

Guidance for the Determination of the Dilution-Attenuation Factor for the
Impact to Ground Water Pathway

June 2, 2008

Introduction

When infiltrating soil water reaches the water table, it is mixed with ground water and contaminants are diluted. The resulting contaminant concentration in the groundwater is therefore lower than that in the infiltrating water. A dilution-attenuation factor (*DAF*) is used to account for this process. This factor is described in the USEPA Soil Screening Level (SSL) document (USEPA 1996). The factor is used in the various options for calculating impact to groundwater soil cleanup criteria, including calculation of the Leachate Criterion (LC).

The *DAF* is calculated using Equation 1. This equation requires a value for the mixing zone depth in the aquifer, which is calculated using Equation 2. These two equations are taken from USEPA SSL guidance document (Equations 37 and 45), respectively.

Equation for calculating the dilution-attenuation factor (*DAF*):

$$DAF = 1 + \frac{Kid}{IL} \quad \text{Equation 1}$$

where

i = gradient (m/m)

d = mixing zone depth (m), calculated below (Equation 2)

I = infiltration rate (m/yr)

L = length of area of concern parallel to ground water flow (m)

K = aquifer hydraulic conductivity (m/yr)

Equation for calculating the aquifer mixing zone depth, d :

$$d = (0.0112L^2)^{0.5} + d_a \{1 - \exp[(-LI)/(Kid_a)]\} \quad \text{Equation 2}$$

where

d_a = aquifer thickness (m)

Dilution of the contaminant due to transport through the unsaturated soil zone is not included; the chemical in soil is assumed to be immediately adjacent to the water table. Chemical degradation is also not included in this model; the calculations assume that the Ground Water Quality Standards must be achieved immediately after remediation.

Default *DAF* value

A default *DAF* of 13 for use with New Jersey remediation cases has been determined. The basis for this value is described in Appendix A.

Site-specific modification of default dilution attenuation factor (*DAF*)

Several parameters that are used in the calculation of the *DAF* may be adjusted on a site-specific basis. A site-specific dilution attenuation factor may then be calculated and used to determine a site-specific LC value and/or a site-specific impact to groundwater soil cleanup criterion. In particular, higher ground water flow rates than those assumed for calculation of the default *DAF* will result in a higher *DAF* (Appendix B), and may significantly increase the soil cleanup criterion.

When determining a site-specific *DAF* value, the length of the area of concern parallel to ground water flow, *L*, must be adjusted in all cases to reflect actual conditions. In addition, the calculated mixing zone depth cannot be greater than the aquifer thickness (see below). The following parameters may be modified in the *DAF* equation:

Length, L

Although the sensitivity of the remediation criterion to the size of the area of concern is small (see Appendix B), if an area of concern contains an *L* value significantly smaller than 100 feet (30.48 m), use of the site-specific value may yield a criterion slightly higher than when using default values. Use the following procedure:

- (1) Measure the length of the area of concern parallel to ground water flow.

- (2) Use the length to develop a site-specific mixing zone depth using Equation 2. If the calculated mixing zone depth is greater than the aquifer thickness (see below), set the mixing zone depth equal to the aquifer thickness.
- (3) Substitute the site-specific values for the mixing zone depth and L into the equation for the DAF (Equation 1).

Infiltration rate, I

The default infiltration rate is 11 inches/year, calculated for sandy loam soil (as described in the Basis and Background Document for the Inhalation Soil Remediation Standards). However, if site-specific infiltration rate data (i.e., ground water recharge data) are available, this information may be used. At this time, site-specific adjustment of infiltration rates is allowed only after consultation with the Department. The Department will not allow impermeable cover to be considered in the development of the infiltration rate. For example, paving, which may result in a reduced infiltration rate, would not be allowed to modify the infiltration rate.

Ground water velocity parameters (hydraulic conductivity, K and gradient, i)

Because K and i are closely linked parameters affecting ground water velocity they must be adjusted together. The DAF is approximately linear with respect to these two parameters. Use the following procedure:

- (1) Determine K and i from field measurements pursuant to the Technical Requirements for Site Remediation N.J.A.C. 7:26E-3.7(e)iv, N.J.A.C. 7:26E-4.4(h)3ii and N.J.A.C. 7:26E-4.4(h)3iii.
- (2) Measure the length (L) of the area of concern parallel to the ground water flow.

- (3) Substitute K , i , and L into the mixing zone equation (Equation 2) to determine a site-specific mixing zone depth. If the calculated aquifer mixing zone depth is greater than the aquifer thickness (see below), set the mixing zone depth equal to the aquifer thickness.
- (4) Substitute the site-specific values for K , i , L and the mixing zone depth into the equation for the dilution attenuation factor (Equation 1) to calculate a site-specific DAF .

Aquifer thickness, d_a .

This parameter influences the mixing zone depth, although its effect is minimal under the default scenario. If the actual aquifer depth for the site under investigation is known, a modified site-specific mixing zone depth, d , may be calculated. Use the following procedure:

- (1) Aquifer thickness shall be measured in the field by logging continuous core in accordance with the Department's Field Sampling Procedures Manual or shall be determined using available data from the New Jersey Geological Survey or the United States Geological Survey where available.
- (2) Measure the length (L) of the area of concern parallel to ground water flow.
- (3) Use the site-specific aquifer thickness and the actual length of the area of concern in the mixing zone depth equation (Equation 2) to calculate a site-specific mixing zone depth. If the calculated aquifer mixing zone depth is greater than the aquifer thickness, set the mixing zone depth equal to the aquifer thickness.
- (4) Use the calculated site-specific mixing zone depth, and the site-specific value for L in the DAF equation to calculate a site specific DAF (Equation 1).

Submission requirements

All input parameters used to determine the site-specific *DAF* value must be submitted to the Department. A spreadsheet is available from the NJDEP to calculate a site-specific *DAF* value. A hard copy and an electronic form of the spreadsheet should be submitted. The *DAF* Calculator spreadsheet is available at http://www.nj.gov/dep/srp/guidance/rs/daf_calc.xls

APPENDIX A

Determination of the Default Dilution-Attenuation Factor (DAF)

To determine a default Dilution Attenuation Factor (DAF) for New Jersey, default values for the variables in Equations 1 and 2 in this guidance document are necessary. The development of each of these values is discussed below. A comparison with the default values used by the USEPA in its Soil Screening Guidance Document (USEPA 1996) is also included.

Source (Area of Concern) Length Parallel to Ground Water Flow (L)

USEPA default value: 45 m (148 feet)

NJDEP default value: 30 m (100 feet)

This parameter is equivalent to the length of the Area of Concern (AOC) parallel to ground water flow and is an input parameter in calculating a *DAF*. The Department's value results in higher remediation criteria than if USEPA's value was used. The 100 feet source length was judged to be larger than most Areas of Concern in New Jersey, and therefore adequately protective. This is also approximately equal to the length of a high density residential lot size (¼ acre). The effect of source length on the calculated remediation standard is small (see Appendix B).

Thickness of Affected Aquifer (d_a)

USEPA: Monte Carlo Distribution

NJDEP: 3.5 m (11.5 ft)

The aquifer thickness is used in calculating the aquifer mixing zone depth, which in turn is used in calculating the *DAF*. For the site size selected, the calculated mixing zone is independent of the aquifer thickness if it is 3.5 m or greater. Since 3.5 m represents a relatively thin aquifer (11.5 ft), this value was considered to be adequately protective and used as the default value. Varying this parameter has no effect on the calculated remediation standard under the default scenario unless its thickness is less than 3.5 m.

Hydraulic conductivity (K) and gradient (i)

USEPA: Monte Carlo Distribution

NJDEP: $K \cdot i$ product (Darcy velocity) = 30m/yr (statistical study of Kirkwood Cohansey Aquifer System)

The product of these two parameters is the aquifer flow rate, and are considered together to determine a default aquifer flow rate. Data available for the Kirkwood-Cohansey aquifer in southern New Jersey was used. This 3,069 square mile aquifer is relatively shallow, lies underneath soils with considerable sand content, often exhibits low flow rates due to generally flat terrain. It also has the most field measurements of hydraulic conductivity (K) of all the formations in New Jersey, and represents a large percentage of the total area of the Coastal Plain physiographic province. Because it is extensive, and vulnerable to contamination, it was selected as an appropriate aquifer to develop an adequately protective, default aquifer flow rate for New Jersey.

A Geographic Information System (GIS) was used to determine a default aquifer flow rate for the Kirkwood-Cohansey aquifer. The approach involved multiplying hydraulic conductivity and aquifer slope data layers. A recent research project conducted by the Department's Division of Science, Research and Technology has resulted in the availability of a GIS grid data layer of hydraulic conductivity values for the Kirkwood-Cohansey aquifer over its entire area (Vyas et al., 2004). The layer was developed using 109 high quality measured values for hydraulic conductivity from water allocation pump tests. Values between the measured points were interpolated using Bayesian mapping techniques. Bayesian methods are a significant advance beyond kriging or Radial Basis Function methods because they are able to formally incorporate theoretical and empirical knowledge base information pertaining to ground water flow within the interpolation.

To obtain a hydraulic gradient data layer, two approaches were used. The first used a generally accepted procedure for the New Jersey coastal plain that assumes the hydraulic gradient is approximately equal to one-half the topographic surface gradient (Spayd and Johnson, 2003). The New Jersey Geological Survey has developed an extremely high quality topographic GIS

layer that based on a 10 meter grid. In this grid the area coincident with the Kirkwood-Cohansey aquifer contains over 77 million grid cells. The topographic grid was clipped to the Kirkwood-Cohansey boundary and the elevation values were translated into topographic slope values (decimal percent) using GIS conversions. The topographic slope values were then divided by 2 to obtain a hydraulic slope value in each grid cell. The grid cell size was then enlarged (number of cells reduced to 17 million) to enable processing with the horizontal conductivity grid layer. This approach has the advantages of 1) an extremely high quality input data set, and 2) generating slope values that are consistent relative to each other across the entire aquifer. A disadvantage is that the effect of groundwater pumping, which may affect the hydraulic gradient, is not considered.

In the second approach to calculate a hydraulic gradient, existing GIS contour files of groundwater elevations from 8 separate United States Geological Survey (USGS) watershed studies were edge matched together (Watt et al., 1994, 2003), Charles et al. (2001), Johnson and Charles (1997), Johnson and Watt (1996), Lacombe and Rosman (1995)). The mosaic line work was converted to a triangulated irregular network file (TIN), then converted to a grid file. The grid's water table elevation values were converted to slope values. This approach has the advantage of using actual measured water table elevations, which should reflect the effect of water table pumping. A disadvantage of this approach is the use of data points collected over 8 different time periods, 8 different input data densities, and 8 different levels of data quality. Because water table elevations vary with time, the consistency of these data points relative to each other is uncertain.

To determine the aquifer flow rate, the hydraulic conductivity grid layer was independently multiplied by each of the 2 hydraulic gradient grid layers. The aquifer flow rate based on the topographic slope yielded a mean, median and mode for the aquifer flow rate of 101, 51 and 1 m/yr. The second approach based on the USGS water table elevation grid layer yielded mean, median and mode values of 12, 9 and 2 m/yr.

Given that both methods for calculating the hydraulic gradient have significant advantages and disadvantages, that all summary values have been observed in the aquifer, and that neither

approach was clearly preferable; both were used to estimate a representative aquifer flow rate. The average of the two median values (51 and 9 m/yr) was used, which gives a Darcy flow rate of 30 m/yr. The median, rather than the mean, of each method was used since the mean may be overly influenced by outliers in the data sets while the median represents the mid point in the data. The remediation standard is approximately linear with respect to these two parameters (Appendix B).

Infiltration Rate (*I*)

USEPA: Monte Carlo Distribution

NJDEP: 0.28 meters/yr (11 inches/yr)

The infiltration rate corresponds to the rate of recharge of precipitation to the ground water. The infiltration rate is an input parameter for calculating a *DAF*. The infiltration rate was calculated for a default sandy loam soil and a New Jersey climate using a model from the New Jersey Geological Survey. See the Basis and Background Document for the Inhalation Soil Remediation Standards for further details.

Mixing Zone Depth (*d*)

USEPA: Monte Carlo Distribution

NJDEP: 3.5 m (11.5 ft)

The mixing zone depth corresponds to the depth to which the contaminant is diluted in ground water. It is calculated from the mixing zone depth equation (Equation 2) using several other field parameters. The mixing zone depth is then used in the *DAF* Equation (Equation 1). Using the default values for all of the parameters that are used in this equation, the default mixing zone depth is calculated to be 11.5 feet, which is equal to the default aquifer thickness. The parameter remains at this value under the default scenario even if the aquifer thickness is increased.

Sensitivity analysis was not conducted for this parameter, because its dependant parameters are incorporated in the sensitivity analysis for the *DAF* equation (Appendix B).

Dilution/Attenuation Factor (*DAF*)

USEPA value: 1 or 20

NJDEP value: 13

Substituting the parameters discussed above into Equations 1 and 2, a default dilution-attenuation factor of 13 was calculated.

It is of interest to compare the NJDEP default value with USEPA's values of 1 and 20 and to discuss the USEPA approach to determine their default factors. Nationally, *DAF* values for a half-acre site have been found to vary from 1 to several thousand (USEPA, 1996). To derive a default *DAF* value, the USEPA used a "weight of evidence" approach to derive its default attenuation factor of 20. This was based on two studies where attenuation factors were estimated or calculated.

In the first study, USEPA's Composite Model for Leachate Migration with Transformation Products (EPACMP) model was used to derive *DAF* values by running the model in the Monte Carlo mode. *DAF* distributions were generated using expected variations in the input parameters that are used in its calculation. While this approach has its advantages, it results in a nationwide distribution of *DAF* values that was judged to be inappropriate for New Jersey use, based on both technical and policy issues. Technically, many areas in New Jersey have sandy soil, a shallow water table, and relatively high infiltration rates relative to other parts of the country, particularly the western United States. These factors would tend to reduce the *DAF* relative to many other areas of the country. Regarding policy issues, *DAF* values were calculated at the location of a receptor well, which was varied in its location and was often outside the main body of the groundwater plume. If the well was outside the plume, a high *DAF* was calculated. This is incompatible with New Jersey policy, since the probability of a receptor well being outside of the plume is not considered in the New Jersey Ground Water Quality Standards. All groundwater is to be protected for potential potable uses. Therefore, the *DAF* should be calculated within the plume itself. Finally, the USEPA assumed a variable distance between the downgradient edge of the source and the receptor well. This is incompatible with the Ground Water Quality Standards (N.J.A.C. 7:9C), which require compliance at the down gradient edge of the source.

For these reasons, the USEPA Monte Carlo modeling approach using the EPACMP model was not appropriate for New Jersey.

In the second study, the USEPA used data from two large surveys of hydrogeological site investigations, and calculated *DAF* values using Equation (2). These surveys were the American Petroleum Institute's (API's) hydrogeologic database (HGDB) and USEPA's database of conditions at Superfund sites contaminated with DNAPL (USEPA 1996). Between these two databases, a total of 300 *DAF* calculations were made. The sites are classified according to hydrologic region in the United States. Two of these regions, the Northeast and Superior Uplands, and the Atlantic and Gulf Coast, include the area of New Jersey. The HGDB is the larger of the two databases and yielded 21 sites in the Uplands region and 19 sites in the Atlantic Coast region. The median *DAF* values calculated for these sites (0.5 acre site size) were 13 and 3, respectively. The DNAPL database yielded 50 sites in the Uplands region and 12 sites in the Atlantic Coast region, with median *DAF* values (0.5 acre site size) of 22 and 20, respectively. The DNAPL database results support the USEPA default *DAF* of 20; however none of the sites in the database were in New Jersey. The HGDB database does not indicate site location, but suggests that dilution factors for the two hydrogeologic regions should be significantly lower than 20.

New Jersey's default *DAF* of 13 is equal to the median *DAF* calculated for the Uplands from the HGDB database, is approximately four times higher than the coastal plain median HGDB *DAF* of 3, and about 40% lower than the *DAFs* calculated from the DNAPL database. Therefore, the New Jersey default *DAF* is compatible with the USEPA data.

APPENDIX B

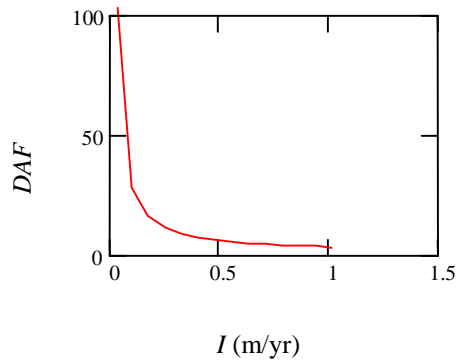
Sensitivity of the *DAF* to its Constituent Parameters

For this analysis, one variable was modified at a time, while the other chemical and environmental parameter values were set at default New Jersey values (see Basis and Background Document for the Inhalation Soil Remediation Standards). The examples below are for specific contaminants, but the observed sensitivities are the same for all contaminants.

1. Sensitivity of Dilution Attenuation Factor (*DAF*) to infiltration rate (*I*). Results shown for xylene.

DAF sensitivity is inversely proportional to infiltration rate, *I*. Mixing zone depth not constrained by aquifer thickness.

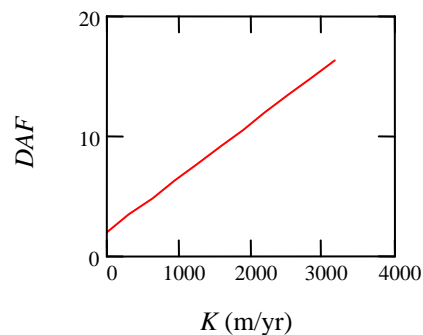
<i>I</i> (m/yr)	<i>DAF</i>
0.025	127
0.102	33
0.178	19.8
0.254	14.5
0.33	11.6
0.406	9.8
0.483	8.5
0.559	7.6
0.635	6.9
0.711	6.4
0.787	5.9
0.864	5.6
0.94	5.3
1.016	5



2. Sensitivity of dilution attenuation factor (*DAF*) to hydraulic conductivity (*K*). Results are shown for xylene.

DAF sensitivity is slightly less than linear with respect to conductivity, *K*. Mixing zone depth not constrained by aquifer thickness in this calculation.

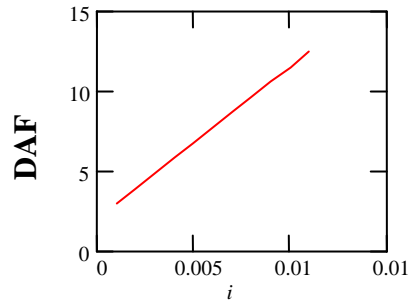
<i>K</i> (m/yr)	<i>DAF</i>
0.3	2
315	3.4
630	4.9
946	6.3
1261	7.7
1576	9.2
1891	10.6
2207	12
2522	13.4
2837	14.9
3152	16.3



3. Sensitivity of dilution attenuation factor (*DAF*) to gradient (*i*). Results are shown for xylene.

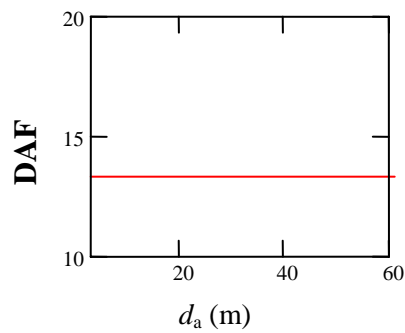
DAF sensitivity is slightly less than linear with respect to gradient, *i*. Mixing zone depth not constrained by aquifer thickness in this calculation.

<i>i</i>	<i>DAF</i>
0.001	3
0.002	3.9
0.003	4.9
0.004	5.8
0.005	6.8
0.006	7.7
0.007	8.7
0.008	9.6
0.009	10.6
0.01	11.6
0.011	12.5



4. Sensitivity of dilution attenuation factor (*DAF*) to aquifer thickness (d_a). Results shown for xylene.

Under default scenario, aquifer thickness has no affect on *DAF*.



5. Effect of size of area of concern on the *DAF*.

Results shown for xylene.

<i>DAF for xylene as a function of the size of the area of concern</i>			
	<i>Length of Site</i>		
	<i>Parallel to GW flow (m)</i>		
	<i>15.2</i>	<i>30.5</i>	<i>152</i>
Aquifer thickness = 3.5 m	13	13	3
Aquifer thickness = 15.2 m	13	13	12

Under default conditions, a lower *DAF* results when the site length becomes large. However, this effect is reduced when the aquifer thickness increases.

References

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