.0.) GOTO 90
C
C2B11---MODIFY CC(J1,I1,K) TO ACCOUNT FOR BARRIER
      CC(J1,I1,K)=TDW*CC(J1,I1,K)*DELR(J1)/(TDW*DELR(J1)+CC(J1,I1,K))
      GOTO 90
C
C2B12---PRINT ERROR MESSAGE AND SET ERROR FLAG.
   80 WRITE (IOUT,1) II
    1 FORMAT (1X,'ERROR DETECTED IN LOCATION DATA OF BARRIER NO.',I4)
      IERFLG=1
   90 CONTINUE
  100 CONTINUE
C
C3-----HALT EXECUTION IF ERRORS ARE DETECTED.
      IF (IERFLG.EQ.1) STOP
C
C4-----RETURN
      RETURN
      END
```

List of variables for submodule SHFB1N.--

Variable	Range	Definition
CC	Global	DIMENSION (NCOL,NROW,NLAY), Conductance in the column direction. CC(J,I,K) contains conductance between nodes (J,I,K) and (J,I+1,K).
CR	Global	DIMENSION (NCOL,NROW,NLAY), Conductance in the row direction. CR(J,I,K) and (J+1,I,K).
DELC	Global	DIMENSION (NROW), Cell dimension in the column direction. DELC(I) contains width of row I.
DELR	Global	DIMENSION (NCOL), Cell dimension in the row direction. DELR(J) contains width of column J.
HFBR	Package	DIMENSION (5,NHFB), Horizontal-flow-barrier data list. Contains row and column numbers of the two cells on either side of the barrier and the hydraulic characteristics of the barrier.
I1	Submodule	Row number of cell whose horizontal branch conductances are to be modified.
I2	Submodule	Row number of the cell next to cell (J2,I2,K) and separated from it by the horizontal-flow barrier.
IERFLG	Submodule	Error flag.
II	Submodule	Counter for horizontal-flow barriers.
IN	Package	Primary unit number from which input for this package will be read.
IOUT	Global	Primary unit number for all printed output. IOUT is set to be 6 in MAIN.
J1	Submodule	Column number of cell whose horizontal branch conductances are to be modified.
J2	Submodule	Column number of the cell next to cell (J2,I2,K) and separated from it by the horizontal-flow barrier.
JJ	Submodule	Counter for horizontal-flow barriers in a layer.
K	Submodule	Index for layers.
LAYCON	Package	DIMENSION (80) Layer type code: 0 - Layer strictly confined. 1 - Layer strictly unconfined. 2 - Layer confined/unconfined (transmissivity is constant). 3 - Layer confined/unconfined (transmissivity varies).
NBRLAY	Package	DIMENSION (80), Number of horizontal-flow barriers in each layer. NBRLAY(K) is the number of horizontal-flow barriers in layer K.
NCOL	Global	Number of columns in the grid.
NHFB	Package	Number of horizontal-flow barriers in the grid.
NLAY	Global	Number of layers in the grid.
NROW	Global	Number of rows in the grid.
TDW	Submodule	Barrier transmissivity divided by barrier width.

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