AERMOD Deposition Algorithms – Science Document (Revised Draft)

This Science Document describes the equations used to implement the dry and wet deposition algorithms contained in the AERMOD model, based on the draft Argonne National Laboratory (ANL) report (Wesely, et al., 2001), with modifications based on peer review. Treatment of wet deposition is revised based on recommendations by peer review panel members (Walcek, et al., 2001).

The dry deposition algorithms are described first, followed by the wet deposition algorithms. Within each type of deposition, the particle mode deposition is described first followed by the algorithms for gaseous deposition.

Dry Deposition Algorithms

The dry deposition flux, F_d, is calculated as the product of the concentration, χ_d, and a deposition velocity, V_d, computed at a reference height, z_r:

$$F_d = \chi_d \cdot V_d \tag{1}$$

where

F_d = dry deposition flux ($\mu g/m^2/s$),
χ_d = concentration ($\mu g/m^3$), calculated at reference height, z_r,
V_d = deposition velocity (m/s),
z_r = deposition reference height (m) = $z_o + 1$, and
z_o = surface roughness length for the application site (m), from the meteorological file.

The dry deposition flux is calculated on an hourly basis, and summed to obtain the total flux for the user-specified period. The default output units for dry deposition flux are g/m^2.

Particle Dry Deposition

The dry deposition velocities of particulate HAPs are simulated with a resistance scheme in which the deposition velocity is determined based on the predominant particle size distribution, as described below:

Method 1:

Method 1 is used when a significant fraction (greater than about 10 percent) of the total particulate mass has a diameter of 10 μm or larger. The particle size distribution must be known reasonably well in order to use Method 1. Equation 1 is applied for each particle size category specified by the user, and the results are summed by the model.

The particle deposition velocity, V_{dp}, for Method 1 is given as,

$$V_{dp} = \frac{1}{R_a + R_p + R_a R_p V_g} + V_g \qquad (2)$$

where

V_{dp} = deposition velocity for particles (m/s),
R_a = aerodynamic resistance (s/m),
R_p = quasilaminar sublayer resistance (s/m), and
V_g = gravitational settling velocity for particles (m/s).

The aerodynamic resistance, R_a, is calculated as follows:

for stable and neutral conditions $(L > 0)$,

$$R_a = \frac{1}{(ku_*)}\left[\ln\left(\frac{z_r}{z_o}\right) + \frac{5z_r}{L}\right] \qquad (3a)$$

for unstable conditions $(L < 0)$,

$$R_a = \frac{1}{(ku_*)}\left[\ln\frac{\left(\sqrt{1 - 16\frac{z_r}{L}} - 1\right)\left(\sqrt{1 - 16\frac{z_o}{L}} + 1\right)}{\left(\sqrt{1 - 16\frac{z_r}{L}} + 1\right)\left(\sqrt{1 - 16\frac{z_o}{L}} - 1\right)}\right] \qquad (3b)$$

where

k = von Karman constant (0.4),
u_* = friction velocity (m/s) from the meteorological file, and
L = Monin-Obukhov length scale (m) from the meteorological file.

For Method 1, the quasilaminar sublayer resistance, R_p, is calculated as follows:

$$R_p = \frac{1}{(Sc^{-2/3} + 10^{-3/St})(1 + 0.24w_*^2 / u_*^2)u_*} \qquad (4)$$

where

Sc = Schmidt number $(Sc = \upsilon/D_B)$ (dimensionless),
υ = kinematic viscosity of air $(\approx 0.1505 \times 10^{-4}$ m^2/s, and corrected below),
D_B = Brownian diffusivity (cm^2/s) of the pollutant in air,
St = Stokes number $[St = (V_g/g)(u_*^2/\upsilon)]$ (dimensionless),
g = acceleration due to gravity (9.80616 m/s^2), and
w_* = convective velocity scale (m/s) from the meteorological file.

The kinematic viscosity of air (υ) used in Equation 4 is corrected based on the hourly ambient air temperature and pressure as follows:

$$\upsilon = 0.1505 \times 10^{-4} \left(\frac{T_a}{T_0} \right)^{1.772} \left(\frac{P}{P_0} \right) \left[1 + 0.0132 \, (P - P_0) \right] \tag{5}$$

where

T_a	=	ambient air temperature (K) from the meteorological file,
T_0	=	reference air temperature = 273.16 K,
P	=	ambient air pressure (kPa) from the meteorological file, and
P_0	=	reference pressure = 101.3 kPa.

The Brownian diffusivity of the pollutant, D_B (cm^2/s) is computed from the following relationship:

$$D_B = 8.09 \times 10^{-10} \left[\frac{T_a \, S_{CF}}{d_p} \right] \tag{7}$$

where

d_p	=	particle diameter input by user (μm), and
S_{CF}	=	slip correction factor (dimensionless), which is computed as:

$$S_{CF} = 1 + \frac{2x_2 (a_1 + a_2 e^{-(a_3 d_p / x_2)})}{10^{-4} d_p} \tag{9}$$

where x_2, a_1, a_2, a_3 are constants with values of 6.5 x 10^{-6}, 1.257, 0.4, and 0.55 x 10^{-4}, respectively.

The gravitational settling velocity, V_g (m/s), is calculated as follows:

$$V_g = \frac{(\rho - \rho_{AIR}) g \, d_p^2 \, c_2}{18\mu} S_{CF} \tag{8}$$

where

ρ	=	particle density input by user (g/cm^3),
ρ_{AIR}	=	air density ($\approx$ 1.2 x 10^{-3} g/cm^3),
μ	=	absolute viscosity of air ($\approx$ 1.81 x 10^{-4} g/cm/s), and
c_2	=	air units conversion constant (1.0 x 10^{-8} cm^2/μm^2).

Method 2:

Method 2 is used when the particle size distribution is not well known and when a small fraction (less than 10 percent of the mass) is in particles with a diameter of 10 μm or larger. The deposition velocity for Method 2 is given as the weighted average of the deposition velocity for particles in the fine mode (i.e., less than 2.5 μm in diameter) and the deposition velocity for the coarse mode (i.e., greater than 2.5 μm but less than 10 μm in diameter):

$$V_{dp} = f_p V_{dpf} + (1 - f_p) V_{dpc} \tag{10}$$

where

V_{dp} = overall particle deposition velocity (m/s),
f_p = fraction of particulate substance that is fine mode (smaller than 2.5 μm in diameter),
input by the user from Appendix B of ANL report (Wesely, et al., 2001),
V_{dpf} = deposition velocity (m/s) of fine particulate substance, calculated from Equation 2
with V_g set to zero; $V_{dpf} = \dfrac{1}{R_a + R_p}$, and
V_{dpc} = deposition velocity (m/s) of coarse particulate substance, calculated from Equation 2
with $V_g = 0.002$ m/s; $V_{dpc} = \dfrac{1}{R_a + R_p + 0.002 R_a R_p} + 0.002$

For Method 2, the aerodynamic resistance is calculated using Equation 3, and the quasilaminar sublayer resistance, R_p, is calculated with parameterizations based on observations of sulfate dry deposition. For stable and neutral conditions (L > 0),

$$R_p = \frac{500}{u_*} \tag{11a}$$

for unstable conditions (L < 0),

$$R_p = \frac{500}{u_*\left(1 - \dfrac{300}{L}\right)} \tag{11b}$$

Gaseous Dry Deposition

For dry deposition of gases, the deposition velocity is given as,

$$V_{dg} = \frac{1}{R_a + R_b + R_c} \tag{12}$$

where

V_{dg} = deposition velocity for gases (m/s),
R_a = aerodynamic resistance (s/m),
R_b = quasilaminar resistance for bulk surface (s/m), and
R_c = bulk surface resistance (s/m).

The aerodynamic resistance, R_a, for gases is calculated the same as for particles using Equation 3, except that a lower limit of 1000 s/m is applied to R_a for gases if the surface is wetted by dew. The criterion for when a surface is wetted by dew is described below by Equation 26.

   The quasilaminar sublayer resistance for bulk surface, R_b, is calculated as follows:

$$R_b = \frac{2.2}{(ku_*)}\left(\frac{\upsilon}{D_a}\right)^{2/3} \tag{13}$$

where

D_a = diffusivity of modeled gas in air (m^2/s) input by user from Appendices in the ANL report (Wesley et al., 2001).

   The bulk surface resistance, R_c, is calculated as follows:

$$R_c = \frac{1}{\left[\dfrac{LAI_r}{(R_s + R_m)} + \dfrac{LAI_r}{R_{cut}} + \dfrac{1}{(R_{ac} + R_g)}\right]} \tag{14}$$

where

LAI_r = relative leaf area index (dimensionless),
R_s = canopy stomatal resistance (s/m),
R_m = canopy mesophyll resistance (s/m),
R_{cut} = canopy cuticular resistance (s/m),
R_{ac} = aerodynamic resistance in the vegetative canopy (s/m), and
R_g = resistance to uptake at the ground (s/m).

The aerodynamic resistance in the vegetative canopy, R_{ac}, is calculated as follows:

$$R_{ac} = 0.3\frac{R_{aci}}{u_*} \tag{15}$$

where

R_{aci} = aerodynamic resistance (s/m) in the vegetative canopy based on land use type (from

Table 1) and obtained from Table 2.

The relative leaf area index is calculated as follows, based on land use type (from Table 1) and season (defined below):

$$LAI_r = F \quad \text{for land use types 4 and 6 (forests), and} \tag{16a}$$

$$LAI_r = F^{0.5} \quad \text{for all other land use types.} \tag{16b}$$

F depends on the user specified seasonal category, based on the following general characteristics:

1. Midsummer with lush vegetation
2. Autumn with unharvested cropland
3. Late autumn after frost and harvest, or winter with no snow
4. Winter with snow on the ground
5. Transitional spring with partial green coverage or short annuals

$F = 1$ for categories 1, 3, and 4

F is set to the user input value for categories 2 and 5, or to the default values of:
$F = 0.5$ for category 2, and
$F = 0.25$ for category 5.

The canopy stomatal resistance, R_s, is calculated as follows:

$$R_s = R_i \left(\frac{D_v}{D_a} \right) \frac{1}{(f_1 f_2 f_3 f_4)} \tag{17}$$

where

R_i = minimum stomatal resistance (s/m) from Table 2,
D_v = diffusivity of water vapor in air (0.219×10^{-4} m^2/s),
f_1 = multiplicative scaling factors for solar irradiance (dimensionless),
f_2 = multiplicative scaling factor for soil moisture (dimensionless),
f_3 = multiplicative scaling factor for humidity (dimensionless), and
f_4 = multiplicative scaling factor for temperature (dimensionless).

The multiplicative scaling factor for solar irradiance, f_1, is calculated as follows:

$$f_1 = \frac{(G / G_r + 0.01)}{(G / G_r + 1)} \tag{18}$$

where

G_r =   30 W/m^2 for forests and 100 W/m^2 for other land use types, and
G =   solar irradiance (W/m^2) from the meteorological file,

with the limit that $0.01 \leq f_1 \leq 1$.

The multiplicative scaling factor for soil moisture, f_2, is calculated as follows:

$$f_2 = \theta_r = \frac{w_h}{200} \tag{19}$$

where

θ_r =   extractable soil moisture (dimensionless), and
w_h =   available root zone water for the current hour (mm),

with the limit that $f_2 \geq 0.01$. The available root zone water, w_h, is calculated as:

$$w_h = w_{h-1} + P_{h-1} - 0.5 f_2 \frac{e_s(T_a)}{e_s(25)} \tag{20}$$

where

w_{h-1} =   available root zone water for the preceding hour; w_{h-1} = 180 mm for first hour of model run,
P_{h-1} =   precipitation rate (mm/h) for preceding hour, from the meteorological file,
$e_s(T_a)$ =   saturation vapor pressure (kPa) for ambient temperature,
$e_s(25)$ =   saturation vapor press (kPa) for T_a = 25 °C, equal to 3.167 kPa, and
f_2 = f_2 from previous time step; f_2 = 0.9 for first hour of model run.

For ambient temperatures above T_0, the saturation vapor pressure, e_s, is calculated as a function of ambient temperature, as follows:

$$e_s = 0.6112 \, e^{(19.83 - 5417.4/T_a)} \tag{21}$$

The multiplicative scaling factor for humidity, f_3, is calculated as follows:

$$f_3 = \frac{1}{(1 + \alpha \, \delta e)} \tag{22}$$

where

δe =   vapor pressure deficit (kPa) = $\left(\frac{100 - RH}{100} \right) \times e_s(T_a)$,

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RH   =   relative humidity (percent) from the meteorological file, and

α   =   coefficient $= 0.1$ kPa^{-1},

with the limit that $f_3 \geq 0.01$.

The multiplicative scaling factor for temperature, f_4, is calculated as follows:

$$f_4 = 1 - 0.0016\,(298.0 - T_a)^2 \tag{23}$$

with the limit that $f_4 \geq 0.01$.

The bulk canopy leaf mesophyll resistance, R_m (s/m) in Equation 14, is calculated as follows:

$$R_m = \frac{1}{\left(\dfrac{0.034}{H} + 100 f_o\right)} \tag{24}$$

where

H =   Henry's Law Constant input by user (Pa-m^3/mol),
f_o =   reactivity factor (dimensionless), and is equal to:
      1.0 for ozone, titanium tetrachloride, and divalent mercury,
      0.1 for nitrogen oxide, and
      0 for other substances.

The canopy cuticular resistance, R_{cut}, is calculated as follows:

$$R_{cut} = \frac{1}{\left[\dfrac{10^{-3}}{(H\,R_{cS})} + \dfrac{(f_o + f_o^2 \,/\, H)}{R_{cO}} + \dfrac{1}{R_{cl}}\right]} \tag{25}$$

where

R_{cS} =   resistance to SO$_2$ uptake by cuticle (s/m), from Table 2 if dry, and is equal to 50 s/m if canopy is wetted by rain or dew,
R_{cO} =   resistance to O$_3$ uptake by cuticle (s/m), from Table 2 if dry, and is equal to 0.75 times R_{cO} from Table 2 if canopy is wetted by rain or dew, and
R_{cl} =   bulk canopy cuticular resistance (s/m) by lipid solubility, defined below.

The surface is assumed to be wetted by rain if precipitation occurs within the previous two hours. However, the adjustments to R_{cS} and R_{cO} for wetted surface are not applied if the seasonal category is 4 (winter with snow), the precipitation code for the current hour indicates frozen precipitation, and the ambient temperature is below freezing.

The surface is assumed to be wetted by dew if the following condition is satisfied during the hours between 8pm and 7am Local Standard Time (LST) (inclusive):

$$u_* < \frac{f_c}{\delta q} \tag{26}$$

where

f_c = factor based on cloud cover and is equal to:
  0.45 when the cloud cover fraction is less than 2/8,
  0.30 when the cloud cover fraction is between 2/8 and 6/8,
  0.15 when the cloud cover fraction is greater than 6/8, and
δq = the specific humidity deficit (g/kg).

The specific humidity deficit is calculated as the difference in the specific humidity at saturation and the specific humidity at ambient conditions ($\delta q = q_{sat} - q$). The specific humidity, q (g/kg), is calculated at follows:

$$q = 10^3 \left(\frac{0.622 \, e_s \, (RH/100)}{P - 0.378 \, e_s \, (RH/100)} \right) \tag{27}$$

where e_s is calculated according to Equation 21, and q_{sat} is calculated by setting $RH = 100$.

In order to push the resistances to high values if there is a hard freeze, the values of R_{cS} and R_{cO} used in Equation 25 are modified by adding the following term, R_x:

$$R_x = 1000 \, e^{(-T_a + 269.2)} \tag{28}$$

The bulk canopy cuticular resistance by lipid solubility, R_{cl}, is calculated as follows:

$$R_{cl} = \frac{r_{cl}}{(LAI_r \, S)} + R_x \tag{29}$$

where

r_{cl} = leaf cuticular resistance to lipid uptake input by user (s/m) from Appendices in ANL report (Wesely, et al., 2001), and
S = scaling factor by land use category from Table 3,

with the limit that $R_{cl} \geq 100$ s/m.

The ground resistance, R_g in Equation 14, is calculated as follows:

$$R_g = \cfrac{1}{\left[\cfrac{10^{-3}}{\left(H\,R_{gS}\right)} + \cfrac{(f_o + 0.1f_o^2 \,/\, H)}{R_{gO}}\right]} \tag{30}$$

where

R_{gS} = resistance to SO_2 uptake by ground (s/m), from Table 2 if dry, and is equal to 50 s/m if canopy is wetted by rain or dew, and

R_{gO} = resistance to O_3 uptake by ground (s/m), from Table 2.

As with the cuticular resistances in Equation 25, in order to push the ground resistances to a high value if there is a hard freeze, the values of R_{gS} and R_{gO} used in Equation 30 are modified by adding the term R_x, calculated from Equation 28. In addition, the adjustment to R_{gS} for wetted surface is not applied if the seasonal category is 4 (winter with snow), the precipitation code for the current hour indicates frozen precipitation, and the ambient temperature is below freezing.

Wet Deposition Algorithms

Particle Wet Deposition Flux

The wet deposition flux for particulate substances, F_{wp}, is calculated from the particle-phase washout coefficient as follows:

$$F_{wp} = 10^{-3}\,\rho_p\,W_p\,r \tag{31}$$

where

F_{wp} = flux of particulate matter by wet deposition ($\mu g/m^2/hr$),
ρ_p = column average concentration of particulate in air ($\mu g/m^3$),
W_p = particle washout coefficient (dimensionless), and
r = water or water equivalent precipitation rate (mm/hr), from the meteorological file.

The wet deposition flux is calculated on an hourly basis, and summed to obtain the total flux for the user-specified period. The default output units for wet deposition flux are g/m^2. The constant of 10^{-3} is a conversion factor to convert the precipitation rate units from mm/hr to m/hr.

The column average concentration, ρ_p, is calculated by integrating the vertical term for the Gaussian plume equation for each particle size category, V_j, over all heights (z), such that

$$\int_0^{z_p} \left(\frac{V_j}{\sigma_z}\right) dz = \sqrt{2\pi} \tag{32}$$

where

V_j = Gaussian vertical term for particle size category j,

σ_z = vertical dispersion coefficient (m), and

z_p = height of the top of plume or mixing height, whichever is greater (m).

The height of the top of the plume used to define z_p is calculated as the plume centerline height plus 2.15 times σ_z, evaluated at a downwind distance of 20 kilometers. The integrated vertical term from Equation 32 is then multiplied by the other terms in the Gaussian plume equation that do not vary with height, including the emission rate and lateral dispersion term, to obtain the vertically integrated concentration. Dividing by the height of the vertical column, z_p, then provides the column average concentration.

The particle washout coefficient, W_p, is calculated as follows:

$$W_p = \frac{3z_p E}{2D_m} \tag{33}$$

where,

E = collision efficiency (dimensionless), and

D_m = mean diameter of raindrop (m) = $r^{0.232}/905.5$ with r in mm/hr.

It is assumed that the washout coefficient, W_p, and therefore the wet deposition flux, F_{wp}, is the same for frozen precipitation as for liquid precipitation.

The collision efficiency, E, is calculated as follows, based on Slinn (1984) and Seinfeld and Pandis (1998):

$$E = \frac{4}{R_e Sc}\left[1 + 0.4R_e^{1/2}Sc^{1/3} + 0.16R_e^{1/2}Sc^{1/2}\right] + 4\phi\left[\frac{\mu}{\mu_w} + \phi\left(1 + 2R_e^{1/2}\right)\right] + \left(\frac{\rho_w}{\rho}\right)^{1/2}\left(\frac{St - S^*}{St - S^* + \frac{2}{3}}\right)^{3/2} \tag{34}$$

where,

R_e = Reynolds number of raindrop (aV_{fall}/υ) (dimensionless),

V_{fall} = precipitation fall speed (m/s) = $3.75\, r^{0.111}$, with r in mm/hr,

N   = ratio of particle diameter to raindrop diameter = d_p/D_m,

μ_w = viscosity of water (≈ 1.0 x 10^{-2} g/cm/s),

ρ_w = density of water = 10^6 g/m^3,

St = Stokes number of collected particle [$St = (V_g/g)(V_{fall}\text{-}V_g)/a)$] (dimensionless), and

S^* = critical Stokes number (dimensionless), calculated as:

$$S^* = \frac{1.2 + \frac{1}{12}\ln(1 + R_e)}{1 + \ln(1 + R_e)} \tag{35}$$

Gaseous Wet Deposition Flux

The wet deposition flux for gases, F_{wg}, is calculated as follows:

$$F_{wg} = 10^6 C_l M_w r \tag{36}$$

where

F_{wg} = flux of gaseous pollutants by wet deposition ($\mu g/m^2/hr$),
C_l = concentration of pollutant in the liquid phase (moles/liter), and
M_w = molecular weight of pollutant (grams/mole).

The wet deposition flux is calculated on an hourly basis, and summed to obtain the total flux for the user-specified period. The default output units for wet deposition flux are g/m^2. The constant of 10^6 is a combined conversion factor to convert the precipitation rate units from mm/hr to m/hr, to convert volume from liters to m^3, and to convert from μg to grams. As with particle wet deposition, the wet deposition flux for gases is assumed to be the same for frozen and liquid precipitation.

The concentration of pollutant in liquid phase, C_l, is calculated based on the saturated concentration, C_{lsat}, and the fraction of saturation, f_{sat}:

$$C_l = f_{sat} C_{lsat} \tag{37}$$

where

f_{sat} = fraction of saturation (dimensionless), and
C_{lsat} = concentration of pollutant in liquid phase at saturation (moles/liter).

The pollutant concentration in liquid phase at concentration, C_{lsat}, is calculated as follows:

$$C_{lsat} = \frac{\rho_g R T_a}{H M_w 10^9 \left[1 + \dfrac{L_w R T_a}{\rho_w H} \right]} \tag{38}$$

where

ρ_g = column average concentration of gaseous pollutant in air ($\mu g/m^3$),
R = universal gas constant = 8.3145 Pa-m^3/mole-K,
L_w = liquid water content of falling rain (g/m^3) = $r^{0.889}/13.28$, with r in mm/hr.

The column average concentration in air, ρ_g, is calculated the same as for particles using Equation 32. The constant of 10^9 is a combined unit conversion factor to convert from µg to grams, and from liters to m^3. The fraction of saturation, f_{sat}, is calculated as follows:

$$f_{sat} = MIN\left(1, \frac{t_{res}}{t_{abs}}\right)$$

(39)

where

t_{res} = residence time of rain drops in the plume or boundary layer (s),
t_{abs} = time for rain drops to become saturated (absorption time) (s).

The rainfall drop's residence time in the plume or boundary layer is given by

$$t_{res} = \frac{z_p}{V_{fall}}$$

(40)

where

V_{fall} = precipitation fall speed (m/s) = $3.75 \, r^{0.111}$, with r in mm/hr.

The absorption time scale, t_{abs}, is calculated as follows:

$$t_{abs} = \frac{\left[\dfrac{a^2 R T_a}{3 H D_a f_g} + \dfrac{4a \, R T_a}{3 H v \alpha_s} + \dfrac{a^2 \, 0.17}{3 D_w f_l}\right]}{\left[1 + \dfrac{L_w \, R T_a}{\rho_w \, H}\right]}$$

(41)

where

a = rain drop radius (cm), equal to $r^{0.232}/18.11$, with r in mm/hr,
f_g = gas-side diffusion-enhancement factor (dimensionless), equal to $80a+1$,
v = gaseous molecular velocity (~50,000 cm/s),
α_s = sticking coefficient (dimensionless) = 0.01,
D_w = liquid-phase molecular diffusion coefficient input by user (cm^2/s), from Appendices in ANL report (Wesely, et al., 2001), and
f_l = liquid-side diffusion-enhancement factor (dimensionless),
       1.0 for drops with a radius less than 0.01 cm,
       2.6 for drops with a radius between 0.01 and 0.05 cm (inclusive), and
       20.0 for drops with a radius greater than 0.05 cm.

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Dry Depletion (Removal)

The dry deposition of pollutants at the surface, whether particle or gaseous, will result in removal of pollutant mass from the plume as the plume travels downwind from the source. This removal process is referred to as dry depletion, and will act to reduce ground-level concentrations and deposition fluxes. The dry depletion algorithm in AERMOD is based on the simple source depletion method (Chamberlain, 1953). This method results in a source depletion factor that is multiplied by the undepleted concentration and/or deposition flux to account for depletion, but does not include an adjustment to the vertical profile.

Particle Dry Depletion

For Method 1, gravitational settling of particles is assumed to result in a "tilted plume", so that the effective plume height (h_e) is replaced by

$$h_{ed} = h_e - h_v = h_e - \frac{x}{u_s} V_g \tag{42}$$

where

h_{ed} = effective plume height adjusted for gravitational settling (m),
h_e = effective plume height, without gravitational settling (m),
h_v = plume height adjustment due to gravitational settling (m) = $(x/u_s)V_g$,
x = downwind distance (m), and
u_s = wind speed adjusted to stack height (m/s).

For the simplified approach to particle deposition under Method 2, an effective plume tilt is calculated based on the gravitational settling velocity for the representative particle size input by the user.

The undepleted concentration or deposition flux is multiplied by a source depletion factor, $F_Q(x)$, which represents the fraction of material that remains in the plume at the downwind distance x (i.e., the mass that has not yet been deposited on the surface). The source depletion factor is calculated as the ratio of the adjusted source strength at downwind distance x, $Q(x)$, to the initial source strength, Q_0. The adjusted source strength is calculated as follows:

$$Q(x) = Q_0 \exp\left[-\int_0^x \frac{V_d}{u} \overline{D}(x)\, dx \right] \tag{43}$$

where

$Q(x)$ = adjusted source strength at distance x (g/s),
Q_0 = initial source strength (g/s),
V_d = deposition velocity (m/s),

u = transport wind speed (m/s),

$\overline{D}(x)$ = crosswind integrated diffusion function, $\overline{D} = \overline{\chi}\, u / Q$ (m^{-1}), and

$\overline{\chi}$ = crosswind integrated concentration (g/m^2)

Gaseous Dry Depletion

The dry depletion (removal) of gaseous plumes is calculated using the same approach as described above for dry depletion of particulate plumes, except that there is no vertical tilt to the plume centerline height, i.e., the gravitational settling velocity, V_g, is set to 0.0 in Equation 42 and $h_{ed} = h_e$.

Wet Depletion (Removal)

The wet deposition or washout of pollutant by precipitation, whether particle or gaseous, will remove pollutant mass as the plume travels downwind from the source. This removal process is referred to as wet depletion, and will act to reduce ground-level concentrations and deposition fluxes. Since the washout of pollutants due to precipitation occurs through the full vertical extent of the plume, the wet depletion algorithm in AERMOD is based on a source depletion approach that calculates the fraction of plume material that has been removed from the plume, and multiplies the source depletion factor times the undepleted concentration and/or deposition flux.

The wet depletion factor, i.e., the ratio of the source strength modified by depletion at the receptor location ($Q(x)$) to the original unmodified source strength (Q_0), is calculated as follows:

$$\frac{Q(x)}{Q_0} = e^{-\Lambda t} \tag{44}$$

where

Q_0 = unmodified source strength (g/s),
$Q(x)$ = source strength modified for wet depletion at downwind distance x (g/s),
Λ = equivalent scavenging ratio (s^{-1}), and
t = plume travel time from source to receptor (s) = x/u .

The wet depletion factor calculated from Equation 43 is then multiplied by the undepleted concentration and/or deposition flux to account for removal of plume mass due to wet depletion.

Particle Wet Depletion

For particle wet depletion, the equivalent scavenging ratio, Λ, in Equation 43 is calculated based on the wet time scale, i.e., the time scale for removal of pollutant from the plume by precipitation. The wet time scale is given by the mass of pollutant in the column of air divided by the flux of pollutant out of the column:

$$WetTimeScale = \Lambda^{-1} = \frac{\rho_p\, z_p}{F_{wp}} \tag{45}$$

Substituting for F_{wp} from Equation 31 into Equation 45 and using Equation 33 yields the following equation for the equivalent scavenging ratio, Λ (s^{-1}):

$$\Lambda = \frac{3E_0 r}{2\, D_m\, 3.6 \times 10^6} \tag{46}$$

where the constant 3.6×10^6 converts units from meters to mm and from hours to seconds.

Gaseous Wet Depletion

The wet depletion factor for gaseous pollutants is calculated similar to the wet depletion factor for particles using Equation 43, and with an equivalent scavenging ratio defined based on the wet time scale, i.e.,

$$WetTimeScale = \Lambda^{-1} = \frac{\rho_g\, z_p}{F_{wg}} \tag{47}$$

As with particle wet depletion, substituting for F_{wg} from Equation 36 into Equation 47 with Equations 37 and 38 yields the following equation for the equivalent scavenging ratio, Λ (s^{-1}):

$$\Lambda = \frac{f_{sat}\, R\, T_a\, r}{3.6 \times 10^6\, z_p\, H\left[1 + \dfrac{L\, R\, T_a}{\rho_w\, H}\right]} \tag{48}$$

where the constant 3.6×10^6 converts units from meters to mm and from hours to seconds.

Table 1. Land Use Types

No.	Land Use Type
1	Urban land, no vegetation
2	Agricultural land
3	Rangeland
4	Forest
5	Suburban areas, grassy
6	Suburban areas, forested
7	Bodies of water
8	Barren land, mostly desert
9	Non-forested wetlands

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Table 2. Values of surface resistances (s/m) by land use type and seasonal category

Resistance	Land Use Type								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Season #1: Midsummer with lush vegetation									
R_i	1.e07	60.	120.	100.	200.	150.	1.e07	1.e07	80.
R_{cS}	1.e07	2000.	2000.	2000.	2000.	2000.	1.e07	1.e07	2500.
R_{cO}	1.e07	1000.	1000.	1000.	2000.	2000.	1.e07	1.e07	1000.
R_{aci}	100.	200.	100.	2000.	100.	1500.	0.	0.	300.
R_{gS}	400.	150.	350.	300.	500.	450.	0.	1000.	0.
R_{gO}	300.	150.	200.	200.	300.	300.	2000.	400.	1000.
Season #2: Autumn with unharvested cropland									
R_i	1.e07	1.e07	1.e07	350.	1.e07	700.	1.e07	1.e07	1.e07
R_{cS}	1.e07	6500.	6500.	3000.	2000.	2000.	1.e07	1.e07	6500.
R_{cO}	1.e07	400.	300.	500.	600.	1000.	1.e07	1.e07	300.
R_{aci}	100.	150.	100.	1700.	100.	1200.	0.	0.	200.
R_{gS}	400.	200.	350.	300.	500.	450.	0.	1000.	0.
R_{gO}	300.	150.	200.	200.	300.	300.	2000.	400.	800.
Season #3: Late autumn after frost and harvest, or winter with no snow									
R_i	1.e07	1.e07	1.e07	500.	1.e07	1000.	1.e07	1.e07	1.e07
R_{cS}	1.e07	1.e07	9000.	6000.	2000.	2000.	1.e07	1.e07	9000.
R_{cO}	1.e07	1.e07	400.	600.	800.	1600.	1.e07	1.e07	800.
R_{aci}	100.	0.	100.	1500.	100.	1000.	0.	0.	100.
R_{gS}	400.	150.	350.	300.	500.	450.	0.	0.	1000.
R_{gO}	300.	150.	200.	200.	300.	300.	2000.	400.	1000.
Season #4: Winter with snow on the ground									
R_i	1.e07	1.e07	1.e07	800.	1.e07	1600.	1.e07	1.e07	1.e07
R_{cS}	1.e07	1.e07	1.e07	400.	1.e07	800.	1.e07	1.e07	9000.
R_{cO}	1.e07	2000.	1000.	600.	2000.	1200.	1.e07	1.e07	800.
R_{aci}	100.	0.	10.	1500.	100.	1000.	0.	0.	50.
R_{gS}	100.	100.	100.	100.	200.	200.	0.	1000.	100.
R_{gO}	600.	3500.	3500.	3500.	500.	500.	2000.	400.	3500.
Season #5: Transitional spring with partial green coverage or short annuals									
R_i	1.e07	100.	120.	100.	200.	150.	1.e07	1.e07	80.
R_{cS}	1.e07	2000.	2000.	1500.	2000.	2000.	1.e07	1.e07	2000.
R_{cO}	1.e07	1000.	250.	350.	500.	700.	1.e07	1.e07	300.
R_{aci}	100.	50.	80.	1500.	100.	1000.	0.	0.	200.
R_{gS}	500.	150.	350.	300.	500.	450.	0.	1000.	0.
R_{gO}	300.	150.	200.	200.	300.	300.	2000.	400.	1000.

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Table 3. Values of factor S for scaling r_{cl}

Land Use Cat.	Scaling Factor
1	1.0×10^{-5}
2	6
3	5
4	7
5	3
6	4
7	1.0×10^{-5}
8	1.0×10^{-5}
9	3

References

Chamberlain, A. C., 1953: Aspects of travel and deposition of aerosol and vapor clouds. Atomic Energy Research Establishment, HP/R 1261.

Seinfeld, J. H. and S. N. Pandis, 1998: Atmospheric Chemistry and Physics, John Wiley & Sons, Inc., New York, NY.

Slinn, W. G. N., 1984: Precipitation Scavenging, in Atmospheric Science and Power Production, D. Randerson (ed.). DOE/TIC-27601. U. S. Department of Energy, Washington, DC.

Walcek, C., G. Stensland, L. Zhang, H. Huang, J. Hales, C. Sweet, W. Massman, A. Williams, J, Dicke, 2001: Scientific Peer-Review of the Report "Deposition Parameterization for the Industrial Source Complex (ISC3) Model." The KEVRIC Company, Durham, North Carolina.

Wesely, M. L, P. V. Doskey, and J.D. Shannon, 2001: Deposition Parameterizations for the Industrial Source Complex (ISC3) Model. Draft ANL report ANL/ER/TM-nn, DOE/xx-nnnn, Argonne National Laboratory, Argonne, Illinois 60439.

List of Symbols

a = rain drop radius (cm)

C_l = concentration of pollutant in the liquid phase (moles/liter)

C_{lsat} = concentration of pollutant in liquid phase at saturation (moles/liter)

c_2 = air units conversion constant (1.0×10^{-8} cm^2/μm^2)

D_a = diffusivity of modeled gas in air (m^2/s)

D_B = Brownian diffusivity (cm^2/s) of the pollutant in air

D_m = mean diameter of raindrop (m)

D_v = diffusivity of water vapor in air (0.219×10^{-4} m^2/s)

D_w = liquid-phase molecular diffusion coefficient input by user (cm^2/s)

d_p = particle diameter input by user (μm)

E = collision efficiency (dimensionless)

$e_s(25)$ = saturation vapor press (kPa) for $T_a = 25$ °C, equal to 3.167 kPa

$e_s(T_a)$ = saturation vapor pressure (kPa) for ambient temperature

F_d = dry deposition flux (μg/m^2/s)

F_{wg} = flux of gaseous pollutants by wet deposition (μg/m^2/hr)

F_{wp} = flux of particulate matter by wet deposition (μg/m^2/hr)

f_o = reactivity factor (dimensionless)

f_1 = multiplicative scaling factors for solar irradiance (dimensionless)

f_2 = multiplicative scaling factor for soil moisture (dimensionless)

f_3 = multiplicative scaling factor for humidity (dimensionless)

f_4 = multiplicative scaling factor for temperature (dimensionless)

f_c = factor based on cloud cover for dew test (dimensionless)

f_g = gas-side diffusion-enhancement factor (dimensionless)

f_l = liquid-side diffusion-enhancement factor (dimensionless)

f_p = fraction of particulate substance that is fine mode, smaller than 2.5 μm (dimensionless)

f_{sat} = fraction of saturation (dimensionless)

G = solar irradiance (W/m^2)

G_r = reference solar irradiance = 30 W/m^2 for forests and 100 W/m^2 for other land use types

g = acceleration due to gravity (9.80616 m/s^2)

H = Henry's Law Constant input by user (Pa-m^3/mol)

h_e = effective plume height (m)

h_{ed} = effective plume height, adjusted for gravitational settling (m)

h_v = plume height adjustment due to gravitational settling (m)

k = von Karman constant (0.4)

L = Monin-Obukhov length scale (m)

L_w = liquid water content of falling rain (g/m^3)

LAI_r = relative leaf area index (dimensionless)

M_w = molecular weight of pollutant (grams/mole)

P = ambient air pressure (kPa)

P_0 = reference pressure = 101.3 kPa

P_{h-1} = precipitation rate (mm/h) for preceding hour

Q_0 = unmodified source strength (g/s)

$Q(x)$ = source strength modified for wet depletion at downwind distance x (g/s)

R = universal gas constant = 8.3145 Pa-m^3/mole-K

R_a =   aerodynamic resistance (s/m)

R_{ac} =   aerodynamic resistance in the vegetative canopy (s/m)

R_{aci} =   aerodynamic resistance (s/m) in the vegetative canopy

R_b =   quasilaminar resistance for bulk surface (s/m)

R_c =   bulk surface resistance (s/m)

R_{cl} =   bulk canopy cuticular resistance (s/m) by lipid solubility

R_{cO} =   resistance to O_3 uptake by cuticle (s/m)

R_{cS} =   resistance to SO_2 uptake by cuticle (s/m)

R_{cut} =   canopy cuticular resistance (s/m)

R_e =   Reynolds number of raindrop (dimensionless)

R_g =   resistance to uptake at the ground (s/m)

R_{gO} =   resistance to O_3 uptake by ground (s/m)

R_{gS} =   resistance to SO_2 uptake by ground (s/m)

R_i =   minimum stomatal resistance (s/m)

R_m =   canopy mesophyll resistance (s/m)

R_p =   quasilaminar sublayer resistance (s/m)

R_s =   canopy stomatal resistance (s/m)

RH =   relative humidity (percent)

r =   water or water equivalent precipitation rate (mm/hr)

r_{cl} =   leaf cuticular resistance to lipid uptake input by user (s/m)

S =   scaling factor by land use category

Sc =   Schmidt number ($Sc = v/D_B$) (dimensionless)

S_{CF} =   slip correction factor (dimensionless)

St =   Stokes number (dimensionless)

S^* =   critical Stokes number (dimensionless)

T_0 =   reference air temperature = 273.16 K

T_a =   ambient air temperature (K)

t =   plume travel time from source to receptor (s)

t_{abs} =   time for rain drops to become saturated (absorption time) (s)

t_{res} =   residence time of rain drops in the plume or boundary layer (s)

u =   transport wind speed (m/s)

u_s =   wind speed adjusted to stack height (m/s)

u_* =   friction velocity (m/s)

V_d =   deposition velocity (m/s)

V_{dg} =   deposition velocity for gases (m/s)

V_{dp} =   deposition velocity for particles (m/s)

V_{dpf} =   deposition velocity (m/s) of fine particulate substance

V_{dpc} =   deposition velocity (m/s) of coarse particulate substance

V_{fall} =   precipitation fall speed (m/s)

V_g =   gravitational settling velocity for particles (m/s)

V_j =   vertical term for particle size category j

W_p =   particle washout coefficient (dimensionless)

w_h =   available root zone water for the current hour (mm)

w_{h-1} =   available root zone water for the preceding hour (mm)

w_* =   convective velocity scale (m/s)

x =   downwind distance (m)

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z_i =   mixing height (m)

z_o =   surface roughness length for the application site (m)

z_p =   height of the top of plume or mixing height, whichever is greater (m)

z_r =   deposition reference height (m) = z_o+1

α =   coefficient = 0.1 kPa^{-1}

α_s =   sticking coefficient (dimensionless) = 0.01

δe =   vapor pressure deficit (kPa)

δq =   the specific humidity deficit (g/kg)

θ_r =   extractable soil moisture (dimensionless)

Λ =   equivalent scavenging ratio (s^{-1})

μ =   absolute viscosity of air ($\approx 1.81 \times 10^{-4}$ g/cm/s)

μ_w =   viscosity of water ($\approx 1.0 \times 10^{-2}$ g/cm/s)

v =   gaseous molecular velocity (~50,000 cm/s)

$\boldsymbol{N}$ =   ratio of particle diameter to raindrop diameter (dimensionless)

ρ =   particle density input by user (g/cm^3)

ρ_g =   column average concentration of gaseous pollutant in air (μg/m^3)

ρ_p =   column average concentration of particulate in air (μg/m^3)

ρ_{AIR} =   air density ($\approx 1.2 \times 10^{-3}$ g/cm^3)

ρ_w =   density of water = 10^6 g/m^3

σ_z =   vertical dispersion coefficient (m)

υ =   kinematic viscosity of air ($\approx 0.1505 \times 10^{-4}$ m^2/s)

χ_d =   concentration (μg/m^3), calculated at reference height, z_r