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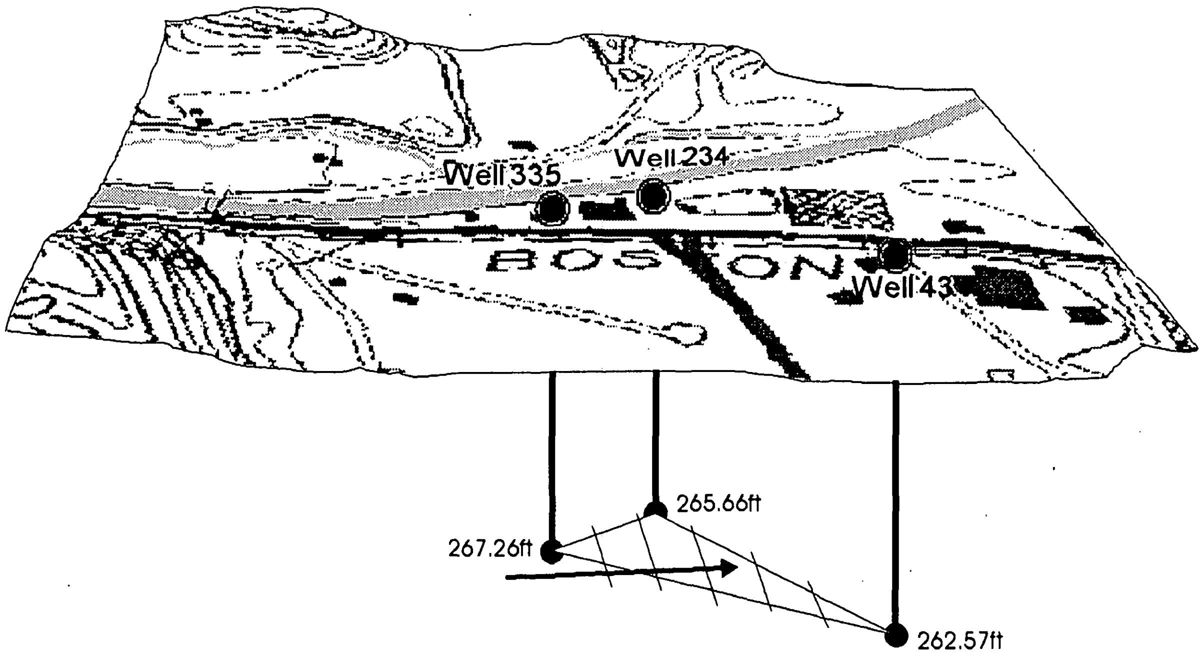
Documentation and Application of a Method to Compute Maximum Slope and Aspect of Hydraulic Gradients

Water-Resources Investigations Report 98-4021



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Three-dimensional perspective view of the study area in Milford, New Hampshire. The triangle below the land surface represents a three-point triangulated area defined by well heads. Calculated direction of ground-water flow (aspect) is shown with the arrow (Not drawn to scale; base from U.S. Geological Survey Digital Raster Graph and Digital Elevation Model, 5x vertical exaggeration).

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Documentation and Application of a Method to Compute Maximum Slope and Aspect of Hydraulic Gradients

By Craig M. Johnston and Philip T. Harte

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Pembroke, New Hampshire
1998

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Documentation and Application of a Method to Compute Maximum Slope and Aspect of Hydraulic Gradients

By Craig M. Johnston *and* Philip T. Harte

ABSTRACT

A computer technique, designed to handle a large number of three-point solutions that are used to calculate maximum slope and aspect of hydraulic gradients of ground-water, was developed for a ground-water flow study in New Hampshire. The computer technique is simple to use but requires the use of a Geographic Information System and a computer program written specifically for the study.

The report contains documentation of computer techniques used for the study and a sample application from a test site in a river-valley aquifer where the seasonal variability of ground-water flow is being assessed. Similar applications also can benefit from this computer technique.

INTRODUCTION

Calculations of maximum slope (maximum gradient) and aspect (direction of maximum gradient) of surfaces from fundamental geometric theorems (Marschak and Gautan, 1988) are widely used to determine the strike and dip of geologic beds and the direction of surface drainages, and to estimate the configuration of ground-water-head contours and thus the primary direction of ground-water flow (Todd, 1980, p. 87). The mathematics are simple, and it is a useful tool in quantifying slopes of surfaces.

In aquifers, a minimum of three wells is required to compute the maximum slope and aspect of hydraulic gradients. Calculation of gradients between two wells will yield a maximum gradient only in cases when the two wells are coincidentally aligned with the maximum gradient. Gradients compiled from two wells will most likely yield a gradient that is less than the maximum gradient of the aquifer. The terms "true" and "apparent" gradients are used to distinguish between the maximum gradient (true) and a gradient less than the maximum gradient (apparent).

A computer technique was developed to handle a large number of solutions to calculate the direction of maximum slope and aspect of ground-water heads from a triangulated network of wells. The solutions are being used to assess the variability of maximum slope and aspect from seasonal recharge and discharge in a river-valley aquifer (Harte and others, 1997).

This report describes a computer technique that solves the three-point planar solution. The computer technique uses available computer software and a computer program written specifically for this application to solve multiple readings of heads from three wells that define a triangular network.

SUMMARY OF THREE-POINT PLANAR SOLUTION

The three-point planar solution allows for computation of aspect and slope of the true or maximum gradient of ground-water heads from a triangulated network or plane. The triangulated plane derived from measurements of ground-water heads represent a water-table surface, if head measurements are from wells screened near the water table, or a potentiometric surface, and if head measurements are from wells screened below the water table.

A surface defined by three points allows for computation of a true gradient in the aquifer, which corresponds to the maximum gradient of the surface. Gradients that are not parallel to the maximum gradient, called the apparent gradient, will be less than the maximum gradient.

The computerized solution technique of the triangulated plane discussed in this report assumes a linear slope within the triangulated area and, therefore, is best suited for calculating slopes in fully confined aquifers. The approach can be used for unconfined aquifers if the size of the triangulated areas are small and the slope of the water table is small (generally less than 0.02 feet per feet). Under these cases, a linear slope is an adequate approximation to the parabolic shape of the water table. The maximum slope and aspect of linearly sloping triangulated planes can be computed by use of graphical or arithmetic techniques (fig. 1).

The solution of computing slope and aspect can be solved graphically (fig. 1A) by defining contours of equal surface values. The direction of the maximum slope is then computed at 90 degrees from the contours of equal surface value.

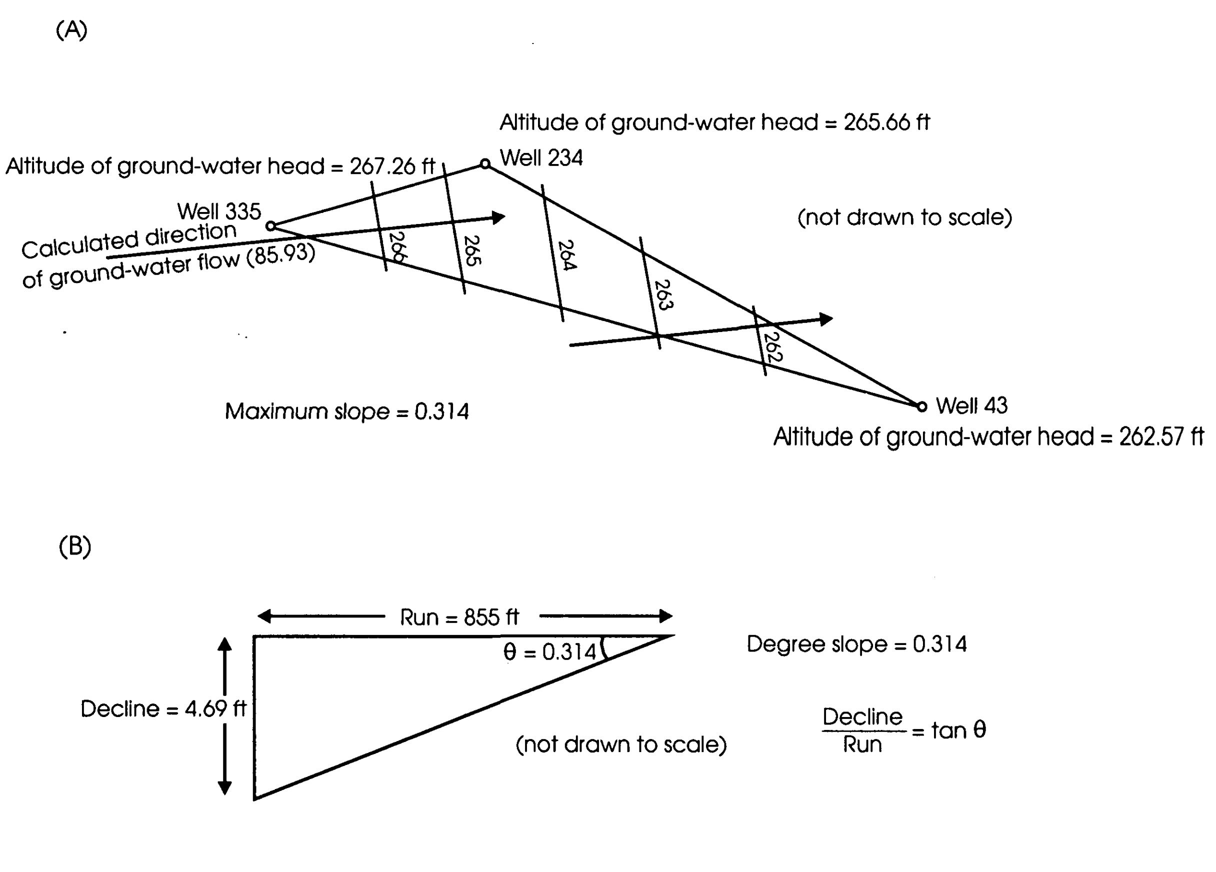


Figure 1. Graphical (A) and mathematical (B) solutions to a three-point computation.

The slope solution of the three-point problem can also be solved mathematically (fig. 1B) by finding the ratio between the maximum vertical distance (decline) and the horizontal distance (run), expressed as a simple fraction. Slope also can be expressed as units of angular measure, or degrees, based on the fact that the slope value as a simple fraction is the trigonometric tangent of the slope angle (Muehrke and Muehrke, 1992). The computation of slope in one dimension is shown in figure 1B. For two dimensions, the gradient of a spatial function is defined as:

$$G(x, y) = \sqrt{((\Delta x)^2 + (\Delta y)^2)}, \qquad (1)$$

where

Δx = slope in x-direction

Δy = slope in y-direction.

The computer software allows for computation of slope and aspect from irregular shaped triangles based on the location of wells at the corner of the triangle. Conceptually, computational errors of maximum gradients will be reduced if uniform-shaped triangular networks are used. In most cases, however, the locations of head data are not uniformly distributed in the aquifer.

DOCUMENTATION OF METHOD

ARC/INFO, a computer Geographic Information System (GIS) software, developed by Environmental Systems Research Institute (1995), was used for this study. Head-measurement data were analyzed using the ARC/INFO module TIN (Triangulated Irregular Network). TIN capabilities allow for surface analysis using the location of wells in x,y coordinates, and the head measurements as the z coordinate. The TIN data model represents a surface of non-overlapping contiguous triangles. The analysis functions of TIN were used to calculate the slope and aspect for each head surface from the z coordinates of the triangulated area.

To facilitate data input and analysis of slope and aspect, a computer program was created and called RUNSLOPE.AML (appendix 2). RUNSLOPE.AML was written in Arc Macro Language (AML), a proprietary computer language designed to run in ARC/INFO. RUNSLOPE.AML also can be used to conduct a time-series analysis to assess the variability of a hydraulic gradient for a given triangle.

Input Requirements

The location of the wells and well-head measurements are used to create TINs for computations of slope and aspect. An American Standard Character Code for Information Interchange (ASCII) data file is used for initial input in RUNSLOPE.AML. The contents of the data file should contain a numeric well identifier, followed by a time series of head measurements for the well in a space delimited format (table 1). Each column of head values represents an associated time period; for example, the first column of head values are all from the same day and so on. Well-identifier values should be a numeric identifier with a value range of 1–999.

Table 1. Example of input file to ARC MACRO LANGUAGE (AML) program for computation of slope and aspect

[Column 1 = well identifier; Columns 2–8 = altitude of ground-water head]

1	2	3	4	5	6	7	8
335	267.26	267.12	266.43	266.31	266.57	266.58	266.39
234	265.66	265.51	264.82	264.69	264.94	264.95	264.77
43	262.57	262.22	261.68	261.35	261.27	261.18	261.15

An ARC/INFO coverage of well locations is also needed with locations of wells in x,y state-plane coordinates. Data loaded from the ASCII file into an INFO data base table are linked to the well locations by the numeric well identifier. A master wells coverage was created by use of the ARC/INFO command GENERATE. The wells coverage contains the wells for the entire network, which are used in selecting the well network, in groups of three, for individual triangles. Each triangle must be processed separately when selected areas overlap, because TIN does not allow for overlap.

RUNSLOPE.AML requires no additional input data except interactive queries, which are used to identify input and output information, and dates of head measurements. The program can be modified to allow batch processing of additional ASCII files of time series of head measurements.

Program Operation

RUNSLOPE.AML requires an input ASCII file, and a coverage of well locations, which contains wells for the entire triangulated network. Prior to program operation, the user must decide which triangle to process and analyze. Program operation instructions are provided in detail in appendix 1.

Output Files

The final results of RUNSLOPE.AML is an ASCII output file that contains dates and corresponding computed slopes and aspects for a given triangular network of three head measurements (table 2). Aspect results are given in degrees from true north and slope in degrees from the horizontal.

A benefit of summarizing information into a separate ASCII output file is that the information on slope and aspect can be imported into other software programs for analyzing and plotting.

Table 2. Example of output file from ARC MACRO LANGUAGE (AML) program for computation of slope and aspect

[Slope and aspect expressed as degrees; Column 1 = date; Column 2 = slope in degrees from horizontal; Column 3 = aspect in degrees from true north]

1	2	3
`6/21/94'	0.314	85.930
`7/5/94'	0.321	89.745
`7/15/94'	0.317	86.587
`8/1/94'	0.324	90.353
`8/15/94'	0.339	96.439
`8/29/94'	0.344	98.307
`9/12/94'	0.335	95.913
`9/26/94'	0.356	101.212
`10/11/94'	0.334	94.132
`10/24/94'	0.334	93.319
`11/7/94'	0.336	95.294
`11/21/94'	0.340	96.013
`12/5/94'	0.411	111.975
`12/19/94'	0.379	106.136
`1/3/95'	0.328	91.555
`1/16/95'	0.329	91.756
`1/30/95'	0.326	91.169
`2/13/95'	0.330	93.575
`2/27/95'	0.336	94.486
`3/13/95'	0.331	93.150

APPLICATION EXAMPLE

The usefulness of the computer technique described in this report is demonstrated at a test site where a ground-water-flow system has been studied to assess the variability of seasonal effects of ground-water recharge and discharge on the transport of contaminated ground waters (Harte and others, 1997).

Description of Test Site

A large contaminant plume of volatile organic compounds exists in the western-half of the Milford-Souhegan glacial-drift aquifer in Milford, New Hampshire (Harte and others, 1997; fig. 2). The aquifer is unconfined, highly permeable, and ground-water velocities exceed several feet per day in some areas. To assess the effect of seasonal patterns of ground-water recharge and discharge on the spread of contaminated ground waters, water levels were measured at 77 wells in the aquifer.

Important areas of the aquifer were divided into 14 triangulated groups of wells, where information on biweekly water levels were available for 1 year (Harte and others, 1997; fig. 3). An alphabetic coding system was used to identify each triangle.

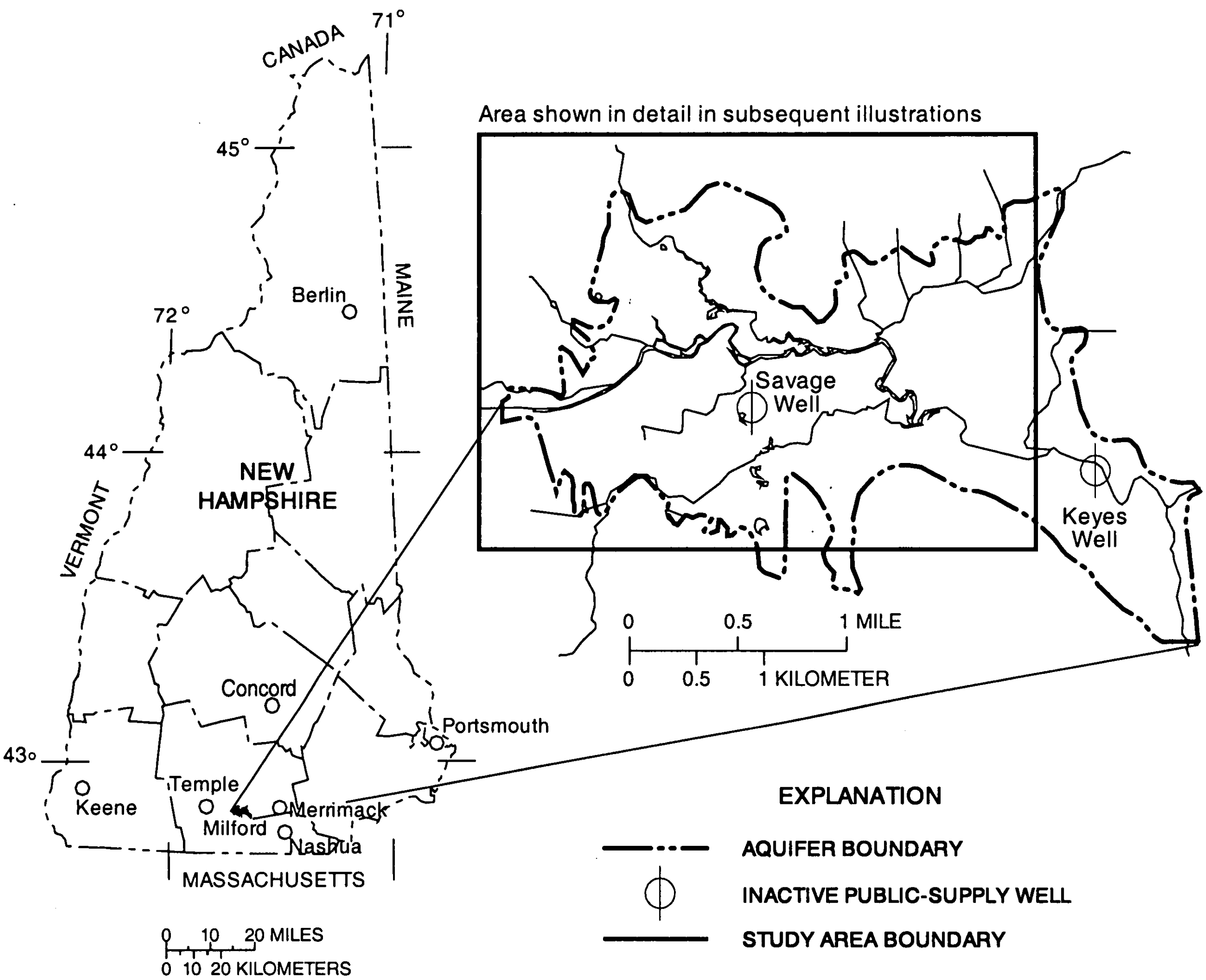
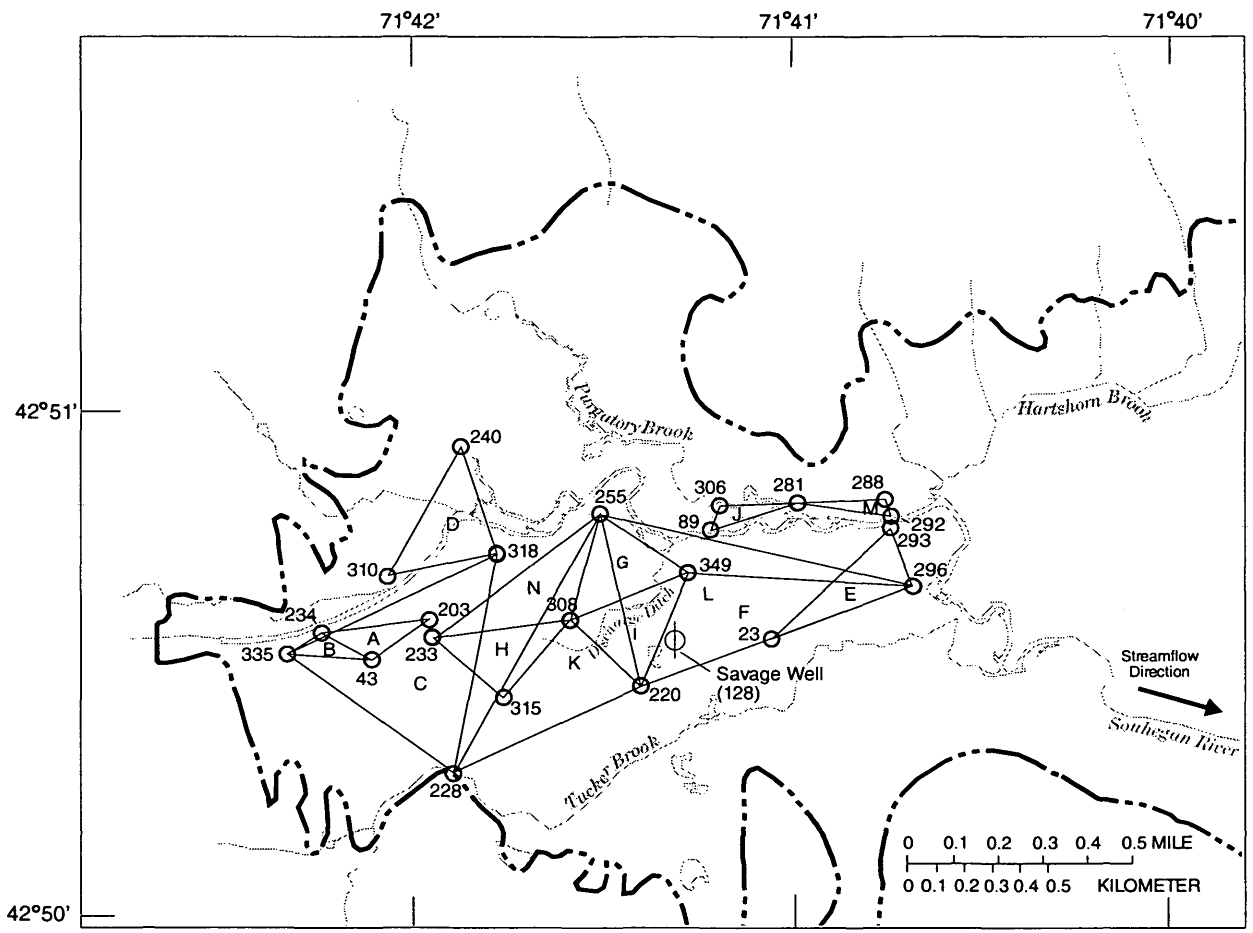


Figure 2. Location of glacial-drift aquifer test site, Milford, New Hampshire (from Harte and others, 1997).



EXPLANATION

Boundary of Aquifer

Triangle of Adjoining Wells

Savage Well (128) — Well Name and Number for Unused Well

240 — Well and Number Used for Triangulation of Water Level

Triangle name	Wells
A	43, 203, 234
B	43, 234, 335
C	228, 318, 335
D	240, 310, 318
E	23, 293, 296
F	220, 296, 349
G	255, 308, 349
H	233, 308, 315
I	220, 308, 349
J	89, 281, 306
K	220, 228, 255
L	220, 255, 296
M	281, 288, 292
N	233, 255, 308

Figure 3. A triangular network of wells in a glacial-drift aquifer in Milford, New Hampshire (from Harte and others, 1997).

Computation of Slope and Aspect

A ranking of the variability of computed slope and aspect calculations is given in table 3. The data were compiled from results of the output file of RUNSLOPE.AML, and input into a statistical software package for analysis. The analysis shows that triangles located at the extreme western and eastern areas of the triangular network have the greatest seasonal variability (see triangles M, J, B, and D, fig. 3). These triangles are located adjacent to the Souhegan River and show that the river exerts a strong influence on ground-water flow.

Table 3. Summary statistics on direction of maximum ground-water hydraulic gradient (aspect) and ground-water hydraulic gradient (slope) from test site

[Triangles listed from maximum to minimum changes in direction and slope. Triangle locations are shown in figure 16. To convert slope, in degrees, to slope in feet per feet, take the tangent of the value of slope in degrees.]

Direction of maximum ground-water gradient			Slope of maximum ground-water gradient		
Triangle	Mean direction, in degrees from true north	Standard deviation	Triangle	Mean slope, in degrees	Standard deviation
M	86.3	50.9	D	0.537	0.113
J	77.2	33.9	B	.429	.084
B	131.5	4.3	M	.206	.078
D	11.0	9.4	A	.401	.056
H	52.3	5.6	J	.131	.032
E	86.8	5.1	E	.207	.026
C	75.5	4.3	N	.223	.020
A	125.4	4.1	H	.258	.018
N	82.0	3.2	K	.184	.011
G	67.9	2.9	G	.142	.008
I	31.2	2.5	I	.177	.007
K	52.8	2.2	F	.196	.007
F	48.9	2.1	L	.191	.006
L	53.8	1.6	C	.273	.003

The frequency of observed aspects is shown for triangle B (fig 4.). The distribution of aspects shows that there is a large variability around the arithmetic mean of the computed aspects, which in this case is 131 degrees from true north. In this example, the other statistical properties besides the mean, such as the variance or standard deviation, should be utilized to adequately describe the direction of maximum hydraulic gradient.

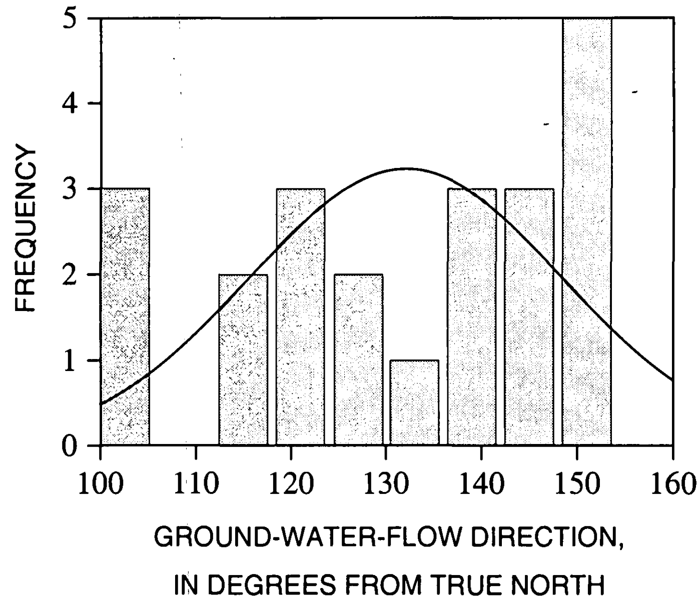
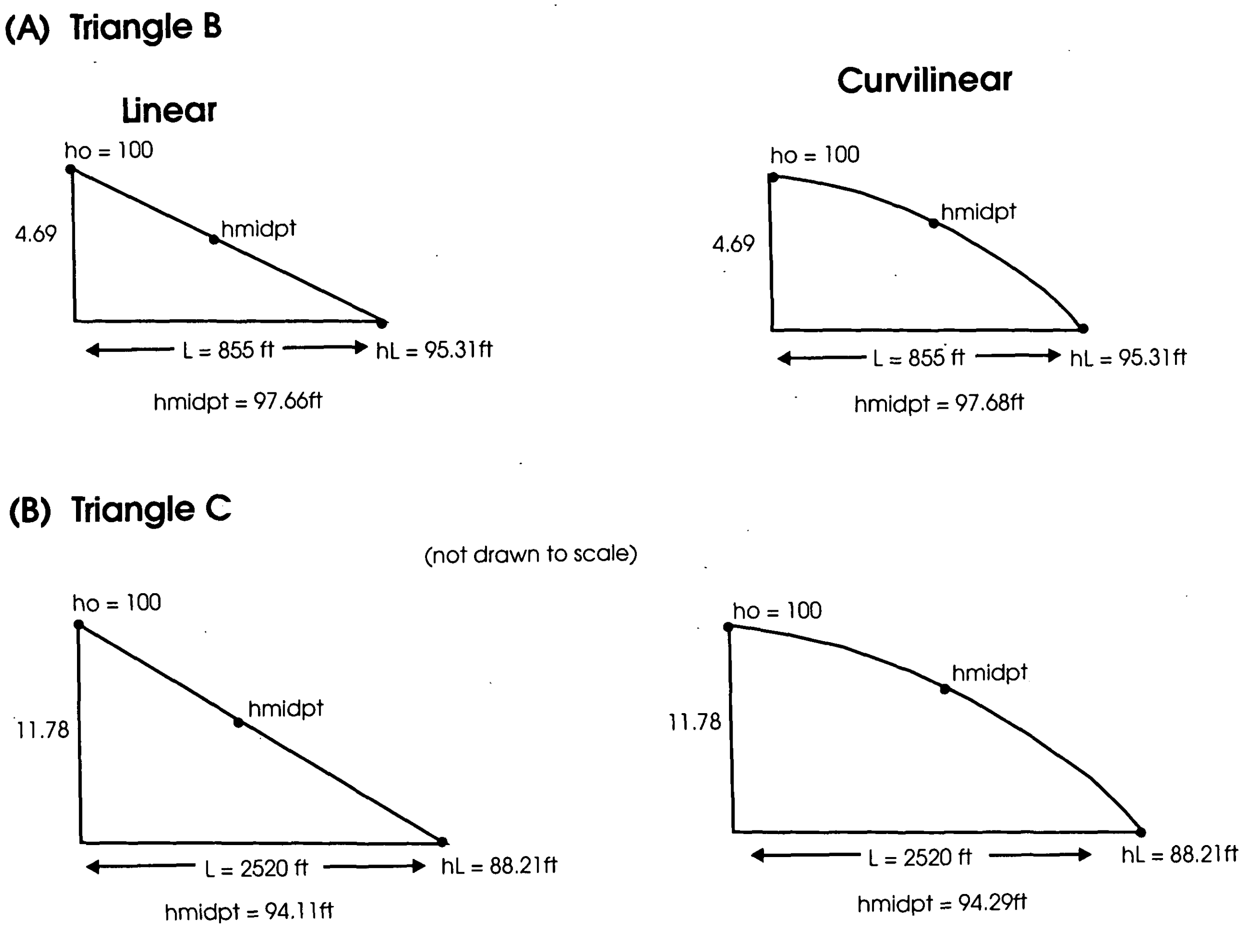


Figure 4. Frequency of direction of maximum ground-water hydraulic gradient (aspect).

Accuracy of Computed Gradients

The slope of the water-table surface in the aquifer at the test site is generally small (less than 0.02 feet per feet), thus the errors in the approximation of the water table by a linear gradient are also small. Furthermore, the largest triangulated areas used for the study introduce only small errors. Examples of errors from the linear approximation technique for triangles B and C are shown in figure 5.

A one-dimensional slice was taken through each triangle corresponding to the direction of maximum gradient. Ground-water heads were computed at the midpoint of each slice based on a linear sloping water table and a parabolic sloping water table (curvilinear) and heads were compared to determine the relative difference between each solution. The midpoint of each triangle represents the most likely location of greatest difference between the computed heads. In the examples provided, the difference in heads at triangle B are 0.02 feet (ft) out of a potential range in head of 4.69 ft, an error of 0.4 percent, and the difference in heads at triangle C are 0.18 ft out of a range in head of 11.79 ft, an error of 1.5 percent.



Equation for head

$$h(x) = ho - \left(\frac{ho - hL}{L}\right) x$$

Equation for head

$$h(x) = ho^2 - \left(\frac{(ho)^2 - (hL)^2}{L}\right)$$

where h = ground-water head
ho = ground-water head at x = zero (0)
hL = ground-water head at x = Length

Figure 5. Linear and curvilinear slopes of hydraulic gradients from (A) triangle B and (B) triangle C at the test site in Milford, New Hampshire.

SUMMARY

This report describes a computer technique that can be used to calculate the true aspect and slope of ground-water head from three points. The technique uses a Geographic Information System (GIS) and a computer program to compute results. The GIS uses a linear solution to compute slopes.

The application of the computer technique in a shallow surficial-aquifer system showed that the technique allows for easy synthesis of multiple measurements of ground-water head and computation of variability of surface aspect and slope. These results are being used to assess the effect of seasonal recharge and discharge on transport of contaminated ground waters. Similar applications also can benefit from this technique.

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Muehrke, P.C., and Muehrke, J.O., 1992, Map use: JP, Madison, Wis., p. 631.

Todd, D.K., 1980, Groundwater hydrology: John Wiley and Sons, Inc., N.Y., p. 87.

APPENDIX 1

APPENDIX 1. EXPLANATION OF PROGRAM OPERATION FOR ARC MACRO LANGUAGE (AML) PROGRAM RUNSLOPE.AML

RUNSLOPE.AML EXPLANATION

Before initial program operation of RUNSLOPE.AML, the user must establish a few required parameters—define triangular areas, select which wells define those areas, how many measurements will be used, and what dates will be used to represent the date measurements were taken. Triangular areas must first be defined and named by selecting wells that define the endpoints of each triangle.

A master wells coverage must also be created for the program to select wells based upon a well identifier (WELL-ID) field item from within the point attribute table (PAT). The master wells coverage should contain all the wells used for the entire network. The ARC command GENERATE can be used to create a master wells coverage. The coverage should contain a WELL-ID item using an input and output width of 3, defined as an integer type with 0 decimal places. The range of acceptable WELL-ID values is from 1–999.

The glacial-drift aquifer in Milford, New Hampshire (study example, see fig. 3), uses 14 triangulated areas that were named in alphabetical order from A to N. For this study area, RUNSLOPE.AML was created; therefore, the AML uses default WELL-IDs for each triangle specified for processing. The default WELL-IDs and the triangle letter symbol can be changed within RUNSLOPE.AML on lines 42–55 using a text editor (see RUNSLOPE.AML program in appendix 2).

Multiple-head measurements can be processed to represent a time-series analysis. The glacial-drift aquifer study uses a total of 26 biweekly dates of measurements yielding one year of analysis. The program allows for default dates to be used for each column of measurements. These default dates also can be changed using a text editor for lines 174–183, 193, and 209–233. All default parameters in the AML code are commented with remark lines pointing to the values that can be updated. By default, the maximum number of dates is 26.

Below is a brief checklist to use before using RUNSLOPE.AML

1. Define and name the triangulated areas using well locations as endpoints (for example, A, B, etc.).
2. Make sure wells have a numeric identifier value range from 1–999.
3. Select which dates of measurements to use.
4. The input ASCII file must follow the specified format shown in table 1 of this report.
5. Obtain or create a well coverage that contains all well locations for the various triangles.
6. The master-wells coverage must contain a WELL-ID item using the specified format.

NOTE: Default values for triangle-identifiers, well identifiers, and measurement dates may need editing in RUNSLOPE.AML before initial program use.

Program Operation and Process Description

Run RUNSLOPE.AML at the ARC prompt: **Arc: &r runslope.aml**
The following ARC/INFO commands used in the explanation are executed in RUNSLOPE.AML and are provided as examples to the program. Triangle B will be used for this example.

1. RUNSLOPE.AML first prompts the user for the input and output ASCII file names. Next, the program prompts the user to enter the number of measurements. The program then prompts the user for the letter code of the triangulated area to be processed (for example, B). The last prompt asks for an input master wells coverage (default is TRI-WELLS).
2. The first process involves creating a wells coverage by selecting the three wells that define triangle B from the master wells coverage. The newly created wells coverage is named WELLSB.
   The process is done in ARCEDIT, an ARC/INFO module.

```
     Arc: ARCEDIT
Arcedit: EDITCOVERAGE tri-well
Arcedit: EDITFEATURE point
Arcedit: SELECT WELL-ID in {43,234,335}
Arcedit: PUT wellsb
```

3. RUNSLOPE.AML creates an INFO table called work.dbf, using the following item definitions:

COLUMN	ITEM NAME	WIDTH	OUTPUT	TYPE	N.DEC
1	WELL-ID	3	3	I	-
4	DATE1	8	8	F	2
12	DATE2	8	8	F	2
20	DATE3	8	8	F	2

The user-specified measurement dates are used in a program loop to create the DATE fields.

4. Next, the data from the ASCII File are loaded into the INFO table using the ARC/INFO module TABLES.

```
           Arc:  TABLES
Enter Command:  SELECT work.dbf
Enter Command:  ADD WELL-ID date1 date2 date3 date4 date5 date6 date7 date8
                date9 date10 date11 date12 date13 date14 date15 date16 date17
                date18 date19 date20 date21 date22 date23 date24 date25 date26
                FROM (ASCII file)
```

Format of contents of WORK.DBF after loading of data from input ASCII file.

```
WELL-ID  =  335
  DATE1  =  267.26
  DATE2  =  267.12
  DATE3  =  266.43
```

5. The contents of the INFO table is then merged with the wells coverage PAT. The WELL-ID is used as the relate item between the PAT and the INFO table.

   Arc: JOINITEM wellsb.pat work.dbf wellsb.pat WELL-ID WELL-ID linear

   Format of Contents of WELLSB.PAT after merging of data from WORK.DBF

AREA	=	0.00000
PERIMETER	=	0.00000
WELLSB#	=	1
WELLSB-ID	=	335
WELL-ID	=	335
DATE1	=	267.26
DATE2	=	267.12
DATE3	=	266.43

   WORK.DBF is deleted after the JOINITEM command since it is no longer needed.

6. After the initial variables are set, RUNSLOPE.AML creates a TIN using the wells point coverage. TIN generates a surface from measurements of head from wells contained in the coverage's PAT. If only one date is used, RUNSLOPE.AML will use the measurement for the DATE1 field contained in the WELLSBPAT. If numerous dates are used, the first measurement will be DATE1 and later incremented with the &DO loop in the program so that DATE2 will be the next value used to create the TIN for the second date and so on.

   ARC commands used to generate TIN surface:

   Arc: CREATETIN <out_tin (tin_%num%)>
   Createtin: COVER <in_cover(wellsb)> Point {spot item (date%num%)}
   Createtin: END

   %num% is the incremented numeric variable

7. Next, to obtain slope and aspect calculations from the surface analysis, the TIN must be converted to a polygon coverage. The results of the surface analysis are stored in the coverage's polygon attribute table as attribute items (degree_slope, aspect). Aspect is expressed in positive degrees from 0 to 360, measured clockwise from true north. The slope statistics are expressed in degrees for use in this project but can be changed to percent. Once the coverage has been created, the input TIN will be deleted or "killed" with the ARC KILL command.

   ARC command used to convert TIN to ARC/INFO coverage:

   Arc: TINARC <in_tin (tin_%num%)> <out_cover (cov%num%)> Poly {Percent | Degree}

Example of items contained in the attribute table of an output polygon coverage converted from a TIN:

Arc: LIST cov1.pat

1		
AREA	=	-250001.27000
PERIMETER	=	1942.85465
COV1#	=	1
COV1-ID	=	0
DEGREE_SLOPE	=	-9999.000
ASPECT	=	-9999.000
SAREA	=	-250005.04167
2		
AREA	=	250001.27000
PERIMETER	=	2768.52182
COV1#	=	2
COV1-ID	=	1
DEGREE_SLOPE	=	0.315
ASPECT	=	138.491
SAREA	=	250005.04167

NOTE: Record 2 contains the slope and aspect data for triangle B. Record 1 reflects the outside universal polygon.

8. The last step involves a retrieval of the slope and aspect values from all 26 coverages representing the biweekly analysis for each triangle. At this time, the polygon attribute table of each coverage is assigned a DATE field, which will store the date for that triangle's computed maximum slope and aspect.

If the user wishes to use one date, the program will prompt the user for the date. If multiple dates are to be used, the user can interactively enter each date or use the default dates. These default dates can easily be changed in RUNSLOPE.AML.

After all dates are loaded into the coverage's DATE field, the date, slope, and aspect values are exported to an ASCII output file. Afterwards, the coverage is removed with the KILL command since it is no longer needed.

ARC commands used to add date field and unload the slope and aspect values to an ASCII file:

```
            Arc: TABLES
Enter Command: ADDITEM cov1.pat DATE 8 8 C
Enter Command: SELECT cov1.pat
Enter Command: RESELECT cov1-id = 1 (see above)
Enter Command: MOVE%date% to DATE (%date% is a variable: see AML)
Enter Command: UNLOAD <output> date degree_slope aspect
```

APPENDIX 2

APPENDIX 2. PROGRAM RUNSLOPE.AML

```
/*************************************************************************
/* RUNSLOPE.AML for UNIX ARC/INFO
/* This AML used to create TINS from INFO files and converted to
/* ARC/INFO coverages to find max slope (hydraulic gradient) and aspect
/* (direction of maximum hydraulic gradient) of triangulated areas over a
/* users defined time series
/* Created November 13, 1996 - Craig Johnston - U.S. Geological Survey WRD
/* Modified September 10, 1997
/*************************************************************************

&sv.in := [unquote [response 'Enter name of input ASCII file']]
&sv.out := [unquote [response 'Enter name of output ASCII file']]
&sv.d := [unquote [response 'Enter amount of measurement dates (26 max)']]
&sv p = [show workspace]
&sv tri := [unquote [response 'Enter the letter symbol for the triangle: Ex. b']]
&sv w := [unquote [response 'Name of master wells coverage (def tri-wells)' tri-wells]]
/*                                                   ______|________|
/*                                                         |
/*                *Change master wells coverage default here as needed *

&if [calc [ITEMINFO  %w% -point WELL-ID -definition] ne 3,3,I,0] &then
 &do
 &type Input wells coverage must contain WELL-ID item in the specified format:
 &type
 &type       ITEM NAME    WIDTH    OUTPUT  TYPE N.DEC
 &type        WELL-ID        3         3        I      -
 &type
 &type BAILING OUT...
 &STOP
 &end
&else
&do
AE
&SELECT %tri%
/*************************************************************************
/* Change defaults for triangle-id and WELL-IDs here as needed
/*        ___________/       /
/*       /           ________/
/*       |          /       \
/*       V         [         ]
&WHEN a ; &sv sel = 43,203,234
&WHEN b ; &sv sel = 43,234,335
&WHEN c ; &sv sel = 228,318,335
&WHEN d ; &sv sel = 240,310,318
```

```
&WHEN e ; &sv sel = 23,293,296
&WHEN f ; &sv sel = 220,296,349
&WHEN g ; &sv sel = 255,308,349
&WHEN h ; &sv sel = 233,308,315
&WHEN i ; &sv sel = 220,308,349
&WHEN j ; &sv sel = 89,281,306
&WHEN k ; &sv sel = 220,228,255
&WHEN l ; &sv sel = 220,255,296
&WHEN m ; &sv sel = 281,288,292
&WHEN n ; &sv sel = 233,255,308
/*   |           |
/* triangle-id  [well-id,well-id,well-id]
/*
/***********************************************************************
&OTHERWISE
  &type ERROR
&END
ec %w%
ef point
sel well-id in {%sel%}
put wells%tri%
save
q

TABLES
DEFINE work.dbf
well-id
3
3
I
;
SEL
&sv .ds := [calc %.d% - 1]
  &do a = 0 &to %.ds% &by 1
  &sv .num = [calc %a% + 1]
    &do
     ADDITEM work.dbf date%.num% 8 8 f 2
     &sv index = %.num%
     &sv .%index% = date%.num%
    &end
  &end
```

```
&SELECT %.d%
&WHEN 1 ; &sv opt = %.1%
&WHEN 2 ; &sv opt = %.1% %.2%
&WHEN 3 ; &sv opt = %.1% %.2% %.3%
&WHEN 4 ; &sv opt = %.1% %.2% %.3% %.4%
&WHEN 5 ; &sv opt = %.1% %.2% %.3% %.4% %.5%
&WHEN 6 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6%
&WHEN 7 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% %.7%
&WHEN 8 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% %.7% %.8%
&WHEN 9 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% %.7% %.8% %.9%
&WHEN 10 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% %.7% %.8% %.9% %.10%
&WHEN 11 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% %.7% %.8%............%.11%
&WHEN 12 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% %.7%..........%.11%%.12%
&WHEN 13 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% .......%.11% %.12% %.13%
&WHEN 14 ; &sv opt = %.1% %.2% %.3% %.4% %.5%... %.11% %.12% %.13% %.14%
&WHEN 15 ; &sv opt = %.1% %.2% %.3% %.4%... %.11% %.12% %.13% %.14% %.15%
&WHEN 16 ; &sv opt = %.1% %.2% ...........%.11% %.12% %.13% %.14% %.15% %.16%
&WHEN 17 ; &sv opt = %.1%........ %.11% %.12% %.13% %.14% %.15% %.16% %.17%
&WHEN 18 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% %.7% %.8% %.9% %.10%
  %.11% %.12% %.13% %.14% %.15% %.16% %.17% %.18%
&WHEN 19 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% %.7% %.8% %.9% %.10%
  %.11% %.12% %.13% %.14% %.15% %.16% %.17% %.18% %.19%
&WHEN 20 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% %.7% %.8% %.9% %.10%
  %.11% %.12% %.13% %.14% %.15% %.16% %.17% %.18% %.19% %.20%
&WHEN 21 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% %.7% %.8% %.9% %.10%
  %.11% %.12% %.13% %.14% %.15% %.16% %.17% %.18% %.19% %.20% %.21%
&WHEN 22 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% %.7% %.8% %.9% %.10%
  %.11% %.12% %.13% %.14% %.15% %.16% %.17% %.18% %.19% %.20% %.21%
  %.22%
&WHEN 23 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% %.7% %.8% %.9% %.10%
  %.11% %.12% %.13% %.14% %.15% %.16% %.17% %.18% %.19% %.20% %.21%
  %.22% %.23%
&WHEN 24 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% %.7% %.8% %.9% %.10%
  %.11% %.12% %.13% %.14% %.15% %.16% %.17% %.18% %.19% %.20% %.21%
  %.22% %.23% %.24%
&WHEN 25 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% %.7% %.8% %.9% %.10%
  %.11% %.12% %.13% %.14% %.15% %.16% %.17% %.18% %.19% %.20% %.21%
  %.22% %.23% %.24% %.25%
&WHEN 26 ; &sv opt = %.1% %.2% %.3% %.4% %.5% %.6% %.7% %.8% %.9% %.10%
  %.11% %.12% %.13% %.14% %.15% %.16% %.17% %.18% %.19% %.20% %.21%
  %.22% %.23% %.24% %.25% %.26%
&OTHERWISE
 &do
 &type ERROR...Number of dates exceed program maximum of 26
 &type Bailing out...
 q
 KILL work.dbf
 &end
&END
```

```
SELECT work.dbf
ADD well-id %opt% FROM %.in%
;
q

JOINITEM %p%/wells%tri%.pat work.dbf %p%/wells%tri%.pat well-id well-id linear

TABLES
KILL work.dbf
q

&sv ds := [calc %.d% - 1]

  &do a = 0 &to %ds% &by 1
  &sv num = [calc %a% + 1]

   &do
    CREATETIN %p%/tin_%num%
    COVER %p%/wells%tri% point date%num%
    end
    TINARC %p%/tin_%num% %p%/cov%num% poly degree
    KILL  %p%/tin_%num%
      &IF %.d% = 1 &then; &sv date := [unquote [response 'Enter the date ']]
      &ELSE
       &DO
        &IF %.d% gt 1 and %num% = 1 &THEN
         &DO
         ;
         &type THE FOLLOWING BIWEEKLY DATES WERE USED FOR THE
MILFORD STUDY ~ AREA
         ;
         &type  1 = 06/21/94      11 = 11/07/94      21 = 3/327/95
         &type  2 = 07/05/94      12 = 11/21/94      22 = 4/10/95
         &type  3 = 07/15/94      13 = 12/05/94      23 = 4/24/95
         &type  4 = 08/01/94      14 = 12/19/94      24 = 5/8/95
         &type  5 = 08/15/94      15 = 01/03/95      25 = 5/22/95
         &type  6 = 08/29/94      16 = 01/16/95      26 = 6/5/95
         &type  7 = 09/12/94      17 = 01/30/95
         &type  8 = 09/26/94      18 = 02/13/95
         &type  9 = 10/11/94      19 = 02/27/95
         &type 10 = 10/24/94      20 = 03/13/95
         ;
         /**** Change dates above as needed ****
         ;
         &sv .q := [unquote [response 'Do you wish to use the above dates? y or n']]
         &SELECT %.q%
```

```
 &WHEN n
   &sv date := [response [quote Enter date [value num]]]
 &WHEN y
 /**************************************************
   &sv date := 6/21/94
 /*               \
 /* Default date for date1 can be changed as needed
 /**************************************************
 &OTHERWISE
   &type ENTER y or n only
 &END
&END

&ELSE
 &DO
 &IF %.d% gt 1 and %num% gt 1 and %.q% = 'y' &then
 &SELECT %num%
 /**************************************************
 /* Default dates for dates 2-26; change as needed  *
 /*                           \
 &when 2 ; &sv date := 7/5/94
 &when 3 ; &sv date := 7/15/94
 &when 4 ; &sv date := 8/1/94
 &when 5 ; &sv date := 8/15/94
 &when 6 ; &sv date := 8/29/94
 &when 7 ; &sv date := 9/12/94
 &when 8 ; &sv date := 9/26/94
 &when 9 ; &sv date := 10/11/94
 &when 10 ; &sv date := 10/24/94
 &when 11 ; &sv date := 11/7/94
 &when 12 ; &sv date := 11/21/94
 &when 13 ; &sv date := 12/5/94
 &when 14 ; &sv date := 12/19/94
 &when 15 ; &sv date := 1/3/95
 &when 16 ; &sv date := 1/16/95
 &when 17 ; &sv date := 1/30/95
 &when 18 ; &sv date := 2/13/95
 &when 19 ; &sv date := 2/27/95
 &when 20 ; &sv date := 3/13/95
 &when 21 ; &sv date := 3/27/95
 &when 22 ; &sv date := 4/10/95
 &when 23 ; &sv date := 4/24/95
 &when 24 ; &sv date := 5/8/95
 &when 25 ; &sv date := 5/22/95
 &when 26 ; &sv date := 6/5/95
 /************************************************
```

```
        &otherwise
          &type ERROR...Number of dates exceeds maximum of 26
        &end
        &ELSE
        &sv date := [response [quote Enter date [value num]]]
        &end
      &end

    TABLES
    ADDITEM cov%num%.pat DATE 8 8 C
    SELECT cov%num%.pat
    RESELECT cov%num%-id = 1
    MOVE [QUOTE %date%] to DATE
    UNLOAD %.out% date degree_slope aspect columnar format
    q
    KILL cov%num%
   &end
  &end

&sys rm format
KILL wells%tri%
more %.out%
;
&type DONE
&end
&RETURN
```

Johnston and Harte—DOCUMENTATION AND APPLICATION OF A METHOD TO COMPUTE MAXIMUM SLOPE AND ASPECT OF HYDRAULIC GRADIENTS

USGS/WRIR 98-4021