USACE Hazardous, Toxic, and Radioactive Waste (HTRW) Center of Expertise

Omaha, NE

2DSTREAM and 3DLEAKY MODELS FOR SOIL VAPOR EXTRACTION APPLICATIONS

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May 1996

Document Number 9000-048-712

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1.0 INTRODUCTION

This report provides the mathematical development and example applications for 2DSTREAM and 3DLEAKY, two subsurface air flow models distributed as part of the April, 1996 Soil Vapor Extraction and Bioventing Training Workshop. This workshop was held on April 2-4, 1996 at Fort Richardson, Alaska, sponsored by the U.S. Army Corps of Engineers (USACE) - Center of Expertise and the USACE - Alaska District, and presented by ENSR Consulting and Engineering. Program development was partialy funded by a contract between ENSR and the USACE Hazardous, Toxic, and Radioactive Waste (HTRW) Center of Expertise; the remaining program development was performed at the sole expense of the author. The U.S. Government is granted the right to use this software without restriction; however, other parties must first obtain written permission from David Brailey, 6911 Terry Place, Anchorage, Alaska.

Input files, output files, and graphic results included in this report were generated using 2DSTREAM Version 1.0 and 3DLEAKY Version 1.0. These programs have not been extensively "beta tested" and may contain errors. Problems with program execution or presentation of results may be addressed to the USACE HTRW Center of Expertise in Omaha, NE, or to the author at the above address.

2.0 MATHEMATICAL DEVELOPMENT

The following section provides the mathematical development for programs 2DSTREAM and 3DLEAKY. Program 2DSTREAM calculates pressure and the stream function for fully penetrating wells in a tabular vadose zone with impermeable boundaries at the ground surface and at the water table. Program 3DLEAKY calculates pressure and the stream function for partially penetrating wells in a tabular vadose zone with an impermeable boundary at the water table and surface boundaries ranging from impermeable to a constant pressure, atmospheric boundary.

Both programs are based on analytical solutions to the partial differential equation (PDE) for steady air flow in porous media. The PDE is obtained by combining equations Darcy's law for vapor flow;

$$q = \frac{k_a}{\mu} \nabla P \qquad (1)$$

with conservation of mass for a compressible fluid;

$$\nabla \cdot (\rho \, q) = \frac{\partial (\rho \, n_a)}{\partial t} \qquad (2)$$

and the ideal gas law:

$$\rho = \frac{\omega P}{RT} \qquad (3)$$

where:

q	=	air flow velocity (L/T)
ρ	=	density of air (M/L^3)
n_a	=	air-filled porosity (L^3/L^3)
t	=	time (T)
k_a	=	air permeability (L^2)
P	=	air pressure ($M/L\text{-}T^2$)
μ	=	dynamic viscosity of air (M/L-T)
ω	=	molecular weight (M/mole)
R	=	universal gas constant ($L^3M/L\text{-}T^2\text{-mole-}°K$)
T	=	absolute temperature (°K)

Treating air filled porosity and viscosity as constants, the resulting PDE is;

$$\nabla \cdot \left(k_a \nabla P^2\right) = 2 n_a \mu \frac{\partial P}{\partial t} \qquad (4)$$

and for steady flow:

$$\nabla \cdot \left(k_a \nabla P^2\right) = 0 \qquad (5)$$

For isotropic systems, k_a is independent of $\nabla^2 P^2$, and equation (5) becomes:

$$\nabla^2 P^2 = 0 \qquad (6)$$

Equation (6) is equivalent to LaPlace's equation in P^2. In this regard, the square of pressure can be regarded as a fluid potential (ϕ) with a corresponding stream function (ψ). Both potential functions and stream functions satisfy the LaPlace equation, and are related by the Cauchy-Rieman equations:

$$\frac{\partial \phi}{\partial x} = \frac{\partial \psi}{\partial y}; \quad \frac{\partial \phi}{\partial y} = -\frac{\partial \psi}{\partial x} \qquad (7)$$

Programs 2DSTREAM and 3DLEAKY are based on superposition of pressure and stream function solutions for radial flow to a line sink (i.e., a well). The principle of superposition states that if two functions satisfy a linear PDE, then their sum satisfies the same PDE. The principle of superposition applies to linear PDEs of any order, including the LaPlace equation.

Program 2DSTREAM is based on the solution to equation (6) for 1-dimensional radial flow to a fully penetrating line sink. The single coordinate direction r, can be expressed as $(x^2 + y^2)^{1/2}$ in cartesian coordinates. For steady flow in a homogeneous, isotropic vadose zone with impermeable upper and lower boundaries, the pressure solution is (USACE 1995):

$$P^2 - P_{atm}^2 = \frac{Q_v P^* \mu}{\pi b k_a} \ln\left(\frac{r_e}{\sqrt{(x-x_1)^2 + (y-y_1)^2}}\right) \qquad (8)$$

where:

P	=	air pressure (M/L-T^2)
P_{atm}	=	atmospheric pressure (M/L-T^2)
Q_v	=	volumetric flow rate (L^3/T)
P^*	=	pressure at the point of flow measurement (M/L-T^2)
b	=	vadose zone thickness (L)
x_1, y_1	=	x and y coordinates of the well (L)
r_e	=	radius of pressure influence (L)

and the stream function solution is (USACE 1995):

$$\psi = \frac{Q_v P^* \mu}{\pi b k_a} \tan^{-1}\left\{\frac{y-y_1}{x-x_1}\right\} + C \qquad (9)$$

where C is a constant of integration. Equation (9) represents a family of straight lines passing through (x_1,y_1), where the arctangent term is equivalent to the angle θ (in radians) between each line and the x-axis. Defining the angle θ as:

$$\theta = \tan^{-1}\left|\frac{y-y_1}{x-x_1}\right| \qquad (10)$$

unique values of ψ can be specified by defining the constant of integration so that:

$$\begin{aligned}
\psi &= \frac{Q_v P^* \mu}{\pi b k_a}\theta \quad for \quad 0<\theta<\frac{\pi}{2};\\
\psi &= \frac{Q_v P^* \mu}{\pi b k_a}(\pi - \theta) \quad for \quad \frac{\pi}{2}<\theta<\pi;\\
\psi &= \frac{Q_v P^* \mu}{\pi b k_a}(\pi + \theta) \quad for \quad \pi<\theta<\frac{3\pi}{2};\\
\psi &= \frac{Q_v P^* \mu}{\pi b k_a}(2\pi - \theta) \quad for \quad \frac{3\pi}{2}<\theta<2\pi
\end{aligned} \qquad (11)$$

For both 2DSTREAM and 3DLEAKY, multiple wells are simulated using the principle of superposition. In program 2DSTREAM, the pressure distribution for multiple fully penetrating wells in a tabular vadose zone is calculated as:

$$P^2 - P_{atm}^2 = \sum_{i=1}^{n} \frac{Q_i P_i^* \mu}{\pi b k_a} \ln\left(\frac{r_{e_i}}{\sqrt{(x-x_i)^2 + (y-y_i)^2}}\right) \qquad (12)$$

where: n = the total number of wells

Similarly, 2DSTREAM calculates the stream function for multiple wells as:

$$\psi = \sum_{i=1}^{n} \frac{Q_i P_i^* \mu}{\pi b k_a} \tan^{-1}\left\{\frac{y-y_i}{x-x_i}\right\} + C \qquad (13)$$

Program 3DLEAKY is based on the solution to equation (6) for 2-dimensional radial flow to a partially penetrating line sink. Again, the single radial coordinate r, can be expressed as $(x^2 +$

$y^2)^{1/2}$ in cartesian coordinates. For steady flow in a homogeneous, isotropic vadose zone with an upper atmospheric boundary and a lower impermeable boundary, the pressure solution is (USACE 1995):

$$P^2 - P_{atm}^2 = \frac{Q_v P^* \mu}{2\pi k_a (L - l)} \Bigg[\ln\left\{ \frac{z-l+\sqrt{r^2+(z-l)^2}}{z-L+\sqrt{r^2+(z-L)^2}} \cdot \frac{z+L+\sqrt{r^2+(z+L)^2}}{z+l+\sqrt{r^2+(z+l)^2}} \right\}$$
$$- \sum_{n=1}^{\infty} (-1)^n \ln\Bigg\{ \frac{z-2nb+L+\sqrt{r^2+(z-2nb+L)^2}}{z-2nb+l+\sqrt{r^2+(z-2nb+l)^2}} \cdot \frac{z-2nb-L+\sqrt{r^2+(z-2nb-L)^2}}{z-2nb-l+\sqrt{r^2+(z-2nb-l)^2}}$$
$$\cdot \frac{z+2nb-L+\sqrt{r^2+(z+2nb-L)^2}}{z+2nb-l+\sqrt{r^2+(z+2nb-l)^2}} \cdot \frac{z+2nb+L+\sqrt{r^2+(z+2nb+L)^2}}{z+2nb+l+\sqrt{r^2+(z+2nb+l)^2}} \Bigg\} \Bigg] \quad (14)$$

where: l = depth to the top of the well screen (L)
L = depth to the bottom of the well screen (L)

and the stream function solution is (USACE 1995):

$$\psi = \frac{Q_v P^* \mu}{2\pi k_a (L-l)} r \Bigg[\frac{r-(z-L)+\sqrt{r^2+(z-L)^2}}{r+(z-L)+\sqrt{r^2+(z-L)^2}} - \frac{r-(z-l)+\sqrt{r^2+(z-l)^2}}{r+(z-l)+\sqrt{r^2+(z-l)^2}}$$
$$- \frac{r-(z+L)+\sqrt{r^2+(z+L)^2}}{r+(z+L)+\sqrt{r^2+(z+L)^2}} + \frac{r-(z+l)+\sqrt{r^2+(z+l)^2}}{r+(z+l)+\sqrt{r^2+(z+l)^2}}$$
$$- \sum_{n=1}^{\infty} (-1)^n \Bigg\{ \frac{r-(z-2nb+L)+\sqrt{r^2+(z-2nb+L)^2}}{r+(z-2nb+L)+\sqrt{r^2+(z+2nb+L)^2}} - \frac{r-(z-2nb+l)+\sqrt{r^2+(z-2nb+l)^2}}{r+(z-2nb+l)+\sqrt{r^2+(z-2nb+l)^2}}$$
$$+ \frac{r-(z-2nb-L)+\sqrt{r^2+(z-2nb-L)^2}}{r+(z-2nb-L)+\sqrt{r^2+(z-2nb-L)^2}} - \frac{r-(z-2nb-l)+\sqrt{r^2+(z-2nb-l)^2}}{r+(z-2nb-l)+\sqrt{r^2+(z-2nb-l)^2}}$$
$$- \frac{r-(z+2nb+L)+\sqrt{r^2+(z+2nb+L)^2}}{r+(z+2nb+L)+\sqrt{r^2+(z+2nb+L)^2}} + \frac{r-(z+2nb+l)+\sqrt{r^2+(z+2nb+l)^2}}{r+(z+2nb+l)+\sqrt{r^2+(z+2nb+l)^2}}$$
$$+ \frac{r-(z+2nb-L)+\sqrt{r^2+(z+2nb-L)^2}}{r+(z+2nb-L)+\sqrt{r^2+(z+2nb-L)^2}} - \frac{r-(z+2mb-l)+\sqrt{r^2+(z+2nb-l)^2}}{r+(z+2nb+l)+\sqrt{r^2+(z+2nb-l)^2}} \Bigg\} \Bigg] \quad (15)$$

Equations (14) and (15) are equivalent to the pressure and stream function solutions obtained by Shan et al. (1992). As explained in USACE (1995), these solutions are obtained by reflecting image well screens about an atmospheric boundary at the ground surface and an impermeable boundary at the water table. For the pressure solution, each image well screen is represented by a term of the form:

$$\ln\left\{\frac{z \pm \tau + \sqrt{r^2 + (z \pm \tau)^2}}{z \pm \tau + \sqrt{r^2 + (z \pm \tau)^2}}\right\}; \quad or \quad \ln\left\{\frac{z \pm 2nb \pm \tau + \sqrt{r^2 + (z \pm 2nb \pm \tau)^2}}{z \pm 2nb \pm \tau + \sqrt{r^2 + (z \pm 2nb \pm \tau)^2}}\right\} \tag{16}$$

where $\tau = l$ or L. By changing the signs of the image well screens, equations (14) and (15) can be modified to simulate an impermeable boundary at the ground surface (Figure 2-1[a]). Furthermore, by changing the flow rate of the image well screens, the amount of leakage across the surface boundary can be varied from zero to a maximum value corresponding to an atmospheric pressure boundary. This is accomplished in program 3DLEAKY by defining a 'leakage factor' ranging from zero to one. A leakage factor of zero corresponds to an impermeable surface boundary, and a leakage factor of one corresponds to an atmospheric surface boundary. As shown on Figure 2-1, varying degrees of leakage can be specified by choosing leakage factors ranging from zero to one.

For systems that are anisotropic in the r,z plane, program 3DLEAKY solves the pressure and the stream function equations in a transformed coordinate system;

$$r' = r\sqrt{\frac{k_z}{k_r}}; \quad z' = z \tag{17}$$

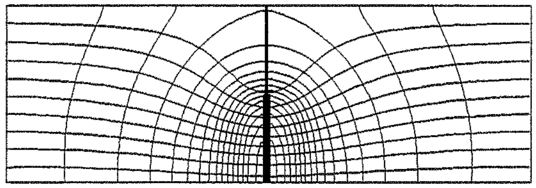
using a transformed air permeability;

$$k' = \sqrt{k_r \cdot k_z} \tag{18}$$

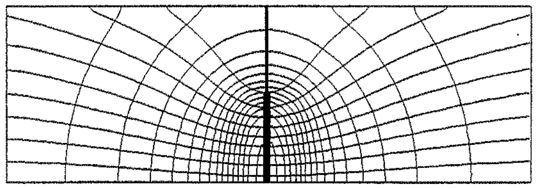
at which point the resulting pressure and stream function values are translated back into the original coordinate system using equation (17).

Figure 2-1. Streamlines and Pressure Isobars for Various 'Leakage Factors'

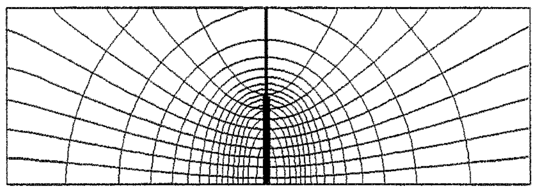
(a) Leakage Factor = 0 (Impermeable Boundary at Ground Surface)



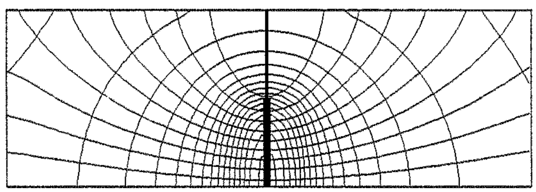
(b) Leakage Factor = 0.25



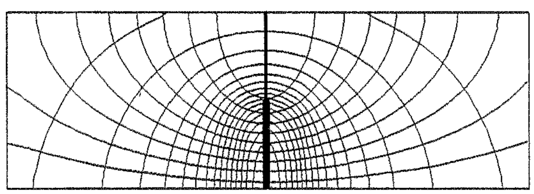
(c) Leakage Factor = 0.5



(d) Leakage Factor = 0.75



(e) Leakage Factor = 1.0 (Atmospheric Boundary at Ground Surface)



3.0 EXAMPLE APPLICATIONS

3.1 Program 2DSTREAM

An example application of program 2DSTREAM is shown on Figure 3-1. Two injection wells and one extraction well are operated so that the total injection rate equals the extraction rate. An input file to calculate streamlines and pressure isobars using program 2DSTREAM is shown on Figure 3-2. The input file includes explanatory notes describing the parameters and units for all input data.

Strictly speaking, the streamlines and pressure isobars obtained using program 2DSTREAM apply only for fully penetrating wells in a vadose zone with an impermeable surface cover. As shown in Section 3.2, however, the resulting flow geometry is similar to that for flow near the water table beneath an atmospheric or leaky surface boundary.

Figure 3-1. Well Geometry and Flow Rates for Example Application

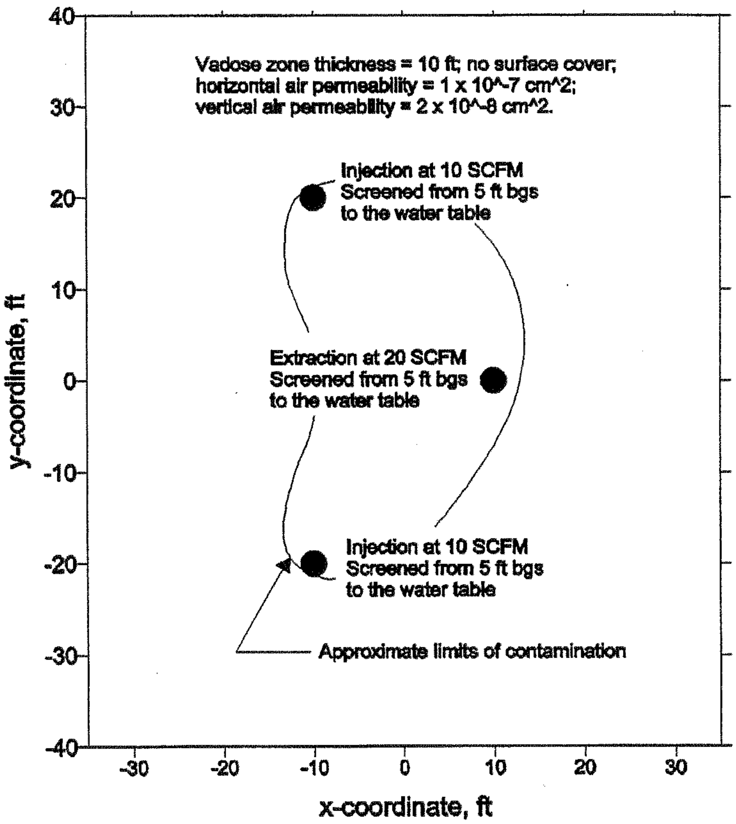


Figure 3-2. Example Input File for Program 2DSTREAM

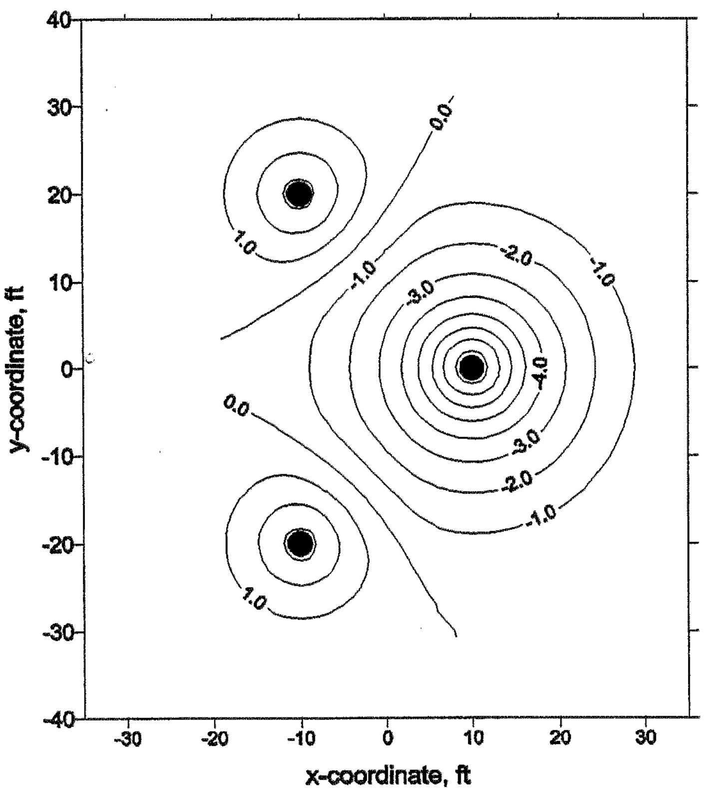
```
c  Input file for program 2DSTREAM.BAS.  Lines beginning with a "c" are explanatory notes
c  that are not read as input data.  Enter data following the ">>>" prompt below each explana-
c  tory note.  Where multiple data elements are requested on one line, data elements must be
c  separated by commas (,) or semicolons (;).  If data elements are requested that are not
c  relevant to your application, enter zeros for the requested elements.
c  Enter the path and filename for a text file to record the model input parameters and a
c  description of your application [1 text string]:
>>>      c:\temp\2dstream\2dstream.txt
c  Enter a one-line description of the model run [1 text string]:
>>>      Example run for program 2DSTREAM
c  Path and filename of output file for pressure data [1 text string]?
>>>      c:\temp\2dstream\2dpress.dat
c  Path and filename of output file for left hand stream function data [1 text string]?
>>>      c:\temp\2dstream\lstream.dat
c  Path and filename of output file for right hand stream function data [1 text string]?
>>>      c:\temp\2dstream\rstream.dat
c  Minimum x and  y coordinates (ft) of output grid [2 values]?
>>>      -35,  -40
c  Maximum x and y coordinates (ft) of output grid [2 values]?
>>>      35,   40
c  Number of grid nodes in the x and y directions [2 values]?
>>>      50,   50
c  If you would like to make Golden Software blanking files, enter the path and filename for the
c  right-hand blanking file below [1 text string], or "\NA\" if you dont want this file.
>>>      c:\temp\2dstream\rblank.bln
c  Enter the path and filename for the left-hand Golden Software blanking file [1 text string],
c  or "\NA\" if you don't want this file:
>>>      c:\temp\2dstream\lblank.bln
c  Enter the width of the blanked margin for the Golden Software blanking files (ft) [1value]:
>>>      0.5
c  Air permeability (cm^2), thickness of the vadose zone (ft), dynamic viscosity of the soil gas
c  (dyne-s/cm^2), and total number of wells [4 values]?
>>>      1e-7,      10,   1.8e-4,     3
c  Following these instructions, enter one line for each well, listing the following parameters
c  (in sequential order): x-coordinate (ft); y-coordinate (ft); flow rate in ft^3/min at standard
c  temperature and pressure (SCFM); and radius of pressure influence at the specified flow rate
c  [4 values].  Be sure to include the ">>>" prompt at the beginning of each line:
>>>      -10,        -20,        10,        15
>>>       10,         0,        -20,        25
>>>      -10,         20,        10,        15
```

The output of program 2DSTREAM includes the following:

- A numeric ASCII file of gauge pressures in inches of water, with corresponding x- and y-coordinates (in feet);
- A numeric ASCII file of the left-hand stream function in radians, with corresponding x- and y-coordinates (in feet);
- A numeric ASCII file of the right-hand stream function in radians, with corresponding x- and y-coordinates (in feet);
- Two numeric "blanking files" used to superimpose the left-hand and right-hand stream functions in commercial contouring programs; and
- An ASCII text file recording the input parameters and a description of the model application.

The numeric output files are intended to be used with commercial contouring programs. For example, a contour map of subsurface pressures calculated using the example input file is shown on Figure 3-3.

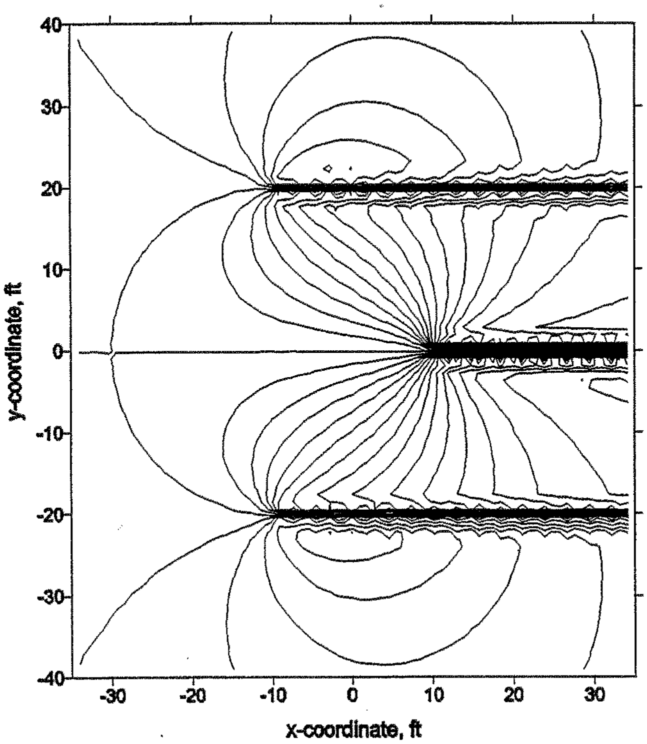
Figure 3-3. Pressure Isobars for the Example Application Using 2DSTREAM



Pressure Isobars in Inches of Water

As shown by equation (9), the axial stream function for a single well is equivalent to a family of straight lines passing through the well location. Each line represents a different value of the stream function, equal to the angle θ (in radians) between the line and the x-axis. Because the possible values of the stream function range from 0 to 2π, there is a discontinuity in the axial stream function at $\theta = 2\pi$ radians. Defining the constant of integration as shown by equation (11), the discontinuity extends in the positive *x*-direction from each well location. Because the stream function is continuous for the negative *x*-direction (i.e., to the left), this convention is termed the "left-hand" stream function. A plot of the left-hand stream function for the example application is shown in Figure 3-4.

Figure 3-4. Left-Hand Stream Function for the Example Application



For the right-hand stream function, the constant of integration is redefined so that the discontinuities appear to the left of each well (Figure 3-5). By superimposing the left- and right-hand stream functions, a continuous plot of streamlines can be obtained (Figure 3-6). In most contouring software programs, this can be accomplished using grid "blanking files" such as those written by program 2DSTREAM. The blanking files produced by program 2DSTREAM are designed for use with SURFER®, but can be readily modified for use with other contouring programs.

Figure 3-5. Right-Hand Stream Function for the Example Application

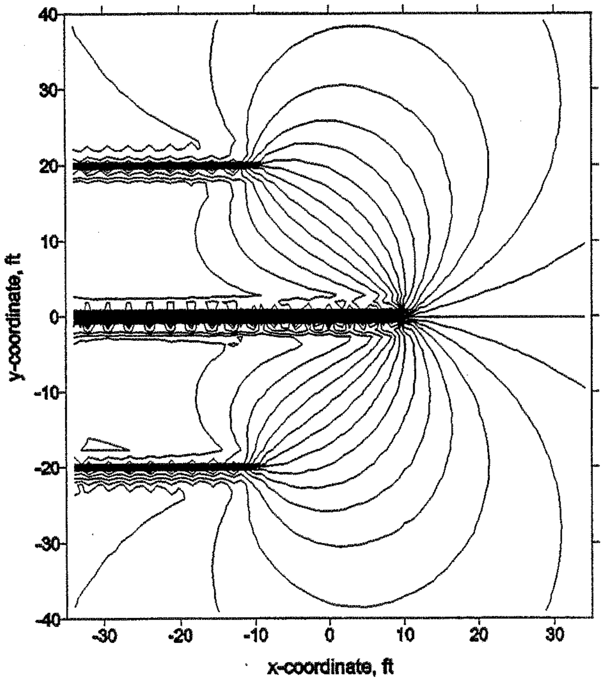
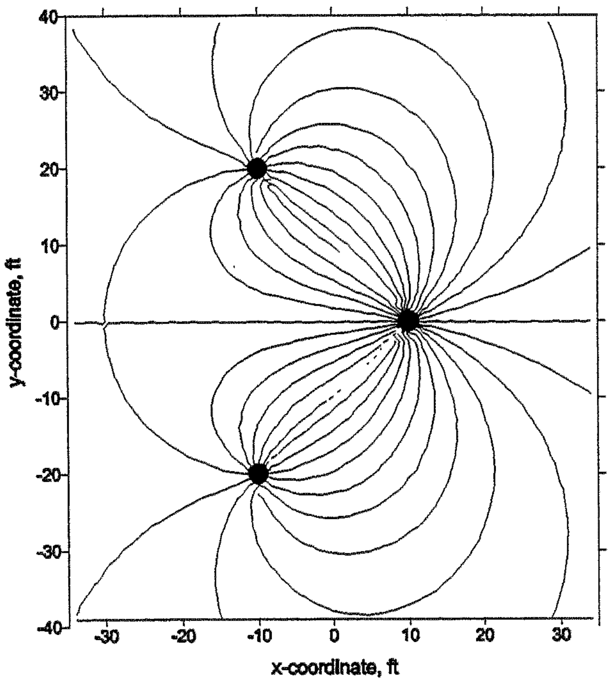
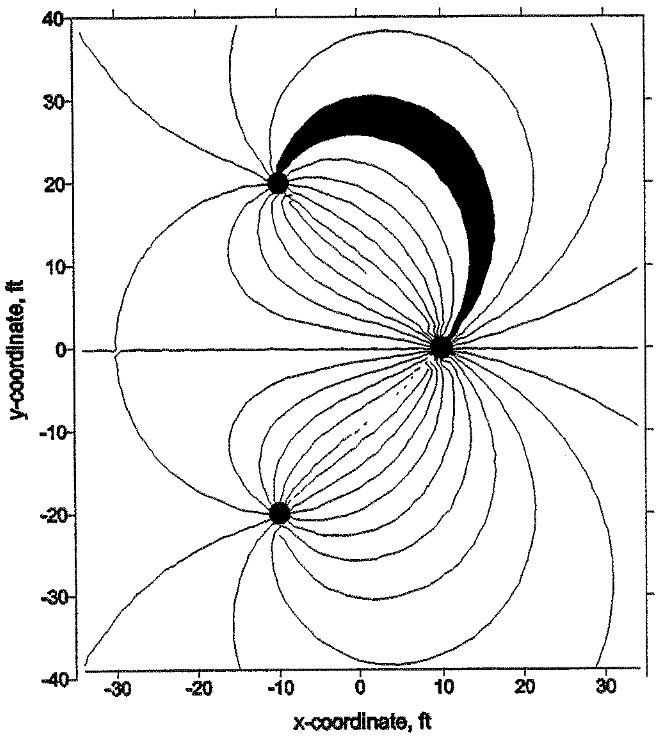


Figure 3-6. Superposition of Figures 3-4 and 3-5



Most contouring programs include area calculation routines that permit quantification of streamtube areas. For example, the area within the streamtube shown on Figure 3-7 was calculated using SURFER® as 166.8 ft^2. These results can be used to calculate approximate flow rates and travel times, as described in USACE (1995).

Figure 3-7. Calculation of Streamtube Areas



The text file produced by program 2DSTREAM can be used to document the file locations and input parameters for each run. The text file can also be used to check for input errors in the event that program execution is terminated. Figure 3-8 shows the output text file produced by program 2DSTREAM for the example application.

Figure 3-8. 2DSTREAM Text File for the Example Application

```
FILE: C:\TEMP\2DSTREAM.INP - INPUT DATA FOR PROGRAM 2DSTREAM,
VERSION 1.0, WRITTEN BY DAVID BRAILEY, MAY 1996.

RUN TITLE: EXAMPLE RUN FOR PROGRAM 2DSTREAM
INPUT FILE: C:\TEMP\2DSTREAM.INP
OUTPUT FILE FOR PRESSURE DATA: C:\TEMP\2DSTREAM\2DPRESS.DAT
OUTPUT FILE FOR LEFT HAND STREAM FUNCTION DATA: C:\TEMP\2DSTREAM\LSTREAM.DAT
OUTPUT FILE FOR RIGHT HAND STREAM FUNCTION DATA: C:\TEMP\2DSTREAM\RSTREAM.DAT

PRESSURE DATA WILL BE CALCULATED FOR A PLAN VIEW GRID STARTING AT
(-35.00,-40.00) FT. AND ENDING AT ( 35.00, 40.00); FT.

VADOSE ZONE AIR PERMEABILITY =  .0000001  CM^2
VADOSE ZONE THICKNESS =  10  FT.
ABSOLUTE VISCOSITY OF SOIL GAS =  .00018  DYNE-S/CM^2

TOTAL NUMBER OF EXTRACTION/INJECTION WELLS =  3

WELL LOCATION FLOW          RADIUS OF
X(FT)       Y(FT)       RATE, SCFM    INFLUENCE, FT
-10.00      -20.00              10            15
 10.00        0.00             -20            25
-10.00       20.00              10            15
```

3.2 Program 3DLEAKY

Program 3DLEAKY can be used to calculate a plan view pressure distribution or a cross sectional view of pressure isobars and streamlines. 3DLEAKY does not calculate the stream function in plan view because this function has not yet been developed for partially penetrating wells. Figure 3-9 shows a plan view of pressure contours for the example application, at a depth of 7.5 feet bgs. For comparison with program 2DSTREAM, the same air permeability was used (1×10^{-7} cm^2), and the soil profile was assumed to be isotropic. Results indicate a similar pressure distribution as that obtained using program 2DSTREAM (Figure 3-3). The input file used to generate Figure 3-9 is shown in Figure 3-10.

Figure 3-9. Pressure Isobars at 7.5 feet bgs Using 3DLEAKY

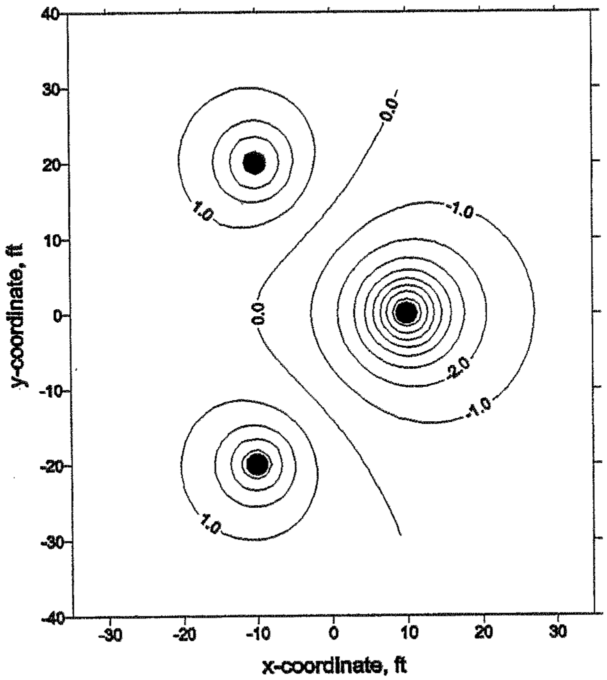


Figure 3-11 shows the effect of anisotropy on the plan view pressure distribution. The input parameters used to generate Figure 3-11 are identical to those for Figure 3-9, except that the anisotropy ratio was changed from 1 to 5. Leaving the horizontal air permeability unchanged (1×10^{-7} cm^2), this modification effectively reduces the vertical air permeability from 1×10^{-7} cm^2 to 2×10^{-8} cm^2. The magnitude of pressure variations is significantly larger for the anisotropic case, as a result of the reduced vertical air permeability.

A cross sectional application of program 3DLEAKY is shown on Figure 3-12, along the line of section shown on Figure 3-11. Model input parameters are identical to those used to generate

Figure 3-10. 3DLEAKY Input File for Figure 3-9

```
c  Input file for program 3DLEAKY.BAS. Lines beginning with a "c" are explanatory notes
c  that are not read as input data. Enter data following the ">>>" prompt below each explana-
c  tory note. Where multiple data elements are requested on one line, data elements must be
c  separated by commas (,) or semicolons (;). If data elements are requested that are not
c  relevant to your application (e.g., cross section endpoints for a plan view representation),
c  enter zeros for the requested elements.
c  Enter the path and filename for a text file to record the model input parameters and a
c  description of your application [1 text string]:
>>>      c:\temp\3dleaky\3dplan.txt
c  Enter a one-line description of the model run [1 text string]:
>>>      Plan view at 7.5 feet bgs for the example application
c  Path and filename of output file for pressure data [1 text string]?
>>>      c:\temp\3dleaky\3dplan.dat
c  Path and filename of output file for stream function data [1 text string]?
>>>      na
c  Are you preparing a vertical cross section of pressure and streamlines, or a plan view of
c  pressure contours (enter 1 for section, or 2 for plan view)? Note - a separate program is
c  required to calculate streamlines in plan view.
>>>      2
c  Minimum x, y, and z coordinates (ft) of output grid [3 values]. The z-coordinate is
c  equivalent to depth below the surface datum, positive downward.
>>>      -35,  -40, 7.5
c  Maximum x, y, and z coordinates (ft) of output grid [3 values]?
>>>      35,   40,  7.5
c  Number of grid nodes in the x, y, and z-directions [3 values]?
>>>      30,   30,   1
c  For cross section applications, enter the x, y grid limits corresponding to the right-hand end
c  of the cross section [2 values].
>>>      0,    0
c  If you want depth printed as elevation, enter the ground surface elevation (ft), or "\NA\"
c  if you want depth printed as z, increasing downward.
>>>      \NA\
c  For cross sections, set your x-axis datum
c  by entering the position of 1 well along the line of section. Enter the well number (see last
c  set of input instructions, below) and position along the line of section [2 values]:
>>>      0,        0
c  Horizontal air permeability (cm^2), anisotropy ratio, and leakage across surface boundary,
c  ranging from 0 for an impermeable cover to 1 for no surface cover [3 values]?
>>>  1e-7,    5,        1
c  Thickness of the vadose zone (ft), total number of wells, and dynamic viscosity of the soil
c  gas (dyne-s/cm^2) [3 values]?
>>>  10,      3,    1.8e-4
c  Following these instructions, enter one line for each well, listing the following parameters
c  (in sequential order): well number, x-coordinate (ft); y-coordinate (ft); depth to the top of
c  the well screen (ft); depth to the bottom of the well screen (ft); and flow rate in ft^3/min at
c  standard temperature and pressure (SCFM) [5 values]. Be sure to include the ">>>"
c  prompt at the beginning of each line:
>>>  1,     -10,     -20,     5,      10,     10
>>>  2,     10,      0,       5,      10,     -20
>>>  3,     -10,     20,      5,      10,     10
```

Figure 3-11. Pressure Isobars at 7.5 ft bgs, Anisotropic Case

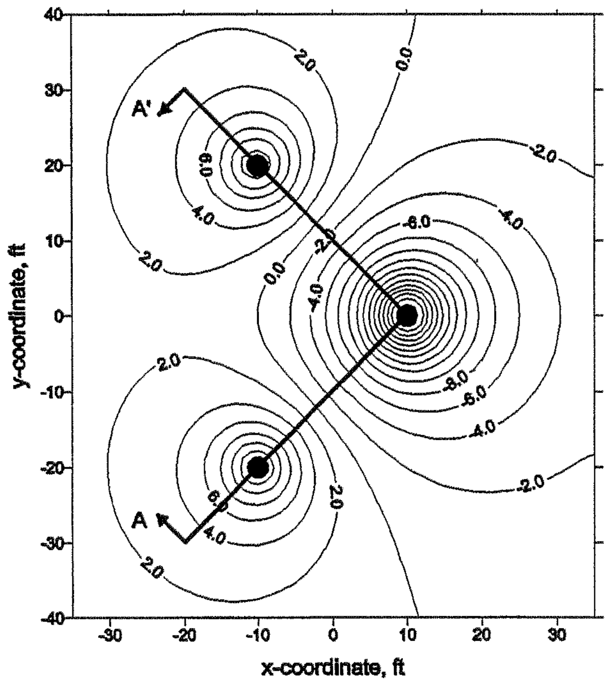


Figure 3-11, except for the model orientation. The cross section was prepared from two model runs, one for each half of the section. Slightly higher pressure contours on the right half of Figure 3-12 result from grid nodes that are slightly closer to the well locations. The input file used to generate the left half of Figure 3-12 is shown on Figure 3-13.

Figure 3-12. Cross Section A-A' Generated Using Program 3DLEAKY

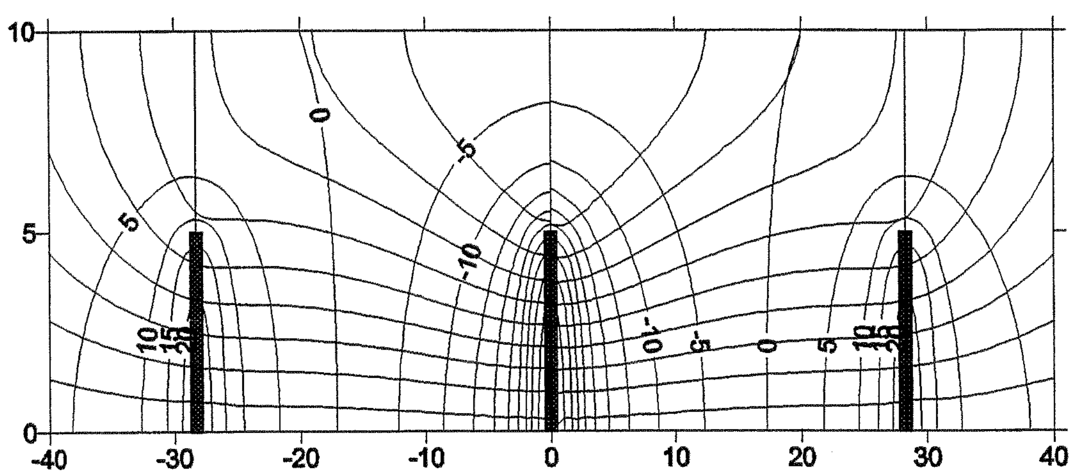


Figure 3-13. 3DLEAKY Input File for Figure 3-12 (Left Half)

```
c  Input file for program 3DLEAKY.BAS. Lines beginning with a "c" are explanatory notes
c  that are not read as input data. Enter data following the ">>>" prompt below each explana-
c  tory note. Where multiple data elements are requested on one line, data elements must be
c  separated by commas (,) or semicolons (;). If data elements are requested that are not
c  relevant to your application (e.g., cross section endpoints for a plan view representation),
c  enter zeros for the requested elements.
c  Enter the path and filename for a text file to record the model input parameters and a
c  description of your application [1 text string]:
>>>     c:\temp\3dleaky\3dxsec2.txt
c  Enter a one-line description of the model run [1 text string]:
>>>     Left half of cross section for the example application
c  Path and filename of output file for pressure data [1 text string]?
>>>     c:\temp\3dleaky\xpress1.dat
c  Path and filename of output file for stream function data [1 text string]?
>>>     c:\temp\3dleaky\xstream1.dat
c  Are you preparing a vertical cross section of pressure and streamlines, or a plan view of
c  pressure contours (enter 1 for section, or 2 for plan view)? Note - a separate program is
c  required to calculate streamlines in plan view.
>>>     1
c  Minimum x, y, and z coordinates (ft) of output grid [3 values]. The z-coordinate is
c  equivalent to depth below the surface datum, positive downward.
>>>     -20,  -30, 0
c  Maximum x, y, and z coordinates (ft) of output grid [3 values]?
>>>     10,   0,   10
c  Number of grid nodes in the x, y, and z-directions [3 values]?
>>>     30,   1,   30
c  For cross section applications, enter the x, y grid limits corresponding to the right-hand end
c  of the cross section [2 values].
>>>     10,   0
c  If you want depth printed as elevation, enter the ground surface elevation (ft), or "\NA\"
c  if you want depth printed as z, increasing downward.
>>>     10
c  For cross sections, set your x-axis datum
c  by entering the position of 1 well along the line of section. Enter the well number (see last
c  set of input instructions, below) and position along the line of section [2 values]:
>>>     2,        0
c  Horizontal air permeability (cm^2), anisotropy ratio, and leakage across surface boundary,
c  ranging from 0 for an impermeable cover to 1 for no surface cover [3 values]?
>>>  1e-7,   5,        1
c  Thickness of the vadose zone (ft), total number of wells, and dynamic viscosity of the soil
c  gas (dyne-s/cm^2) [3 values]?
>>>  10,     3,   1.8e-4
c  Following these instructions, enter one line for each well, listing the following parameters
c  (in sequential order): well number, x-coordinate (ft); y-coordinate (ft); depth to the top of
c  the well screen (ft); depth to the bottom of the well screen (ft); and flow rate in ft^3/min at
c  standard temperature and pressure (SCFM) [5 values]. Be sure to include the ">>>"
c  prompt at the beginning of each line:
>>>  1,     -10,     -20,      5,       10,       10
>>>  2,      10,       0,      5,       10,      -20
>>>  3,     -10,      20,      5,       10,       10
```

4.0 OPERATING INSTRUCTIONS

Programs 2DSTREAM and 3DLEAKY can be run from the MS-DOS prompt by typing "2DSTREAM" or "3DLEAKY" in a directory containing the executable files (2DSTREAM.EXE or 3DLEAKY.EXE). The programs can be run with the input files provided with this report; however, these input files require two destination directories named C:\TEMP\2DSTREAM and C:\TEMP\3DLEAKY. You can either create these directories on your C:\ drive, or modify the input files to write to directories on other (e.g., network) drives. In the Appendix are hard copies of the example input files that are provided on the accompanying diskette.

The input files provided can be used as "templates" for site-specific applications by changing the well coordinates, flow rates, grid positions, etc. Both programs will accept x- and y-coordinates containing up to 16 digits, permitting the use of state-plane survey data. With the exception of text strings, the remaining input data will be truncated at 7 digits during file input.

A partial list of error messages has been included in the source code. Input errors can be identified by viewing the output text file for each run. Because the input data is read as a sequential file, it is important to provide entries for all requested input data. The input files provide further instructions regarding data entry.

5.0 REFERENCES

Shan, C., Falta, R.W., and Javandel, I. 1992. Analytical Solutions for Steady State Gas Flow to a Soil Vapor Extraction Well. Water Resources Research, Vol. 28, pp. 1105-1120.

U.S. Army Corps of Engineers (USACE) 1995. Soil Vapor Extraction and Bioventing Engineering and Design. Engineer Manual No. 1110-1-4001. Prepared by ENSR Consulting and Engineering under contract to USACE HTRW-CX, Omaha, NE, 262 pp.

APPENDIX
EXAMPLE INPUT FILES

2DSTREAM.INP

```
c  Input file for program 2DSTREAM.BAS.  Lines beginning with a "c" are explanatory notes
c  that are not read as input data.  Enter data following the ">>>" prompt below each explana-
c  tory note.  Where multiple data elements are requested on one line, data elements must be
c  separated by commas (,) or semicolons (;).  If data elements are requested that are not
c  relevant to your application, enter zeros for the requested elements.
c  Enter the path and filename for a text file to record the model input parameters and a
c  description of your application [1 text string]:
>>>  c:\temp\2dstream\2dstream.txt
c  Enter a one-line description of the model run [1 text string]:
>>>  Example run for program 2DSTREAM
c  Path and filename of output file for pressure data [1 text string]?
>>>  c:\temp\2dstream\2dpress.dat
c  Path and filename of output file for left hand stream function data [1 text string]?
>>>  c:\temp\2dstream\lstream.dat
c  Path and filename of output file for right hand stream function data [1 text string]?
>>>  c:\temp\2dstream\rstream.dat
c  Minimum x and  y coordinates (ft) of output grid [2 values]?
>>>  -35,     -40
c  Maximum x and y coordinates (ft) of output grid [2 values]?
>>>  35,      40
c  Number of grid nodes in the x and y directions [2 values]?
>>>  50,     50
c  If you would like to make Golden Software blanking files, enter the path and filename for the
c  right-hand blanking file below [1 text string], or "\NA\" if you dont want this file.
>>>  c:\temp\2dstream\rblank.bln
c  Enter the path and filename for the left-hand Golden Software blanking file [1 text string],
c  or "\NA\" if you don't want this file:
>>>  c:\temp\2dstream\lblank.bln
c  Enter the width of the blanked margin for the Golden Software blanking files (ft) [1value]:
>>>  0.5
c  Air permeability (cm^2), thickness of the vadose zone (ft), dynamic viscosity of the soil gas
c  (dyne-s/cm^2), and total number of wells [4 values]?
>>>           1e-7,   10,     1.8e-4,        3
c  Following these instructions, enter one line for each well, listing the following parameters
c  (in sequential order): x-coordinate (ft); y-coordinate (ft); flow rate in ft^3/min at standard
c  temperature and pressure (SCFM); and radius of pressure influence at the specified flow rate
c  [4 values].  Be sure to include the ">>>" prompt at the beginning of each line:
>>>          -10,            -20,           10,     15
>>>          10,     0,      -20,    25
>>>          -10,            20,     10,     15
```

3DPLAN.INP

```
c  Input file for program 3DLEAKY.BAS.  Lines beginning with a "c" are explanatory notes
c  that are not read as input data.  Enter data following the ">>>" prompt below each explana-
c  tory note.  Where multiple data elements are requested on one line, data elements must be
c  separated by commas (,) or semicolons (;).  If data elements are requested that are not
c  relevant to your application (e.g., cross section endpoints for a plan view representation),
c  enter zeros for the requested elements.
c  Enter the path and filename for a text file to record the model input parameters and a
c  description of your application [1 text string]:
>>>  c:\temp\3dleaky\3dplan.txt
c  Enter a one-line description of the model run [1 text string]:
>>>  Plan view at 7.5 feet bgs for the example application
c  Path and filename of output file for pressure data [1 text string]?
>>>  c:\temp\3dleaky\3dplan.dat
c  Path and filename of output file for stream function data [1 text string]?
>>>  na
c  Are you preparing a vertical cross section of pressure and streamlines, or a plan view of
c  pressure contours (enter 1 for section, or 2 for plan view)?  Note - a separate program is
c  required to calculate streamlines in plan view.
>>>  2
c  Minimum x, y, and z coordinates (ft) of output grid [3 values].  The z-coordinate is
c  equivalent to depth below the surface datum, positive downward.
>>>  -35,     -40,    7.5
c  Maximum x, y, and z coordinates (ft) of output grid [3 values]?
>>>  35,      40,     7.5
c  Number of grid nodes in the x, y, and z-directions [3 values]?
>>>  30,      30,     1
c  For cross section applications, enter the x, y grid limits corresponding to the right-hand end
c  of the cross section [2 values].
>>>  0,       0
c  If you want depth printed as elevation, enter the ground surface elevation (ft), or "\NA\"
c  if you want depth printed as z, increasing downward.
>>>  \NA\
c  For cross sections, set your x-axis datum
c  by entering the position of 1 well along the line of section.  Enter the well number (see last
c  set of input instructions, below) and position along the line of section [2 values]:
>>>          0,      0
c  Horizontal air permeability (cm^2), anisotropy ratio, and leakage across surface boundary,
c  ranging from 0 for an impermeable cover to 1 for no surface cover [3 values]?
>>>  1e-7,  5,       1
c  Thickness of the vadose zone (ft), total number of wells, and dynamic viscosity of the soil
c  gas (dyne-s/cm^2) [3 values]?
>>>  10,     3,      1.8e-4
c  Following these instructions, enter one line for each well, listing the following parameters
c  (in sequential order): well number, x-coordinate (ft); y-coordinate (ft); depth to the top of
c  the well screen (ft); depth to the bottom of the well screen (ft); and flow rate in ft^3/min at
c  standard temperature and pressure (SCFM) [5 values].  Be sure to include the ">>>"
c  prompt at the beginning of each line:
>>>  1,     -10,          -20,          5,     10,     10
```

>>>	2,	10,	0,	5,	10,	-20	
>>>	3,	-10,		20,	5,	10,	10

3DXSEC1.INP

```
c  Input file for program 3DLEAKY.BAS.  Lines beginning with a "c" are explanatory notes
c  that are not read as input data.  Enter data following the ">>>" prompt below each explana-
c  tory note.  Where multiple data elements are requested on one line, data elements must be
c  separated by commas (,) or semicolons (;).  If data elements are requested that are not
c  relevant to your application (e.g., cross section endpoints for a plan view representation),
c  enter zeros for the requested elements.
c  Enter the path and filename for a text file to record the model input parameters and a
c  description of your application [1 text string]:
>>>  c:\temp\3dleaky\3dxsec2.txt
c  Enter a one-line description of the model run [1 text string]:
>>>  Left half of cross section for the example application
c  Path and filename of output file for pressure data [1 text string]?
>>>  c:\temp\3dleaky\xpress1.dat
c  Path and filename of output file for stream function data [1 text string]?
>>>  c:\temp\3dleaky\xstream1.dat
c  Are you preparing a vertical cross section of pressure and streamlines, or a plan view of
c  pressure contours (enter 1 for section, or 2 for plan view)?  Note - a separate program is
c  required to calculate streamlines in plan view.
>>>  1
c  Minimum x, y, and z coordinates (ft) of output grid [3 values].  The z-coordinate is
c  equivalent to depth below the surface datum, positive downward.
>>>  -20,    -30,   0
c  Maximum x, y, and z coordinates (ft) of output grid [3 values]?
>>>  10,     0,     10
c  Number of grid nodes in the x, y, and z-directions [3 values]?
>>>  30,     1,     30
c  For cross section applications, enter the x, y grid limits corresponding to the right-hand end
c  of the cross section [2 values].
>>>  10,     0
c  If you want depth printed as elevation, enter the ground surface elevation (ft), or "\NA\"
c  if you want depth printed as z, increasing downward.
>>>  10
c  For cross sections, set your x-axis datum
c  by entering the position of 1 well along the line of section.  Enter the well number (see last
c  set of input instructions, below) and position along the line of section [2 values]:
>>>          2,     0
c  Horizontal air permeability (cm^2), anisotropy ratio, and leakage across surface boundary,
c  ranging from 0 for an impermeable cover to 1 for no surface cover [3 values]?
>>>  1e-7,  5,      1
c  Thickness of the vadose zone (ft), total number of wells, and dynamic viscosity of the soil
c  gas (dyne-s/cm^2) [3 values]?
>>>  10,    3,      1.8e-4
c  Following these instructions, enter one line for each well, listing the following parameters
c  (in sequential order): well number, x-coordinate (ft); y-coordinate (ft); depth to the top of
c  the well screen (ft); depth to the bottom of the well screen (ft); and flow rate in ft^3/min at
c  standard temperature and pressure (SCFM) [5 values].  Be sure to include the ">>>"
c  prompt at the beginning of each line:
```

```
>>> 1, -10, -20, 5, 10, 10
>>> 2, 10, 0, 5, 10, -20
>>> 3, -10, 20, 5, 10, 10
```

3DXSEC2.INP

```
c  Input file for program 3DLEAKY.BAS.  Lines beginning with a "c" are explanatory notes
c  that are not read as input data.  Enter data following the ">>>" prompt below each explana-
c  tory note.  Where multiple data elements are requested on one line, data elements must be
c  separated by commas (,) or semicolons (;).  If data elements are requested that are not
c  relevant to your application (e.g., cross section endpoints for a plan view representation),
c  enter zeros for the requested elements.
c  Enter the path and filename for a text file to record the model input parameters and a
c  description of your application [1 text string]:
>>>  c:\temp\3dleaky\3dxsec2.txt
c  Enter a one-line description of the model run [1 text string]:
>>>  Right half of cross section for the example application
c  Path and filename of output file for pressure data [1 text string]?
>>>  c:\temp\3dleaky\xpress2.dat
c  Path and filename of output file for stream function data [1 text string]?
>>>  c:\temp\3dleaky\xstream2.dat
c  Are you preparing a vertical cross section of pressure and streamlines, or a plan view of
c  pressure contours (enter 1 for section, or 2 for plan view)?  Note - a separate program is
c  required to calculate streamlines in plan view.
>>>  1
c  Minimum x, y, and z coordinates (ft) of output grid [3 values].  The z-coordinate is
c  equivalent to depth below the surface datum, positive downward.
>>>  -20,    0,     0
c  Maximum x, y, and z coordinates (ft) of output grid [3 values]?
>>>  10,     30,    10
c  Number of grid nodes in the x, y, and z-directions [3 values]?
>>>  30,     1,     30
c  For cross section applications, enter the x, y grid limits corresponding to the right-hand end
c  of the cross section [2 values].
>>>  -20,    30
c  If you want depth printed as elevation, enter the ground surface elevation (ft), or "\NA\"
c  if you want depth printed as z, increasing downward.
>>>  10
c  For cross sections, set your x-axis datum
c  by entering the position of 1 well along the line of section.  Enter the well number (see last
c  set of input instructions, below) and position along the line of section [2 values]:
>>>          2,     0
c  Horizontal air permeability (cm^2), anisotropy ratio, and leakage across surface boundary,
c  ranging from 0 for an impermeable cover to 1 for no surface cover [3 values]?
>>>  1e-7,  5,      1
c  Thickness of the vadose zone (ft), total number of wells, and dynamic viscosity of the soil
c  gas (dyne-s/cm^2) [3 values]?
>>>  10,    3,      1.8e-4
c  Following these instructions, enter one line for each well, listing the following parameters
c  (in sequential order): well number, x-coordinate (ft); y-coordinate (ft); depth to the top of
c  the well screen (ft); depth to the bottom of the well screen (ft); and flow rate in ft^3/min at
c  standard temperature and pressure (SCFM) [5 values].  Be sure to include the ">>>"
c  prompt at the beginning of each line:
>>>  1,     -10,          -20,          5,      10,     10
```

> > >	2,	10,	0,	5,	10,	-20	
> > >	3,	-10,		20,	5,	10,	10