12/31/94
RF

Implementation of Borehole Dilution into TPA

Use flux-based dilution factor approach of previous work in this scientific notebook but apply only to 5 km critical group.

Assumptions:

① critical group varies from 15 to 300 households
② plume configuration is → width of streamtubes
→ unknown thickness
→ concentration uniformly distributed
③ fixed $K_{sat} = 1 \frac{m}{s}$ saturated hydraulic conductivity
$\nabla h = 0.00125$ hydraulic gradient
$r_w = 0.254$ m radius of well
sampled from distribution (uniform)
$b = U[300, 1000\ m]$ aquifer thickness
$B = U[10, 100\ m]$ plume thickness
$Q = U[50, 1000\ \frac{m^3}{s}]$ pump rate

Refer to the 6-page report for further details and suggested TPA modifications; the report is attached to this notebook after making some comments concerning the development of the methodology.

(1.) The length of the screened portion is to be dependent on the volumetric pump rate. To obtain this relationship, I will use the Thiem eqn and Muskat eqn

$$\text{specific capacity} = \frac{Q}{S_w} = \frac{2\pi K b}{\ln\left(\frac{r_e}{r_w}\right)} \qquad \text{Thiem eqn}$$

for confined aquifer (or an aquifer where drawdown will be small relative to the aquifer thickness)

S_w = drawdown
r_e = radius of influence
π = 3.14159....

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RP

The assumption of a confined aquifer for this study state may introduce small errors when the aquifer is thin and the pump rate is large. As it turned out, drawdowns were limited to a maximum of ~20 m and the minimum aquifer thickness was 300 m. For simplicity, I stuck with the confined assumption instead of using the unconfined eqn with Dupuit-Forchheimer assumptions

$$\frac{Q}{S_w} = \frac{\pi K(2h_e - S_w)}{\ln\left(\frac{r_e}{r_w}\right)} \Rightarrow \frac{2\pi T_{avg}}{\ln\left(\frac{r_e}{r_w}\right)}$$

h_e = hydraulic head at point of interest
T_{avg} = average value of transmissivity = $K_{sat}\bar{b}$

(2.) Note that the specific capacity is constant for steady state. The Muskat eqn relates the specific capacity of a fully penetrating well (which the Thiem eqn assumes) to the specific capacity of a partially penetrating well.

$$\left(\frac{Q}{S_w}\right)_p = \left(\frac{Q}{S_w}\right)\left[\frac{l}{b}\left\{1 + 7\left(\frac{r_w}{2l}\right)^{1/2} \cos\left(\frac{\pi l}{2b}\right)\right\}\right]$$

l = screened length = S_L in report on following pages

Bear (1979) notes that Muskat introduced correction factors to account for the higher flux expected at lower end of well due to partial penetration (nonuniform distribution of flux along the screened portion) ... also noting that the Muskat eqn is a simpler empirical eqn which is sufficiently accurate for most practical purposes.
We are just using it to design wells.

To solve this eqn for the screen length, given a pumping rate, we also need to know the radius of influence and the drawdown

One option is to fix the drawdown as a fraction of the screen length

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The chart below illustrates the sensitivity of screen lengths to fractions of 0.5 to 0.1 for a fixed radius of influence

* see note $r_e = 1000$ m

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```
fraction=0.5
   q & b     300.000   440.000   580.000   720.000   860.000   1000.000
  50.0000    8.41877   8.41762   8.41720   8.41700   8.41689    8.41682
  145.000    15.2817   15.2761   15.2740   15.2730   15.2725    15.2721
  240.000    20.1852   20.1733   20.1690   20.1669   20.1657    20.1650
  335.000    24.2376   24.2184   24.2113   24.2080   24.2061    24.2050
  430.000    27.7791   27.7516   27.7415   27.7367   27.7341    27.7324
  525.000    30.9693   30.9327   30.9193   30.9129   30.9095    30.9073
  620.000    33.8985   33.8521   33.8351   33.8270   33.8226    33.8198
  715.000    36.6236   36.5669   36.5460   36.5361   36.5306    36.5273
  810.000    39.1834   39.1157   39.0909   39.0790   39.0725    39.0685
  905.000    41.6059   41.5267   41.4976   41.4838   41.4762    41.4715
 1000.000    43.9118   43.8205   43.7871   43.7712   43.7624    43.7570
fraction=0.3
   q & b     300.000   440.000   580.000   720.000   860.000   1000.000
  50.0000    11.2230   11.2206   11.2196   11.2192   11.2190    11.2188
  145.000    20.2621   20.2502   20.2458   20.2437   20.2425    20.2418
  240.000    26.7043   26.6796   26.6704   26.6661   26.6637    26.6623
  335.000    32.0234   31.9835   31.9688   31.9619   31.9580    31.9557
  430.000    36.6698   36.6129   36.5920   36.5820   36.5765    36.5732
  525.000    40.8544   40.7789   40.7511   40.7379   40.7307    40.7262
  620.000    44.6963   44.6007   44.5657   44.5490   44.5398    44.5342
  715.000    48.2706   48.1538   48.1110   48.0907   48.0795    48.0726
  810.000    51.6284   51.4893   51.4383   51.4142   51.4008    51.3927
  905.000    54.8064   54.6439   54.5844   54.5562   54.5406    54.5311
 1000.000    57.8318   57.6451   57.5767   57.5443   57.5264    57.5155
fraction=0.25
   q & b     300.000   440.000   580.000   720.000   860.000   1000.000
  50.0000    12.4276   12.4243   12.4231   12.4226   12.4222    12.4220
  145.000    22.3959   22.3804   22.3746   22.3719   22.3704    22.3695
  240.000    29.4952   29.4630   29.4512   29.4456   29.4425    29.4406
  335.000    35.3554   35.3037   35.2847   35.2756   35.2706    35.2676
  430.000    40.4741   40.4004   40.3733   40.3605   40.3534    40.3490
  525.000    45.0841   44.9863   44.9505   44.9335   44.9241    44.9183
  620.000    49.3166   49.1932   49.1479   49.1264   49.1146    49.1073
  715.000    53.2547   53.1039   53.0487   53.0225   53.0080    52.9992
  810.000    56.9546   56.7751   56.7094   56.6782   56.6610    56.6506
  905.000    60.4568   60.2472   60.1706   60.1342   60.1141    60.1019
 1000.000    63.7912   63.5503   63.4623   63.4206   63.3975    63.3835
fraction=0.10
   q & b     300.000   440.000   580.000   720.000   860.000   1000.000
  50.0000    20.6433   20.6308   20.6262   20.6240   20.6227    20.6220
  145.000    36.9002   36.8424   36.8211   36.8110   36.8055    36.8020
  240.000    48.4523   48.3344   48.2912   48.2707   48.2593    48.2524
  335.000    57.9873   57.7992   57.7304   57.6977   57.6797    57.6687
  430.000    66.3205   66.0542   65.9569   65.9108   65.8853    65.8698
  525.000    73.8319   73.4806   73.3524   73.2917   73.2581    73.2377
  620.000    80.7355   80.2932   80.1320   80.0557   80.0136    79.9879
  715.000    87.1659   86.6274   86.4314   86.3385   86.2873    86.2561
  810.000    93.2145   92.5750   92.3423   92.2322   92.1715    92.1345
  905.000    98.9466   98.2016   97.9309   97.8028   97.7322    97.6891
 1000.000   104.4107  103.5562  103.2460  103.0992  103.0183   102.9691
```

r_e = fixed = 1000 m

$q \Rightarrow$ m³/d

$b \Rightarrow$ meters

table of screen lengths

* see page 98 of scientific notebook for methodology of calculation

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letting $r_e \Rightarrow 575\,(\text{fraction})(l)\left(b\,\frac{K}{24 \cdot 3600}\right)^{1/2}$

- reduces screen length for low Q
- keeps screen lengths about same for large Q
- screens get longer for larger aquifer thickness (contrary to intuition)

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Given specific capacity and lift costs, 0.7 as a fraction drawdown to screen length is a maximum (Ground Water Manual, 1981) Also presume that well drillers will only drill deep enough (and screen as small lengths) to get production zones to fulfill their pump rate requests. Hence, too small of a fraction is not reasonable. Use 0.5 = fraction for further work.

As for radius of influence, note that the sensitivity of results (calc. of screen length) only depends on the natural log of re. Also note that the concept of radius of influence is a nebulous concept ⇒ distance where drawdown is zero (negligible). How much of an impact does re have on calculation of screen lengths, see chart below of screen lengths (meters) for various values of Q (m³/d) and aquifer thickness (meters). Calculation methodology described on following page except drawdown is fixed at 5 meters.

change these to elev. of screen

```
Dec 12, 97 15:17                  qbl.out.re                          Page 1/1
re=1000m
      q & b     300.000    440.000    580.000    720.000    860.000   1000.000
    50.0000     6.71503    6.71358    6.71304    6.71279    6.71265    6.71256
    240.000     46.7003    46.4689    46.3848    46.3449    46.3229    46.3095
    430.000     92.0962    90.7757    90.3056    90.0849    89.9638    89.8901
    620.000     141.475    137.571    136.216    135.586    135.242    135.033
    810.000     195.264    186.646    183.724    182.380    181.649    181.208
   1000.000     254.023    238.098    232.758    230.323    229.006    228.213

re=2000m
      q & b     300.000    440.000    580.000    720.000    860.000   1000.000
    50.0000     7.46703    7.46511    7.46440    7.46406    7.46387    7.46376
    240.000     51.3081    51.0133    50.9062    50.8555    50.8276    50.8106
    430.000    101.1419    99.4664    98.8725    98.5943    98.4416    98.3489
    620.000     155.707    150.752    149.044    148.252    147.820    147.559
    810.000     215.650    204.732    201.052    199.365    198.450    197.897
   1000.000     281.523    261.569    254.857    251.805    250.158    249.167

re=3000m
      q & b     300.000    440.000    580.000    720.000    860.000   1000.000
    50.0000     7.91267    7.91043    7.90961    7.90921    7.90900    7.90886
    240.000     54.0263    53.6895    53.5673    53.5097    53.4779    53.4585
    430.000     106.499   104.5889   103.9140   103.5981   103.4249   103.3197
    620.000     164.190    158.541    156.601    155.704    155.215    154.918
    810.000     227.878    215.454    211.278    209.367    208.332    207.707
   1000.000     298.028    275.533    267.926    264.471    262.609    261.489
```

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Instead of arbitrarily fixing the re for all values of pump rate,

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use the following empirical relation (Bear, 1979; page 306)

$$r_e = 575\, S_w (\cancel{b}K)^{1/2}$$

using units of meters, seconds

Hydrologists generally estimate r_e from experience, instead we will this empirical relation which is apparently from fully penetrating wells.

The method used to calculate the charts on the previous pages is to do picard iterations on the combined equations (Thiem eqn substituted into the Muskat eqn).

Muskat eqn ⇒ $$\left(\frac{Q}{S_w}\right)_p = \left(\frac{Q}{S_w}\right)\left[\frac{S_L}{b}\left\{1+7\left(\frac{r_w}{2S_L}\right)^{1/2}\cos\frac{\pi S_L}{2b}\right\}\right]$$

use Thiem eqn to substitute for specific capacity of fully penetrating well

$$\left(\frac{Q}{S_w}\right)_p = \frac{2\pi K b}{\ln\left(\frac{r_e}{r_w}\right)}\left[\frac{S_L}{b}\left\{1+7\left(\frac{r_w}{S_L \cdot 2}\right)^{1/2}\cos\frac{\pi S_L}{2b}\right\}\right]$$

Rearrange into picard format to solve for nonlinear in S_L

$$\frac{S_L}{b} = \frac{Q}{S_w}\frac{\ln\left(\frac{r_e}{r_w}\right)}{2\pi K b}\left\{1+7\left(\frac{r_w}{2S_L}\right)^{1/2}\cos\frac{\pi S_L}{2b}\right\}^{-1}$$

$$S_L = \frac{Q\ln\left(\frac{r_e}{r_w}\right)}{2\pi K S_w}\frac{1}{1+7\left(\frac{r_w}{2S_L}\right)^{1/2}\cos\frac{\pi S_L}{2b}}$$

and let

$$r_e = 575\, s_w\,(bK)^{1/2}$$

} this is used when drawdown is fixed as constant

To let drawdown be fixed as a function of screen length ⇒ fraction

let $S_w = f_\ell \cdot S_L$ where f_ℓ = fraction ⇒ 0.5 is final value used

use f_ℓ as a variable for sensitivity.

then $$\frac{Q}{S_w} = \frac{2\pi K b}{\ln\left(\frac{r_e}{r_w}\right)}\left[\frac{S_L}{b}\left\{1+7\left(\frac{r_w}{2S_L}\right)^{1/2}\cos\frac{\pi S_L}{2b}\right]\right.$$

letting $S_w = f_\ell \cdot S_L$

$$\frac{Q}{(f_\ell \cdot S_L)} = \frac{2\pi K b}{\ln\left(\frac{r_e}{r_w}\right)}\left[\frac{S_L}{b}\left\{1+7\left(\frac{r_w}{2S_L}\right)^{1/2}\cos\frac{\pi S_L}{2b}\right\}\right]$$

rearrang to solve for S_L as a nonlinear term

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$$(f_\ell \cdot S_L)\frac{S_L}{b} = \frac{Q\ln\left(\frac{r_e}{r_w}\right)}{2\pi K b}\left\{1+7\left(\frac{r_w}{2S_L}\right)^{1/2}\cos\frac{\pi S_L}{2b}\right\}^{-1}$$

$$S_L^2 = \frac{Q\ln\left(\frac{r_e}{r_w}\right)}{2\pi K \cdot f_\ell}\left\{1+7\left(\frac{r_w}{2S_L}\right)^{1/2}\cos\frac{\pi S_L}{2b}\right\}^{-1}$$

$$S_L = \left[\frac{Q\ln\left(\frac{r_e}{r_w}\right)}{2\pi K f_\ell}\frac{1}{1+7\left(\frac{r_w}{2S_L}\right)^{1/2}\cos\frac{\pi S_L}{2b}}\right]^{1/2}$$

where $$r_e = 575\, f_\ell S_L\left[\frac{bK}{(24)(3600)}\right]^{1/2}$$

$\left(\frac{24\text{ hrs}}{d}\right)\left(\frac{3600\text{ sec}}{hr}\right)$

where K is in units of $\frac{m^3}{d}$

→ This is the equation solved in the fortran code on the following page. An input and output file printout is attached to the next page.

To verify the code, take one of the output results and substitute it into the equation at the top of the page, for example

For $Q = 1000\ m^3/d$ and $b = 1000$ m ⟹ $S_L = 44.666$ m

$S_w = f_\ell \cdot S_L = 0.5\,(44.666\text{ m}) = 22.333$ m

$r_e = 575\,(0.5)(44.666\text{ m})\left\{(1000\text{ m})(1\ m^3/d)/24\frac{hr}{d}/3600\frac{sec}{hr}\right\}^{1/2} = 1381$ m

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$$\frac{Q}{S_w} = \frac{1000\ m^3/d}{22.333\text{ m}} = 44.777\frac{m^2}{d} = \frac{2\pi(1\ m/d)(1000\text{ m})}{\ln\left(\frac{1381}{.254\text{ m}}\right)}\left[\frac{44.666\text{ m}}{1000\text{ m}}\left\{1+7\left(\frac{.254\text{ m}}{2(44.666\text{ m})}\right)^{1/2}\cos\frac{\pi(44.666\text{ m})}{2(1000\text{ m})}\right\}\right]$$

$$44.77 \cong 44.33$$

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RF

This is the fortran code to calculate screen length
command ⇒ `f77 -o muskat musk.f` compiles on SUN (UNIX)

RF
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```
**********************************************************************
** Given a pump rate (qpp) and an aquifer thickness (b), the screen length  **
** is estimated by trial and error using Muskat's equation for              **
** adjusting specific capacity from that of a fully penetrating well.       **
** Increments of Q and b are used to build a matrix of screen length values.**
**                                                                          **
**    Borehole dilution, modification to TPA code at 5km                    **
**    RFedors  (11Dec97)                                                    **
**********************************************************************
** Assumes consistent units across all variables; meters & days work
** well for the incrementing.
**    qpp = pump rate for partially penetrating well (input value)
**    satk = hydraulic conductivity  (input value)
**    b = aquifer thickness (input value)
**    screen = screen length (usually "l" in equations)
**    rw = well radius (input value)
**    re = radius of influence (=575*sw*sqrt(bK); Bear, p.306)
**    sw = drawdown at well (fraction of screen length, sw=0.5*screen)
**********************************************************************
*        1         2         3         4         5         6         7
*23456789012345678901234567890123456789012345678901234567890123456789012
      program musk

      parameter  (pi=3.14159265, max=1000, tol=0.001)
      implicit real  (a-h,o-z)
      implicit integer  (i-n)
      real  qbl(max,max)

      open(8,file='qbl.in',status='unknown')
      open(9,file='qbl.out',status='unknown')

      read(8,*) satk, frac, rw
      read(8,*) nq, nb
      read(8,*) q1, q2
      read(8,*) b1, b2

      fnq = float(nq)
      fnb = float(nb)
      qinc = ( q2 - q1 ) / (fnq - 1)
      binc = ( b2 - b1 ) / (fnb - 1)
      b = b1
c Loop through all values of pump rate and aquifer thickness.
      do 300 ib = 1,nb
       qpp = q1
       do 200 iq = 1,nq
         screen = 50.
c Use Picard method to solve for screen length;
c drawdown now is fraction of screen length.
         do 50 j = 1,max
           cs = pi * screen *0.5 / b
           tmp =   1. + 7. * sqrt(rw*0.5/screen) * cos(cs)
           re = 575. * frac * screen * sqrt( b * satk/24./3600.)
           scn_tmp = sqrt( qpp *log(re/rw) *0.5 / (pi*satk*frac) / tmp )
           if(abs(scn_tmp-screen).le.tol) goto 100
           screen = scn_tmp
 50      continue
 100     qbl(iq,ib) = scn_tmp
c         write(6,*)  j, ' iterations'
         qpp = qpp + qinc
 200   continue
       b = b + binc
 300  continue

c Print matrix to file.
      qpp = q1
      b = b1
      write(9,*) '  q&b', b, b+binc, b+2.*binc
     &                    , b+3.*binc, b+4.*binc, b+5.*binc
      do 400 iq = 1,nq
```

```
        write(9,*)  qpp, ( qbl(iq,ib), ib = 1,nb )
        qpp = qpp + qinc
 400  continue

      stop
      end
```

$$l = \left[\frac{Q \ln\left\{ \frac{575 \cdot f_l \cdot l \cdot (b \cdot K/24/3600)^{1/2}}{r_w} \right\}}{2\pi K f_l} \frac{1}{1 + 7\left(\frac{r_w}{2l}\right)^{1/2} \cos\frac{\pi l}{2b}} \right]^{\frac{1}{2}}$$

or

$$l = \left[\frac{Q \ln\left(\frac{r_e}{r_w}\right)}{2\pi K f_l} \frac{1}{1 + 7\left(\frac{r_w}{2l}\right)^{1/2} \cos\frac{\pi l}{2b}} \right]^{1/2}$$

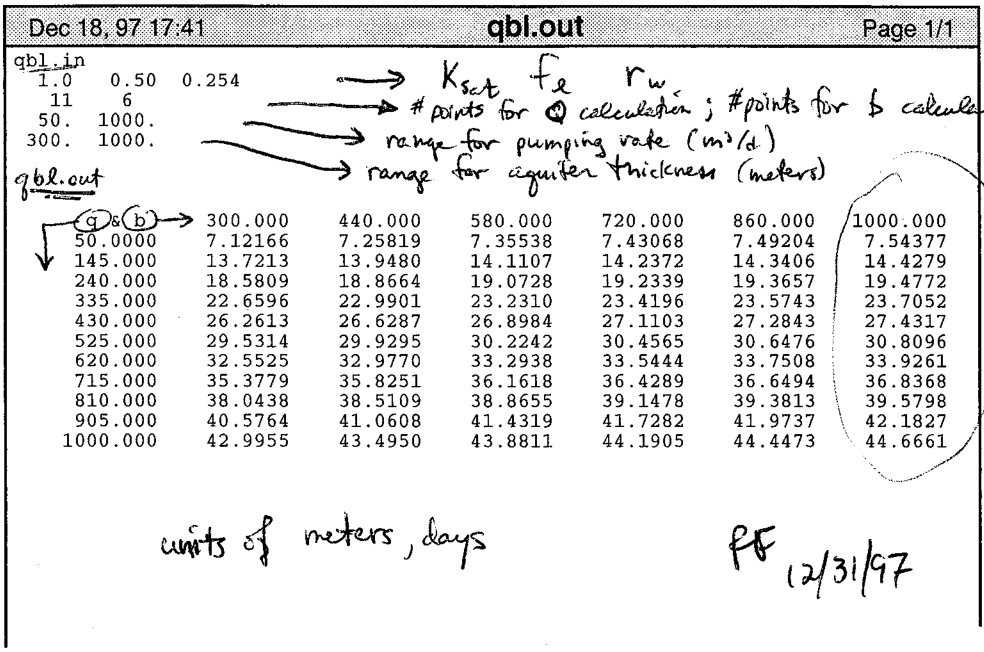
where $r_e = 575\, S_w (bK)^{1/2}$

$K \Rightarrow$ units m/s

$S_w = f_l \cdot l$

f_l = fraction

Here is an input file and an output printout



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```
qbl.in
  1.0    0.50  0.254
   11     6
  50.   1000.
 300.   1000.
```

→ K_{sat} f_e r_w

→ # points for Q calculation ; # points for b calculation

→ range for pumping rate (m^3/d)

→ range for aquifer thickness (meters)

qbl.out

```
     q&b →    300.000      440.000      580.000      720.000      860.000     1000.000
     50.0000    7.12166      7.25819      7.35538      7.43068      7.49204      7.54377
     145.000    13.7213      13.9480      14.1107      14.2372      14.3406      14.4279
     240.000    18.5809      18.8664      19.0728      19.2339      19.3657      19.4772
     335.000    22.6596      22.9901      23.2310      23.4196      23.5743      23.7052
     430.000    26.2613      26.6287      26.8984      27.1103      27.2843      27.4317
     525.000    29.5314      29.9295      30.2242      30.4565      30.6476      30.8096
     620.000    32.5525      32.9770      33.2938      33.5444      33.7508      33.9261
     715.000    35.3779      35.8251      36.1618      36.4289      36.6494      36.8368
     810.000    38.0438      38.5109      38.8655      39.1478      39.3813      39.5798
     905.000    40.5764      41.0608      41.4319      41.7282      41.9737      42.1827
    1000.000    42.9955      43.4950      43.8811      44.1905      44.4473      44.6661
```

units of meters, days

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input data ⇒ $K_{sat} = 1\ m/d$

$f_e = 0.5$ drawdown as a fraction of screen length

$r_w = 0.254\ m$

11 points of Q at which to calculate screen length

6 points of b at which to calculate screen length

$Q = U[50, 1000\ m^3/d]$ } ranges of possible

$b = U[300, 1000\ m]$ } Q and b

Note that aquifer thickness is not a particularly sensitive parameter for screen length; hence I will only have screen length as a function of pumping rate and I will use the values from an aquifer of thickness 1000 m for the TPA look up table.

Why use a range of $Q = 50 - 1000\ m^3/d$?

Assuming a critical group of 15 to 300 households

$$15 \text{ households} \left(\frac{1 \frac{\text{Ac-ft}}{\text{yr}}}{\text{household}} \right) \Longrightarrow \sim 50\ m^3/d$$

noting that

$$1 \frac{\text{Ac-ft}}{\text{yr}} = 892 \text{ gpd} = 3.377 \frac{m^3}{d}$$

instead of using water use of $1 \frac{\text{Ac-ft}}{\text{yr}}$ for a household

use 300 gpd per person

assuming 3 people per household

$$(15 \text{ households}) \left(3 \frac{\text{people}}{\text{household}}\right) \left(300 \frac{\text{gpd}}{\text{person}}\right) \left(3.785 \times 10^{-3} \frac{m^3}{\text{gallon}}\right) \simeq 51 \frac{m^3}{d}$$

Similar calculations for 300 households leads to $\sim 1000\ m^3/d$

GFLOW

Up to this point, we've designed the wells. Now it is time to look at well operation, i.e., what will the capture widths and depths be for various pumping rates. The aquifer thickness will impact the widths and depths so a 2-D matrix of capture widths and a corresponds matrix for capture thicknesses will be needed.

The program GFLOW version 1.1 will be used to calculate capture widths and thicknesses (see page 10 and subsequent pages of this notebook Re: GFLOW)

Inputs needed for GFLOW are:

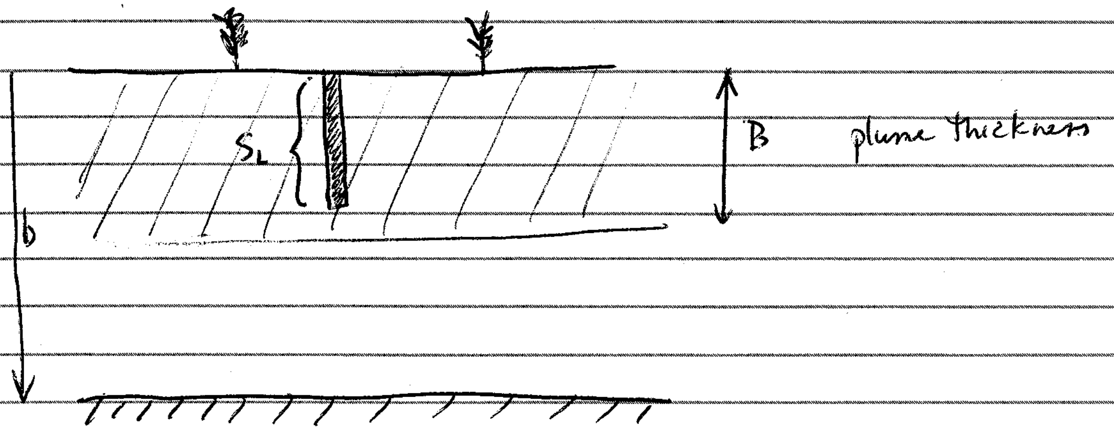
$K_{sat} = 1\ m/d$
$\nabla h = 0.00125$
$r_w = 0.254$ m
$b =$ range 300 to 1000 m
$Q =$ range from 50 to 1000 m^3/d
$S_L \Rightarrow$ from table on previous page (p. 101)

note that uniform gradient potential $= T\nabla h = Kb\nabla h$

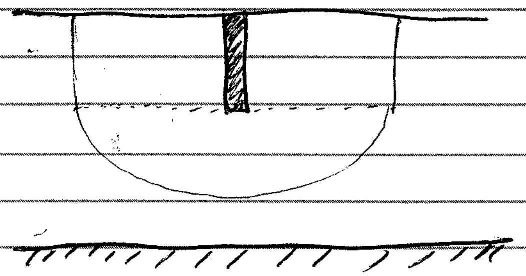
The procedure for using GFLOW has been previously described in this notebook (GFLOW is under TOP-018 control).
Tables of results (capture thickness & widths) are included in the 6-page report attached on following page, shortly.

First, the method for calculating the fraction of mass captured by the pumping well needs to be described.

Table 1 of report $\Rightarrow C_w = C_w(Q, b)$ capture width
Table 2 of report $\Rightarrow C_t = C_t(Q, b)$ capture thickness



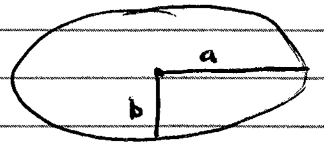
To calculate the fraction of the mass captured, calculate the intersection of the capture area and the plume. Assume the capture area can be described as a combination of a rectangle and half-ellipse as shown below



rectangle area $= C_w * S_L$

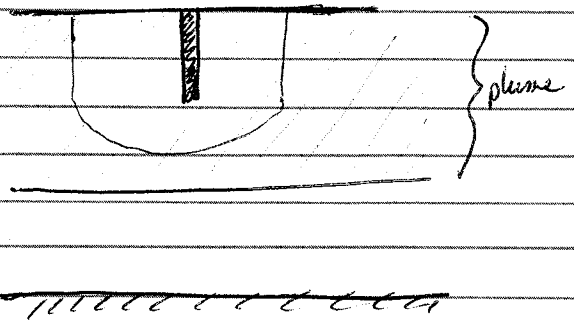
ellipse area $= \frac{\pi}{2}\left(\frac{C_w}{2}\right)(C_t - S_L)$

where area of an ellipse is $= \pi ab$



Note that there are 3 scenarios to consider

①



capture thickness not as thick as plume

Then fraction of mass captured ⇒ $MC(\cancel{\%})$ is area of capture divided by area of plume

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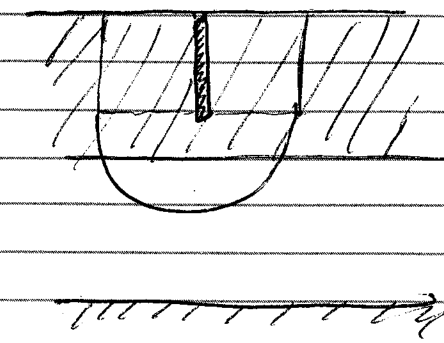
$$MC(\cancel{\%}) = \frac{\left[\frac{\pi}{2}\frac{C_w}{2}(C_t - S_L)\right] + \left[C_w S_L\right]}{B\,t_w}$$

where t_w is the streamtube width

②



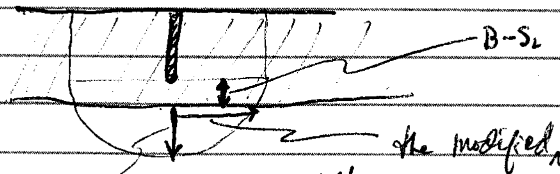
screen length is less then plume thickness but capture thickness is greater then plume thickness

$$MC(\cancel{\%}) = \frac{\text{capture area} - \text{area of ellipse below the plume}}{\text{plume thickness} * \text{streamtube width}}$$

PF 1/11/98 See modification to approach, page 11[illegible]

The capture area is again ⇒ $\left[C_w S_L\right] + \left[\frac{\pi}{2}\frac{C_w}{2}(C_t - S_L)\right]$

area below plume is elliptical but the width of the ellipse may be significantly less than the capture width



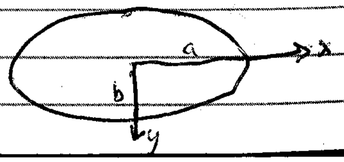
$B - S_L$

the modified half ellipse width = $\cancel{X}$

$C_t - B$ = the modified half ellipse thickness

Using the equation for the line describing a half-ellipse

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$



and knowing the modified half-ellipse thickness $(C_t - B)$, the modified half-ellipse width may be calculated from:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

$$x^2 = a^2\left[1 - \frac{y^2}{b^2}\right]$$

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$$x = \left\{a^2\left[1 - \frac{y^2}{b^2}\right]\right\}^{1/2}$$

where $y = \cancel{C_t - B} = B - S_L$
$a = C_w/2$
$b = C_t - S_L$

and the ellipse is centered (origin) at bottom of screen

hence, the portion of the ellipse below the plume is:

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$$\left(\frac{\pi}{2}\right)\left\{\left(\frac{C_w}{2}\right)^2\left[1 - \frac{\overset{(B-S_L)}{\cancel{(C_t - B)}}^2}{(C_t - S_L)^2}\right]\right\}^{1/2}(C_t - B)$$

③

If screen length is greater than plume thickness then

PF 1/7/98

$$MC(\cancel{\%}) = \frac{\text{plume thickness} * \text{capture width}}{\text{plume thickness} * \text{streamtube width}} = \frac{C_w}{t_w}$$

this calculation should also be used for cases where capture thickness is at least most of aquifer thickness (if not all). In this scenario, the shape of the capture area below the the screen is not well approximated by a half-ellipse

And finally, to calculate dilution using fraction of mass captured:

$$\underset{(C_{RN})}{\text{radionuclide concentration}} = \frac{\text{mass rate} * MC(\%)}{\text{Volumetric pump rate}}$$

if using values of radionuclide mass rate reflective of annual averages, then

PF 3/23/99

$$\cancel{C_{RN}(\tfrac{Ci}{l})} \quad C_{RN}\left(\frac{Ci}{l}\right) = \frac{\dot{M}_{RN}\left(\frac{Ci}{yr}\right) * MC(\%)}{Q\left(\frac{m^3}{d}\right)\left(\frac{365\,d}{yr}\right)\left(\frac{1000\,l}{m^3}\right)}$$

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Tabulation of GFLOW runs to calculate capture width and capture thickness

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Q(m3/d)	b(m)	uniform potential T*grad	elev screen bottom	elev screen top	capture half-width (m)	width(m)	elev of capture depth(m)	capture thickness (m)
50	300	0.375	292	300	163.4	327	150	150
50	475	0.5938	467	475	161.3	323	319	156
50	650	0.8125	642	650	160.2	320	492.4	158
50	825	1.031	817	825	159.4	319	666.4	159
50	1000	1.25	992	1000	159.4	319	841.4	159
240	300	0.375	281	300	425	850	32	268
240	475	0.5938	456	475	380	760	160.6	314
240	650	0.8125	631	650	365	730	319.6	330
240	825	1.031	806	825	360	720	487.3	338
240	1000	1.25	981	1000	356	712	658.6	341
430	300	0.375	273	300	646	1292	0	300
430	475	0.5938	448	475	542	1084	88.1	387
430	650	0.8125	623	650	505	1010	227	423
430	825	1.031	798	825	492	984	385.3	440
430	1000	1.25	973	1000	483	966	551	449
620	300	0.375	266	300	864	1728	0	300
620	475	0.5938	441	475	689	1378	47.6	427
620	650	0.8125	616	650	630	1260	164.6	485
620	825	1.031	791	825	602	1204	311.6	513
620	1000	1.25	966	1000	589	1178	471.3	529
810	300	0.375	260	300	1090	2180	0	300
810	475	0.5938	435	475	831	1662	24.4	451
810	650	0.8125	610	650	745	1490	119.6	530
810	825	1.031	785	825	706	1412	254	571
810	1000	1.25	960	1000	685	1370	407.1	593
1000	300	0.375	255	300	1295	2590	0	300
1000	475	0.5938	430	475	970	1940	11	464
1000	650	0.8125	605	650	853	1706	86.3	564
1000	825	1.031	780	825	800	1600	208.3	617
1000	1000	1.25	955	1000	765	1530	353.6	646

GFLOW inputs

GFLOW output

calculation post-GFLOW

GFLOW output

calculation post-GFLOW

See corrections

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Summary of Methodology & TPA suggested modifications

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Method to account for borehole dilution at 5km in TPA code

This is the development of a methodology to incorporate wellbore dilution into the TPA code for a pumping well located at 5km from the repository. The conceptualization necessarily accounts for a lack of information on aquifer production zones, radionuclide configuration, and well pumping flow rate through the treatment of these as sampled parameters.

The conceptual model consists of a single, partially penetrating well pumping in an aquifer of unknown thickness (see figure 1). The well pumping flow rates are limited to a range appropriate for up to a few hundred households. The radionuclides are assumed to be uniformly mixed in a plume which is the width of the currrently employed streamtubes but of unknown thickness. The range of plume thicknesses are limited from 10 to 100m. The aquifer thickness is also unknown but will be constrained between 300 and 1000m.

The conceptual model recommended for use assumes homogeneous, isotropic porous media. A more tangible model incorporating production zones along fault and fracture zones was not pursued due to a lack of data for both the number of production zones as well as the properties of the indivivdual production zones. Whereas, the vertically-averaged parameter values currently used in the site-wide models are appropriate for the homogeneous, isotropic porous media model.

1. Assumptions.

Assume steady state flow in a homogeneous, isotropic porous media with a plume which is the width of the streamtubes but vertically mixed over an unknown thickness. Also assume constant values for the parameters hydraulic conductivity (K=1m/d), well radius (r_w=0.254m), and regional hydraulic gradient (∇h=0.00125). The streamtube width (t_w) will be calculated from the existing streamtube.dat file as the sum of the widths of all the streamtubes.

2. Sampling Distributions.

Sample uniform fields for pump flow rate, Q=U[50,1000m^3/d], aquifer thickness, b=U[300,1000m], and mixing zone (plume) thickness, B=U[10,100m]. The pump flow rate is based a range of 15 to 300 households annually using 1 ac-ft per household, or about 300 gpd per person if there are 3 people per household.

3. Well Design.

Compute screen length needed to support the sampled pump flow rate and aquifer thickness using Thiem's equation for confined radial flow (Lohman, 1972) and Muskat's adjustment for partially penetrating wells (McWhorter and Sunada, 1977). A matrix of screen lengths for various pump flow rates and aquifer thicknesses will be used to develop the lookup table described in part 4, below.

The Thiem equation for confined radial flow for a fully penetrating well is

$$\frac{Q}{s_w} = \frac{2\pi K b}{\ln(r_e/r_w)}$$

where the ratio of pump flow rate to drawdown (s_w) is the specific capacity, and r_e is the radius of influence. The Muskat equation for a partially penetrating well is

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$$\left(\frac{Q}{s_w}\right)_p = \left(\frac{Q}{s_w}\right)\left[\frac{S_L}{b}\left\{1+7\left(\frac{r_w}{2S_L}\right)^{\frac{1}{2}}\cos\frac{\pi S_L}{2b}\right\}\right]$$

where the subscript "p" denotes the the partially penetrating well and S_L is the length of the screened portion of the well. This solution accounts for the nonuniform distribution of flux along the well screen due to the partial penetration. Kruseman and de Ridder (1983) describe an alternative solution for this problem which they refer to as the Huisman method. However, the Huisman equation is in the form of an infinite series solution, and as such, is not as readily manipulated (nonlinear in screen length) as the Muskat approximation.

Reasonable estimates of the drawdown and radius of influence, both a function of the pump flow rate, are needed. For the purpose of designing a screen length for a well, the drawdown will be constrained to be a specified fraction of the screen length. In terms of specific capacity and lift costs, 0.7 can be taken as an upper limit (U.S. Department of Interior, 1981). Instead of using the upper limit, a fraction equal to 0.5 will be used here; this leads to reasonable screen lengths and drawdowns. As for an estimate of the radius of influence, rather than using a representative value for the entire range of pumping rates, the empirical relation

$$r_e = 575\ s_w\ (b\ K)^{\frac{1}{2}}$$

from Bear (1979) is used noting that the units of hydraulic conductivity must be meters per second. This relation produces results similar to the capture widths estimated using analytic element method (Haitjema, 1995). This is certainly not a justification for the empirical relation since radius of influence and capture width are two slightly different concepts, but it does offer a means of approximating the relation between discharge and radius of influence.

4. Well Operation.
Determine capture width and depth as a function of pump flow rate, aquifer thickness, and screen length using using the analytic element method of GFLOW (Haitjema, 1995). The pump flow rate, aquifer thickness, and screen length triplets are obtained from parts 2 & 3 above. Matrices of both capture widths and capture depths for various pump rates and aquifer thicknesses will be incorporated into the TPA code as lookup tables.

5. Fraction of Mass Captured.
The fraction of the plume captured by a well at 5km is calculated as the ratio of the area of the plume captured by the well and the entire area of the plume. The numerator is the well capture width multiplied by the sampled plume thickness for screen lengths greater than the plume thickness; otherwise the numerator is the capture area minus any elliptical portion below the plume. The denominator is the streamtube width multiplied by the sampled plume thickness.

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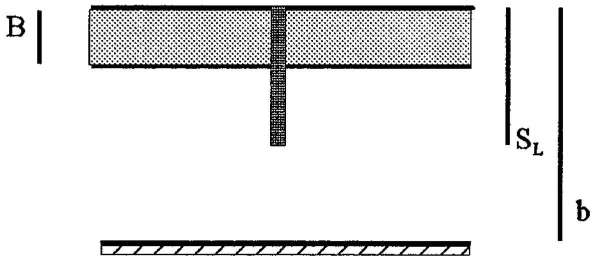

Figure 1. Definition of parameters plume thickness B, aquifer thickness b, and screen length S_L.

References

Bear, J. 1979. *Hydraulics of Groundwater*. McGraw-Hill, New York.

Haitjema, H. 1995. *Analytic Element Modeling of Groundwater Flow*. Academic Press, San Diego.

Kruseman, G.P., and N.A. de Ridder. 1983. Analysis *and Evaluation of Pumping Test Data, 3rd Edition*. Bulletin 11, International Institute for Land Reclamation and Improvement, The Netherlands.

Lohman, S.W. 1972. *Ground-Water Hydraulics*. U.S. Geological Survey Professional Paper 708, Washington D.C.

McWhorter, D.B., and D.K. Sunada. 1977. *Ground-Water Hydrology and Hydraulics*. Water Resources Publications, Fort Collins, Colorado.

U.S. Department of Interior. 1981. Ground Water Manual; A Water Resources Technical Publication, A Guide for the Investigation, Development, and Management of Ground-Water Resources. U.S. Department of Interior and Power Resources Service, reprinted byJohn Wiley & Sons, New York.

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TPA Modifications

1. Sample uniform distributions for:
(i) pump flow rate, Q=U[50,1000m^3/d];
(ii) aquifer thickness, b=U[300,1000m]; and
(iii) mixing zone (plume) thickness, B=U[10,100m].

2. Interpolate three parameters from lookup tables.
Interpolate capture width (c_w) and thickness (c_t) from 2-dimensional lookup table based on pump flow rate and aquifer thickness; e.g., capture width= c_w(Q,b). The first interpolation direction should be for pump flow rate. An example of the tables is included here; 6 rows and 5 columns are expected to be included, missing entries will be added shortly. The categories for the table of capture widths (table 1) correspond to those for capture thickness (table 2) thus simplifying the interpolation for the second table lookup.
Also interpolate screen length as a function of pump flow rate (Table 3).

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Table 1. Capture Widths (meters).

	b=300m	b=475m	b=650m	b=825m	b=1000m
Q=50m^3/d	327	323	320	319	319
Q= 240m^3/d	850	760	730	720	712
Q=430m^3/d	1292	1084	1010	984	966
Q= 620m^3/d	1728	1378	1260	1204	1178
Q=810m^3/d	2180	1662	1490	1412	1370
Q=1000m^3/d	2590	1940	1706	1600	1532

Table 2. Capture Thicknesses (meters).

	b=300m	b=475m	b=650m	b=825m	b=1000m
Q=50m^3/d	150	156	158	159	159
Q= 240m^3/d	268	314	330	338	341
Q= 430m^3/d	300	387	423	440	449
Q= 620m^3/d	300	427	485	513	529
Q= 810m^3/d	300	451	530	571	593
Q=1000m^3/d	300	464	564	617	646

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Table 3. Screen Lengths as a function of pumping flow rates.

Pump Rate (m^3/d)	Screen Length (m)
50	8
240	19
430	27
620	34
810	40
1000	45

* fraction between 0 & 1

3. In the TPA code, the IF-THEN hierarchy for calculating the fraction of mass captured would be:

(i) if screen length (S_L) is greater than plume thickness, or, if capture depth is greater than 90% of the aquifer thickness then

$$\text{Mass Captured }(MC)\ \overset{\text{fraction *}}{(\%)} = \frac{\text{plume thickness} * \text{capture width}}{\text{plume thickness} * \text{streamtube width}} = \frac{B\,c_w}{B\,t_w} = \frac{c_w}{t_w}$$

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where t_w is the streamtube width which is calculated from the streamtube.dat file;

(ii) if screen length is less than plume thickness but capture thickness is greater than the plume thickness then

See modification to approach page 117 of scientific notebook

$$MC\ \overset{\text{fraction}}{(\%)} = \frac{\text{capture area} - \text{area of ellipse below plume}}{\text{plume thickness} * \text{streamtube width}}$$

$$= \frac{\left[c_w\,S_L\right] + \left[\frac{\pi}{2}\frac{c_w}{2}(c_t - S_L)\right] - \left[\frac{\pi}{2}\left(\left\{\frac{c_w}{2}\right\}^2\left\{1-\frac{(c_t-B)^2}{(c_t-S_L)^2}\right\}\right)^{\frac{1}{2}}(c_t - B)\right]}{B\,t_w};$$

changed 1/7/98 see page 115 RF

(iii) if screen length and capture thickness are less than plume thickness then

$$MC\ \overset{\text{fraction}}{(\%)} = \frac{\text{capture area}}{\text{plume thickness} * \text{streamtube width}} = \frac{\left[\frac{\pi}{2}\frac{c_w}{2}(c_t-S_L)\right] + \left[c_w\,S_L\right]}{B\,t_w}.$$

The capture area is calculated assuming that the portion below the screen is the shape of an ellipse. This may be in error when the capture depth approaches the thickness of the aquifer. This error occurs for the situation of large pump flow rates and thin aquifers, however, the second criteria in item (i) catches the most prominent cases.

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4. Calculate the concentration to be used for dose estimates by multiplying the fraction of the mass captured times the mass rate of radionuclides (M_{RN}) transported to the 5km line and divide by the volume pumped over a specified time period. The radionuclide concentration (C_{RN}) is calculated as:

$$radionuclide\ concentration = \frac{mass\ rate\ *\ fraction\ of\ mass\ captured}{volume\ rate\ pumped}$$

which is, when using annual values and units restricted to meters and days for the pump flow rate:

$$\underline{C_{RN}\left(\frac{Ci}{l}\right)} = \frac{M_{RN}\left(\frac{Ci}{yr}\right) * MC(\cancel{\%})\text{ fraction}}{Q\left(\frac{m^3}{d}\right)\left(\frac{365\ d}{yr}\right)\left(\frac{1000\ l}{m^3}\right)} .$$

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→ actually TPA uses $\frac{Ci}{yr}$ and never calculates a conc.

PF 1/7/98

Table of variable descriptions

sample from distribution	Q	pump rate (m^3/d)
sample from distribution	b	aquifer thickness (m)
sample from distribution	B	plume thickness (m)
interpolate from table 1	c_w	capture width (m)
interpolate from table 2	c_t	capture thickness (m)
interpolate from table 3	S_L	screen length (m)
calculate from existing input	t_w	streamtube width (m)
	π	pi = 3.14159...
existing computation	M_{RN}	mass rate (Ci/yr)
calculate	C_{RN}	concentration (Ci/l)

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1/8/98 RF

Borehole Dilution – Testing of Rob Roy's (consultant) Implementation

Rob modified DCAGW.f module to include the borehole dilution; he went directly from the description on page 107 of this notebook. (Noting some corrections to my writeup, % instead of fraction, typo in table ( ).

Files needed: tpa.e (executable), tpa.inp, dilution.dat
↳ ./data/

To check results, also look at:

samplpar.hdr (codes for Q, B, b)
34 36 38

Samplpar.res (find random number using code from samplpar.hdr file)

dcagw.ret (fraction and doses output)

screen output (peak doses for quick check

$$\frac{Ci}{yr} * dcf * MC \Rightarrow dose$$

dcf = dose conversion factor
MC = fraction of mass captured

Rob used units of gpd (gallons per day) for input (tpa.inp) of pumping rate range; meters are used for plume (mixing) thickness and aquifer thickness.

Although the dilution.dat file which contains my three tables uses m^3/d and meters

Conversion $\Rightarrow m^3/d \left(\frac{1\ gal}{3.785 \times 10^{-3}\ m^3}\right) \Rightarrow gpd$

so $50\ m^3/d = 1.321004 \times 10^4$ gpd } tpa.inp range for Q
$1000\ m^3/d = 2.6420 \times 10^5$ gpd

To edit the tpa.inp file for these ranges (Q, B, b), search for "DCAGW" to get to appropriate section

1/8/98
RF

The current ranges

Q = Uniform [1.321×10^4 , 2.642×10^5] gpd
b = Uniform [300, 1000] meters
B = Uniform [10, 100] meters

Probably the easiest way to check Rob Roy's implementation is to set a range that is very small, so as to insure getting a particular number/value

[This is easier than setting the distribution to constant (this changes the number of sampled parameters) or editing the dilution.dat file and changing all the entries to all the tables to the same number so all no matter what value is sampled, the same result occurs, except for sampled Q]

Note that error checking of values of range in tpa.inp does not shutdown the code, only if the sampled number from the range falls outside of table ranges. Hence, to cause error checking to occur, set the highest tpa.inp range value to less than the dilution.dat table range (or vice-versa); otherwise there is just a random possibility of error checking stopping the code.

Streamtube.dat file has tw, streamtube width used in calculation of fraction of mass captured.
Currently there are 4 streamtubes, their widths at 5 km are 1100, 1250, 1250, 900 meters = 4500 meter total = tw

Prior to running (after compiling, since so many units are opened) use the UNIX command

"limit" check to make sure descriptors is not at 64
if so then ~~use~~ "unlimit" to change descriptors to 1024

Also TPA environment variable must be set to working directory
for example setenv TPA /export2/rfedors/TPA

I have also turned off the volcanism, seismic, faulting modules; otherwise Rob says this is the current "base" case tpa.inp file.

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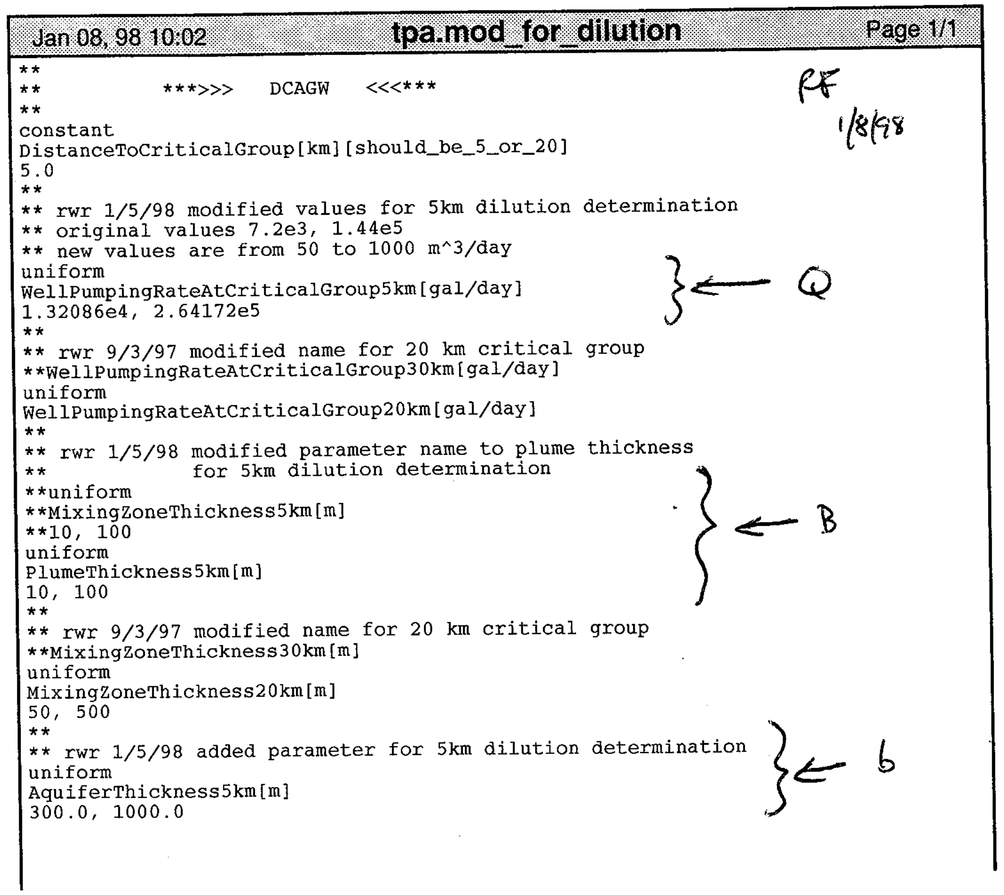
RF

The portion of tpa.inp which will be modified to test the mass fraction captured at 5 km



Jan 08, 98 10:02 **tpa.mod_for_dilution** Page 1/1

```
**
**          ***>>>   DCAGW   <<<***
**
constant
DistanceToCriticalGroup[km][should_be_5_or_20]
5.0
**
** rwr 1/5/98 modified values for 5km dilution determination
** original values 7.2e3, 1.44e5
** new values are from 50 to 1000 m^3/day
uniform
WellPumpingRateAtCriticalGroup5km[gal/day]
1.32086e4, 2.64172e5
**
** rwr 9/3/97 modified name for 20 km critical group
**WellPumpingRateAtCriticalGroup30km[gal/day]
uniform
WellPumpingRateAtCriticalGroup20km[gal/day]
**
** rwr 1/5/98 modified parameter name to plume thickness
**              for 5km dilution determination
**uniform
**MixingZoneThickness5km[m]
**10, 100
uniform
PlumeThickness5km[m]
10, 100
**
** rwr 9/3/97 modified name for 20 km critical group
**MixingZoneThickness30km[m]
uniform
MixingZoneThickness20km[m]
50, 500
**
** rwr 1/5/98 added parameter for 5km dilution determination
uniform
AquiferThickness5km[m]
300.0, 1000.0
```

Check calculation of fraction by knowing Q, B, b from setting values in tpa.inp; looking up capture width, thickness and screen length, and knowing streamtube width

The mass fraction captured shows up at top of dcagw.ret file

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RF

Only the calculation of the mass fraction will be checked here

① $Q = 50\ m^3/d$, $B = 100\ m$; $b = 650$, $t_w = 4500\ m$

Set tpa.inp DCAGW ranges:

Q ⇒ uniform
WellPumpingRateAtCriticalGroup5km[gal/day]
1.32086e4, 1.32090e4

B ⇒ uniform
PlumeThickness5km[m]
99.9, 100.0

b ⇒ uniform
AquiferThickness5km[m]
650.0, 650.1

bottom of screen output

Results at 20,000 yrs sum peak dose at end of TPI 8.3627E03
fraction = 5.9598E-02 in dcagw.ret file

For Q, B, b above: $C_w = 320\ m$, $C_t = 158\ m$, $S_L = 8\ m$ } from look-up table, also page 106 scientific notebook

this case has screen length smaller than plume thickness and capture thickness greater than plume thickness, hence use

$$Mc = \frac{\left[C_w S_L\right] + \left[\frac{\pi}{2}\frac{C_w}{2}(C_t - S_L)\right] - \left[\frac{\pi}{2}\left(\left\{\frac{C_w}{2}\right\}^2\left\{1 - \frac{(C_t - B)^2}{(C_t - S_L)^2}\right\}\right)^{1/2}(C_t - B)\right]}{B t_w}$$

Mc = fraction of mass captured

$$= \frac{\left[320\,m \cdot 8\,m\right] + \left[\frac{\pi}{2}\frac{320\,m}{2}(158\,m - 8\,m)\right] - \left[\frac{\pi}{2}\underbrace{\left(\left\{\frac{320\,m}{2}\right\}^2\left\{1 - \frac{(158\,m - 100\,m)^2}{(158\,m - 8\,m)^2}\right\}\right)^{1/2}}_{147.6\,m}(158\,m - 100\,m)\right]}{(100\,m \cdot 4500\,m)}$$

$$= \frac{26,816}{450,000} = 0.060$$

which ≈ 0.059598 from tpa.e output

Samplpar.res output file indicates the sampled parameters

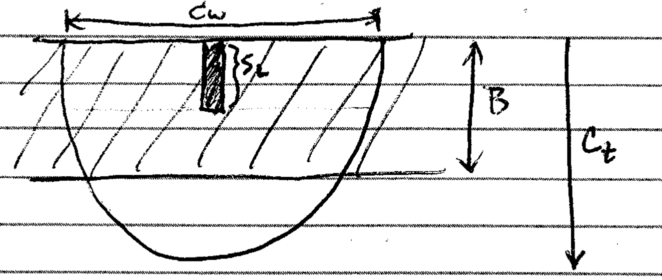
Q ⇒ 0.1320877E+05 34th entry
B ⇒ 0.9996262E+02 36th entry
b ⇒ 0.6500157E+03 38th entry

1/11/98
RF

Problems with Item 2 criteria, page 104

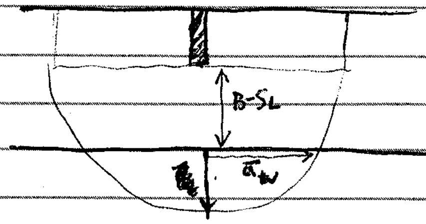
Change in approach suggested by Rob Roy due to problems with fraction values. Criteria 2 $\Rightarrow$ $S_L < B$ and $C_t > B$

RF 1/11/98



$$\frac{\text{entire capture area} - \text{area of ellipse below plume} \; \cancel{\text{of ellipse}}}{\text{entire plume area}}$$

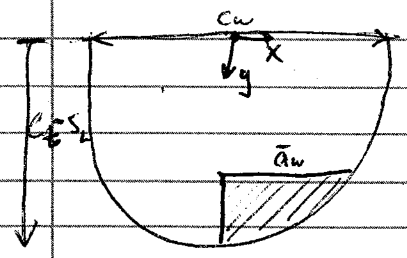
Instead of approximating the area of the ellipse below the plume as another ellipse, just integrate that portion of the ellipse which extends down from the screen



entire capture area =

$$=\left[c_w S_L\right] + \left[\frac{\pi}{2}\left(\frac{c_w}{2}\right)(C_t - S_L)\right]$$

RF 3/23/99



area of ellipse below plume by integrating the area in red

The ellipse is described by the equation

$$\frac{X^2}{a^2} + \frac{Y^2}{b^2} = 1$$

where $a = c_w/2$
$b = C_t - S_L$

integrate in the x-direction, so rearrange ellipse eqn accordingly

$$\frac{X^2}{a^2} + \frac{y^2}{b^2} = 1$$

$$y^2 = b^2\left\{1 - \frac{x^2}{a^2}\right\}$$

$$y = b\left\{1 - \frac{x^2}{a^2}\right\}^{1/2}$$

RF 3/23/99

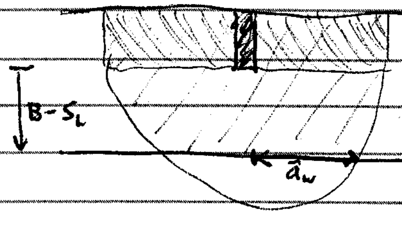
1/12/98
RF

Then integrate this expression from $(B - S_L)$ to $(C_t - S_L)$

It would sure be nice to go from 0 to $\bar{a}_w$ for the integration thus getting some terms to drop out so change the entire method for calculating the mass fraction to:

$$\text{fraction of mass captured} = \frac{\text{capture area within plume}}{\text{entire plume area}}$$

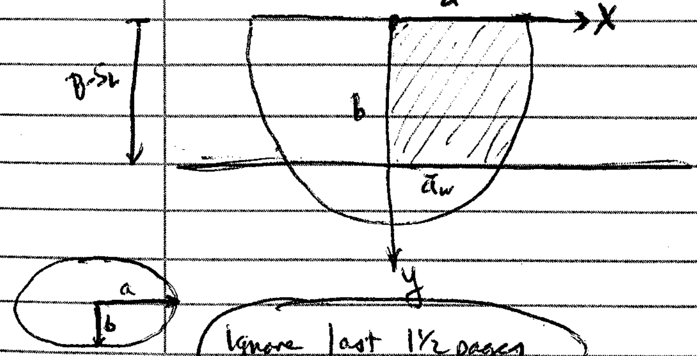
Then the capture area within the plume is



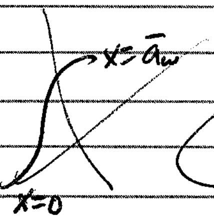
} → $[c_w \cdot S_L]$

} → portion of ellipse, integrate from ~~0 to $\bar{a}_w$ in the x-direction~~ y=0 to y= B-S_L

RF 1/12/98



since there is a mirror image, just double the area of the shaded (red) portion



forget about $\bar{a}w$
RF 1/12/98

Ignore last 1½ pages

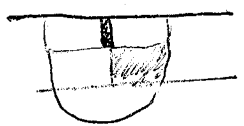
Actually, we want to integrate from y=0 to y= B-S_L

rearrange equation for ellipse $\Rightarrow$ $X = a\left\{1 - \frac{Y^2}{b^2}\right\}^{1/2}$

$$\text{area} = \int_{y=0}^{y=B-S_L} a\left\{1 - \frac{Y^2}{b^2}\right\}^{1/2} dY = \text{area of red shaded area in figure immediately above}$$

1/12/98 PF

area = $\int_0^{B-S_L} 2a\left\{1-\frac{Y^2}{b^2}\right\}^{1/2} dY$



need twice the shaded area

$= 2a\int_0^{B-S_L}\left\{\frac{b^2}{b^2}-\frac{Y^2}{b^2}\right\}^{1/2}dY = 2a\int_0^{B-S_L}\frac{1}{b}\left\{b^2-Y^2\right\}^{1/2}dY =$

$= \frac{2a}{b}\int_0^{B-S_L}(b^2-Y^2)^{1/2}\,dY$

look up in integration table

$\int\sqrt{a^2-x^2}\,dx = \frac{1}{2}\left[x\sqrt{a^2-x^2}+a^2\sin^{-1}\left(\frac{x}{|a|}\right)\right]$

$= \frac{2a}{b}\left[\frac{1}{2}\left\{y\sqrt{b^2-y^2}+b^2\sin^{-1}\left(\frac{y}{b}\right)\right\}\right]_{y=0}^{y=B-S_L}$ noting that b will always be positive

when y=0 (evaluated at zero) ⇒ 0

noting that $\sin^{-1}(0)=0$ ← PF 3/23/99

hence

$= \frac{2a}{2b}\left[(B-S_L)\sqrt{b^2-(B-S_L)^2}+b^2\sin^{-1}\left(\frac{B-S_L}{b}\right)\right]$

where $a=\frac{C_w}{2}$ $b=C_t-S_L$

$= \frac{C_w\cdot 2}{2\cdot 2(C_t-S_L)}\left[(B-S_L)\underbrace{\sqrt{(C_t-S_L)^2-(B-S_L)^2}}_{(C_t^2-2C_tS_L+S_L^2)-(B^2-2BS_L+S_L^2)}+(C_t-S_L)^2\sin^{-1}\left(\frac{B-S_L}{C_t-S_L}\right)\right]$

$C_t^2-2C_tS_L+\cancel{S_L^2}-B^2+2BS_L-\cancel{S_L^2}$

just leave as is

area = $\frac{2\cdot C_w}{4(C_t-S_L)}\left[(B-S_L)\left\{(C_t-S_L)^2-(B-S_L)^2\right\}^{1/2}+(C_t-S_L)^2\sin^{-1}\left(\frac{B-S_L}{C_t-S_L}\right)\right]$

1/12/98 PF

PF 3/23/99

Then fraction of mass captured is

$$MC = \frac{[C_w\cdot S_L]+\left[\frac{C_w}{\cancel{2}(C_t-S_L)}\left\{(B-S_L)\sqrt{(C_t-S_L)^2-(B-S_L)^2}+(C_t-S_L)^2\sin^{-1}\left(\frac{B-S_L}{C_t-S_L}\right)\right\}\right]}{B\cdot t_w}$$

t_w = streamtube width = 4500 m

check of equation for area of ellipse

example S_L = 8 m, C_w = 320 m, C_t = 158 m

area of ellipse = $\frac{\pi}{2}\left(\frac{320\,m}{2}\right)(158-8)$ = 37699 m²

Using Equation on bottom of previous page

B = 100m ⟹ 27473 m²

B = 10 m ⟹ 640 m² (approx by 2 x 320, 2 m below screen)

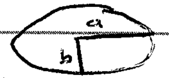
B = 158 m ⟹ 37699 m² (checks w/ above)

B = 9 m ⟹ 320 m²

At small values of B (plume thickness)

The contribution from the ellipse can be approx as a rectangle

As the plume becomes thick enough to include the entire capture depth, the eqn at bottom of previous page should give same as eqn for an ellipse (half) ⇒ $\frac{\pi}{2}ab$



⇒ Remember to run "unlimit" UNIX command to allow more files

check ⇒ Rob modified dcagust to reflect this change

Re-check TPA output

tpa.inp file			Lookup in table			output tpa fraction	my calc.
Q range (gpd)	B range (m)	b range (m)	C_w (m)	C_t (m)	S_L (m)	MC	M
50 m³/d 1.32086E4, 1.3209E4	99.9, 100	650, 650.1	320	158	8	6.6744E-2	.0668

checked samplpar.res file to confirm Q, B, b values

falls in criteria 2, use eqn at top of this page

$$MC = \frac{[320\cdot 8]+\left[\frac{320}{2(158-8)}\left\{(100-8)\sqrt{(158-8)^2-(100-8)^2}+(158-8)^2\sin^{-1}\left(\frac{100-8}{158-8}\right)\right\}\right]}{100\cdot 4500}$$

Q range (gpd)	B range (m)	b range (m)	C_w (m)	C_t (m)	S_L (m)	MC	M
810 m³/d 2.14002E5, 2.14003E5	29.9, 30.0	999.9, 1000	1370	593	40	3.0447E-1	.304

criteria 1 $MC = C_w/t_w = 1370/4500$

Q range (gpd)	B range (m)	b range (m)	C_w (m)	C_t (m)	S_L (m)	MC	M
1.38705E5, 1.38705E5	49.9, 50.0	737.49, 737.5	1114.5	465.25	30.5	2.4765E-1	.2476

criteria 2, use "MC" eqn on top of this page; this example interpolated for C_w, C_t

1/13/98 RF

Updated criteria, replaces appropriate page of report on page 107 scientific notebook.

3. In the TPA code, the IF-THEN hierarchy for calculating the fraction of mass captured would be:

(i) if screen length (S_L) is greater than plume thickness, or, if capture depth is greater than 90% of the aquifer thickness then

$$\text{Fraction of Mass Captured } (MC) = \frac{\text{plume thickness} * \text{capture width}}{\text{plume thickness} * \text{streamtube width}} = \frac{B\, c_w}{B\, t_w} = \frac{c_w}{t_w}$$

where t_w is the streamtube width which is calculated from the streamtube.dat file;

(ii) if screen length is less than plume thickness but capture thickness is greater than the plume thickness then

$$MC = \frac{\text{capture area within plume}}{\text{plume thickness} * \text{streamtube width}}$$

$$= \frac{\left[c_w\, S_L\right] + \left[\frac{c_w}{2(c_t-S_L)}\left\{(B-S_L)\sqrt{(c_t-S_L)^2-(B-S_L)^2} + (c_t-S_L)^2 \sin^{-1}\frac{B-S_L}{c_t-S_L}\right\}\right]}{B\, t_w}$$

where the first term in the numerator is the portion at the level of the screen, and the second term is the portion below the screen yet still within the plume (the result of integrating the equation for an ellipse for portion which is in the plume);

(iii) if screen length and capture thickness are less than plume thickness then

$$MC = \frac{\text{capture area}}{\text{plume thickness} * \text{streamtube width}} = \frac{\left[c_w\, S_L\right] + \left[\frac{\pi}{2}\frac{c_w}{2}(c_t-S_L)\right]}{B\, t_w}.$$

The capture area is calculated assuming that the portion below the screen is the shape of an ellipse. This may be in error when the capture depth approaches the thickness of the aquifer. This error occurs for the situation of large pump flow rates and thin aquifers, however, the second criteria in item (i) catches the most prominent cases.

4. Calculate the dose by multiplying the mass rate of radionuclides (M_{RN}) transported to the 5km line by the fraction of the mass captured and by the dose conversion factor (dcf) and then divide by the volume pumped over a specified time period. The dose is calculated as:

$$\text{dose} = \frac{\text{mass rate} * \text{fraction of mass captured} * \text{dose conversion factor}}{\text{volume rate pumped}}$$

which is, when using annual values and units restricted to meters and days for the pump flow rate:

$$\text{dose}\left(\frac{rem}{yr}\right) = \frac{M_{RN}\left(\frac{Ci}{yr}\right) * MC * dcf\left(\frac{rem}{yr}\frac{m^3}{Ci}\right)}{Q\left(\frac{m^3}{d}\right)\left(\frac{365\ d}{yr}\right)}.$$

RF
1/13/98

9/20/99 RF

Expand TPA table for Dilution ⇒ lower Qpump

Request made to expand tables ① capture width vs pump rate, ② capture thickness vs pump rate, and ③ screen length vs pump rate such that lower pumping rates are included. McCartin wants lower, but unspecified pump rates. Zero rates are easy but impractical; a non-zero pump rate is needed for the lowest interpolation point. 1 household at 1 ac-ft/yr is a good low Q ; Q = 3.37~~8~~ m^3/d
RF 9/20/99

$$1\ \frac{ac\text{-}ft}{yr} \cong 3.377\ \frac{m^3}{d} = \left(\frac{4047\ m^2}{ac}\ \frac{.3048\ m}{ft}\ \frac{yr}{365.25\ d}\right) 1\ \frac{ac\text{-}ft}{yr}$$

Work on this update of TPA will be saved in
bren: rfedors/Bore-Update1999/*

Running GFLOW v. 1.0

① Screen output does not work well because DOS is emulated under WinNT (graphical displays are over-written by text instead of text just being replaced).

② To start GFLOW at the DOS (emulated) prompt:
D:\Randy\GFLOW\gflow1

③ Set Aquifer properties
Permeability = 1.0 m/d (porosity does matter)
Thickness = 300 (range 300 - 1000)
Base = 0
Uniform - $(T\nabla h)_x$ $(T\nabla h)_y$
for Thick=300 m ↓ ↓
.375 0
Reference 0 -1000 300 (for Thickness b=300 m)

$T\nabla h = (1\ \frac{m}{day})(\text{Thick})(.00125)$
$\nabla h = 0.00125$
$K = 1\ m/d$

④ PPWELL (back to main menu) ← {and choose reference head not affected by well
↳ discharge
↳

x	y	z1	z2	Q	radius
0	0	295	300	3.4	.254

⑤ Solve

⑥ Grid plan view ⇒ window $X_1\ Y_1\ X_2\ Y_2$ -100 -100 50 100
cross-section window $X_1\ Y_1\ Z_1\ X_2\ Y_2\ Z_2$
horizontal points = 100
Z_1 ↘ 275 Z_2 ↘ 300
$X_1 = -100$ $X_2 = 50$ $Y_1 = Y_2 = 0$

9/21/99
RF

⑦ Trace
cursor on
contour on
direction forward

⑧ Loop back through ⑥ & ⑦ to get both
plan view ($\frac{1}{2}$ capture width)
and cross-section (depth)
Check grid → window X_1 distance to confirm that
I have gone far enough away from the well (that the capture area is not still increasing).
For $Q = 3.4$ $X_1 = 150$ m
$Q = 10 \ m^3/d$, $X_1 = 300$ m

The summary table below contain the results from GFLOW for the 2 pumping rates. Note that capture width and thickness do not vary significantly from the different aquifer thicknesses, hence, within the accuracy of the method, all capture widths for each pump rate are considered the same. Ditto for capture thickness

The screen lengths used in this analysis were all set to $S_L = 3$ as a practical lower limit for screens installed. (Also see page 100, musk.f)

file = bren:~/Bore-Update1999/Muskat/low-pump-rate.xls

Q (m3/d)	b(m)	T*grad (m2/d)	screen length (m)	elev (m) screen bottom	elev (m) screen top	capture half-width (m)	capture width (m)	elev (m) capture depth	capture thickness (m)
3.4	300	0.375	3	297	300	41.2	82.4	258.9	41.1
3.4	475	0.59375	3	472	475	41	82	433.8	41.2
3.4	650	0.8125	3	647	650	40.9	81.8	608.7	41.3
3.4	825	1.03125	3	822	825	40.9	81.8	783.7	41.3
3.4	1000	1.25	3	997	1000	40.9	81.8	958.7	41.3
10	300	0.375	3	297	300	70.5	141	230	70
10	475	0.59375	3	472	475	71	142	404.3	70.7
10	650	0.8125	3	647	650	71	142	579.3	70.7
10	825	1.03125	3	822	825	71	142	754.5	70.5
10	1000	1.25	3	997	1000	71	142	929.3	70.7

Conclusion is that aquifer thickness does not affect capture width and thickness at the low pump rates !!!
Just take the capture widths and thicknesses as constant for each pump rate.

RF
9/21/99

Output from musk.f - Screen Lengths

For Q (m3/d) = 3.4

Aquifer Thick (m)	Screen Length (m)
300	1.20428
475	1.2478
650	1.27671
825	1.29827
1000	1.31544

For Q (m3/d) = 10.

Aquifer Thick (m)	Screen Length (m)
300	2.51824
475	2.59246
650	2.64201
825	2.6791
1000	2.70868

Just set a minimum practical screen length of 3 m

RF 9/21/99

The tables below are the 3 tables required for TPA external files/hardcoded (??). The tables includede previously determined entries for pump rates between $Q = 50 \ m^3/d$ to $Q = 1000 \ m^3/d$. EXCEL 97 spreadsheet program was used to create these.

file = bren:~/Bore-Update1999/Muskat/low-pump-rate.xls

Modifications made Sept 1999 to add data for lower pump rates

Capture Widths

	Aquifer Thickness, b (m)				
Q, m3/d	300	475	650	825	1000
3.4	82	82	82	82	82
10	142	142	142	142	142
50	327	323	320	319	319
240	850	760	730	720	712
430	1292	1084	1010	984	966
620	1728	1378	1260	1204	1178
810	2180	1662	1490	1412	1370
1000	2590	1940	1706	1600	1532

Capture Thicknesses

3.4	41	41	41	41	41
10	71	71	71	71	71
50	150	156	158	159	159
240	268	314	330	338	341
430	300	387	423	440	449
620	300	427	485	513	529
810	300	451	530	571	593
1000	300	464	564	617	646

RF
9/21/99

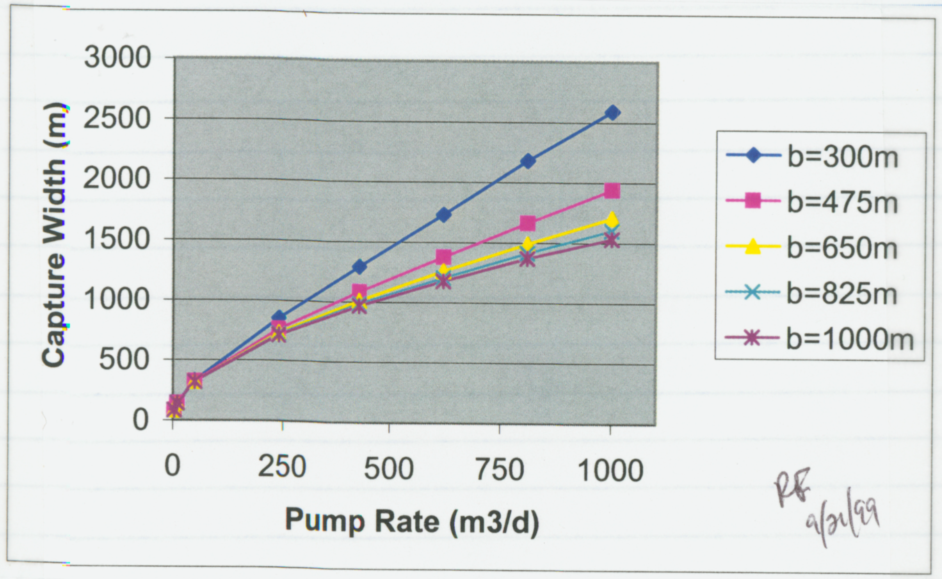
Screen Length Needed (from musk.f code)

Q	Screen (m)					TPA table
3.4	1.204	1.248	1.277	1.298	1.316	3
10	2.518	2.592	2.642	2.679	2.709	3
50	7.122	7.285	7.395	7.478	7.544	8
240	18.581	18.924	19.158	19.335	19.477	19
430	26.261	26.703	27.010	27.244	27.432	27
620	32.552	33.064	33.426	33.703	33.926	34
810	38.044	38.608	39.014	39.327	39.580	40
1000	42.995	43.600	44.044	44.387	44.666	45

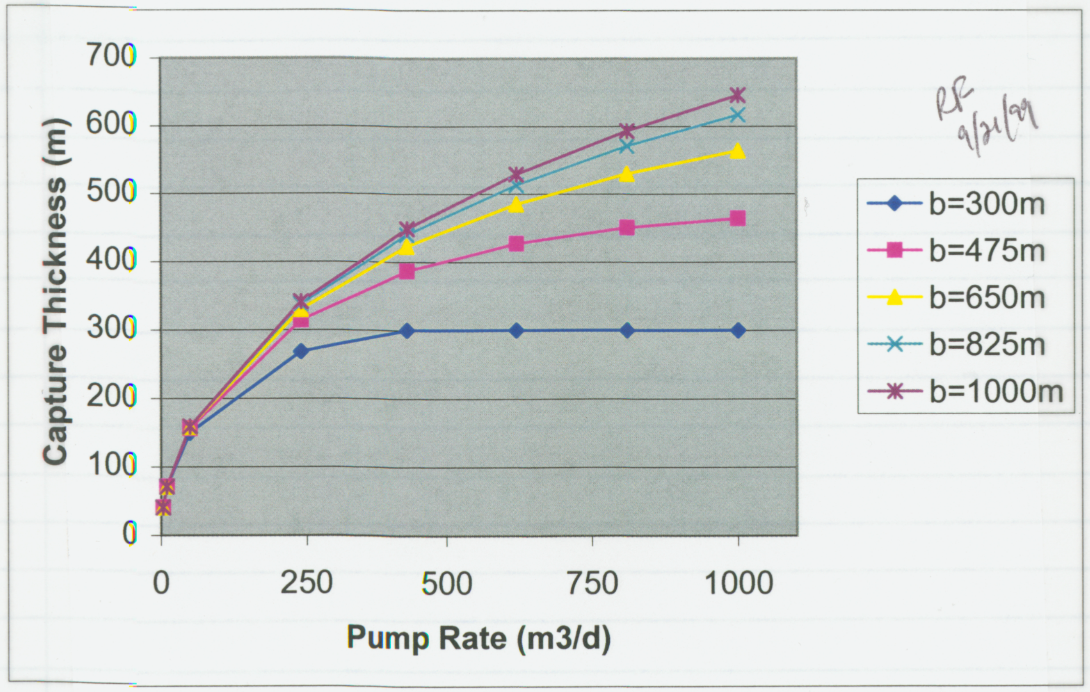
For table in TPA, use values from aquifer thickness of 1000m except for that a restriction for the lower pump rates having at least a 3 m screen length because of practical concerns.

9/21/99 RF

Plots of capture width and thickness from EXCEL file low-pump-rate.xls



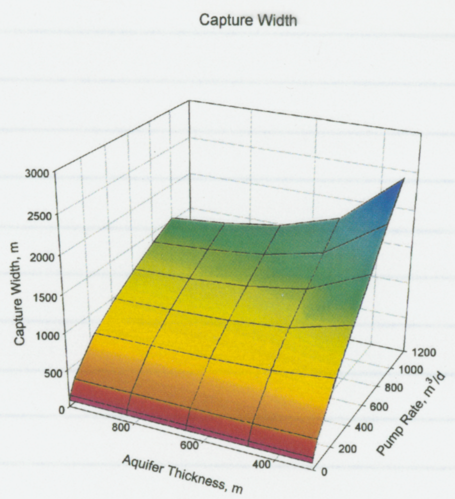
RF 9/21/99

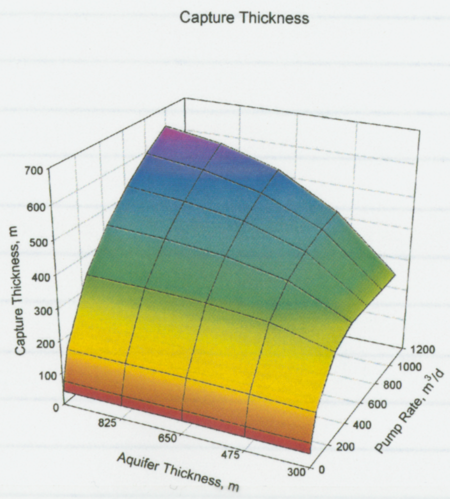


RF 9/21/99

9/21/99 RF

Surface Plots of capture width and capture thickness plotted against pump rate and aquifer thickness. Data translated & imported into SigmaPlot version 4.0





9/27/99 RF Report from page 107 of this notebook was updated to include the lower pumping rates. K and ∇h are still considered constant; expression of the method to include $K*\nabla h$ in the tables is not considered necessary since David Farrell is using a numerical model to replace this methodology.

RF
9/27/99

Methodology to Account for Borehole Dilution at 5km in TPA code

Two changes have been made to the calculation of borehole dilution at 5 km:

1. The range of pump rates has been extended to include lower rates. The lower end of the range now corresponds to the water needed by a single household; the previous lower end was for 15 households.

2. An additional criteria has been added to ensure that the fraction of mass captured equal to 1 when the capture zone for the pumping well was wider than the streamtube. Rob Rice has confirmed that this criteria is covered by a final check on the value of the mass fraction; the check ensures that it is not greater than one.

122 9/27/99 RF

9/27/99 RF Report from page 107 of this notebook was updated to include the lower pumping rates. K and ∇h are still considered constant; expansion of the method to include $K*\nabla h$ in the tables is not considered necessary since David Farrell is using a numerical model to replace this methodology.

RF
9/27/99

Methodology to Account for Borehole Dilution at 5km in TPA code

This is the development of a methodology to incorporate wellbore dilution into the TPA code for a pumping well located at 5km from the repository. The conceptualization necessarily accounts for a lack of information on aquifer production zones, radionuclide plume configuration, and well pumping flow rate through the treatment of these as sampled parameters. Analytic solutions for a partially penetrating pumping well in a uniform flow field are used to estimate capture zones for a range of pump rates. Together with a plume configuration based on the streamtube width and an stochastically-sampled plume thickness, the well capture zone is used to estimate the fraction of mass captured by the well.

This approach does not explicitly estimate the dilution effects caused by transverse dispersion along the plume pathway, nor the dilution by mixing of clean (no repository-based radionuclides) water from the well extracting water from depths below the plume; these dilution effects lumped into the dilution estimate through the use of a uniformly mixed plume of uncertain thickness. This approach does not account for the uncertainty in hydraulic conductivity or hydraulic gradient at the 5 km location.

Conceptual Model

The conceptual model consists of a single, partially penetrating well pumping in an aquifer of unknown thickness (see figure 1) located 5 km downgradient from the repository. The well pumping flow rates are limited to a range appropriate to support the domestic requirements of one to a few hundred households. The radionuclides are assumed to be uniformly mixed in a plume that is the width of the streamtubes but of unknown thickness. The range of plume thicknesses are constrained to a range from 10 to 100m. The aquifer thickness is constrained between 300 and 1000 m.

The conceptual model assumes a homogeneous, isotropic porous media. A more realistic model incorporating production zones for water flow along fault and fracture zones was not pursued due to a lack of data for both the number of production zones as well as the properties of the individual production zones. Whereas, the vertically-averaged parameter values currently used in the site-wide groundwater flow models are appropriate for the homogeneous, isotropic porous media model used here.

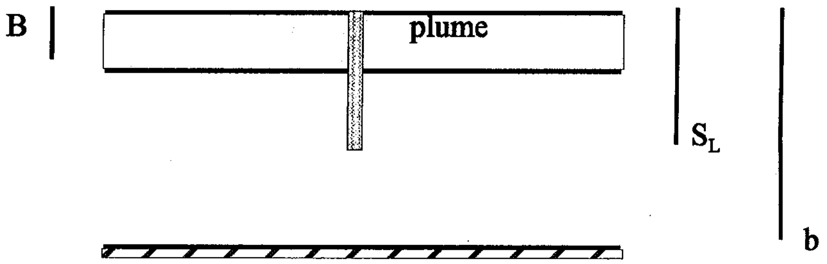


Figure 1. Definition of parameters of plume thickness *B*, aquifer thickness *b*, and screen length S_L

9/27/99 RF

9/27/99 RF Report from page 107 of this notebook was updated to include the lower pumping rates. K and ∇h are still considered constant; expansion of the method to include K*∇h in the tables is not considered necessary since David Farrell is using a numerical model to replace this methodology.

RF
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Parameter Values and Ranges

Steady state flow in a homogeneous, isotropic porous media is assumed with a plume that is the width of the streamtubes but vertically mixed over an unknown thickness. The streamtube width (t_w) is calculated from the existing streamtube.dat file as the sum of the widths of all the streamtubes. It is also assumed that constant values for the parameters hydraulic conductivity (K=1m/d) and regional hydraulic gradient (∇h=0.00125) are appropriate for the 5 km location. Extension of this approach for modeling borehole dilution to include the uncertainty in K and ∇h would require regression equations, instead of two-dimensional lookup tables, for estimating capture width and thickness as functions of pumping rate, aquifer thickness, and the composite parameter of $K_{*}\nabla h$.

Pump flow rate, aquifer thickness, and mixing zone (plume) thickness are intended to be sampled parameters with uniform distribution. The range of pump flow rates is based on the domestic needs of 1 to 300 households. Annual use is assumed to be 1 ac-ft per household, or about 300 gpd per person if there are 3 people per household (Fedors and Wittmeyer, 1998). This leads to the volumetric flow rate of 3.4 m^3/d for one household, 50 m^3/d for 15 households, and 1000 m^3/d for 300 households.

Well Design

Two important parameters of well design well are wellbore radius (r_w) and screen length. For this analysis, a wellbore radius reflective of domestic or quasi-municipal wells is 0.254 m and is considered constant in this analysis. The other important well design parameter is screen length. It is used to determine the extent of the capture zone for a partially penetrating well and for calculation of the fraction of radionuclide mass captured. Intuitively, a greater screen length is needed to support larger pump rates; hence, screen length is estimated using the an analytic expression for flow from a partially penetrating well.

The computed screen length needed to support the sampled pump flow rate and aquifer thickness using Thiem's equation for confined radial flow (Lohman, 1972) and Muskat's adjustment for partially penetrating wells (McWhorter and Sunada, 1977). The Thiem equation for confined radial flow for a fully penetrating well is

$$\frac{Q}{s_w} = \frac{2\pi K b}{\ln(r_e/r_w)}$$

where the ratio of pump flow rate (Q) to drawdown (s_w) is the specific capacity, π is 3.14159...,and r_e is the radius of influence. The Muskat equation for a partially penetrating well is

$$\left(\frac{Q}{s_w}\right)_p = \left(\frac{Q}{s_w}\right)\left[\frac{S_L}{b}\left\{1+7\left(\frac{r_w}{2S_L}\right)^{\frac{1}{2}}\cos\frac{\pi S_L}{2b}\right\}\right]$$

where the subscript "p" denotes the the partially penetrating well and S_L is the length of the screened portion of the well. This solution accounts for the nonuniform distribution of flux along the well screen due to partial penetration into the aquifer. Kruseman and de Ridder (1983) describe an alternative solution for this problem that they refer to as the Huisman method. However, the Huisman equation is in

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the form of an infinite series solution, and as such, is not as readily manipulated as the Muskat approximation.

Reasonable estimates of the drawdown and radius of influence, both a function of the pump flow rate, are needed. For the purpose of designing a screen length for a well, the drawdown will be constrained to be a specified fraction of the screen length. In terms of specific capacity and lift costs, 0.7 can be taken as an upper limit (U.S. Department of Interior, 1981). Instead of using the upper limit, a fraction equal to 0.5 will be used here. The estimate of the radius of influence, rather than using a representative value for the entire range of pumping rates, is allowed to vary with the pump rate. The estimate uses the empirical relation

$$r_e = 575\ s_w\ (b\ K)^{\frac{1}{2}}$$

from Bear (1979) is used noting that the units of hydraulic conductivity must be meters per second. This relation produces results similar to the capture widths estimated using analytic element method of GFLOW v1.0 (Haitjema, 1995) described below. This is certainly not a justification for the empirical relation since radius of influence and capture width are two slightly different concepts, but it does offer a means of approximating the relation between discharge and radius of influence.

Well Capture Zone Estimation

Once values of wellbore radius and screen length are specified, the capture zone for partially penetrating well in a uniform flow field can be estimated. The capture width and depth are determined as a function of pump flow rate, aquifer thickness, and screen length using using the analytic element method of GFLOW v1.0 (Haitjema, 1995). Matrices of both capture widths and capture depths for various pump rates and aquifer thicknesses will be incorporated into the TPA code as lookup tables.

The Analytic Element Method (AEM) used in GFLOW v1.0 provides a composite analytic solution which satisfies the differential equation in an unbounded domain. Delineation of streamlines is more precise than with standard numerical methods since both the head and the velocities are known at every point, rather than solely at computational nodes. Combined 2D and 3D modeling is accomplished by superposition of 3D effects on the general 2D solution. For example, near a partially penetrating well, a 3D solution is used. At a location sufficiently far from the well, however, the vertical flow components are negligible and a 2D approximation for the pumping well may be superimposed on the solution.

The equations for flow in AEM are written in terms of discharge potentials instead of hydraulic head. The discharge potential is defined differently for confined, unconfined, 1D flow, 2D flow, or for any other analytic element. Once the strength of the potential is known for each analytic element, the head or groundwater discharge may be determined at any point in the flow domain. The solution for the partially penetrating well is based on work by both Muskat and Polubarinova-Kochina (Haitjema, 1995) for the representation of the strength distribution along a line sink (point sinks along a line) while constraining the discharge to a fixed value.

GFLOW v1.0 is used to estimate the capture zone geometry for a partially penetrating well in a uniform regional gradient . The 3D effects of the partially penetrating well are superimposed on the 2D regional flow field. At some distance from the well, the vertical components due to pumping become negligible. Forward or backward particle tracking is used in GFLOW to determine a capture area at some

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distant, upgradient point where vertical flux components become insignificant. This capture area is a vertical plane normal to the direction of regional flow.

Fraction of Radionuclide Mass Captured

The fraction of the plume captured by a well at 5km is calculated as the ratio of the area of the plume captured by the well and the entire area of the plume. The numerator is the well capture width multiplied by the sampled plume thickness for screen lengths greater than the plume thickness; otherwise the numerator is the capture width multiplied by the screen length plus the elliptical portion of the capture area within the plume. The denominator is the streamtube width multiplied by the sampled plume thickness.

IMPLEMENTATION OF WELLBORE DILUTION AT 5 KM IN TPA CODE

Wellbore dilution at 5 km is implemented in TPA 3.2 through three sampled parameters, three lookup tables, and equations for the calculation of mass fraction captured based on criteria relating the wellbore construction, capture depth, and aquifer thickness.

Parameter Distributions

The three parameters values and distributions for pump flow rate, aquifer thickness, and mixing zone thickness are in the tpa.input file. Although other distributions may be used, uniform distributions for all three parameters are chosen here since there is little data to support a more complex distribution. The ranges specified below are the minimum and maximum allowed since the tables developed in following section (Interpolation Tables) were developed for these ranges, and hence, extrapolation would be avoided:

- pump flow rate, Q=U[3.4,1000m^3/d];
- aquifer thickness, b=U[300,1000m]; and
- mixing zone (plume) thickness, B=U[10,100m].

Interpolation Tables

The three parameters that need to be determined by interpolation from lookup tables are screen length, capture width (c_w), and capture thickness (c_t, depth of capture zone). All three parameters are functions of pump rate and aquifer thickness. The method used to calculate screen length, described earlier, led to screen length strictly as a function of pump rate (table 1); aquifer thickness did not significantly affect the estimated screen length. Practical limitations are imposed for the lower pump rates where small screen lengths were estimated. The screen lengths were restricted to be greater than or equal to 3 m; this restriction affected the two smallest pump rates in table 1.

Capture zone width (table 2) and thickness (table 3) are interpolated from 2-dimensional lookup tables based on pump flow rate and aquifer thickness; e.g., capture width= c_w(Q,b). The categories for the table of capture widths (table 2) correspond to those for capture thickness (table 3) thus simplifying the interpolation process for the two parameters. Figure 2 illustrates the variation in capture geometry caused by variations in pump rate and aquifer thickness.

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Table 1. Screen Lengths as a function of pumping flow rates.

Pump Rate (m^3/d)	Screen Length (m)
3.4	3
10	3
50	8
240	19
430	27
620	34
810	40
1000	45

Table 1. Capture Widths (meters).

	b=300m	b=475m	b=650m	b=825m	b=1000m
Q = 3.4 m^3/d	82	82	82	82	82
Q = 10 m^3/d	142	142	142	142	142
Q = 50 m^3/d	327	323	320	319	319
Q = 240 m^3/d	850	760	730	720	712
Q = 430 m^3/d	1292	1084	1010	984	966
Q = 620 m^3/d	1728	1378	1260	1204	1178
Q = 810 m^3/d	2180	1662	1490	1412	1370
Q = 1000 m^3/d	2590	1940	1706	1600	1532

Table 2. Capture Thicknesses (meters).

	b=300m	b=475m	b=650m	b=825m	b=1000m
Q = 3.4 m^3/d	41	41	41	41	41
Q = 10 m^3/d	71	71	71	71	71
Q = 50 m^3/d	150	156	158	159	159
Q = 240 m^3/d	268	314	330	338	341
Q = 430 m^3/d	300	387	423	440	449
Q = 620 m^3/d	300	427	485	513	529
Q = 810 m^3/d	300	451	530	571	593
Q = 1000 m^3/d	300	464	564	617	646

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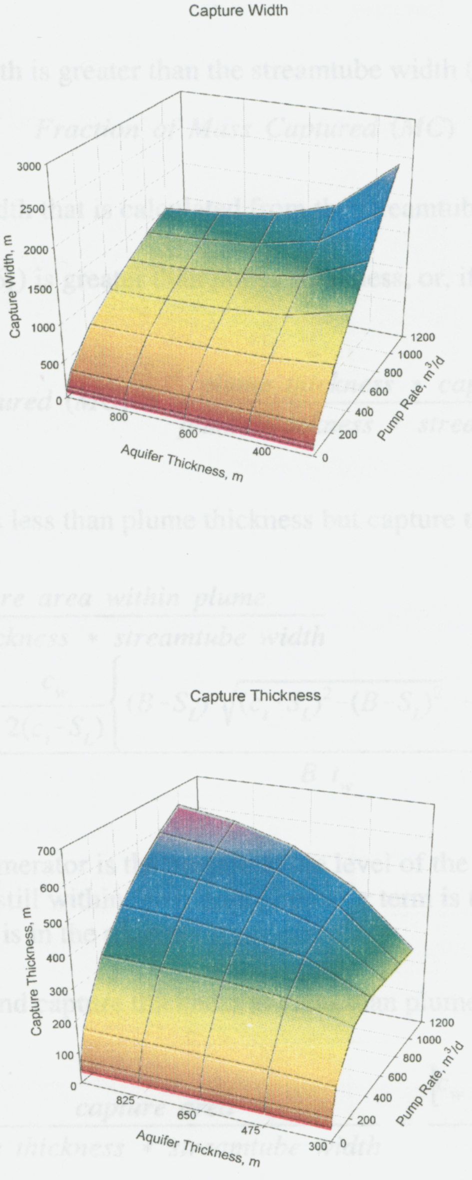

Figure 2. Surface plots of capture width and thickness versus pump rate and aquifer thickness

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Criteria for Calculation of Mass Fraction

To calculate the fraction of mass captured, the relationship between the screen length, the capture zone geometry, and the aquifer thickness must be considered. The first criteria ensures that all the mass is captured if the well capture zone is larger than the streamtube. The remaining three criteria calculate the portion of the plume captured using different equations based on the geometry of the capture zone and the plume thickness. In the TPA code, the IF-THEN hierarchy for calculating the fraction of mass captured is:

Criteria 1: If the capture width is greater than the streamtube width ($c_w > t_w$), then:

$$\textit{Fraction of Mass Captured } (MC) = 1$$

where t_w is the streamtube width that is calculated from the streamtube.dat file;

Criteria 2: If screen length (S_L) is greater than plume thickness, or, if capture depth is greater than 90% of the aquifer thickness then:

$$\textit{Fraction of Mass Captured } (MC) = \frac{\textit{plume thickness} * \textit{capture width}}{\textit{plume thickness} * \textit{streamtube width}} = \frac{B\ c_w}{B\ t_w} = \frac{c_w}{t_w}\ ;$$

Criteria 3: If screen length is less than plume thickness but capture thickness is greater than the plume thickness then:

$$MC = \frac{\textit{capture area within plume}}{\textit{plume thickness} * \textit{streamtube width}}$$

$$= \frac{\left[c_w\ S_L\right] + \left[\frac{c_w}{2(c_t - S_L)}\left\{(B - S_L)\sqrt{(c_t - S_L)^2 - (B - S_L)^2} + (c_t - S_L)^2 \sin^{-1}\frac{B - S_L}{c_t - S_L}\right\}\right]}{B\ t_w}$$

where the first term in the numerator is the portion at the level of the screen, and the second term is the portion below the screen yet still within the plume; the latter term is the result of integrating the equation for an ellipse for portion that is in the plume);

Criteria 4: If screen length and capture thickness are less than plume thickness then:

$$MC = \frac{\textit{capture area}}{\textit{plume thickness} * \textit{streamtube width}} = \frac{\left[c_w\ S_L\right] + \left[\frac{\pi}{2}\frac{c_w}{2}(c_t - S_L)\right]}{B\ t_w}\ .$$

The capture area is calculated assuming that the portion below the screen is the shape of an ellipse. This assumption may be in error when the capture depth approaches the thickness of the aquifer. This error, however, occurs for the situation of large pump flow rates and thin aquifers for which the second part in **Criteria 1** catches the significant cases.

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Estimation of Dose

Once the mass fraction is known, the dose is calculated by multiplying the mass rate of radionuclides (M_{RN}) transported to the 5 km distance by the fraction of the mass captured and by the dose conversion factor (*dcf*) and then dividing by the volume pumped over a specified time period. The dose is calculated as:

$$dose = \frac{mass\ rate * fraction\ of\ mass\ captured * dose\ conversion\ factor}{volume\ rate\ pumped} ,$$

which is, when using annual values and units restricted to meters and days for the pump flow rate:

$$dose\left(\frac{rem}{yr}\right) = \frac{M_{RN}\left(\frac{Ci}{yr}\right) * MC * dcf\left(\frac{rem\ m^3}{yr\ Ci}\right)}{Q\left(\frac{m^3}{d}\right)\left(\frac{365\ d}{yr}\right)} .$$

Table 4 contains a summary of variables, their definitions, and how obtained in the TPA implementation of wellbore dilution at 5 km.

Table 4. Variable descriptions

Source of Value	Symbol	Description
sample from distribution	Q	pump rate (m^3/d)
sample from distribution	b	aquifer thickness (m)
sample from distribution	B	plume thickness (m)
interpolate from table 1	c_w	capture width (m)
interpolate from table 2	c_t	capture thickness (m)
interpolate from table 3	S_L	screen length (m)
calculate from existing TPA input	t_w	streamtube width (m)
	π	pi = 3.14159...
existing computation	M_{RN}	mass rate (Ci/yr)
existing parameter	dcf	dose conversion factor [(rem/yr)(m^3/Ci)]

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A cdrom was written that includes all working directories for the borehole dilution. This cdrom includes files from tape #1 of scientific notebook #232, however, some of the files have been updated to reflect changes and improvements since that tape was written (12/97).

This notebook appears to comply with QAP-001.

P. C.

6/5/2000

ADDITIONAL INFORMATION FOR SCIENTIFIC NOTEBOOK #: 232

Document Date:	07/11/1997
Availability:	Southwest Research Institute® Center for Nuclear Waste Regulatory Analyses 6220 Culebra Road San Antonio, Texas 78228
Contact:	Southwest Research Institute® Center for Nuclear Waste Regulatory Analyses 6220 Culebra Road San Antonio, TX 78228-5166 Attn.: Director of Administration 210.522.5054
Data Sensitivity:	■"Non-Sensitive" ☐ Sensitive ☐"Non-Sensitive - Copyright" ☐ Sensitive - Copyright
Date Generated:	09/20/1999
Operating System: (including version number)	Windows
Application Used: (including version number)	NA
Media Type: (CDs, 3 1/2, 5 1/4 disks, etc.)	1 CD
File Types: (.exe, .bat, .zip, etc.)	xls, wpd, jpg, txt
Remarks: (computer runs, etc.)	Media contains: Various data relating to borehole dilution for Amargosa farm critical group analyses