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DAF*fy* Graphs

An Innovative Approach for Modeling the Soil to Groundwater Pathway

With the availability of powerful desktop computers and state of the art groundwater fate and transport software, why would anyone want to model with a pencil, ruler and hand calculator? For many of us the answer might be "because it's easier!" The Graphical Approach for Determining Site-Specific Dilution Attenuation Factors (a.k.a. the DAF*fy* Graphs), developed by the American Petroleum Institute, distills complex contaminant fate and transport calculations into nomographs that are employed to make a simple calculation of contaminant dilution and attenuation. A key advantage of the DAFfy Graph approach is that it allows the user to quickly make estimates of dilution and attenuation with limited site-specific information and to perform more refined, less conservative estimates by accessing a few additional graphs. This approach also provides a unique visual indication of parameter sensitivity not easily gleaned from most numerical software simulators.

Why Were the DAF*fy* Graphs Created?

Dilution attenuation factors (DAFs) are useful for evaluating exposure to chemicals of concern via the soil to groundwater pathway because, depending on the objective, they can be used to a) estimate potential downgradient effects from known source concentrations or b) back calculate the maximum allowable source leachate concentration from an "action" concentration established at a receptor well or point of compliance. However, historical attempts to develop a "one size fits all" generic DAF for regulatory purposes have resulted in very conservative DAFs. These generic DAFs fail to reflect site-specific or chemical-specific characteristics that may result in additional attenuation of compounds of concern. The DAF*fy* Graph approach addresses this shortcoming by allowing the user (regulator or consultant) to develop a less conservative DAF utilizing site-specific information.

How Were the DAF*fy* Graphs Developed?

A number of mathematical solutions amenable to spreadsheet calculation were reviewed for their ability to handle time-varying sources and vertically averaged dissolved concentrations along a plume centerline. Graphs for sources at or below the water table ("submerged sources") were developed from a version of the Domenico (1987) equation, modified to incorporate aquifers of finite thickness and retarded solute transport due to sorption onto soil surfaces. For sources in the vadose zone, the Brooks and Corey (1964) soil characteristic model and standard advection equations were employed to model transport through the vadose zone via infiltrating water. The Horizontal Plane Source solution developed by Galya (1987) was used to simulate saturated zone transport for vadose zone sources. To develop the vadose zone source graphs, transport in the vadose and saturated zone is modeled independently, then coupled in a way that conserves mass across the vadose-saturated zone boundary. A rigorous discussion of these models and graph development are provided in the *Technical Background Document for The Graphical Approach for Determining Site-Specific Dilution Attenuation Factors* (1998).

How Is a DAF Calculated With the DAF*fy* Graphs?

With the aid of worksheets provided in the *User's Guide for The Graphical Approach for Determining Site-Specific Dilution Attenuation Factors (1998)* the user performs a few simple calculations to obtain some dimensionless parameters which are used to read factors from a series of graphs.

An initial DAF can be estimated using knowledge of the source geometry, location and well screen length of an existing or proposed downgradient receptor well, the aquifer thickness and dispersivity estimates [provided in the *User's Guide for The Graphical Approach for Determining Site-Specific Dilution Atten-*

What Is A Dilution Attenuation Factor?

Not all dilution attenuation factors (DAF) are the same. The processes accounted for by a DAF vary depending on how the DAF is defined and the model(s) used to develop the DAF. In the DAF*fy* Graph system, the DAF is defined as the ratio of the *initial* source leachate concentration divided by the maximum-time-average of the estimated well concentration at the point of interest, e.g., a receptor well. DAFs generated by the DAF*fy* Graphs system can account for:

- sources located in the vadose or saturated zone
- continuous or finite sources
- single component, multicomponent, residual or adsorbed sources
- biodegradation in the vadose or saturated zone

Models used to generate graphs for the DAF*fy* Graph system assume:

- all soil properties are homogeneous and constant with time
- all flows are steady and one-dimensional
- linear partitioning isotherms to describe sorbed-dissolved phase equilibrium
- all reactions follow first-order kinetics

uation Factors (1998)]. Thus, an initial DAF calculation based on dilution and dispersion between the source and receptor can be made with a modest amount of information about a site. This DAF estimate is easily refined by including factors for biodecay and a time-varying source obtained from additional graphs.

The DAF for a **submerged source** is obtained by multiplying four factors read from a series of easy to use graphs. The equation for calculating a submerged source DAF is

$$DAF = \frac{1}{< S_L^* > \times f \times g \times \left(h^*_{\text{inf}} + h^*_{cor}\right)}$$

where:

$<S_L^*>$	=	finite source factor (optional);
f	=	factor for longitudinal dispersion and attenuation due to biodecay or chemical reaction (optional);
g	=	factor for lateral spreading; and
$(h^*_{\text{inf}} + h^*_{cor})$	=	factor for vertical mixing.

The process for calculating a DAF for sources in the vadose zone is similar to that for a submerged source except for the inclusion of a few additional DAF factors obtained from addition graphs provided in the *User's Guide*. A DAF for a vadose zone source is calculated from the equation:

$$DAF = \frac{1}{< S_L^* > \times < f > \times \left(\frac{I_f}{\phi_s U_{GW}}\right) \times V \times \Omega \times \sigma}$$

where:

$<S_L^*>$	=	finite source factor (optional),
$<f>$	=	factor for longitudinal dispersion and attenuation due to biodecay or chemical reaction (optional),
I_f	=	time-averaged water infiltration rate per unit area,
ϕ_s	=	aquifer porosity,
U_{GW}	=	groundwater seepage velocity,
V	=	attenuation factor for vadose zone transport (optional),
Ω	=	attenuation factor for centerline concentrations at the groundwater table, and
σ	=	attenuation factor correction term for vertical averaging.

To make an initial DAF estimate when the source is in the vadose zone, one needs to know the:

- area of the source,
- aquifer thickness,
- distance from the source to the downgradient receptor well or point of compliance,
- length of the receptor well screen below the top of the water table,
- infiltration rate, and
- groundwater specific discharge ($\phi_s U_{GW}$).

If the user wishes to refine the initial DAF to include the effects of vadose and saturated zone biodegradation and finite source, additional graphs are utilized to obtain factors V, $< f >$, and $<S_L^*>$, respectively.

DAF and Time

As mentioned earlier, the DAF reflects the maximum time averaged concentration seen at the receptor well. However, it does not provide any information about when this maximum concentration will occur, especially under conditions where:

- groundwater moves very slowly,
- the distance from the source to the receptor is large,
- infiltration rates are low,
- the distance from the source to the groundwater is very large, or
- compounds are strongly sorbing.

The expected travel time between the source and receptor may be decades, even centuries. Because of this, a formula is provided to estimate the travel time (in years) necessary for chemical migration from the source to the receptor location.

DAF*FY* Graphs in Action

Consider the following situation: A regulatory agency and a responsible party wish to develop DAF values for an underground storage tank (UST) release site. A schematic of the site is shown below in Figure 1.

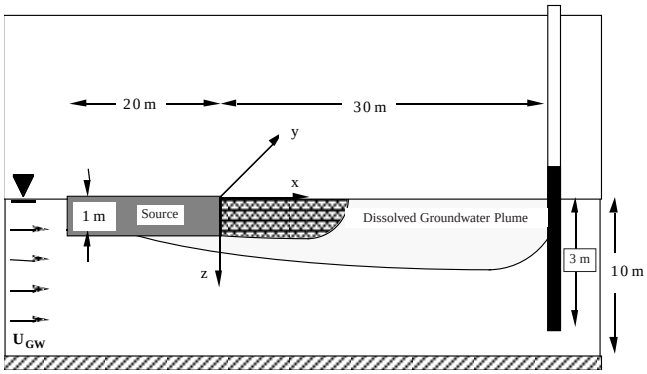

Figure 1. *Schematic of submerged source zone example problem (not to scale).*

Initial DAF Estimate

The responsible party's consultant has conducted a site characterization and determined site-specific values for the following parameters:

b	=	aquifer thickness = 10m
H	=	thickness of source zone below the groundwater table (assumed to start at the groundwater table and extend downward a distance H) = 1m
H_W	=	well screen thickness (assumed to start at the groundwater table and extend downward a distance) = 3m
L_R	=	distance to the receptor (i.e., distance to neighboring property boundary) measured from the down gradient source edge = 30m
U_{GW}	=	linear groundwater velocity = 0.1m/d
W	=	source zone width perpendicular to flow in y-direction = 20m

With only this minimal data set, the graphical approach can be used to generate an initial DAF estimate, provided that the following standard estimates of dispersivities are acceptable:

$$\alpha_L = L_R/10,\ \alpha_T = L_R/30,\ \alpha_V = L_R/100$$

where:

α_L = the longitudinal (x-direction) dispersivity [m]
α_T = the transverse (y-direction) dispersivity [m]
α_V = the vertical (z-direction) dispersivity [m]

The equation for a submerged source DAF is:

$$DAF = \frac{1}{< S_L^* > \times f \times g \times \left(h^*_{inf} + h^*_{cor}\right)}$$

In making the initial DAF estimate, source decay ($<S_L^*>$) and aerobic biodegradation (f) are being neglected; therefore, the value for each is = 1. Consulting the *User's Guide for Graphical Approach for Determining Site-Specific Dilution Attenuation Factors*, the only parameter groups that need to be calculated to find factors g and ($h^*_{inf} + h^*_{cor}$) are:

$$\frac{W}{\sqrt{\alpha_T L_R}} = \frac{20\ m}{\sqrt{(30\ m/30)(30\ m)}} = 3.7$$

$$\frac{\sqrt{\alpha_V L_R}}{H} = \frac{\sqrt{(30\ m/100)(30\ m)}}{1\ m} = 3.0$$

$$\frac{H}{H_W} = \frac{1\ m}{3\ m} = 0.3$$

$$\frac{\sqrt{\alpha_V L_R}}{b} = \frac{\sqrt{(30\ m/100)(30\ m)}}{10\ m} = 0.3$$

$$\frac{H}{b} = \frac{1\ m}{10\ m} = 0.1$$

Given these, g and ($h^*_{inf} + h^*_{cor}$) are obtained from Figures 2-4:

$<S_L^*>$ = 1 (source depletion is being neglected at this point)
f = 1 (biodegradation is being neglected at this point)
g ≈ 0.8
h^*_{inf} ≈ 0.18
h^*_{cor} = negligible compared to h^*_{inf} ($h^*_{cor} << 0.18$)

and therefore the initial DAF estimate is:

$$DAF = \frac{1}{1 \times 1 \times 0.8 \times 0.18} = 7$$

As an indication of the magnitude of the uncertainty associated with reading values from the graphs, the actual computed values are: g = 0.83, h^*_{inf} = 0.17, and DAF = 7.1.

Note that the initial DAF estimate was generated after specifying only the geometry of the problem (source width, thickness, distance to receptor, etc.). Thus, the graphical approach can be used when minimal data are available. An illustration is given of how initial estimates can be refined when more site-specific information is available.

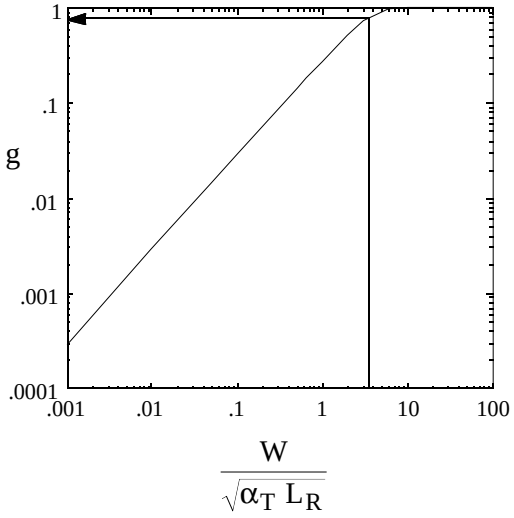

Figure 2. *Illustration of g-value determination from the graphs for the source zone example. In this case* $g \approx 0.8$.

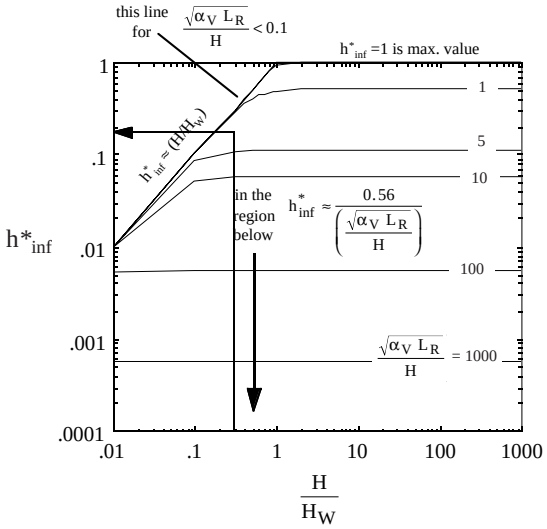

Figure 3. *Illustration of h^*_{inf} value determination from the graphs for the source zone example. In this case* $(H/H_W)=0.3$, $(\alpha_V L_R/H^2)^{1/2}=3$, *and* $h^*_{inf} \approx 0.18$. *While a contour line for* $(\alpha_V L_R/H^2)^{1/2}=3$ *is not given in the figure, the estimation equation contained in the figure yields a reasonable estimate for* h^*_{inf}.

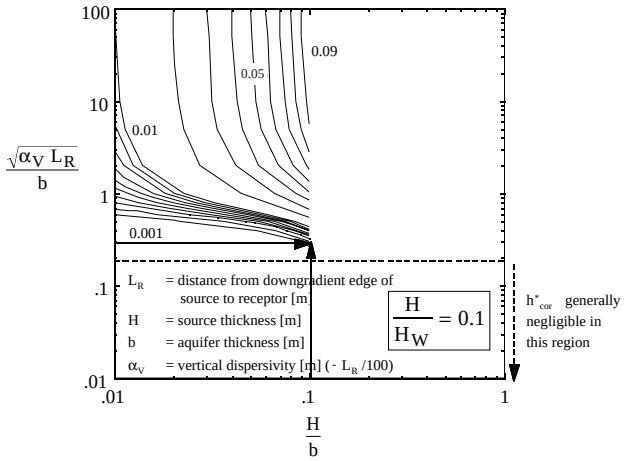

Figure 4. *Illustration of h^*_{cor}-value determination from the graphs for the source zone example. In this case* $(H/H_W)=0.3$, $(\alpha_V L_R/b^2)^{1/2}=0.3$, $H/b=0.1$, *and* $h^*_{cor} \approx 0.003$.

Refined DAF Estimate

Suppose that, for the specific site used in the previous calculations, the agency and responsible party wish to refine the generic DAF estimate. Recall that both biodegradation and source zone decay were neglected above, and both could be included when refining the DAF value. However, upon examination of the graphs for biodegradation and source zone decay, it is apparent that accounting for biodegradation has the potential to more significantly impact the DAF estimate than accounting for a depleting source. Furthermore, focusing on biodegradation also requires the collection of fewer additional parameters (as the source decay rate depends on many other parameters).

At this particular site the groundwater velocity has been estimated to be U_{GW}=0.1 m/d based on the water level measurements (to obtain the hydraulic gradient) and aquifer testing (to obtain the hydraulic conductivity).

Groundwater monitoring data (primarily dissolved oxygen concentrations) suggest that aerobic biodegradation is occurring at this site, although a specific rate has not been determined. The peer-reviewed literature suggests that apparent first-order degradation rates β_s for aromatic hydrocarbons typically fall in the range 0.001 - 0.01 d^{-1}, and the agency agrees to permit the responsible party to calculate a range of refined DAF values, from which a final value will be chosen after sufficient compliance monitoring data have been collected.

In calculating the refined estimate, the values of the functions **g** and **h*** do not change. The value of **f** (which was taken to be **f**=1 when biodegradation was neglected) is obtained by first calculating the parameter group (described in the *User's Guide*):

$$0.03 \le \frac{\beta_s \, \alpha_L}{U_{GW}} \le 0.3$$

which leads to the following range of **f** values:

$$0.7 \le f \le 0.09$$

Figure 5 illustrates how values of **f** are obtained from the graph.

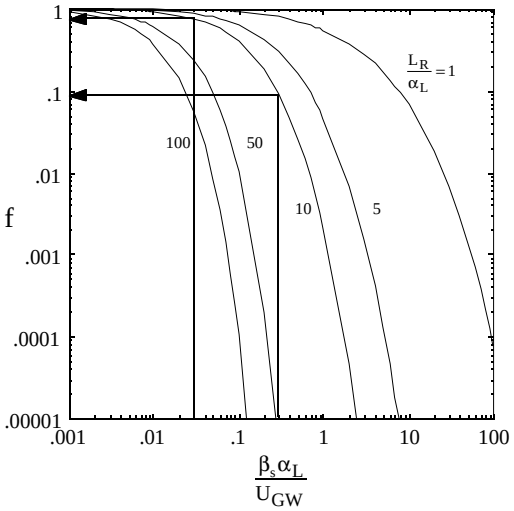

Figure 5*. Use of the graphical approach for obtaining f values. In this case* L_R/α_L=10, $\beta_s\alpha_L/U_{GW}$ = 0.03 and 0.3, and f =0.7 and 0.09.

Using the submerged source DAF equation, this leads to the following range of refined DAF estimates:

$$\frac{1}{1 \times 0.7 \times 0.8 \times 0.18} \le \text{DAF} \le \frac{1}{1 \times 0.09 \times 0.8 \times 0.18}$$

or:

$$10 \le \text{DAF} \le 77$$

Again, as an indication of the magnitude of the uncertainty associated with reading values from the graphs, the actual computed values are: 9 ≤ DAF ≤ 70.

These results illustrate the sensitivity of the DAF results to changes in the parameter group ($\beta_s\alpha_L/U_{GW}$). Had the distance to the receptor been larger (increasing α_L), or the groundwater velocity slower, the impact of including/neglecting biodegradation would have been even more significant.

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Johnson, P.C., R.J. Charbeneau, D. Abranovic, T. Hemstreet. 1998. *Graphical Approach for Determining Site-Specific Dilution-Attenuation Factors (DAFs) User's Guide*. API Publication 4659. American Petroleum Institute. Washington D.C.

API Publication 4659, *Graphical Approach for Determining Site-Specific Dilution Attenuation Factors* contains a *User's Guide* and a *Technical Background Document.* The *User's Guide* contains step-by-step instructions for performing calculations and using the system graphs. Worksheets and graphs are printed on loose leaf paper for ease of use. The *Technical Background Document* describes, in detail, the theoretical basis for the DAF*fy* Graph system. It also contains example problems applying the graphical approach, an extensive data and parameter selection guide, in-depth information on source depletion options, and supplemental graphs for some system parameters.

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