

## 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  $K_{sat} = 1 \text{ m/s}$  saturated hydraulic conductivity  
 $dh = 0.00125$  hydraulic gradient  
 $r_w = 0.254 \text{ m}$  radius of well  
sampled from distribution (uniform)  
 $b = 4[300, 1000 \text{ m}]$  aquifer thickness  
 $B = 4[10, 100 \text{ m}]$  plume thickness  
 $Q = 4[50, 1000 \text{ m}^3/\text{s}]$  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

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

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

$S_w$  = drawdown

$r_e$  = radius of influence

$\pi = 3.14159 \dots$

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 =  $K_{sb}$

- 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.

$$\left(\frac{Q}{S_w}\right)_p = \left(\frac{Q}{S_w}\right) \left[ \frac{l}{b} \left\{ 1 + 7 \left( \frac{r_w}{2l} \right)^{3/2} \cos\left(\frac{\pi l}{2b}\right) \right\} \right]$$

$l$  = screened length =  $S_e$  in report on following pages

Bean (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

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

$r_e = 1000 \text{ m}$

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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	

$r_e = \text{fixed} = 1000 \text{ m}$

$g \Rightarrow \text{m}^3/\text{s}$

$b \Rightarrow \text{meters}$

table of screen lengths

\* see page 98 of scientific notebook for methodology of calculation

letting  $r_e \Rightarrow 575 \text{ (fraction)} (L) \left( \frac{b \cdot K}{24 \cdot 3600} \right)^{1/2}$   
- 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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$r_e = \text{fixed} = 1000 \text{ m}$

$q \Rightarrow \text{m}^3/\text{s}$

$b \Rightarrow \text{meters}$

table of screen lengths

\* see page 98 of scientific notebook for methodology of calculation



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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  $r_e$ . Also note that the concept of radius of influence is a nebulous concept  $\Rightarrow$  distance where drawdown is zero (negligible). How much of an impact does  $r_e$  have on calculation of screen lengths, see chart below of screen lengths (meters) for various values of  $Q$  ( $m^3/d$ ) 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  $r_e$  for all values of pump rate,

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

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

using units of meters, seconds

Hydrologists generally estimate  $r_e$  from experience, instead we will use 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).

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

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

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

Rearrange into picard format to solve for nonlinear in  $S_L$

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

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

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  $\Rightarrow$  fraction

let  $S_w = f_e \cdot S_L$  where  $f_e = \text{fraction} \Rightarrow 0.5$  is final value used

use  $f_e$  as a variable for sensitivity.

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

$$\text{letting } S_w = f_e \cdot S_L$$

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

rearrange to solve for  $S_L$  as a nonlinear term

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

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

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

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

where  $K$  is in units of  $\frac{m^3}{d}$  ( $\frac{24 \text{ hrs}}{d} \cdot \frac{3600 \text{ sec}}{\text{hr}}$ )

→ 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

$$\text{For } Q = 1000 \text{ m}^3/d \text{ and } b = 1000 \text{ m} \Rightarrow S_L = 44.666 \text{ m}$$

$$S_w = f_e \cdot S_L = 0.5 (44.666 \text{ m}) = 22.333 \text{ m}$$

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

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

$$44.77 \approx 44.33$$

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

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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 "1" 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
*2345678901234567890123456789012345678901234567890123456789012
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

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

stop
end

```

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

or

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

where  $r_e = 575 \cdot sw \cdot (bK)^{1/2}$   
 $K \Rightarrow \text{units } m/s$   
 $sw = f_e \cdot l$   
 $f_e = \text{fraction}$

musk.f

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Here is an input file and an output printout

Dec 18, 97 17:41			qbl.out						Page 1/1
qbl.in									
1.0	0.50	0.254							
11	6								
50.	1000.								
300.	1000.								
qbl.out									
g	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  $\Rightarrow$   $K_{set} = 1 \frac{m}{d}$   
 $f_e = 0.5$  drawdown as a fraction of screen length  
 $r_w = 0.254 \text{ m}$   
 11 points of  $Q$  at which to calculate screen length  
 6 points of  $b$  at which to calculate screen length  
 $Q = 4 [50, 1000 \text{ m}^3/d]$  } ranges of possible  
 $b = 4 [300, 1000 \text{ m}]$  }  $Q$  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 lookup table.

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

Assuming a critical group of 15 to 300 households

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

noting that

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

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

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

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

### 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 corresponding 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:

$$K_{sat} = 1 \text{ m/d}$$

$$\alpha h = 0.00135$$

$$r_w = 0.254 \text{ m}$$

$$b = \text{range } 300 \text{ to } 1000 \text{ m}$$

$$Q = \text{range from } 50 \text{ to } 1000 \text{ m}^3/\text{d}$$

$$S_L \Rightarrow \text{from table on previous page (p. 101)}$$

note that uniform gradient  
potential =  $T \alpha h = K b \alpha h$

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 pages, shortly.

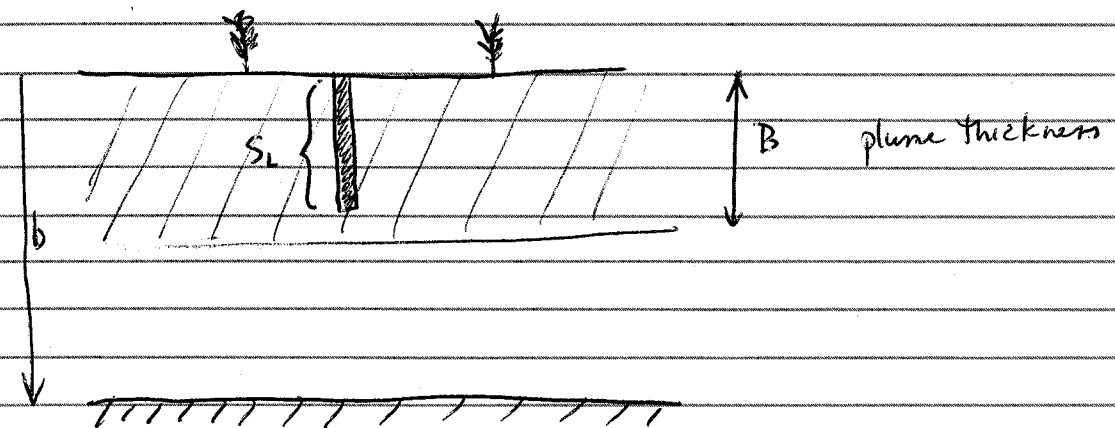
First, the method for calculating the <sup>fraction of</sup> mass captured by the pumping well needs to be described.

$$\text{Table 1 of report} \Rightarrow C_w = C_w(Q, b)$$

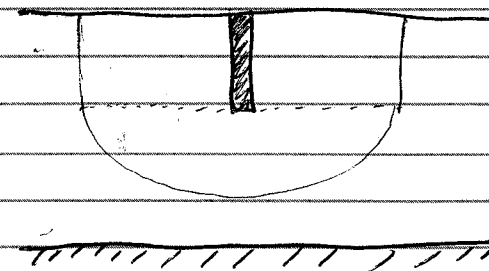
capture width

$$\text{Table 2 of report} \Rightarrow C_t = C_t(Q, b)$$

capture thickness



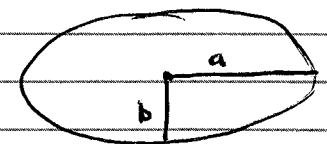
To calculate the fraction of the mass captured, calculate the intersection of the capture area and the plume. Assume the capture area can be described as a combination of a rectangle and half-ellipse as shown below



$$\text{rectangle area} = C_w * S_L$$

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

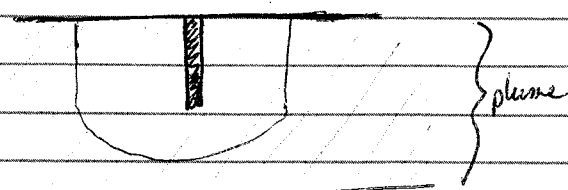
where area  
of an ellipse is  
 $= \pi ab$





Note that there are 3 scenarios to consider

(1)



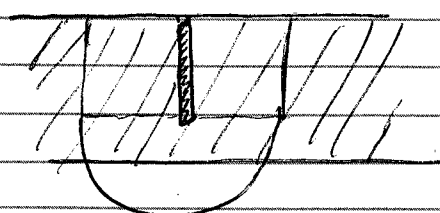
capture thickness not as thick as plume

then fraction of mass captured  $\Rightarrow MC(\%)$  is area of capture divided by area of plume

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

where  $t_w$  is the streamtube width

(2)

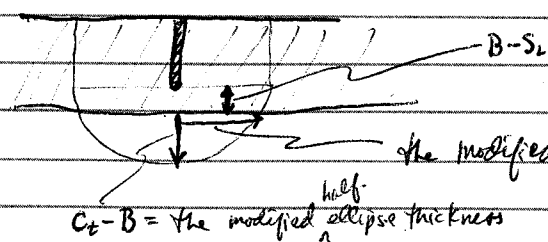


screen length is less than plume thickness but capture thickness is greater than plume thickness

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

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

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

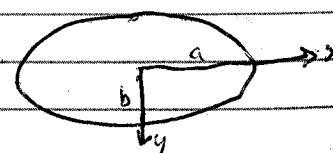


the modified <sup>half</sup> ellipse width =  $\times$

$C_t - B =$  the modified <sup>half</sup> 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:

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

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

PE 1/11/98

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

where  $y = C_t - B = B - S_L$   
 $a = C_w / 2$   
 $b = C_t - S_L$

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

PE 1/11/98

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

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

(3)

If screen length is greater than plume thickness then

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

PE 1/11/98

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 screen is not well approximated by a half-ellipse

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

$$\text{radionuclide concentration } (C_{RN}) = \frac{\text{mass rate} \times MC(\%)}{\text{volumetric pump rate}}$$

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

$$C_{RN} \left( \frac{Ci}{l} \right) = \frac{M_{RN} \left( \frac{Ci}{yr} \right) \times MC(\%)}{Q \left( \frac{m^3}{d} \right) \left( \frac{365 d}{yr} \right) \left( \frac{1000 l}{m^3} \right)}$$

PE 3/23/99

PE 1/11/98  
See modification to approach, page 104

Tabulation of GFlow runs to calculate capture width  
and capture thickness

RF 12/31/97

		uniform	elev	elev	capture		elev of	capture
Q(m3/d)	b(m)	potential	screen	screen	half-width		capture	thickness
		T*grad	bottom	top	(m)	width(m)	depth(m)	(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  
inputsGFlow  
outputcalculation  
post-  
GFlowGFlow  
outputcalculation  
post-GFlow

DRAFT 29Dec97

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 currently 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 individual 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 ( $K=1\text{m/d}$ ), well radius ( $r_w=0.254\text{m}$ ), and regional hydraulic gradient ( $V_h=0.00125$ ). 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,  $Q=U[50,1000\text{m}^3/\text{d}]$ , aquifer thickness,  $b=U[300,1000\text{m}]$ , and mixing zone (plume) thickness,  $B=U[10,100\text{m}]$ . 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

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

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

See corrections

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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 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 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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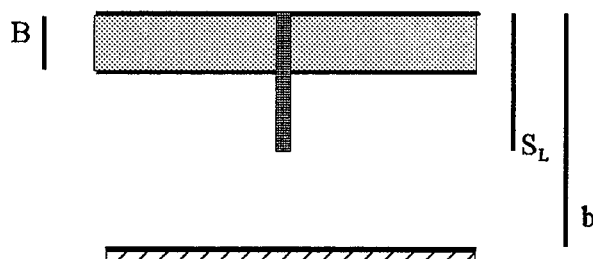


Figure 1. Definition of parameters plume thickness  $B$ , aquifer thickness  $b$ , and screen length  $S_L$ .

### 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 by John Wiley & Sons, New York.

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TPA Modifications

## 1. Sample uniform distributions for:

- (i) pump flow rate,  $Q=U[50,1000\text{m}^3/\text{d}]$ ;
- (ii) aquifer thickness,  $b=U[300,1000\text{m}]$ ; and
- (iii) mixing zone (plume) thickness,  $B=U[10,100\text{m}]$ .

## 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).

Table 1. Capture Widths (meters).

*RF 1/5/98*

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

Table 2. Capture Thicknesses (meters).

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

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

Pump Rate (m <sup>3</sup> /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

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

RF  
1/7/98

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

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

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

changed  
see page 115  
RF  
1/2/98

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

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

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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modification  
to approach  
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notebook

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:

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

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

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

PF 1/7/98

→ 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 <sup>3</sup> /d)
sample from distribution	b	aquifer thickness (m)
sample from distribution	B	plume thickness (m)
interpolate from table 1	c <sub>w</sub>	capture width (m)
interpolate from table 2	c <sub>t</sub>	capture thickness (m)
interpolate from table 3	S <sub>L</sub>	screen length (m)
calculate from existing input	t <sub>w</sub>	streamtube width (m)
	π	pi = 3.14159...
existing computation	M <sub>RN</sub>	mass rate (Ci/yr)
calculate	C <sub>RN</sub>	concentration (Ci/l)

## 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, e.g. instead of function, type in table 1).

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

To check results, also look at:

samplpar.hdr (codes for Q, B, b)

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

dcagw.res (fraction and doses output)

screen output (peak doses for quick check)

$$\frac{C_i}{y} * def * MC \Rightarrow \text{dose}$$

def = 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<sup>3</sup>/d and meters

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

$$\begin{aligned} \text{so } 50 \text{ m}^3/\text{d} &= 1.321004 \times 10^4 \text{ gpd} \\ 1000 \text{ m}^3/\text{d} &= 2.6420 \times 10^5 \text{ gpd} \end{aligned} \quad \left. \vphantom{\begin{aligned} \text{so } 50 \text{ m}^3/\text{d} &= 1.321004 \times 10^4 \text{ gpd} \\ 1000 \text{ m}^3/\text{d} &= 2.6420 \times 10^5 \text{ gpd} \end{aligned}} \right\} \text{tpa.inp range for Q}$$

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

The current ranges

$$Q = \text{Uniform} [1.321 \times 10^4, 2.642 \times 10^5] \text{ gpd}$$

$$b = \text{Uniform} [300, 1000] \text{ meters}$$

$$B = \text{Uniform} [10, 100] \text{ meters}$$

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 meters 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.

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

```

RF 1/8/98

$\left. \begin{array}{l} \text{WellPumpingRateAtCriticalGroup5km[gal/day]} \\ 1.32086e4, 2.64172e5 \end{array} \right\} \leftarrow Q$

$\left. \begin{array}{l} \text{MixingZoneThickness5km[m]} \\ 10, 100 \end{array} \right\} \leftarrow B$

$\left. \begin{array}{l} \text{AquiferThickness5km[m]} \\ 300.0, 1000.0 \end{array} \right\} \leftarrow b$

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

Only the calculation of the mass fraction will be checked here

①  $Q = 50 \text{ m}^3/\text{s}$ ,  $B = 100 \text{ m}$ ;  $b = 650$ ,  $t_w = 4500 \text{ m}$

Set tpa.inp DCAGW ranges:

$Q \Rightarrow$  uniform

WellPumpingRateAtCriticalGroup5km[gal/day]

1.32086e4, 1.32090e4

$B \Rightarrow$  uniform

PlumeThickness5km[m]

99.9, 1000

$b \Rightarrow$  uniform

AquiferThickness5km[m]

650.0, 650.1

bottom of screen output  
↓

Results at 20,000 yrs sum peak dose at end of TP1 8.3627E03  
fraction = 5.9598E-02 in dcagw.ret file

For  $Q, B, b$  above:  $C_w = 320 \text{ m}$   
 $C_t = 158 \text{ m}$   
 $S_L = 8 \text{ m}$  } 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

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

MC = fraction of mass captured Btw

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

147.6 m

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

which  $\approx 0.059598$  from tpa.e output

Samplepar.res output file indicates the sampled parameters

$Q \Rightarrow 0.1320877E+05$  34<sup>th</sup> entry

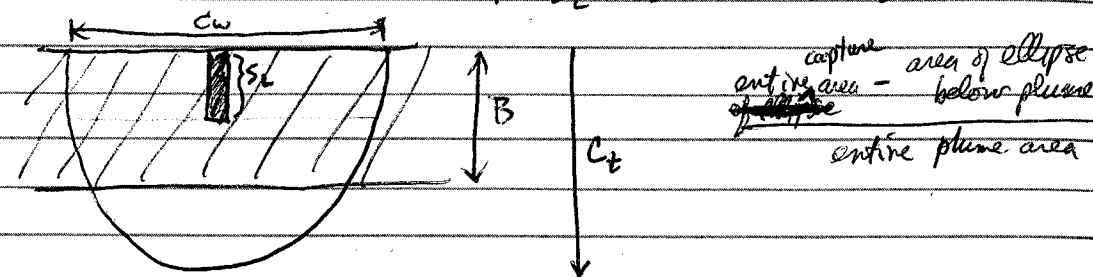
$B \Rightarrow 0.9996262E+02$  36<sup>th</sup> entry

$b \Rightarrow 0.6500157E+03$  38<sup>th</sup> entry

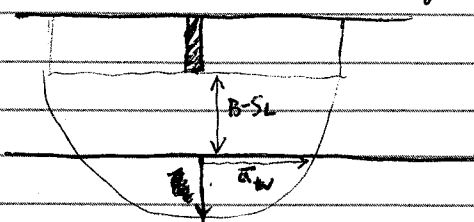


# Problems with Item 2 criteria, page 104

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



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



$$\text{entire capture area} = [C_w S_L] + \left[ \frac{\pi}{2} \left( \frac{C_w}{2} \right) (C_t - S_L) \right]$$

area of ellipse below plume by integrating the area in red

The ellipse is described by the equation

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

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

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

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

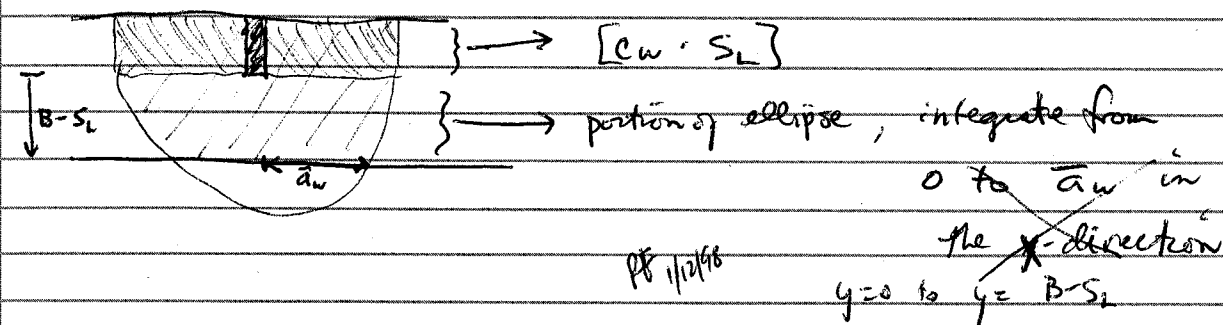
RF 3/23/99

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:

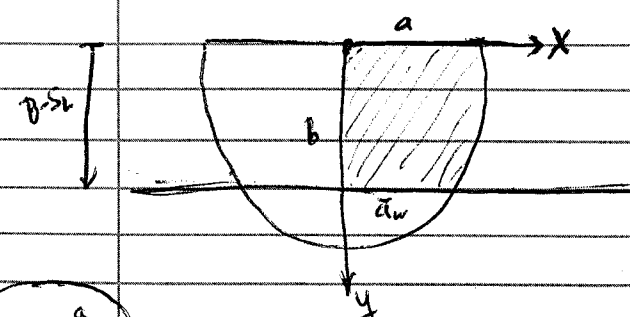
$$\text{fraction of mass captured} = \frac{\text{capture area within plume}}{\text{entire plume area}}$$

then the capture area within the plume is

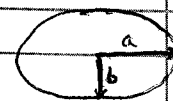


RF 11/2/98

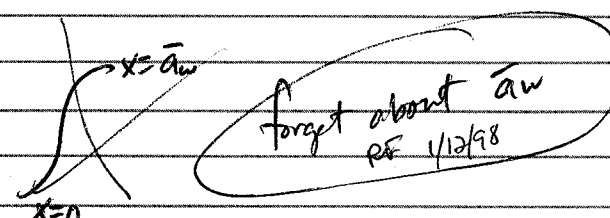
0 to  $\bar{a}_w$  in the x-direction  
 $y=0$  to  $y=B-S_L$



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



ignore last 1 1/2 pages



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

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

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

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



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

$$MC = \frac{\text{capture area within plume}}{\text{plume thickness} * \text{streamtube width}} = \frac{[c_w S_L] + \left[ \frac{c_w}{2(c_i - S_L)} \left\{ (B - S_L) \sqrt{(c_i - S_L)^2 - (B - S_L)^2} + (c_i - S_L)^2 \sin^{-1} \frac{B - S_L}{c_i - S_L} \right\} \right]}{B t_w}$$

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

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

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:

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

PF  
1/13/98

## Expand TPA table for Dilution $\Rightarrow$ Lower $Q_{\text{pump}}$

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. McCain 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  $Q$ ;  $Q = 3.377 \text{ m}^3/\text{d}$

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

Work on this update of TPA will be saved in  
bren: mredors/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 -  $T_{oh} \times (T_{oh})_y$   
for Thick = 300m  $\downarrow$   $\downarrow$   
375 0  
Reference 0 -1000 300 (for Thickness b=300m)  
and choose reference head not affected by well

④ PPWELL (back to main menu)  
 $\hookrightarrow$  discharge  
 $\hookrightarrow$  x y z1 z2 Q rad.in  
0 0 295 300 3.4 .254

⑤ Solve

⑥ Grid plan view  $\Rightarrow$  window X1 Y1 X2 Y2 -100 -100 50 100  
cross-section window X1 Y1 Z1 X2 Y2 Z2  
horizontal points = 100  
 $\downarrow$   $\downarrow$   
275 300  
X1 = -100 X2 = 300 Y1 = Y2 = 0

⑦ Trace

cursor on  
contour on  
direction forward

⑧ loop back through ⑥ & ⑦ to get both  
plan view (1/2 capture width)  
and cross-section (depth)

check grid → window X, 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<sup>3</sup>/d,  $X_1 = 300$  m

The summary table below contains the results from GROW  
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.

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

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The tables below are the 3 tables required for TPA external  
files/hardcoded (?). The tables included previously determined  
entries for pump rates between  $Q = 50$  m<sup>3</sup>/d to  $Q = 1000$  m<sup>3</sup>/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					
Q, m3/d	300	475	650	825	1000
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

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

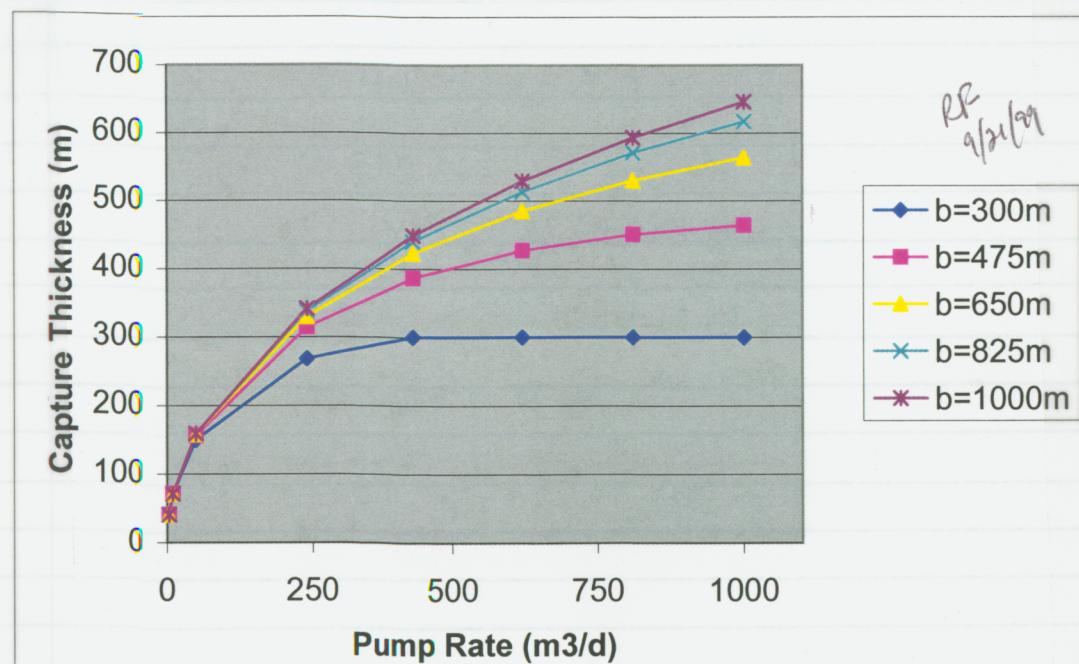
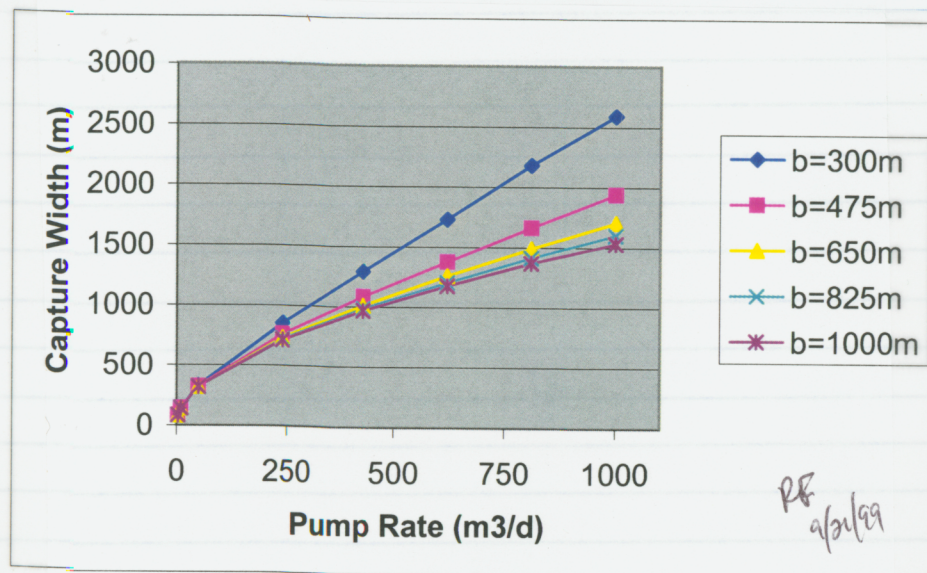
For table in TPA, use values from aquifer thickness of 1000m except for that a restriction  
for the lower pump rates having at least a 3 m screen length because of practical concerns.

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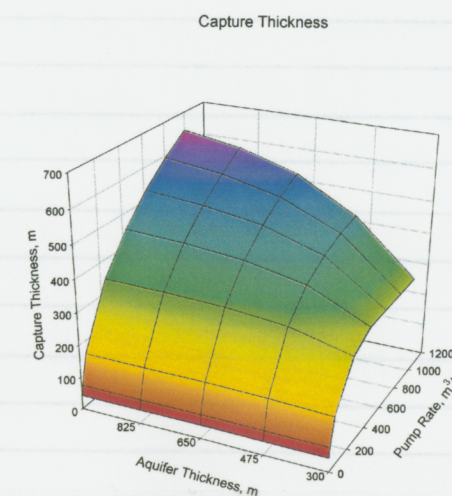
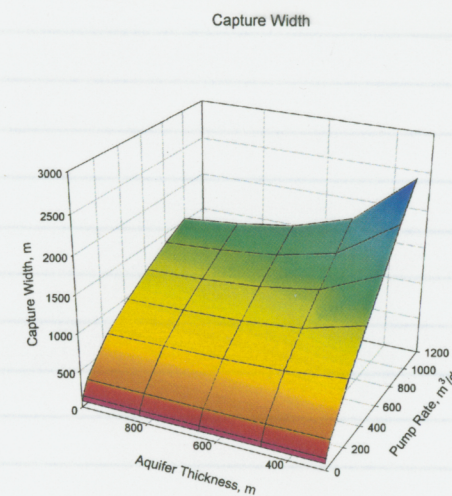


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RF

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



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





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Report from page 107 of this notebook was updated to include the lower pumping rates. K and Ph are still considered constant; expansion of the method to include K<sub>100h</sub> in the tables is not considered necessary since David Farrell is using a numerical model to replace this methodology.

RF  
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## 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.

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PF

Report from page 107 of this notebook was updated to include the lower pumping rates.  $K$  and  $Ph$  are still considered constant; expansion of the method to include  $K$  and  $Ph$  in the tables is not considered necessary since David Farrell is using a numerical model to replace this methodology.

PF  
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.

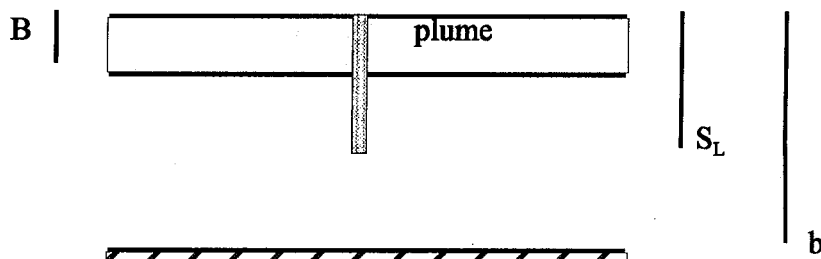


Figure 1. Definition of parameters of plume thickness  $B$ , aquifer thickness  $b$ , and screen length  $S_L$

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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 ( $K=1\text{ m/d}$ ) and regional hydraulic gradient ( $\nabla h=0.00125$ ) are appropriate for the 5 km location. Extension of this approach for modeling borehole dilution to include the uncertainty in  $K$  and  $\nabla h$  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  $K \cdot \nabla h$ .

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  $3.4\text{ m}^3/\text{d}$  for one household,  $50\text{ m}^3/\text{d}$  for 15 households, and  $1000\text{ m}^3/\text{d}$  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  $0.254\text{ m}$  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,  $\pi$  is  $3.14159\dots$ , 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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Report from page 107 of this notebook was updated to include the, lower pumping rates. K and rh are still considered constant; expansion of the model to include K and rh in the tables is not considered necessary since David Farrell is using a numerical model to replace this methodology.

122 9/27/99 RF

Report from page 107 of this notebook was updated to include the lower pumping rates. K and rh are still considered constant, expansion of the method to include K<sub>0</sub> in the tables is not considered necessary since David Farrell is using a numerical model to replace this methodology.

RF  
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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 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,  $Q=U[3.4,1000\text{m}^3/\text{d}]$ ;
- aquifer thickness,  $b=U[300,1000\text{m}]$ ; and
- mixing zone (plume) thickness,  $B=U[10,100\text{m}]$ .

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

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

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

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

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Table 1. Capture Widths (meters).

	b=300m	b=475m	b=650m	b=825m	b=1000m
Q = 3.4 m <sup>3</sup> /d	82	82	82	82	82
Q = 10 m <sup>3</sup> /d	142	142	142	142	142
Q = 50 m <sup>3</sup> /d	327	323	320	319	319
Q = 240 m <sup>3</sup> /d	850	760	730	720	712
Q = 430 m <sup>3</sup> /d	1292	1084	1010	984	966
Q = 620 m <sup>3</sup> /d	1728	1378	1260	1204	1178
Q = 810 m <sup>3</sup> /d	2180	1662	1490	1412	1370
Q = 1000 m <sup>3</sup> /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 <sup>3</sup> /d	41	41	41	41	41
Q = 10 m <sup>3</sup> /d	71	71	71	71	71
Q = 50 m <sup>3</sup> /d	150	156	158	159	159
Q = 240 m <sup>3</sup> /d	268	314	330	338	341
Q = 430 m <sup>3</sup> /d	300	387	423	440	449
Q = 620 m <sup>3</sup> /d	300	427	485	513	529
Q = 810 m <sup>3</sup> /d	300	451	530	571	593
Q = 1000 m <sup>3</sup> /d	300	464	564	617	646



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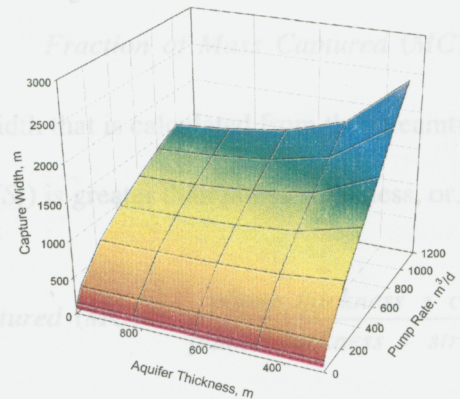
Report from page 107 of this notebook was updated to include the, lower pumping rates. K and Th are still considered constant, expensive of the method to include K and Th in the tables is not considered necessary since David Farrell is using a numerical model to replace this methodology.

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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 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 ( $c_w > l_s$ ), then:



where  $l_s$  is the streamtube width that is found in the streamtube.dat file;

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

$$\text{Fraction of Mass Captured} = \frac{\text{capture width}}{\text{streamtube width}} = \frac{B c_w}{B l_s} = \frac{c_w}{l_s}$$

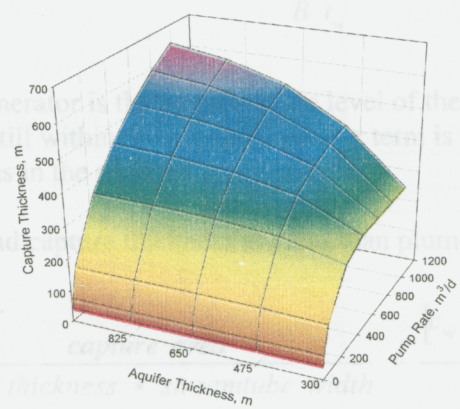
Criteria 3: If screen length is less than plume thickness but capture thickness is greater than the plume thickness then:

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

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

where the first term in the numerator is the area of the screen, and the second term is the portion below the screen yet still within the plume. The third term is the result of integrating the equation for an ellipse for portion that is below the screen.

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



$$MC = \frac{\text{capture area}}{\text{plume thickness} \times \text{streamtube width}} = \frac{\pi c_w (c_w - S_L)}{2 B l_s}$$

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

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



## 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:

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

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:

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

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

$$\begin{aligned} MC &= \frac{\text{capture area within plume}}{\text{plume thickness} * \text{streamtube width}} \\ &= \frac{[c_w S_L] + \left[ \frac{c_w}{2(c_i - S_L)} \left\{ (B - S_L) \sqrt{(c_i - S_L)^2 - (B - S_L)^2} + (c_i - S_L)^2 \sin^{-1} \frac{B - S_L}{c_i - S_L} \right\} \right]}{B t_w} \end{aligned}$$

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:

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

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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Report from page 107 of this notebook was updated to include the lower pumping rates. K and Rk are still considered constant; expansion of the model to include K<sub>1</sub> in the tables is not considered necessary since David Farrell is using a numerical model to replace this methodology.

pf  
9/22/99

Report from page 107 of this notebook was updated to include the lower pumping rates. K and Ph are still considered constant; expenses of the report to include K and Ph in the tables is not considered necessary since K and Ph are still considered constant. The model is using a numerical model to replace the methodology.

## 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:

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

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

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

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 ( $\text{m}^3/\text{d}$ )
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)
	$\pi$	pi = 3.14159...
existing computation	$M_{RN}$	mass rate (Ci/yr)
existing parameter	$dcf$	dose conversion factor [(rem/yr)( $\text{m}^3/\text{Ci}$ )]

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Report from page 107 of this notebook was updated to include the lower pumping rates. K and Rh are still considered constant; expansion of the method to include K<sub>100h</sub> in the tables is not considered necessary since David Farrell is using a numerical model to replace this methodology.

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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.

E.C. P  
6/5/2000

**ADDITIONAL INFORMATION FOR SCIENTIFIC NOTEBOOK #: 232**

<b>Document Date:</b>	07/11/1997
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<b>Data Sensitivity:</b>	<input checked="" type="checkbox"/> "Non-Sensitive" <input type="checkbox"/> Sensitive <input type="checkbox"/> "Non-Sensitive - Copyright" <input type="checkbox"/> Sensitive - Copyright
<b>Date Generated:</b>	09/20/1999
<b>Operating System:</b> (including version number)	Windows
<b>Application Used:</b> (including version number)	NA
<b>Media Type:</b> (CDs, 3 1/2, 5 1/4 disks, etc.)	1 CD
<b>File Types:</b> (.exe, .bat, .zip, etc.)	xls, wpd, jpg, txt
<b>Remarks:</b> (computer runs, etc.)	Media contains: Various data relating to borehole dilution for Amargosa farm critical group analyses