

# **AnnAGNPS TECHNICAL PROCESSES**

**Documentation**

**Version 3.2**

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LIST OF EQUATIONS

$SED\_TOT = SED\_RATE \cdot R_E \cdot A_{cell}$  Equation 3-3-1.....16

$SM_{t+1} = SM_t + \frac{WI_t - Q_t - PERC_t - ET_t - Q_{lat} - Q_{tile}}{Z}$  Equation 5-1 .....16

$FCMWP = FC - WP$  Equation 5-2.....18

$POMWP = f - WP$  Equation 5-3.....18

$KSAT\_DT = \frac{KSAT}{NTS}$  Equation 5-4 .....18

$\ln \lambda = -0.7842831 + 1.77544SAND - 1.062498f - 0.5304SAND^2 - 27.3493CLAY^2$   
 $+ 1.11134946f^2 - 3.088295SANDf + 2.6587SAND^2f^2 - 61.0522CLAY^2f^2$  Equation 5-5...18  
 $- 2.35SAND^2CLAY + 79.8746CLAY^2f - 0.674491f^2CLAY$

$BC\_EXP = 3 + \frac{2}{\lambda}$  Equation 5-6.....19

$MIN\_SMMWP = POMWP \left( \frac{0.0000000001}{KSAT\_DT} \right)^{(1/BC\_EXP)}$  Equation 5-7 .....19

$FSDEPTH = \frac{KSAT}{f}$  Equation 5-8.....19

$FR = 1 - \frac{D_{SL1}}{FSDEPTH}$  Equation 5-9 .....19

$SMCX = FSDEPTH(1) FCMWP(1) + FSDEPTH(2) FCMWP(2)$  Equation 5-10 .....19

$AVAIL\_H2O = D_{SL1} FCMWP(1) + (1000 - D_{SL1}) FCMWP(2)$  Equation 5-11 .....19

$AVAIL\_H2O = D_{SL1} FCMWP(1) + (D_{SL2} - D_{SL1}) FCMWP(2)$  Equation 5-12 .....20

$\gamma = 6.6 \times 10^{-4} (101 - 0.0115Z + 5.44 \times 10^{-7} Z^2)$  Equation 5-13.....20

$CN_1 = CN_2 - \frac{20(100 - CN_2)}{100 - CN_2 + \exp[2.533 - 0.0636(100 - CN_2)]}$  Equation 5-14 .....20

$CN_1 = 0.4 CN_2$  Equation 5-15.....20

$CN_3 = CN_2 \exp[0.00673(100 - CN_2)]$  Equation 5-16.....20

$S = 254 \left( \frac{100}{CN} - 1 \right)$  Equation 5-17 .....20

$$W_1 = \ln \left( \frac{1}{1 - \frac{S_3}{S_1}} - 1 \right) + W_2$$

Equation 5-18.....21

$$W_2 = 2 \left[ \ln \left( \frac{0.5}{1 - \frac{S_2}{S_1}} - 0.5 \right) - \ln \left( \frac{1}{1 - \frac{S_3}{S_1}} - 1 \right) \right]$$

Equation 5-19 .....21

$$S = 254 \left( \frac{100}{CN} - 1 \right)$$

Equation 5-20.....22

$$S_t = S_1 \left( 1 - \frac{FS_t}{FS_t + \exp(W_1 - W_2 FS_t)} \right)$$

Equation 5-21 .....22

$$FS_t = \frac{FSDEPTH(1)(SM(1)_t - WP(1)) + FSDEPTH(2)(SM(2)_t - WP(2))}{FSDEPTH(1)(FC(1) - WP(1)) + FSDEPTH(2)(FC(2) - WP(2))}$$

Equation 5-22.....22

$$Q = \frac{(WI - 0.2 S)^2}{WI + 0.8 S}$$

Equation 5-23.....23

$$F_a = \frac{a'' + \left( \frac{1 - a' - d_{sr}}{2} \right)}{1 - \alpha \left( \frac{1 - a' + d_{sr}}{2} \right)}$$

Equation 5-24.....24

$$a' = \exp \left\{ -m_a (0.465 + 0.134w) [0.129 + 0.171 \exp(-0.880m_a)] \right\}$$

Equation 5-25 .....24

$$a'' = \exp \left\{ -m_a (0.465 + 0.134w) [0.179 + 0.421 \exp(-0.721m_a)] \right\}$$

Equation 5-26 .....24

$$w = 0.85 \exp(0.110 + 0.0614 T_D)$$

Equation 5-27 .....24

$$F_a = 0.75 + 0.0002 Z_e$$

Equation 5-28 .....25

$$F_c = 0.22 + 0.78 \left( \frac{S}{S_o} \right)^{2/3}$$

Equation 5-29.....25

$$F_c = 0.35 + 0.61 \left( \frac{S}{S_o} \right)^{2/3}$$

Equation 5-30.....25

$$R_{sl} = F_a F_c R_x$$

Equation 5-31 .....25

$R_{SI} = \left[ 0.19 + 0.55 \left( \frac{S}{S_o} \right) \right] R_X$  Equation 5-32 .....25

$R_{SR} = \alpha R_{SI}$  Equation 5-33.....25

$R_{SN} = (1 - \alpha) F_a F_c R_X$  Equation 5-34 .....26

$R_L = \varepsilon \sigma T_K^4$  Equation 5-35 .....26

$\varepsilon_a = a + b\sqrt{e}$  Equation 5-36 .....26

$e = 6.11 \exp\left(\frac{17.62 T_D}{243.12 + T_D}\right)$  Equation 5-37.....26

$e = 6.11 \exp\left(\frac{22.46 T_D}{272.62 + T_D}\right)$  Equation 5-38 .....27

$\frac{R_{Lc}}{R_{La}} = 1 + kC^m$  Equation 5-39.....27

$R_{LN} = -\varepsilon \sigma (T + 273.16)^4 (0.56 - 0.08\sqrt{e}) \left( 0.1 + 0.9 \frac{S}{S_o} \right)$  Equation 5-40.....28

$R_{LN} = \sigma (T + 273.16)^4 \left[ (0.61 + 0.05\sqrt{e}) (1 + 0.17C^2) - \varepsilon \right]$  Equation 5-41.....28

$R_{LN} = -\sigma (T + 273.16)^4 (0.34 - 0.04\sqrt{e}) \left( 1.35 \frac{R_s}{R_{So}} - 0.35 \right)$  Equation 5-42.....28

$R_N = R_{SN} + R_{LN}$  Equation 5-43.....28

$R_X = \frac{S_c}{\pi} d_r (h_s \sin \phi \sin \delta + \sin h_s \cos \phi \cos \delta)$  Equation 5-44.....29

$d_r = \left( \frac{\bar{d}}{d_{es}} \right)^2$  Equation 5-45 .....29

$d_r = \frac{(1 + e_o \cos \theta)^2}{(1 - e_o^2)}$  Equation 5-46.....29

$\theta = \frac{2\pi}{365} (J - 2)$  Equation 5-47 .....29

$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right)$  Equation 5-48 .....30



$$h_s = \arccos(-\tan \phi \tan \delta) \quad \text{Equation 5-49} \dots\dots\dots 30$$

$$\delta = 0.40928 \cos \left[ \left( \frac{2\pi}{365} \right) (172 - J) \right] \quad \text{Equation 5-50} \dots\dots\dots 30$$

$$A = \arcsin \left\{ (\sin \phi \sin \delta) + \left[ \cos \phi \cos \delta \cos \left( \frac{h_s}{2} \right) \right] \right\} \quad \text{Equation 5-51} \dots\dots\dots 30$$

$$m_a = \frac{\left( \frac{288 - 0.0065Z_e}{288} \right)^{5.256}}{\sin A + 0.15 \left[ \left( \frac{180}{\pi} \right) A + 3.885 \right]^{-1.253}} \quad \text{Equation 5-52} \dots\dots\dots 30$$

$$ET_p = \frac{1}{H_v} \left[ \left( \frac{\Delta}{\Delta + \gamma} \right) (R - G) + \left( \frac{\gamma}{\Delta + \gamma} \right) W (e_{sat} - e) \right] \quad \text{Equation 5-53} \dots\dots\dots 31$$

$$H_v = 2.501 - 0.0022 T \quad \text{Equation 5-54} \dots\dots\dots 31$$

$$e_{sat} = 0.1 \exp \left( 54.879 - 5.029 \ln T_k - \frac{6790.5}{T_k} \right) \quad \text{Equation 5-55} \dots\dots\dots 31$$

$$e = RH e_{sat} \quad \text{Equation 5-56} \dots\dots\dots 31$$

$$\Delta = \left( \frac{e_{sat}}{T_k} \right) \left( \frac{6790.5}{T_k} - 5.029 \right) \quad \text{Equation 5-57} \dots\dots\dots 31$$

$$\gamma = 6.6 \times 10^{-4} (101 - 0.0115Z + 5.44 \times 10^{-7} Z_e^2) \quad \text{Equation 5-58} \dots\dots\dots 32$$

$$G = 0.12 \left[ T_0 - \left( \frac{T_{-1} + T_{-2} + T_{-3}}{3} \right) \right] \quad \text{Equation 5-59} \dots\dots\dots 32$$

$$W = 6.43 + 3.4079 U \quad \text{Equation 5-60} \dots\dots\dots 32$$

$$q_{drain} = \frac{8K_s d_e m + 4K_s m^2}{L_D^2} \quad \text{Equation 5-61} \dots\dots\dots 33$$

$$d_e = \frac{d}{1 + \frac{d}{L_D} \left[ \frac{8}{\pi} \ln \left( \frac{d}{r} \right) - \alpha_c \right]} \quad \text{Equation 5-62} \dots\dots\dots 34$$

$$\alpha_c = 3.55 - \frac{1.6d}{L_D} + 2 \left( \frac{d}{L_D} \right)^2 \quad \text{Equation 5-63} \dots\dots\dots 34$$

$$d_e = \frac{L_D \pi}{8 \left[ \ln \left( \frac{L_D}{r} \right) - 1.15 \right]} \quad \text{Equation 5-64} \dots\dots\dots 34$$

$$SM_{t+1} = SM_t + \frac{WI_t - PERC_t - ET_t}{Z} \quad \text{Equation 5-65} \dots\dots\dots 34$$

$$h = \frac{(SM_{t+1} - FC) * Z}{(PO - FC)} \quad \text{Equation 5-66} \dots\dots\dots 34$$

$$Q_{Tile} = \frac{q_{drain} * A_{cell}}{1000} \quad \text{Equation 5-67} \dots\dots\dots 35$$

$$q_{lat} = -K_s \frac{dh}{dl} \quad \text{Equation 5-68} \dots\dots\dots 35$$

$$Q_{lat} = \frac{q_{lat} * A_{across}}{1000} \quad \text{Equation 5-69} \dots\dots\dots 35$$

$$A_{across} = \frac{h * L_{Reach}}{1000} \quad \text{Equation 5-70} \dots\dots\dots 35$$

$$f(d_t; Q_t, Z, W, n, S_0) = 0 = 1 - \left\{ \left[ \frac{\sqrt{S_0}}{n \cdot Q_t} \right] \cdot \left[ \frac{[(W \cdot d_t) + (Z \cdot d_t^2)]^{5/3}}{[W + (2 \cdot Z \cdot d_t)]^{2/3}} \right] \right\}$$

$$f'(d_t; Q_t, Z, W, n, S_0) =$$

$$\left\{ \frac{\sqrt{S_0}}{(3 \cdot n \cdot Q_t)} \right\} \cdot \left[ \left[ (4 \cdot Z) \cdot \left( \frac{(W \cdot d_t) + (Z \cdot d_t^2)}{W + (2 \cdot Z \cdot d_t)} \right)^{5/3} \right] - \left[ 5 \cdot \left( \frac{((W \cdot d_t) + (Z \cdot d_t^2))^2}{(W + (2 \cdot Z \cdot d_t))^{-1}} \right)^{1/3} \right] \right]$$

$$d_{t,i=0}(Q_t, Z, W, n, S_0) = MIN \left[ \left( \frac{n \cdot Q_t}{W \cdot \sqrt{S_0}} \right)^{3/5}, \left( \frac{2^{2/3} \cdot n \cdot Q_t}{Z \cdot \sqrt{S_0}} \right)^{3/8} \right] \quad \text{Equation 5-71} \dots\dots 37$$

$$d_t(Q_t, W, n, S_0) = \left( \frac{n \cdot Q_t}{W \cdot \sqrt{S_0}} \right)^{3/5} \quad \text{Equation 5-72} \dots\dots\dots 37$$

$$d_t(Q_t, Z, n, S_0) = \left( \frac{2^{2/3} \cdot n \cdot Q_t}{Z \cdot \sqrt{S_0}} \right)^{3/8} \quad \text{Equation 5-73} \dots\dots\dots 37$$

$$V(Q_t, d_t, Z, W) = \frac{Q_t}{(W \cdot d_t) + (Z \cdot d_t^2)} \quad \text{Equation 5-74} \dots\dots\dots 38$$

$$V(Q_t, d_t, W) = \frac{Q_t}{W \cdot d_t} \quad \text{Equation 5-75} \dots\dots\dots 38$$

$$V(Q_t, d_t, Z) = \frac{Q_t}{Z \cdot d_t^2} \quad \text{Equation 5-76} \dots\dots\dots 38$$

$$V(d_t, n, W, Z, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot \left[ \frac{(W \cdot d_t) + (Z \cdot d_t^2)}{W + (2 \cdot Z \cdot d_t)} \right]^{2/3}$$

Equation 5-77.....38

$$V(d_t, n, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot d_t^{2/3}$$

Equation 5-78.....38

$$V(d_t, n, Z, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot \left( \frac{d_t}{2} \right)^{2/3}$$

Equation 5-79.....38

$$V(d_h, n, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot d_h^{2/3}$$

Equation 5-80 .....39

$$Q_t(d_t, n, W, Z, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot \left\{ \frac{[(W \cdot d_t) + (Z \cdot d_t^2)]^{5/3}}{[W + (2 \cdot Z \cdot d_t)]^{2/3}} \right\}$$

Equation 5-81.....39

$$Q_t(d_t, n, W, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot W \cdot d_t^{5/3}$$

Equation 5-82.....39

$$Q_t(d_t, n, Z, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot (Z \cdot d_t^2) \cdot \left( \frac{d_t}{2} \right)^{2/3}$$

Equation 5-83.....39

$$q_t(d_t, n, W, Z, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot \left[ \frac{(W \cdot d_t) + (Z \cdot d_t^2)}{W + (2 \cdot Z \cdot d_t)} \right]^{5/3}$$

Equation 5-84.....40

$$q_t(d_t, n, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot d_t^{5/3}$$

Equation 5-85 .....40

$$q_t(d_t, n, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot \left( \frac{d_t}{2} \right)^{5/3}$$

Equation 5-86.....40

$$q_t(Q_t, d_t, W, Z) = \left[ \frac{Q_t}{W + (2 \cdot Z \cdot d_t)} \right]$$

Equation 5-87 .....40

$$q_t(Q_t, W) = \frac{Q_t}{W}$$

Equation 5-88.....40

$$q_t(Q_t, n, Z, S_0) = \left[ \left( \frac{\sqrt{S_0}}{n} \right) \cdot \left( \frac{Q_t}{4 \cdot Z} \right)^{5/3} \right]^{3/8}$$

Equation 5-89.....40

$$Q_b(d_b, W_b, n_c, S_0) = \left( \frac{\sqrt{S_0}}{n_c} \right) \cdot W_b \cdot d_b^{5/3}$$

Equation 5-90.....41

$$d_t(Q_t, W_b, n_c, S_0) = \left( \frac{n_c \cdot Q_t}{W_b \cdot \sqrt{S_0}} \right)^{3/5}$$

$$d_c = d_t$$

$$d_f = 0$$

Equation 5-91.....42

Equation 5-92 .....42

$$V_c(Q_t, W_b, d_t) = \frac{Q_t}{W_b \cdot d_t}$$

$$V_f = 0$$

Equation 5-93 .....43

$$V_c(Q_c, W_b, d_c) = \frac{Q_c}{W_b \cdot d_c}$$

$$V_f(Q_f, W_f, d_f, d_b) = \frac{Q_f}{W_f \cdot (d_f - d_b)}$$

Equation 5-94.....43

$$Q_t(d_t, W_b, n_c, S_0) = \left( \frac{\sqrt{S_0}}{n_c} \right) \cdot W_b \cdot d_t^{5/3}$$

$$Q_c = Q_t$$

$$Q_f = 0$$

Equation 5-95 .....44

$$Q_c(d_t, W_b, n_c, S_0) = \left( \frac{W_b}{n_c} \right) \cdot d_t^{5/3} \cdot \sqrt{S_0}$$

$$Q_f(d_t, W_f, d_b, n_f, S_0, F_s) = \left( \frac{W_f}{n_f} \right) \cdot (d_t - d_b)^{5/3} \cdot \sqrt{F_s \cdot S_0}$$

$$Q_t(W_b, W_f, d_t, d_b, n_c, n_f, S_0, F_s) = Q_c + Q_f$$

Equation 5-96.....44

$$q_t(d_t, n_c, S_0) = \left( \frac{\sqrt{S_0}}{n_c} \right) \cdot d_t^{5/3}$$

$$q_c = q_t$$

$$q_f = 0$$

Equation 5-97 .....45

$$q_c(d_t, n_c, S_0) = \left( \frac{d_t^{5/3}}{n_c} \right) \cdot \sqrt{S_0}$$

$$q_f(d_t, d_b, n_f, S_0, F_s) = \left[ \frac{(d_t - d_b)^{5/3}}{n_f} \right] \cdot \sqrt{F_s \cdot S_0}$$

Equation 5-98 .....45

$$q_c = \frac{Q_t}{W_b}$$

$$q_f = 0$$

Equation 5-99.....46

$$q_c = \frac{Q_c}{W_b}$$

$$q_f = \frac{Q_f}{W_f}$$

Equation 5-100.....46

$$d_w = R = A_H / W_H$$

**Equation 5-101** .....46

$$v_w = (1/n) \cdot d_w^{2/3} \cdot S_0^{1/2}$$

**Equation 5-102** .....46

$$v_w = Q_w / (W_H \cdot d_w) = q_w / d_w$$

**Equation 5-103** .....47

$$d_w \cdot S_0 = n^{0.6} \cdot S_0^{0.7} \cdot q_w^{0.6}$$

**Equation 5-104** .....47

$$T_{c, in\_cell} = T_{t, ov} + T_{t, scf} + T_{t, cf}$$

Equation 5-105 .....48

$$L_{ov\_max} = 50$$

$$L_{ov} = MIN(L_{ov\_max}, L)$$

$$T_{t, ov} = \frac{0.09 \cdot (n_{ov} \cdot L_{ov})^{0.8}}{(P_2^{0.5} \cdot S_{ov}^{0.4})}$$

Equation 5-106 .....48

$$L_{ov\_max} = 50$$

If  $L > L_{ov\_max}$ , then

$$L_{scf} = MIN[L_{ov\_max}, (L - L_{ov})]$$

$$V_{scf} = MIN[0.61, (4.9178 \cdot S_{ov}^{0.5})]$$

$$T_{t, scf} = \frac{L_{scf}}{(3600 \cdot V_{scf})}$$

Otherwise,

$$T_{t, scf} = 0$$

Equation 5-107 .....49

If  $L > L_{ov\_max} + L_{scf\_max}$ , then

$$L_{cf} = L - (L_{ov} + L_{scf})$$

$$T_{t,cf} = \frac{L_{cf}}{(3600 \cdot V_{cf})}$$

Otherwise,

$$T_{t,cf} = 0$$

Equation 5-108 .....49

$$T_{t,reach} = \frac{\Delta L}{(3600 \cdot V_{Reach})}$$

Equation 5-109 .....50

If there are no contributing reaches, then

$$T_{c,reach\_in} = 0$$

Otherwise,

$$T_{c,reach\_in} = \text{MAX}(T_{c,reach\_out} \text{ 's of all immediately contributing reaches})$$

$$T_{c,reach\_out} = T_{c,reach\_in} + T_{t,reach}$$

Equation 5-110 .....50

$$Q_{24} \equiv (P_{24} - I_a)^2 / (P_{24} + 4 I_a) \quad \text{Equation 5-111 .....51}$$

$$I_a^2 + (-2P_{24} + 4Q_{24}) I_a + (P_{24}^2 - Q_{24}P_{24}) = 0 \quad \text{Equation 5-112 .....51}$$

$$I_a = (P_{24} + 2Q_{24}) - (5Q_{24}P_{24} + 4Q_{24}^2)^{0.5} \quad \text{Equation 5-113 .....51}$$

$$(I_a / P_{24}) \equiv [(P_{24} + 2Q_{24}) - (5Q_{24}P_{24} + 4Q_{24}^2)^{0.5}] / P_{24} \quad \text{Equation 5-114 .....51}$$

$$(I_a / P_{24}) \equiv \{1 + 2(Q_{24}/P_{24}) - [4(Q_{24}/P_{24})^2 + 5(Q_{24}/P_{24})]^{0.5}\} \quad \text{Equation 5-115 .....51}$$

$$q_p = \frac{a + (c \cdot T_c) + (e \cdot T_c^2)}{1 + (b \cdot T_c) + (d \cdot T_c^2) + (f \cdot T_c^3)}$$

Equation 5-116 .....52

$$Q_p = \text{factor} \cdot P_{24} \cdot D_a \cdot q_p$$

$$t_b = 20 \cdot (R_Q \cdot D_a / Q_p) \quad \text{Equation 5-117 .....57}$$

$$Q_w = (Q_p / t_b) \cdot t, \text{ and} \quad \text{Equation 5-118 .....57}$$

$$q_p = Q_p / W \quad \text{Equation 5-119 .....57}$$

$$EI = \frac{A \cdot \exp(2.119 \cdot \log(R)) \cdot \exp(0.0086 \cdot \log(24))}{\exp(B \cdot \log(24))}$$

Equation 6-1 .....65

$$K = K_0 \cdot (1 + 14 \cdot (1 - \exp(-4 \cdot (M - 0.5)))) \quad \text{Equation 6-2 .....65}$$

$$S_y = 0.22 \cdot Q^{0.68} \cdot q_p^{0.95} \cdot \text{KLSCP} \quad \text{Equation 6-3 .....66}$$

$$D_r = S_{y2} / S_{y1} = (q_{p2} / q_{p1})^{0.95} \quad \text{Equation 6-4 .....66}$$

$$C_s = S_m / W_m \quad \text{Equation 6-5 .....70}$$

$$q_s = c_s \cdot q_w \quad \text{Equation 6-6 .....70}$$

$U_* = [g \cdot d_w \cdot S_o]^{1/2} = g^{0.5} \cdot n^{0.3} \cdot S_o^{0.35} \cdot q_w^{0.3}$  **Equation 6-7** .....71

$q_{sc} = \eta \cdot k \cdot \tau \cdot v_w^2 / v_f$  **Equation 6-8** .....71

$\eta = 0.322 \cdot [(\gamma_p - \gamma_w) / (\tau / D_p)]^{1.626} \leq 1$  **Equation 6-9** .....71

$\tau = \gamma_w \cdot d_w \cdot S_o$  **Equation 6-10** .....71

$C_1 = \{ [D_p / 2004] \cdot [(\gamma_p - \gamma_w) / \gamma_w] \}$  **Equation 6-11** .....72

$q_\eta = [C_1 / (n^{0.6} \cdot S_o^{0.7})]^{5/3}$  **Equation 6-12** .....72

$t_\eta = t_b \cdot (q_\eta / q_p)$  **Equation 6-13** .....72

For  $t \geq t_\eta$ :  $C_3 = C_{11} \cdot 6.26 \cdot C_2$ , and  $q_{sc} = C_3 \cdot n - 1.5756 \cdot S_o \cdot 0.1618 \cdot q_w \cdot 0.4244$   
**Equation 6-14** .....73

$S_{sc} = \int_0^{t_b} (W \cdot q_{sc}) dt = W \cdot C_2 \cdot n^{-0.6} \cdot S_o^{1.3} \cdot q_p^{1.4} \cdot t_b / 2.4$  **Equation 6-15** .....73

**Equation 6-16** .....73

$q_{s2} = q_{sc} + [(q_{s1} - q_{sc}) \cdot \exp(-N_d)]$  **Equation 6-17** .....74

$N_d = (A_E \cdot v_f \cdot L_2) / q_w$  **Equation 6-18** .....75

$A_E = [(6 \cdot v_f) / (\kappa \cdot U_*)] / \{1 - \exp[-(6 \cdot v_f) / (\kappa \cdot U_*)]\}$  **Equation 6-19** .....75

$\int_{t_1}^{t_2} Q_s dt \cong (t_2 - t_1) \cdot \left[ \sum_{i=1}^{i=N} (\omega_i \cdot Q_{s,i}) \right]$  **Equation 6-20** .....76

**Equation 7-1** .....78

$V_p = a \cdot h_o^b$  **Equation 7-2** .....79

$Q_o = c \cdot \{ [(V_p + V_l / 2) / a]^{1/b} \}^{0.5}$  **Equation 7-3** .....79

$Q_o = c \cdot \{ [(V_p + V_l / 2) / a]^{1/b} - h_o \}^{1.5}$  **Equation 7-4** .....79

$A_s = a \cdot b \cdot [(V_p + V_l / 2) / a]^{[(b-1)/b]}$  **Equation 7-5** .....79

$M_s = M_c / (1 + K_d)$  **Equation 8-1** .....82

## LIST OF SYMBOLS

## Uppercase Variables

Variable	Meaning	Unit
A	Average solar altitude	radians
A <sub>H</sub>	Flow area for the hydraulics section	m <sup>2</sup>
A <sub>E</sub>	Einstein's constant of proportionality, for any given flow and particle size, between the depth-average suspended sediment concentration and the concentration at the laminar sublayer plane	
A <sub>across</sub>	Lateral flow across cell area	m <sup>2</sup>
A <sub>cell</sub>	Cell Area	m <sup>2</sup>
A <sub>s</sub>	Average impoundment surface area during respective runoff event	ha
AVAIL_H2O	Available moisture content between field capacity and wilting point in the top one meter of soil	mm
BC_EXP	Brooks-Corey exponent, used to calculate hydraulic conductivity for a soil layer	
C	Fraction of cloudiness	
C <sub>1</sub>	Particle-size class constant for the effective transport factor	m
C <sub>2</sub>	Particle-size class constant for the effective transport factor for $\eta = 1$	Mg-s/m <sup>4</sup>
C <sub>3</sub>	Particle-size class constant for the effective transport factor for $\eta < 1$	Mg-s/m <sup>2.374</sup>
C <sub>s</sub>	Sediment concentration	(Mg-sediment)/(Mg-water)
C <sub>x</sub>	Mixing coefficient	
CLAY	Clay content for a soil layer	
CN <sub>1</sub>	Dry condition SCS curve number based on soil moisture	



Uppercase Variables

Variable	Meaning	Unit
	storage	
CN <sub>2</sub>	SCS curve number for average conditions	
CN <sub>3</sub>	Wet condition SCS curve number based on soil moisture storage	
D <sub>a</sub>	Total drainage area	ha
D <sub>p</sub>	Equivalent sand size particle diameter	m
D <sub>r</sub>	Total delivery ratio for all five particle-sized classes combined	
D <sub>SL1</sub>	Thickness for the top soil layer	mm
D <sub>SL2</sub>	Thickness for the second soil layer	mm
ET <sub>P</sub>	Potential evapotranspiration	mm
F <sub>a</sub>	Atmospheric correction factor	
F <sub>c</sub>	Cloud correction factor	
FC	Field capacity of a soil layer	
F <sub>s</sub>	Sinuosity (assumed to be 1.25)	m/m
FCMWP	Field capacity minus wilting point for a soil layer	
FSDEPTH	Depth affecting fraction of saturation for curve number calculation for a soil layer	mm
G	Soil heat flux	MJ/m <sup>2</sup>
H <sub>v</sub>	Latent heat of vaporization	MJ/kg
I <sub>a</sub> /P <sub>24</sub>	Ratio of initial abstraction to 24-hour precipitation, including snowmelt	
I <sub>a</sub>	Initial abstraction	

### Uppercase Variables

Variable	Meaning	Unit
IFRZ	Frozen soil flag for a soil layer (1=frozen, 0=not frozen)	
J	Julian day of a year	
$K_S$	Saturated lateral hydraulic conductivity	mm/time period
KSAT	Saturated hydraulic conductivity of a soil layer	mm/d
KSAT_DT	Time-step saturated hydraulic conductivity of a soil layer	mm/NTS
$\Delta L$	Channel length of the reach segment for the in_stream processes	m
L	Total flow path length of all segments for the in_cell processes (hydraulically most distant point within the cell to the downstream end of the receiving reach)	m
$L_2$	Distance from $x_1$ to $x_2$	m
$L_{cf}$	Flow path length for the concentrated flow segment	m
$L_D$	Distance between drains	m
$L_{ov}$	Flow path length for the overland flow segment	m
$L_{ov\_max}$	Maximum flow path length for the overland flow segment	m
$L_{scf}$	Flow path length for the shallow concentrated flow segment	m
$L_{scf\_max}$	Maximum flow path length for the shallow concentrated flow segment	m
MIN_SMMWP	Minimum value of soil moisture minus wilting point to avoid numerical problems	
N	Last Guass-Legendre time point	
$N_d$	Deposition number, $(A v_f L_2)/q_w$	
$N_{id}$	Impoundment deposition number	
NTS	Number of computational time steps per day for soil moisture calculations	

### Uppercase Variables

Variable	Meaning	Unit
$P_2$	The 2-year return frequency, 24 hour duration precipitation	mm
$P_{24}$	The spatially-averaged total 24-hour rainfall amount plus the water equivalent of any snowmelt for that period.	mm
PO	Porosity of the soil layer	
POMWP	Porosity minus wilting point for a soil layer	
R	Hydraulic radius	m
$R_E$	Effective depth, taking into account the fraction of the field receiving irrigation water	m
$R_L$	Emitted long wave radiation	$W/m^2$
$R_{La}$	Long wave atmospheric emittance	$W/m^2$
$R_{Lc}$	Long wave emittance under cloudy skies	$W/m^2$
$R_{LN}$	Net long wave radiation	$W/m^2$
$R_n$	Net radiation	$W/m^2$
$R_{SI}$	Incoming short wave radiation	$W/m^2$
$R_S$	Incoming short wave radiation (including the effect of clouds)	$W/m^2$
$R_{So}$	Incoming short wave radiation under clear skies	$W/m^2$
$R_{SN}$	Net short wave radiation	$W/m^2$
$R_{SR}$	Reflected short wave radiation	$W/m^2$
$R_Q$	Surface runoff volume from the upstream drainage area	mm
$R_x$	Extraterrestrial short wave radiation	$W/m^2$
RH	Relative humidity	
S	Sunshine hours for the day	hour
$S_1$	Retention parameter associated with $CN_1$	mm

Uppercase Variables

Variable	Meaning	Unit
$S_2$	Retention parameter associated with $CN_2$	mm
$S_3$	Retention parameter associated with $CN_3$	mm
$S_o$	Maximum possible sunshine hours for the day	hour
$S/S_o$	Fraction of possible sunshine for the day	
$S_0$	Channel slope	m/m
$S_c$	Solar constant	
$S_m$	Sediment mass	Mg
$S_{m1}$	Incoming sediment mass	Mg
$S_{m2}$	Outgoing sediment mass	Mg
$S_{ov}$	Overland flow land surface slope	m/m
$S_{sc}$	The total sediment transport capacity mass	Mg
SAND	Sand content for a soil layer	
SED_RATE	Sediment yield rate (including all particle sizes) at the end of the field	Mg/m <sup>3</sup>
SED_TOT	Total sediment loss	Mg
SM	Moisture content for a soil layer at the beginning of a time period	
SMCX	Maximum soil moisture content	mm
T	Air temperature	°C
$T_D$	Dew point temperature	°C
$T_K$	Absolute temperature	°K
$T_c$	Time of concentration	hr
$T_{c,in\_cell}$	Time of concentration for the local contributions from the in-cell processes to the downstream end of the cell's receiving	hr

## Uppercase Variables

Variable	Meaning	Unit
	reach	
$T_{t,reach}$	Travel time through the reach segment	hr
$T_{t,reach\_in}$	Time of concentration at the reach inlet	hr
$T_{t,reach\_out}$	Time of concentration at the reach outlet	hr
$T_{t,cc}$	Travel time for the in_cell concentrated flow period	hr
$T_{t,ov}$	Travel time for the overland flow period	hr
$T_{t,scf}$	Travel time for the shallow concentrated flow period	hr
$T_{t,sf}$	Travel time for the concentrated flow period	hr
$Q$	Surface runoff	Mm or m <sup>3</sup>
$Q_{24}$	The spatially-averaged runoff volume for the 24-hour runoff event covering the drainage area to the cell outlet.	mm
$Q_b$	Bankfull discharge	m <sup>3</sup> /s
$Q_c$	Channel section discharge	m <sup>3</sup> /s
$Q_f$	Floodplain discharge	m <sup>3</sup> /s
$Q_o$	Average outflow discharge during a runoff event	m <sup>3</sup> /s
$Q_p$	Peak discharge	m <sup>3</sup> /s
$Q_s$	Sediment load as a function of time	Mg/s
$Q_{s,i}$	Sediment load at Gauss-Legendre time point $t_i$	Mg/s
$Q_t$	Total flow discharge	m <sup>3</sup> /s
$Q_w$	Water discharge	m <sup>3</sup> /s
$U$	Wind speed	m/s
$U_*$	Shear velocity at $x_1$	m/s
$V$	Velocity of flow at $Q_t$	m/s

## Uppercase Variables

Variable	Meaning	Unit
$V_c$	Velocity of flow of channel section at $Q_c$	m/s
$V_{cf}$	Velocity of flow for the concentrated flow segment	m/s
$V_f$	Velocity of flow of floodplain section at $Q_f$	m/s
$V_I$	Runoff event water volume	ha-m
$V_p$	Permanent pool volume	ha-m
$V_{Reach}$	Velocity of flow through a reach	m/s
$V_{scf}$	Velocity of flow for the shallow concentrated flow segment	m/s
$V_{cf}$	Velocity of flow for the concentrated flow segment	m/s
$W$	Trapezoidal channel bottom width	m
$W_1, W_2$	Weights used in calculating the retention variable, $S$ , as a function of soil moisture content	
$W_b$	Bankfull top width	m
$W_f$	Floodplain width	m
$W_H$	Hydraulic flow width	m
$WI$	Water input to the soil	mm
$W_m$	Water mass from upstream drainage area	Mg
$WP$	Wilting point for a soil layer	
$Z$	Trapezoidal channel side slope	m/m
$Z_c$	Elevation	m

## Lowercase Variables

Variable	Meaning	Unit
a, b	Input coefficient and exponent for the impoundment stage-storage relationship	

## Lowercase Variables

Variable	Meaning	Unit
$a'$	Mean atmospheric transmission coefficient for dust-free moist air after scattering only	
$a''$	Mean distance transmission coefficient for dust-free moist air after scattering and absorption	
$c, d$	Input coefficient and exponent for the impoundment stage-storage relationship	
$d_e$	Equivalent depth of the impermeable layer below the drain	m
$\bar{d}$	Average distance between the earth and the sun	km
$d_b$	Bankfull depth of flow	ft
$d_c$	Channel section depth of flow at $Q_c$	m (ft?)
$d_{es}$	Actual distance between the earth and the sun	km
$d_f$	Floodplain section depth of flow at $Q_f$	m (ft?)
$d_h$	Hydraulic depth	ft (m?)
$d_r$	Relative distance of the earth from the sun	
$d_{sr}$	Total depletion coefficient of the direct solar radiation by scattering and absorption due to dust	
$d_t$	Total depth of flow at $Q_t$	m (ft?)
$d_w$	Hydraulic depth	m
$e$	Water vapor pressure	Mb (kPa?)
$e_o$	Orbital eccentricity = 0.0167238	
$e_{sat}$	Saturation vapor pressure	kPa
$f$	Porosity for each soil layer	
$g$	Gravitational constant, $9.81 \text{ m/s}^2$	
$h$	Depth of saturation above the impervious layer	m

Lowercase Variables

Variable	Meaning	Unit
$h_o$	Permanent pool stage	m
$h_s$	Sunrise/sunset hour angle	Radians
$i$	First Gauss-Legendre time point	
$k$	Transport capacity factor	
$m$	Midpoint water table height above the drain	m
$m_a$	Optical air mass	
$n$	Manning's retardance	
$n_c$	Manning's n for channel flow	
$n_f$	Manning's n for the floodplain	
$n_{ov}$	Manning's n for overland flow	
$r$	Radius of the drain tube	m
$t$	Time to the beginning of runoff	s
$t_1$	Time at the beginning of the time period	s
$t_2$	Time at the end of the time period	s
$t_b$	The time to the base of the hydrograph	s
$t_d$	Detention time for runoff event	s
$t_\eta$	Critical effective transport factor time	s
$q_c$	Channel section unit discharge	$m^3/s/m$
$q_{drain}$	Drainage flux	mm/time period
$q_f$	Floodplain section unit discharge	$m^3/s/m$
$q_\eta$	Critical unit-width water discharge below which the effective transport factor ( $\eta$ ) is 1 and above which it is calculated	$m^3/s/m$



## Lowercase Variables

Variable	Meaning	Unit
	according to Equation 6-9	
$q_p$	Unit-width peak water discharge	$m^3/s/m$
$q_p, T_c > 0$	Peak discharge at the location of interest	mm/hr
$q_p, T_c = 0$	Peak discharge for time of concentration of zero	mm/hr
$q_s$	Unit-width sediment load	Mg/s/m
$q_{s1}$	Upstream unit-width sediment discharge at $x_1$	Mg/s/m
$q_{s2}$	Downstream unit-width sediment discharge at $x_2$	Mg/s/m
$q_{sc}$	Unit-width sediment transport capacity	Mg/s/m
$q_t$	Total unit discharge	$m^3/s/m$
$q_w$	$Q_w/W$ , unit-width water discharge	$m^3/s/m$
$v_f$	Particle fall velocity	m/s
$v_w$	Flow velocity of water	m/s
$w$	Precipitable water content	
$w_f$	Gauss-Legendre weight	

## Symbols

Variable	Meaning	Unit
$\alpha$	Total reflectivity of the ground	
$\alpha_c$	A constant defined by Equation 5-63	
$\delta$	Sun declination	Radians (?)
$\varepsilon$	Emissivity of the ground and vegetative surface	
$\varepsilon_a$	Atmospheric emissivity	

$\phi$	latitude	radians
$\gamma$	Psychrometric constant	kPa/°C
$\gamma_p$	Particle density	Mg/m <sup>3</sup>
$\gamma_w$	Water density, equal to 1.00	Mg/m <sup>3</sup>
$\eta$	Effective sediment transport factor	
$\kappa$	Von Karman's turbulent-flow mixing-length constant (can be assumed as 0.4)	
$\lambda$	Brooks-Corey (1964) parameter	
$\theta$	Earth orbital position about the sun	radians
$\sigma$	Stefan-Boltzmann constant	W/m <sup>2</sup> /K <sup>4</sup>
$\tau$	Bed shear stress	Mg/m <sup>2</sup>
$\Delta$	Slope of saturation vapor pressure – temperature curve	kPa/°C

## 1. INTRODUCTION

The development of a continuous version of the single event Agricultural NonPoint Source model (AGNPS) watershed model (Young et al, 1989) has been in progress, in one form or another, since the 1980's. This continuous version, the Annualized Agricultural NonPoint Source model (AnnAGNPS) (Cronshey and Theurer, 1998), is available through the Internet WEB address:

<http://www.sedlab.olemiss.edu/AGNPS.html>

Since AnnAGNPS is designed to analyze the impact of non-point source pollutants from predominately agricultural watersheds on the environment, other models that simulate additional processes have been integrated with AnnAGNPS. These integrated models have been developed within the AGNPS suite of modules (Figure 1-1). Each module provides information needed by other modules to enhance the predictive capabilities of each. The modules in AGNPS include: (1) AnnAGNPS, a watershed-scale, continuous-simulation, pollutant loading computer model designed to quantify & identify the source of pollutant loadings anywhere in the watershed for optimization & risk analysis; (2) Center for Computational Hydroscience and Engineering – One Dimensional channel model (CCHE1D) (Wu and Vieira, 2000) is a stream network program designed to integrate the impact of upland loadings and channel characteristics on the evolution of the stream channel; (3) Conservational Channel Evolution and Pollutant Transport System (CONCEPTS) (Langendoen et al, 1998, and Langendoen, 2001), a stream corridor computer model designed to predict & quantify the effects of bank erosion & failures, bank mass wasting, bed aggradation & degradation, burial & re-entrainment of contaminants, and streamside riparian vegetation on channel morphology and pollutant loadings; (4) The Stream Network TEMPerature model (SNTEMP) (Theurer et al, 1984), a watershed-scale, stream network, water temperature computer model to predict daily average, minimum, & maximum water temperatures; (5) The Sediment Intrusion & Dissolved Oxygen (SIDO) model (Alonso et al, 1996), a set of salmonid life-cycle models designed specifically to quantify the impact of pollutant loadings on their spawning & rearing habitats as well as include other important life-threatening obstacles; and (6) an economic model that determines the net economic value of Pacific Northwest salmonids restored to either the commercial or recreational catch.

As part of the input data preparation process there are a number of modules that support the user in developing the needed AGNPS databases. These include: (1) the Topographic ParameteriZation program (TOPAZ) (Garbrecht and Martz, 1995), to generate cell and stream network information from a watershed digital elevation model (DEM) and provide all of the topographic related information for AnnAGNPS. A subset of TOPAZ, TOPAGNPS, is the set of TOPAZ modules used for AGNPS. The use of the TOPAGNPS generated stream network is also incorporated by CONCEPTS to provide the link of where upland sources are entering the channel and then routed downstream; (2) The Agricultural watershed FLOWnet generation program (AGFLOW) (Bingner et al, 1997; Bingner et al, 2001a) is used to determine the topographic-related input parameters for AnnAGNPS and to format the TOPAGNPS output for importation into the form needed by AnnAGNPS; (3) The Generation of weather Elements for Multiple applications (GEM) program (Johnson et al, 2000) is used to generate the climate information for AnnAGNPS; (4) The program Complete Climate takes the information from GEM and formats the data for use by AnnAGNPS, along with determining a few additional parameters; (5) A graphical input editor that assists the user in developing the AnnAGNPS database (Bingner et al, 1998); (6) A visual interface program to view the TOPAGNPS related geographical information system (GIS) data (Bingner et al, 1996); and, (7) A conversion program that transforms a single event AGNPS 5.0 dataset into what is needed to perform a single event simulation with AnnAGNPS. In addition to these input modules, there are procedures that utilize the ArcView program to facilitate the use of TOPAGNPS. There is an output processor that can be used to help analyze the results from AnnAGNPS by generating a summary of the results in tabular or GIS format.

This documentation will provide the details and background on the AnnAGNPS program. Many individuals have been involved in the development of AnnAGNPS with

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**AnnAGNPS: Technical Descriptions**

**DRAFT**

File Name: Technical\_Documentation.doc

Table 1-1 listing those responsible for the various subprojects.

Table 1-1 Development subproject leaders of AnnAGNPS.

Subproject	Developer (s)
Chemical	Terry Sobecki and William Merkel
Climate	Fred Theurer and William Merkel
Data_Structures	Roger Cronshey
Dates_and_Days	Roger Cronshey and Fred Theurer
Error and Warning messages	Roger Cronshey
Feedlot	Kevin Baker
Gully	Kevin Baker
Impoundments	Fred Theurer and Jenny Zhen
Irrigation	David Garen and Gary Conaway
Pesticide	Frank Davis
Point_Source	Roger Cronshey
Reach_Processes	Fred Theurer, Vance Justice, and Eddy Langendoen
Read_Input	William Merkel and Roger Cronshey
Revise_CN	David Garen
RUSLE	Frank Geter and George Foster
Sediment Distribution	Frank Geter and Roger Cronshey
Soil_Composite	Fred Theurer
Soil_Moisture	David Garen
System(Cleanup)	Roger Cronshey
System(Preparation)	Roger Cronshey
System(Simulation)	Roger Cronshey
Testing for Model Verification	Roger Cronshey
Tile Drainage and Subsurface Flow	Yongping Yuan and Ron Bingner
Utilities	Roger Cronshey
Winter_Routines	Resa Sabavi and Fred Theurer

### **AnnAGNPS**

AnnAGNPS is the pollutant loading modeling module designed for risk and cost/benefit analyses. It is a batch-process, continuous-simulation, surface-runoff, pollutant loading (PL) computer model written in standard ANSI Fortran 90, which provides for studies of very large watersheds. The model was developed to simulate long-term sediment & chemical transport from ungaged agricultural watersheds. The basic modeling components are hydrology, sediment, nutrient, and pesticide transport. Land area (cell) representations of a watershed are used to

provide landscape spatial variability (Figure 1-2). Each cell homogeneously represents the landscape within its respective land area boundary (Figure 1-3). The physical or chemical constituents are routed from their origin within the land area and are either deposited within the stream channel system or transported out of the watershed. Pollutant loadings (PLs) can then be identified at their source and tracked as they move through the watershed system (Figure 1-4). The data sections used for the continuous AnnAGNPS are integrated together through a relational database approach (Figure 1-5). The data sections used for the single-event version of AnnAGNPS are similarly used to describe the input parameters for the model simulation (Figure 1-6).

The philosophy of the development of AnnAGNPS has been to maintain the simplicity of the single event version, AGNPS, while enhancing the features that are needed for a continuous simulation. The use of NRCS or ARS technology was adopted whenever feasible to ensure acceptance and readily available databases nationwide. This provides a watershed model that incorporates currently accepted science and databases from any location in the country, capable of simulating most of the management practices that are applied on farms.

The main components within AnnAGNPS are the incorporation of the SCS curve number technique (USDA, 1972) used to generate daily runoff and RUSLE 1.05 technology (Renard et al, 1997) to generate daily sheet and rill erosion from fields (Geter and Theurer, 1998). The parameters that are used for RUSLE are also used within AnnAGNPS. Each cell within AnnAGNPS can have different RUSLE parameters associated with describing the farm operations. This can provide a spatial and temporal variation of the management practices associated with a watershed system. Sheet and rill erosion is calculated for each runoff event during a user-defined simulation period and averaged for this same time period. A runoff event can occur from any combination of rainfall, snowmelt, and irrigation. All subsequent sediment is routed throughout the stream system down to the watershed outlet. An account of each individual field contribution to the sediment yield at any user-defined stream location can be determined.

Since RUSLE is used only to predict sheet and rill erosion and not field deposition, a delivery ratio of the sediment yield from this erosion to sediment delivery to the stream is needed. The Hydro-geomorphic Universal Soil Loss Equation (HUSLE) is used for this procedure (Theurer and Clarke, 1991). The procedure was initially developed to predict the total sediment yield at a user-defined point in the stream system using spatially- and time-averaged RUSLE parameters; and to ensure that sheet and rill-related sediment was properly calculated. This procedure utilizes the time of concentration ( $T_c$ ) that is determined from parameters from AGFLOW and TOPAGNPS. Additionally, the instantaneous peak discharge of the runoff hydrograph is required for  $T_c$  and can easily be calculated using TR-55 (SCS, 1986) technology incorporated within AnnAGNPS.

Since RUSLE is used to calculate the amount of sheet and rill erosion and HUSLE is used to determine the delivery ratio for total sediment, the only factor remaining is to determine the particle-size distribution of the deposition in the field (Bingner & Theurer, 2001b). This allows for the particle-size distribution of the sediment yield of the sheet and rill erosion to the receiving reach of the stream system.

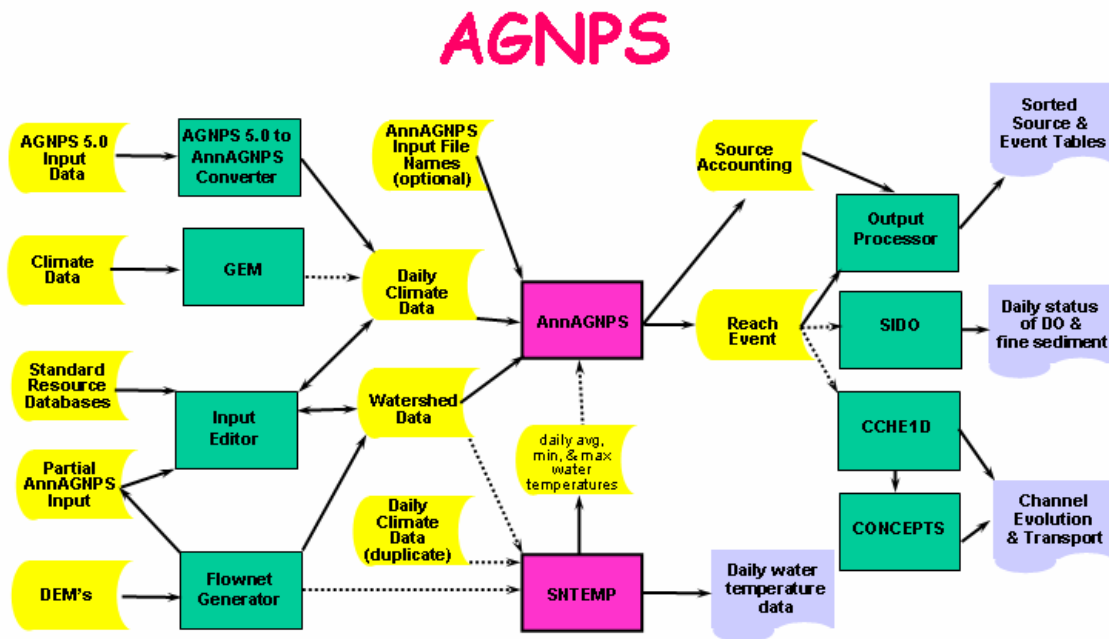
The particle-size of the sediment deposited within the field is assumed to be proportional to the mass fall velocity of the individual particle-size classes. Since the density of both the large and small aggregates are noticeably less than the discrete particles of clay, silt, and sand, a product of the respective densities times its fall velocity is used to represent each particle-size class. This is called the deposition mass rate and has units of mass per length squared per time. The resulting deposition mass rate values for each particle-size class are summed and then normalized with respect to this sum. These normalized values are called deposition rate ratios. They are further normalized with respect to the smallest value, which will normally be clay, and are called the deposition ratio mass rate. From these calculations, the field deposition is determined, but careful consideration is given to exhausting any of the particular particle-size classes; i.e., when any of the particle-size classes are totally deposited, the calculations begin again at that point along the landscape with that particle-size class eliminated from further calculations. A modified Einstein equation is used to transport the sediment in the stream system and uses the Bagnold equation (Bagnold, 1966) to determine the sediment transport capacity of the flow (Theurer and Cronshey, 1998).

The soil moisture, nutrients, and pesticides are also tracked within each field and subsequent movement downstream. Soil databases developed by the NRCS are used to describe each cell or field. Crop information developed for RUSLE is also needed by AnnAGNPS, along with additional parameters that describe how the crop uses nutrients from the soil.

The major chemical reach routing processes have been updated to include partitioning between absorbed and dissolved states. The reach routing processes include: (a) the fate & transport of nitrogen & phosphorus; (b) a separate reach routing routine for organic carbon; and (c) the fate and transport for an unlimited number of individual pesticides.

From any point in the watershed, any loadings that are produced from upstream can be determined along with the location that they originated. This can be used to provide source accounting information to planners to assess the impact of various management practices downstream. This can be used in the development of management plans to meet the needs of total maximum daily load programs (TMDLs) that states are having to formulate to meet EPA guidelines for the 1972 Clean Water Act.

Included in this documentation are chapters describing in detail the runoff and sediment processes within AnnAGNPS; the input specifications; the output specifications; and, an AGNPS user's guide.

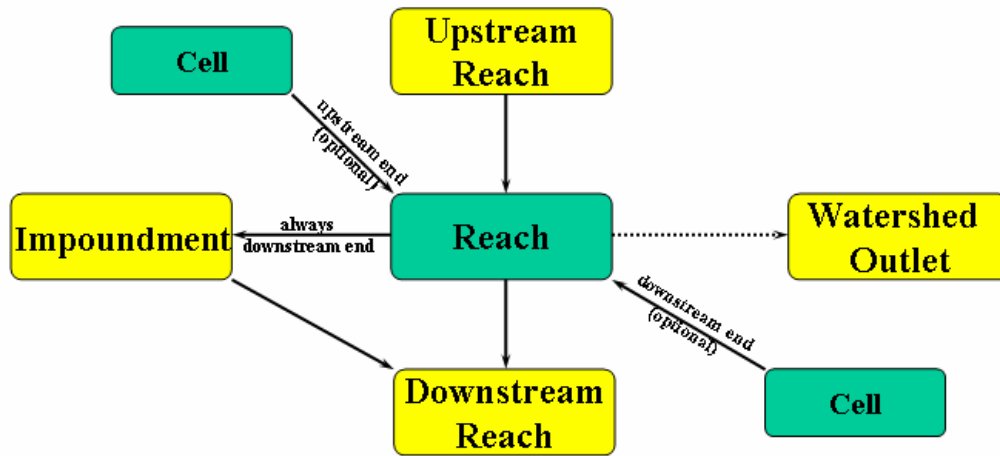


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Figure 1-1. The suite of modeling components contained within AGNPS.

# AnnAGNPS: runoff event processes

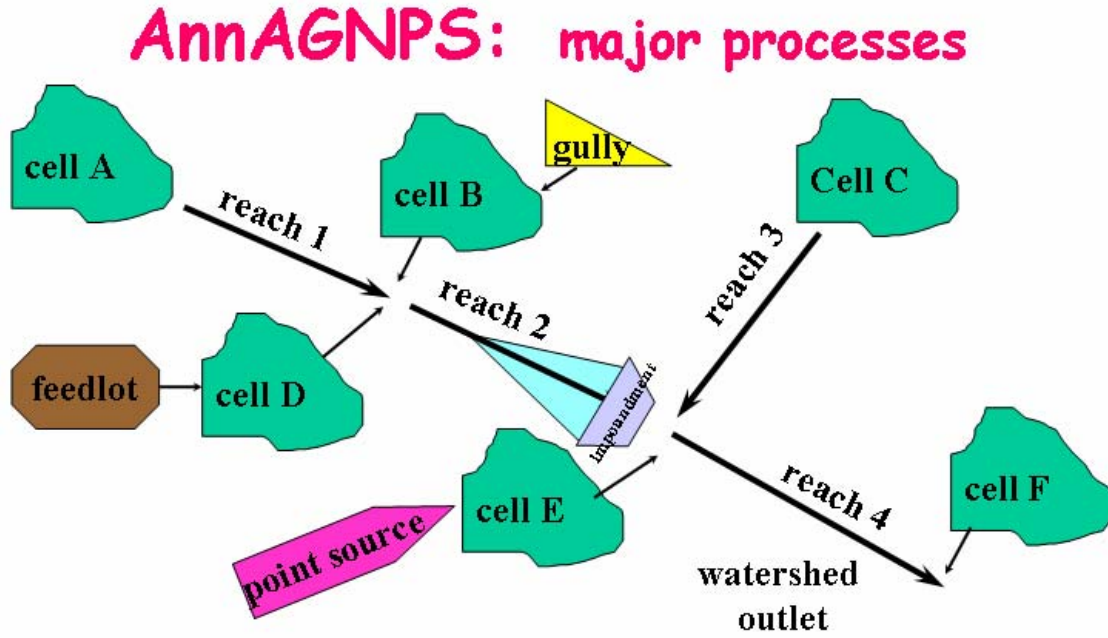


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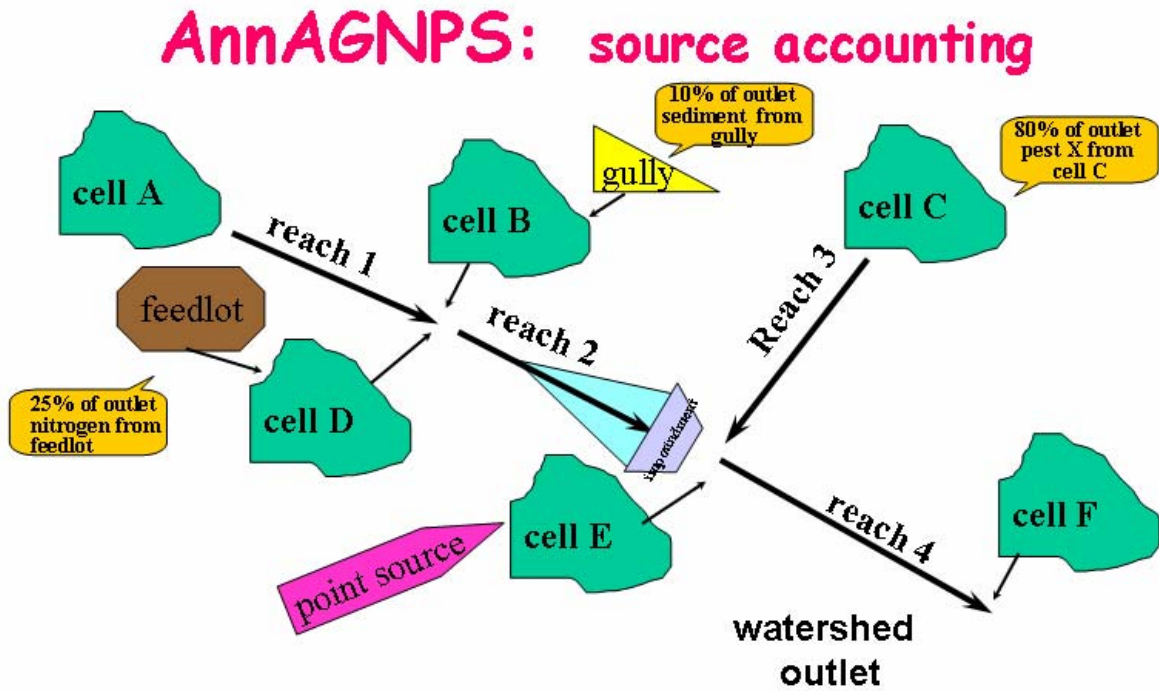
Figure 1-2. Runoff event processes within AnnAGNPS.



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Figure 1-3. Major processes simulated within AnnAGNPS.



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Figure 1-4. Built into AnnAGNPS is the capability to track pollutants using source accounting techniques.

# AnnAGNPS Input Header Section Links (AnnAGNPS mode)

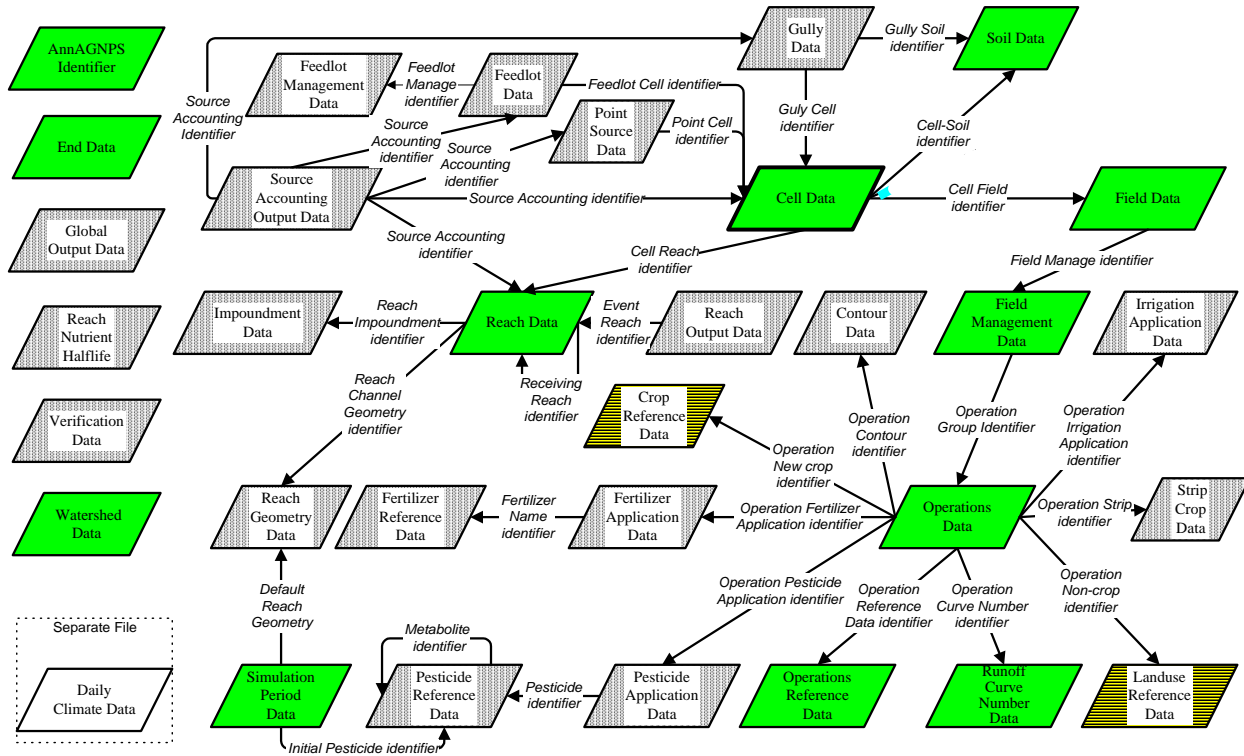


Figure 1-5. Flowchart showing the relational integration of the data sections used within the continuous AnnAGNPS. The green boxes indicate required data sections. The yellow and black bar boxes indicate either one or the other data sections are required.

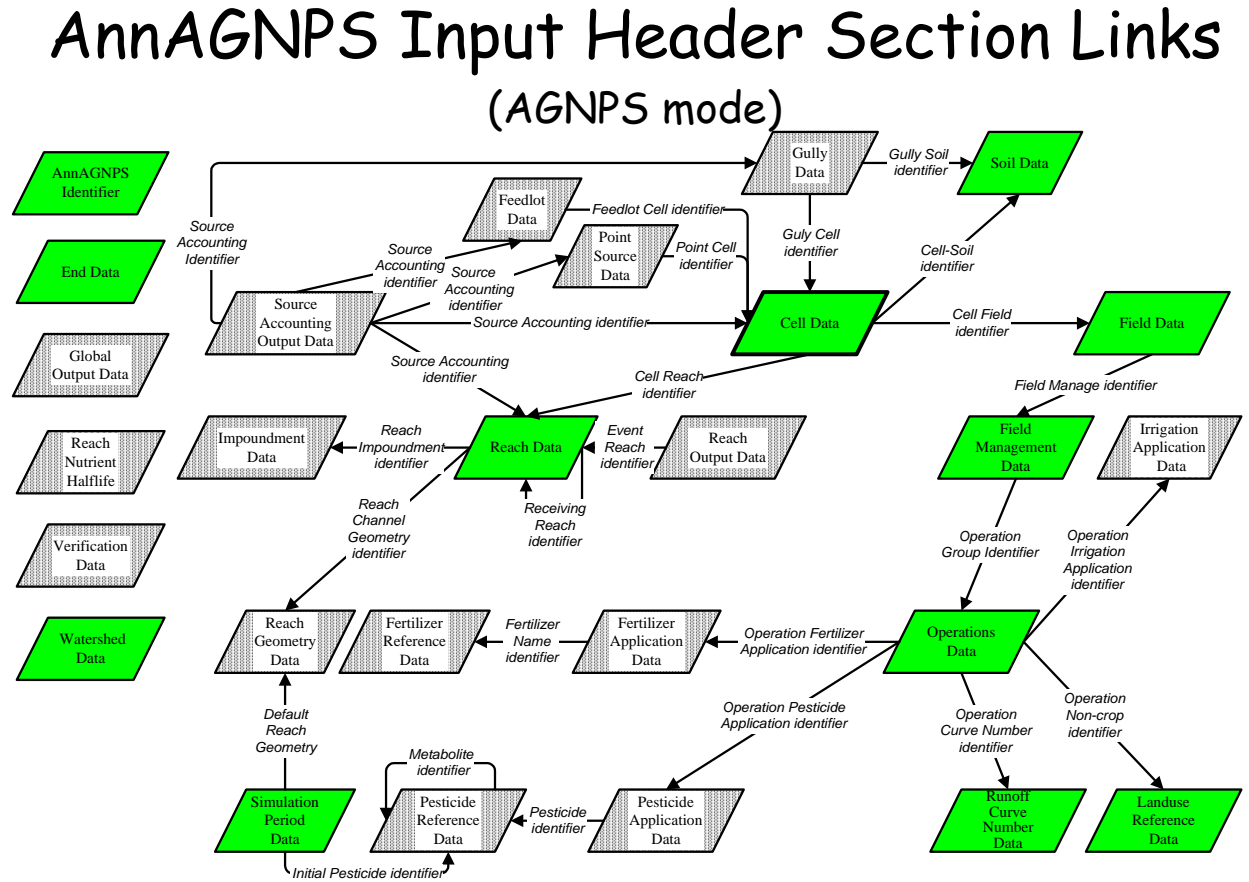


Figure 1-6. Flowchart showing the relational integration of the data sections used within the single-event version built within AnnAGNPS (AGNPS mode). The green boxes indicate required data sections.

## 2. CLIMATE

### 2.1 Precipitation

Precipitation is the water equivalent of what falls from the sky as either rain or snow. The source of this data is from the climate files. It is given as a daily (24-hour) amount in millimeters. Climate data used with AnnAGNPS may be historically recorded data, synthetically generated data, or a combination of the two. Daily precipitation, maximum and minimum temperature, dew point temperature, sky cover, and wind speed are the data requirements of AnnAGNPS (wind direction is currently not used). Careful consideration needs to be given to the source of climate data and how many years are analyzed. Climatic data are of great importance in AnnAGNPS. Daily precipitation is the prime driver of the hydrologic cycle, temperatures are used to define frozen conditions, and with the remaining climate elements are used in computing potential evapotranspiration.

### 2.1.1 Rainfall

Rainfall is that portion of the precipitation that falls directly from the sky in a liquid form. The units are in millimeters.

### 2.1.2 Snowfall

Snowfall is that portion of the precipitation that falls directly from the sky in a solid form. The units are in millimeters of snow-water equivalent. Precipitation falls as snow if the average air temperature for the specified time period is less than 0° C.

### 2.1.3 Variation of precipitation with cell elevation

Precipitation may be varied with elevation in AnnAGNPS by entering certain data in the climate data input file. The user enters the climate station elevation, elevation difference elevations (2), and elevation rain factors (2) in order for precipitation to vary with elevation. The first elevation difference entered must be less than the second elevation difference.

To allow the user the most flexibility, the following options are available:

1. If both elevation differences and elevation rain factors parameters are left blank, then the climate station precipitation is used for all cells. If the user desires to adjust precipitation with elevation, both elevation differences and elevation rain factors must be entered (even one blank will trigger an error message).
2. The two elevation differences entered may be both below, one below and one above, or both above the climate station elevation. In the general case that either of the elevation differences do not equal the climate station elevation, these three points are used to define two line segments. Whichever of the three elevations is in the middle is the point where the slope of the elevation versus factor (multiplier of precipitation) relationship may change. In this case, the factor associated with the climate station elevation is assumed to be 1.0. For example, if a cell elevation is the same as the climate station, the precipitation for the cell will equal that precipitation read from the climate data input file. For any other cell, if it is below the middle elevation (where the slope changes) the equation for the lower line segment is used to interpolate or extrapolate to compute the precipitation on the cell. If the cell elevation is above the middle point, the upper line segment is used to interpolate or extrapolate to compute the precipitation on the cell.
3. In the more unusual case where one of the elevation differences is equal to the climate station elevation, the two elevation differences and associated factors are used to define one line segment relating precipitation with elevation. In this case, the assumed factor (multiplier) of 1.0 at the climate station elevation is ignored. The user can enter any factor associated with the two elevation differences entered. For example, if the user wants to run AnnAGNPS with increased or decreased precipitation from the climate data file, one of the elevation differences is set equal to the climate station elevation and the factor is set at the multiplier of increase or decrease.
4. With extrapolation and possible errors in entering data, there may be a possibility that the extrapolation of cell precipitation could be a negative number. This could happen for example if an error was made in entering the cell elevation, climate station elevation, elevation difference, or elevation factor. It could also be caused by errors in estimating the rate of change of precipitation with elevation. To check for this error, the minimum cell elevation is determined during data preparation. If the extrapolated precipitation would be negative, an error is produced. The AnnAGNPS run will continue through data preparation but will not begin simulation.
5. The user should plot the desired elevation versus precipitation relationship (and identify the climate station elevation and the range of cell elevations) before entering the elevation differences and elevation rain factors into the AnnAGNPS input file. This will provide the user with confidence that the precipitation over the watershed is computed as expected. Daily precipitation and monthly normal precipitation are adjusted with elevation according to the same elevation differences and elevation rain factors.

### 2.1.4 frequency

#### 2.1.4.1 [precipitation \(Gumbel Distribution\)](#)

## Gumbel Distribution of Maximum Daily Precipitation from Daily Precipitation Data

### Assumptions:

- If a frequency distribution of maximum 24-hour or maximum daily precipitation data is readily available, it should be used in lieu of the following procedure.
- The following procedure is independent of any computer application using precipitation data; it should not be imbedded in a water quality model but should be used once when new precipitation data is obtained.
- All precipitation data are continuous (no missing periods) and any data exceptions (trace amounts, estimated amounts or lumped days) have been rectified
- Precipitation data are available in complete years whether they are based on calendar or water year.
- The entire period of record is used to establish the frequency curve, regardless of whether a shorter period will be used in a simulation run.
- Each daily precipitation is independent of any precipitation on either the day before or day after.

### Procedure:

1. Determine number of years in the record period ( $N_{yr}$ ).

```

 $N_{yr} = 0$ 
Loop (i) for each day in record
  If Day(i) = January 1st then  $N_{yr} = N_{yr} + 1$ 

```

2. Make partial duration series of  $N_{yr}$  largest values Keep ordered highest to lowest ( $Values_{hi}$ ).

```

Loop (i) from 1 to  $N_{yr}$ 
   $Values_{hi}(i) = 0.0$ 

Loop (i) for each day in period of record
  Loop (j) for 1 to  $N_{yr}$ 
    If Daily(i) <  $Values_{hi}(j)$  then
       $k = 0$ 
      Loop (l) for j to  $N_{yr}$ 
         $k = k + 1$ 
         $Values_{hi}(N_{yr}-k+1) = Values_{hi}(N_{yr}-k)$ 
       $Values_{hi}(j) = Daily(i)$ 
    End (j) loop

```

3. Determine mean of partial duration series.

```

 $Sum = 0$ 
Loop (i) for 1 to  $N_{yr}$ 
   $Sum = Sum + Values_{hi}(i)$ 
 $X = Sum / N_{yr}$ 

```

4. Determine standard deviation of partial duration series (S)

```

 $Sum = 0$ 
Loop (i) for 1 to  $N_y$ 
   $Sum = Sum + (Values_{hi}(i) - X)^2$ 
 $S = \sqrt{Sum / (N_{yr} - 1)}$ 

```

5. Determine Gumbel distribution fitting parameters: central tendency (mode) ( $\mu$ ) and dispersion ( $\alpha$ )

$$\alpha = 1.282 / S$$

$$\mu = \bar{X} - 0.577 / \alpha$$

6. Solve for selected precipitation points along frequency curve ( $P_x$ ).

Loop (i) for 1 to Number of Frequencies

$$P_x(i) = \mu + \omega(i) / \alpha$$

Table 2.1.4-1 variate values were derived from the relationship :

$$\text{Probability} = 1 - e^{-e^{\omega}}$$

Reference for the Gumbel distribution is pages 273-275 and Table A.5 in **Probability, Statistics and Decision for Civil Engineers** by Jack R. Benjamin and C. Allin Cornell 1970

**Table 2.1.4-1: Precalculated Probability-Variate Values**

Return Period	Probability	Variate ( $\omega$ )
2 yr	.50	0.36651292
5 yr	.20	1.49993999
10 yr	.10	2.25036733
25 yr	.04	3.19853426
50 yr	.02	3.90193865
100 yr	.01	4.60014925

7. Retain precipitation frequency data with the daily data set for use in application models

**Table 2.1.4-2: Definitions**

Symbol	Definition	Units
$\alpha$	Gumbel distribution dispersion parameter	
$\mu$	Gumbel distribution central tendency parameter (mode).	
$\omega( )$	Gumbel distribution variate for selected return periods or probabilities.	
Daily( )	Daily precipitation amount for each day in the weather record.	inches
Day( )	Day of the year for a daily precipitation value in weather record	
i	Loop counter and array pointer	
j	Loop counter and array pointer	
k	Array pointer	
l	Loop counter	
$N_{vr}$	Number of complete years in the precipitation record	
$P_x( )$	X-yr precipitation based on Gumbel distribution fit.	inches
S	Standard deviation (square root of variance) of sample data.	inches
Sum	Temporary storage of summation during the summing process. Used in calculation of the mean and variance (double precision required)	inches
Values <sub>hi</sub> ( )	The highest daily precipitation values from the period of record. These values represent a partial duration series equal in length to the number of years of record in the weather station record.	inches
$\bar{X}$	Arithmetic mean of the sample data.	inches

## 3. IRRIGATION SYSTEMS

Irrigation systems within AnnAGNPS consist of three types:

- Surface Irrigation
- Sprinkler Irrigation
- Trickle Irrigation

Each of these systems is further described in the following sections.

### 3.1 Surface Irrigation Systems

Surface Irrigation systems can consist of:

- border, level or graded
- furrow, block irrigated w/open ends
- furrow, alternate furrow w/open ends
- furrow, block irrigated w/blocked ends
- furrow, alternate furrow w/blocked ends
- furrow, surge irrigated

#### 3.1.1 Border Irrigation, Level or Graded

Border irrigation applies irrigation water to the soil surface by advancing and/or ponding a given depth of water over the soil surface for infiltration. This form of irrigation is accomplished with the use of borders for containment of all waters. No runoff or sediment would be expected from this condition and it acts as a sink for both irrigation and precipitation waters.

#### 3.1.2 Furrow Irrigation, With Open Ends

Furrow irrigation is the application of irrigation water to the soil surface through the use of small channels placed between crop rows. Irrigations may occur on every row or on alternating rows. When on alternating rows, the antecedent moisture condition increases near equally for both irrigated and non irrigated furrows. Runoff and sediment yield will occur from both irrigation and precipitation on the irrigated furrows and only precipitation runoff and sediment yield will occur on the non irrigated furrows.

#### 3.1.3 Furrow Irrigation, With Blocked Ends

This form of irrigation is very similar to normal furrow irrigation except that the ends of the furrow are blocked and runoff waters and sediment are contained within the furrow. When alternate furrow irrigation is used, none irrigation furrows may or may not be blocked. When all are blocked, the total field is contained and would act as a sink. Generally if furrow blocking is applied, all field furrows are blocked.

#### 3.1.4 Surge Irrigation

Surge irrigation is a modification of furrow irrigation where water is pulsed down the furrow with on and off cycles, that establishes prewetted conditions for the next surge. Proper application allows for the near even distribution of irrigation depths along the furrow and significantly reduced tailwater runoff and sediment yield.

### 3.2 Sprinkler Systems

For sprinkler systems, the following systems can be defined:

- handline system
- wheelline system
- solid set system



- set place big gun system
- moving big gun system
- center pivot system (includes LEPA)
- linear move system

### 3.2.1 Handline, Wheelline, and Solid Set Sprinkler Systems

The application of water uniformly to a soil surface through the use of sprinkler nozzles fixed on a lateral line. Uniform application is achieved by moving lines by hand (handline) or mounted on wheels (wheel lines) an established distance based on sprinkler overlap for uniformity. Uniformity can also be achieved by permanently installing lines with nozzles (solid set) at design distances.

### 3.2.2 Set Place and Moving Gun Systems

These systems apply water to a circular area using high pressure and flows. The set system is moved into position and remains at the same location during an irrigation application. Moving big guns are attached to a wench cable or supply line and apply water while in motion created from reeling in the cable or supply hose. These systems are generally restricted to flatter slopes or permanent crops, such as pasture, on steeper slopes.

### 3.2.3 Center Pivot Systems

Center pivot systems apply water to the soil surface from sprinklers or emitters attached to a tower that rotates in a circular fashion above the ground surface. The Low Energy Precision Application (LEPA) system is a modification that applies water on or directly above to soil surface in furrows through the use of drop tubes from the tower and use of near zero pressure. LEPA systems are generally applied on 1% or less slope, treated with reservoir tillage or pits, seldom producing runoff or sediment yield off the field.

### 3.2.4 Linear Move Systems

Linear move systems apply water to the soil surface from sprinklers or emitters attached to a tower that moves along a direct line while applying irrigation water above or on the ground surface. These systems can also be LEPA equipped.

## 3.3 Trickle Irrigation Systems

Trickle irrigation is the application of irrigation waters on or near the soil surface through the use of emitters, bubblers, or spray devices. Water is generally applied only to the crop "drip line" (effective canopy cover) and not to an entire field surface.

## 3.4 Surface Irrigation – Water, Infiltration and Runoff Processes

Surface irrigation operations add moisture to the fields where AnnAGNPS calculates the amount of water that is effectively added to the soil profile during an irrigation event and any resulting surface runoff. The assumptions involved are that the intake value of the soil is held constant throughout the irrigation season and that the average depth applied to the field is uniform throughout the furrow length.

Surface runoff will be reduced when the tailwater recovery system option has been tagged. The factor value for tail water recovery should not exceed 0.90, with general ranges being 0.65 to 0.85 recovery efficiencies.

## 3.5 Surface Irrigation – Sediment Processes

The total irrigation-induced sediment loss and the resulting distribution by particle size class are determined within AnnAGNPS. Irrigation-induced erosion occurs primarily for furrow irrigation where the ends of the furrows are open. Irrigation runoff and sediment loss are therefore only considered for open-end furrow irrigation methods. If an irrigation using one of these methods occurs for a given grid cell on a given day, whether due to an automatic or manual interval schedule or due to a fixed-date manual irrigation, the total sediment loss (SED\_TOT) is calculated as

$$SED\_TOT = SED\_RATE \cdot R_E \cdot A_{cell} \quad \text{Equation 3-3-1}$$

$R_E$  is the effective depth, taking into account the fraction of the field receiving irrigation water,  $A_{cell}$  is the area of the field (cell), and  $SED\_RATE$  is the sediment yield rate (including all particle sizes) at the end of the field. The total sediment loss is disaggregated into five particle size classes using a simple fractioning approach. The same fractions applied for erosion that is determined from RUSLE are used here.

## 4. GENERATING CLIMATE DATA FOR ANNAGNPS

**GEM** (climate generator) is a program that generates synthetic climatic data for locations in the United States. It can be downloaded from the web site. **GEM** generates daily precipitation, maximum and minimum temperature, and solar radiation. AnnAGNPS requires six climatic elements for each day which are precipitation, maximum and minimum temperature, sky cover, average daily dew point temperature, and average daily wind speed (wind direction is currently not used). **GEM** is recommended to be run whether or not historical climatic records are available for use. Detailed instructions for running **GEM** can be downloaded from the web site.

The information produced by **GEM** is not in the format needed for input to AnnAGNPS nor is the information complete. The format of data needed by AnnAGNPS is contained in the Input Data Specifications. AnnAGNPS does not require solar radiation. Daily dew point temperature, sky cover, and wind speed are needed to complete the climate series for use with AnnAGNPS. An interim program named **Complete\_Climate** was written to generate the missing climate elements and format the climatic data for input to AnnAGNPS. Input to **Complete\_Climate** includes the **GEM** output file generated previously and a file created by the user containing monthly average sky cover, dew point temperature, and wind speed. These three remaining climate elements are generated for each day based on the monthly averages. These averages are available from a climatic data atlas or climatic summary for the desired location. The output file of **Complete\_Climate** then contains all six climatic elements (three generated by **GEM** and three generated by **Complete\_Climate**).

Currently, the input and output files have fixed file names. The **GEM** output file name must be **GEM\_output.inp**. The file with the monthly information is named **MonClim.inp** (an example of file contents and format follows). The output file of **Complete\_Climate** is named **DayClim.inp** (the default climate file name for input to AnnAGNPS). With respect to English and SI (Metric) units, both of the input files to **Complete\_Climate** must be in the same units (if not, then the climate input to AnnAGNPS will be in mixed units).

## 5. WATER

The hydrology model is based on a water balance equation, which is based on a simple bookkeeping of inputs and outputs of water during a day. The erosion calculation from RUSLE is based on whether there has been any runoff for each day. The amount of soil moisture is used to determine the effect of the SCS curve number and is thus the basis for the surface and subsurface runoff in the system. The soil moisture balance is simulated for two AnnAGNPS composite soil layers. The first one is 203.2 mm in depth from the surface and is called tillage layer, as defined by RUSLE. The second layer is from the bottom of the tillage layer to either an impervious layer or the user supplied depth of the soil profile.

The following equation is used to determine soil moisture for each time step in a day.

$$SM_{t+1} = SM_t + \frac{WI_t - Q_t - PERC_t - ET_t - Q_{lat} - Q_{tile}}{Z} \quad \text{Equation 5-1}$$

### Where:

$SM_t$  = moisture content for each soil layer at beginning of time period (fraction),

$SM_{t+1}$  = moisture content for each soil layer at end of time period (fraction),

$WI_t$  = water input, consisting of precipitation or snowmelt plus irrigation water (mm),

$Q_t$  = surface runoff (mm),

$PERC_t$  = percolation of water out of each soil layer (mm),

$ET_t$  = potential evapotranspiration (mm),

$Q_{lat}$  = subsurface lateral flow (mm)

$Q_{tile}$  = tile drainage flow (mm)

$Z$  = thickness for soil layer (mm), and

$t$  is the time period.

Because of the strong nonlinear dependence of the rate of percolation and evapotranspiration on soil water content, soil moisture is calculated using a sub-daily time steps, as a daily time step of 24 hours would be too large to simulate this adequately. A simple constant-time-step procedure is used. The day is therefore divided into several time steps of equal length, and the moisture input is considered to be uniform during the course of each time step. The number of time steps within a day is specified by the user, with a default value of 8 time steps.

The soil moisture is considered to be valid for the beginning of a day, while the inputs and outputs occur during the course of the day. For the second soil layer, WI is the percolation from the first layer, and  $Q = 0$ . The parameter  $Q_t$  is calculated in as part of the SCS curve number technique. The parameter, WI, includes snowmelt, precipitation, and sprinkler irrigation water. The irrigation water from all other methods is added to WI so that this water can also be included in the soil moisture accounting.

## 5.1 Interception Evaporation

Interception evaporation occurs with every precipitation event. It is that portion of precipitation that neither is runoff nor infiltrates but is retained. Its physical cause is due to water being exposed on the surface and eventually evaporating. Water coats every exposed surface—vegetation, etc. It also is detained in depressions or puddles where some can evaporated while being detained. Literature suggests that interception evaporation can range from 1 mm to 2.5 mm (van Dijk et al, 2001). AnnAGNPS assumes that the actual evaporation for any specific day's precipitation varies linearly between a lower and upper bound as a function of the relative humidity. AnnAGNPS allows the user to specify the lower and upper bounds but by default AnnAGNPS assumes 1.0 mm for the lower bound and 2.5 mm for the upper.

## 5.2 Surface Runoff

### 5.2.1 SCS Curve Number Technique

The SCS curve number technique is used within AnnAGNPS to determine the surface runoff from a field. The application of the technique within AnnAGNPS is described here. First, by describing parameters that are held constant throughout the simulation. The methods that are used to vary the curve number throughout the simulation are then described as well as the curve number technique itself.

#### 5.2.1.1 Constant Parameters within the SCS Curve Number Technique

There are a number of parameters used within soil moisture calculations that remain constant throughout the simulation period. Since these parameters remain as constants, they are calculated once and stored to save computational time.

The parameters used within the SCS curve number methods utilized within AnnAGNPS can be divided into those parameters that are defined by the user (inputs) and those that are calculated and stored for later use (outputs) in the determination of the curve number. These parameters are defined as:

#### Input:

CLAY(2) = clay content for each soil layer (fraction)

$Z_e$  = elevation (m)

FC(2) = field capacity for each soil layer (fraction)

KSAT(2) = saturated hydraulic conductivity for each soil layer (mm/d)

NTS = number of computational time steps per day for soil moisture calculations

$f$  = porosity for each soil layer (fraction)

SAND(2) = sand content for each soil layer (fraction)

WP(2) = wilting point for each soil layer (fraction)

$D_{SL1}$  = thickness for the top soil layer (mm)

$D_{SL2}$  = thickness for the second soil layer (mm)

#### Output:

AVAIL\_H2O = available moisture content between field capacity and wilting point in the top 1 m of soil (mm)

BC\_EXP(2) = Brooks-Corey exponent, used to calculate hydraulic conductivity (no units)

FCMWP(2) = field capacity minus wilting point for each soil layer (fraction)

FSDEPTH(2) = soil layer depths affecting fraction of saturation for curve number calculation (mm)

$\gamma$  = psychrometric constant (kPa/°C)

KSAT\_DT(2) = time-step saturated hydraulic conductivity for each soil layer (mm per time step)

MIN\_SMMWP(2) = minimum value of soil moisture minus wilting point to avoid numerical problems (fraction)

POMWP(2) = porosity minus wilting point for each soil layer (fraction)

SMCX = maximum soil moisture content (mm)

The soil hydraulic properties for each soil layer are calculated in a straightforward manner:

$$FCMWP = FC - WP \quad \text{Equation 5-2}$$

$$POMWP = f - WP \quad \text{Equation 5-3}$$

Since soil moisture calculations are done with sub-daily time steps, it is most efficient if saturated hydraulic conductivity is expressed as mm per time step. Hence, the daily value is simply divided by the number of time steps in a day:

$$KSAT\_DT = \frac{KSAT}{NTS} \quad \text{Equation 5-4}$$

The actual (unsaturated) hydraulic conductivity ( $K_{DT}$ ) is calculated. This is based on the method of Brooks and Corey (1964, 1966) and is described in the Soil Moisture section of the documentation. This equation uses an exponent, which is a function of soil texture characteristics. The exponent can be calculated using a pedo-transfer function, and that of Rawls and Brakensiek (1989) is used here. The equation calculates the Brooks-Corey  $\lambda$  parameter as:

$$\begin{aligned} \ln \lambda = & -0.7842831 + 1.77544SAND - 1.062498f - 0.5304SAND^2 - 27.3493CLAY^2 \\ & + 1.11134946f^2 - 3.088295SANDf + 2.6587SAND^2f^2 - 61.0522CLAY^2f^2 \\ & - 2.35SAND^2CLAY + 79.8746CLAY^2f - 0.674491f^2CLAY \end{aligned} \quad \text{Equation 5-5}$$

The final value of the exponent is calculated as

$$BC\_EXP = 3 + \frac{2}{\lambda}$$

Equation 5-6

At low soil moisture contents, K\_DT becomes a very small number, which can cause numerical problems (underflow). To avoid this, a minimum soil moisture is set, below which the hydraulic conductivity is set to zero. This is done by setting the minimum K\_DT to  $1 \times 10^{-10}$  mm per time step and solving the K\_DT equation for SMMWP, which is actual soil moisture minus wilting point. The calculation is:

$$MIN\_SMMWP = POMWP \left( \frac{0.0000000001}{KSAT\_DT} \right)^{(1/BC\_EXP)}$$

Equation 5-7

In the soil moisture calculations, the fraction of saturation of the soil is needed to adjust curve number on a daily basis. The depth of the soil used to calculate this fraction was set to a fixed value of 1 m in the SWRRB (Simulator for Water Resources in Rural Basins; Williams et al., 1985) model. The depth of soil affecting curve number, however, really should be variable, depending upon hydraulic conductivity. Under the most favorable percolation conditions, that is, when the soil is saturated, there is a maximum depth to which water can percolate in a day. The soil below this depth cannot affect curve number. This maximum depth is calculated as follows.

For the first soil layer,

$$FSDEPTH = \frac{KSAT}{f}$$

Equation 5-8

is calculated. If this is greater than the thickness of the first soil layer, the fraction of the day remaining after percolation through the first layer is calculated as

$$FR = 1 - \frac{D_{SL1}}{FSDEPTH}$$

Equation 5-9

then FSDEPTH(1) is set equal to the thickness of the layer  $D_{SL1}$ . FSDEPTH is calculated for the second soil layer as above, but it is then multiplied by FR, because part of the day is already taken for the water to percolate through the first layer. Again, if the depth so calculated is greater than the thickness of the layer  $D_{SL2}$ , then FSDEPTH(2) is set equal to  $D_{SL2}$ . The total depth of soil affecting the curve number is the sum of FSDEPTH(1) and FSDEPTH(2).

The maximum depth of water that can be held by the two-layer soil system between wilting point and field capacity is a quantity needed in the soil moisture calculations. It is:

$$SMCX = FSDEPTH(1) FCMWP(1) + FSDEPTH(2) FCMWP(2)$$

Equation 5-10

For automatic irrigation scheduling, irrigation is triggered when the soil moisture falls below a specified fraction of the maximum available soil moisture content. This maximum, which is very similar to SMCX, is defined as the soil moisture held between field capacity and wilting point in the top 1 m of soil (or the entire soil depth, if it is less than 1 m deep). It is calculated as:

$$AVAIL\_H2O = D_{SL1} FCMWP(1) + (1000 - D_{SL1}) FCMWP(2)$$

Equation 5-11

or, if  $D_{SL2} < 1000$  mm, then it is:

$$AVAIL\_H2O = D_{SL1}FCMWP(1) + (D_{SL2} - D_{SL1})FCMWP(2) \quad \text{Equation 5-12}$$

The psychrometric constant is needed for the calculation of potential evapotranspiration. It is calculated in the EPIC (Erosion-Productivity Impact Calculator; Williams et al., 1982) model as:

$$\gamma = 6.6 \times 10^{-4} (101 - 0.0115Z + 5.44 \times 10^{-7} Z^2) \quad \text{Equation 5-13}$$

The quantity in parentheses is an estimate of barometric pressure.

### 5.2.1.2 SCS Curve Number Parameters

Additional parameters are calculated associated with the runoff curve number for an individual field. The curve number parameters  $S_1$ ,  $S_3$ ,  $W_1$ , and  $W_2$  are used to vary the curve number for a given day between the dry condition curve number ( $CN_1$ ) and the wet condition curve number ( $CN_3$ ) based on soil moisture storage. This procedure comes from the SWRRB and EPIC models. This module is run at the beginning of a simulation and any time the curve number for average conditions ( $CN_2$ ) changes (e.g., when a crop is harvested).

To simplify data input,  $CN_1$  and  $CN_3$  are calculated as a function of  $CN_2$  based on curve fits. The equations, as given in the SWRRB and EPIC models, are:

$$CN_1 = CN_2 - \frac{20(100 - CN_2)}{100 - CN_2 + \exp[2.533 - 0.0636(100 - CN_2)]} \quad \text{Equation 5-14}$$

OR

$$CN_1 = 0.4 CN_2 \quad \text{Equation 5-15}$$

whichever is greater, and

$$CN_3 = CN_2 \exp[0.00673(100 - CN_2)] \quad \text{Equation 5-16}$$

The retention parameter  $S$  associated with each of the three curve numbers is calculated by:

$$S = 254 \left( \frac{100}{CN} - 1 \right) \quad \text{Equation 5-17}$$

where  $S$  is in mm. It is assumed, as in SWRRB and EPIC, that  $CN_1$  (and  $S_1$ ) correspond to the wilting point, or the minimum value of soil moisture storage.  $CN_3$  (and  $S_3$ ) are interpreted to correspond to soil moisture being equal to field capacity, as in the SWRRB and EPIC models, although one could also make the case that, based on the description of  $CN_3$  in the SCS National Engineering Handbook (Section 4, Hydrology), it should correspond to saturation (i.e., soil moisture equal to porosity).  $CN_2$  is taken here to correspond to a soil moisture halfway between wilting point and saturation.

The equations for calculating the weights for the daily updating of the retention  $S$  are:

$$W_1 = \ln \left( \frac{1}{1 - \frac{S_3}{S_1}} - 1 \right) + W_2$$

Equation 5-18

$$W_2 = 2 \left[ \ln \left( \frac{0.5}{1 - \frac{S_2}{S_1}} - 0.5 \right) - \ln \left( \frac{1}{1 - \frac{S_3}{S_1}} - 1 \right) \right]$$

Equation 5-19

$S_1$  = retention parameter associated with  $CN_1$  (mm)

$S_3$  = retention parameter associated with  $CN_3$  (mm)

$W_1, W_2$  = weights used in calculating the retention variable  $S$  as a function of soil moisture content

These equations are derived from the EPIC model. The alternate interpretations described above do not affect the mathematics for the calculation of the weights.

### 5.2.1.3 Determination of the SCS Curve Number

The average curve number ( $CN_2$ ) can change due to an operation event that makes a significant change to the land surface (e.g., harvest), and it can also change slowly after planting during the active growth phase of a crop as the plant foliage develops and covers the ground. These two situations have their effect primarily by changing the ground cover and have an obvious impact on runoff. Other operations, particularly tillage, can affect the hydraulic properties of the soil and can, therefore, affect runoff and percolation. These effects, however, are difficult to represent in the curve number because it is such an integrated and conceptual parameter, and they are therefore not considered within AnnAGNPS.

The two situations that can affect curve number are:

- (1) When an operation is indicated for the current day in the simulation, and a new curve number is given. This is primarily applicable to a harvest operation, where there is a sudden change in the plant cover, but there may be other operations with such effects.
- (2) When a newly planted crop is in its active growth phase.

Within AnnAGNPS all operations are examined during the current simulation day. If a new curve number is specified for the operation, the model then checks to see if a corresponding harvest operation is specified. If so, this indicates that the operation is a planting, and the new curve number is the value applicable for a fully developed crop. If it is not a planting operation, the module simply updates the  $CN_2$  and recalculates the associated parameters as described in the previous section.

For a planting, the module then sets up the information needed to transition the curve number from its current value to the value applicable to when the crop is fully developed. In the Crop Reference Data, information is given by the user specifying the fraction of time between planting and harvest for each of four plant growth stages: initial, development, maturity, and senescence. (If the operations data indicate that a new crop is being grown, i.e., one different from the previous planting, this information is updated within AnnAGNPS.) It is assumed that the curve number transition occurs during the development stage. Before this (i.e., after planting and during the initial stage), the curve number remains at its current value. After this (i.e., during the maturity and senescence stages until harvest), the curve number is the value specified in the operations information for the fully developed crop. On the day of harvest, the curve number is simply changed to the new value applicable to the harvested field situation, as specified in the operations information.

The first step in setting up the transition is to calculate the number of days between planting and harvest by examining the dates for each operation. Next, the number of days until the beginning of the transition is calculated as the number of days between planting and harvest times the fraction specified for the initial phase of the crop. This number is decremented every day until it reaches zero. When this happens, the transition begins.

The transition is effected by making a daily change to the  $CN_2$  and recalculating the associated parameters. The daily change is calculated as the difference between the mature crop curve number and the current curve number divided by the number of days in the transition period. The number of days in this period is calculated as the number of days between planting and harvest times the fraction specified for the development phase of the crop. The  $CN_2$  is changed every day until the new value is reached. This is then used until harvest.

### 5.2.2 Determination of Surface Runoff

The daily volume of runoff for each day from each field is determined by AnnAGNPS, i.e., the amount of incoming moisture lost to the soil and delivered to the channel system. The algorithm used here is a conceptual model based on the SCS curve number, as used in the SWRRB and EPIC models. Although the use of the curve number procedure in this context represents an extension of its original application, the procedure is mathematically similar to algorithms commonly used in conceptual watershed models, such as the National Weather Service Sacramento Model, the U.S. Army Corps of Engineers SSARR model, and the Swedish HBV model. The mathematics and the quantitative effects differ somewhat, but the procedure has the effect of apportioning a greater fraction of the moisture input to runoff with increasing soil water content and with increasing precipitation amount.

Runoff is defined as that portion of the incoming moisture that leaves a grid cell within a day. It is therefore an undifferentiated mixture of overland flow over part or all of the watershed and shallow flow through the upper soil. It is lost to the soil system. The remainder of the incoming moisture either evaporates or is added to the soil moisture. Interception, as a separate process for the disposition of this remaining moisture, is not considered here.

As implemented in SWRRB and EPIC, an equivalence is made between the curve number for dry conditions ( $CN_1$ ) and the wilting point (WP), and between the curve number for wet conditions ( $CN_3$ ) and the field capacity (FC). These equivalences are also used here, although  $CN_3$  could be interpreted to be equivalent to saturation (i.e., soil moisture equal to porosity) rather than field capacity, based on the description of  $CN_3$  in the SCS National Engineering Handbook (Section 4, Hydrology). The actual curve number used for calculating runoff is allowed to vary depending on soil water content. Actually, curve number is not used directly, but rather the associated retention variable  $S$  is used in the calculations:

$$S = 254 \left( \frac{100}{CN} - 1 \right) \quad \text{Equation 5-20}$$

where  $S$  is in mm. The actual value of  $S$  used in the runoff calculation for a specific day  $t$ , then, is a state variable with a unique relationship to  $SM$ , according to the equation:

$$S_t = S_1 \left( 1 - \frac{FS_t}{FS_t + \exp(W_1 - W_2 FS_t)} \right) \quad \text{Equation 5-21}$$

where  $FS_t$  is the fraction of saturation of the two-layer soil system at the beginning of day  $t$ , an intermediate variable calculated as

$$FS_t = \frac{FSDEPTH(1)(SM(1)_t - WP(1)) + FSDEPTH(2)(SM(2)_t - WP(2))}{FSDEPTH(1)(FC(1) - WP(1)) + FSDEPTH(2)(FC(2) - WP(2))} \quad \text{Equation 5-22}$$

where

$FSDEPTH(2)$  = soil layer depths affecting fraction of saturation for curve number calculation (mm)



SM(2) = moisture content for each soil layer at beginning of time period (fraction)

WP(2) = wilting point for each soil layer (fraction)

$S_1$  (the  $S$  value corresponding to  $CN_1$ ),  $W_1$ , and  $W_2$  are calculated as constants in a preprocessing step described previously. The two values of FSDEPTH and the denominator of Equation 5-22, which do not vary with time, are also calculated beforehand as previously described (the latter is stored as the variable SMCX).

This algorithm allows  $S$  to vary in a smooth curvilinear fashion from a maximum value of  $S_1$  (i.e., a minimum curve number of  $CN_1$ ) when  $SM = WP$ , through the value of  $S_2$  (corresponding to the "average condition" curve number  $CN_2$ ) when the soil moisture is halfway between  $WP$  and  $FC$ , down to a minimum value of  $S_3$  (i.e., a maximum curve number of  $CN_3$ ) when  $SM = FC$ . The result of these calculations is simply a rescaling of  $SM$  into values that can be used in the curve number runoff equation.

If the soil is frozen,  $S$  is adjusted as follows. If the soil is frozen at the surface ( $0^\circ$  isotherm at a depth of zero),  $S$  is given the value of  $S_3$ . If the shallowest  $0^\circ$  isotherm is below the maximum soil depth with an effect on curve number, as given by the variable FSDEPTH, then no adjustment of  $S$  for frozen ground is made. In between, the value of  $S$  is decreased linearly between the value it would have in unfrozen soil (based on soil moisture, as described above) and  $S_3$ , as a function of the depth of the shallowest  $0^\circ$  isotherm.

With the value of  $S$  calculated for the current day, runoff is calculated as

$$Q = \frac{(WI - 0.2 S)^2}{WI + 0.8 S}$$

**Equation 5-23**

where

$Q$  = runoff (mm)

$WI$  = water input to soil (mm)

as long as  $WI > 0.2 S$ , otherwise  $Q = 0$ .  $WI$  is equal to the snowmelt amount, if a snowpack exists, or the daily precipitation, if no snow is present, plus any sprinkler irrigation water applied. (Runoff from other irrigation methods is not considered to be appropriately described by the curve number equation and is dealt with in the irrigation and soil moisture calculations.) To obtain the volume of runoff,  $Q$  is multiplied by the field area. The value of  $S$  is also converted into curve number for use by other modules and for user information. This can be later modified in the soil moisture calculations to give an overall curve number considering all forms of water input and runoff from the cell.

## 5.3 POTENTIAL EVAPOTRANSPIRATION

### 5.3.1 Net Radiation

Net radiation is needed for calculating potential evapotranspiration and is the daily net incoming short and long wave radiation to a flat ground surface. The net radiation is calculated by adding four terms: incoming short wave, reflected short wave, incoming long wave, and outgoing long wave. The determination of each of these terms varies somewhat among sources, depending on the particular functional forms used and the effects the various authors chose to include and exclude. There is, for the most part though, a good deal of commonality among the methods. The equations chosen for AnnAGNPS represent an attempt to use generally accepted procedures, as reflected in the commonality among sources (listed in the References section) and as verified by some limited testing. Each of the four terms is described below.

#### Short Wave Radiation:

**Incoming Short Wave Radiation** Incoming short wave radiation is a fraction of the extraterrestrial radiation that is received at the top of the earth's atmosphere. The calculation of extraterrestrial short wave radiation is a fairly straightforward geometric procedure and is described later in the Extra Solar Radiation section. As the radiation travels through the atmosphere, some of it is absorbed or reflected back into space. Correction factors to take

account of the effects of dust, water vapor, the path length, and reflection and rescattering are applied to the extraterrestrial radiation to obtain the short wave radiation received at the ground surface. The corrections are often applied as two multiplicative factors, one for the effects of the atmosphere and one for clouds.

The atmospheric correction factor (here denoted by  $F_a$ ) used by USFWS (1984) is based on Beer's law and is fairly detailed, with several sub-components to account for dust, water vapor, and reflection and rescattering. The equation is given as:

$$F_a = \frac{a'' + \left( \frac{1 - a' - d_{sr}}{2} \right)}{1 - \alpha \left( \frac{1 - a' + d_{sr}}{2} \right)} \quad \text{Equation 5-24}$$

where

$a'$  = mean atmospheric transmission coefficient for dust-free moist air after scattering only (decimal)

$a''$  = mean distance transmission coefficient for dust-free moist air after scattering and absorption (decimal)

$d_{sr}$  = total depletion coefficient of the direct solar radiation by scattering and absorption due to dust (decimal)

$\alpha$  = total reflectivity of the ground (decimal)

The two transmission coefficients are calculated as:

$$a' = \exp\left\{-m_a(0.465 + 0.134w)\left[0.129 + 0.171\exp(-0.880m_a)\right]\right\} \quad \text{Equation 5-25}$$

$$a'' = \exp\left\{-m_a(0.465 + 0.134w)\left[0.179 + 0.421\exp(-0.721m_a)\right]\right\} \quad \text{Equation 5-26}$$

where

$w$  = precipitable water content (cm)

$m_a$  = optical air mass (decimal)

The precipitable water content is calculated as:

$$w = 0.85 \exp(0.110 + 0.0614T_D) \quad \text{Equation 5-27}$$

with  $T_D$  = dew point temperature. The optical air mass is a measure of both the path length and absorption coefficient of a dust-free dry atmosphere. It is a function of the site elevation and the solar altitude and is described in the Extra Solar Radiation section.

The dust coefficient  $d$  is an empirical coefficient, and only a few examples of values are given in USFWS (1984). These are for three cities (Washington, DC, Madison, WI, and Lincoln, NE), and values for each season are given separately. The values given range from 0.03 to 0.13; a value of 0.05 appears to be typical, and this was selected as a constant value, lacking any other readily available firm basis.

The reflectivity of the ground is taken here to be synonymous with the albedo and depends on the soil and vegetation types and whether there is snow on the ground. The albedo is set within the module to 0.2, unless there is snow on the ground, in which case it is set to 0.8. This is an oversimplification but was done for expediency and will be improved upon in future versions. With these values, all terms in Equation 5-24 for  $F_a$  are now defined.

In comparison, ASCE (1996) adopts a much simpler approach for the atmospheric correction factor, basing it only on elevation:

$$F_a = 0.75 + 0.0002Z_e$$

Equation 5-28

where

$Z_e$  = elevation (m)

This, of course, is a constant for any given location and has some implicit assumptions about the turbidity of the atmosphere and the absorption and scattering of short wave radiation. For dusty or polluted locations, this  $F_a$  would need to be reduced by up to 10%.

The other correction factor is for clouds. USFWS (1984) gives the cloud correction factor  $F_c$  as:

$$F_c = 0.22 + 0.78 \left( \frac{S}{S_o} \right)^{2/3}$$

Equation 5-29

where  $S/S_o$  is the fraction of possible sunshine for the day.  $S/S_o$  can be estimated from cloudiness as  $1 - C^{5/3}$  (USFWS, 1984, Eq. II.22). ASCE (1996) gives a similar equation:

$$F_c = 0.35 + 0.61 \left( \frac{S}{S_o} \right)^{2/3}$$

Equation 5-30

With these factors, incoming short wave radiation  $R_{SI}$  is calculated as:

$$R_{SI} = F_a F_c R_X$$

Equation 5-31

where

$R_X$  = extraterrestrial short wave radiation ( $W m^{-2} = J m^{-2} sec^{-1}$ , average value for day)

In contrast, DVWK (1995) combines the two correction factors and calculates  $R_{SI}$  as:

$$R_{SI} = \left[ 0.19 + 0.55 \left( \frac{S}{S_o} \right) \right] R_X$$

Equation 5-32

A limited comparison of the USFWS (1984), ASCE (1996), and DVWK (1995) methods of calculating incoming short wave radiation was carried out using data for 1980-1984 at the Goodwin Creek watershed in Mississippi (Blackmarr, 1995). This resulted in average values of 197, 209, and 206  $W m^{-2}$ , respectively, with very little variation from year to year. Since all three methods produced similar results, the USFWS (1984) procedure was chosen, as it has a more comprehensive basis.

**Reflected Short Wave Radiation** Reflected short wave radiation  $R_{SR}$  is simply a function of the albedo  $\alpha$  of the surface:

$$R_{SR} = \alpha R_{SI}$$

Equation 5-33

**Net Short Wave Radiation** Net short wave radiation  $R_{SN}$  is simply the incoming minus reflected. Combining the above equations yields:

$$R_{SN} = (1 - \alpha) F_a F_c R_x \quad \text{Equation 5-34}$$

### Long Wave Radiation:

**Incoming Long Wave Radiation** The basic equation for long wave radiation is the Stefan-Boltzmann law:

$$R_L = \varepsilon \sigma T_K^4 \quad \text{Equation 5-35}$$

where  $R_L$  = emitted long-wave radiation,  $\varepsilon$  = emissivity (fraction, 0.0 - 1.0),  $\sigma$  = Stefan-Boltzmann constant ( $5.672 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ ), and  $T_K$  = absolute temperature (K). A so-called black body has an emissivity of 1.0. Most soil and vegetative surfaces have an emissivity of about 0.90 - 0.98, while a water surface is generally considered to have an emissivity of 0.97. For the atmosphere, the emissivity depends upon the water vapor content (humidity). An additional effect is the presence, amount, and type of clouds.

The Brunt equation for calculating the atmospheric emissivity  $\varepsilon_a$  is commonly used (USFWS, 1984, Eq. II.62; DVWK, 1995, Eq. 5.14; ASCE, 1996, Eq. 4.32):

$$\varepsilon_a = a + b\sqrt{e} \quad \text{Equation 5-36}$$

where  $a$  and  $b$  are constants and  $e$  = water vapor pressure. The values of the constants  $a$  and  $b$  vary among sources, and they also are different if the emissivity is expressed as a net of incoming and outgoing radiation and whether the algebraic sign of the radiation is positive toward the ground or away from it. With  $e$  in units of mb (= hPa), the values of  $a$  reported in the various literature sources range from 0.26 to 0.71 and those for  $b$  range from 0.02 to 0.11. A value for  $a$  of 0.61 and a value for  $b$  of 0.05 appear to be somewhat standard (Sellers, 1965; USFWS, 1984). With some algebraic rearranging, a unit conversion, and assuming a ground/vegetation emissivity of 0.98, the equation from ASCE (1996) uses  $a = 0.640$  and  $b = 0.044$ . DVWK (1995) appears to recommend two different, but similar, values of  $a$  and  $b$ . In an equation describing atmospheric emittance for cloudless skies (Eq. 5.14),  $a = 0.520$  and  $b = 0.065$ , whereas in a second equation that is given for calculating net outgoing long wave radiation (Eq. 5.27), it appears that slightly different values are used, but it is unclear how this was derived. At any rate, all of these values are quite similar, so the values of  $a = 0.61$  and  $b = 0.05$  were selected.

DVWK (1995, Eq. 5.17) also gives one example of using a root of 0.3 instead of 0.5 for  $e$ , but 0.5 seems to be the standard practice. Another variant encountered is that DVWK (1995, Eq. 5.27) and Sellers (1965, Eq. 4.6) leave an epsilon in the Stefan-Boltzmann equation as well as include the  $a$  plus  $b$  root  $e$  term. It is implied that the epsilon is the emissivity of the vegetated soil surface, but then it is unclear exactly what the Brunt equation represents. ASCE (1996, Eq. 4.36) presents yet another variation, in which the Brunt equation form is used to calculate the difference between ground and atmospheric emissivity. As it was difficult to evaluate all of these variations, it was decided to use the basic form with the parameter values as described in the preceding paragraph.

The vapor pressure  $e$  is generally thought of as the saturation vapor pressure (at the given air temperature) times the relative humidity. It can also be thought of as the saturation vapor pressure at the dew point temperature. There are numerous formulas given in the literature for calculating  $e$  from temperature. Only one of the sources (DVWK, 1995) reviewed here, however, distinguished between vapor pressure over water and that over ice. A numerical comparison among the methods showed that they all give very similar results. Because of this important distinction in vapor pressure at above or below freezing temperatures, the DVWK (1995) procedure was chosen:

$$e = 6.11 \exp\left(\frac{17.62 T_D}{243.12 + T_D}\right) \quad \text{Equation 5-37}$$

for air temperatures above 0°, and

$$e = 6.11 \exp\left(\frac{22.46T_d}{272.62 + T_d}\right)$$

Equation 5-38

for air temperatures below 0°. For this purpose, air temperature is taken as the average of the daily maximum and minimum temperatures.

A commonly used form for the cloud cover correction is (Sellers, 1965, Eq. 4.10; USFWS, 1984, Eq. II.61; DVWK, 1995, Eq. 5.15):

$$\frac{R_{Lc}}{R_{La}} = 1 + kC^m$$

Equation 5-39

where  $R_{La}$  = long wave atmospheric emittance (clear sky),  $R_{Lc}$  = long wave emittance under cloudy skies,  $C$  is the fraction of cloudiness, and  $k$  and  $m_a$  are parameters. This correction increases the incoming long wave radiation to reflect the effect of clouds. Sellers (1965) states that clouds increase the incoming radiation by as much as a factor of about 1.25 (for a fog), although the amount of increase is a function of cloud type (more for low thick clouds, less for high thin clouds) as well as fraction of coverage.

The values of the two parameters vary somewhat among authors. Considering first the parameter  $m_a$ , the optical air mass, Sellers (1965) cites several authors who use values of  $m_a$  ranging from 1.0 to 2.7, with an average value of about 2.0, although he says that  $m_a$  is usually set to 1.0. USFWS (1984) uses  $m_a = 2.0$ , while DVWK (1995) cites two German authors, one of whom uses  $m_a = 2.5$ , the other  $m_a = 1.0$  (the corresponding values of  $k$  are different as well). The main effect of the parameter  $m_a$  is to determine how rapidly the cloud cover correction factor reaches its maximum value as a function of  $C$ . With  $m_a = 1.0$ , the increase is linear, whereas if  $m_a > 1.0$ , the rate of increase is slower such that the cloud cover correction factor is smaller for any given value of  $C$  (except for  $C = 0.0$  and  $1.0$ ).

The value of  $k$  also varies and is dependent on  $m_a$  as well as the cloud type. USFWS (1984) uses  $k = 0.17$  (with  $m_a = 2.0$ ), which apparently is some sort of average value. DVWK (1995) gives values of  $k$  ranging from 0.04 for cirrus to 0.24 for stratocumulus, to be used with  $m_a = 2.5$ . This same source also cites values of  $k$  ranging from 0.16 in July to 0.35 in December (apparently average values for German climate conditions), to be used with  $m_a = 1.0$ . In the former case, the cloud correction factors reach a maximum (under full cloud cover) of 1.04 for cirrus and 1.24 for stratocumulus cloud types. For the latter case, where the  $k$  values are given as a function of month, the maximum cloud correction factors are 1.16 for July and 1.35 for December. These maximum values are all in general agreement.

An alternative, but nearly equivalent, way to formulate the cloud cover correction is to apply a factor to the net, rather than incoming, radiation. ASCE (1996), DVWK (1995), and Sellers (1965) give examples of this. In all of these cases, net radiation is considered to be positive outwards, and the correction factor is small (or even negative) under cloudy conditions and equal to 1.0 under a clear sky. The effect of the clouds, then, is represented as a decrease in net outgoing radiation because the clouds are contributing more toward the ground.

The functional forms chosen to implement are described below with respect to net long wave radiation.

**Outgoing Long Wave Radiation** The ground surface also emits long wave radiation according to the Stefan-Boltzmann law. ASCE (1996) recommends an emissivity of 0.98 for vegetated surfaces.

**Net Long Wave Radiation** The incoming minus the outgoing gives the net long wave radiation,  $R_{LN}$ . DVWK (1995) and ASCE (1996) both give equations that already combine the incoming and outgoing components into a net long wave radiation equation. The USFWS (1984) keeps them separate, but it is simple to combine the two into a single equation. These are shown below:

DVWK:

$$R_{LN} = -\varepsilon \sigma (T + 273.16)^4 (0.56 - 0.08\sqrt{e}) \left( 0.1 + 0.9 \frac{S}{S_o} \right)$$

Equation 5-40

USFWS:

$$R_{LN} = \sigma (T + 273.16)^4 \left[ (0.61 + 0.05\sqrt{e}) (1 + 0.17C^2) - \varepsilon \right]$$

Equation 5-41

ASCE:

$$R_{LN} = -\sigma (T + 273.16)^4 (0.34 - 0.04\sqrt{e}) \left( 1.35 \frac{R_s}{R_{s_o}} - 0.35 \right)$$

Equation 5-42

where  $\varepsilon$  = emissivity of the ground and vegetative surface,  $S$  = sunshine hours for the day,  $S_o$  = maximum possible sunshine hours for the day,  $R_s$  = incoming short wave radiation (including effect of clouds),  $R_{s_o}$  = incoming short wave radiation under clear skies, and  $T$  is the air temperature ( $^{\circ}\text{C}$ ). The sign on the DVWK and ASCE equations is negative because these were formulated as net *outgoing* radiation, whereas here we consider positive to be *incoming*. The coefficients in the atmospheric emissivity term are also affected by this difference in sign. Note that the DVWK and ASCE equations have the cloud cover correction applied as an increase to the net outgoing radiation, whereas the USFWS equation applies a reduction factor to the incoming radiation. For  $\varepsilon$ , DVWK (1995) states that a value 0.97 should be used for a water surface, otherwise use 1.0, whereas in the USFWS equation, it would be more reasonable to use a value that better represented the actual emissivity of the ground and vegetative surface, such as 0.98. Although not strictly correct, the temperature used in these calculations is the standard air temperature, in the absence of measured temperatures of ground and vegetative surfaces or of clouds.

A limited comparison among these three procedures using data for 1980-1984 at the Goodwin Creek watershed in Mississippi was carried out. In these calculations, the ratio  $S/S_o$  was estimated from the cloud cover fraction as  $1 - C^{5/3}$ , as mentioned earlier.  $R_s/R_{s_o}$  is equivalent to the short wave cloud cover correction factor, also taken from USFWS (1984) and discussed above. For the five years, the average net long wave radiation was -110, -79, and -71  $\text{W m}^{-2}$  for the DVWK, USFWS, and ASCE equations, respectively. There was very little variation in the individual average annual values for these five years.

Based on this test and on the comments above, the USFWS (1984) procedure was selected to implement. It produced values in the middle of the three procedures, and its basis was well documented and was, to this author, the most straightforward and understandable conceptually.

### Net Radiation:

The net radiation to the ground surface is simply the sum of the net short wave and net long wave components:

$$R_N = R_{SN} + R_{LN}$$

Equation 5-43

where

$R_N$  = net radiation ( $\text{W m}^{-2}$ )

Using the average values of short and long wave radiation calculated with the USFWS (1984) procedure using the Goodwin Creek data given above, the average net radiation is  $79 \text{ W m}^{-2}$  using an albedo of 0.2.

Within AnnAGNPS, all radiation terms are calculated using units of  $\text{W m}^{-2}$  (average value for day). The calculation of potential ET uses  $\text{MJ m}^{-2} \text{ d}^{-1}$  (total radiation for day), so  $R_N$  is multiplied by 0.0864 to accomplish this unit conversion.

### 5.3.2 Extraterrestrial Solar Radiation

Extraterrestrial solar radiation is the amount of radiation received at the top of the atmosphere and is needed to determine the net radiation described previously. The optical air mass, which is a measure of the absorption of radiation through a dust-free dry atmosphere, is also needed in the net radiation calculations. These values are always the same for a given calendar day, as they depend only upon elevation and latitude. Therefore, the calculations can be done once for each day of the year and stored for use in any given simulation year.

#### Extraterrestrial Solar Radiation:

The calculation of extraterrestrial solar radiation is purely a geometrical problem. It is a function of the solar constant, the relative distance of the earth from the sun, and the zenith angle of the sun at the location and time in question. To obtain the total amount of radiation during a day, the radiation must be integrated from sunrise to sunset.

The solar constant is the amount of energy received on a surface perpendicular to the sun's direction at the top of the earth's atmosphere at the mean distance between the earth and the sun. The accepted value of this constant has changed over the years as measurements have become more accurate. The most recent internationally accepted value of this constant is  $1367 \text{ W m}^{-2}$  (Linacre, 1992; ASCE, 1996).

The basic equation for daily extraterrestrial solar radiation  $R_x$  ( $\text{W m}^{-2}$ ) on a horizontal surface is (Sellers, 1965; USFWS, 1984; ASCE, 1996):

$$R_x = \frac{S_c}{\pi} d_r (h_s \sin \phi \sin \delta + \sin h_s \cos \phi \cos \delta) \quad \text{Equation 5-44}$$

where  $S_c$  = solar constant,  $d_r$  = relative distance of the earth from the sun,  $h_s$  = sunrise/sunset hour angle,  $\phi$  = latitude (radians), and  $\delta$  = sun declination.

The factor  $d_r$  equals 1.0 when the earth is at its mean distance from the sun. It is slightly less than one during the northern hemisphere winter and slightly greater than one during the northern hemisphere summer. The representation of this factor varies among sources, for example:

Sellers (1965, Eq. 3.7); List (1971, p. 417):

$$d_r = \left( \frac{\bar{d}}{d_{es}} \right)^2 \quad \text{Equation 5-45}$$

where  $\bar{d}$  = average distance between the earth and the sun and  $d_{es}$  = actual distance between the earth and the sun on the given day.

USFWS (1984, Eq. II.1):

$$d_r = \frac{(1 + e_o \cos \theta)^2}{(1 - e_o^2)} \quad \text{Equation 5-46}$$

where  $e_o$  = orbital eccentricity = 0.0167238 and  $\theta$  = earth orbit position about the sun (radians). The equation given in this reference for  $\theta$  is (USFWS (1984), Eq. II.3):

$$\theta = \frac{2\pi}{365} (J - 2) \quad \text{Equation 5-47}$$

where  $J$  = Julian day.

ASCE (1996, Eq. 4.22):

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right)$$

**Equation 5-48**

These three methods were compared, using values of  $d/d$  from List (1971, Table 169) in the Sellers/List equation. The USFWS equation gives values almost the same as the Sellers/List equation (very slightly smaller), whereas the ASCE equation gives values noticeably smaller than these other two. The USFWS equation was chosen to implement, as it is a continuous function that does not require a table lookup, and it appears to give correct results.

The sunrise/sunset hour angle for flat terrain is calculated as (Sellers, 1965, Eq. 3.3; USFWS, 1984, Eq. II.5; ASCE, 1996, Eq. 4.23):

$$h_s = \arccos(-\tan \phi \tan \delta)$$

**Equation 5-49**

The declination of the sun is calculated as (USFWS, 1984, Eq. II.4):

$$\delta = 0.40928 \cos\left[\left(\frac{2\pi}{365}\right)(172 - J)\right]$$

**Equation 5-50**

An (essentially) equivalent equation using the sine instead of cosine is given in ASCE (1996, Eq. 4.21).

### Optical Air Mass:

The optical air mass is a measure of both the path length and absorption coefficient of a dust-free dry atmosphere. It is a function of the site elevation and the solar altitude. This procedure is taken from USFWS (1984).

The average solar altitude for a given day is calculated as (USFWS, 1984, Eq. II.16):

$$A = \arcsin\left\{(\sin \phi \sin \delta) + \left[\cos \phi \cos \delta \cos\left(\frac{h_s}{2}\right)\right]\right\}$$

**Equation 5-51**

where  $\phi$  = latitude,  $\delta$  = sun declination, and  $h_s$  = sunrise/sunset hour angle. The last two are calculated as shown above. With this, the optical air mass,  $m_a$ , is (USFWS, 1984, Eq. II.18):

$$m_a = \frac{\left(\frac{288 - 0.0065Z_e}{288}\right)^{5.256}}{\sin A + 0.15 \left[\left(\frac{180}{\pi}\right)A + 3.885\right]^{-1.253}}$$

**Equation 5-52**

where  $Z_e$  = elevation (m) and  $A$  is in radians.

The extraterrestrial solar radiation and optical air mass are first calculated and stored for each calendar day of a 365-day year. Then, to handle leap year, the values from Julian day 60 (February 29 in a leap year) on are shifted ahead by one day to create a 366-day year. Day 60 and 61 are thus copies of each other. This prepares the data for the main program, in which a leap year is handled by skipping day 60 in a non-leap year.



### 5.3.3 Determination of Potential Evapotranspiration

The Penman equation is a commonly accepted form of determining the potential evapotranspiration. The Penman equation is as follows:

$$ET_p = \frac{1}{H_v} \left[ \left( \frac{\Delta}{\Delta + \gamma} \right) (R - G) + \left( \frac{\gamma}{\Delta + \gamma} \right) W (e_{sat} - e) \right]$$

**Equation 5-53**

where:

$ET_p$  = potential evapotranspiration (mm)

$H_v$  = latent heat of vaporization (MJ/kg)

$\Delta$  = slope of saturation vapor pressure-temperature curve (kPa/°C)

$\gamma$  = psychrometric constant (kPa/°C)

$R$  = net radiation (MJ/m<sup>2</sup>)

$G$  = soil heat flux (MJ/m<sup>2</sup>)

$W$  = wind function

$e_{sat}$  = saturation vapor pressure (kPa)

$e$  = actual vapor pressure (kPa)

The evaluation of each term is given below. As a preliminary item, mean air temperature for a day  $T$  is calculated as the average of the day's maximum and minimum temperatures.

The latent heat of vaporization is a function of the mean air temperature for day,  $T$  (°C), and is calculated as:

$$H_v = 2.501 - 0.0022 T$$

**Equation 5-54**

The saturation vapor pressure is also a function of air temperature:

$$e_{sat} = 0.1 \exp \left( 54.879 - 5.029 \ln T_k - \frac{6790.5}{T_k} \right)$$

**Equation 5-55**

where  $T_k = T + 273.18$ , that is, temperature in °K. Actual vapor pressure is simply:

$$e = RH e_{sat}$$

**Equation 5-56**

where  $RH$  is the relative humidity (fraction).

The slope of the saturation vapor pressure-temperature curve is calculated as:

$$\Delta = \left( \frac{e_{sat}}{T_k} \right) \left( \frac{6790.5}{T_k} - 5.029 \right)$$

**Equation 5-57**

The psychrometric constant is calculated as:

$$\gamma = 6.6 \times 10^{-4} \left( 101 - 0.0115Z + 5.44 \times 10^{-7} Z_e^2 \right) \quad \text{Equation 5-58}$$

where the quantity in parentheses is an estimate of barometric pressure and is a function of elevation,  $Z_e$  (m). This quantity is described previously as part of the soil moisture calculations. This is stored as a constant parameter, as it does not vary with time.

The soil heat flux is calculated as a function of the air temperature for the current day and the three previous days:

$$G = 0.12 \left[ T_0 - \left( \frac{T_{-1} + T_{-2} + T_{-3}}{3} \right) \right] \quad \text{Equation 5-59}$$

where  $T_0$  is the current day's temperature, and the other subscripts on T refer to the number of days prior to the current day. (This term is ignored in WEPP.)

The wind function appears in different forms in the WEPP and EPIC models and in the literature. Part of the differences are due to different assumed heights at which the wind speed is valid, and part of the difference is whether the function has already been divided by  $H_v$  (which must be some sort of average value, as it actually varies as a function of air temperature). In the United States, the standard height for measurement of wind speed at first-order weather observation stations is approximately 3 m, but in fact, strict adherence to this standard is not practiced, so that these measurements are taken anywhere from 2 m to 10 m (J. Marron, personal communication, 1996). The WEPP and EPIC models use equations valid for a 10 m height, with the justification that this is what the stochastic climate generator model (CLIGEN) produces. In light of these uncertainties, it was decided simply to use the original Penman wind function, which is valid for a height of 2 m (Jensen et al., 1990):

$$W = 6.43 + 3.4079 U \quad \text{Equation 5-60}$$

where

U = wind speed (m/s)

With this, all terms are now available to calculate the potential evapotranspiration with the volume calculated based on the area of the field.

## 5.4 SUBSURFACE FLOW

The components of subsurface flow within AnnAGNPS consist of lateral subsurface flow or tile drain flow. Each are used to determine the contribution of subsurface drainage within a field to the corresponding reach. Subsurface flow only occurs within AnnAGNPS when an impervious layer is present within the soil profile. Amount of lateral flow and tile flow taken out from each cell is added to the reach the same time as runoff (no lateral flow and drainage flow between cells) and both are considered as the quick return flow to the reach. When the water table does not rise above the depth of drainage system, lateral flow is calculated using Darcy's equation as described for lateral subsurface flow.

The hydraulic gradient can be approximated by the local surface topographic slope,  $\tan\alpha$  which was used by the TOPMODEL (Beven et al., 1995).  $K_s$  can be estimated using the same method as percolation, soil profile is assumed as isotropic.

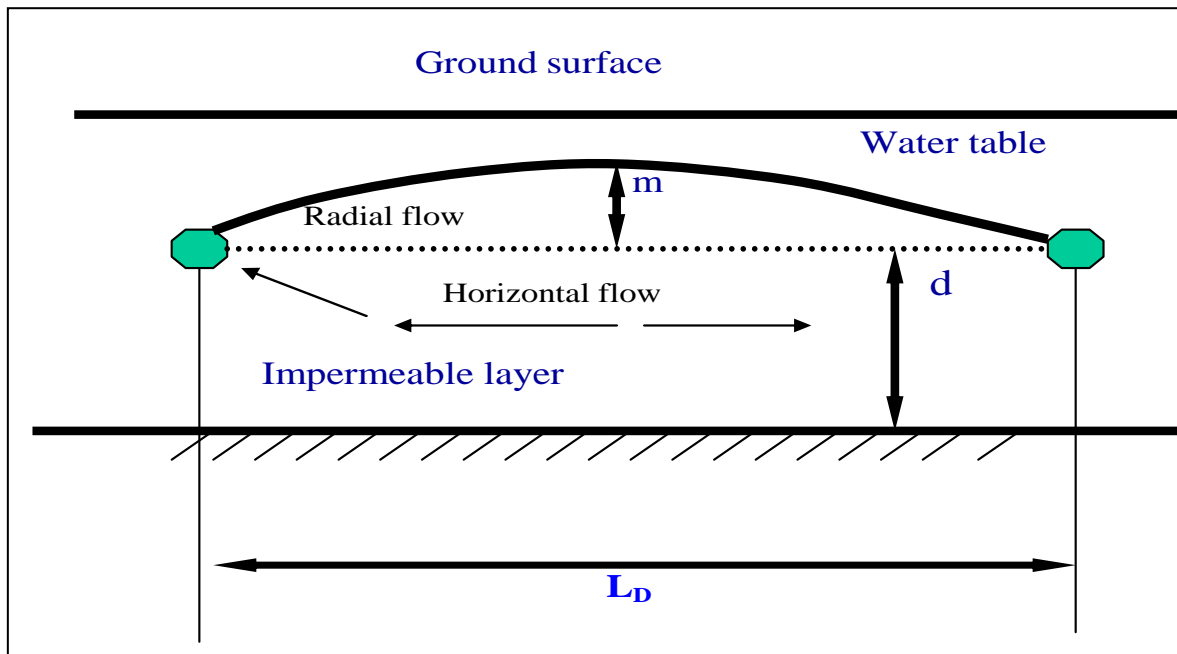
### 5.4.1 Tile Drainage Flow

Subsurface drainage by means of buried pipes has been studied very comprehensive in land drainage. The flow can be described as steady state or unsteady state flow. The steady state flow is based on the assumption that a steady constant flow occurs through the soil to the drains. Discharge equals recharge and the head is also constant. In the non-steady state formula all these parameters vary in time (Smedema and Rycroft, 1983). In most cases, subsurface drainage flow can be estimated based on steady state conditions. Hooghoudt's equation is chosen for use within

AnnAGNPS because this formula has a wide applicability and a relatively simple structure (Smedema and Rycroft, 1983) and is also commonly used by the USDA-NRCS.

The water table above parallel drains is often approximated using an elliptical shape, as shown in Figure 5-1. The streamlines for the drainage flow towards two parallel pipes typically show a pattern as in Figure 5-1. Horizontal flow occurs towards the drains and the flow converges radially into the drain towards the end of its path. The extent of two flow zones differs from case to case depending particularly upon the relative magnitude of  $L$ ,  $m$  and  $d$ . When  $L$  is large in comparison of both  $m$  and  $d$ , the flow is predominantly horizontal. An extensive radial flow sector is to be expected when  $d$  is large (van Schilfgaarde, 1957).

Hooghoudt used the result of both of these observations to model the practical case of flow in drains. Hooghoudt's equation was originally developed for application in the Netherlands, where steady state rainfall is a reasonable assumption. The following is the Hooghoudt equation:



**Figure 5-1.** Schematic for Hooghoudt Tile Flow

$$q_{\text{drain}} = \frac{8K_s d_e m + 4K_s m^2}{L_D^2}$$

**Equation 5-61**

where  $q_{\text{drain}}$  = drainage flux (mm per time period),

$K$  = saturated lateral hydraulic conductivity (mm per time period),

$L_D$  = distance between drains (m),

$m$  = midpoint water table height above the drain (m),

$d_e$  = equivalent depth of the impermeable layer below the drain (m).

the effective depth,  $d_e$  is computed using Equations 5-62 and 5-63 when the actual depth,  $d$ , to the impermeable layer is such that  $0 < d/L_D < 0.3$  (Skaggs, 1980).

$$d_e = \frac{d}{1 + \frac{d}{L_D} \left[ \frac{8}{\pi} \ln\left(\frac{d}{r}\right) - \alpha_c \right]} \quad \text{Equation 5-62}$$

r = radius of the drain tube (m)

$\alpha_c$  = a constant defined by:

$$\alpha_c = 3.55 - \frac{1.6d}{L_D} + 2\left(\frac{d}{L_D}\right)^2 \quad \text{Equation 5-63}$$

For  $d/L_D > 0.3$ ,  $d_e$  can be computing using Equation 5.64 (Skaggs, 1980).

$$d_e = \frac{L_D \pi}{8 \left[ \ln\left(\frac{L_D}{r}\right) - 1.15 \right]} \quad \text{Equation 5-64}$$

The depth of saturation above the impervious layer, h, is important to determine if there is flow into the tile drains. This requires keeping track of the soil moisture. For the top soil layer, the soil moisture is calculated as described previously. For the second soil layer, soil moisture is calculated as:

$$SM_{t+1} = SM_t + \frac{WI_t - PERC_t - ET_t}{Z} \quad \text{Equation 5-65}$$

If the soil moisture does not exceed the field capacity then there is no subsurface flow into the tile drains and the soil moisture is recalculated for next time step.

Otherwise, depth of saturation above the impervious layer is calculated as:

$$h = \frac{(SM_{t+1} - FC) * Z}{(PO - FC)} \quad \text{Equation 5-66}$$

where PO is the porosity of the soil layer

When the water table, h, is determined to be above the depth of drainage system, then the tile drainage rate is used based on the following conditions provided by the user:

- If pipe spacing, pipe depth, depth to imperious layer and pipe diameter are supplied by user, then Hooghout's equation is used in calculating drainage flow.
- If pipe spacing, pipe depth, depth to imperious layer are supplied, Equation 5-61 is used and effective depth is assumed the same as the depth to the imperious layer.
- If none of the above parameters are supplied by user and the user supplies the drainage rate (mm/hr), then the user supplied drainage rate is used.
- If none of the parameters are supplied by user, based on practical USDA-NRCS design recommendation, then a value of 12.7 mm/day is used for the drainage rate. Therefore, 0.53 mm/hr or 1.6 mm for each three hours was used for AnnAGNPS.

The total tile drainage flow out of the field to the corresponding reach then is:

$$Q_{Tile} = \frac{q_{drain} * A_{cell}}{1000}$$

Equation 5-67

$Q_{Tile}$  = total volume of tile drainage flow out of cell each time step ( $m^3$ )

$A_{cell}$  = Cell area ( $m^2$ )

## 5.4.2 Lateral Subsurface Flow

Subsurface flow is a very complicated process that we want to apply very simply within AnnAGNPS. Darcy's equation is a widely used and provides an accurate description of the subsurface flow. In general, Darcy's equation applies to saturated flow and unsaturated flow, steady state flow and transient flow, flow in homogeneous systems or heterogeneous systems, and isotropic media or anisotropic media (Freeze and Cherry, 1979). Therefore, Darcy's equation was chosen to simulate subsurface lateral flow and only the saturated condition is considered.

$$q_{lat} = -K_s \frac{dh}{dl}$$

Equation 5-68

$q_{lat}$  = subsurface lateral flow (mm per time period)

KSAT(2) = saturated hydraulic conductivity for each soil layer (mm per time period)

Dh/dl = Hydraulic gradient.

Subsurface flow is assumed to be homogeneous through the entire soil profile of the field and the stream length represents the length of the field.

$$Q_{lat} = \frac{q_{lat} * A_{across}}{1000}$$

Equation 5-69

$$A_{across} = \frac{h * L_{reach}}{1000}$$

Equation 5-70

$Q_{lat}$  = total volume of lateral flow out of cell each time step ( $m^3$ )

$A_{across}$  = Lateral flow across area ( $m^2$ )

h = Saturated depth from the imperious layer (mm)

$L_{reach}$  = Reach length (m)

## 5.5 Channel Hydraulics and Hydrology

The description of the channels provides information to AnnAGNPS that is used to calculate in-stream and in-cell concentrated flows. This information is critical when sediment transport algorithms are used to determine the sediment yield within any location of the watershed. The following sections describe the methods used to determine the flow characteristics within channels.

### 5.5.1 Channel Hydraulics

The purpose of this channel hydraulics section is to describe the hydraulic geometry requirements, their options & defaults, and the algorithms necessary to solve for the flow depths, discharges, & velocities for both the in-cell & the in-stream transport processes within AnnAGNPS. Optional hydraulic geometry's, defaults, & values will also be described.

The general geometric shape for the in-cell concentrated flow channel cross-section is a trapezoid, since a trapezoid can be used as either a rectangle or a triangle by simply setting the proper parameter to zero;  $W = 0$  for a triangle, or  $Z = 0$  for a rectangle.

Whenever the geomorphic parameters for the cross-section are given, the depth is always interpreted to be:

1. for in-cell channel flow--hydraulic depth at the 2-year frequency; i.e., the 2-year frequency flow area divided by the top width for this same flow area; and
2. for in-stream channel flow--hydraulic depth at bankfull; i.e., the bankfull flow area divided by the top width for this same flow area.

The default Manning's roughness for the concentrated flow channel ( $n_{ch}$ ) is the overland flow Manning's roughness ( $n_{ov}$ ) value. The default slope ( $S_0$ ) is the average land slope for the cell ( $S_{ov}$ ). The ultimate default for the in-cell channel total length ( $L$ ) is the standard power curve formula using the universal coefficient & exponent from Leopold et al (1964) corrected for units.

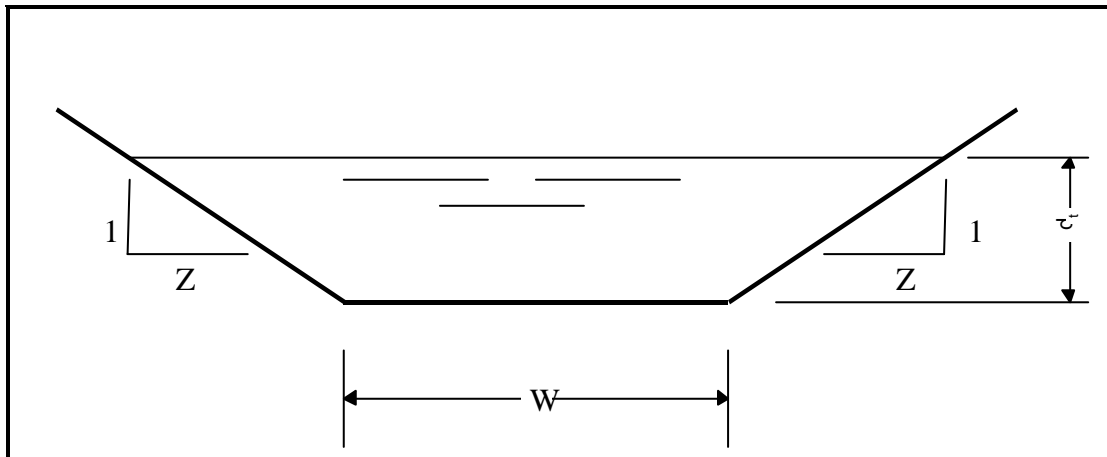
The preferred option is to give the cell channel segment length. The next preferred option is the total channel length from the hydraulically most distant point. The final option is to use the geomorphic parameters provided with the standard power curve formula. If all of the length fields are blank, the default in-stream channel total length is to be calculated by the standard power curve formula using the universal coefficient & exponent from Leopold et al (1964) corrected for units.

The compound in-stream cross-section shape assumes a rectangular main channel and a rectangle out-of-bank (floodplain) flow section. Provision is made for direct input of the basic shape parameters or for the use of geomorphic power curve functions. When out-of-bank flow is not desired, assume the average valley width is equal to the channel top width.

#### 5.5.1.1 In-Cell Concentrated Flow

A key assumption used in the derivation for the following hydraulic equations is that the wetted perimeter is equal to the top width. This assumption greatly simplifies their solution without sacrificing any significant accuracy.

Figure 5-2 is a diagram of the trapezoidal cross-section dimensions used to define the generalized in-cell concentrated flow channel hydraulic geometry.



**Figure 5-2. Generalized In-Cell Channel Shape--trapezoid**

To solve for the total depth ( $d_t$ ) when given total discharge ( $Q_t$ ), use:

For a trapezoid, use the Newton method where

$$f(d_t; Q_t, Z, W, n, S_0) = 0 = 1 - \left\{ \left[ \frac{\sqrt{S_0}}{n \cdot Q_t} \right] \cdot \left[ \frac{[(W \cdot d_t) + (Z \cdot d_t^2)]^{5/3}}{[W + (2 \cdot Z \cdot d_t)]^{2/3}} \right] \right\}$$

$$f'(d_t; Q_t, Z, W, n, S_0) = \left\{ \frac{\sqrt{S_0}}{(3 \cdot n \cdot Q_t)} \right\} \cdot \left\{ \left[ (4 \cdot Z) \cdot \left( \frac{(W \cdot d_t) + (Z \cdot d_t^2)}{W + (2 \cdot Z \cdot d_t)} \right)^{5/3} \right] - \left[ 5 \cdot \left( \frac{((W \cdot d_t) + (Z \cdot d_t^2))^2}{(W + (2 \cdot Z \cdot d_t))^{-1}} \right)^{1/3} \right] \right\}$$

$$d_{t,i=0}(Q_t, Z, W, n, S_0) = \text{MIN} \left[ \left( \frac{n \cdot Q_t}{W \cdot \sqrt{S_0}} \right)^{3/5}, \left( \frac{2^{2/3} \cdot n \cdot Q_t}{Z \cdot \sqrt{S_0}} \right)^{3/8} \right]$$

**Equation 5-71**

Note that the term  $[(W \cdot d_t) + (Z \cdot d_t^2)]$  is the flow area and the term  $[W + (2 \cdot Z \cdot d_t)]$  is the top width. Each is used once in the function and is repeated twice in its 1st derivative.

For a rectangle

$$d_t(Q_t, W, n, S_0) = \left( \frac{n \cdot Q_t}{W \cdot \sqrt{S_0}} \right)^{3/5}$$

**Equation 5-72**

For a triangle

$$d_t(Q_t, Z, n, S_0) = \left( \frac{2^{2/3} \cdot n \cdot Q_t}{Z \cdot \sqrt{S_0}} \right)^{3/8}$$

**Equation 5-73**

where:

- dt = total depth of flow, ft;
- n = Manning's roughness ( $n_{ch}$ ), non-dimensional;
- $Q_t$  = total discharge,  $m^3/sec$ ;
- $S_0$  = channel slope, m/m;
- W = trapezoidal channel bottom width, m; and
- Z = trapezoidal channel side slope, m/m.

To solve for the velocity (V) when given discharge ( $Q_t$ ), use:

For a trapezoid, first solve for the total depth ( $d_t$ ), then

$$V(Q_t, d_t, Z, W) = \frac{Q_t}{(W \cdot d_t) + (Z \cdot d_t^2)}$$

**Equation 5-74**

For a rectangle, first solve for the total depth ( $d_t$ ), then

$$V(Q_t, d_t, W) = \frac{Q_t}{W \cdot d_t}$$

**Equation 5-75**

For a triangle, first solve for the total depth ( $d_t$ ), then

$$V(Q_t, d_t, Z) = \frac{Q_t}{Z \cdot d_t^2}$$

**Equation 5-76**

where:

- $d_t$  = total depth of flow, ft;
- $Q_t$  = total discharge, m<sup>3</sup>/sec;
- $V$  = velocity of flow, m/sec;
- $W$  = trapezoidal channel bottom width, m; and
- $Z$  = trapezoidal channel side slope, m/m.

To solve for the velocity ( $V$ ) when given the total depth ( $d_t$ ), use:

For a trapezoid

$$V(d_t, n, W, Z, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot \left[ \frac{(W \cdot d_t) + (Z \cdot d_t^2)}{W + (2 \cdot Z \cdot d_t)} \right]^{2/3}$$

**Equation 5-77**

For a rectangle

$$V(d_t, n, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot d_t^{2/3}$$

**Equation 5-78**

For a triangle

$$V(d_t, n, Z, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot \left( \frac{d_t}{2} \right)^{2/3}$$

**Equation 5-79**

where:

- $d_t$  = total depth of flow, ft;
- $n$  = Manning's roughness ( $n_{ch}$ ), non-dimensional;
- $S_0$  = channel slope, m/m;
- $V$  = velocity of flow, m/sec;
- $W$  = trapezoidal channel bottom width, m; and
- $Z$  = trapezoidal channel side slope, m/m.



To solve for the velocity (V) when given the hydraulic depth ( $d_h$ ), use:

For all three shapes; i.e., the trapezoid, rectangle, and triangle

$$V(d_h, n, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot d_h^{2/3}$$

**Equation 5-80**

where:

- $d_h$  = hydraulic depth, ft;
- $n$  = Manning's roughness ( $n_{ch}$ ), non-dimensional;
- $S_0$  = channel slope, m/m; and
- $V$  = velocity of flow, m/sec.

To solve for the total discharge ( $Q_t$ ) when given the total depth ( $d_t$ ), use:

For a trapezoid

$$Q_t(d_t, n, W, Z, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot \left\{ \frac{[(W \cdot d_t) + (Z \cdot d_t^2)]^{5/3}}{[W + (2 \cdot Z \cdot d_t)]^{2/3}} \right\}$$

**Equation 5-81**

For a rectangle

$$Q_t(d_t, n, W, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot W \cdot d_t^{5/3}$$

**Equation 5-82**

For a triangle

$$Q_t(d_t, n, Z, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot (Z \cdot d_t^2) \cdot \left( \frac{d_t}{2} \right)^{2/3}$$

**Equation 5-83**

where:

- $d_t$  = total depth of flow, ft;
- $n$  = Manning's roughness ( $n_{ch}$ ), non-dimensional;
- $Q_t$  = total discharge,  $m^3/sec$ ;
- $S_0$  = channel slope, m/m;
- $W$  = trapezoidal channel bottom width, m; and
- $Z$  = trapezoidal channel side slope, m/m.

To solve for the unit total discharge ( $q_t$ ) when given the total depth ( $d_t$ ), use:

For a trapezoid

$$q_t(d_t, n, W, Z, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot \left[ \frac{(W \cdot d_t) + (Z \cdot d_t^2)}{W + (2 \cdot Z \cdot d_t)} \right]^{5/3}$$

**Equation 5-84**

For a rectangle

$$q_t(d_t, n, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot d_t^{5/3}$$

**Equation 5-85**

For a triangle

$$q_t(d_t, n, S_0) = \left( \frac{\sqrt{S_0}}{n} \right) \cdot \left( \frac{d_t}{2} \right)^{5/3}$$

**Equation 5-86**

where:

- $d_t$  = total depth of flow, ft;
- $n$  = Manning's roughness ( $n_{ch}$ ), non-dimensional;
- $q_t$  = unit total discharge,  $m^3/sec/m$ ;
- $S_0$  = channel slope, m/m;
- $W$  = trapezoidal channel bottom width, m; and
- $Z$  = trapezoidal channel side slope, m/m.

To solve for the unit total discharge ( $q_t$ ) when given the total discharge ( $Q$ ), use:

For a trapezoid, first solve for the total depth ( $d_t$ ), then

$$q_t(Q_t, d_t, W, Z) = \left[ \frac{Q_t}{W + (2 \cdot Z \cdot d_t)} \right]$$

**Equation 5-87**

For a rectangle

$$q_t(Q_t, W) = \frac{Q_t}{W}$$

**Equation 5-88**

For a triangle

$$q_t(Q_t, n, Z, S_0) = \left[ \left( \frac{\sqrt{S_0}}{n} \right) \cdot \left( \frac{Q_t}{4 \cdot Z} \right)^{5/3} \right]^{3/8}$$

**Equation 5-89**

where:

- $d_t$  = total depth of flow, ft;
- $n$  = Manning's roughness ( $n_{ch}$ ), non-dimensional;
- $q_t$  = unit total discharge,  $m^3/sec/m$ ;
- $Q_t$  = total discharge,  $m^3/sec$ ;
- $S_0$  = channel slope, m/m;

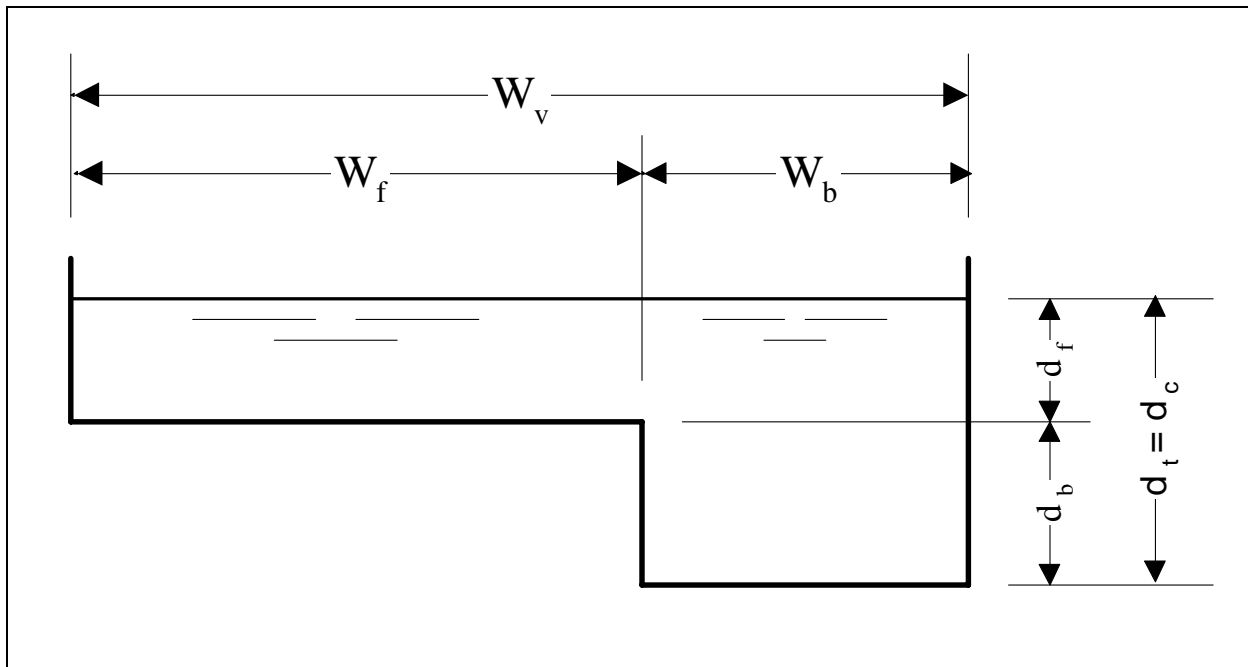
- $W$  = trapezoidal channel bottom width, m; and  
 $Z$  = trapezoidal channel side slope, m/m.

### 5.5.1.2 In-Stream Channel Compound Cross-sections

A key assumption used in the derivation for the following hydraulic equations is that the wetted perimeter is equal to the top width. This assumption greatly simplifies the solution without sacrificing any significant accuracy.

Channel lengths are known to have a sinuosity ( $F_S$ ) with respect to valley lengths. Since the energy gradient ( $S_0$ ) is given for channels, a correction for the energy gradient ( $S_v$ ) of the valley slope could be done in terms of  $S_0$ ; i.e.,  $S_v = F_S \cdot S_0$ . This model will assume  $F_S = 1.25$ .

Figure 5-3 is a diagram of the cross-section dimensions required to define the complete compound in-stream channel hydraulic geometry. If  $W_v \leq W_b$ , then assume  $W_f = 0$ ; otherwise  $W_f = W_v - W_b$ .



**Figure 5-3. Generalized In-Stream Channel Shape--Compound X-Section**

An important variable to determine whether only the channel section of the compound section is active is whether the discharge is above bankfull. To solve for bankfull discharge ( $Q_b$ ), use:

$$Q_b(d_b, W_b, n_c, S_0) = \left( \frac{\sqrt{S_0}}{n_c} \right) \cdot W_b \cdot d_b^{5/3}$$

**Equation 5-90**

where:

- $d_b$  = bankfull depth of flow, ft;  
 $n_c$  = Manning's roughness for channel section, non-dimensional;  
 $Q_b$  = bankfull discharge,  $m^3/sec$ ;  
 $S_0$  = channel section slope, m/m; and  
 $W_b$  = bankfull top width, m.

To solve for the total & sectional depths ( $d_t$ ,  $d_c$ , &  $d_f$ ) when given the total discharge ( $Q_t$ ), use:

For  $Q_t \leq Q_b$  or  $W_f = 0$

$$d_t(Q_t, W_b, n_c, S_0) = \left( \frac{n_c \cdot Q_t}{W_b \cdot \sqrt{S_0}} \right)^{3/5}$$

$$d_c = d_t$$

$$d_f = 0$$

**Equation 5-91**

For  $Q_t > Q_b$ , use the Newton method where

$$f(d_t; Q_t, W_b, W_f, d_b, n_c, n_f, S_0, F_s) = 0 = 1 - \left\{ \left( \frac{\sqrt{S_0}}{Q_t} \right) \cdot \left[ \frac{W_b \cdot d_t^{5/3}}{n_c} \right] + \left[ \sqrt{F_s} \cdot \left( \frac{W_f}{n_f} \right) \cdot (d_t - d_b)^{5/3} \right] \right\}$$

$$f'(d_t; Q_t, W_b, W_f, d_b, n_c, n_f, S_0, F_s) = \left\{ \frac{-5 \cdot \sqrt{S_0}}{3 \cdot Q_t} \right\} \cdot \left\{ \left[ \frac{W_b \cdot d_t^{2/3}}{n_c} \right] + \left[ \sqrt{F_s} \cdot \left( \frac{W_f}{n_f} \right) \cdot (d_t - d_b)^{2/3} \right] \right\}$$

$$d_{t,i=0}(Q_t, W_b, W_f, d_b, n_c, n_f, S_0, F_s) = \text{MIN} \left[ \left( \frac{n_c \cdot Q_t}{W_b \cdot \sqrt{S_0}} \right)^{3/5}, d_b + \left( \frac{n_c \cdot Q_t}{W_b \cdot \sqrt{F_s \cdot S_0}} \right)^{3/5} \right]$$

$$d_c = d_t$$

$$d_f = d_t + d_b$$

**Equation 5-92**

where:

- $d_c$  = channel section depth of flow, ft;
- $d_f$  = floodplain section depth of flow, ft;
- $d_t$  = total depth of flow, ft;
- $F_s$  = sinuosity (assume to be 1.25), m/m;
- $n_c$  = Manning's roughness for channel section, non-dimensional;
- $n_f$  = Manning's roughness for floodplain section, non-dimensional;
- $Q_t$  = total discharge, m<sup>3</sup>/sec;
- $S_0$  = channel section slope, m/m;
- $W_b$  = bankfull top width, m; and
- $W_f$  = floodplain width, m.

To solve for the sectional velocities ( $V_c$  &  $V_f$ ) when given the total discharge ( $Q_t$ ), use:

For  $Q_t \leq Q_b$  or  $W_f = 0$ , first solve for the total depth ( $d_t$ ), then

$$V_c(Q_t, W_b, d_t) = \frac{Q_t}{W_b \cdot d_t}$$

$$V_f = 0$$

**Equation 5-93**

For  $Q_t > Q_b$ , first solve for the sectional depths ( $d_c$  &  $d_f$ ), then solve for the sectional discharges ( $Q_c$  &  $Q_f$ ), and use:

$$V_c(Q_c, W_b, d_c) = \frac{Q_c}{W_b \cdot d_c}$$

$$V_f(Q_f, W_f, d_f, d_b) = \frac{Q_f}{W_f \cdot (d_f - d_b)}$$

**Equation 5-94**

where:

- $d_c$  = channel section depth of flow, ft;
- $d_f$  = floodplain section depth of flow, ft;
- $d_t$  = total depth of flow, ft;
- $Q_c$  = channel section discharge, m<sup>3</sup>/sec;
- $Q_f$  = floodplain discharge, m<sup>3</sup>/sec;
- $Q_t$  = total discharge, m<sup>3</sup>/sec;
- $V_c$  = channel section velocity of flow, m/s;
- $V_f$  = floodplain section velocity of flow, m/s;
- $W_b$  = bankfull top width, m; and
- $W_f$  = floodplain width, m.

To solve for the sectional velocities ( $V_c$  &  $V_f$ ) when given the total depth ( $d_t$ ), use:

For  $Q_t \leq Q_b$  or  $W_f = 0$ , use Equation 5-93

For  $Q_t > Q_b$ , first solve for the sectional discharges ( $Q_c$  &  $Q_f$ ; see Equation 5-96), then use Equation 5-94.

Where:

- $Q_b$  = bankfull discharge, m<sup>3</sup>/sec;
- $Q_c$  = channel section discharge, m<sup>3</sup>/sec;
- $Q_f$  = floodplain discharge, m<sup>3</sup>/sec;
- $Q_t$  = total discharge, m<sup>3</sup>/sec; and
- $W_f$  = floodplain width, m.

To solve for the total & sectional discharges ( $Q_t$ ,  $Q_c$ , &  $Q_f$ ) when given the total depth ( $d_t$ ), use:

For  $Q_t \leq Q_b$  or  $W_f = 0$

$$Q_t(d_t, W_b, n_c, S_0) = \left( \frac{\sqrt{S_0}}{n_c} \right) \cdot W_b \cdot d_t^{5/3}$$

$$Q_c = Q_t$$

$$Q_f = 0$$

**Equation 5-95**

For  $Q_t > Q_b$ , use

$$Q_c(d_t, W_b, n_c, S_0) = \left( \frac{W_b}{n_c} \right) \cdot d_t^{5/3} \cdot \sqrt{S_0}$$

$$Q_f(d_t, W_f, d_b, n_f, S_0, F_s) = \left( \frac{W_f}{n_f} \right) \cdot (d_t - d_b)^{5/3} \cdot \sqrt{F_s \cdot S_0}$$

$$Q_t(W_b, W_f, d_t, d_b, n_c, n_f, S_0, F_s) = Q_c + Q_f$$

**Equation 5-96**

where:

- $d_b$  = bankfull depth of flow, ft;
- $d_t$  = total depth of flow, ft;
- $F_s$  = sinuosity (assume to be 1.25), m/m;
- $n_c$  = Manning's roughness for channel section, non-dimensional;
- $n_f$  = Manning's roughness for floodplain section, non-dimensional;
- $Q_c$  = channel section discharge, m<sup>3</sup>/sec;
- $Q_f$  = floodplain discharge, m<sup>3</sup>/sec;
- $Q_t$  = total discharge, m<sup>3</sup>/sec;
- $S_0$  = channel section slope, m/m;
- $W_b$  = bankfull top width, m; and
- $W_f$  = floodplain width, m.

To solve for the sectional unit discharges ( $q_c$  &  $q_f$ ) when given the total depth ( $d_t$ ), use:

For  $Q_t \leq Q_b$  or  $W_f = 0$

$$q_t(d_t, n_c, S_0) = \left( \frac{\sqrt{S_0}}{n_c} \right) \cdot d_t^{5/3}$$

$$q_c = q_t$$

$$q_f = 0$$

**Equation 5-97**

For  $Q_t > Q_b$ , use

$$q_c(d_t, n_c, S_0) = \left( \frac{d_t^{5/3}}{n_c} \right) \cdot \sqrt{S_0}$$

$$q_f(d_t, d_b, n_f, S_0, F_s) = \left[ \frac{(d_t - d_b)^{5/3}}{n_f} \right] \cdot \sqrt{F_s \cdot S_0}$$

**Equation 5-98**

where:

- $d_b$  = bankfull depth of flow, ft;
- $d_t$  = total depth of flow, ft;
- $F_s$  = sinuosity (assume to be 1.25), m/m;
- $n_c$  = Manning's roughness for channel section, non-dimensional;
- $n_f$  = Manning's roughness for floodplain section, non-dimensional;
- $q_c$  = channel section unit discharge,  $m^3/sec/m$ ;
- $q_f$  = floodplain unit discharge,  $m^3/sec/m$ ;
- $q_t$  = total unit discharge,  $m^3/sec/m$ ;
- $Q_c$  = channel section discharge,  $m^3/sec$ ;
- $Q_f$  = floodplain discharge,  $m^3/sec$ ;
- $Q_t$  = total discharge,  $m^3/sec$ ;
- $S_0$  = channel section slope, m/m;
- $W_b$  = bankfull top width, m; and
- $W_f$  = floodplain width, m.

To solve for the sectional unit discharges ( $q_c$  &  $q_f$ ) when given the total discharge ( $Q_t$ ), use:

For  $Q_t \leq Q_b$  or  $W_f = 0$

$$q_c = \frac{Q_t}{W_b}$$

$$q_f = 0$$

**Equation 5-99**

For  $Q_t > Q_b$ , first solve for the sectional depths ( $d_c$  &  $d_f$ ), then solve for the sectional discharges ( $Q_c$  &  $Q_f$ ), and use:

$$q_c = \frac{Q_c}{W_b}$$

$$q_f = \frac{Q_f}{W_f}$$

**Equation 5-100**

where:

- $q_c$  = channel section unit discharge,  $m^3/sec/m$ ;
- $q_f$  = floodplain unit discharge,  $m^3/sec/m$ ;
- $q_t$  = total unit discharge,  $m^3/sec/m$ ;
- $Q_c$  = channel section discharge,  $m^3/sec$ ;
- $Q_f$  = floodplain discharge,  $m^3/sec$ ;
- $Q_t$  = total discharge,  $m^3/sec$ ;
- $W_b$  = bankfull top width, m; and
- $W_f$  = floodplain width, m.

### 5.5.1.3 Hydraulic Depth and Velocity

Rectangular shape channels offer computational efficiencies, especially when coupled with unit-width assumptions. Therefore, the NRCS version will use these efficiencies.

For the hydraulic radius, use the hydraulic depth; i.e., let:

$$d_w = R = A_H/W_H$$

**Equation 5-101**

where:  $d_w$  = hydraulic depth, m;  
 $R$  = hydraulic radius, m;  
 $A_H$  = flow area,  $m^2$ ; and  
 $W_H$  = flow width, m.

To solve for the velocity of flow when given the hydraulic depth of flow, use:

$$v_w = (1/n) \cdot d_w^{2/3} \cdot S_o^{1/2}$$

**Equation 5-102**

where:  $v_w$  = flow velocity of water, m/s;  
 $n$  = Manning's retardance;  
 $d_w$  = hydraulic depth, m; and  
 $S_o$  = channel slope, m/m.

For impoundments, always use a constant channel slope of 0.0000001; otherwise, use the user supplied input value.

To solve for the hydraulic depth and velocity when given the discharge, use:

$$d_w = [(n \cdot q_w)/(S_o^{1/2})]^{0.6} = n^{0.6} \cdot S_o^{-0.3} \cdot q_w^{0.6}$$



$$v_w = Q_w / (W_H \cdot d_w) = q_w / d_w$$

**Equation 5-103**

where:  $d_w$  = hydraulic depth, m;  
 $v_w$  = flow velocity of water, m/s;  
 $W_H$  = flow width of flow area, m;  
 $n$  = Manning's retardance;  
 $Q_w$  = water discharge, m<sup>3</sup>/s;  
 $q_w = Q_w/W$ , unit-width water discharge, m<sup>3</sup>/s/m; and  
 $S_o$  = channel slope, m/m.

And the term,  $d_w$ , derived from  
 formulas:

**Equation 5-104**, will be used in subsequent

$$d_w \cdot S_o = n^{0.6} \cdot S_o^{0.7} \cdot q_w^{0.6}$$

**Equation 5-104**

where:  $d_w$  = hydraulic depth, m;  
 $v_w$  = flow velocity of water, m/s;  
 $n$  = Manning's retardance;  
 $q_w = Q_w/W$ , unit-width water discharge, m<sup>3</sup>/s/m; and  
 $S_o$  = channel slope, m/m.

### 5.5.1.4 Time of Concentration ( $t_c$ )

The purpose of the Time of Concentration Module is to calculate the in-cell time of concentration for flow to each cell outlet ( $T_{c,in\_cell}$ ) and the travel time for flow between the inlet and outlet of each channel reach ( $T_t$ ).  $T_{c,in\_cell}$  and  $T_t$  are used to calculate time of concentration to the channel reach outlet ( $T_{c,reach\_outlet}$ ).  $T_{c,reach\_outlet}$  is defined as the time required for flow from the hydraulically most distant point in the channel reach drainage area to the reach outlet.  $T_{c,reach\_outlet}$  and  $T_t$  are needed to calculate peak water discharge and pre-peak runoff fraction using the extended TR55 methodology.

Sources for information in this description are: 1) the AGNPSv5.00 source code (loop1tr5.c, chantr55.c), 2) Chapter 3 in TR55 Manual, and 3) pages B-3 to B-5 in SCS AGNPS Evaluation (3/93).

In general, there are three segments of flow for the in\_cell processes—overland flow, shallow concentrated flow, and concentrated flow (see TR55).

#### In-cell flow ( $T_{c,in\_cell}$ ):

For in-cell flow, the flowpath is divided into a section of overland sheet flow, followed by a section of shallow concentrated flow and a section of in-cell concentrated flow. The length of the in-cell flowpath ( $L$ ) is an input. Travel times for flow in these sections are designated as time of overland flow ( $T_{t,ov}$ ), time of shallow concentrated flow ( $T_{t,scf}$ ), and time of in-cell concentrated flow ( $T_{t,cf}$ ).  $T_{c,in\_cell}$  is calculated using the following equations:

$$T_{c,in\_cell} = T_{t,ov} + T_{t,scf} + T_{t,cf} \quad \text{Equation 5-105}$$

where:

- $T_{c,in\_cell}$  = time of concentration for the local contributions from the in-cell processes to the downstream end of the cell's receiving reach, hr;
- $T_{t,cc}$  = travel time for the in\_cell concentrated flow period, hr;
- $T_{t,ov}$  = travel time for the overland flow period, hr; and
- $T_{t,scf}$  = travel time for the shallow concentrated flow period, hr.

See TR55 for further clarification.

Overland flow is the first segment of flow and the length of the overland flow section ( $L_{ov}$ ) is assumed to be no longer than a maximum length (50 m).

For the overland sheet flow segment:

$$L_{ov\_max} = 50$$

$$L_{ov} = MIN(L_{ov\_max}, L)$$

$$T_{t,ov} = \frac{0.09 \cdot (n_{ov} \cdot L_{ov})^{0.8}}{(P_2^{0.5} \cdot S_{ov}^{0.4})} \quad \text{Equation 5-106}$$

where:

- $n_{ov}$  = Manning's overland flow roughness, nondimensional;
- $L$  = total flow path length of all segments for the in\_cell processes (hydraulically most distant point within the cell to the downstream end of the cell's receiving reach, m; flow, m);
- $L_{ov}$  = flow path length for the overland flow segment, m;
- $L_{ov\_max}$  = maximum flow path length for the overland flow segment, m;
- $P_2$  = 2-year precipitation;
- $S_{ov}$  = overland flow land slope, m/m; and
- $T_{t,ov}$  = travel time for the overland flow period, hr.

For continuous simulation (two or more precipitation events), determine the 2-year 24 hour precipitation.

For a single-event, use the input precipitation for P<sub>2</sub>.

Shallow concentrated flow is the second segment of flow and the length of this segment ( $L_{scf}$ ) is assumed to be no longer than a maximum length ( $L_{ov\_max}$ ) of approximately 50m. An additional restriction on shallow concentrated flow is that the velocity ( $V_{scf}$ ) is assumed to be no greater than 0.61 m/sec (2.0 fps).

For the shallow concentrated flow segment:

$$L_{ov\_max} = 50$$

*If  $L > L_{ov\_max}$ , then*

$$L_{scf} = MIN[L_{ov\_max}, (L - L_{ov})]$$

$$V_{scf} = MIN[0.61, (4.9178 \cdot S_{ov}^{0.5})]$$

$$T_{t,scf} = \frac{L_{scf}}{(3600 \cdot V_{scf})}$$

*Otherwise,*

$$T_{t,scf} = 0$$

**Equation 5-107**

where:

- L = total flow path length for the in\_cell processes (hydraulically most distant point within the cell to the downstream end of the cell's receiving reach, m; flow, m;
- L<sub>ov</sub> = flow path length for the overland flow segment, m;
- L<sub>ov\_max</sub> = maximum flow path length for the overland flow segment, m;
- L<sub>scf</sub> = flow path length for the shallow concentrated flow segment, m;
- S<sub>ov</sub> = overland flow land slope, m/m;
- T<sub>t,scf</sub> = travel time for the shallow concentrated flow period, hr; and
- V<sub>scf</sub> = velocity of flow for the shallow concentrated flow segment, m/s.

The concentrated flow section in a channel with a triangular, rectangular, or trapezoidal cross-section is the final in-cell section of flow. The length of the in-cell, concentrated flow section ( $L_{conc,in-cell}$ ) is the remainder of the in-cell flow length. The velocity ( $V_{conc,in-cell}$ ) is calculated using one of the hydraulic equations, substituting the in-cell values for channel slope ( $S_0$ ) and Manning's roughness coefficient ( $n_{ch}$ ), and the hydraulic depth at a 2 year return frequency ( $d_{2-yr}$ ) for  $d_h$ . For the in-cell, concentrated flow section:

*If  $L > L_{ov\_max} + L_{scf\_max}$ , then*

$$L_{cf} = L - (L_{ov} + L_{scf})$$

$$T_{t,cf} = \frac{L_{cf}}{(3600 \cdot V_{cf})}$$

*Otherwise,*

$$T_{t,cf} = 0$$

**Equation 5-108**

where:

- L = total flow path length for the in\_cell processes (hydraulically most distant point within the cell to the downstream end of the cell's receiving reach), m;
- L<sub>cf</sub> = flow path length for the concentrated flow segment, m;
- L<sub>ov</sub> = flow path length for the overland flow segment, m;

$L_{ov\_max}$	=	maximum flow path length for the overland flow segment, m;
$L_{scf}$	=	flow path length for the shallow concentrated flow segment, m;
$L_{scf\_max}$	=	maximum flow path length for the shallow concentrated flow segment, m;
$L_{scf}$	=	flow path length for the shallow concentrated flow segment, m;
$T_{t,sf}$	=	travel time for the concentrated flow period, hr; and
$V_{cf}$	=	velocity of flow for the concentrated flow segment, m/s.

#### Channel reach travel time ( $T_{t,reach}$ ):

For channel flow, the flowpath is divided into sections of flow referred to as reaches. Channel reaches are assumed to have either rectangular or compound rectangular cross-sections. The length of the channel reach ( $\Delta L$ ) is an input value or is calculated directly from input. The velocity ( $V_{reach}$ ) is calculated using one of the hydraulic equations substituting the channel reach values for channel slope ( $S_0$ ) and Manning's roughness coefficient ( $n_c$ ), and the hydraulic depth at bankfull flow ( $d_b$ ) for  $d_h$ . To calculate  $T_{t,reach}$  use:

$$T_{t,reach} = \frac{\Delta L}{(3600 \cdot V_{Reach})}$$

**Equation 5-109**

where:

$T_{t,reach}$	=	travel time through the reach segment, hr;
$V_{reach}$	=	velocity of flow through the reach, m/s; and
$\Delta L$	=	channel length of the reach segment for the in_stream processes, m.

#### Time of concentration to channel reach outlet ( $T_{c,reach\_out}$ ):

To calculate  $T_{c,reach\_in}$ , the maximum value of the time of concentrations for all reaches flowing into the reach being considered (including flows from adjacent cells or incoming reaches) and assigning the largest of these values. Then, to calculate  $T_{c,reach\_out}$  use:

*If there are no contributing reaches, then*

$$T_{c,reach\_in} = 0$$

*Otherwise,*

$$T_{c,reach\_in} = \text{MAX}(T_{c,reach\_out} \text{ 's of all immediately contributing reaches})$$

$$T_{c,reach\_out} = T_{c,reach\_in} + T_{t,reach}$$

**Equation 5-110**

where:

$T_{t,reach\_in}$	=	time of concentration at the reach inlet, hr;
$T_{t,reach\_out}$	=	time of concentration at the reach outlet, hr; and
$T_{t,reach}$	=	travel time through the reach segment, hr.

## Special Notes:

- The value to be used for precipitation ( $P_2$ ) in the time for overland flow calculation for ANNAGNPS was selected based on the TR55 reference which states that a 2-year (return frequency), 24-hour (duration) precipitation amount for the location of interest be used. AGNPS v5.00 used the actual precipitation amount that was input for the single storm event analyzed by AGNPS v5.00.

## 5.5.2 Channel Hydrology

### 5.5.2.1 Ratio of Initial Abstraction to 24-Hour Precipitation

This section will describe the procedures used to calculate the ratio of initial abstraction,  $I_a$ , to 24-hour precipitation total,  $P_{24}$ , ( $I_a/P_{24}$ ), which is needed to calculate the peak discharge for hydrograph construction for each cell during each runoff event.  $I_a/P_{24}$  must be a spatially-averaged value representing the entire drainage area to the cell outlet.

The basis for this calculation is from chapter 2 of the TR55 manual (SCS, 1986). Combining  $I_a = 0.2 S$ , where  $S$  is the potential maximum retention after runoff begins, and Eq. 5-23 gives:

$$Q_{24} \equiv (P_{24} - I_a)^2 / (P_{24} + 4 I_a) \quad \text{Equation 5-111}$$

Algebraic manipulation gives:

$$I_a^2 + (-2P_{24} + 4Q_{24}) I_a + (P_{24}^2 - Q_{24}P_{24}) = 0 \quad \text{Equation 5-112}$$

Solving using the quadratic formula and testing for the correct radical sign gives:

$$I_a = (P_{24} + 2Q_{24}) - (5Q_{24}P_{24} + 4Q_{24}^2)^{0.5} \quad \text{Equation 5-113}$$

To calculate the  $I_a / P_{24}$  divide both sides by  $P_{24}$ :

$$(I_a / P_{24}) \equiv [(P_{24} + 2Q_{24}) - (5Q_{24}P_{24} + 4Q_{24}^2)^{0.5}] / P_{24} \quad \text{Equation 5-114}$$

Or the ratio of initial abstraction over the 24-hour precipitation in its completely non-dimensional form:

$$(I_a / P_{24}) \equiv \{1 + 2(Q_{24}/P_{24}) - [4(Q_{24}/P_{24})^2 + 5(Q_{24}/P_{24})]^{0.5}\} \quad \text{Equation 5-115}$$

### 5.5.2.2 Unit Peak Discharge

The purpose of unit peak discharge (Unit\_Peak\_Discharge.doc) is to calculate the unit peak discharge. It is necessary for hydrograph construction and for the HUSLE sediment yield model.

## Variables In:

The variables necessary to be passed to this module are:

$I_R$  ≡ indicator for the SCS rainfall distribution types from a set of nine predetermined distributions. Integer number from 1 to 9, respectively stands for: (a) the standard SCS rainfall distributions Type I, Ia, II, & III; (b) uniform rainfall distribution for snowmelt & irrigation; and (c) the four new distributions for the Southwest—Types Ila60, Ila65, Ila70, & Ila75.

$I_a/P_{24}$  ≡ ratio of initial abstraction to 24-hour effective precipitation including snowmelt & irrigation but less snowfall (non-dimensional);

$t_c$  ≡ time of concentration (hr).

## Variables Out:

The variables needed by other modules are:

$q_p/P_{24}$  ≡ unit peak discharge ratio to 24-hour effective precipitation which includes snowmelt & irrigation amounts but less any snowfall (mm/hr per millimeter of precipitation);

The following set of regression coefficients were generated using the Extended TR55 procedures and curve-fitted using TableCurve 2D. The general form for the regression equation to calculate the peak discharge is:

$$q_p = \frac{a + (c \cdot T_c) + (e \cdot T_c^2)}{1 + (b \cdot T_c) + (d \cdot T_c^2) + (f \cdot T_c^3)}$$

Equation 5-116

$$Q_p = \text{factor} \cdot P_{24} \cdot D_a \cdot q_p$$

where:  $q_p$  = unit peak discharge, [(mm/hr) per mm-rainfall];  
 $Q_p$  = peak discharge,  $m^3/s$ ;  
 $D_a$  = total drainage area, hectares;  
 $P_{24}$  = 24-hour effective rainfall over the total drainage area mm;  
 $T_c$  = time of concentration hr;  
factor  $\equiv 2.7777777778 \cdot 10^{-3}$  [hr/sec) per (mm-ha/ $m^3$ )]; and  
a, b, c, d, e, & f are the unit peak discharge regression coefficients for a given  $I_a/P_{24}$  and rainfall distribution type.

The following tables are the regression coefficients for each rainfall distribution:

**Table 5-1: Unit Peak Discharge ( $q_p$ ) Regression Coefficients—Type 1 (I)**

$I_a/P_{24}$	a	b	c	d	e	f
0.00	8.191203E-01	2.098577E+00	1.420600E-01	6.403418E-02	-1.798058E-03	-9.691654E-04
0.05	6.919276E-01	2.109991E+00	1.081450E-01	6.347507E-02	-1.622012E-03	-1.210682E-03
0.10	5.257620E-01	2.126639E+00	7.114301E-02	4.932504E-02	-2.354271E-04	1.702570E-04
0.15	3.911779E-01	2.164178E+00	4.843322E-02	3.898827E-02	7.191297E-04	1.750109E-03
0.20	2.881040E-01	2.269473E+00	3.648846E-02	3.394364E-02	1.194882E-03	3.185709E-03
0.25	2.046130E-01	2.378271E+00	2.870114E-02	3.023519E-02	1.409403E-03	4.554133E-03
0.30	1.364564E-01	2.452425E+00	2.293463E-02	2.771656E-02	1.494880E-03	5.966169E-03
0.35	8.314092E-02	2.462049E+00	1.824892E-02	2.575244E-02	1.468654E-03	7.318409E-03
0.40	4.209120E-02	2.107367E+00	1.253109E-02	2.416459E-02	1.257576E-03	7.818349E-03
0.45	1.514096E-02	6.839693E-01	2.620520E-03	7.442042E-03	4.536918E-04	3.498770E-03
0.50	7.218079E-03	8.104122E-03	-1.926595E-04	1.437835E-04	1.753325E-05	1.498123E-04
0.55	5.195935E-03	1.650006E-02	8.599060E-05	2.397559E-03	5.659238E-06	6.045672E-05
0.60	4.166588E-03	2.719060E-02	1.090675E-04	3.126468E-03	7.904181E-06	1.235070E-04
0.65	3.288864E-03	4.228829E-02	1.330839E-04	4.336509E-03	1.099875E-05	2.482510E-04
0.70	2.540703E-03	6.181280E-02	1.503776E-04	6.225186E-03	1.459598E-05	4.833020E-04
0.75	1.904672E-03	8.235525E-02	1.524927E-04	9.004310E-03	1.705867E-05	8.629756E-04
0.80	1.358244E-03	4.526567E-02	9.085505E-05	9.939561E-03	2.978380E-07	0.000000E+00
0.85	9.140984E-04	7.422017E-02	1.007703E-04	1.820688E-02	1.747810E-07	0.000000E+00
0.90	5.573419E-04	1.351745E-01	1.016625E-04	4.003236E-02	7.839465E-08	0.000000E+00
0.95	2.634720E-04	3.418091E-01	9.845720E-05	1.530589E-01	0.000000E+00	0.000000E+00

**Table 5-2: Unit Peak Discharge ( $q_p$ ) Regression Coefficients—Type 2 (Ia)**

$I_a/P_{24}$	a	b	c	d	e	f
0.00	2.593320E-01	6.463246E-01	2.573810E-02	7.243833E-03	2.161611E-05	1.398574E-04
0.05	2.103536E-01	5.787296E-01	8.960153E-03	4.176511E-04	4.662938E-04	5.957680E-04
0.10	1.534586E-01	5.863319E-01	4.299067E-03	3.782405E-03	6.349957E-04	9.820728E-04
0.15	1.092383E-01	6.063397E-01	2.714056E-03	-5.769199E-03	6.702009E-04	1.307089E-03
0.20	7.630642E-02	6.560184E-01	2.566400E-03	-6.452636E-03	6.961028E-04	1.709310E-03
0.25	5.162438E-02	8.262968E-01	4.669195E-03	-2.590814E-03	8.247653E-04	2.527921E-03
0.30	3.219182E-02	1.372765E+00	1.169386E-02	1.232772E-02	1.095941E-03	4.263898E-03
0.35	1.389971E-02	5.953180E-01	5.118616E-03	1.104682E-02	4.137916E-04	2.015238E-03
0.40	9.523307E-03	3.028293E-02	2.788554E-04	2.240374E-03	1.933978E-05	1.080512E-04
0.45	7.947428E-03	4.343201E-02	3.361887E-04	2.995202E-03	2.363104E-05	1.724346E-04
0.50	6.603513E-03	5.296087E-02	3.495237E-04	3.849553E-03	2.518278E-05	2.391575E-04
0.55	5.461055E-03	6.381239E-02	3.535194E-04	4.953487E-03	2.671026E-05	3.351053E-04
0.60	4.480394E-03	7.302563E-02	3.394787E-04	6.287665E-03	2.609098E-05	4.407477E-04
0.65	3.629760E-03	7.391494E-02	2.960874E-04	7.681127E-03	2.013478E-05	4.683609E-04
0.70	2.904604E-03	7.634941E-02	2.549939E-04	9.596277E-03	1.432665E-05	4.757768E-04
0.75	2.284124E-03	8.606065E-02	2.219254E-04	1.263373E-02	1.038930E-05	5.201617E-04
0.80	1.741268E-03	8.602862E-02	1.642964E-04	1.576832E-02	2.481447E-07	0.000000E+00
0.85	1.252801E-03	1.275459E-01	1.491703E-04	2.577755E-02	1.715766E-07	0.000000E+00
0.90	8.011775E-04	2.137939E-01	1.402272E-04	5.486350E-02	9.894536E-08	0.000000E+00
0.95	3.796023E-04	5.118736E-01	1.678194E-04	2.602381E-01	0.000000E+00	0.000000E+00

**Table 5-3: Unit Peak Discharge ( $q_p$ ) Regression Coefficients—Type 3 (II)**

$I_a/P_{24}$	a	b	c	d	e	f
0.00	1.519530E+00	2.112862E+00	7.955306E-02	6.263867E-02	8.513482E-03	6.758214E-03
0.05	1.338024E+00	2.177418E+00	4.462696E-02	3.891612E-02	6.773656E-03	7.265634E-03
0.10	1.084275E+00	2.309563E+00	3.214664E-02	2.928899E-02	4.187178E-03	5.914179E-03
0.15	8.552839E-01	2.409625E+00	2.220279E-02	2.093824E-02	3.167149E-03	5.759206E-03
0.20	6.687890E-01	2.523586E+00	1.716150E-02	1.954410E-02	2.908914E-03	6.678482E-03
0.25	5.204481E-01	2.707240E+00	1.865985E-02	3.106130E-02	2.609529E-03	7.563368E-03
0.30	3.965887E-01	2.892446E+00	1.957488E-02	4.369223E-02	2.304790E-03	8.452182E-03
0.35	3.035455E-01	3.306239E+00	2.688043E-02	7.654164E-02	1.599703E-03	7.657173E-03
0.40	2.272377E-01	3.907665E+00	3.469720E-02	1.245753E-01	9.446148E-04	6.197919E-03
0.45	1.623361E-01	4.672595E+00	4.017034E-02	1.831037E-01	5.288035E-04	5.107105E-03
0.50	1.052873E-01	5.412166E+00	4.032126E-02	2.354091E-01	4.239395E-04	5.708259E-03
0.55	5.467159E-02	5.310563E+00	3.077002E-02	2.320090E-01	5.350362E-04	8.502971E-03
0.60	1.690395E-02	2.321569E+00	8.300435E-03	7.991502E-02	4.118532E-04	7.692973E-03
0.65	4.984477E-03	1.510427E-01	-1.350363E-04	-2.639579E-03	5.052332E-05	1.185892E-03
0.70	2.604670E-03	1.067922E-02	-9.847605E-05	-9.597972E-04	3.665667E-06	1.012225E-04
0.75	1.605259E-03	1.063624E-02	-1.018709E-05	1.621910E-03	1.314348E-06	4.652552E-05
0.80	1.042173E-03	-1.020764E-04	-3.811053E-06	2.567960E-03	9.359939E-09	-3.038358E-05
0.85	7.344981E-04	4.101026E-02	2.234531E-05	5.882155E-03	1.608977E-07	0.000000E+00
0.90	4.707279E-04	1.018389E-01	3.250327E-05	1.440050E-02	7.240176E-08	0.000000E+00
0.95	2.238719E-04	2.894003E-01	5.153391E-05	8.043160E-02	0.000000E+00	0.000000E+00

**Table 5-4: Unit Peak Discharge ( $q_p$ ) Regression Coefficients—Type 4 (III)**

$I_a/P_{24}$	a	b	c	d	e	f
0.00	9.357636E-01	1.368530E+00	7.585186E-02	5.733524E-02	5.252073E-03	4.195782E-03
0.05	8.253479E-01	1.413947E+00	5.841517E-02	5.400238E-02	4.030500E-03	4.353034E-03
0.10	6.683331E-01	1.508040E+00	4.965229E-02	5.391574E-02	1.853956E-03	2.702981E-03
0.15	5.276991E-01	1.583411E+00	4.012233E-02	5.251510E-02	1.124370E-03	2.170778E-03
0.20	4.129800E-01	1.675525E+00	3.451340E-02	5.585967E-02	8.903714E-04	2.210996E-03
0.25	3.207203E-01	1.813219E+00	3.311754E-02	6.787772E-02	7.510814E-04	2.384131E-03
0.30	2.417654E-01	1.940402E+00	3.132061E-02	8.146421E-02	6.731751E-04	2.708124E-03
0.35	1.767351E-01	2.097120E+00	3.093827E-02	1.017525E-01	5.002872E-04	2.645343E-03
0.40	1.218296E-01	2.203114E+00	2.877259E-02	1.196262E-01	3.657518E-04	2.572314E-03
0.45	7.666285E-02	2.128711E+00	2.292102E-02	1.212507E-01	3.368914E-04	2.981235E-03
0.50	4.507926E-02	1.948361E+00	1.620488E-02	1.105793E-01	3.712890E-04	4.019728E-03
0.55	2.469452E-02	1.758470E+00	1.105166E-02	9.845579E-02	3.614453E-04	4.994300E-03
0.60	1.103889E-02	7.637374E-01	2.652503E-03	3.138008E-02	2.008206E-04	3.555352E-03
0.65	4.885440E-03	6.905722E-02	-4.164706E-05	-3.984385E-04	0.000000E+00	0.000000E+00
0.70	3.230059E-03	5.962268E-02	-2.828449E-05	-2.916562E-04	0.000000E+00	0.000000E+00
0.75	2.042210E-03	4.884191E-02	-2.357561E-05	-4.019053E-04	0.000000E+00	0.000000E+00
0.80	1.130600E-03	1.856640E-02	-1.739106E-05	1.191404E-03	2.667614E-06	1.966816E-04
0.85	6.371840E-04	2.524817E-02	2.657251E-05	6.623725E-03	1.693389E-07	0.000000E+00
0.90	3.760393E-04	7.045939E-02	3.777876E-05	1.627031E-02	7.137928E-08	0.000000E+00
0.95	1.733055E-04	2.152918E-01	4.377647E-05	6.838585E-02	0.000000E+00	0.000000E+00



**Table 5-5: Unit Peak Discharge ( $q_p$ ) Regression Coefficients—Type 5 (Uniform)**

$I_a/P_{24}$	a	b	c	d	e	f
0.00	4.161024E-02	-2.291070E-02	-8.630791E-04	6.634947E-04	1.701998E-05	2.227598E-06
0.05	3.979048E-02	5.092441E-03	2.152859E-04	1.102779E-03	2.492990E-05	1.945509E-05
0.10	3.632114E-02	7.808752E-02	2.622925E-03	3.031724E-03	9.491374E-05	1.381052E-04
0.15	3.249215E-02	9.929542E-02	2.873268E-03	4.161972E-03	1.039547E-04	1.947430E-04
0.20	2.878569E-02	8.682334E-02	2.068912E-03	4.156828E-03	7.760004E-05	1.814001E-04
0.25	2.537079E-02	8.066222E-02	1.557404E-03	4.249363E-03	6.150914E-05	1.788971E-04
0.30	2.227825E-02	8.056172E-02	1.264393E-03	4.563556E-03	5.305982E-05	1.927498E-04
0.35	1.949576E-02	8.307306E-02	1.062776E-03	5.022079E-03	4.764117E-05	2.171972E-04
0.40	1.699438E-02	8.378853E-02	8.549266E-04	5.391781E-03	4.058543E-05	2.325788E-04
0.45	1.474423E-02	8.762779E-02	7.174500E-04	6.013094E-03	3.631944E-05	2.643426E-04
0.50	1.271507E-02	9.494599E-02	6.315947E-04	7.007431E-03	3.454916E-05	3.242427E-04
0.55	1.087971E-02	1.076499E-01	5.964348E-04	8.697202E-03	3.635605E-05	4.495760E-04
0.60	9.214130E-03	1.278936E-01	6.050135E-04	1.159786E-02	4.280640E-05	7.157927E-04
0.65	7.696619E-03	1.585702E-01	6.500133E-04	1.663992E-02	5.473745E-05	1.275028E-03
0.70	6.303996E-03	1.952142E-01	6.822582E-04	2.435995E-02	6.180361E-05	2.078914E-03
0.75	5.023117E-03	2.328726E-01	6.621729E-04	3.536096E-02	5.633198E-05	2.878526E-03
0.80	3.838705E-03	2.412793E-01	4.980051E-04	4.502355E-02	4.258091E-07	0.000000E+00
0.85	2.758660E-03	3.391635E-01	5.398263E-04	8.855883E-02	3.006980E-07	0.000000E+00
0.90	1.761202E-03	5.353092E-01	5.895198E-04	2.231582E-01	2.020430E-07	0.000000E+00
0.95	8.290956E-04	1.187117E+00	7.973469E-04	1.230884E+00	0.000000E+00	0.000000E+00

**Table 5-6: Unit Peak Discharge ( $q_p$ ) Regression Coefficients—Type 6 (IIa60)**

$I_a/P_{24}$	a	b	c	d	e	f
0.00	2.889749E+00	3.273784E+00	1.446065E-01	1.008957E-01	0.000000E+00	0.000000E+00
0.05	2.555281E+00	3.521407E+00	-2.077133E-02	-3.123522E-02	5.280334E-03	5.720657E-03
0.10	2.014897E+00	3.765950E+00	4.714605E-02	1.147399E-01	9.959438E-03	1.304637E-02
0.15	1.737517E+00	4.676390E+00	4.224428E-02	5.770636E-02	2.545697E-03	4.536371E-03
0.20	1.369500E+00	5.064453E+00	4.248368E-02	6.499361E-02	1.513193E-03	3.541284E-03
0.25	1.280323E+00	7.044645E+00	1.017763E-01	2.355049E-01	-2.278100E-05	0.000000E+00
0.30	9.429418E-01	7.061187E+00	7.161921E-02	1.820348E-01	-9.994900E-05	0.000000E+00
0.35	7.182716E-01	7.639481E+00	5.316553E-02	4.278090E-02	-2.271260E-03	-8.340510E-03
0.40	6.334482E-01	1.025432E+01	8.351263E-02	3.603484E-01	-7.260700E-05	0.000000E+00
0.45	4.259475E-01	1.028394E+01	6.349476E-02	3.125918E-01	-1.202100E-04	0.000000E+00
0.50	2.692505E-01	1.034082E+01	4.980712E-02	2.842677E-01	-1.411800E-04	0.000000E+00
0.55	1.835174E-01	1.291002E+01	5.106351E-02	3.623601E-01	-1.720400E-04	0.000000E+00
0.60	6.916727E-02	9.339188E+00	2.710800E-02	2.062759E-01	-1.364500E-04	0.000000E+00
0.65	1.384630E-02	3.980493E+00	8.583843E-03	5.246778E-02	-1.425600E-04	-1.749120E-03
0.70	2.336685E-03	1.862485E-01	6.191490E-05	-9.897200E-04	1.063460E-05	3.971680E-04
0.75	1.035009E-03	-2.467000E-06	-2.044200E-05	1.523060E-04	7.576090E-07	3.014060E-05
0.80	6.231650E-04	-3.411600E-05	1.982740E-06	1.572730E-03	5.316790E-07	3.229390E-05
0.85	4.293740E-04	-8.846200E-05	5.013270E-07	2.077569E-03	1.286990E-07	0.000000E+00
0.90	2.737480E-04	6.518359E-02	1.723000E-05	6.843226E-03	0.000000E+00	0.000000E+00
0.95	1.313010E-04	1.588290E-01	1.671480E-05	2.642581E-02	0.000000E+00	0.000000E+00

**Table 5-7: Unit Peak Discharge ( $q_p$ ) Regression Coefficients—Type 7 (IIa65)**

$I_a/P_{24}$	a	b	c	d	e	f
0.00	3.105260E+00	3.109283E+00	1.921849E-02	2.558174E-03	0.000000E+00	0.000000E+00
0.05	2.601980E+00	3.110117E+00	1.287613E-01	2.937898E-01	3.550040E-02	3.589748E-02
0.10	2.248406E+00	3.817762E+00	9.398129E-02	2.646257E-01	2.145066E-02	2.792177E-02
0.15	1.926927E+00	4.629238E+00	5.158494E-02	1.605948E-01	1.029643E-02	1.724115E-02
0.20	1.545424E+00	5.073367E+00	4.194001E-02	1.385273E-01	6.308154E-03	1.344247E-02
0.25	1.309995E+00	6.041730E+00	3.927469E-02	7.795246E-02	1.572915E-03	4.616676E-03
0.30	1.174823E+00	7.801992E+00	4.997872E-02	1.773560E-02	-2.539170E-03	-7.511360E-03
0.35	-2.951412E-01	1.686236E+00	-5.398405E+00	1.509496E-01	-8.349467E-01	-2.599300E-04
0.40	-3.892790E-01	2.625254E+00	-8.147355E+00	3.551340E-01	-1.974840E+00	-6.946600E-04
0.45	5.483178E-01	1.068401E+01	6.227067E-02	3.282760E-01	-8.089200E-05	0.000000E+00
0.50	3.490867E-01	1.020214E+01	4.437194E-02	2.637825E-01	-1.086600E-04	0.000000E+00
0.55	2.627942E-01	1.319733E+01	4.976446E-02	3.953937E-01	-1.183400E-04	0.000000E+00
0.60	1.437442E-01	1.328429E+01	3.844520E-02	3.615960E-01	-1.330700E-04	0.000000E+00
0.65	4.839431E-02	9.273763E+00	1.930901E-02	1.965048E-01	-1.011500E-04	0.000000E+00
0.70	6.741546E-03	2.565110E+00	3.579878E-03	2.937768E-02	-3.852900E-05	-3.148400E-04
0.75	1.268564E-03	2.994430E-05	-8.701000E-05	-2.016760E-03	4.262720E-06	1.962620E-04
0.80	6.041370E-04	-1.627500E-05	-3.202300E-06	9.379760E-04	4.116320E-07	2.514860E-05
0.85	3.766250E-04	-6.513000E-05	2.853730E-06	2.047539E-03	9.593800E-08	0.000000E+00
0.90	2.429130E-04	-1.176000E-04	-4.056800E-06	1.615521E-03	9.478770E-08	0.000000E+00
0.95	1.154210E-04	1.361173E-01	1.277410E-05	2.031453E-02	0.000000E+00	0.000000E+00

**Table 5-8: Unit Peak Discharge ( $q_p$ ) Regression Coefficients—Type 8 (IIa70)**

$I_a/P_{24}$	a	b	c	d	e	f
0.00	3.431447E+00	3.225395E+00	1.107677E-02	0.000000E+00	0.000000E+00	0.000000E+00
0.05	2.869989E+00	3.182274E+00	3.884154E-01	6.929520E-01	6.436193E-02	6.518419E-02
0.10	2.438596E+00	3.758407E+00	2.447405E-01	6.078293E-01	4.219337E-02	5.500927E-02
0.15	2.172945E+00	4.759018E+00	9.158589E-02	3.171158E-01	1.998050E-02	3.340377E-02
0.20	1.839241E+00	5.556090E+00	5.400739E-02	2.103572E-01	1.038225E-02	2.210380E-02
0.25	1.464127E+00	5.927198E+00	3.956267E-02	1.780217E-01	6.781065E-03	1.826737E-02
0.30	1.153486E+00	6.277552E+00	2.842483E-02	1.359005E-01	4.146938E-03	1.422740E-02
0.35	9.512284E-01	7.205833E+00	2.654640E-02	7.769687E-02	1.299604E-03	6.120586E-03
0.40	7.815830E-01	8.413013E+00	3.026382E-02	4.524973E-02	-4.612800E-04	-1.478290E-03
0.45	6.266075E-01	9.798142E+00	4.379926E-02	2.051772E-01	-1.001600E-04	0.000000E+00
0.50	4.868607E-01	1.147337E+01	4.774697E-02	3.153346E-01	-7.648700E-05	0.000000E+00
0.55	3.591478E-01	1.346988E+01	4.766281E-02	4.161072E-01	-7.341500E-05	0.000000E+00
0.60	2.420561E-01	1.570367E+01	4.432599E-02	4.906144E-01	-9.166000E-05	0.000000E+00
0.65	1.244429E-01	1.569281E+01	3.303735E-02	4.395804E-01	-1.082400E-04	0.000000E+00
0.70	3.827265E-02	1.131768E+01	1.662718E-02	2.446881E-01	-8.660700E-05	0.000000E+00
0.75	2.958632E-03	1.442613E+00	1.241802E-03	1.181724E-02	-1.119000E-05	0.000000E+00
0.80	6.652130E-04	7.173470E-06	-2.262900E-05	-4.840900E-04	8.703930E-07	6.233150E-05
0.85	3.359670E-04	-3.627000E-05	1.354030E-06	1.631560E-03	2.804330E-07	3.128900E-05
0.90	2.086070E-04	-1.072200E-04	-1.427700E-06	1.940768E-03	7.128770E-08	0.000000E+00
0.95	9.946310E-05	1.136462E-01	9.436390E-06	1.511657E-02	0.000000E+00	0.000000E+00

**Table 5-9: Unit Peak Discharge ( $q_p$ ) Regression Coefficients—Type 9 (IIa75)**

$Ia/P_{24}$	a	b	c	d	e	f
0.00	3.774411E+00	3.340085E+00	5.425804E-03	0.000000E+00	0.000000E+00	0.000000E+00
0.05	3.061572E+00	3.152286E+00	1.070998E+00	1.623152E+00	1.192100E-01	1.212473E-01
0.10	2.729266E+00	3.933369E+00	5.021964E-01	1.088275E+00	6.803488E-02	8.937710E-02
0.15	2.381037E+00	4.745188E+00	2.235835E-01	6.896012E-01	3.820492E-02	6.410296E-02
0.20	1.997334E+00	5.379884E+00	1.185453E-01	4.992425E-01	2.332722E-02	4.956452E-02
0.25	1.660762E+00	6.009108E+00	6.523742E-02	3.603347E-01	1.418991E-02	3.808352E-02
0.30	1.368318E+00	6.656175E+00	3.805490E-02	2.535455E-01	8.369200E-03	2.843815E-02
0.35	1.114050E+00	7.336381E+00	2.452078E-02	1.667050E-01	4.572807E-03	1.986567E-02
0.40	8.924026E-01	8.062642E+00	1.867840E-02	9.565487E-02	2.095755E-03	1.197524E-02
0.45	6.987504E-01	8.843503E+00	1.755848E-02	4.614858E-02	5.744860E-04	4.940427E-03
0.50	5.751427E-01	1.076727E+01	3.062259E-02	1.578379E-01	-1.057000E-04	0.000000E+00
0.55	4.561843E-01	1.312618E+01	3.997804E-02	3.537645E-01	-5.890500E-05	0.000000E+00
0.60	3.367238E-01	1.578486E+01	4.151122E-02	5.092234E-01	-4.802100E-05	0.000000E+00
0.65	2.081836E-01	1.753566E+01	3.938414E-02	7.276944E-01	0.000000E+00	0.000000E+00
0.70	9.856882E-02	1.700168E+01	2.469235E-02	4.787730E-01	-7.764700E-05	0.000000E+00
0.75	2.221086E-02	9.994124E+00	9.524705E-03	2.019446E-01	-5.244900E-05	0.000000E+00
0.80	1.123760E-03	9.764010E-05	-1.679900E-04	-6.339630E-03	1.133440E-05	8.685300E-04
0.85	3.253000E-04	-1.173700E-05	-2.944400E-06	7.128280E-04	2.131840E-07	2.451440E-05
0.90	1.737860E-04	-7.130700E-05	1.138570E-06	2.080533E-03	-6.612400E-08	-3.992700E-05
0.95	8.334140E-05	9.067789E-02	6.581840E-06	1.067120E-02	0.000000E+00	0.000000E+00

## Hydrograph Shape

A triangular shape is assumed. Since the sediment transport is only concerned with the duration for an average discharge, the time to peak is not important and a right angle will be used to calculate the sediment transport!

The time to base of the hydrograph (duration of surface runoff event) is:

$$t_b = 20 \cdot (R_Q \cdot D_a / Q_p) \quad \text{Equation 5-117}$$

where:  $Q_p$  = peak discharge,  $m^3/s$ ;  
 $D_a$  = total drainage area, hectares;  
 $R_Q$  = surface runoff volume from upstream drainage area, mm;  
and  
 $t_b$  = time to base, s.

The hydrograph as a function of time is:

$$Q_w = (Q_p / t_b) \cdot t, \text{ and} \quad \text{Equation 5-118}$$

$0 \leq t \leq t_b$   
where:  $Q_w$  = discharge as a function of time,  $m^3/s$ ;  
 $Q_p$  = peak discharge,  $m^3/s$ ;  
 $t_b$  = time to base, s; and  
 $t$  = time from beginning of runoff, s.

And the unit-width peak discharge is:

$$q_p = Q_p / W \quad \text{Equation 5-119}$$

where:  $q_p$  = unit-width peak discharge,  $m^3/s/m$ ;  
 $Q_p$  = peak discharge,  $m^3/s$ ; and

W = flow width, m.

## 6. SEDIMENT

### 6.1 Erosion

#### 6.1.1 Sheet & Rill

##### 6.1.1.1 Revised Universal Soil Loss Equation (RUSLE)

This section describes the design modifications to the Revised Universal Soil Loss Equation (RUSLE) to simplify and enhance its inclusion in the multi-cell continuous simulation model AnnAGNPS. These modifications include the: (a) ability to process multiple cells; (b) elimination of redundant calculations for cells with identical field management and soil conditions; (c) ability for contours and mechanical disturbances to rotate on non-cropland landuses; (d) calculation of sediment delivery ratio to the edge of the field for every cell; and (e) erosion modifications for frozen soil conditions.

Soil detachment, deposition and transport are important considerations when modeling pollutant loads from agricultural watersheds. Detached soil particles are deleterious contaminants in downstream watercourses causing degradation in stream and lake habitats and can result in premature filling of lakes and reservoirs. In addition, detached soil particles are carriers of many other contaminants such as phosphorus and pesticides. Given the importance of soil erosion, deposition, and transport, it was critical that an appropriate level of technology was chosen to simulate these processes.

The Agricultural Non-Point Source Pollution Model (AGNPS) (Young et al 1987), the predecessor to AnnAGNPS, used the Universal Soils Loss Equation (USLE) (Wischmeier et al 1978) to predict soil erosion for a single storm event. Since AGNPS is a single storm event model, the fact that the soil erodibility factor (K factor), cover and management factor (C factor) and the practice factor (P factor) are fixed values, input by the user, is not a significant limitation. However, since AnnAGNPS is a continuous simulation model, temporal changes in cover, soil erodibility and conservation practices can have a significant impact on simulated pollutant loads. In addition, AnnAGNPS has virtually no limitation on the number of cells that can be defined by the user to make up a watershed, therefore manually estimating fixed USLE K, C, and P factors for each cell prior to simulation would impose a significant usability limitation. Several erosion prediction models and subroutines were considered in deciding which erosion technology should be incorporated into AnnAGNPS. Factors that were considered were; the number of inputs, time step, process detail, data availability, degree of model acceptance, and runtime.

The Revised Universal Soils Loss Equation (RUSLE) (Renard et al 1997) technology was selected as the most appropriate level of technology for the following reasons:

1. The number of inputs required did not significantly add to what was already required.
2. The minimum time step was 15 days. Although this is larger than the single day time step in AnnAGNPS it was not considered a significant limitation because RUSLE K and C factors do not vary significantly on a day to day basis and adjustments to K factor would be made on daily time step during the actual simulation.
3. The process detail was considerable but appropriate. The level of detail in calculating a time variant C factor in RUSLE is considerable because of the many processes involved such as; tillage effects, soil consolidation, and residue decomposition. This detail however was considered necessary and appropriate since cover conditions change frequently and tillage effects, soil consolidation and residue decomposition are critical factors.
4. Availability of data and broad model acceptance by an action agency were primary factors in the selection of RUSLE technology. At the time of consideration, Natural Resource Conservation Service (NRCS) agronomists were involved in an organized effort to collect tillage and crop management data across the country to enable RUSLE technology to be implemented in NRCS field offices. This indicated to the AnnAGNPS model developers a high degree of future data availability and a broad acceptance of RUSLE technology.
5. Model runtime was fairly low due to the fact that LS, K, C, and P factors are calculated at no less than a 15 day time step for only the length of the specified rotation. The calculation of the LS, K, C, and P factors is performed in a data preparation step in AnnAGNPS and not during the day to day simulation. However, during

the AnnAGNPS simulation, the Erosion Index (EI) and K factor may be adjusted on a daily basis based on storm precipitation and frozen soil conditions respectively. This will be discussed in more detail later.

RUSLE technology documented in this section describes the current state of RUSLE technology incorporated within the latest version of AnnAGNPS. This section will also primarily focus on how the technology from the RUSLE model was incorporated into the AnnAGNPS model and not discuss or debate the use or validity of RUSLE technology itself.

### **RUSLE CODE IN AnnAGNPS**

RUSLE code in AnnAGNPS was converted from the RUSLE Model, Version 1.5 pre.h, written in the 'C' programming language. The RUSLE Model, Version 1.5 pre.h will be referred to as the original RUSLE model for the remainder of the document. AnnAGNPS is written in Fortran90 therefore the original 'C' code had to be converted to Fortran90. In the process of converting the original RUSLE model code, significant organizational revisions were made to, separate the technology engine from the original RUSLE model user interface, simplify code maintenance, produce debug reports, and increase code readability. In essence, RUSLE code was totally re-written. Every attempt was made to maintain the original technology contained in the code and where technical changes were made, they are noted here. Fortunately, few technology related changes were necessary.

### **ESTIMATION OF RUSLE FACTORS**

During the data preparation pre-processing step, RUSLE technology within AnnAGNPS calculates the LS, C, and P factors for each cell in the watershed and a K factor for each soil in the watershed. The highest level subroutine that controls the calculations of these parameters has the following flow control.

The remainder of the discussion describing the estimation of RUSLE parameters will follow the high-level process control flow depicted in Figure 6-1.

### High Level View of C Factor Calculation

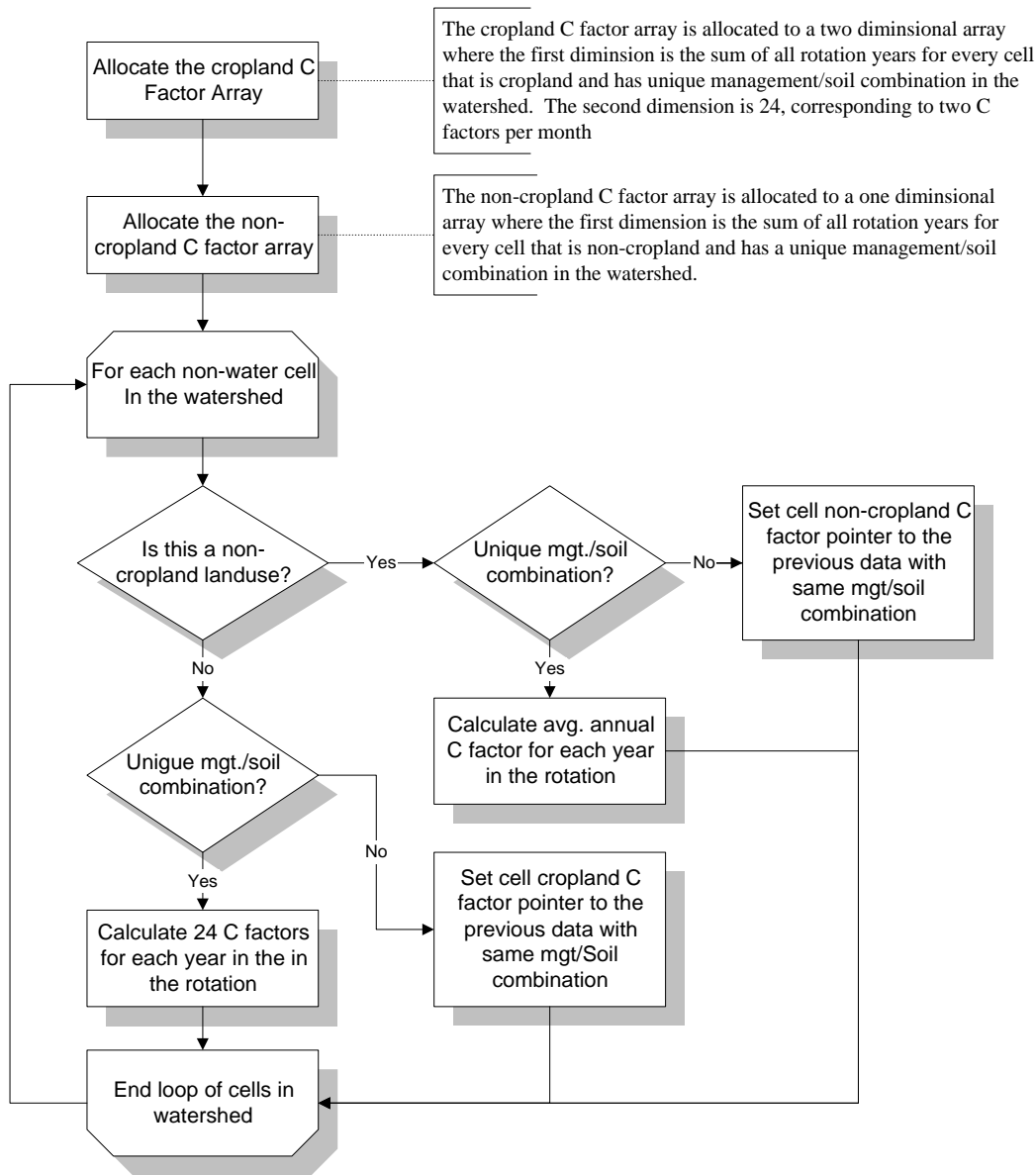


Figure 6-1: A high level view of the process used in AnnAGNPS to calculate C-factors

**Initialize Contour Rotation Information:** AnnAGNPS allows the user to specify the application of a contour or mechanical disturbance by month, day, and relative year in a rotation for every landuse. This capability is an enhancement to existing RUSLE technology. In the original RUSLE technology, only a single contour or mechanical application is allowed on a non-cropland landuse.

Contour and mechanical disturbances are both described in the AnnAGNPS input data under the contour data section. The only difference between the two is that mechanical disturbance has a ridge height of zero. For the remainder of this discussion, when a contour application or contour practice is mentioned, it applies to both a contour and a mechanical disturbance.

The routine to initialize contour rotation information results in information that will be used in later calculations to determine average annual C and P factors. For each non-water cell that has a rotation of operations with contours specified, the contour rotation initialization routine sets a pointer to the dominant contour information for each year

in the rotation and calculates the number of years since the dominant contour was first applied. The dominant contour is the contour that is on the ground for the greatest number of days in a rotation year. A contour applied in a previous rotation year will carry over into the current year and its days for the current year considered until a new contour is applied.

An example will help to explain. If there are two contour applications in four year rotation and the first contour was applied on day 100 in rotation year one and the second contour is applied on day 200 in rotation year 3, the resulting contour rotation information is in Table 6-1.

Table 6-1. Contour Rotation Example

Rotation Year	Pointer to Dominant Contour	Years Since Applied
1	contour 1	0
2	contour 1	1
3	contour 1	2
4	contour 2	1

Note that in rotation year three, when the second contour was actually applied, it is not the dominant contour for that year because it was on the ground for only 165 days where as the first contour was on the ground for 199 days.

**Initialize RUSLE Climate Information:** RUSLE requires certain climate-related data that is common to most of the RUSLE routines. The logic and method used in each of these calculations is identical to that in the original RUSLE. These calculations are: 1) Calculating a weighted

average temperature and precipitation for each of the 24, 15 day periods, 2) Derive a monthly non-cumulative EI distribution from the input monthly cumulative EI data, 3) Calculate the soil moisture replenishment rate based on average annual rainfall. (This is used in the computation of the soil moisture C sub-factor for the Pacific Northwest.)

**RUSLE K Factors:** For each unique soil in the watershed, K factor information is calculated or provided through user input. The only change from the original RUSLE model is the ability to cycle through all the soils in the watershed. The structure of the K factor computations in AnnAGNPS was changed significantly from the original model. Figure 6-2. illustrates the high level structure of the K factor routines used in AnnAGNPS.

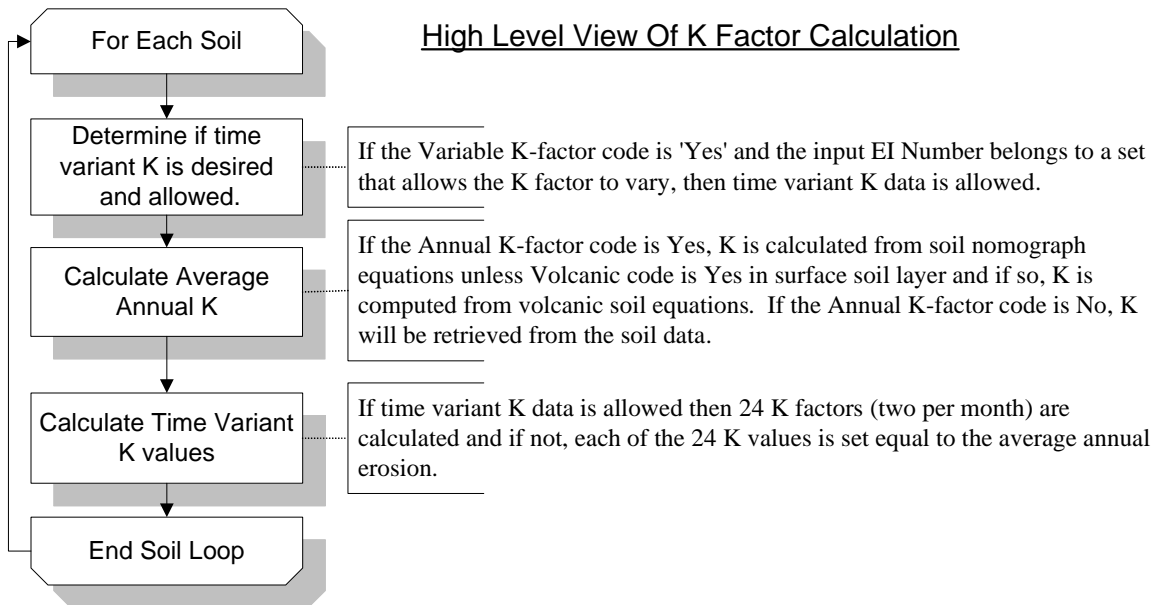


Figure 6-2. A high level view of the process used in AnnAGNPS to calculate K-factors

**RUSLE C Factors:** The computation of C factors in AnnAGNPS for a single cell is identical to that of the original model with one exception. The original RUSLE model only allowed one contour practice to be applied to a non-cropland cell. AnnAGNPS allows multiple contour practices to be applied in rotation on a non-cropland landuse.

In the original RUSLE model, when a contour is specified on a non-cropland landuse, the average annual C factors degrade over a period of time. The length of time is equal to the number of years it takes the soil to consolidate as specified in the soils data. For example, if it takes seven years for the soil to consolidate, the original RUSLE model will calculate seven average annual C factors with the C factor decreasing each successive year until it reaches its minimum value the seventh year.

The same algorithm is used in AnnAGNPS to degrade average annual C factors but since contours can be in a rotation on a non-cropland landuse, the C factor may not reach its fully degraded value before another contour is applied. The contour rotation information discussed under Initialize Contour Rotation Information is used to calculate the average annual C factors if contours have been applied. For each year in the rotation, the average annual C factor is calculated for the dominant contour. The number of years since the contour was first applied is used to determine the number of years the contour has degraded.

In implementing the C factor computations into AnnAGNPS it became obvious that computation time and memory requirements to store C factors for later use could be greatly reduced if redundant calculations and storage could be eliminated. An AnnAGNPS watershed can be subdivided into many cells that can have any shape and each cell is assumed to have homogenous management and soil. Often the cell size will be substantially smaller than a field size resulting in many cells having identical management. If two or more fields have the same management, even more cells will have the same management. In addition, the smaller the cell size, the more likely the chance that two or more cells will have the same soil type. Therefore, in theory, as AnnAGNPS individual cell size decreases, the number of cells with the same management/soil combination increases.

To reduce the number of C factor computations and storage requirements, calculations are made only on cells where the management/soil combination has not been encountered previously. When a cell is encountered that has an identical management/soil combination that has already been computed, the calculations are skipped and that cell's pointer to its C factor data is set to point to the previous cell's C factor data that had the same management/soil combination. This dramatically reduces computation time since thousands of lines of code are skipped and reduces the internal storage requirements for C factor data as well.

In implementing C factor computations, major structural changes were made. The major difference between the original RUSLE model and AnnAGNPS is that, in AnnAGNPS, each C sub-factor is calculated individually for the entire rotation period. In the original RUSLE model, one large loop sequences through the rotation on 15-day increments and all the C sub-factors are calculated in succession. AnnAGNPS, however, has many small subroutines with each subroutine sequencing through the rotation. The advantage is that smaller subroutines are easier to; code, verify, understand, and maintain. The disadvantage is that temporary storage requirements are higher since individual C sub-factors for the entire rotation period must be stored until all the other C sub-factors are computed and those results combined to compute the final C factor. Figure 6-2. depicts a high level view of the calculation of C factors in AnnAGNPS.

**RUSLE LS Factor:** The LS factor determinations within RUSLE have been replaced with a user input requirement of the LS factor. Procedures have been developed that can calculate the LS factor for multiple cells within a watershed that relates to the procedures defined by RUSLE (Bingner and Theurer, 2001).



### High Level View of C Factor Calculation

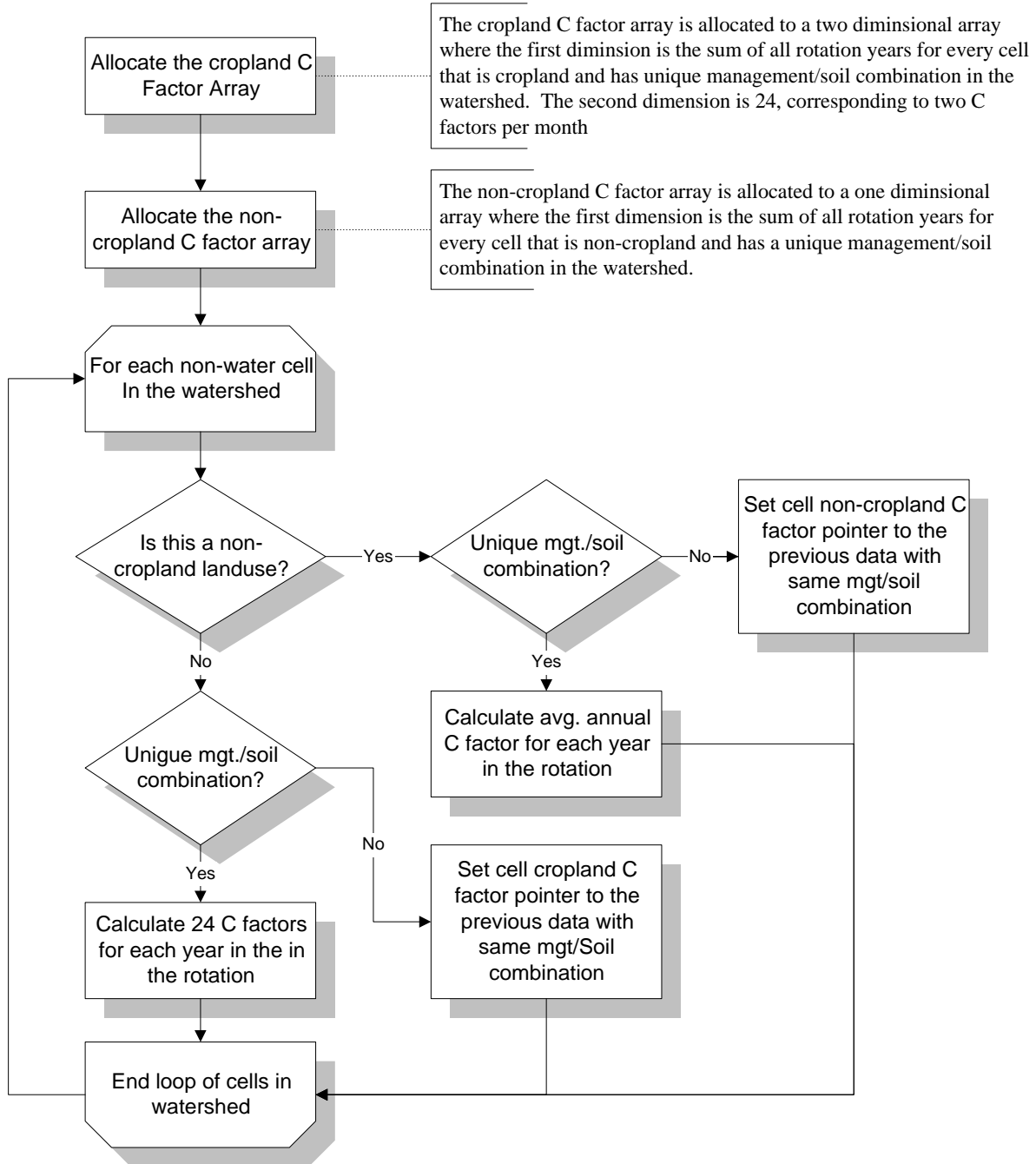


Figure 6-3. A high level view of the process used in AnnAGNPS to calculate C-factors

**RUSLE P Factors and Sediment Delivery Ratio's:** The calculation of RUSLE P factors and sediment delivery ratio's in AnnAGNPS are the same as in the original model with two exceptions. The original RUSLE model allowed only one contour practice to be applied on a non-cropland landuse and a sediment delivery ratio was calculated only when a strip crop conservation practice was applied. AnnAGNPS allows for the application of more than one contour practice to be applied in a rotation on a non-cropland landuse and a sediment delivery ratio is calculated for each non-water cell regardless of whether a strip crop has been applied or not.

In the original RUSLE model, when a contour is specified on a non-cropland landuse, the average annual contour P sub-factors degrade over a period of time. The length of time is equal to the number of years it takes the soil to consolidate as specified in the soils data. For example, if it takes seven years for the soil to consolidate, then the original RUSLE model will calculate seven average annual contour P sub-factors with the sub-factor decreasing each successive year until it reaches its minimum value the seventh year.

The same algorithm to degrade average annual contour P sub-factors is used in AnnAGNPS but since contours can be in a rotation, they may not reach their fully degraded value before another contour is applied. The contour rotation information discussed under Initialize Contour Rotation Information is used to calculate the average annual contour P sub-factors. For each year in the rotation, the average annual contour P sub-factor is calculated for the dominant contour. The number of years since the contour was first applied is used to determine the number of years the contour has degraded.

The same algorithm that was used in the original RUSLE model to calculate a sediment delivery ratio is used when a strip crop is applied within AnnAGNPS to calculate a sediment delivery ratio to the edge of the field. The parameters used to determine sediment delivery from a strip crop are determined internally based on the selection users provide to AnnAGNPS with the choices given in **Table 6-2**. If there is not a strip crop specified for a cell, AnnAGNPS determines the sediment delivery based on methods discussed later. Otherwise, the cover codes assigned to each cell based on **Table 6-2** assigns a RUSLE predefined cover code to each cell based on the type of landuse specified in the field data as shown in **Table 6-2**. The rangeland code is also used to determine a P factor for rangeland conditions even if there are no strip crops within the cell.

Table 6-2. Assigned Cover Code for Various Landuses

Landuse Specified in Field Data	RUSLE Predefined Cover Code
Cropland	5 - light cover and/or moderately rough
Pasture	1 - established sod-forming grass
Rangeland	4 - moderate cover and/or rough
Forest	3 - heavy cover and/or very rough
Urban	2 - 1st year grass or cut for hay

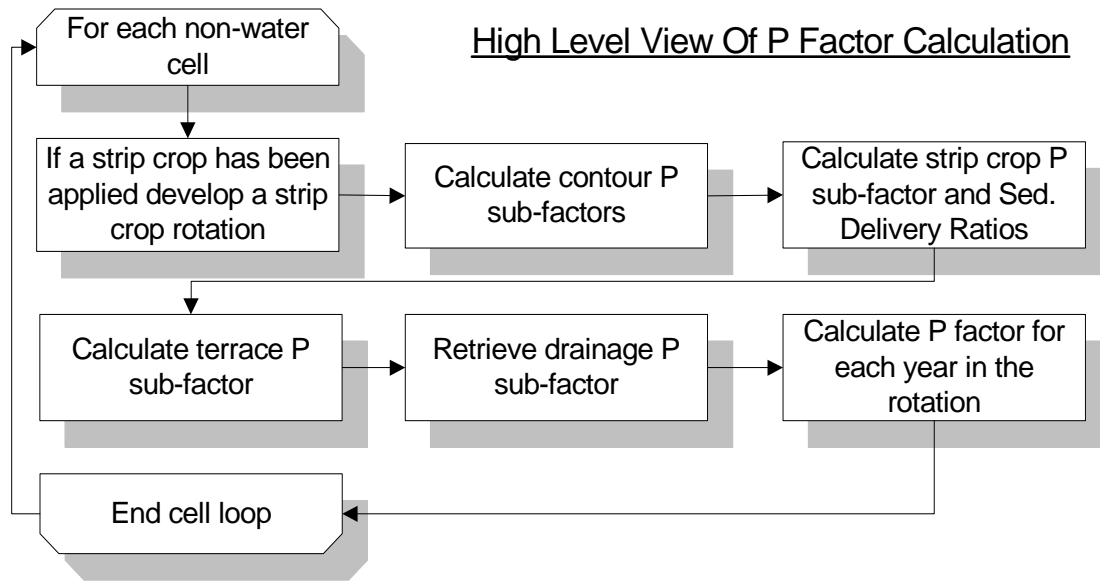


Figure 6-4: A high level view of the process used in AnnAGNPS to calculate P factors.

**Determination of RUSLE Parameters**

The EI value is used to determine the erosion within a cell using RUSLE technology and is calculated given the rainfall distribution type and the rainfall amount using Equation 6-1 which is taken from AGNPS 5.0, and was also derived from CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems; Knisel, 1980).

$$EI = \frac{A * \exp(2.119 * \log(R) * \exp(0.0086 * \log(24)))}{\exp(B * \log(24))}$$

**Equation 6-1**

Table 6-3: EI Coefficient and Exponent by Storm Type

where: *R* = Precipitation or Snowmelt in inches

A = EI coefficient, from **Table 6-3**.

B = EI exponent, from **Table 6-3**.

Given each of the cumulative rainfall distributions, Keith Cooley, ARS Scientist, Boise ID (*after* Cooley, 1980), calculated the A and B coefficients to derive the storm EI value. For snowmelt, the Uniform distribution is used. If precipitation and snowmelt occur on the same day, their respective EI values summed together.

Storm Distribution Type	A	B
I	15.03	0.5780
IA	12.98	0.7488
II	17.90	0.4134
III	8.00	0.2788
Uniform	9.41	1.1401
IIA-60	20.99	0.2904
IIA-65	21.84	0.2631
IIA-70	22.87	0.2365
IIA-75	23.96	0.2118

The K value is retrieved and modified for frozen soil conditions if the watershed is in the Palouse region using Equation 6-2 supplied by Don McCool, ARS Scientist, Pullman WA,:

$$K = K_0 * (1 + 14 * (1 - \exp(-4 * (M - 0.5))))$$

**Equation 6-2**

where: K = frozen soil K factor;

K<sub>0</sub> = original RUSLE K factor; and

M = Moisture fraction in surface soil layer.

The remaining RUSLE factors, LS, C, P, and sediment delivery ratio are retrieved from previously entered or calculated data, then the product of EI, LS, K, C and P is computed to determine the total potential erosion. This product is then compared to the amount of thawed soil available for erosion and the lesser of the two quantities is then multiplied by the sediment delivery ratio to determine the amount of sediment delivered to the edge of the field. The sediment delivered into to the edge of the field is broken into five particle size classes: clay, silt, sand, large aggregate, and small aggregate. The large and small aggregate amounts are assumed to immediately break down into its constituent parts of sand, silt and clay once it leaves the edge of the field and becomes a part of the watercourse, therefore the amount that is sand, silt and clay in the large aggregate is added to the amount of sand, silt, and clay leaving the field as well as the amounts that are silt and clay in the small aggregates.

**6.1.1.2 AnnAGNPS Delivery Ratio**

Sediment delivery to the edge of the field is calculated whenever a runoff event occurs from rainfall, irrigation, or snowmelt in the Simulation Processing phase of the AnnAGNPS model run. Each of the RUSLE parameters is either calculated or retrieved from previously calculated data.

Since RUSLE is used only to predict sheet and rill erosion and not field deposition, a delivery ratio of the sediment yield from this erosion to sediment delivery to the stream is needed. The Hydro-geomorphic Universal Soil Loss Equation (HUSLE) is used for this procedure (Theurer and Clarke, 1991).

HUSLE calculates the total sediment yield for a given storm event to any point in the watershed when given the upstream: (a) average RUSLE parameters; (b) drainage area; (c) volume of water runoff; (d) peak discharge; and (e) the RUSLE regression coefficients for the applicable hydro-geomorphic area. As the drainage area goes to zero, the time of concentration goes to zero. When the drainage area is at the point where RUSLE assumes that sheet &

rill erosion stops and concentrated flow begins, the time of concentration is nearly zero; i.e., the difference between the peak discharge at this point and the instantaneous unit peak discharge (maximum point runoff intensity) is negligible. The particle-size class density and fall velocity can be used to estimate the relative deposition between the five classes.

The procedure was initially developed to predict the total sediment yield at a user-defined point in the stream system using spatially- and time-averaged RUSLE parameters; and to ensure that sheet and rill-related sediment was properly calculated. The form of the equation also lends itself to a non-dimensional ratio where the RUSLE parameters are cancelled and only the hydrograph-related parameters remain.

The sheet and rill component from Theurer and Clarke (1991) is:

$$S_y = 0.22 * Q^{0.68} * q_p^{0.95} * KLSCP \quad \text{Equation 6-3}$$

Where:  $S_y$  = sediment yield (Mg/ha);  
 $Q$  = surface runoff volume (mm);  
 $q_p$  = peak rate of surface runoff (mm/s); and  
 $K, L, S, C, P$  are RUSLE factors as per AHN 537 or AHN 703.

Note that all three variables ( $S_y$ ,  $Q$ , and  $q_p$ ) are based on unit area; i.e., divided by their drainage areas as is the proper form for RUSLE.

If a ratio is made of Equation 6-3 at two different locations in a homogeneous watershed where "2" is downstream of "1" and noting that the unit area runoff volume is identical at all locations within the homogeneous area, the result is:

$$D_r = S_{y2}/S_{y1} = (q_{p2} / q_{p1})^{0.95} \quad \text{Equation 6-4}$$

Where:  $S_{y1}$  = sediment yield at location "1" (Mg/ha);  
 $S_{y2}$  = sediment yield at location "2" (Mg/ha);  
 $q_{p1}$  = peak rate of surface runoff at location "1" (mm/s);  
 $q_{p2}$  = peak rate of surface runoff at location "2" (mm/s);  
 $D_r$  = delivery ratio from location "1" to "2"

Since sheet and rill erosion usually occurs within a few tens of feet along their flow paths, resulting in small drainage areas, Equation 6-4 is computed assuming location "1" is for a zero drainage area, which is the same as a time of concentration of zero, and location "2" is for the time of concentration of the local field or cell. The peak discharge for a time of concentration of zero is the instantaneous peak discharge of the runoff hydrograph and can be easily calculated from TR-55 (SCS, 1986).

## PARTICLE-SIZE DISTRIBUTION OF FIELD DEPOSITION

Since RUSLE is used to calculate the amount of sheet and rill erosion and HUSLE is used to determine the delivery ratio for total sediment, the only factor remaining is to determine the particle-size distribution of the deposition in the field. This allows for the particle-size distribution of the sediment yield of the sheet and rill erosion to the receiving reach of the stream system.

The particle-size sediment deposition within the field is assumed to be proportional to the mass fall velocity of the individual particle-size classes. Since the density of both the large and small aggregates are noticeably less than the discrete particles of clay, silt, and sand, a product of the respective densities times its fall velocity is used to represent each particle-size class. This is called the deposition mass rate and has units of mass per length squared per time. The resulting deposition mass rate values for each particle-size class are summed and then normalized with respect to this sum. These normalized values are called deposition rate ratios. They are further normalized with respect to the smallest value, which will normally be clay, and are called the deposition ratio mass rate. From these calculations, the field deposition is determined, but careful consideration is given to exhausting any of the particular particle-size classes; i.e., when any of the particle-size classes are totally deposited, the calculations begin again at that point along the landscape with that particle-size class eliminated from further calculations.

The following tables are used to describe the procedures used to determine the sediment delivery ratio between the 5 classes of particle distribution of eroded soil.

Table 6-4 contains the static properties for each particle-size class (Column 1) that originates from their respective densities and fall velocities. The value in each column in the bottom row is the sum of the values for respective particle-size class above. Depending upon the column, this sum is either a normalizing value for subsequent calculations or indicates that the sum total is unity.

The values shown in Columns 2 (Particle Density) & 3 (Particle Fall Velocity) are taken directly from AGNPS 5.0 (after Young et al 1987). Column 4 (Deposition Mass Rate) is equal to the product of Columns 2 & 3 times 1000 to correct for units.

Column 5 (Deposition Rate Ratio), is the only set of values from this table that will be used in subsequent delivery ratio calculations, and the values in Column 5 may be predefined within AnnAGNPS. Column 6 (Deposition Mass Ratio Rate), is shown to illustrate the relative deposition of the various particle-size class with respect to the clay class. For example, for an equal sediment particle-size class distribution (i.e., each of the five classes are equally represented in the column of water with each class equal to 20% of the total concentration), 7570 grams of sand will settle out for each gram of clay.

**Table 6-4: Sediment Particle-Size Class Static Parameters**

Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6
Sediment Particle Class	Particle Density	Particle Fall Velocity	Deposition Mass Rate	Deposition Rate Ratio	Deposition Ratio Mass Rate
	(Mg/m <sup>3</sup> )	(mm/s)	(g/m <sup>2</sup> /s)	(-)	(g-particle / g-clay)
clay	2.60	3.11E-03	8.086	0.000091	1
silt	2.65	8.02E-02	212.530	0.002401	26
sand	2.65	2.31E+01	61215.000	0.691528	7570
SAGG	1.80	3.81E-01	685.800	0.007747	85
LAGG	1.60	1.65E+01	26400.000	0.298233	3265
Sum		40.064	88521.416	1.000	

Table 6-5 shows an example of the calculations for the delivery ratios for each particle-size class when given the HUSLE delivery ratio, the total sediment yield (using RUSLE), and the initial sediment distribution (also from RUSLE). These input requirements are shown in italics in Table 6-5. The non-italicized fields are calculated within the RUSLE\_Delivery\_Ratio subprogram.

Table 6-5 shows an initial estimate of the delivery ratio and up to four iterations to correct for an upper limit of deposition for each particle-size class. The coarser particles (e.g., sand) could all deposit at the bottom of a hillslope well before the remaining sediment is delivered to the stream system. Furthermore, although the finer sediments deposit at a much slower rate than the coarse sediments, the amount available may be so small that the fines may all deposit before reaching the stream system. An upper bound check is required to satisfy the physical logic.

Column 1 (Sediment Particle Class) is a repeat of each respective particle-size class and the sum row. The sum row serves the same role as in Table 6-4. Column 2 (Sediment Distribution) is a required input and is available as output from the RUSLE subprogram.

Column 3 (Sediment Settling Ratio) is product of Column 5 (Deposition Rate Ratio) from Table 6-4 and Column 2 (Sediment Distribution) from Table 6-5 divided by the Sediment Settling Ratio Normalizing Ratio which is the sum of the cross products of Column 5 (Deposition Rate Ratio) from Table 6-4 and Column 2 (Sediment Distribution) from Table 6-5. This product reflects the actual relative settling rates due to the unequal distribution of the particle-size classes.

Column 4 (Particle Deposition Ratio) is equal to Column 3 (Sediment Settling Ratio) times the HUSLE Delivery Ratio but cannot be greater than the sediment distribution shown in Column 2 of Table 6-5. Column 5 (Particle Delivery Ratio) is 1 minus Column 4 (Particle Deposition Ratio) from Table 6-5.

Column 6 (Deposition Mass Ratio Rate), is shown to illustrate the relative deposition of the various particle-size class with respect to the clay class for the actual distribution. Column 7 (Sediment Delivered) is the product of the respective particle-size class delivery ratio times the RUSLE erosion. This column is the objective of the algorithm.

Table 6-5: Sediment Particle-Size Class Delivery Ratio

Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7
Sediment Particle Class	Sediment Distribution	Sediment Settling Ratio	Particle Deposition Ratio	Particle Delivery Ratio	Deposition Mass Rate Ratio	Sediment Delivered
	(-)	(-)	(-)	(-)	(g-particle /g-clay)	(g)
<b>HUSLE Delivery Ratio (-) = 0.200000</b>				<b>RUSLE Erosion (g) = 1000000</b>		
<b>Initial Estimate</b>						
clay	0.200000	0.000091	0.000073	0.199927	1	199927
silt	0.200000	0.002401	0.001921	0.198079	26	198079
sand	0.200000	0.691528	0.200000	0.000000	7570	0
SAGG	0.200000	0.007747	0.006198	0.193802	85	193802
LAGG	0.200000	0.298233	0.200000	0.000000	3265	0
Sum	1.000000	1.000000	0.408192	0.591808		398006
Sediment Settling Ratio Normalizing Factor =				0.20000000		
<b>1st Correction</b>						
clay	0.200000	0.000296	0.000189	0.199811	1	199811
silt	0.200000	0.007783	0.004970	0.195030	26	195030
sand	0.000000	0.000000	0.200000	0.000000	0	0
SAGG	0.200000	0.025115	0.016038	0.183962	85	183962
LAGG	0.200000	0.966806	0.200000	0.000000	3265	0
Sum	0.800000	1.000000	0.421197	0.578803		578803
Sediment Settling Ratio Normalizing Factor =				0.06169449		
<b>2nd Correction</b>						
clay	0.200000	0.008921	0.003568	0.196432	1	196432
silt	0.200000	0.234473	0.093789	0.106211	26	106211
sand	0.000000	0.000000	0.200000	0.000000	0	0
SAGG	0.200000	0.756606	0.200000	0.000000	85	0
LAGG	0.000000	0.000000	0.200000	0.000000	0	0
Sum	0.600000	1.000000	0.697358	0.302642		302642
Sediment Settling Ratio Normalizing Factor =				0.00204790		
<b>3rd Correction</b>						
clay	0.200000	0.036652	0.007330	0.192670	1	192670
silt	0.200000	0.963348	0.192670	0.007330	26	7330
sand	0.000000	0.000000	0.200000	0.000000	0	0
SAGG	0.000000	0.000000	0.200000	0.000000	0	0
LAGG	0.000000	0.000000	0.200000	0.000000	0	0
Sum	0.400000	1.000000	0.800000	0.200000		200000
Sediment Settling Ratio Normalizing Factor =				0.00049845		
<b>4th Correction</b>						
clay	0.200000	0.036652	0.007330	0.192670	1	192670
silt	0.200000	0.963348	0.192670	0.007330	26	7330
sand	0.000000	0.000000	0.200000	0.000000	0	0
SAGG	0.000000	0.000000	0.200000	0.000000	0	0
LAGG	0.000000	0.000000	0.200000	0.000000	0	0
Sum	0.400000	1.000000	0.800000	0.200000		200000
Sediment Settling Ratio Normalizing Factor =				0.00049845		

Note that the sum of the particle-size class sediment delivered as shown in Column 7 is equal to the HUSLE delivery ratio times the initial RUSLE erosion for any combination of HUSLE delivery ratio and initial sediment distribution. This is the logical objective of this algorithm

## 6.2 Channel Sediment Processes

### 6.2.1 Sediment Transport

All sediment routing in the concentrated flow channels used within AnnAGNPS are performed using the five particle-size classes (sand, large & small aggregates, silt, and clay) and for each increment of the hydrograph. Although, inflow from the cells contains only the primary particles of clay, silt, and sand, aggregates can be routed if they are present in the channel or from other sources.

The notation convention used in this section is as follows:

- upper case stands for totals, e.g.  $Q_w$  is total water discharge, Mg/s;
- lower case stands for unit-width, e.g.  $q_w$  is unit-width discharge, Mg/s/m;
- in the first subscript position,  $w$  stands for water;
- in the first subscript position,  $s$  stands for sediment;
- in the second subscript position,  $c$  stands for capacity;
- in the second subscript position, 1 stands for upstream end of concentrated flow channel segment; and
- in the second subscript position, 2 stands for downstream end of concentrated flow channel segment.

Unit-width means dividing the respective parameter by the top width at the surface of the flow area. For rectangular channels, this is a constant. For example, the unit-width water discharge ( $q_w$ ) is equal to the total water discharge ( $Q_w$ ) divided by the top width ( $W$ ); i.e.,  $q_w = Q_w/W$ .

If the sum of all incoming sediment ( $q_{s1}$ ) is greater than the sediment transport capacity ( $q_{sc}$ ), then the sediment deposition algorithm is used. If that sum is less than or equal to the sediment transport capacity, the sediment discharge at the outlet of the reach ( $q_{s2}$ ) will be equal to the sediment transport capacity for an erodible channel (by particle-size). Otherwise, if the upstream sediment discharge ( $q_{s1}$ ) is less than or equal to the sediment transport capacity ( $q_{sc}$ ) and the channel is non-erodible for that particular particle-size, the downstream sediment discharge ( $q_{s2}$ ) is equal to the upstream sediment discharge ( $q_{s1}$ ).

- If  $(q_{s1}-q_{sc}) \leq 0$  & the bed is erodible for the particular particle-size class, then  $q_{s2} = q_{sc}$ ; or
- if  $(q_{s1}-q_{sc}) \leq 0$  & the bed is non-erodible for the particular particle-size class, then  $q_{s2} = q_{s1}$ ; or
- if  $(q_{s1}-q_{sc}) > 0$ , then use the sediment deposition algorithm.

### Sediment Concentration

The definition for sediment concentration is:

$$C_s = S_m/W_m \quad \text{Equation 6-5}$$

where:  $C_s$  = sediment concentration, Mg-sediment/Mg-water;  
 $S_m$  = sediment mass, Mg; and  
 $W_m$  = water mass from upstream drainage area, Mg.

Sediment concentration is assumed to be constant throughout the hydrograph; therefore, the sediment load for a given discharge at any time during the runoff hydrograph is:

$$q_s = c_s q_w \quad \text{Equation 6-6}$$

where:  $c_s$  = sediment concentration, Mg-sediment/Mg-water;  
 $q_s$  = unit-width sediment load, Mg/s/m; and  
 $q_w$  = unit-width water discharge at any time, Mg/s/m;

### Sediment Transport Capacity Algorithm

The sediment transport capacity ( $q_{sc}$ ) and the unit-width water discharge ( $q_w$ ) will be based upon the parameters at the upstream end of the reach ( $x_1$ ).



The shear velocity, assuming unit-width, will be based upon the parameters at the upstream end of the reach ( $x_1$ ) and is defined to be:

$$U_* = [g \cdot d_w \cdot S_o]^{1/2} = g^{0.5} \cdot n^{0.3} \cdot S_o^{0.35} \cdot q_w^{0.3} \quad \text{Equation 6-7}$$

where:  $d_w$  = hydraulic depth at  $x_2$ , m;  
 $g$  = gravitational constant, 9.81 m/sec<sup>2</sup>;  
 $q_p$  = unit-width water discharge, m<sup>3</sup>/s/m;  
 $S_o$  = channel slope, m/m; and  
 $U_*$  = shear velocity at  $x_1$ , m/s.

For each particle-size, the sediment transport capacity is:

$$q_{sc} = \eta \cdot k \cdot \tau \cdot v_w^2 / v_f \quad \text{Equation 6-8}$$

where:  $q_{sc}$  = unit-width sediment transport capacity, Mg/s/m;  
 $\eta$  = effective transport factor, non-dimensional;  
 $k$  = transport capacity factor (see Table 6-6), non-dimensional;  
 $\tau$  = bed shear stress; Mg/m<sup>2</sup>  
 $v_w$  = flow velocity of water, m/s; and  
 $v_f$  = particle fall velocity (see Table 6-6), m/s.

The effective transport factor currently estimated as:

$$\eta = 0.322 \cdot [(\gamma_p - \gamma_w) / (\tau / D_p)]^{1.626} \leq 1 \quad \text{Equation 6-9}$$

where:  $\eta$  = effective transport factor, non-dimensional;  
 $\tau$  = bed shear stress; Mg/m<sup>2</sup>  
 $\gamma_w$  = 1.00, water density, Mg/m<sup>3</sup>;  
 $\gamma_p$  = particle density, (see Table 6-6), Mg/m<sup>3</sup>; and  
 $D_p$  = equivalent sand size particle diameter (see Table 6-6), m.

The bed shear stress can be computed as follows:

$$\tau = \gamma_w \cdot d_w \cdot S_o \quad \text{Equation 6-10}$$

where:  $\tau$  = bed shear stress; Mg/m<sup>2</sup>  
 $\gamma_w$  = 1.00, water density, Mg/m<sup>3</sup>;  
 $d_w$  = hydraulic depth, m; and  
 $S_o$  = channel slope, m/m.

Table 6-6 contains the physical properties for each particle-size class (note  $D_p$  is in millimeters and  $v_f$  is in millimeters per second).

**Table 6-6: Particle-size Class Physical Properties  
(after Young et al 1987)**

Particle-size Class	Particle Size Range (mm)	$\gamma_p$ Particle Density (Mg/m <sup>3</sup> )	$v_f$ Fall Velocity (mm/s)	k Transport Capacity Factor (-)	$D_p$ Equivalent Sand Size (mm)
clay	<0.002	2.60	$3.11 \cdot 10^{-3}$	$6.242 \cdot 10^{-3}$	$2.00 \cdot 10^{-3}$
silt	0.002-0.050	2.65	$8.02 \cdot 10^{-2}$	$6.053 \cdot 10^{-3}$	$1.00 \cdot 10^{-2}$
sand	0.050-2.000	2.65	$2.31 \cdot 10^{+1}$	$6.053 \cdot 10^{-3}$	$2.00 \cdot 10^{-1}$
small aggregates (SAGG)	0.020-0.075	1.80	$3.81 \cdot 10^{-1}$	$12.478 \cdot 10^{-3}$	$3.51 \cdot 10^{-2}$
large aggregates (LAGG)	0.200-1.000	1.60	$1.65 \cdot 10^{+1}$	$16.631 \cdot 10^{-3}$	$5.00 \cdot 10^{-1}$

Substituting

**Equation 6-10** into

**Equation 6-9** and using **Equation 5-103** to replace  $d_w$  with  $q_w$ , and separating the hydraulic from the sediment particle related terms, and including the conversion for  $D_p$  from millimeters to meters, results in:

$$\eta = [C_1 / (n^{0.6} \cdot S_o^{0.7} \cdot q_w^{0.6})]^{1.626} \leq 1, \text{ and}$$

$$C_1 = \{ [D_p / 2004] \cdot [(\gamma_p - \gamma_w) / \gamma_w] \} \tag{Equation 6-11}$$

where:  $\eta$  = effective transport factor, non-dimensional;  
 $\gamma_w = 1.00$ , water density, Mg/m<sup>3</sup>;  
 $\gamma_p$  = particle density, (see Table 6-7), Mg/m<sup>3</sup>;  
 $C_1$  = particle-size class constant for the effective transport factor (see Table 6-7), m;  
 $D_p$  = particle diameter (see Table 6-7), mm;  
 $n$  = Manning's retardance;  
 $q_w$  = unit-width water discharge, m<sup>3</sup>/s/m; and  
 $S_o$  = channel slope, m/m.

The effective transport factor ( $\eta$ ) is equal to 1 when  $S_o \cdot d_w = C_1$ . Therefore, using

**Equation 5-104** in **Equation 6-11**, results in:

$$q_\eta = [C_1 / (n^{0.6} \cdot S_o^{0.7})]^{5/3} \tag{Equation 6-12}$$

where:  $q_\eta$  = critical unit-width water discharge below which effective transport factor ( $\eta$ ) is 1 and above which it is calculated according to **Equation 6-11**, m<sup>3</sup>/s/m;  
 $C_1$  = particle-size class constant for the effective transport factor (see Table 6-7), m;  
 $n$  = Manning's retardance; and  
 $S_o$  = channel slope, m/m.

And the critical unit-width water discharge ( $q_\eta$ ) occurs at the critical transport factor time ( $t_\eta$ ). When  $0 \geq t < t_\eta$ ,  $\eta = 1$ ; and when  $t \geq t_\eta$ ,  $\eta$  is solved according to **Equation 6-11**.

$$t_\eta = t_b \cdot (q_\eta / q_p) \tag{Equation 6-13}$$

where:  $t_\eta$  = critical effective transport factor time, when  $t < t_\eta$   $\eta = 1$ , s;  
 $q_\eta$  = critical unit-width water discharge below which effective transport factor ( $\eta$ ) is 1 and above which it is calculated according to **Equation 6-11**,  $m^3/s/m$ ;  
 $q_p$  = unit-width peak discharge,  $m^3/s/m$ ; and  
 $t_b$  = time to base, s.

Combining

**Equation 6-8** and**Equation 6-11**, correcting for  $v_f$  in millimeters per second to meters per second, and using **Equation 6-12** results in:For  $0 \leq t \leq t_\eta$ : $C_2 = 322 \cdot k \cdot \gamma_w / v_f$ , and $q_{sc} = C_2 \cdot n^{-0.6} \cdot S_0^{1.3} \cdot q_w^{1.4}$ For  $t \geq t_\eta$ : $C_3 = C11.626 \cdot C_2$ , and $q_{sc} = C_3 \cdot n - 1.5756 \cdot S_0 \cdot 0.1618 \cdot q_w^{0.4244}$ **Equation 6-14**

where:  $q_{sc}$  = unit-width sediment transport capacity,  $Mg/s/m$ ;  
 $C_1$  = particle-size class constant for the effective transport factor (see Table 6-7), m;  
 $C_2$  = particle-size class constant for the sediment transport capacity for  $\eta = 1$  (see Table 6-7),  $Mg-s/m^4$ ;  
 $C_3$  = particle-size class constant for the sediment transport capacity for  $\eta < 1$  (see Table 6-7),  $Mg-s/m^{2.374}$ ;  
 $k$  = transport capacity factor (see Table 6-6), non-dimensional;  
 $n$  = Manning's retardance;  
 $q_w$  = unit-width water discharge,  $m^3/s/m$ ;  
 $S_0$  = channel slope, m/m.  
 $t$  = time between 0 and time to base of hydrograph, s;  
 $t_\eta$  = critical effective transport factor time, s;  
 $t_b$  = time to base of hydrograph, s;  
 $v_f$  = particle fall velocity (see Table 6-6), mm/s; and  
 $\gamma_w = 1.00$ , water density,  $Mg/m^3$ .

Using

**Equation 5-118** and**Equation 5-119** in **Equation 6-14**, the total sediment transport capacity for the hydrograph is:When  $t_\eta \geq t_b$  is:

$$S_{sc} = \int_0^{t_b} (W \cdot q_{sc}) dt = W \cdot C_2 \cdot n^{-0.6} \cdot S_0^{1.3} \cdot q_p^{1.4} \cdot t_b / 2.4$$

**Equation 6-15**Otherwise, when  $0 < t_\eta < t_b$ :

$$S_{sc} = \left[ \int_0^{t_\eta} q_{sc} dt + \int_{t_\eta}^{t_b} q_{sc} dt \right]$$

$$= W \cdot \left\{ \left[ C_2 \cdot n^{-0.6} \cdot S_0^{1.3} \cdot q_p^{1.4} \cdot t_\eta / 2.4 \right] + \left[ \left( C_3 \cdot n^{-1.5756} \cdot S_0^{0.1618} \cdot (q_p / t_b)^{0.4244} \right) \cdot (t_b^{1.4244} - t_\eta^{1.4244}) / 1.4244 \right] \right\}$$

**Equation 6-16**

where:  $C_2$  = particle-size class constant for the sediment transport capacity for  $\eta = 1$  (see Table 6-7),  $\text{Mg-s/m}^4$ ;  
 $C_3$  = particle-size class constant for the sediment transport capacity for  $\eta < 1$  (see Table 6-7),  $\text{Mg-s/m}^{2.374}$ ;  
 $n$  = Manning's retardance;  
 $q_p$  = unit-width peak discharge,  $\text{m}^3/\text{s/m}$ ;  
 $q_{sc}$  = unit-width sediment transport capacity,  $\text{Mg/s/m}$ ;  
 $q_{\eta}$  = critical unit-width water discharge below which effective transport factor ( $\eta$ ) is 1 and above which it is calculated according to **Equation 6-11**,  $\text{m}^3/\text{s/m}$ ;  
 $S_{sc}$  = total sediment transport capacity mass,  $\text{Mg}$ .  
 $S_o$  = channel slope,  $\text{m/m}$ .  
 $t$  = time from beginning of runoff,  $\text{s}$ ;  
 $t_{\eta}$  = critical effective transport factor time,  $\text{s}$ ;  
 $t_b$  = time to base,  $\text{s}$ ; and  
 $W$  = flow width,  $\text{m}$ .

Table 6-7 contains the sediment transport capacity constants for each particle-size class (note  $D_p$  is in millimeters and  $v_f$  is in millimeters per second).

**Table 6-7: Sediment Particle-size Class Sediment Transport Capacity Values**

Sediment Class	$D_p$ (mm)	$\gamma_p$ ( $\text{Mg/m}^3$ )	$v_f$ (mm/s)	$k$ (-)	$C_1$ (m)	$C_2$ ( $\text{Mg-s/m}^4$ )	$C_3$ ( $\text{Mg-s/m}^{2.374}$ )
clay	$2.00 \cdot 10^{-3}$	2.60	$3.11 \cdot 10^{-3}$	$6.242 \cdot 10^{-3}$	1.5968E-06	2.0071E+03	7.5344E-07
silt	$1.00 \cdot 10^{-2}$	2.65	$8.02 \cdot 10^{-2}$	$6.053 \cdot 10^{-3}$	8.2335E-06	7.5474E+01	4.0789E-07
sand	$2.00 \cdot 10^{-1}$	2.65	$2.31 \cdot 10^{+1}$	$6.053 \cdot 10^{-3}$	1.6467E-04	2.6203E-01	1.8475E-07
SAGG	$3.51 \cdot 10^{-2}$	1.80	$3.81 \cdot 10^{-1}$	$1.248 \cdot 10^{-2}$	1.4012E-05	3.2756E+01	4.2024E-07
LAGG	$5.00 \cdot 10^{-1}$	1.60	$1.65 \cdot 10^{+1}$	$1.663 \cdot 10^{-2}$	1.4970E-04	1.0079E+00	6.0859E-07

### Sediment Deposition Algorithm

The sediment routing for each reach is performed using the unit-width, steady-state, uniform, spatially-varied sediment discharge model as explained in the Report.

The sediment routing for all reaches will be the same. All upstream sediment discharges ( $q_{s1}$ ) will be the sum of all incoming sediment from upstream reaches plus the local sediment associated with the immediate upstream reach. Primary cell upstream sediment discharges ( $q_{s1}$ ) will consist only of local loadings since there is no incoming sediment from upstream reaches to a primary cell.

$$q_{s2} = q_{sc} + [(q_{s1} - q_{sc}) \cdot \exp(-N_d)] \quad \text{Equation 6-17}$$

where:  $N_d$  = deposition number, non-dimensional;  
 $q_{sc}$  = unit-width sediment transport capacity,  $\text{Mg/s/m}$ ;  
 $q_{s1}$  = upstream unit-width sediment discharge at  $x_1$ ,  $\text{Mg/s/m}$ ;  
 $q_{s2}$  = downstream unit-width sediment discharge at  $x_2$ ,  $\text{Mg/s/m}$ ;

The determination of the deposition number,  $N_d$ , is performed using the following equation:

$$N_d = (A_E \cdot v_f \cdot L_2) / q_w \quad \text{Equation 6-18}$$

where:  $A_E$  = Einstein's constant of proportionality, for any given flow and particle-size, between the depth-average suspended sediment concentration and the concentration at the laminar sublayer plane, non-dimensional; (see

**Equation 6-19**);

$v_f$  = particle fall velocity, m/s.

$L_2$  = distance from  $x_1$  to  $x_2$ , m; and

$q_w$  = unit-width water discharge,  $m^3/s/m$ .

For clay, silt, and small aggregates,  $A_E = 1$ ; for sand and large aggregates, use:

$$A_E = [(6 \cdot v_f) / (\kappa \cdot U_*)] / \{1 - \exp[-(6 \cdot v_f) / (\kappa \cdot U_*)]\} \quad \text{Equation 6-19}$$

where:  $\kappa$  = von Karman's turbulent-flow mixing-length constant (assume 0.4), non-dimensional;

$U_*$  = shear velocity at  $x_1$  (see m/s; and

**Equation 6-7**),

$v_f$  = particle fall velocity, m/s.

Einstein's constant of proportionality ( $A_E$ ) is actually the ratio of the suspended sediment concentration at the bottom of the water column (near the bed surface) to the average concentration of suspended sediment throughout the water column.

For primary cells, the distance from  $x_1$  to  $x_2$  is the distance from the hydraulically most distant point ( $x_1$ ) to the cell outlet ( $x_2$ ).

For secondary cells, the distance from  $x_1$  to  $x_2$  of its associated reach is the length of the concentrated flow channel segment for the reach. The outlet for each reach is always  $x_2$  in the above equations. All incoming sediment from upstream reaches is assumed to enter at the upstream end of the reach ( $x_1$ ). Local loadings (originating within the associated cells) are assumed to be delivered to the downstream end of the cell's associated reach ( $x_2$ ).

The channel dimensions for each reach will be based upon the flow characteristics for the respective reach; and for the geomorphic option, the top width and depth will be based upon the drainage area at the upstream end of each respective reach.

Gaussian-Legendre quadrature is used for numerical integration when closed form analytic solutions are not known. The subprogram GAULEG (Press et al 1987) generates the abscissas ( $t_i$ ) & weights ( $\omega_i$ ) for a given N-point Gauss-Legendre quadrature. Points for the 15-point Gaussian-Legendre quadrature (Carnahan et al 1969) are shown in Table 6-8.

**Table 6-8: 15-Point Gaussian-Legendre Quadrature for Numerical Integration**

Point No.	$t_i/t_b$	$\omega_i$
1	.006003741	.015376621
2	.031363304	.035183024
3	.075896109	.053579610
4	.137791135	.069785339
5	.214513914	.083134603
6	.302924330	.093080500
7	.399402954	.099215743
8	.500000000	.101289120
9	.600597047	.099215743
10	.697075674	.093080500
11	.785486087	.083134603

Point No.	$t_i/t_b$	$\omega_i$
12	.862208866	.069785339
13	.924103292	.053579610
14	.968636696	.035183024
15	.993996259	.015376621

The N-point Gaussian-quadrature numerical integration of y as a function of t is:

$$\int_{t=t_1}^{t=t_2} Q_s dt \cong (t_2 - t_1) \cdot \left[ \sum_{i=1}^{i=N} (\omega_i \cdot Q_{s,i}) \right]$$

Equation 6-20

where:  $Q_s$  = sediment load as a function of time; Mg/sec;  
 $Q_{s,i}$  = sediment load at Gauss-Legendre time point  $t_i$ ; Mg/sec;  
 $t_1$  = time at beginning of time period, sec;  
 $t_2$  = time at end of time period, sec;  
 $i$  = first Gauss-Legendre time point;  
 $N$  = last Gauss-Legendre time point; and  
 $w_f$  = Gauss-Legendre weight, non-dimensional.

### 6.2.2 Bed and Bank Erosion

This section will describe the conditions that AnnAGNPS checks for and calculates when bed and bank erosion will occur for any of the five particle classes. If so, the amount of bed and bank erosion is calculated for that particle class.

#### Sediment Aggradation Algorithm

If the sediment load is supply limited and the particular particle size is available in the bed & banks of the reach, then the downstream total sediment load for the particular particle size will be assumed to be equal to the total sediment transport capacity for that particular particle size.

Table 6-9 contains the default conditions regarding the availability of a particle-size class in the channel bed.

Table 6-9: Availability of Particle-size Class in the Channel

Particle-size Class	Yes/No
clay	no
silt	no
sand	yes
small aggregates (SAGG)	no
large aggregates (LAGG)	no

Table 6-10 is the decision table for all possible combinations of scour indicators for the five particle-size classes.

Table 6-10: Bed &amp; Bank Scour Decision Table

Code	Silt	Clay	Sand	SMAGG	LGAGG
0	no	no	no	no	no
1	yes	no	no	no	no
2	no	yes	no	no	no
3	yes	yes	no	no	no
4	no	no	yes	no	no
5	yes	no	yes	no	no
6	no	yes	yes	no	no
7	yes	yes	yes	no	no
8	no	no	no	yes	no
9	yes	no	no	yes	no
10	no	yes	no	yes	no
11	yes	yes	no	yes	no
12	no	no	yes	yes	no
13	yes	no	yes	yes	no
14	no	yes	yes	yes	no
15	yes	yes	yes	yes	no
16	no	no	no	no	yes
17	yes	no	no	no	yes
18	no	yes	no	no	yes
19	yes	yes	no	no	yes
20	no	no	yes	no	yes
21	yes	no	yes	no	yes
22	no	yes	yes	no	yes
23	yes	yes	yes	no	yes
24	no	no	no	yes	yes
25	yes	no	no	yes	yes
26	no	yes	no	yes	yes
27	yes	yes	no	yes	yes
28	no	no	yes	yes	yes
29	yes	no	yes	yes	yes
30	no	yes	yes	yes	yes
31	yes	yes	yes	yes	yes

## 7. IMPOUNDMENTS

The application of impoundments within AnnAGNPS utilizes a modified sediment deposition algorithm. The simplifications reflect the detention time associated with temporary storage due to restricted pressurized or weir outflow and/or dilution due to permanent pool storage. These simplifications are: (1) constant detention discharge that is a storage-weighted average over the temporary storage interval; (2) zero sediment transport capacity for all sediment sizes; and (3) dilution of the incoming water-sediment mixture by the permanent pool storage. The purpose for impoundments within the model is to reflect the settling or “desilting” of incoming sediment due to the lengthened detention time as sediment laden water passes through an impoundment. The impoundment can be “dry”, which is due to restricted outflow only; or wet, which will have additional storage (“dead” or permanent storage below the crest of the principal spillway) to slow the velocity through the pool and/or restricted outflow. As users choose, the impoundment module can “memorize” the volume and depth of sediment captured and accumulated in the impoundment. The sediment accumulated in the impoundment can be cleaned out at a user-specified time.

### Assumptions

Actual reservoir routing is performed for each runoff event and sediment deposition within the impoundment is determined for the effects of: (1) dilution due to mixing with permanent impounded water (wet pool); and (2) detention time due to temporary flood storage during the passage of a runoff event through the impoundment. The following assumptions were modeled:

- the incoming water and sediment is mixed with a different ratio of clear permanent pool water within the impoundment for each particle size according to the mixing coefficients shown in Table 7-1;
- the permanent pool storage is stratified clear & sediment-laden water whose sediment-laden water does not contribute to the outflow;
- the zero discharge elevation (reference elevation) for the elevation-discharge relationship is the thalweg at the outlet of the impoundment for pressure flow control ( $Q_o = c \cdot h^{1/2}$ );
- the zero discharge elevation (reference elevation) for elevation-discharge relationship is the permanent pool elevation of the impoundment for weir flow control [ $Q_o = c \cdot (h - h_0)^{3/2}$ ];
- the elevation-storage relationship for the impoundment starts at zero from the thalweg of the impoundment (same reference elevation as for pressure flow);
- reservoir routing is performed to determine the temporary detention storage which in turn is ;
- the sediment deposition for each particle size due to detention storage is calculated assuming free drawdown of the detention storage;
- the total sediment deposition for each particle size is calculated to be the dilution of the entire inflow volume and the effect of the detention time only of the detention storage which is corrected for dilution;

### Input Requirements

The input requirements are: (1) elevation-storage power curve coefficient (a) and exponent (b); (2) elevation-discharge coefficient (c) and exponent (d); (3) permanent pool stage ( $h_o$ ); (4) runoff event water volume ( $V_1$ ); and (5) incoming mass of sediment by particle size ( $S_{m1}$ ) and its associated fall velocity ( $v_f$ ).

### Impoundment Sediment Outflow Mass

The mass of sediment outflow for each particle size is:

$$\text{sediment\_out} = \{[\text{total\_inflow} / (\text{total\_inflow} + (\text{mixing\_coef} * \text{permanent\_storage}))] * \text{sediment\_in}\} + \{[(\text{detention\_depth} - \text{settling\_depth}) / \text{detention\_depth}] * [\text{detention\_storage}]\}$$

**Equation 7-1**

where:

total\_inflow = runoff amount into impoundment;

permanent\_storage = total storage from the reference elevation to the elevation of the permanent pool (zero of dry pool);

sediment\_in = amount of sediment entering the impoundment with the runoff;



sediment\_out = amount of sediment leaving the impoundment;  
 detention\_dep = elevation difference between the permanent pool and the maximum elevation during the passage of the runoff through the impoundment corresponding to the detention storage;  
 settling\_depth = settling depth of sediment corresponding to the particle size's fall velocity and the detention time during drawdown; and  
 detention\_storage = maximum temporary storage during the passage of the runoff.

**Table 7-1: Sediment Properties—Impoundments**

Sediment Class	Mixing Coef. (-)	Fall Velocity (mm/s)
clay	0.0500	$3.11 \cdot 10^{-3}$
silt	0.2500	$8.02 \cdot 10^{-2}$
sand	1.0000	$2.31 \cdot 10^{+1}$
SAGG	0.5000	$3.81 \cdot 10^{-1}$
LAGG	1.0000	$1.65 \cdot 10^{+1}$

Table 7-1 shows the fall velocities ( $v_f$ ) for each of the sediment particle size classes. They are taken from Table 6-7. Note that the fall velocities are shown in the table in millimeters per second and have to be divided by 1000 to get them in the correct units shown in the equations ( $m^3/s$ ).

The mixing coefficient is to account for the fact that the very fine sediments such as clay particles do not settle out of suspension easily.

Note that the SI units for a metric ton (Mg), which is 1,000,000 grams, of water mass is equivalent to a volume measure of 1,000,000  $m^3$  of water. A hectare-meter (ha-m) volume is equivalent to 10,000  $m^3$ .

**Elevation-Discharge-Area-Storage Relationships**

Figure 7-1. Elevation-Discharge-Area-Storage Relationships shows the elevation-discharge (both pressure flow and weir flow control), elevation-area, and elevation-storage relationships for impoundments.

The impoundment permanent pool storage is:

$$V_p = a \cdot h_o^b$$

**Equation 7-2**

where:  $a, b$  = input coefficient & exponent for the impoundment elevation-storage relationship;  
 $h_o$  = permanent pool stage, m; and  
 $V_p$  = permanent pool storage, ha-m.

The average event outflow discharge under pressure flow control ( $d = 0.5$ ) is:

$$Q_o = c \cdot \{[(V_p + V_I/2) / a]^{1/b}\}^{0.5}$$

**Equation 7-3**

where:  $a, b$  = input coefficient & exponent for the impoundment elevation-storage relationship;  
 $c, d$  = input coefficient & exponent for the impoundment elevation-discharge relationship;  
 $Q_o$  = average outflow during runoff event,  $m^3/s$ ; and  
 $V_I$  = runoff event water volume, ha-m; and  
 $V_p$  = permanent pool storage, ha-m.

The average event outflow discharge under weir flow control ( $d = 1.5$ ) is:

$$Q_o = c \cdot \{[(V_p + V_I/2) / a]^{1/b} - h_o\}^{1.5}$$

**Equation 7-4**

where:  $a, b$  = input coefficient & exponent for the impoundment elevation-storage relationship;  
 $c, d$  = input coefficient & exponent for the impoundment elevation-discharge relationship;  
 $h_o$  = permanent pool stage, m;  
 $Q_o$  = average outflow during runoff event,  $m^3/s$ ; and  
 $V_I$  = runoff event water volume, ha-m; and  
 $V_p$  = permanent pool storage, ha-m.

The average surface area of the impoundment during the respective runoff event is:

$$A_s = a \cdot b \cdot [(V_p + V_I/2) / a]^{[(b-1)/b]}$$

**Equation 7-5**

where:  $a, b$  = input coefficient & exponent for the impoundment elevation-storage relationship;  
 $A_s$  = average impoundment surface area during respective runoff event, ha;  
 $V_I$  = runoff event water volume, ha-m; and  
 $V_p$  = permanent pool storage, ha-m.

Reservoir routing is performed to obtain the maximum temporary storage using an iterative, bisection method, numerical solution.

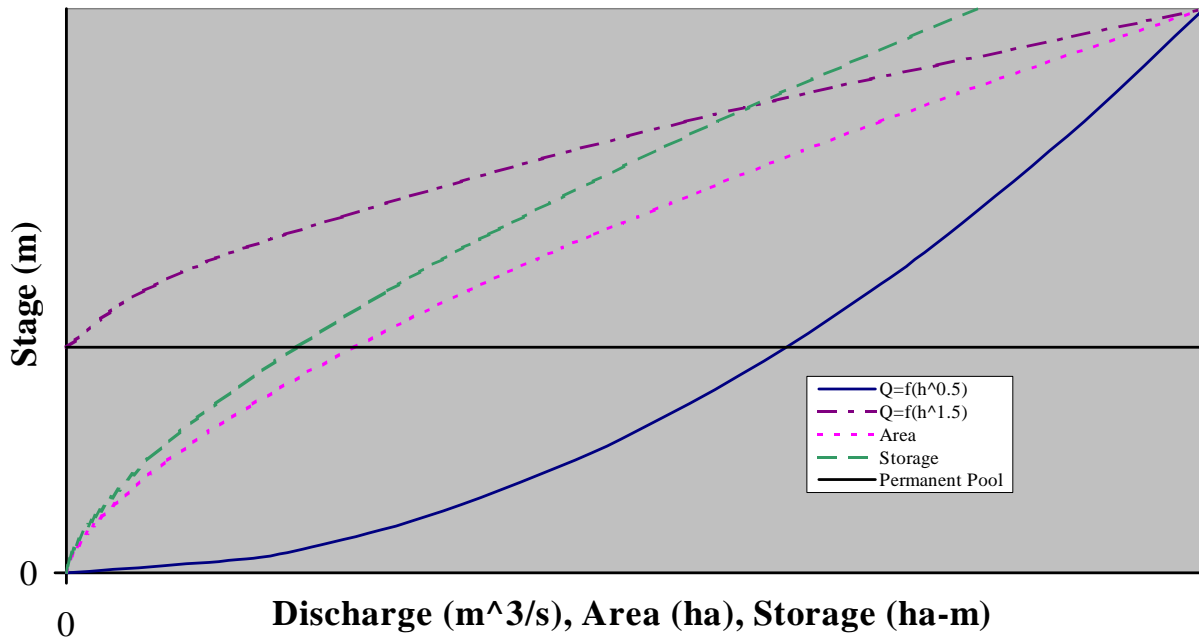


Figure 7-1. Elevation-Discharge-Area-Storage Relationships

### 7.1.1 Effect of Sediment Accumulation

A significant amount of accumulated sediment could potentially affect the performance of the pond, and reduce the sediment removal efficiency after a long period of time. In the new impoundment module, the total amount of sediment trapped is memorized, and the related pond parameters are updated accordingly after every runoff event.

**For wet ponds**, as shown in Figure 7-2. Schematic diagram showing the effect of sediment accumulation (wet ponds), sediment settled at the bottom of the pond will take up the permanent pool water storage volume.

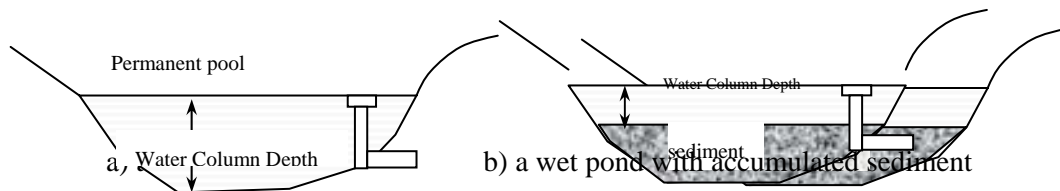


Figure 7-2. Schematic diagram showing the effect of sediment accumulation (wet ponds)

The mass of sediment trapped in the pond is tracked for each runoff event for all the particle size classes, and the total volume taken by accumulated sediment is the summation of the accumulated volume for each particle class. Volumes of sediment of all particle sizes are estimated by dividing the masses by the submerged sediment bulk density (see Table 7-2. Bulk density of sediment by particle size).

The impoundment module subtracts the total sediment volume from the original permanent pool storage volume ( $V_p$ ), resulting in a smaller  $V_p$ . The reduced permanent pool storage volume lessens the dilution effect, and potentially causes a higher chance of sediment resuspension as water column depth is reduced.

**For dry ponds,** the accumulated sediment takes up the runoff storage volume (as shown in Figure 7-3. Schematic diagram showing the effect of sediment accumulation (dry ponds). During a runoff event, the water level in a sediment-filled pond is higher than that of a clean pond. Consequently, the detention time decreases, resulting in lower sediment trap efficiency. In addition, with sediment exposed at the bottom, sediment re-suspension during storms can potentially impair pond performance.



**Figure 7-3. Schematic diagram showing the effect of sediment accumulation (dry ponds)**

The mass of sediment trapped in the pond is tracked on a runoff event basis for each particle size class, and the total volume taken by accumulated sediment is estimated by dividing the total mass of each class by the aerated sediment bulk density (see Table 7-2. Bulk density of sediment by particle size). In the modified new impoundment routine, the sediment volume is added to the inflow runoff volume, which results in an increase of the outflow discharge rate. Consequently, the suspended solid removal efficiency is reduced due to the shortened detention time.

**Table 7-2. Bulk density of sediment by particle size**

Particle Size	Bulk Density (lb/ft <sup>3</sup> )	
	Submerged	Aerated
Clay	35-55	55-75
Silt	55-75	75-85
Sand	85-100	85-100

After National Engineering Handbook, Section 3: Sedimentation, USDA, SCS

## 8. CHEMICAL ROUTING

In general, chemicals exist in two phases: (1) dissolved (solution); and (2) attached (adsorbed) to clay-size particles.

Three nutrients are recognized by AnnAGNPS: (1) nitrogen; (2) phosphorous; & (3) organic carbon. Nitrogen & phosphorous are recognized as to be able to exist in both the soluble and adsorbed state. Organic phosphorous is assumed to be insoluble; therefore, only inorganic phosphorous is subject to equilibration. Organic carbon is assumed to be part of the clay-size particles with a known organic carbon to clay ratio.

AnnAGNPS allows any number of pesticides, each with their own independent chemical properties, but they are treated separately; i.e., there is no interaction assumed. Independent equilibration is assumed for each pesticide.

**Adsorbed Chemicals:** Conservation of mass calculations are made for any adsorbed chemicals if the clay-size particles are deposited within the stream reach. Re-equilibration, for the necessary chemicals, are repeated at the downstream end if clay-size particles are deposited or entrained from the bed & banks, or if there is any loss of water.

**Solution Chemicals:** Conservation of mass calculations are made for any chemicals in solution if there is any loss of water within the stream reach. Re-equilibration, for the necessary chemicals, are repeated at the downstream end if there is any change in the amount or source of clay-size, or if there is any loss of water.

$$M_s = M_c / (1 + K_d)$$

**Equation 8-1**

**Equilibration:** A simple first order equilibration model for equilibration is used:

where:

- $K_d$  = partition coefficient of chemical, non-dimensional;
- $M_c$  = total mass of chemical both adsorbed & in solution, Mg; and
- $M_s$  = total mass of chemical in solution, Mg.

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