GUIDE TO USER MODIFICATION OF A THREE-DIMENSIONAL DIGITAL GROUND-WATER MODEL FOR SALT LAKE VALLEY, UTAH

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ABSTRACT

A digital-computer model was calibrated to simulate, in three dimensions, the ground-water flow in the principal and shallow-unconfined aquifers in Salt Lake Valley, Utah. The model can be used to predict water-level and water-budget changes that would be caused by changes in well recharge or discharge. This report shows how a user can revise the input data so that recharging or discharging wells may be simulated and how stress-period intervals can be varied to simulate different periods of recharge or discharge.

INTRODUCTION

Purpose and Scope

McDonald and Harbaugh (1984) documented a program for simulating three-dimensional ground-water flow. Waddell and others (in press) used the program to simulate ground-water flow in the shallow-unconfined and principal aquifers of Salt Lake Valley, Utah. This report shows how a user can modify the input data used by Waddell and others (in press) in order to simulate the effects of different water-management proposals. A copy of the report by McDonald and Harbaugh (1984) for reference may be purchased from: Open-File Services Section, Western Distribution Branch, Box 25425, Denver Federal Center, Denver, Colorado 80225.

This report was prepared by the U.S. Geological Survey in cooperation with the following organizations that contributed to the investigation through the Utah Department of Natural Resources: Salt Lake County Water Conservancy District, Central Utah Water Conservancy District, Granger-Hunter Improvement District, Magna Water Co. and Improvement District, City of Midvale, City of Murray, Salt Lake City Department of Public Utilities, City of Sandy, City of South Salt Lake, Taylorsville-Bennion Improvement District, City of West Jordan, Holladay Water Co, and White City Water Co.

Uses of the Model

The Geological Survey uses the model for analyzing the flow system in Salt Lake Valley and for testing hypothesis about the flow system. The model is useful for water-management planning for large areas but managers should be aware of the limitations and assumptions expressed in previous reports. The user should be a knowledgeable hydrologist and model user. The conclusions drawn from model simulations are the responsibility of the user and not of the U.S. Geological Survey.

Waddell and others (in press) used the model to simulate the water-level and water-budget changes that would be caused throughout Salt Lake Valley by (1) continuing ground-water withdrawals from wells at 1982 rates and (2) increasing the rate of withdrawal by 65,000 acre-feet per year more than the 1982 rate. The model can be used for parts of the valley, but the results of the simulation may not be accurate if the model is used for areas only a few nodes in extent, or smaller.

Location of Data Files

All data files needed to run the model for Salt Lake Valley are available in the District office, Water Resources Division, U.S. Geological Survey, Salt Lake City, Utah. The source code for the McDonald-Harbaugh model and the input data files can be downloaded on tape in most formats.

Modification of the Model for Other Computers

The program for the model is written in Fortran 66, and it has run successfully without modification on computers manufactured by many companies, including IBM, Control Data, Digital Equipment, Cray, Prime, Amdahl, and Univac (McDonald and Harbaugh, 1984, p. 503). The U.S. Geological Survey in Salt Lake City runs the model on a Prime 750 minicomputer[1]. The only data file that is computer specific is RUNMODEL.CPL, which is the control file that opens the data files for reading, opens the output files for writing, and invokes the compiled Fortran program. The RUNMODEL.CPL file is documented so that all operations which are computer specific can be modified for other computer systems.

Figure 1 is an exact copy of a part of the model output, and it shows the volumetric budget at the end of the last stress period for the transient calibration. This figure will allow users to confirm that the model is working correctly before beginning to make simulations.

DESCRIPTION OF THE MODEL

Type of Model

The finite-difference digital-computer flow model of McDonald and Harbaugh (1984) was selected to simulate the ground-water system of Salt Lake Valley because it is well documented and has the flexibility to adapt to a wide variety of ground-water systems. The program is written in Fortran 66, and it has a modular structure which consists of a main program and a series of independent subroutines that are grouped into 10 packages. Each package deals with a specific feature of the hydrologic system, such as rivers or evapotranspiration.

Relation of Model to Physical System

The model was constructed with two layers, one representing the shallow-unconfined aquifer and the other the principal aquifer. Figure 2 shows the relation of the modeled layers to the physical ground-water system for one cell in each layer. Layer 1 simulates the shallow-unconfined aquifer, which lies above the confining bed. Layer 2 simulates the principal aquifer, which

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[1] Use of firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

```
VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 2 IN STRESS PERIOD 14

CUMULATIVE VOLUMES      L**3                 RATES FOR THIS TIME STEP      L**3/T

      In:                                          In:

          Storage =  0.96197E+10                       Storage =  0.65960
    Constant head =  0.96618E+09                 Constant head =   1.2585
            Wells =  0.73811E+11                         Wells =   167.06
         Recharge =  0.13753E+12                      Recharge =   412.56
               ET =  0.00000                                ET =  0.00000
    River leakage =  0.24042E+09                 River leakage =  0.50811
  Head dep bounds =  0.20996E+09               Head dep bounds =  0.36365
         Total in =  0.22237E+12                      Total in =   582.41

      Out:                                         Out:

          Storage =  0.95836E+10                       Storage =   92.503
    Constant head =  0.24956E+10                 Constant head =   12.701
            Wells =  0.89593E+11                         Wells =   206.13
         Recharge =  0.00000                          Recharge =  0.00000
               ET =  0.32823E+11                            ET =   74.425
    River leakage =  0.86666E+11                 River leakage =   193.54
  Head dep bounds =  0.12169E+10               Head dep bounds =   2.9649
        Total out =  0.22238E+12                     Total out =   582.26
         In - out = -0.32113E+07                      In - out =  0.15112

Percent discrepancy =           0.00        Percent discrepancy =           0.03
```

Figure 1.--Part of the output file from the model for the Salt Lake Valley showing the volumetric budget at the end of stress period 14.

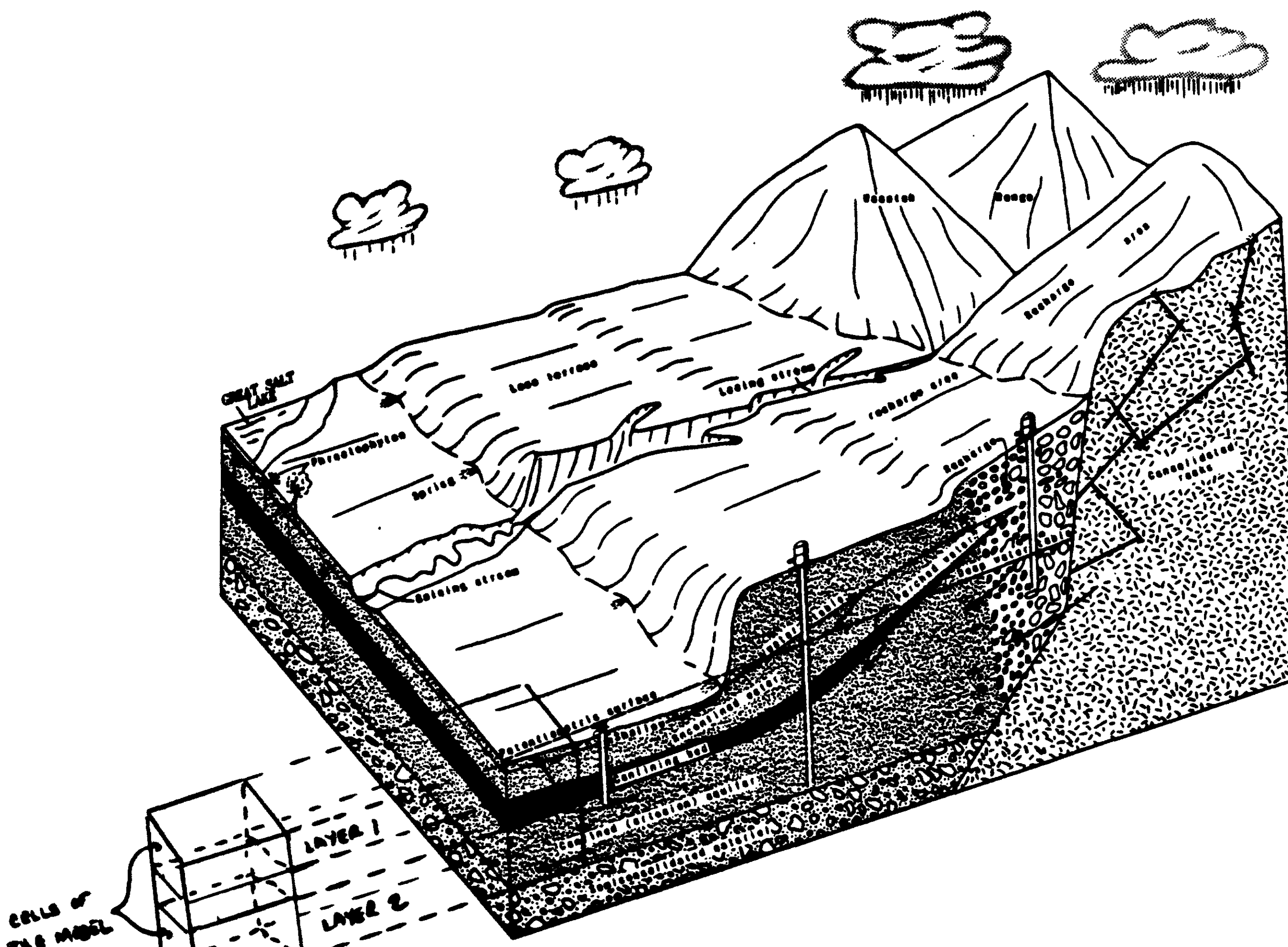

Figure 2.--Part of the ground-water reservoir in Salt Lake Valley showing the relation of cells of the model to the physical system. (Modified from Hely, Mower, and Harr, 1971, fig. 57.)

includes the confined aquifer in the central part of the valley and the deep-unconfined aquifer along the mountain block.

Model Grid

A rectangular grid with variable spacing was used to divide the principal aquifer into two layers of rectangular blocks which are called cells. The rectangular grid, which divided the study area into 38 rows and 28 columns, has a grid spacing that ranges from 0.7 to 1.0 mile and cells with areas that range from 0.49 to 1.0 square mile. The smallest cells are in areas where there are a large number of wells, steep hydraulic gradients, or large changes in transmissivity. Plate 1 shows the orientation and placement of the grid over a map of Salt Lake Valley.

Model Calibration

The model was calibrated so that the simulated changes in water levels favorably matched the measured changes in water levels for 1969-82. The calibration procedure also included matching simulated and measured gains to the Jordan River from ground-water inflow. Waddell and others (in press, p. 38) discuss the calibration of the model in more detail.

Certain areas of the model are calibrated better than others. For example, little water-level data were available for calibration of the area near the tailings pond north of Magna (plate 1), so care must be taken with results obtained in that area. The model is best calibrated in the area east of Midvale because considerable water-level data were available in that area, and there is a good match between simulated and measured water levels in that part of the valley (Waddell and others, in press, fig. 21).

Part of the model input, such as hydraulic properties of the aquifer or evapotranspiration rates, can not be changed without recalibration of the model. Those interested in modifications that require recalibration of the model are referred to McDonald and Harbaugh (1984) and Waddell and others (in press). Other parts of the model input, such as well and spring discharge and recharge from precipitation, can be changed without affecting the calibration.

Limitations of the Model

Under certain conditions, the cells in layer 1 may go dry, that is, the simulated water level drop below the bottom of the shallow-unconfined aquifer. If a cell in layer 1 goes dry, it will become irreversibly inactive. If the principal aquifer (layer 2) is stressed enough so that cells in layer 1 go dry, the water budget can be in error. For example, the Jordan River is in layer 1, and all discharge to the river is through layer 1. If a cell simulating a reach of the Jordan River goes dry, there will be no further discharge simulated to that reach of the river. Even if water levels rise again so that the shallow-unconfined aquifer could discharge to the river, the fact that the cell in layer 1 has become inactive means that the model can not simulate discharge to this reach of the river. This may cause unrealistically high water levels in the principal aquifer because the normal mode of discharge is no longer being simulated and the simulated water budget will be in error.

The model can not be used as a replacement for aquifer tests or for the calculation of site-specific drawdown because the grid scale is too large and the hydraulic data and water-surface elevation are averaged over the entire cell. The model would not be appropriate to aid in decisions such as where to place the pump bowls in a well, for example, because the computed head of the model is the average head over the entire node and not the head at the open interval of the well. The program could be used to simulate aquifer tests if the grid spacing were smaller, and those interested in such uses of the program are refered to McDonald and Harbaugh (1984) for more information.

All the input data for the model are yearly average values for yearly stress periods, with no allowance for seasonal variation. For example, recharge is applied at a uniform rate throughout the year. Major modification of many of the data files would be required to provide for most of the recharge during 6 months and little recharge during the remainder of the year. Thus, although heads and discharge values can be printed for 1, 2 or 3 months, the model will not simulate seasonal variations in water levels or discharge to the river.

Care must be taken when interpreting results near model boundaries. For example, in the north part of the valley along the county line, a no-flow boundary is simulated. Such a simulation does not allow water to enter Salt Lake County from Davis County or leave Salt Lake County to Davis County. Potentiometric contours for Salt Lake Valley in 1983 and southern Davis County in 1985 imply that this is a reasonable simulation. If a discharging well were simulated near the boundary, however, the predicted drawdown might be greater than actual because the model assumes no water can come from Davis County.

MODIFICATION OF THE INPUT-DATA FILES

The instructions in this report are specific for revision of only the following files: basic (BAS), output control (OC), well (WELL), and recharge (RECH). Thus, the user of the model may modify the input data to (1) change the length and number of stress periods, (2) change the recharge or discharge rates from specific cells, and (3) change the areal recharge rate. Any other changes to the input data would require recalibration.

Numbers must be placed in the correct columns of the data files. If numbers are placed in the wrong columns, they may be read incorrectly and the simulation results will be in error. Format statements for all input lines are given by McDonald and Harbaugh (1984, p. 67, 72, 244, 268, 467). Knowledge of the format statements are not needed, however, if care is taken so that new data values are in the same columns as the old values.

Modifying Length of Stress Period or Pumping Interval

The model is calibrated in 14 one-year stress periods (pumping intervals) for 1969-82. There is an offset of one year between model simulation periods and water-level-measurement periods because February-March water levels of a given year were used to represent water-level conditions on December 31 of the prior year. Stress periods 15 and beyond are used for predictive simulations, and the length of time may be modified to suit the particular purposes of the user. The number and length of the stress periods may be changed by modifying the BAS file. (See fig. 3)

The number of stress periods, NPER, the length of the stress period in seconds, PERLEN, and the number of time steps in the stress period, NSTP, are labeled in Figure 3, which is an exact copy of the important parts of the BAS file. As the BAS file is now written, there are 15 stress periods. The first 14 stress periods, which are required for the calibration of the model, cover 1969-1982. Stress period 15 starts in 1983 and ends 17 sidereal years (536,488,533 seconds) later at the end of the year 1999. The water levels simulated at the end of this stress period would represent those of the year 2000.

If the user wants to add a stress period and modify the length so that stress period 15 is from 1983 to 1986 (3 years) and stress period 16 is from 1986 to 2000 (14 years). NPER (figure 3) must be increased from 15 to 16. The length of the stress periods, in seconds, must be entered in the variable PERLEN at the bottom of the BAS file. The length of the new stress period 15 will be 3 sidereal years (94,674,447 seconds) and the length of stress period 16 will be 14 sidereal years (441,814,085 seconds).

The number of time steps in the stress period, NSTP, is also specified by the user and may be modified. For the existing model, it was convenient to use two time steps during the 1-year stress period and eight time steps during the 17-year stress period. In this example, stress period 15 will have three time steps and stress period 16 will have five time steps. These values are entered into the variable NSTP in the BAS file (fig. 3).

The number of time steps can be reduced in order to decrease computation time, but care must be taken because there can be convergence problems during a long stress period if there are insufficient time steps. Comparison of the simulation results resulting from stress periods with different numbers of time steps can guide the user in choosing the appropriate number of time steps.

Computation time can be greatly decreased by using only one stress period, that of the period to be simulated. This requires using the computed heads in the last period from the transient calibration as the start heads and modifying several other data files.

File OC is the part of the basic package that controls the output. As now written, the OC file causes printing of computed water-level and drawdown values for the last time step of each stress period after stress period 13. If the number of stress periods or the number of time steps in an existing stress period is modified, the OC file must be changed also. Figure 4 shows an exact copy of part of the OC file before and after the modifications. The -1 in the first column indicates that the values for the previous time step are to be repeated.

The volumetric budget always is printed at the end of each stress period. The OC file can be modified to cause water level, drawdown, and cell-by-cell budget values to be saved as unformatted files suitable for input to graphics programs. (See McDonald and Harbaugh, 1983, p 72).

Before modifications

```
        2        38        28         15      1
 11 38  0 61 73  0 60 36 29  0  0 57   NPER
        0        1
        5        1    (28I2)                 -1    Ibound1

                           * * * * * * *

            PERLEN     NSTP
  31558149           2       1.5                   Stress period 14
 536488533           8       1.5                   Stress period 15, 17 years
```

After modifications

```
        2        38        28         16      1
 11 38  0 61 73  0 60 36 29  0  0 57
        0        1
        5        1    (28I2)                 -1    Ibound1

                           * * * * * * *

  31558149           2       1.5                   Stress period 14
  94674447           3       1.5                   Stress period 15, 3 years
 441814085           5       1.5                   Stress period 16, 14 years
```

Figure 3.--Part of the BAS file showing modification to change the number and length of the stress periods. Variables NPER, PERLEN, and NSTP have been labeled.

Before modifications

0	0	0	0	Time step 1	Stress period 14, 1982
0	0	0	0	do.	
0	0	0	0	Time step 2	
1	1	0	0	do.	
0	0	0	0	Time step 1	Stress period 15, 1983-2000
0	0	0	0	do.	
-1	0	0	0	Time step 2	
-1	0	0	0	Time step 3	
-1	0	0	0	Time step 4	
-1	0	0	0	Time step 5	
-1	0	0	0	Time step 6	
-1	0	0	0	Time step 7	
0	0	0	0	Time step 8	
1	1	0	0	do.	

After modifications

0	0	0	0	Time Step 1	Stress period 14, 1982
0	0	0	0	do.	
0	0	0	0	Time step 2	
1	1	0	0	do.	
0	0	0	0	Time step 1	Stress period 15, 1983-1986
0	0	0	0	do.	
0	0	0	0	Time step 2	
1	1	0	0	do.	
0	0	0	0	Time step 1	Stress period 16, 1987-2000
0	0	0	0	do.	
-1	0	0	0	Time step 2	
-1	0	0	0	Time step 3	
-1	0	0	0	Time step 4	
0	0	0	0	Time step 5	
1	1	0	0	do.	

Figure 4.--Part of the OC file showing modification to change the number of stress periods or the number of time steps in a stress period.

Unless otherwise modified, all input-data files will duplicate the input for stress period 15 for five additional stress periods. Thus, all input files can be used without modification as long as the number of stress periods does not exceed 20.

Modifying Well Discharge and Recharge

The WELL file, in addition to containing the discharge from wells, contains the discharge from springs, seepage to canals, and recharge as seepage from canals, streams, and irrigated fields. This information must be included for each stress period. In order to preserve the model calibration, the only modifications to the WELL file should be the addition of new sources of discharge or recharge to part of the file for stress periods 15 and beyond. The withdrawals from wells in stress period 15 in the WELL file, as currently written, is equal to the 1982 (stress period 14) rate.

Additional discharge from or recharge to the principal aquifer can be simulated by adding wells to the WELL file. To add a well, the layer number, column and row numbers, and discharge or recharge rate, in cubic feet per second (ft^3/s), of the new well must be specified in the WELL file. The layer number specifies the aquifer in which the well is perforated: 1 for the shallow-unconfined aquifer and 2 for the principal aquifer. The column and row numbers specify the cell in which the well is located. A positive discharge value (+) indicates recharge to the aquifer, and a negative discharge value (-) indicates discharge from the aquifer. For example, the user desires to simulate the effects on the water budget and water levels in the principal aquifer of a new production well near South Salt Lake and an injection well east of Sandy. The production well is to be at 2100 South Street, and about 0.25 mile west of 700 East Street, it is to be finished in the principal aquifer, and it will produce about 10 million gallons per day (Mgal/d) for 6 months per year starting in 1983. The location of the proposed well is first plotted on Plate 1, and the location is found to be column 21 and row 15. As the well will be finished in the principal aquifer, the layer number will be 2. The discharge rate is converted to a rate in cubic feet per second (ft^3/s) for the entire year, as is shown in equation 1, using the relationship that 1 million gallons per day equals 1.547 cubic feet per second.

$$(-10\ \text{Mgal/d}) \times \frac{6\ \text{months}}{12\ \text{months}} \times \frac{1.547\ ft^3/s}{1\ \text{Mgal/d}} = -7.735\ ft^3/s \qquad (1)$$

The proposed injection well is to be at 9400 South and 1300 East Streets, and it would inject 500 gallons per minute (gal/min) for 9 months each year, starting in 1983, into the principal aquifer (layer number 2). The location of the injection well is plotted on Plate 1, and the column and row are determined to be 23 and 28. The injection rate is converted to a rate in cubic feet per second (ft^3/s) for the entire year, as is shown in equation 2, using the relationship that 1 gal/min equals 0.00223 ft^3/s.

$$(500\ \text{gal/min}) \times \frac{9\ \text{months}}{12\ \text{months}} \times \frac{0.00223\ ft^3/s}{1\ \text{gal/min}} = 0.836\ ft^3/s \qquad (2)$$

Figure 5 shows an exact copy of part of the WELL file before and after addition of the production and injection wells. The rate for the production well is negative, indicating water is withdrawn from the aquifer and the rate for the injection well is positive, indicating recharge to the aquifer.

The total number of wells active during the current stress period, ITMP, must be increased if wells are added to the WELL file. In this example, two wells are added, so ITMP is increased from 769 to 771. The Print Control Flag value is set to -1, and it is not changed when revising recharge or discharge. The Print Control Flag is a modification to the source code of the model made by the Utah District. If the value is less than 0, the input data from the WELL file is not printed for every stress period.

The comments are optional and may contain any information that the user desires. The comments are not read by the model.

Modifying Rates of Areal Recharge

The quantity of recharge to the principal aquifer from direct infiltration by precipitation and through fractures in the bedrock along the edge of the valley fill is controled by the variable CNSTNT in the RCH file. Figure 6 shows an exact copy of part of the RCH file. The user may wish to modify the recharge rate to evaluate different water-management proposals.

If the variable CNSTNT is equal to 1.00E-9, the areal recharge rate is the same as during 1968; and if CNSTNT is 1.02E-9, the recharge rate is the same as the average recharge during 1969-82. Waddell and others (in press, p. 34) made predictive simulations for 1983-2000 and 2000-2020 assuming that the recharge rate would be the same as the average rate for 1969-82. During the drought year 1976, CNSTNT was 0.66E-9; and during the extremely wet year 1982, it was 1.35E-9. The value 1.35E-9 are is exponential notation used by the computer for the value 1.35×10^{-9}, or 0.00000000135.

The computation of the CNSTNT is discussed in Waddell and others (in press, p. 8), and it is a function of precipitation at the Salt Lake City Airport weather station, about 5 miles west of Salt Lake City, and at the Silver Lake Brighton weather station, about 16 miles east of Sandy. The user may simulate, for example, recharge being 5 percent greater than the 1969-82 average by multiplying 1.02E-9 by 1.05 and substituting the computed value (1.07E-9) in the RCH file for the appropriate stress period.

Before modifications

```
  ITMP        Print Control Flag
769         -1                                   Stress period 15, 1983-2000
  2         38          17          0            Provo reservoir canal
  2         38          16       2.00
  LAYER       ROW         COLUMN      RATE
```

After modifications

```
771         -1                                   Stress period 15, 1983-2000
  2         21          15      -7.74            Hypothetical production well near South Salt Lake
  2         23          28        .84            Hypothetical injection well near Sandy
  2         38          17          0            Provo reservoir canal
  2         38          16       2.00
```

Figure 5.--Part of the WELL file for stress period 15 before and after addition of the production and injection wells. The variable ITMP and the Print Control Flag, and columns for layer, row, column, and rate have been labeled.

```
                  CNSTNT
 0        0
37   1.35E-9  (20F4.0)               -1      Stress period 14, 1982
 0        0
37   1.02E-9  (20F4.0)               -1      Stress period 15
```

Figure 6.--Part of the RCH file showing the multipliers used to control the recharge rate. The variable CNSTNT has been labeled.

REFERENCES CITED

McDonald, M. G., and Harbaugh, A. W., 1984, A modular three-dimensional finite-difference ground-water flow model, U.S. Geological Survey Open-File Report 83-875, 528 p.

Waddell, K. M., Seiler, R. L., Santini, M., and Solomon, D. K., 1986, Ground-water conditions in Salt Lake Valley, Utah, 1969-82, and predicted effects of increased withdrawals from wells, U.S. Geological Survey Open-File Report 86-237, 60 p. (in press).

Hely, A. G., Mower, R. W., and Harr, C. A., 1971, Water resources of Salt Lake County, Utah: Utah Department of Natural Resources Technical Publication 31, 244 p.