

AnnAGNPS TECHNICAL PROCESSES

Documentation

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AnnAGNPS: Technical Descriptions

TABLE OF CONTENTS

1. Introduction	1
2. Climate.....	6
2.1 Climate Dataset(s)	6
2.1.1 Daily Weather Parameters	6
2.1.2 Storm Types.....	7
2.2 Precipitation.....	7
2.2.1 Rainfall	7
2.2.2 Snowfall.....	7
2.2.3 Variation of precipitation with cell elevation.....	7
2.2.4 Frequency	8
2.2.4.1 Precipitation (Gumbel Distribution)	8
3. Irrigation Systems.....	10
3.1 Surface Irrigation Systems.....	10
3.1.1 Border Irrigation, Level or Graded	10
3.1.2 Furrow Irrigation, With Open Ends	10
3.1.3 Furrow Irrigation, With Blocked Ends	10
3.1.4 Surge Irrigation.....	11
3.2 Sprinkler Systems	11
3.2.1 Handline, Wheelline, and Solid Set Sprinkler Systems	11
3.2.2 Set Place and Moving Gun Systems	11
3.2.3 Center Pivot Systems	11
3.2.4 Linear Move Systems	11
3.3 Trickle Irrigation Systems	11
3.4 Surface Irrigation – Water, Infiltration and Runoff Processes.....	11
3.5 Automatic Irrigation Method	12
3.6 Surface Irrigation – Sediment Processes.....	12
4. Historical Climate for AnnAGNPS	12
5. Synthetic Weather Generators for AnnAGNPS	12
6. Water	13
6.1 Surface Runoff.....	14
6.1.1 SCS Curve Number Technique.....	14
6.1.1.1 Constant Parameters within the SCS Curve Number Technique	14
6.1.1.2 SCS Curve Number Parameters.....	16
6.1.1.3 Determination of the SCS Curve Number	17
6.1.2 Determination of Surface Runoff.....	18
6.2 Potential evapotranspiration	19
6.2.1 Net Radiation	19
6.2.2 Extraterrestrial Solar Radiation.....	24
6.2.3 Determination of Potential Evapotranspiration.....	26
6.3 FAO Enhancement for Calculating Evapotranspiration, ET_c , within AnnAGNPS	28
6.3.1 Reference evapotranspiration, ET_o :.....	29
6.3.2 Growth stages:	30
6.3.3 Basal crop coefficient, K_{cb}	30
6.3.4 Evaporation coefficient, K_e :	33
6.3.5 Crop evapotranspiration, ET_c :	39
6.3.6 Actual Crop evapotranspiration, ET_a :.....	39
6.4 Subsurface flow	39
6.4.1 Tile Drainage Flow	40
6.4.2 Lateral Subsurface Flow	42
6.5 Channel Hydraulics and Hydrology.....	42
6.5.1 Channel Hydraulics.....	42
6.5.1.1 In-Cell Concentrated Flow.....	43
6.5.1.2 In-Stream Channel Compound Cross-sections	47
6.5.1.3 Hydraulic Depth and Velocity	52

AnnAGNPS: Technical Descriptions

6.5.1.4	Time of Concentration (t_c).....	53
6.5.2	Channel Hydrology.....	56
6.5.2.1	Ratio of Initial Abstraction to 24-Hour Precipitation.....	56
6.5.2.2	Unit Peak Discharge	56
6.5.3	RCN Calibration	62
7.	Sediment	62
7.1	Erosion.....	62
7.1.1	Sheet & Rill	62
7.1.1.1	Revised Universal Soil Loss Equation (RUSLE).....	62
7.1.1.2	AnnAGNPS Delivery Ratio.....	68
7.1.2	Tillage-Induced Ephemeral Gully Erosion	73
7.1.2.1	Introduction.....	73
7.1.2.1.1	AnnAGNPS Ephemeral Gully Model Enhancements.....	73
7.1.2.1.2	Current Model Limitations	74
7.1.2.2	Soil Properties.....	74
7.1.2.2.1	Critical shear	74
7.1.2.2.2	Nickpoint Erodibility Coefficient	74
7.1.2.2.3	Headcut Migration Erodibility Coefficient	75
7.1.2.3	Hydrograph Development.....	75
7.1.2.3.1	Minimum Gully Width	75
7.1.2.3.2	Gully Mouth (Nickpoint).....	77
7.1.2.3.3	Upstream Stations.....	80
7.1.2.4	Plunge Pool Development at the Nickpoint.....	81
7.1.2.4.1	Gully Width, Flow Depth, & Bed Shear.....	81
7.1.2.4.2	Rate of Nickpoint Development	83
7.1.2.5	Headcut Migration (advancement).....	91
7.1.2.5.1	Headcut Dimensions	91
7.1.2.5.2	Headcut Scour Pool	92
7.1.2.5.3	Gully Width Adjustment.....	92
7.1.2.6	Sediment Transport of Deposition	93
7.2	Channel Sediment Processes	93
7.2.1	Sediment Transport.....	93
7.2.2	Bed and Bank Erosion	99
8.	Impoundments	101
8.1.1	Effect of Sediment Accumulation.....	104
9.	Chemical Routing	106
10.	Nitrogen	106
10.1	General Introduction.....	106
10.1.1	Nitrogen Cycle.....	106
10.1.2	Nitrate Leaching and Runoff Losses.....	107
10.1.3	Nitrogen Balance	109
10.2	AnnAGNPS Nitrogen Processes.....	109
10.2.1	Soil Initial Nitrogen Contents and Conversion Factor.....	109
10.2.2	Organic Nitrogen Simulation Processes	110
10.2.2.1	Cell Residue Nitrogen Calculations.....	110
10.2.2.2	Cell Organic Nitrogen from Fertilizer Application.....	111
10.2.2.3	Mineralized Nitrogen from Organic Nitrogen on Current Day.....	111
10.2.2.4	Calculation of Mass of Nitrogen Attached to Sediment	113
10.2.3	Inorganic Nitrogen Simulation Processes.....	113
10.2.3.1	Calculation of Inorganic N Additions to a Cell	113
10.2.3.2	Calculation of Intermediate Inorganic N Mass Balance	116
10.2.3.3	Calculation of Inorganic N Losses From a Cell.....	116
10.2.3.4	Reconcile Inorganic N Mass Balance	117
10.2.4	Total Inorganic Nitrogen Losses to Surface Runoff	117
10.2.5	Leaching	118
10.2.6	Losses to Subsurface Flow	118

AnnAGNPS: Technical Descriptions

10.2.6.1 Calculation of Inorganic N Loss Through Subsurface Drainage (Tile Drain) Systems 118

10.2.6.2 Calculation of Inorganic N Loss to Subsurface Lateral Flow 119

11. Phosphorus 120

11.1 General Introduction 120

11.1.1 Phosphorus Cycle 120

11.2 Annagnps Phosphorus Processes 121

11.2.1 Initial Soil Phosphorus—Contents and Conversion Factors 122

11.2.2 Organic Phosphorus Simulation Processes 123

11.2.2.1 Cell Residue P Calculations 123

11.2.2.2 Cell Organic P From Fertilizer Application 124

11.2.2.3 Mineralized P From Organic P on Current Day 125

11.2.2.4 Calculation of Mass of P Attached to Sediment 126

11.2.3 Inorganic P Simulation Processes 127

11.2.3.1 Calculation of Inorganic P Additions to a Cell 127

11.2.3.2 Calculation of Intermediate Inorganic P Mass Balance 129

11.2.3.2.1 Calculation of Flow Rate between Labile P and Active P 129

11.2.3.3 Calculation of Additions From P Mineralization 132

11.2.3.4 Calculation of Inorganic P Losses From a Cell 133

11.2.4 Total Inorganic P Losses to Surface Runoff 134

11.2.5 Leaching 134

12. Carbon 135

12.1 General Introduction 135

12.2 AnnAGNPS Carbon Processes 135

12.2.1 Soil Initial Carbon Contents and Conversion Factor 136

12.2.2 Organic Carbon Simulation Processes 136

12.2.2.1 Carbon/Nitrogen Ratio (C:N) and C Mineralization 137

12.2.2.2 Cell Residue Decomposition 138

12.2.2.3 Cell Organic Carbon Addition from Manures or Other Sources 140

12.2.2.4 Calculation of Mass of Carbon Attached to Sediment (sedC) 140

12.2.3 AnnAGNPS CARBON PROCESSES: Input Parameterization 141

13. Wetland Nitrogen Removal Component 142

13.1 Wetland Components 142

13.2 Implementation of the Wetland Feature in AnnAGNPS 146

13.3 User Interface 146

14. Riparian Buffer Component 149

14.1 Cell-Located Buffers 152

14.2 Reach-Located Buffers 155

14.3 Riparian Buffer Effects on Ephemeral Gullies 156

15. References 158

LIST OF TABLES

Table 1-1 Former and Current Development subproject leaders of AnnAGNPS 1

Table 2-1: Definitions for Gumble Distribution 9

Table 2-2: Precalculated Probability—variate Values 10

Table 6-1: Unit Peak Discharge Regression Coefficients—Type 1 (I) 57

Table 6-2: Unit Peak Discharge Regression Coefficients—Type 2 (Ia) 57

Table 6-3: Unit Peak Discharge Regression Coefficients—Type 3 (II) 58

Table 6-4: Unit Peak Discharge Regression Coefficients—Type 4 (III) 58

Table 6-5: Unit Peak Discharge Regression Coefficients—Type 5 (Uniform) 59

Table 6-6: Unit Peak Discharge Regression Coefficients—Type 6 (IIa60) 59

Table 6-7: Unit Peak Discharge Regression Coefficients—Type 7 (IIa65) 60

AnnAGNPS: Technical Descriptions

Table 6-8: Unit Peak Discharge Regression Coefficients—Type 8 (IIa70).....	60
Table 6-9: Unit Peak Discharge Regression Coefficients—Type 9 (IIa75).....	61
Table 7-1. Contour Rotation Example.....	65
Table 7-2. Assigned Cover Code for Various Landuses.....	67
Table 7-3: Sediment Particle-Size Class Static Parameters.....	70
Table 7-4: Sediment Particle-Size Class Delivery Ratio.....	72
Table 7-5. Particle-size Class Physical Properties (after Young et al 1987).....	95
Table 7-6: Sediment Particle-size Class Sediment Transport Capacity Values.....	97
Table 7-7: 15-Point Gaussian-Legendre Quadrature for Numerical Integration.....	98
Table 7-8: Availability of Particle-size Class in the Channel.....	99
Table 7-9: Bed & Bank Scour Decision Table.....	100
Table 8-1: Sediment Properties—Impoundments.....	102
Table 8-2. Bulk density of sediment by particle size.....	105
Table 13-1. Input parameters needed to describe the wetland feature and user guidance associated with various parameters. Input parameters are required for each wetland to be simulated.	147
Table 14-1. Associated AnnAGNPS particle sizes with the Meyer et al. (1995) coefficients and illustrated in Figure 14-1.	150
Table 14-2. Sediment Particle-Size Class Static Parameters.....	151

LIST OF FIGURES

Figure 1-1. The suite of modeling components contained within AGNPS.....	4
Figure 1-2. Major processes simulated within AnnAGNPS.....	5
Figure 1-3. Built into AnnAGNPS is the capability to track pollutants using source accounting techniques.	5
Figure 1-4. Flowchart showing the relational integration of the data sections used within the continuous AnnAGNPS. The orange boxes indicate required data sections.....	6
Figure 6-1. Transpiration, T, and evaporation, E, comprise the total evapotranspiration from a field. The soil surface under the canopy is not part of the soil evaporative surface, since that is included in the transpiration component. Soil evaporation is only assumed to occur in the fraction of surface where most of the evaporation occurs, f_w , and is only associated with the top layer, Z_e . The fraction of the surface wetted by precipitation or irrigation is f_w . (Allen et al., 1998).....	29
Figure 6-2.. Constructed basal crop coefficient (K_{cb}) curve for a dry bean crop using example growth stage lengths of $L_{ini}=25$, $L_{dev}=25$, $L_{mid}=30$ and $L_{late}=20$ days. For this example, L_{late} associated with $K_{cb\ end}$ should extend to 100. (FAO, Figure 37).	32
Figure 6-3. The fraction of surface from which most evaporation occurs, f_{ew} , comprised of the exposed and wetted soil fractions of a field.....	36
Figure 6-4. Energy limiting and falling rate stages of the evaporation reduction coefficient, K_r	38
Figure 6-5. Schematic for Houghoudt Tile Flow.....	40
Figure 6-6. Generalized In-Cell Channel Shape--trapezoid.....	43
Figure 6-7. Generalized In-Stream Channel Shape--Compound X-Section.....	48
Figure 7-1. Flow chart of the AnnAGNPS C-factor calculation.....	64
Figure 7-2. Flow chart of AnnAGNPS K factor calculation.....	66

AnnAGNPS: Technical Descriptions

Figure 7-3. A high level view of the process used in AnnAGNPS to calculate P factors.....	68
Figure 7-4: Triangular hydrograph showing the key variables.....	77
Figure 7-5. Normalized times versus nickpoint depth development showing erosivity (D'_c) versus critical shear discharge ratio (Q'_c) and erosivity (D'_2) versus relative times (t'_2) for time to peaks (t'_p) ranging from 0 to time to base ($t'_b=1$) when critical shear (τ_c) is equal to 0.....	90
Figure 7-6. Definition sketch of a flow profile over a ventilated overfall (<i>after</i> Alonso & Bennett, 2002).	91
Figure 7-7: Definition sketch of flow pattern in the pool region showing impinging and wall jets, confined eddies, and control volume used in energy balance analysis. It should be noted that shear friction is neglected along the interface between the downstream wall jet and captive eddy. (<i>after</i> Alonso & Bennett, 2002).	92
Figure 8-1. Elevation-Discharge-Area-Storage Relationships.....	104
Figure 8-2. Schematic diagram showing the effect of sediment accumulation (wet ponds).....	104
Figure 8-3. Schematic diagram showing the effect of sediment accumulation (dry ponds)	105
Figure 10-1. A simplification of nitrogen processes (Havlin et al., 1999).....	106
Figure 10-2. Nitrogen processes simulated in AnnAGNPS.....	109
Figure 11-1. A simplification of phosphorus processes (Havlin et al., 1999).....	121
Figure 11-2. Processes simulated in AnnAGNPS.....	122
Figure 13-1. Processes simulated in AnnAGNPS. Wetlands are located on AnnAGNPS reaches, and the effluent from wetland goes back to the same AnnAGNPS reach where the wetland is constructed. As shown in this figure, a wetland is located on reach 2, more wetlands can be constructed on other reaches such as reach 1 and 3.	148
Figure 14-1. Sediment trapping efficiency defined by Meyer et al. (1995) and applied to the particle sizes utilized within AnnAGNPS.....	151
Figure 14-2. Buffer width and sediment trapping efficiency for predominant grass-like vegetation and local slope values smaller than or equal to 5%.....	154
Figure 14-3. Buffer width and sediment trapping efficiency for predominant grass-like vegetation and local slope values greater than 5%.....	154
Figure 14-4. Buffer width and sediment trapping efficiency for bush-like and/or forest-like vegetation types.	155

LIST OF EQUATIONS

$p = 1 - e^{-e^{-\omega}}$	Equation 2-1	10
$SED_TOT = SED_RATE \bullet R_E \bullet A_{cell}$	Equation 3-3-1	12
$SM_{t+1} = SM_t + \frac{WI_t - Q_t - PERC_t - ET_t - Q_{lat} - Q_{tile}}{Z}$	Equation 6-1	13
$FCMWP = FC - WP$	Equation 6-2	15
$POMWP = f - WP$	Equation 6-3	15
$KSAT_DT = \frac{KSAT}{NTS}$	Equation 6-4	15

AnnAGNPS: Technical Descriptions

$$\ln(\lambda) = -0.7842831 + (1.77544 \cdot SAND) - (1.062498 \cdot f) - (0.5304 \cdot SAND^2) - (27.3493 \cdot CLAY^2) \\ + (1.11134946 \cdot f^2) - (3.088295 \cdot SAND \cdot f) + (2.6587 \cdot SAND^2 \cdot f^2) - (61.0522 \cdot CLAY^2 \cdot f^2) \\ - (2.35 \cdot SAND^2 \cdot CLAY) + (79.8746 \cdot CLAY^2 \cdot f) - (0.674491 \cdot f^2 \cdot CLAY)$$

Equation

6-5
15

$$BC_EXP = 3 + \frac{2}{\lambda} \quad \text{Equation 6-6}$$

15

$$MIN_SMMWP = POMWP \left(\frac{0.0000000001}{KSAT_DT} \right)^{(1/BC_EXP)} \quad \text{Equation 6-7}$$

15

$$FSDEPTH = \frac{KSAT}{f} \quad \text{Equation 6-8}$$

16

$$FR = 1 - \frac{D_{SL1}}{FSDEPTH} \quad \text{Equation 6-9}$$

16

$$SMCX = FSDEPTH(1) FCMWP(1) + FSDEPTH(2) FCMWP(2) \quad \text{Equation 6-10}$$

16

$$AVAIL_H2O = D_{SL1} FCMWP(1) + (1000 - D_{SL1}) FCMWP(2) \quad \text{Equation 6-11}$$

16

$$AVAIL_H2O = D_{SL1} FCMWP(1) + (D_{SL2} - D_{SL1}) FCMWP(2) \quad \text{Equation 6-12}$$

16

$$\gamma = 6.6 \times 10^{-4} (101 - 0.0115Z + 5.44 \times 10^{-7} Z^2) \quad \text{Equation 6-13}$$

16

$$CN_1 = CN_2 - \frac{20(100 - CN_2)}{100 - CN_2 + \exp[2.533 - 0.0636(100 - CN_2)]} \quad \text{Equation 6-14}$$

16

$$CN_1 = 0.4 CN_2 \quad \text{Equation 6-15}$$

16

$$CN_3 = CN_2 \exp[0.00673(100 - CN_2)] \quad \text{Equation 6-16}$$

17

$$S = 254 \left(\frac{100}{CN} - 1 \right) \quad \text{Equation 6-17}$$

17

$$W_1 = \ln \left(\frac{1}{1 - \frac{S_3}{S_1}} - 1 \right) + W_2 \quad \text{Equation 6-18}$$

17

AnnAGNPS: Technical Descriptions

$$W_2 = 2 \left[\ln \left(\frac{0.5}{1 - \frac{S_2}{S_1}} - 0.5 \right) - \ln \left(\frac{1}{1 - \frac{S_3}{S_1}} - 1 \right) \right] \quad \text{Equation 6-19} \quad 17$$

$$S = 254 \left(\frac{100}{CN} - 1 \right) \quad \text{Equation 6-20} \quad 18$$

$$S_t = S_1 \left(1 - \frac{FS_t}{FS_t + \exp(W_1 - W_2 FS_t)} \right) \quad \text{Equation 6-21} \quad 19$$

$$FS_t = \frac{FSDEPTH(1)(SM(1)_t - WP(1)) + FSDEPTH(2)(SM(2)_t - WP(2))}{FSDEPTH(1)(FC(1) - WP(1)) + FSDEPTH(2)(FC(2) - WP(2))} \quad \text{Equation 6-22} \quad 19$$

$$Q = \frac{(WI - 0.2S)^2}{WI + 0.8S} \quad \text{Equation 6-23} \quad 19$$

$$F_a = \frac{a'' + \left(\frac{1 - a' - d_{sr}}{2} \right)}{1 - \alpha \left(\frac{1 - a' + d_{sr}}{2} \right)} \quad \text{Equation 6-24} \quad 20$$

$$a' = \exp\left\{-m_a(0.465 + 0.134w)\left[0.129 + 0.171\exp(-0.880m_a)\right]\right\} \quad \text{Equation 6-25} \quad 20$$

$$a'' = \exp\left\{-m_a(0.465 + 0.134w)\left[0.179 + 0.421\exp(-0.721m_a)\right]\right\} \quad \text{Equation 6-26} \quad 20$$

$$w = 0.85 \exp(0.110 + 0.0614T_D) \quad \text{Equation 6-27} \quad 20$$

$$F_a = 0.75 + 0.0002Z_e \quad \text{Equation 6-28} \quad 21$$

$$F_c = 0.22 + 0.78 \left(\frac{S}{S_o} \right)^{2/3} \quad \text{Equation 6-29} \quad 21$$

$$F_c = 0.35 + 0.61 \left(\frac{S}{S_o} \right)^{2/3} \quad \text{Equation 6-30} \quad 21$$

$$R_{SI} = F_a F_c R_x \quad \text{Equation 6-31} \quad 21$$

$$R_{SI} = \left[0.19 + 0.55 \left(\frac{S}{S_o} \right) \right] R_x \quad \text{Equation 6-32} \quad 21$$

$$R_{SR} = \alpha R_{SI} \quad \text{Equation 6-33} \quad 21$$

AnnAGNPS: Technical Descriptions

$$R_{SN} = (1 - \alpha) F_a F_c R_x \quad \text{Equation 6-34} \quad 21$$

$$R_L = \varepsilon \sigma T_K^4 \quad \text{Equation 6-35} \quad 22$$

$$\varepsilon_a = a + b\sqrt{e} \quad \text{Equation 6-36} \quad 22$$

$$e = 6.11 \exp\left(\frac{17.62 T_D}{243.12 + T_D}\right) \quad \text{Equation 6-37} \quad 22$$

$$e = 6.11 \exp\left(\frac{22.46 T_D}{272.62 + T_D}\right) \quad \text{Equation 6-38} \quad 22$$

$$\frac{R_{Lc}}{R_{La}} = 1 + kC^m \quad \text{Equation 6-39} \quad 23$$

$$R_{LN} = -\varepsilon \sigma (T + 273.16)^4 (0.56 - 0.08\sqrt{e}) \left(0.1 + 0.9 \frac{S}{S_o}\right) \quad \text{Equation 6-40} \quad 23$$

$$R_{LN} = \sigma (T + 273.16)^4 \left[(0.61 + 0.05\sqrt{e}) (1 + 0.17C^2) - \varepsilon \right] \quad \text{Equation 6-41} \quad 23$$

$$R_{LN} = -\sigma (T + 273.16)^4 (0.34 - 0.04\sqrt{e}) \left(1.35 \frac{R_s}{R_{So}} - 0.35\right) \quad \text{Equation 6-42} \quad 23$$

$$R_N = R_{SN} + R_{LN} \quad \text{Equation 6-43} \quad 24$$

$$R_x = \frac{S_c}{\pi} d_r (h_s \sin \phi \sin \delta + \sin h_s \cos \phi \cos \delta) \quad \text{Equation 6-44} \quad 25$$

$$d_r = \left(\frac{\bar{d}}{d_{es}}\right)^2 \quad \text{Equation 6-45} \quad 25$$

$$d_r = \frac{(1 + e_o \cos \theta)^2}{(1 - e_o^2)} \quad \text{Equation 6-46} \quad 25$$

$$\theta = \frac{2\pi}{365} (J - 2) \quad \text{Equation 6-47} \quad 25$$

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \quad \text{Equation 6-48} \quad 25$$

$$h_s = \arccos(-\tan \phi \tan \delta) \quad \text{Equation 6-49} \quad 25$$

AnnAGNPS: Technical Descriptions

$$\delta = 0.40928 \cos \left[\left(\frac{2\pi}{365} \right) (172 - J) \right] \quad \text{Equation 6-50} \quad 25$$

$$A = \arcsin \left\{ \left(\sin \phi \sin \delta \right) + \left[\cos \phi \cos \delta \cos \left(\frac{h_s}{2} \right) \right] \right\} \quad \text{Equation 6-51} \quad 26$$

$$m_a = \frac{\left(\frac{288 - 0.0065Z_e}{288} \right)^{5.256}}{\sin A + 0.15 \left[\left(\frac{180}{\pi} \right) A + 3.885 \right]^{-1.253}} \quad \text{Equation 6-52} \quad 26$$

$$ET_p = \frac{1}{H_v} \left[\left(\frac{\Delta}{\Delta + \gamma} \right) (R - G) + \left(\frac{\gamma}{\Delta + \gamma} \right) W (e_{sat} - e) \right] \quad \text{Equation 6-53} \quad 26$$

$$H_v = 2.501 - 0.0022 T \quad \text{Equation 6-54} \quad 27$$

$$e_{sat} = 0.1 \exp \left(54.879 - 5.029 \ln T_k - \frac{6790.5}{T_k} \right) \quad \text{Equation 6-55} \quad 27$$

$$e = RH e_{sat} \quad \text{Equation 6-56} \quad 27$$

$$\Delta = \left(\frac{e_{sat}}{T_k} \right) \left(\frac{6790.5}{T_k} - 5.029 \right) \quad \text{Equation 6-57} \quad 27$$

$$\gamma = 6.6 \times 10^{-4} \left(101 - 0.0115Z + 5.44 \times 10^{-7} Z_e^2 \right) \quad \text{Equation 6-58} \quad 27$$

$$G = 0.12 \left[T_0 - \left(\frac{T_{-1} + T_{-2} + T_{-3}}{3} \right) \right] \quad \text{Equation 6-59} \quad 27$$

$$W = 6.43 + 3.4079U \quad \text{Equation 6-60} \quad 27$$

$$q_{drain} = \frac{8K_s d_e m + 4K_s m^2}{L_D^2} \quad \text{Equation 6-61} \quad 40$$

$$d_e = \frac{d}{1 + \frac{d}{L_D} \left[\frac{8}{\pi} \ln \left(\frac{d}{r} \right) - \alpha_c \right]} \quad \text{Equation 6-62} \quad 41$$

$$\alpha_c = 3.55 - \frac{1.6d}{L_D} + 2 \left(\frac{d}{L_D} \right)^2 \quad \text{Equation 6-63} \quad 41$$

$$d_e = \frac{L_D \pi}{8 \left[\ln \left(\frac{L_D}{r} \right) - 1.15 \right]} \quad \text{Equation 6-64} \quad 41$$

$$SM_{t+1} = SM_t + \frac{WI_t - PERC_t - ET_t}{Z} \quad \text{Equation 6-65} \quad 41$$

AnnAGNPS: Technical Descriptions

$$h = \frac{(SM_{t+1} - FC) * Z}{(PO - FC)} \quad \text{Equation 6-66} \quad 41$$

$$Q_{Tile} = \frac{q_{drain} * A_{cell}}{1000} \quad \text{Equation 6-67} \quad 41$$

$$q_{lat} = -K_s \frac{dh}{dl} \quad \text{Equation 6-68} \quad 42$$

$$Q_{lat} = \frac{q_{lat} * A_{across}}{1000} \quad \text{Equation 6-69} \quad 42$$

$$A_{across} = \frac{h * L_{Reach}}{1000} \quad \text{Equation 6-70} \quad 42$$

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

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

$$d_{t,i=0}(Q_t, Z, W, n, S_0) = MIN \left[\left(\frac{n \cdot Q_t}{W \cdot \sqrt{S_0}} \right)^{3/5}, \left(\frac{2^{2/3} \cdot n \cdot Q_t}{Z \cdot \sqrt{S_0}} \right)^{3/8} \right] \quad \text{Equation 6-71} \quad 44$$

$$d_t(Q_t, W, n, S_0) = \left(\frac{n \cdot Q_t}{W \cdot \sqrt{S_0}} \right)^{3/5} \quad \text{Equation 6-72} \quad 44$$

$$d_t(Q_t, Z, n, S_0) = \left(\frac{2^{2/3} \cdot n \cdot Q_t}{Z \cdot \sqrt{S_0}} \right)^{3/8} \quad \text{Equation 6-73} \quad 44$$

$$V(Q_t, d_t, Z, W) = \frac{Q_t}{(W \cdot d_t) + (Z \cdot d_t^2)} \quad \text{Equation 6-74} \quad 45$$

$$V(Q_t, d_t, W) = \frac{Q_t}{W \cdot d_t} \quad \text{Equation 6-75} \quad 45$$

$$V(Q_t, d_t, Z) = \frac{Q_t}{Z \cdot d_t^2} \quad \text{Equation 6-76} \quad 45$$

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

Equation 6-77 45

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

Equation 6-78 45

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

Equation 6-79 45

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

Equation 6-80 46

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

Equation 6-81 46

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

Equation 6-82 46

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

Equation 6-83 46

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

Equation 6-84 47

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

Equation 6-85 47

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

Equation 6-86 47

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

Equation 6-87 47

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

Equation 6-88 47

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

Equation 6-89 47

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

Equation 6-90 48

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

Equation 6-91 49

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

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

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

$d_c = d_t$
 $d_f = d_t + d_b$

Equation 6-92
49

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

Equation 6-93 50

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

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

Equation 6-94 50

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

Equation 6-95 51

AnnAGNPS: Technical Descriptions

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

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

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

Equation 6-96

51

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

$$q_c = q_t$$

$$q_f = 0$$

Equation 6-97

51

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

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

Equation 6-98

51

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

$$q_f = 0$$

Equation 6-99

52

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

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

Equation 6-100

52

$$d_w = R = A_H / W_H \quad \text{Equation 6-101}$$

52

$$v_w = (1/n) \cdot d_w^{2/3} \cdot S_0^{1/2} \quad \text{Equation 6-102}$$

53

$$d_w = [(n \cdot q_w) / (S_0^{1/2})]^{0.6} = n^{0.6} \cdot S_0^{-0.3} \cdot q_w^{0.6}; \quad \& \quad v_w = Q_w / (W_H \cdot d_w) = q_w / d_w \quad \text{Equation 6-103}$$

53

$$d_w \cdot S_0 = n^{0.6} \cdot S_0^{0.7} \cdot q_w^{0.6} \quad \text{Equation 6-104}$$

53

$$T_{c,in_cell} = T_{t,ov} + T_{t,scf} + T_{t,cf} \quad \text{Equation 6-105}$$

53

$$L_{ov_max} = 50$$

$$L_{ov} = MIN(L_{ov_max}, L)$$

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

Equation 6-106

54

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$$L_{ov_max} = 50$$

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 6-107 54

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 6-108 55

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

Equation 6-109 55

If there are no contributing reaches, then

$$T_{c,reach_in} = 0$$

Otherwise,

$$T_{c,reach_in} = MAX(T_{c,reach_out} \text{ 's of all immediately contributing reaches})$$

$$T_{c,reach_out} = T_{c,reach_in} + T_{t,reach}$$

Equation 6-110 56

$$Q_{24} \equiv (P_{24} - I_a)^2 / (P_{24} + 4 I_a) \text{ Equation 6-111} \quad 56$$

$$I_a^2 + (-2P_{24} + 4Q_{24}) I_a + (P_{24}^2 - Q_{24}P_{24}) = 0 \text{ Equation 6-112} \quad 56$$

$$I_a = (P_{24} + 2Q_{24}) - (5Q_{24}P_{24} + 4Q_{24}^2)^{0.5} \text{ Equation 6-113} \quad 56$$

$$(I_a / P_{24}) \equiv [(P_{24} + 2Q_{24}) - (5Q_{24}P_{24} + 4Q_{24}^2)^{0.5}] / P_{24} \text{ Equation 6-114} \quad 56$$

$$Q_p = 2.777777778 \cdot 10^{-3} \cdot P_{24} \cdot D_a \cdot \left[\frac{a + (c \cdot T_c) + (e \cdot T_c^2)}{1 + (b \cdot T_c) + (d \cdot T_c^2) + (f \cdot T_c^3)} \right]$$

Equation 6-115 57

$$t_b = 20 \cdot (R_Q \cdot D_a / Q_p) \text{ Equation 6-116} \quad 61$$

$$Q_w = (Q_p / t_b) \cdot t, \quad 0 \leq t \leq t_b \text{ Equation 6-117} \quad 62$$

$$q_p = Q_p / W \text{ Equation 6-118} \quad 62$$

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$C_n = \frac{1000}{S_{\max} - 10}$	Equation 6-119	62
$K = K * (1 + 14 * (1 - \exp(-4 * (M - 0.5))))$	Equation 7-1	68
$S_y = 0.22 * Q^{0.68} * q_p^{0.95} * KLSCP$	Equation 7-2	69
$D_r = S_{y2}/S_{y1} = (q_{p2} / q_{p1})^{0.95}$	Equation 7-3	69
$\tau_c = (17.9 \cdot C_c) + e^{[1.97 - (9.98 \cdot P_u)]}$	Equation 7-4	74
$k_n = 29.1 \cdot 10^{-6} \cdot e^{(-0.224 \cdot \tau_c)}$	Equation 7-5	74
$k_h = 0.0000002 / \sqrt{\tau_c}$	Equation 7-6	75
$W_n = 2.51 \cdot Q_p^{0.412}$	Equation 7-7	75
$W_h = a \cdot D_a^b$		
$D_h = c \cdot D_a^d$		
$A_h = W_h \cdot D_h$	Equation 7-8	75
$V_h = (D_h^{2/3} \cdot \sqrt{S_0}) / n$		
$Q = A_h \cdot V_h$		
$W_h = \left\{ \left(\frac{a^{(d/b)}}{c} \right)^{5/3} \cdot \left(\frac{n \cdot Q}{\sqrt{S_0}} \right) \right\}^{\left(\frac{1}{1 + [(5/3)(d/b)]} \right)}$	Equation 7-9	76
$W_s = Q_p / \left[\left(d_t^{5/3} \cdot \sqrt{S_0} \right) / n \right]$	Equation 7-10	76
$W_e = 2.66 \cdot Q_p^{0.396} \cdot n^{0.387} \cdot S_0^{-0.160} \cdot \tau_c^{-0.240}$	Equation 7-11	77
$W_u = 179.0 \cdot Q_p^{0.552} \cdot n^{0.556} \cdot S_0^{0.199} \cdot \tau_c^{-0.476}$	Equation 7-12	77
$V_{p,n} = \int_{t=0}^{t=t_p} Q_n dt$	Equation 7-13	78
$V_{b,n} = \int_{t=0}^{t=t_b} Q_n dt$	Equation 7-14	78
$t_{b,n} = 2 \cdot V_{b,n} / Q_{p,n}$	Equation 7-15	78
$t_{p,n} = 2 \cdot V_{p,n} / Q_{p,n}$	Equation 7-16	78
$Q_n = (t/t_p) \cdot Q_p$	Equation 7-17	78

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$$Q_n = \left[(t_b - t) / (t_b - t_p) \right] \cdot Q_p \quad \text{Equation 7-18} \quad 78$$

$$t' = t / t_b \quad \text{Equation 7-19} \quad 79$$

$$dt = t_b dt' \quad \text{Equation 7-20} \quad 79$$

$$r_p = V_p / V_b = t_p / t_b \quad \text{Equation 7-21} \quad 79$$

$$Q_n = (t' / r_p) \cdot Q_p \quad \text{Equation 7-22} \quad 79$$

$$Q_n = \left[(1 - t') / (1 - r_p) \right] \cdot Q_p \quad \text{Equation 7-23} \quad 79$$

$$l = 80.23 \cdot D_a^{0.6} \quad \text{Equation 7-24} \quad 80$$

$$t_{c,s} = t_{c,n} \cdot (l_s / l_n) = t_{c,n} \cdot (D_{a,s} / D_{a,n})^{0.6} \quad \text{Equation 7-25} \quad 80$$

$$V_{b,s} = V_{b,n} \cdot (D_{a,s} / D_{a,n})^{0.6} \quad \text{Equation 7-26} \quad 80$$

$$t_{b,s} = 2 \cdot V_{b,s} / Q_{p,s} \quad \text{Equation 7-27} \quad 80$$

$$t_{p,n} = 2 \cdot V_{p,n} / Q_{p,n} \quad \text{Equation 7-28} \quad 81$$

$$W_n = 2.51 \cdot Q_{n,p}^{0.412} \quad \text{Equation 7-29} \quad 81$$

$$d_{n,t} = \left\{ \left[(n \cdot Q_{n,t}) \right] / W_n \sqrt{S_0} \right\}^{(0.6)} \quad \text{Equation 7-30} \quad 81$$

$$\tau_{b,t} = \gamma_w \cdot d_{n,t} \cdot S_0 \quad \text{Equation 7-31} \quad 81$$

$$\tau_{n,c} = (\gamma_w \cdot S_0) \cdot \left(\frac{n \cdot Q_{n,p}}{W_n \cdot \sqrt{S_0}} \right)^{0.6} \cdot \left(\frac{Q_{n,c}}{Q_{n,p}} \right)^{0.6} = \tau_{n,p} \cdot (Q_{n,c} / Q_{n,p})^{0.6} \quad \text{Equation 7-32} \quad 82$$

$$\tau_{n,c} = 1.35 \cdot \tau_{b,c} = 1.35 \cdot \left[\gamma_w \cdot S_0 \cdot \left(\frac{n \cdot Q_{n,p}}{W_n \cdot \sqrt{S_0}} \right)^{0.6} \right] \cdot \left(\frac{Q_{n,c}}{Q_{n,p}} \right)^{0.6} = \tau_{n,p} \cdot \left(\frac{Q_{n,c}}{Q_{n,p}} \right)^{0.6} \quad \text{Equation 7-33} \quad 82$$

$$\tau_{b,t} = (\gamma_w \cdot S_0) \cdot \left(\frac{n \cdot Q_{n,p}}{W_n \cdot \sqrt{S_0}} \right)^{0.6} \cdot \left(\frac{Q_{n,t}}{Q_{n,p}} \right)^{0.6} \quad \text{Equation 7-34} \quad 83$$

$$\tau_{x,t} = 1.35 \cdot \tau_{b,t} = 1.35 \cdot \left[\gamma_w \cdot S_0 \cdot \left(\frac{n \cdot Q_{n,p}}{W_n \cdot \sqrt{S_0}} \right)^{0.6} \right] \cdot \left(\frac{Q_{n,t}}{Q_{n,p}} \right)^{0.6} = \tau_{x,p} \cdot \left(\frac{Q_{n,t}}{Q_{n,p}} \right)^{0.6} \quad \text{Equation 7-35} \quad 83$$

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When $D_{n,t} < D_{n,x}$: $dD_{n,t} / dt = [(k_n / \gamma_s) \cdot (\tau_{n,t} - \tau_{n,c})]$; and
 when $D_{n,t} = D_{n,x}$: $dD_{n,t} / dt = 0$ Equation 7-36 83

$$\int_{D_{n1}}^{D_{n2}} dD_{n,t} = \int_{t_{c1}}^{t_2 \leq t_{c2}} [(k_n / \gamma_s) \cdot (\tau_{x,t} - \tau_{n,c})] dt \quad \text{Equation 7-37} \quad 84$$

$$\int_{D_{n1}}^{D_{n2}} dD_{n,t} = D_{n2} - D_{n1} = \Delta D_{n,t} \quad \text{Equation 7-38} \quad 84$$

$$\int_{t_{c1}}^{t_2 \leq t_{c2}} [(k_n / \gamma_s) \cdot (\tau_{x,t} - \tau_{n,c})] dt = \left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \int_{t'_{c1}}^{t'_2 \leq t'_{c2}} (\tau_{x,t} - \tau_{n,c}) dt' \quad \text{Equation 7-39} \quad 85$$

Equation 7-40 86

$$\left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_{c1}}^{t'_2} (t' / t_p)^{0.6} dt' \right] = \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[(t_2^{1.6} - t_{c1}^{1.6}) / (1.6 \cdot t_p^{0.6}) \right];$$

$$\text{let, } n_c = \left(\frac{k_n \cdot t_b \cdot \tau_{n,p}}{\gamma_s} \right);$$

$$\text{then, } \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_{c1}}^{t'_2} (t' / t_p)^{0.6} dt' \right] = n_c \cdot \left[(t_2^{1.6} - t_{c1}^{1.6}) / (1.6 \cdot t_p^{0.6}) \right]; \quad \text{Equation 7-41} \quad 87$$

and then let, $a = n_c / (1.6 \cdot t_p^{0.6})$;

$$\text{results in, } \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_{c1}}^{t'_2} (t' / t_p)^{0.6} dt' \right] = a \cdot (t_2^{1.6} - t_{c1}^{1.6})$$

Equation 7-42 87

$$\left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_{c1}}^{t'_p} (t' / t_p)^{0.6} dt' \right] = \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[(t_p^{1.6} - t_{c1}^{1.6}) / (1.6 \cdot t_p^{0.6}) \right];$$

$$\text{let, } n_c = \left(\frac{k_n \cdot t_b \cdot \tau_{n,p}}{\gamma_s} \right); \quad \text{Equation 7-43} \quad 87$$

$$\text{then, } \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_{c1}}^{t'_p} (t' / t_p)^{0.6} dt' \right] = n_c \cdot \left[(t_p^{1.6} - t_{c1}^{1.6}) / (1.6 \cdot t_p^{0.6}) \right]$$

and then again let $a = n_c / (1.6 \cdot t_p^{0.6})$;

$$\text{results in } \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_{c1}}^{t'_p} (t' / t_p)^{0.6} dt' \right] = a \cdot (t_p^{1.6} - t_{c1}^{1.6}) \quad \text{Equation 7-44} \quad 87$$

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$$\left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_p}^{t'_2} \left[(1-t') / (1-t'_p) \right]^{0.6} dt' \right] = \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\frac{(1-t_p)^{1.6} - (1-t'_2)^{1.6}}{1.6 \cdot (1-t'_p)^{0.6}} \right]$$

$$\text{let, } n_c = \left(\frac{k_n \cdot t_b \cdot \tau_{n,p}}{\gamma_s} \right);$$

$$\text{then, } \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_p}^{t'_2} \left[(1-t') / (1-t'_p) \right]^{0.6} dt' \right] = n_c \cdot \left\{ \frac{\left[(1-t'_p)^{1.6} - (1-t'_2)^{1.6} \right]}{\left[1.6 \cdot (1-t'_p)^{0.6} \right]} \right\}$$

ion 7-45

Equat
88

Equation 7-46

88

$$\left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,c} \right] \cdot \left[\int_{t'_{c1}}^{t'_2} dt' \right] = \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,c} \right] \cdot (t'_2 - t'_{c1})$$

$$\text{let, } n_c = \left(\frac{k_n \cdot t_b \cdot \tau_{n,p}}{\gamma_s} \right) \text{ and } c = n_c \cdot \left(\frac{Q_{n,c}}{Q_{n,p}} \right)^{0.6}$$

Equation 7-47

88

$$\text{then, } \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,c} \right] \cdot \left[\int_{t'_{c1}}^{t'_2} dt' \right] = c \cdot (t'_2 - t'_{c1})$$

$$d_{n,c} = \tau_{n,c} / (1.35 \cdot \gamma_w \cdot S_0) \quad \text{Equation 7-48}$$

89

$$Q_{n,c} = \left[(W_n \cdot \sqrt{S_0}) / n \right] \cdot d_{n,c}^{5/3} \quad \text{Equation 7-49}$$

89

$$t'_{c1} = r_p \cdot (Q_{n,c} / Q_{n,p}) = t'_p \cdot (Q_{n,c} / Q_{n,p});$$

$$\text{let, } Q'_c = Q_{n,c} / Q_{n,p}; \text{ then} \quad \text{Equation 7-50}$$

89

$$t'_{c1} = t'_p \cdot Q'_c$$

$$Q_{n,c} / Q_{n,p} = t'_{c1} / t'_p \quad \text{Equation 7-51}$$

89

$$t'_{c2} = 1 - \left[(1 - r_p) \cdot (Q_{n,c} / Q_{n,p}) \right] = 1 - \left[(1 - t'_p) \cdot (Q_{n,c} / Q_{n,p}) \right] \quad \text{Equation 7-52}$$

89

$$Q'_c = (1 - t'_{c2}) / (1 - t'_p) \quad \text{Equation 7-53}$$

90

$$q_w = Q / W \quad \text{Equation 7-54}$$

92

$$d_u = \left[(n \cdot q) / \sqrt{S_0} \right]^{3/5} \quad \text{Equation 7-55}$$

92

$$F_u = (q_w / d_u) / \sqrt{(g \cdot d_u)} \quad \text{Equation 7-56}$$

92

AnnAGNPS: Technical Descriptions

$$d_c = \left[q_w^2 / (2 \cdot g) \right]^{1/3} \quad \text{Equation 7-57} \quad 92$$

$$\text{If } F_u > 1, \text{ then: } d_b = \left[F_u^2 / (F_u^2 + 0.4) \right] \cdot d_u; \quad \text{Equation 7-58} \quad 92$$

$$\text{If } F_u \leq 1, \text{ then: } d_b = \text{MIN} \left[(d_u / 1.4), (C_c \cdot d_c) \right]$$

$$C_s = S_m / W \quad \text{Equation 7-59} \quad 94$$

$$q_s = c_s \cdot q_w \quad \text{Equation 7-60} \quad 94$$

$$U_* = [g \cdot d_w \cdot S_0]^{1/2} = g^{0.5} \cdot n^{0.3} \cdot S_0^{0.35} \cdot q_w^{0.3} \quad \text{Equation 7-61} \quad 94$$

$$q_{sc} = \eta \cdot k \cdot \tau \cdot v_w^2 / v_f \quad \text{Equation 7-62} \quad 94$$

$$C_1 = \{ [D_p / 2004] \cdot [(\gamma_p - \gamma_w) / \gamma_w] \} \quad \text{Equation 7-65} \quad 95$$

$$q_\eta = [C_1 / (n^{0.6} \cdot S_0^{0.7})]^{5/3} \quad \text{Equation 7-66} \quad 96$$

$$t_\eta = t_b \cdot (q_\eta / q_p) \quad \text{Equation 7-67} \quad 96$$

$$\text{For } t \geq t_\eta: C_3 = C_1 \cdot 11.626 \cdot C_2, \text{ and } q_{sc} = C_3 \cdot n \cdot 1.5756 \cdot S_0 \cdot 0.1618 \cdot q_w \cdot 0.4244 \quad \text{Equation 7-68} \quad 96$$

$$S_{sc} = \int_0^{t_b} (W \cdot q_{sc}) dt = W \cdot C_2 \cdot n^{-0.6} \cdot S_0^{1.3} \cdot q_p^{1.4} \cdot t_b / 2.4 \quad \text{Equation 7-69} \quad 97$$

$$S_{sc} = \left[\int_0^{t_\eta} q_{sc} dt + \int_{t_\eta}^{t_b} q_{sc} dt \right] \\ = W \cdot \left\{ \left[C_2 \cdot n^{-0.6} \cdot S_0^{1.3} \cdot q_p^{1.4} \cdot t_\eta / 2.4 \right] + \left[\left(C_3 \cdot n^{-1.5756} \cdot S_0^{0.1618} \cdot (q_p / t_b)^{0.4244} \right) \cdot (t_b^{1.4244} - t_\eta^{1.4244}) / 1.4244 \right] \right\} \quad \text{Equation 7-70} \quad 97$$

$$q_{s2} = q_{sc} + [(q_{s1} - q_{sc}) \cdot \exp(-N_d)] \quad \text{Equation 7-71} \quad 98$$

$$N_d = (A_E \cdot v_f \cdot L_2) / q_w \quad \text{Equation 7-72} \quad 98$$

$$A_E = [(6 \cdot v_f) / (\kappa \cdot U_*)] \cdot \{ 1 - \exp[-(6 \cdot v_f) / (\kappa \cdot U_*)] \} \quad \text{Equation 7-73} \quad 98$$

$$\int_{t_1}^{t_2} Q_s dt \cong (t_2 - t_1) \cdot \left[\sum_{i=1}^{i=N} (\omega_i \cdot Q_{s,i}) \right] \quad \text{Equation 7-74} \quad 99$$

$$\text{sediment_out} = \{ [\text{total_inflow} / (\text{total_inflow} + (\text{mixing_coef} \cdot \text{permanent_storage}))] \cdot \text{sediment_in} \} + \\ \{ [(\text{detention_depth} - \text{settling_depth}) / \text{detention_depth}] \cdot [\text{detention_storage}] \} \quad \text{Equation} \quad 8-1 \quad 101$$

$$V_p = a \cdot h_o^b \quad \text{Equation 8-2} \quad 102$$

$$Q_o = c \cdot \{ [(V_p + V_1/2) / a]^{1/b} \}^{0.5} \quad \text{Equation 8-3} \quad 103$$

$$Q_o = c \cdot \{ [(V_p + V_1/2) / a]^{1/b} - h_o \}^{1.5} \quad \text{Equation 8-4} \quad 103$$

$$A_s = a \cdot b \cdot [(V_p + V_1/2) / a]^{[(b-1)/b]} \quad \text{Equation 8-5} \quad 103$$

$$M_s = M_c / (1 + K_d) \quad \text{Equation 9-1} \quad 106$$

$$\text{conv} = D * 10 * 1000 * \rho_b * A_{cell} \quad \text{Equation 10-1} \quad 110$$

AnnAGNPS: Technical Descriptions

$$orgN_t = orgN_{t-1} + \frac{(resN + fer_orgN - hmnN - sedN) * 1000000}{conv} \quad \text{Equation 10-2} \quad 110$$

$$resN = \frac{(res_decomp) * 0.5}{CNR_{harvest}} \quad \text{Equation 10-3} \quad 110$$

$$res_decomp = (surf_res) * (1 - \exp(-temp_f * (decomp_coeff))) * A_{cell} \quad \text{Equation 10-4} \quad 110$$

$$temp_f = \frac{3200 * ((T_{soil} + 8) ** 2) - (T_{soil} + 8) ** 4}{2560000}, \quad 0 < T_{soil} < 32 \quad temp_f = 0, \quad T_{soil} < 0$$

$$temp_f = 1, \quad T_{soil} > 32 \quad \text{Equation} \quad 10-5 \quad 111$$

$$resN = (res_decomp) * NF \quad \text{Equation 10-6} \quad 111$$

$$res_subsN = (res_decomp) * NF \quad \text{Equation 10-7} \quad 111$$

$$res_decomp = (sub_res) * (1 - \exp(-temp_f * (decomp_coeff))) * A_{cell} \quad \text{Equation 10-8} \quad 111$$

$$fer_orgN = (fer_app) * (frac_orgN) * A_{cell} \quad \text{Equation 10-9} \quad 111$$

$$hmnN = CMN * frac * orgN * corr * \frac{conv}{1000000} \quad \text{Equation 10-10} \quad 112$$

$$frac = 0.4 * \exp(-0.0277 * YC) + 0.1 \quad \text{Equation 10-11} \quad 112$$

$$F_t = \frac{T_t}{T_t + \exp(9.93 - 0.312 * T_t)} \quad 0 < T_t < 100 \quad \text{Equation 10-12} \quad 112$$

$$F_t = MAX(F_t, 0.1) \quad \text{Equation 10-13} \quad 112$$

$$F_w = \frac{SW}{f} \quad \text{Equation 10-14} \quad 112$$

$$corr = sqrt(F_t * F_w) \quad \text{Equation 10-15} \quad 113$$

$$sedN = frac_orgN_clay * (sed_part(1,1) + sed_part(1,2)) * 1000 \quad \text{Equation 10-16} \quad 113$$

$$frac_orgN_clay = \frac{orgN}{(frac_clay) * 1000000} \quad \text{Equation 10-17} \quad 113$$

$$orgN_t = orgN_{t-1} - \frac{hmnN * 1000000}{conv} \quad \text{Equation 10-18} \quad 113$$

AnnAGNPS: Technical Descriptions

$$mnaN = surf_inorgN \quad \text{Equation 10-19} \quad 114$$

$$surf_inorgN = 0 \quad \text{Equation 10-20} \quad 114$$

$$mnaN = \frac{D}{200} * surf_inorgN \quad \text{Equation 10-21} \quad 114$$

$$surf_inorgN = surf_inorgN - mnaN \quad \text{Equation 10-22} \quad 114$$

$$inorgN_applied = (fer_app) * (frac_inorgN) * A_{cell} \quad \text{Equation 10-23} \quad 114$$

$$mnaN = mnaN + inorgN_applied \quad \text{Equation 10-24} \quad 114$$

$$mnaN = mnaN + \frac{D}{200} * inorgN_applied \quad \text{Equation 10-25} \quad 114$$

$$surf_inorgN = surf_inorgN + (1 - \frac{D}{200}) * inorgN_applied \quad \text{Equation 10-26} \quad 114$$

$$surf_inorgN = surf_inorgN + inorgN_applied \quad \text{Equation 10-27} \quad 115$$

$$surf_sol_N = \frac{runoff}{(runoff + inf)} * surf_inorgN \quad \text{Equation 10-28} \quad 115$$

$$inf_sol_N = surf_inorgN - surf_sol_N \quad \text{Equation 10-29} \quad 115$$

$$surf_sol_N = surf_sol_N + (1.0 - \frac{D}{200}) * (inf_sol_N) \quad \text{Equation 10-30} \quad 115$$

$$inf_sol_N = \frac{D}{200} * (inf_sol_N) \quad \text{Equation 10-31} \quad 115$$

$$surf_sol_N = surf_sol_N \quad \text{Equation 10-32} \quad 115$$

$$inf_sol_N = 0 \quad \text{Equation 10-33} \quad 115$$

$$mnaN = mnaN + inf_sol_N \quad \text{Equation 10-34} \quad 115$$

$$surf_inorgN = 0 \quad \text{Equation 10-35} \quad 115$$

$$inf_sol_N = surf_inorgN \quad \text{Equation 10-36} \quad 115$$

$$inf_sol_N = \frac{D}{200} * (inf_sol_N) \quad \text{Equation 10-37} \quad 116$$

$$mnaN = mnaN + inf_sol_N \quad \text{Equation 10-38} \quad 116$$

$$surf_inorgN = surf_inorgN - inf_sol_N \quad \text{Equation 10-39} \quad 116$$

AnnAGNPS: Technical Descriptions

$$inorgN_i = inorgN_{t-1} + \frac{mnaN * 1000000}{conv} \quad \text{Equation 10-40} \quad 116$$

$$cell_soil_sol_N = edi * \frac{inorgN * conv}{D * 1000000} \quad \text{Equation 10-41} \quad 116$$

$$DN = \frac{inorgN * conv}{1000000} * (1 - \exp(-1.4 * F_t * orgC)), \quad F_w > 0.9 \quad \text{Equation 10-42} \quad 116$$

$$uptN = \frac{growth_N_uptake * (yield_wt) * N_uptake_harvest}{stage_length} * A_{cell} \quad \text{Equation 10-43} \quad 117$$

$$limited_uptN = 0.99 * \frac{inorgN * conv}{1000000} \quad \text{Equation 10-44} \quad 117$$

$$inorgN_{i+1} = inorgN_i + \frac{(hmnN - uptN - cell_soil_sol_N - DN) * 1000000}{conv} \quad \text{Equation 10-45} \quad 117$$

$$sol_N = cell_soil_sol_N + surf_sol_N \quad \text{Equation 10-46} \quad 118$$

$$N_Leaching = \frac{perc_loss}{SW - Wilting} * \frac{inorgN * conv}{1000000}, \quad perc_loss > 0 \quad \text{Equation 10-47} \quad 118$$

$$inorgN_t = inorgN_{t+1} - \frac{(N_Leaching) * 1000000}{conv} \quad \text{Equation 10-48} \quad 118$$

$$conv = D * 10 * 1000 * \rho_b * A_{cell} \quad \text{Equation 11-1} \quad 122$$

$$orgP_t = orgP_{t-1} - \frac{(resP + fer_orgP - hmnP - sed_orgP) * 1000000}{conv} \quad \text{Equation 11-2} \quad 123$$

$$resP = \frac{(res_decomp) * 0.5}{CPR_{harvest}} \quad \text{Equation 11-3} \quad 123$$

$$res_decomp = (surf_res) * (1 - \exp(-temp_f * (decomp_coeff))) * A_{cell} \quad \text{Equation 11-4} \quad 123$$

$$temp_f = \frac{3200 * ((T_{soil} + 8) ** 2) - (T_{soil} + 8) ** 4}{2560000}, \quad 0 < T_{soil} < 32 \quad temp_f = 1 \quad temp_f = 0$$

Equation

$$resP = \frac{(Res_decomp) * 0.5}{CPR} \quad \text{Equation 11-6} \quad 124$$

AnnAGNPS: Technical Descriptions

$$res_decomp = (surf_res) * (1 - \exp(-temp_f * (nonc_decomp_coeff))) * A_{cell}$$

Equation 11-7 124

$$res_subsP = \frac{(Res_decomp) * 0.5}{CPR}$$

Equation 11-8 124

$$res_decomp = (sub_res) * (1 - \exp(-temp_f * (nonc_decomp_coeff))) * A_{cell}$$

Equation 11-9 124

$$fer_orgP = (fer_app) * (frac_orgP) * A_{cell}$$

Equation 11-10 125

$$hmnP = CMN * frac * orgP * corr * \frac{conv}{1000000}$$

Equation 11-11 125

$$frac = 0.4 * \exp(-0.0277 * YC) + 0.1$$

Equation 11-12 125

$$F_t = \frac{T_l}{T_l + \exp(9.93 - 0.312 * T_l)}, \quad 0 < T_l < 100$$

$F_t = 0, T_l \leq 0$ Equation 11-13 126

$$F_t = MAX(F_t, 0.1)$$

Equation 11-14 126

$$F_w = \frac{SW}{f}$$

Equation 11-15 126

$$corr = \sqrt{F_t * F_w}$$

Equation 11-16 126

$$sed_orgP = frac_orgP_clay * (sed_part(1,1) + sed_part(1,2)) * 1000$$

Equation 11-17 126

$$frac_orgP_clay = \frac{orgP}{(frac_clay) * 1000000}$$

Equation 11-18 126

$$orgP_t = orgP_{t-1} - \frac{hmnP * 1000000}{conv}$$

Equation 11-19 126

$$mnaP = surf_inorgP$$

Equation 11-20 127

$$surf_inorgP = 0$$

Equation 11-21 127

$$mnaP = \frac{D}{200} * surf_inorgP$$

Equation 11-22 127

$$surf_inorgP = surf_inorgP - mnaP$$

Equation 11-23 127

$$inorgP_applied = (fer_app) * (frac_inorgP) * A_{cell}$$

Equation 11-24 127

$$mnaP = mnaP + inorgP_applied$$

Equation 11-25 128

AnnAGNPS: Technical Descriptions

$$mnaP = mnaP + \frac{D}{200} * inorgP_applied \quad \text{Equation 11-26} \quad 128$$

$$surf_inorgP = surf_inorgP + (1 - \frac{D}{200}) * inorgP_applied \quad \text{Equation 11-27} \quad 128$$

$$surf_inorgP = surf_inorgP + inorgP_applied \quad \text{Equation 11-28} \quad 128$$

$$surf_sol_P = \frac{Q}{(Q + inf)} * surf_inorgP \quad \text{Equation 11-29} \quad 128$$

$$inf_sol_P = surf_inorgP - surf_sol_P \quad \text{Equation 11-30} \quad 128$$

$$surf_sol_P = surf_sol_P + (1.0 - \frac{D}{200}) * (inf_sol_P) \quad \text{Equation 11-31} \quad 128$$

$$inf_sol_P = \frac{D}{200} * (inf_sol_P) \quad \text{Equation 11-32} \quad 128$$

$$surf_sol_P = surf_inorgP \quad \text{Equation 11-33} \quad 128$$

$$inf_sol_P = 0 \quad \text{Equation 11-34} \quad 128$$

$$mnaP = mnaP + inf_sol_P \quad \text{Equation 11-35} \quad 129$$

$$surf_inorgP = 0 \quad \text{Equation 11-36} \quad 129$$

$$inf_sol_P = surf_inorgP \quad \text{Equation 11-37} \quad 129$$

$$inf_sol_P = \frac{D}{200} * (inf_sol_P) \quad \text{Equation 11-38} \quad 129$$

$$mnaP = mnaP + inf_sol_P \quad \text{Equation 11-39} \quad 129$$

$$surf_inorgP = surf_inorgP - inf_sol_P \quad \text{Equation 11-40} \quad 129$$

$$mpr = 0.1 * \frac{SW}{f} * \exp(0.115 * T_{soil} - 2.88) * \left(\frac{start_labP - start_actP * \frac{Psp}{1 - Psp}}{1 - Psp} \right) \quad \text{Equation 11-41} \quad 130$$

$$Psp = 0.58 - 0.61 * CaCO_3 \quad \text{Equation 11-42} \quad 130$$

$$Psp = -0.047 * \ln(frac_clay * 100) + 0.0045 * start_labP - 5.3 * orgC + 0.39 \quad \text{Equation 11-43} \quad 130$$

$$Psp = 0.0045 * start_labP - 5.3 * orgC + 0.39 \quad \text{Equation 11-44} \quad 130$$

$$Psp = 0.0043 * sat + 0.0034 * start_labP + 0.11 * PH - 0.7 \quad \text{Equation 11-45} \quad 130$$

$$aspr = flow * (4 * start_actP - start_stbP) \quad \text{Equation 11-46} \quad 131$$

AnnAGNPS: Technical Descriptions

$flow = 0.00076$	Equation 11-47	131
$flow = \exp(-1.77 * Psp - 7.05)$	Equation 11-48	131
$aspr = start_actP$	Equation 11-49	131
$aspr = (-1) * start_stbP$	Equation 11-50	131
$labP = start_labP - mpr + \frac{Psp * mnaP * 1000000}{conv}$	Equation 11-51	131
$actP = start_actP + mpr + \frac{(1 - Psp) * mnaP * 1000000}{conv} - aspr$	Equation 11-52	131
$aspr = start_actP + mpr + \frac{(1 - Psp) * mnaP * 1000000}{conv}$	Equation 11-53	132
$stbP = start_stbP + aspr$	Equation 11-54	132
$total_inorgP = labP + actP + stbP$	Equation 11-55	132
$frac_labP = \frac{labP}{total_inorgP}$	Equation 11-56	132
$frac_actP = \frac{actP}{total_inorgP}$	Equation 11-57	132
$frac_stbP = \frac{stbP}{total_inorgP}$	Equation 11-58	132
$labP = labP + \frac{hmnP * frac_labP * 1000000}{conv}$	Equation 11-59	132
$actP = actP + \frac{hmnP * frac_actP * 1000000}{conv}$	Equation 11-60	132
$stbP = stbP + \frac{hmnP * frac_stbP * 1000000}{conv}$	Equation 11-61	132
$mplab = \frac{labP * conv}{1000000}$	Equation 11-62	132
$mpact = \frac{actP * conv}{1000000}$	Equation 11-63	132
$mpatb = \frac{stbP * conv}{1000000}$	Equation 11-64	132
$soil_sol_P = \frac{labP}{(1. + Kd_inorgP)}$	Equation 11-65	133
$cell_soil_sol_P = edi * \frac{soil_sol_P * conv}{D * 1000000}$	Equation 11-66	133

AnnAGNPS: Technical Descriptions

$labP = labP - \frac{cell_soil_sol_P * 1000000}{conv}$	Equation 11-67	133
$cell_clay_p_w = \frac{labP + actP + stbP}{(frac_clay) * 1000000}$	Equation 11-68	133
$sed_inorgP = cell_clay_p_w * (sed_part(1,1) + sed_part(1,2)) * 1000$	Equation 11-69	134
$labP = labP - \frac{sed_inorgP * frac_labP * 1000000}{conv}$	Equation 11-70	134
$actP = actP - \frac{sed_inorgP * frac_actP * 1000000}{conv}$	Equation 11-71	134
$stbP = stbP - \frac{sed_inorgP * frac_stbP * 1000000}{conv}$	Equation 11-72	134
$labP = labP - \frac{uptP * 1000000}{conv}$	Equation 11-73	134
$mplab = \frac{labP * conv}{1000000}$	Equation 11-74	134
$sol_P = cell_soil_sol_P + surf_sol_P$	Equation 11-75	134
$orgC = 0.58 * OMR$	Equation 12-1	136
$conv = D * 10 * 1000 * \rho_b * A_{cell}$	Equation 12-2	136
$orgC_t = orgC_{t-1} + \frac{(resC + fer_orgC - hmnC - sedC)}{conv}$	Equation 12-3	136
$\frac{C}{N_{layer-i}} = \frac{orgC_{layer-i} * 1000000}{orgN_{layer-i}}$	Equation 12-4	137
$hmnC_{layer-i} = \frac{C}{N_{layer-i}} * hmnN_{layer-i} * 0.5$	Equation 12-5	137
$resC = (res_decomp) * 0.5 * 0.5$	Equation 12-6	138
$res_decomp = (surf_res) * (1 - temp) * A_{cell}$	Equation 12-7	138
$temp_f = \frac{3200 * ((T_{soil} + 8) ** 2) - (T_{soil} + 8) ** 4}{2560000}, 0 < T_{soil} < 32$		$temp_f = 0, T_{soil} < 0$
$temp_f = 1, T_{soil} > 32$	Equation	12-8
		139
$resC = (res_decomp) * 0.5 * 0.5$	Equation 12-9	139

AnnAGNPS: Technical Descriptions

$$res_decomp = (surf_res) * (1 - \exp(temp)) * A_{cell} \quad \text{Equation 12-10} \quad 139$$

$$fer_orgC = (fer_app) * (frac_orgC) * A_{cell} \quad \text{Equation 12-11} \quad 140$$

$$sedC = 1000 * (orgC_{layer1t-1}) * clay_soil_{layer1} * clay_eroded \quad \text{Equation 12-12} \quad 140$$

$$V_i = V_{(i-1)} + Q_{inflow} - Q_{outflow} + P - ET - I \quad \text{Equation 13-1} \quad 142$$

$$Q_{inflow} = \frac{1000 * Q_{volume_inflow}}{A_{wetland}} \quad \text{Equation 13-2} \quad 143$$

$$Q_{volume_outflow} = B * L * H^a \quad \text{Equation 13-3} \quad 143$$

$$Q_{outflow} = \frac{1000 * Q_{volume_outflow}}{A_{wetland}} \quad \text{Equation 13-4} \quad 143$$

$$H = \frac{V}{1000} - H_{weir} \quad \text{Equation 13-5} \quad 144$$

$$M_i = M_{(i-1)} + M_{inflow} - M_{outflow} - S \quad \text{Equation 13-6} \quad 144$$

$$M_{outflow} = \frac{C_{outflow} * Q_{volume_outflow}}{1000} \quad \text{Equation 13-7} \quad 144$$

$$C = \frac{10^6 * M_{i-1}}{V_{i-1} * A_{wetland}} \quad \text{Equation 13-8} \quad 145$$

$$S = \frac{J * A_{wetland}}{1000} \quad \text{Equation 13-9} \quad 145$$

$$J = k_{20} * C * \theta^{(T-20)} \quad \text{Equation 13-10} \quad 145$$

$$TE = (M_i - M_o) / M_i = 1 - \frac{M_o}{M_i} = 1 - SDR \quad \text{Equation 14-1} \quad 149$$

$$TE_{ps} = 1 - aQ^b \quad \text{Equation 14-2} \quad 149$$

$$Q = Q_p * 60 / l_j \quad \text{Equation 14-3} \quad 150$$

$$TE_m = 0.6261 * (w_j) ** 0.127 \quad \text{Equation 14-4} \quad 152$$

$$TE_m = 0.6747 * (w_j) ** 0.06 \quad \text{Equation 14-5} \quad 152$$

$$TE_m = 0.5957 * (w_j) ** 0.1527 \quad \text{Equation 14-6} \quad 152$$

$$src_yld_aft(:) = src_yld_bfr(:) * (1.0 - TE_{ps}(:)) \quad \text{Equation 14-7} \quad 153$$

$$src_yld_aft(:) = src_yld_aft(:) * (1.0 - TE_m) \quad \text{Equation 14-8} \quad 153$$

$$TE_a(:) = 1 - src_yld_aft(:) / src_yld_bfr(:) \quad \text{Equation 14-9} \quad 153$$

AnnAGNPS: Technical Descriptions

$$src_yld_aft(\cdot) = src_yld_bfr(\cdot) * (1.0 - TE_a(\cdot)) \quad \text{Equation 14-10} \quad 153$$

$$TE_a = TE_m * TE_{ps} \quad \text{Equation 14-11} \quad 155$$

$$Reach_Load(\cdot) = Reach_Load(\cdot) * (1.0 - TE_a(\cdot)) \quad \text{Equation 14-12} \quad 156$$

LIST OF SYMBOLS

Uppercase Variables

Variable	Meaning	Unit
A	Average solar altitude	radians
A _H	Flow area for the hydraulics section	m ²
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	
A _{across}	Lateral flow across cell area	m ²
A _{cell}	Cell Area	m ²
A _s	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	
CaCO ₃	Concentration of CaCO ₃	
C ₁	Particle-size class constant for the effective transport factor	m
C ₂	Particle-size class constant for the effective transport factor for η= 1	Mg-s/m ⁴
C ₃	Particle-size class constant for the effective transport factor for η< 1	Mg-s/m ^{2.374}

AnnAGNPS: Technical Descriptions

Uppercase Variables

Variable	Meaning	Unit
C_s	Sediment concentration	(Mg-sediment)/(Mg-water)
C_x	Mixing coefficient	
CLAY	Clay content for a soil layer	
CMN	Humus rate constant	0.0003
CN ₁	Dry condition SCS curve number based on soil moisture storage	
CN ₂	SCS curve number for average conditions	
CN ₃	Wet condition SCS curve number based on soil moisture storage	
CNR _{harvest}	Ratio of Carbon to Nitrogen for crop at harvest	
CPR _{harvest}	Ratio of Carbon to Phosphorus for crop at harvest	
D	Thickness of the soil layer	mm
D _a	Total drainage area	ha
D _p	Equivalent sand size particle diameter	m
D _r	Total delivery ratio for all five particle-sized classes combined	
D _{SL1}	Thickness for the top soil layer	mm
D _{SL2}	Thickness for the second soil layer	mm
DN	Denitrification rate	kg
ET _P	Potential evapotranspiration	mm
F _a	Atmospheric correction factor	

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Uppercase Variables

Variable	Meaning	Unit
F_c	Cloud correction factor	
FC	Field capacity of a soil layer	
F_s	Sinuosity (assumed to be 1.25)	m/m
F_t	Temperature correction factor	
F_w	Water correction factor	
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 ²
H_v	Latent heat of vaporization	MJ/kg
I_a/P_{24}	Ratio of initial abstraction to 24-hour precipitation, including snowmelt	
I_a	Initial abstraction	
IFRZ	Frozen soil flag for a soil layer (1=frozen, 0=not frozen)	
J	Julian day of a year	
Kd_inorgP	Linear partitioning coefficient for inorganic phosphorus. It is the ratio of the mass of absorbed P to the mass of P in solution	
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
ΔL	Channel length of the reach segment for the in_stream processes	m

AnnAGNPS: Technical Descriptions

Uppercase Variables

Variable	Meaning	Unit
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	
N_leaching	leaching loss from soil layer	kg
NF	Nitrogen fraction of dry total biomass for non-crop field	weight of N/weight of biomass
NTS	Number of computational time steps per day for soil moisture calculations	
Perc	Percolation from top soil layer to the bottom layer	mm
Psp	P absorption coefficient for soil layer on current day	
P ₂	The 2-year return frequency, 24 hour duration precipitation	mm

AnnAGNPS: Technical Descriptions

Uppercase Variables

Variable	Meaning	Unit
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
S ₂	Retention parameter associated with CN ₂	mm

AnnAGNPS: Technical Descriptions

Uppercase Variables

Variable	Meaning	Unit
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 ³
SED_TOT	Total sediment loss	Mg
Soil_ET	Evapotranspiration from soil profile	mm
SM	Moisture content for a soil layer at the beginning of a time period	
SMCX	Maximum soil moisture content	mm
SW	Water content of soil layer on a given day	
T	Air temperature	°C
T_{soil}	Average cell soil temperature	°C
T_D	Dew point temperature	°C
T_K	Absolute temperature	°K
T_c	Time of concentration	hr

AnnAGNPS: Technical Descriptions

Uppercase Variables

Variable	Meaning	Unit
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
$T_{t,reach}$	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 ³
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 ³ /s
Q_c	Channel section discharge	m ³ /s
Q_f	Floodplain discharge	m ³ /s
Q_o	Average outflow discharge during a runoff event	m ³ /s
Q_p	Peak discharge	m ³ /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 ³ /s
Q_w	Water discharge	m ³ /s
U	Wind speed	m/s
U^*	Shear velocity at x_1	m/s

AnnAGNPS: Technical Descriptions

Uppercase Variables

Variable	Meaning	Unit
V	Velocity of flow at Q_t	m/s
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	
YC	Period of cultivation before the simulation starts	years
Z	Trapezoidal channel side slope	m/m
Z_e	Elevation	m

AnnAGNPS: Technical Descriptions

Lowercase Variables

Variable	Meaning	Unit
a, b	Input coefficient and exponent for the impoundment stage-storage relationship	
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	
actP	Active P	ppm
aspr	Flow rate of P between active and stable P pools for soil layer on current day	g/Mg/d
c, d	Input coefficient and exponent for the impoundment stage-storage relationship	
cell_clay_p_w	Concentration of inorganic P in clay fraction of cell soil layer	g/g
cell_soil_sol_N	Mass of inorganic N removed from top soil layer through runoff	kg
cell_soil_sol_P	Phosphate losses to runoff from composite soil layer	kg
conv	Intensive unit to extensive unit conversion factor	kg
corr	Corr_fact computes moisture/temperature correction factor used in N and P mineralization equations	
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?)
decomp_coeff	crop residue decomposition coefficient	unitless
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?)

AnnAGNPS: Technical Descriptions

Lowercase Variables

Variable	Meaning	Unit
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
edi	Effective depth of interaction factor	mm
f	Porosity for each soil layer	
flow	Soil type-dependent P flow coefficient for soil layer on current day	
frac_actP	Fraction of active P	Weight/Weight
frac_clay	Fraction of clay to total composite soil	Weight/Weight
frac_labP	Fraction of labile P	Weight/Weight
frac_inorgN	Fertilizer inorganic N fraction, from fertilizer reference database	Weight/Weight
frac_inorgP	Fertilizer inorganic P fraction, from fertilizer reference database	Weight/Weight
frac_orgP_clay	Decimal fraction of organic P in caly soil layer	g/g
frac_orgN_clay	Decimal fraction of organic N in caly soil layer	g/g
frac_orgN	Fertilizer fraction which is organic N, from fertilizer reference database	Weight/Weight
frac_orgP	Fertilizer fraction which is organic P, from fertilizer reference database	Weight/Weight

AnnAGNPS: Technical Descriptions

Lowercase Variables

Variable	Meaning	Unit
frac_stbP	Fraction stable P	Weight/Weight
fer_app	The rate of fertilizer applied for current day operation	kg/ha
fer_orgN	Organic N from fertilizer application such as manure or other sources	kg
fer_orgP	Organic P from fertilizer application such as manure or other sources	kg
g	Gravitational constant, 9.81 m/s ²	
h	Depth of saturation above the impervious layer	m
h _o	Permanent pool stage	m
h _s	Sunrise/sunset hour angle	Radians
hmnN	Mineralization rate from the humus active organic P pool in soil layer on current day	kg/d
hmnP	The mineralization rate from the humus active organic P pool	kg/d
i	First Gauss-Legendre time point	
inf	Infiltration occurred on current day	mm
inf_sol_N	Infiltrated soluble N	kg
inf_sol_P	Infiltrated soluble P	kg
inorgN	Amount of inorganic N in the cell soil composite layers	g/Mg
inorgP	Amount of inorganic P in the cell soil composite layers	g/Mg
inorgN_applied	Inorganic N from fertilizer application on current day	kg
inorgP_applied	Inorganic P from fertilizer application on current day	kg
k	Transport capacity factor	
labP	Amount of labile pool inorganic phosphorous in the composite cell's soil layer	g/Mg
m	Midpoint water table height above the drain	m
m _a	Optical air mass	

AnnAGNPS: Technical Descriptions

Lowercase Variables

Variable	Meaning	Unit
mnaN	Mass of inorganic N added to a cell from incorporated inorganic additions	kg
mnaP	Mass of inorganic P added to a cell from incorporated inorganic additions	kg
mpact	Mass of active P in cell soil layer	kg
mplab	Mass of labile P in cell soil layer	kg
mpstb	Mass of stable P in cell soil layer	kg
mpr	Flow rate of P between labile and active P pools for soil layer on current day	g/Mg/d
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	
nonc_decomp_ coeff	Noncrop surface residue decomposition coefficient	0.016
orgC	Amount of organic carbon in the cell soil composite layers	g/Mg
orgN	Amount of organic N in the cell soil composite layers	g/Mg
orgP	Amount of organic P in the cell soil composite layers	g/Mg
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 _η	Critical unit-width water discharge below which the effective transport factor (η) is 1 and above which it is calculated according to Equation 6-9	m ³ /s/m

AnnAGNPS: Technical Descriptions

Lowercase Variables

Variable	Meaning	Unit
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	$m^3/s/m$
r	Radius of the drain tube	m
res_decomp	Crop residue mass decomposition for current day	kg
res_subSN	Noncrop organic N addition from decomposed subsurface (below ground) residue	kg
res_subSP	Noncrop organic P addition from decomposed subsurface (below ground) residue	
resN	N addition from decomposition of crop and noncrop residue	kg
resP	Organic P addition to cell soil layer from decomposed fresh crop residue	kg
sat	Base saturation	
sed_inorgP	Current days mass of inorganic P attached to sediment	kg
sedN	Mass of nitrogen attached to sediment on current day	kg
sed_orgP	Current days mass of nitrogen attached to sediment	kg
sed_part	Current day's mass of sediment (by particle size and source) at edge of cell	
soil_sol_P	Concentration of soluble P in cell layer on current day, reflects inorganic P additions that are incorporated in top soil layer	g/Mg

AnnAGNPS: Technical Descriptions

Lowercase Variables

Variable	Meaning	Unit
Sol_N	Total mass of inorganic N lost in surface runoff	kg
Sol_P	Soluble P	
start_labP	Starting day's soil layers' labile pool of inorganic phosphorous	ppm
start_actP	Starting day's soil layers' active pool of inorganic phosphorous	ppm
start_stbP	Starting day's soil layers' stable pool of inorganic phosphorous	ppm
stbP	Stable P	ppm
sub_res	Noncrop subsurface residue for a cell which is computed from RUSLE module	kg/ha
surf_inorgN	Surface inorganic nitrogen for a cell, added through fertilization at the soil surface	kg
surf_inorgP	Surface inorganic phosphate for a cell, added through fertilization at the soil surface	kg
surf_res	Computed surface residue for a cell from RUSLE module	kg/ha
surf_sol_N	Mass of inorganic N in runoff from fertilizer applied on soil surface	kg
surf_sol_P	Mass of inorganic P in runoff from fertilizer applied on soil surface	kg
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 _η	Critical effective transport factor time	s
temp_f	RUSLE temperature correction factor for residue decomposition	unitless
uptN	From growth_stage subroutine. Call cell_growth stage subroutine to get this value.	kg
uptP	Mass of inorganic P taken up by the plant on current day	kg
V _f	Particle fall velocity	m/s
V _w	Flow velocity of water	m/s

AnnAGNPS: Technical Descriptions

Lowercase Variables

Variable	Meaning	Unit
w	Precipitable water content	
w _f	Gauss-Legendre weight	

Greek Letters

Symbols

Variable	Meaning	Unit
α	Total reflectivity of the ground	
α_c	A constant defined by Equation 5-63	
δ	Sun declination	Radians (?)
ε	Emissivity of the ground and vegetative surface	
ε_a	Atmospheric emissivity	
ϕ	latitude	radians
γ	Psychrometric constant	kPa/°C
γ_p	Particle density	Mg/m ³
γ_w	Water density, equal to 1.00	Mg/m ³
ρ_b	bulk density of composite soil layer	g/cc or tons/ m ³
η	Effective sediment transport factor	
κ	Von Karman's turbulent-flow mixing-length constant (can be assumed as 0.4)	
λ	Brooks-Corey (1964) parameter	
θ	Earth orbital position about the sun	radians
σ	Stefan-Boltzmann constant	W/m ² /K ⁴
τ	Bed shear stress	Mg/m ²

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AnnAGNPS: Technical Descriptions

Δ

Slope of saturation vapor pressure – temperature curve

kPa/°C

AnnAGNPS: Technical Descriptions

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) (Bingner and Theurer, 2001b), is available through the Internet WEB address:

<http://www.ars.usda.gov/Research/docs.htm?docid=5199>

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 Sream Network TEMPerature model (SNTTEMP) (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 Table 1-1 listing those responsible for the various subprojects.

Table 1-1 Former and Current Development subproject leaders of AnnAGNPS.

Subproject	Developer (s)
Chemical	Yongping Yuan and William Merkel

AnnAGNPS: Technical Descriptions

Subproject	Developer (s)
Calibrations (water, sediment, & nutrients)	Fred Theurer
Climate	Fred Theurer and, William Merkel, Dan Moore
Data Dictionaries	Fred Theurer and Glenn Herring
Dates and Days	Fred Theurer
Delivery Ratio	Fred Theurer
Error, Warning, & Information messages	Fred Theurer
Feedlot	Kevin Baker
Gullies	Fred TheurerKevin 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	Fred Theurer , William Merkel, and Roger Cronshey
Runoff Curve Numbers	David Garen and Fred Theurer
RUSLE	Frank Geter and George Foster
Sediment Distribution	Frank Geter and Roger Cronshey
Soil Composite	Fred Theurer
Soil Moisture	David Garen
Sorting	Glenn Herring
Storm Type (user-defined)	Fred Theurer
System (Cleanup)	Fred Theurer
System (Preparation)	Fred Theurer
System (Simulation)	Fred Theurer
Testing for Model Verification	Fred Theurer
Tile Drainage and Subsurface Flow	Yongping Yuan and Ron Bingner
Utilities	Fred Theurer and Glenn Herring
Winter Routines	Dan Moore 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

AnnAGNPS: Technical Descriptions

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. Each cell homogeneously represents the landscape within its respective land area boundary (Figure 1-2). 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 1-3). The data sections used for the continuous AnnAGNPS are integrated together through a relational database approach (Figure 1-4). The data sections used for the single-event version of AnnAGNPS are similarly used to describe the input parameters for the model simulation (Figure 1-5).

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 et al, 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).

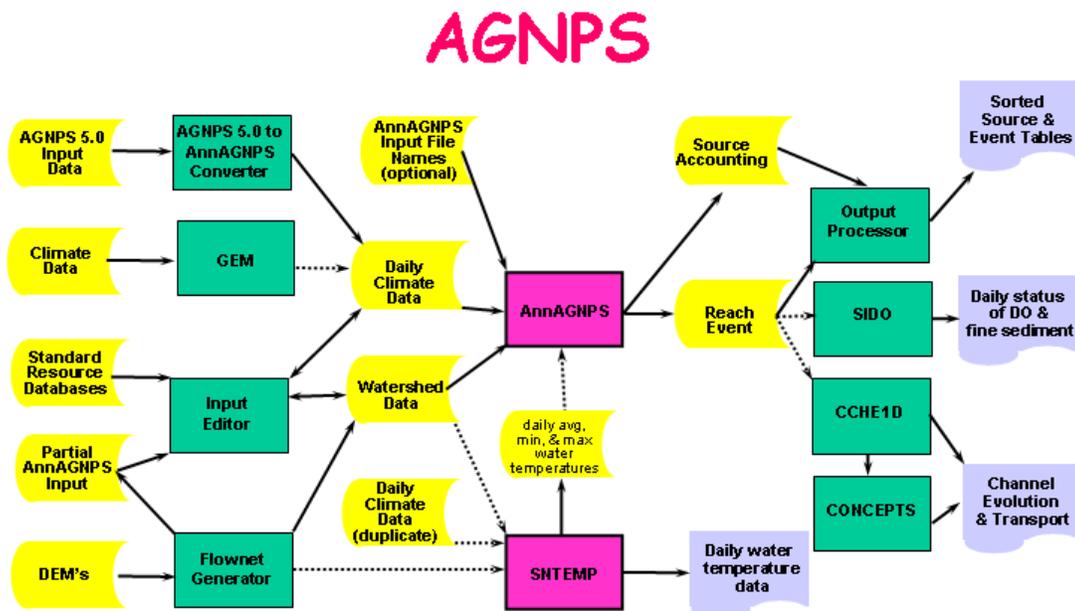
The soil moisture, nutrients, and pesticides are also tracked within each field and subsequent movement downstream. Soil databases developed by the NRCS are used to describe each cell or field. Crop information developed for RUSLE is also needed by AnnAGNPS, along with additional parameters that describe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

AnnAGNPS: Technical Descriptions

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, sediment and water quality processes within AnnAGNPS.

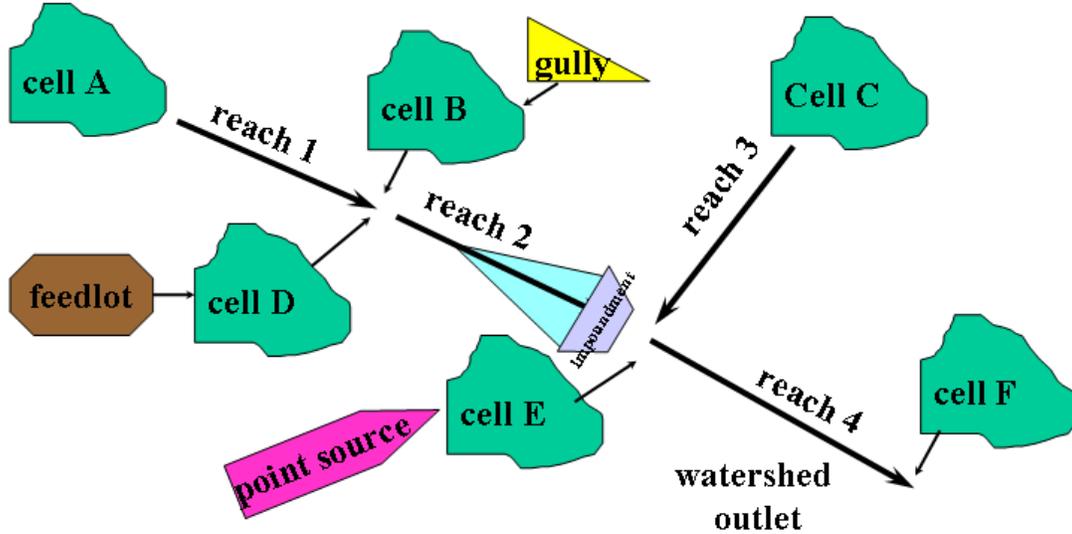


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5

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

AnnAGNPS: major processes

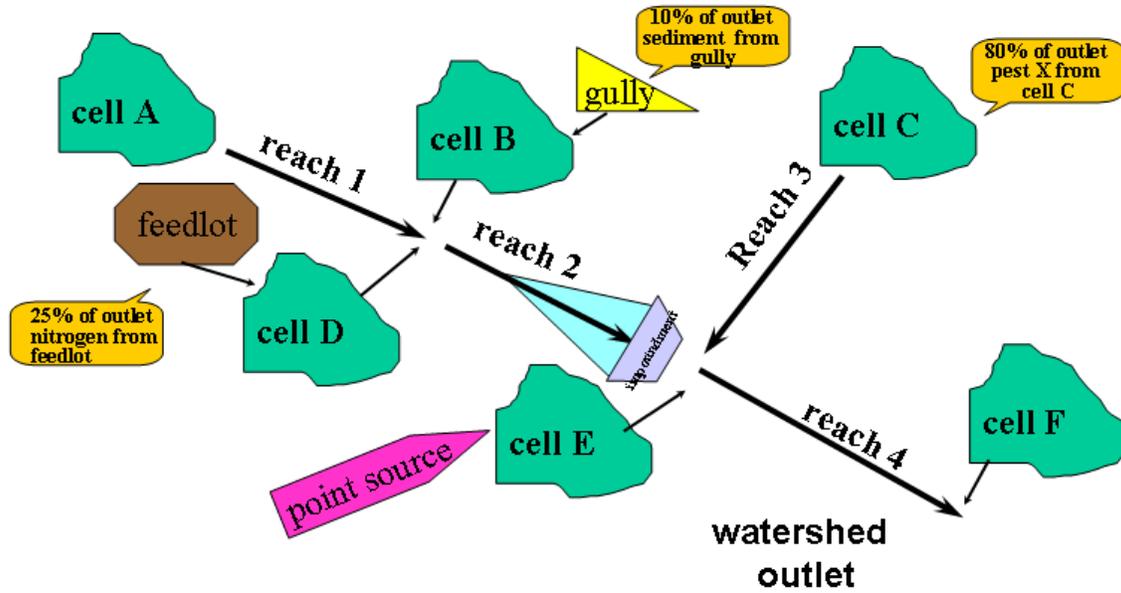


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10

Figure 1-2. Major processes simulated within AnnAGNPS.

AnnAGNPS: source accounting



8/13/01

24

Figure 1-3. Built into AnnAGNPS is the capability to track pollutants using source accounting techniques.

AnnAGNPS: Technical Descriptions

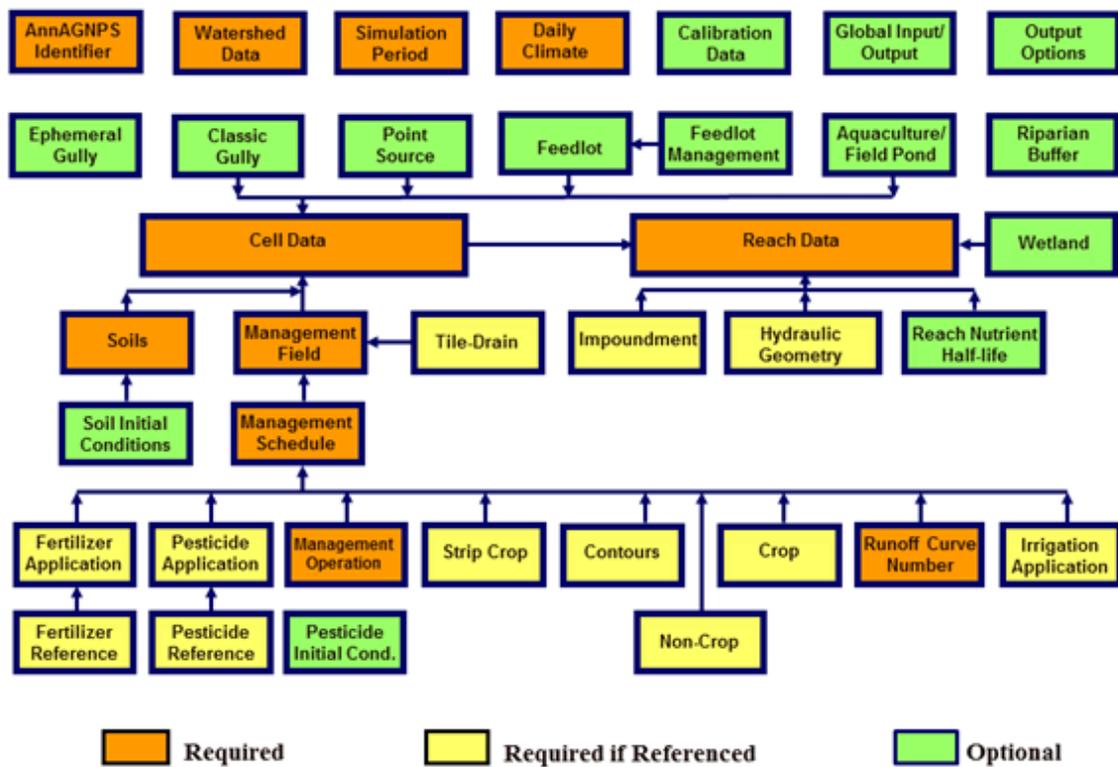


Figure 1-4. Flowchart showing the relational integration of the data sections used within the continuous AnnAGNPS. The orange boxes indicate required data sections.

2. CLIMATE

2.1 CLIMATE DATASET(S)

AnnAGNPS expects a serially complete, daily weather dataset as a primary climate dataset that includes the first day of the requested simulation period through the last day of the simulation period. Secondary climate files may be assigned to a cell or any number of cells. There may be as many secondary climate files as there are cells. These secondary climate files do not have to be either serially complete nor include any particular day within the simulation period. When any particular parameter is missing from any of the secondary climate files, AnnAGNPS will default to the primary climate file but corrects for elevation differences when appropriate. For example, the adiabatic release rate correction is used for air temperature default calculations.

2.1.1 Daily Weather Parameters

The six daily weather parameters needed for AnnAGNPS is : (1) minimum air temperature; (2) maximum air temperature; (3) precipitation; (4) dew point; (5) sky cover; and (6) wind speed. While the various climate datasets may explicitly show the sky cover weather parameter in the climate file, an alterante parameter may be substituted; i.e., solar radiation at the ground. If solar radition is shown, then it is used to calculate sky cover regardless of whether sky cover was given for that day.

AnnAGNPS: Technical Descriptions

2.1.2 Storm Types

Various rainfall distributions can occur for a particular hydro-geomorphic region but generally can be synthesized into a single dominate rainfall distribution that represents the region for the entire simulation period. The storm type's rainfall distribution is used to determine the day's rainfall maximum 30-minute intensity used to calculate the sheet & rills erosion, and also the peak discharge associated with the runoff at any location in the watershed.

A single storm type is specified, at least by default, for the entire simulation period & watershed. However, different storm types may be specified daily, seasonally, or any combination for any combination of the primary or secondary climate files.

There are nine distinct storm types available internally. The first four are the standard SCS/NRCS rainfall distributions; i.e., the: (1) Type I; (2) Type IA; (3) Type II; and (4) Type III. The fifth is a uniform distribution meant to be used when snowmelt and/or irrigation is the dominate form of runoff. The last four are the special rainfall distributions associated with certain runoff/rainfall ratios and are for 60, 65, 70, & 75 percent runoff to rainfall.

The user can add as many new storm type (rainfall distributions) as desired. Each storm type has an associated unit peak discharge regression coefficients. If these associated coefficients are not available, the Type II coefficients are automatically substituted.

2.2 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.

2.2.1 Rainfall

Rainfall is that portion of the precipitation that falls directly from the sky in a liquid form. Irrigation, particularly sprinkler irrigation, is treated as rainfall. Open ended furrow irrigation and surge irrigation are considered part of precipitation added to a field, but not as rainfall.

2.2.2 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.

2.2.3 Variation of precipitation with cell elevation

Precipitation from rainfall or snowfall 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,

AnnAGNPS: Technical Descriptions

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.

2.2.4 Frequency

2.2.4.1 [Precipitation \(Gumbel Distribution\)](#)

The Gumbel distribution is used to determine the 2 year–24 hour precipitation when there is 10 years or more of climate data available in the climate file for AnnAGNPS.

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.

AnnAGNPS: Technical Descriptions

Procedure:

Table 2-1: Definitions for Gumble Distribution

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

$N_{yr} = 0$
 (i) for each day in record
 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
 (j) for 1 to N_{yr}
 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.

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

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

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

5. Determine Gumble distribution fitting parameters: central tendency (mode) (μ) and dispersion (α)

$\alpha = 1.282 / S$
 $\mu = X - 0.577 / \alpha$

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

Loop (i) for 1 to number of frequencies
 $P_x(i) = \mu + \omega(i) / \alpha$

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

Symbol	Definition	Units
α	Gumble distribution dispersion parameter	
μ	Gumble distribution central tendency parameter (mode).	
$\omega()$	Gumble 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_{yr}	Number of complete years in the precipitation record	
$P_x()$	X-yr precipitation based on Gumble 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
$Values_{hi}()$	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

Loop If

Loop If

Loop

Loop

daily

AnnAGNPS: Technical Descriptions

Table 2-2 variate values were derived from the relationship :

$$p = 1 - e^{-e^{-\omega}} \quad \text{Equation 2-1}$$

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

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 irrigated w/open ends
- furrow, adjacent irrigated w/blocked ends
- furrow, alternate irrigated 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, 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.

Table 2-2: Precalculated Probability—variatevValues

Return Period	Probability	Variate (ω)
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

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

AnnAGNPS: Technical Descriptions

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 generally should not exceed 0.90, with general ranges being 0.65 to 0.85 recovery efficiencies.

3.5 Automatic Irrigation Method

Each irrigation method can be applied automatically by defining upper and lower soil moisture depletion limits at the defined application rate of inches or millimeters applied in a 24-hour period. The soil moisture depletion upper limit defines when automatic irrigation is scheduled to stop. This upper limit is the soil column's available soil moisture at this associated highest controlable level divided by the soil column's available soil moisture at field capacity. Automatic irrigation will also stop when soil moisture is at field capacity (an upper depletion limit of 1.0), which is the default if no entry for upper depletion limit is provided. The soil moisture depletion lower limit defines when automatic irrigation scheduling is to begin. This lower limit is the soil column's available soil moisture at this associated lowest allowable level divided by the soil column's available soil moisture at field capacity. Available soil moisture is defined to be the difference between the associated soil moisture less the soil moisture at the wilting point. The depletion lower limit at the wilting point results in a value of 0.0. Automatic irrigation requires that the irrigation season's 'Irrigation End Date' be defined when irrigation will no longer be applied to the field, as well as the start date defined as an event in the management schedule data section assigned to an AnnAGNPS cell.

3.6 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

$$SED_TOT = SED_RATE \bullet R_E \bullet A_{cell} \quad \text{Equation 3-3-1}$$

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. HISTORICAL CLIMATE FOR ANNAGNPS

Historical weather is crucial to be able to calibrate and/or validate because it is necessary to match the driving forces with the resulting streamflow and pollutant loadings. Synthetic weather can only be used to assist with calibrating the average annual values of many particular load, but only if the assumption that the synthetic weather closely matches the historical weather for the simulation period. If the historical climate is sufficiently long (sometimes as little as 30 years, but more than fifty years would be better) and there is no indication that there is a change in the climate, then it should be used for scenario analyses.

5. SYNTHETIC WEATHER GENERATORS FOR ANNAGNPS

While a daily climate dataset derived from a synthetic weather generator should not be used for calibration/validation, they can be a valuable tool to simulate various scenarios when a sufficiently long period of historical data is not available to represent the watershed. However, the synthetic weather generated must match the statistics of the expected weather for the near future to have a valid interpretation.

Four synthetic weather generators have been developed by ARS—three published and one yet unpublished. They are: (1) CLimate GENerator (CLIGEN); (2) Generation of weather Elements for Multiple applications GEM); (3) the more recent version of GEM (GEM6); and (4) SYNTOR, named after a helper of Zeus, a Greek god. All synthetic weather generators are being evaluated currently to determine their ability to reproduce the statistics of their historical data.

AnnAGNPS: Technical Descriptions

When synthetic weather is chosen to represent the climate for a continuous-simulation analysis, CLIGEN is utilized for most ARS computer model simulations. However, previous evaluations done in the 1980's under the direction of SCS, indicated that GEM and its successor GEM6 performed better in reproducing its historical statistics, but still not well enough to be considered acceptable. SYNTOR is a recent addition to the ARS synthetic weather generators. It was developed to assist global climate change research.

GEM 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, but only for scenario simulations—not calibration/validation purposes. 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).

GEM6 generators all the weather parameters needed for AnnAGNPS, so the **Complete_Climate** program is not needed. However, it includes only 1st-order weather stations so has less historical sites available and GEM6 does not interpolate between locations.

SYNTOR has to be evaluated before any recommendations can be offered.

6. 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.

$$SM_{t+1} = SM_t + \frac{WI_t - Q_t - PERC_t - ET_t - Q_{lat} - Q_{tile}}{Z} \quad \text{Equation 6-1}$$

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),

AnnAGNPS: Technical Descriptions

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.

6.1 Surface Runoff

6.1.1 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.

6.1.1.1 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)

AnnAGNPS: Technical Descriptions

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

γ = 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:

$$FCMWP = FC - WP \quad \text{Equation 6-2}$$

$$POMWP = f - WP \quad \text{Equation 6-3}$$

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:

$$KSAT_DT = \frac{KSAT}{NTS} \quad \text{Equation 6-4}$$

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 λ parameter as:

$$\begin{aligned} \ln(\lambda) = & -0.7842831 + (1.77544 \cdot SAND) - (1.062498 \cdot f) - (0.5304 \cdot SAND^2) - (27.3493 \cdot CLAY^2) \\ & + (1.11134946 \cdot f^2) - (3.088295 \cdot SAND \cdot f) + (2.6587 \cdot SAND^2 \cdot f^2) - (61.0522 \cdot CLAY^2 \cdot f^2) \\ & - (2.35 \cdot SAND^2 \cdot CLAY) + (79.8746 \cdot CLAY^2 \cdot f) - (0.674491 \cdot f^2 \cdot CLAY) \end{aligned} \quad \text{Equation 6-5}$$

The final value of the exponent is calculated as

$$BC_EXP = 3 + \frac{2}{\lambda} \quad \text{Equation 6-6}$$

At low soil moisture contents, K_DT becomes a very small number, which can cause numerical problems. 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 1×10^{-10} mm per time step and solving the K_DT equation for SMMWP, which is actual soil moisture minus wilting point. The calculation is:

$$MIN_SMMWP = POMWP \left(\frac{0.0000000001}{KSAT_DT} \right)^{(1/BC_EXP)} \quad \text{Equation 6-7}$$

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,

AnnAGNPS: Technical Descriptions

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

Equation 6-8

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 6-9

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 6-10

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 6-11

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

$$AVAIL_H2O = D_{SL1} FCMWP(1) + (D_{SL2} - D_{SL1}) FCMWP(2)$$

Equation 6-12

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:

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

Equation 6-13

The quantity in parentheses is an estimate of barometric pressure.

6.1.1.2 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:

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

Equation 6-14

OR

$$CN_1 = 0.4 CN_2$$

Equation 6-15

whichever is greater, and

AnnAGNPS: Technical Descriptions

$$CN_3 = CN_2 \exp[0.00673(100 - CN_2)]$$

Equation 6-16

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

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

Equation 6-17

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 6-18

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

Equation 6-19

Where:

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.

6.1.1.3 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

AnnAGNPS: Technical Descriptions

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.

6.1.2 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:

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

Equation 6-20

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:

AnnAGNPS: Technical Descriptions

$$S_t = S_1 \left(1 - \frac{FS_t}{FS_t + \exp(W_1 - W_2 FS_t)} \right) \quad \text{Equation 6-21}$$

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

$$FS_t = \frac{FSDEPTH(1)(SM(1)_t - WP(1)) + FSDEPTH(2)(SM(2)_t - WP(2))}{FSDEPTH(1)(FC(1) - WP(1)) + FSDEPTH(2)(FC(2) - WP(2))} \quad \text{Equation 6-22}$$

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° isotherm at a depth of zero), S is given the value of S_3 . If the shallowest 0° 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° isotherm.

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

$$Q = \frac{(WI - 0.2 S)^2}{WI + 0.8 S} \quad \text{Equation 6-23}$$

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.

6.2 POTENTIAL EVAPOTRANSPIRATION

6.2.1 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

AnnAGNPS: Technical Descriptions

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:

$$F_a = \frac{a'' + \left(\frac{1 - a' - d_{sr}}{2} \right)}{1 - \alpha \left(\frac{1 - a' + d_{sr}}{2} \right)} \quad \text{Equation 6-24}$$

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)
- α = total reflectivity of the ground (decimal)

The two transmission coefficients are calculated as:

$$a' = \exp\left\{-m_a(0.465 + 0.134w)\left[0.129 + 0.171\exp(-0.880m_a)\right]\right\} \quad \text{Equation 6-25}$$

$$a'' = \exp\left\{-m_a(0.465 + 0.134w)\left[0.179 + 0.421\exp(-0.721m_a)\right]\right\} \quad \text{Equation 6-26}$$

Where:

- w = precipitable water content (cm)
- m_a = optical air mass (decimal)

The precipitable water content is calculated as:

$$w = 0.85 \exp(0.110 + 0.0614T_D) \quad \text{Equation 6-27}$$

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:

AnnAGNPS: Technical Descriptions

$$F_a = 0.75 + 0.0002Z_e \quad \text{Equation 6-28}$$

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:

$$F_c = 0.22 + 0.78 \left(\frac{S}{S_o} \right)^{2/3} \quad \text{Equation 6-29}$$

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:

$$F_c = 0.35 + 0.61 \left(\frac{S}{S_o} \right)^{2/3} \quad \text{Equation 6-30}$$

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

$$R_{SI} = F_a F_c R_X \quad \text{Equation 6-31}$$

where

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

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

$$R_{SI} = \left[0.19 + 0.55 \left(\frac{S}{S_o} \right) \right] R_X \quad \text{Equation 6-32}$$

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 α of the surface:

$$R_{SR} = \alpha R_{SI} \quad \text{Equation 6-33}$$

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

$$R_{SN} = (1 - \alpha) F_a F_c R_X \quad \text{Equation 6-34}$$

Long Wave Radiation:

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

AnnAGNPS: Technical Descriptions

$$R_L = \varepsilon \sigma T_K^4 \quad \text{Equation 6-35}$$

where R_L = emitted long-wave radiation, ε = emissivity (fraction, 0.0 - 1.0), σ = 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 ε_a is commonly used (USFWS, 1984, Eq. II.62; DVWK, 1995, Eq. 5.14; ASCE, 1996, Eq. 4.32):

$$\varepsilon_a = a + b\sqrt{e} \quad \text{Equation 6-36}$$

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:

$$e = 6.11 \exp\left(\frac{17.62 T_D}{243.12 + T_D}\right) \quad \text{Equation 6-37}$$

for air temperatures above 0°, and

$$e = 6.11 \exp\left(\frac{22.46 T_D}{272.62 + T_D}\right) \quad \text{Equation 6-38}$$

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):

AnnAGNPS: Technical Descriptions

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

Equation 6-39

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 6-40

USFWS:

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

Equation 6-41

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 6-42

where ε = 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

AnnAGNPS: Technical Descriptions

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 ϵ , 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 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:

$$R_N = R_{SN} + R_{LN} \quad \text{Equation 6-43}$$

where

R_N = net radiation (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 W m^{-2} using an albedo of 0.2.

Within AnnAGNPS, all radiation terms are calculated using units of 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.

6.2.2 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 W m^{-2} (Linacre, 1992; ASCE, 1996).

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

AnnAGNPS: Technical Descriptions

$$R_x = \frac{S_c}{\pi} d_r (h_s \sin \phi \sin \delta + \sin h_s \cos \phi \cos \delta) \quad \text{Equation 6-44}$$

where S_c = solar constant, d_r = relative distance of the earth from the sun, h_s = sunrise/sunset hour angle, ϕ = latitude (radians), and δ = 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):

$$d_r = \left(\frac{\bar{d}}{d_{es}} \right)^2 \quad \text{Equation 6-45}$$

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):

$$d_r = \frac{(1 + e_o \cos \theta)^2}{(1 - e_o^2)} \quad \text{Equation 6-46}$$

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

$$\theta = \frac{2\pi}{365} (J - 2) \quad \text{Equation 6-47}$$

where J = Julian day.

ASCE (1996, Eq. 4.22):

$$d_r = 1 + 0.033 \cos \left(\frac{2\pi}{365} J \right) \quad \text{Equation 6-48}$$

These three methods were compared, using values of d_r 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):

$$h_s = \arccos(-\tan \phi \tan \delta) \quad \text{Equation 6-49}$$

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

$$\delta = 0.40928 \cos \left[\left(\frac{2\pi}{365} \right) (172 - J) \right] \quad \text{Equation 6-50}$$

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

Optical Air Mass:

AnnAGNPS: Technical Descriptions

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):

$$A = \arcsin \left\{ \left(\sin \phi \sin \delta \right) + \left[\cos \phi \cos \delta \cos \left(\frac{h_s}{2} \right) \right] \right\} \quad \text{Equation 6-51}$$

where ϕ = latitude, δ = 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):

$$m_a = \frac{\left(\frac{288 - 0.0065Z_e}{288} \right)^{5.256}}{\sin A + 0.15 \left[\left(\frac{180}{\pi} \right) A + 3.885 \right]^{-1.253}} \quad \text{Equation 6-52}$$

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.

6.2.3 Determination of Potential Evapotranspiration

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

$$ET_p = \frac{1}{H_v} \left[\left(\frac{\Delta}{\Delta + \gamma} \right) (R - G) + \left(\frac{\gamma}{\Delta + \gamma} \right) W (e_{sat} - e) \right] \quad \text{Equation 6-53}$$

where:

ET_p = potential evapotranspiration (mm)

H_v = latent heat of vaporization (MJ/kg)

Δ = slope of saturation vapor pressure-temperature curve (kPa/°C)

γ = psychrometric constant (kPa/°C)

R = net radiation (MJ/m²)

G = soil heat flux (MJ/m²)

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:

AnnAGNPS: Technical Descriptions

$$H_v = 2.501 - 0.0022 T$$

Equation 6-54

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 6-55

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

$$e = RH e_{sat}$$

Equation 6-56

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 6-57

The psychrometric constant is calculated as:

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

Equation 6-58

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:

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

Equation 6-59

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):

$$W = 6.43 + 3.4079U$$

Equation 6-60

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.

AnnAGNPS: Technical Descriptions

6.3 FAO ENHANCEMENT FOR CALCULATING EVAPOTRANSPIRATION, ET_c, WITHIN AnnAGNPS

The FAO (Allen et al., 1998) dual crop coefficient procedure for determining the daily impact of vegetation transpiration (K_{cb}) and soil evaporation (K_e) on evapotranspiration (ET_c) provides a key component that would include the capability to determine management effects on ET within AnnAGNPS. The effect of crop and residue cover on ET would be included as part of this enhancement to AnnAGNPS. Currently within AnnAGNPS, the only management effect on ET occurs as a result of what effects soil moisture. Since soil moisture will limit the amount of ET that can occur. This enhancement will continue to include soil moisture effects, but will now include how cover management affects in the field can affect ET. Cover on a field includes canopy cover as well as cover from residue. Thus, conservation systems with residue management practices like no-till systems could provide more cover conditions resulting in less ET than the existing approach within AnnAGNPS. The effects of only partially wetting the surface from irrigation (furrow and sprinkler) will also be incorporated into AnnAGNPS.

Adjusting ET determined by the current Penman-Monteith equation, as determined within AnnAGNPS (ET_o), with the dual crop coefficient ($K_{cb} + K_e$) provides an improved approach to account for these transpiration and soil moisture losses. The determination of ET_o will remain the same within AnnAGNPS, but will be adjusted by K_{cb} and K_e . The actual evapotranspiration will remain dependent on the available soil moisture needed to meet the demand of the ET_o . Currently within AnnAGNPS, the crop coefficient is assumed to equal one. The calculation procedure incorporating the FAO procedure into AnnAGNPS is described in this document.

AnnAGNPS: Technical Descriptions

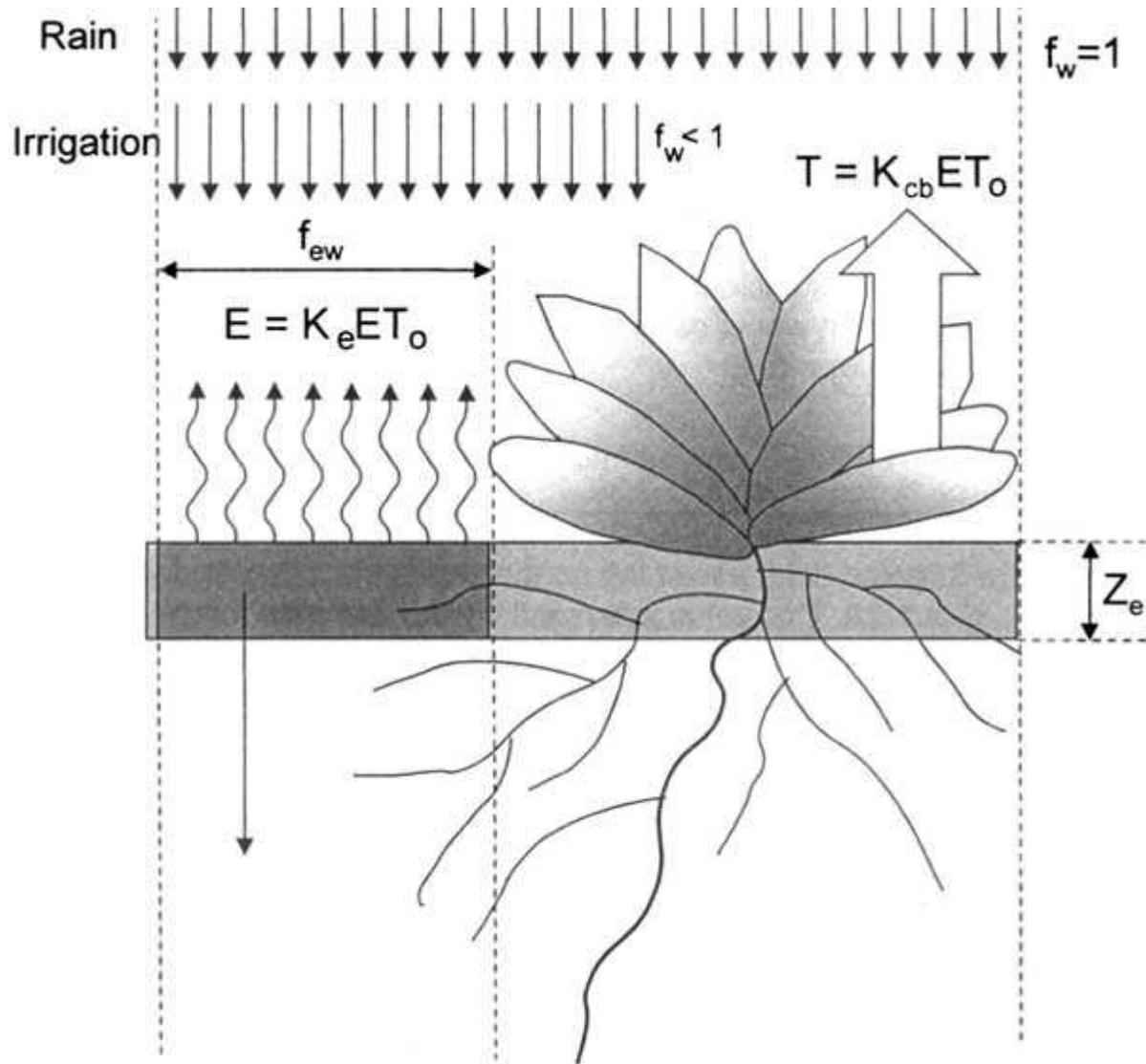


Figure 6-1. Transpiration, T , and evaporation, E , comprise the total evapotranspiration from a field. The soil surface under the canopy is not part of the soil evaporative surface, since that is included in the transpiration component. Soil evaporation is only assumed to occur in the fraction of surface where most of the evaporation occurs, f_{ew} , and is only associated with the top layer, Z_e . The fraction of the surface wetted by precipitation or irrigation is f_w . (Allen et al., 1998)

6.3.1 Reference evapotranspiration, ET_o :

Estimate ET_o : the procedure is given in FAO Chapter 4 and determined by AnnAGNPS in the Potential_ET subroutine.

AnnAGNPS: Technical Descriptions

6.3.2 Growth stages:

According to FAO, as the crop develops, the ground cover, crop height and the leaf area change. Due to differences in evapotranspiration during the various growth stages, the K_c for a given crop will vary over the growing period. The value of K_c for each growing period will also reflect the amount of crop cover during each growing period. The value for K_c will include directly the effect of canopy cover and residue cover during any period. The growing period can be divided into four distinct growth stages: initial, crop development, mid-season and late season. Typical length and start of the growth stages are described in FAO, Table 11. Current AnnAGNPS Crop Data 'Growth Time' input parameters can be associated with the four FAO growth stages as AnnAGNPS defined Initial, Dev., Mature, and Senescence growth stages.

- A. Initial growth stage: L_{ini} . The initial stage runs from planting date to approximately 10% ground cover. The length of the initial period is highly dependent on the crop, the crop variety, the planting date and the climate. The end of the initial period is determined as the time when approximately 10% of the ground surface is covered by green vegetation. For perennial crops, the planting date is replaced by the 'greenup' date, i.e., the time when the initiation of new leaves occurs. During the initial period, the leaf area is small, and evapotranspiration is predominately in the form of soil evaporation. Therefore, the K_c during the initial period ($K_{c\ ini}$) is large when the soil is wet from irrigation and rainfall and is low when the soil surface is dry. The time for the soil surface to dry is determined by the time interval between wetting events, the evaporation power of the atmosphere (ET_o) and the importance of the wetting event.
- B. Crop development stage: L_{dev} . The crop development stage runs from 10% ground cover to effective full cover. Effective full cover for many crops occurs at the initiation of flowering. For row crops where rows commonly interlock leaves such as beans, sugar beets, potatoes and corn, effective cover can be defined as the time when some leaves of plants in adjacent rows begin to intermingle so that soil shading becomes nearly complete, or when plants reach nearly full size if no intermingling occurs. For some crops, especially those taller than 0.5 m, the average fraction of the ground surface covered by vegetation (f_c) at the start of effective full cover is about 0.7-0.8. Fractions of sunlit and shaded soil and leaves do not change significantly with further growth of the crop beyond $f_c \approx 0.7$ to 0.8. It is understood that the crop or plant can continue to grow in both height and leaf area after the time of effective full cover.
- C. Mid-season stage: L_{mid} . The mid-season stage runs from effective full cover to the start of maturity. The start of maturity is often indicated by the beginning of the ageing, yellowing or senescence of leaves, leaf drop, or the browning of fruit to the degree that the crop evapotranspiration is reduced relative to the reference ET_o . The midseason stage is the longest stage for perennials and for many annuals, but it may be relatively short for vegetable crops that are harvested fresh for their green vegetation. At the mid-season stage the K_c reaches its maximum value. The value for K_c ($K_{c\ mid}$) is relatively constant for most growing and cultural conditions. Deviation of the $K_{c\ mid}$ from the reference value '1' is primarily due to differences in crop height and resistance between the grass reference surface and the agricultural crop and weather conditions.
- D. Late season stage: L_{late} . The late season stage runs from the start of maturity to harvest or full senescence. The calculation for K_c and ET_c is presumed to end when the crop is harvested, dries out naturally, reaches full senescence, or experiences leaf drop. For some perennial vegetation in frost free climates, crops may grow year round so that the date of termination may be taken as the same as the date of 'planting'. The K_c value at the end of the late season stage ($K_{c\ end}$) reflects crop and water management practices. The $K_{c\ end}$ value is high if the crop is frequently irrigated until harvested fresh. If the crop is allowed to senesce and to dry out in the field before harvest, the $K_{c\ end}$ value will be small. Senescence is usually associated with less efficient stomatal conductance of leaf surfaces due to the effects of ageing, thereby causing a reduction in K_c .

6.3.3 Basal crop coefficient, K_{cb}

The basal crop coefficient (K_{cb}) is defined by FAO as the ratio of the crop evapotranspiration over the reference evapotranspiration (ET_c/ET_o) when the soil surface is dry but transpiration is occurring at a potential rate, i.e., water is not limiting transpiration. This represents the transpiration component of ET_c and includes a residual diffusive evaporation component supplied by soil water below the dry surface and by soil water from beneath dense vegetation.

AnnAGNPS: Technical Descriptions

Basal crop coefficients for each day of the growing period can be determined using the procedures described below:

- A. Select $K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$ from FAO, Table 17 and use as AnnAGNPS input parameters associated with initial, mature, and senescence entered in the crop data section or associated with an average K_{cb} , with the start of growth date and length of growing season in the non-crop data section. For non-crop data, the average K_{cb} , can be used similarly as $K_{cb\ mid}$;

- B. Determine the daily $K_{cb(Tab)}$ values during the growth stages. First adjust the $K_{cb(Tab)}$ coefficient for any period of the growing season by considering that during the initial and mid-season stages K_{cb} is constant and equal to the $K_{cb(Tab)}$ value of the growth stage under consideration (Figure 1). During the crop development stage, daily $K_{cb(Tab)}$ values vary linearly between the $K_{cb\ ini(Tab)}$ and $K_{cb\ mid(Tab)}$ and during the late season stage $K_{cb(Tab)}$ varies linearly between the $K_{cb\ mid(Tab)}$ and $K_{cb\ end(Tab)}$. For non-crops, $K_{cb(Tab)}$, will always be the user entered value during the growing season and no adjustment for growth stage is needed. In summary,
 - 1.) initial growth stage: $K_{cb(Tab)} = K_{cb(Tab)\ ini}$,
 - 2.) crop development stage: from $K_{cb(Tab)\ ini}$ to $K_{cb(Tab)\ mid}$, adjust linearly,
 - 3.) mid-season or mature stage: $K_{cb(Tab)} = K_{cb(Tab)\ mid}$,
 - 4.) late season or senescence stage: from $K_{cb(Tab)\ mid}$ to $K_{cb(Tab)\ end}$, adjust linearly.

AnnAGNPS: Technical Descriptions

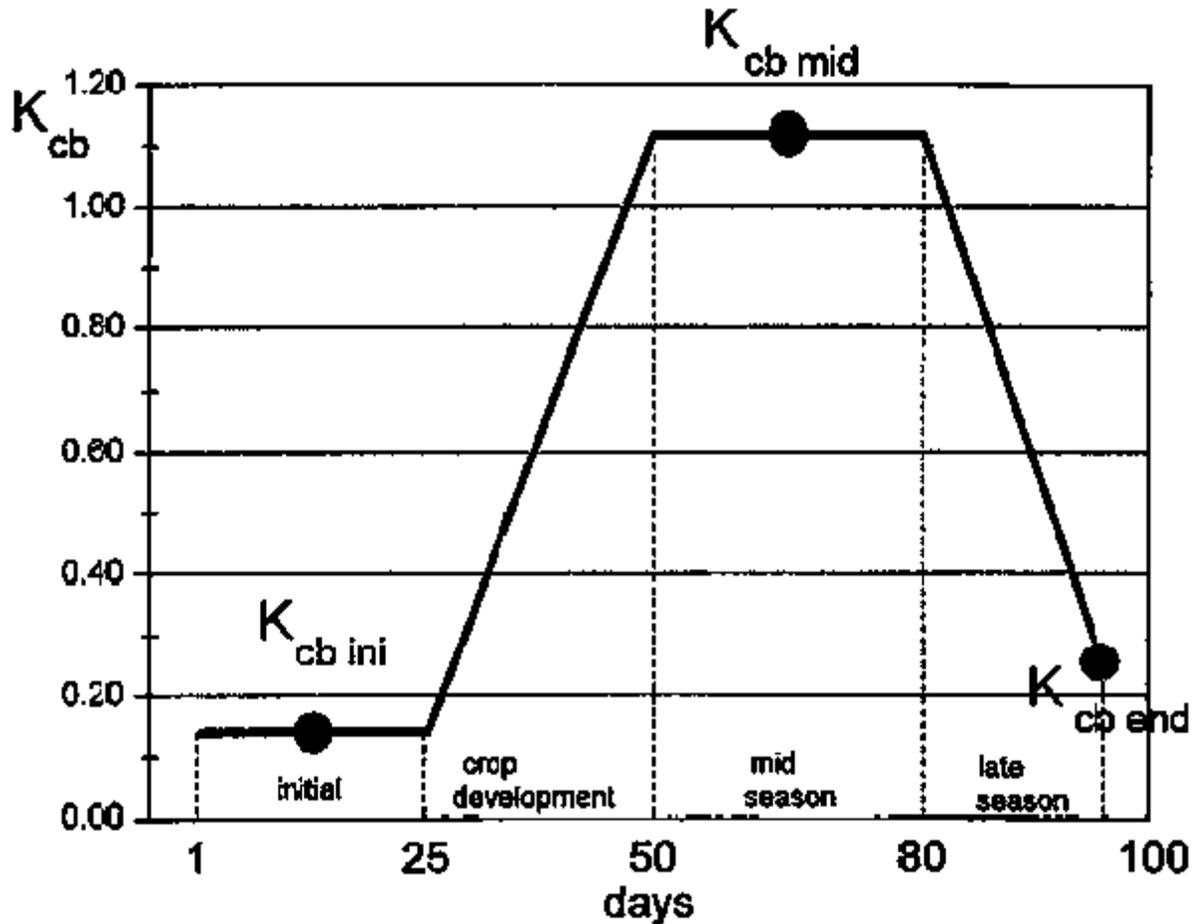


Figure 6-2.. Constructed basal crop coefficient (K_{cb}) curve for a dry bean crop using example growth stage lengths of $L_{ini}=25$, $L_{dev}=25$, $L_{mid}=30$ and $L_{late} =20$ days. For this example, L_{late} associated with $K_{cb\ end}$ should extend to 100. (FAO, Figure 37).

- C. Adjust $K_{cb\ mid}$ and $K_{cb\ end}$ to the local climatic conditions for crops and $K_{cb(Tab)}$ for non-crops (FAO, Equation 70). If the parameters within FAO Equation 70 exceed the associated limits then revert to the input parameters entered by the user for $K_{cb(Tab)\ mid}$ and to the linearly adjusted parameters for $K_{cb(Tab)\ end}$.

$$K_{cb} = K_{cb(Tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \left(\frac{h}{3}\right)^{0.3} \quad (\text{FAO, Equation 70})$$

where

- $K_{cb(Tab)}$ is the value for $K_{cb(Tab)\ mid}$ at the mature growth stage or $K_{cb(Tab)\ end}$ (if $K_{cb(Tab)\ mid}$ or $K_{cb(Tab)\ end}$ (0.45) for crops and the user entered value, $K_{cb(Tab)}$, for non-crops (taken from Table 17 and defined as an AnnAGNPS input parameter),
- u_2 the mean value for daily wind speed at 2 m height over grass during the mid or late season growth stage [$m\ s^{-1}$] for $1\ m\ s^{-1} \leq u_2 \leq 6\ m\ s^{-1}$, (AnnAGNPS input parameter, `wnd_spd`).
- RH_{min} the mean value for daily minimum relative humidity during the mid- or late season growth stage [%] for $20\% \leq RH_{min} \leq 80\%$, (AnnAGNPS input parameter, `cell_rlt_hmd`).
- h the mean plant height during the mid or late season stage [m] (from Table 12) for $20\% \leq RH_{min} \leq 80\%$. (AnnAGNPS input parameter)

AnnAGNPS: Technical Descriptions

Non-crop input parameters should be added to the non-crop data section describing the crop coefficient, the start of the growing season, and the length of the growing season. One other option is to only ask for a crop coefficient in the non-crop data section and then limit transpiration in the code to days when something like the 5-day (or 10-day) moving average air temperature is above 32 degrees F. Maybe don't use an average air temperature, but something like the number of frost-free days has to be greater than 5 around a date before transpiration begins.

6.3.4 Evaporation coefficient, K_e :

The soil evaporation coefficient, K_e , describes the evaporation component of ET_c . Where the topsoil is wet, following rain or irrigation, K_e is maximal. Where the soil surface is dry, K_e is small and even zero when no water remains near the soil surface for evaporation.

A: Calculate the maximum value of the crop coefficient K_c ($K_c = K_{cb} + K_e$), i.e., the upper limit $K_{c\ max}$ (FAO Equation 72).

$K_{c\ max}$ represents an upper limit on the evaporation and transpiration from any cropped surface and is imposed to reflect the natural constraints placed on available energy represented by the energy balance difference $R_n - G - H$ (FAO Equation 1).

$$R_n - G - \lambda ET - H = 0 \quad (\text{FAO Equation 1})$$

where

- R_n is the net radiation,
- H is the sensible heat,
- G is the soil heat flux and
- λET is the latent heat flux.
- λ is the latent heat of vaporization

The various terms can be either positive or negative. Positive R_n supplies energy to the surface and positive G , λET and H remove energy from the surface

$K_{c\ max}$ ranges from about 1.05 to 1.30 when using the grass reference ET_o :

$$K_{c\ max} = \max \left(\left\{ 1.2 + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \left(\frac{h}{3} \right)^{0.3} \right\}, \{ K_{cb} + 0.05 \} \right) \quad (\text{FAO, Equation 72})$$

AnnAGNPS: Technical Descriptions

Where

h is the mean maximum plant height during the period of calculation (initial, development, midseason, or late-season) [m]. For AnnAGNPS, use the rainfall height from the Crop Data section. For the non-growing season of a crop may want to work on how high the residue is during this period. For non-crops use the annual rainfall height.

K_{cb} is the basal crop coefficient,

$\max ()$ is the maximum value of the parameters in braces $\{ \}$ that are separated by the comma.

FAO Equation 72 ensures that $K_{c \max}$ is always greater or equal to the sum $K_{cb} + 0.05$. This requirement suggests that wet soil will always increase the value for K_{cb} by 0.05 following complete wetting of the soil surface, even during periods of full ground cover. A value of 1.2 instead of 1 is used for $K_{c \max}$ in FAO Equation 72 because of the effect of increased aerodynamic roughness of surrounding crops during development, mid-season and late season growth stages which can increase the turbulent transfer of vapor from the exposed soil surface. The "1.2" coefficient also reflects the impact of the reduced albedo of wet soil and the contribution of heat stored in dry soil prior to the wetting event. All of these factors can contribute to increased evaporation relative to the reference.

The "1.2" coefficient in FAO Equation 72 represents effects of wetting intervals that are greater than 3 or 4 days. If irrigation or precipitation events are more frequent, for example daily or for two days, then the soil has less opportunity to absorb heat between wettings, and the "1.2" coefficient in FAO Equation 72 can be reduced to about 1.1. The time step to compute $K_{c \max}$ may vary from daily to monthly. Within AnnAGNPS, if there was precipitation or irrigation the previous day, then 1.1 is used. Otherwise, 1.2 is used in FAO Equation 72.

B: Determine for each day of the growing period:

- 1). Determine the total surface area, f_c , covered by vegetation, f_{cv} , residue, f_{cr} , and rocks, f_r . ($f_c = f_{cv} + f_{cr} + f_r$). (f_c ranges from 0.0 to 1, but can only be equal to 1 if rock cover is at 100%). ($f_{cv} + f_{cr}$ cannot be > 0.99)
 - a. The fraction of surface covered by vegetation (canopy cover), f_{cv} (Table 21 or FAO Equation 76, use AnnAGNPS canopy cover value for the day from the crop data section and the annual cover ratio for the non-crop data section). For the non-growing period, $f_{cv} = 0$, except for non-crop when f_{cv} remains the same as the input value throughout the year;
 - b. The fraction of the surface covered by residue, f_{cr} . For cropland cells this will only include the amount of residue in a cell, which can be associated with the percent of land area covered by residue as defined by AH 713, Equation 5-13 (Gregory, 1982).

$$S_p = \left[1 - e^{-\alpha B_s} \right] \cdot 100 \quad (\text{AH 713, Equation 5-13})$$

Where,

S_p is the percentage of land area covered by residue;

AnnAGNPS: Technical Descriptions

α = the ratio of the area covered by a piece of residue to the mass of that residue (ha/kg). Determined as described below from the AnnAGNPS Crop Data section input parameters;

B_s = the dry weight of the crop residue on the surface (kg/ha). This is the amount of residue on the surface for each AnnAGNPS cell as determined for each day.

For non-crop areas use the surface residue cover input parameter directly. This only includes crop residue, but not the surface covered by vegetation, f_{cv} and the surface covered by rock, f_{rr} . The parameter α is defined as the average ratio of the area covered by a piece of residue to the mass of residue at 30, 60 and 90% residue cover input parameters from the Crop Data section. If any values are not entered at the 30, 60 and 90% levels then they are not included in the average. The best determination of α would occur if all three values are entered, but the next best option would be if the 30 and 60% values are entered. The least desired α value would result if only the 90% level is used. ($\alpha = (.3567/\text{residue at 30\%} + .91629/\text{residue at 60\% cover} + 2.30258/\text{residue at 90\% cover})/3$). The S_p parameter is then equal to $(1 - \exp(-\alpha * \text{cell_surf_res}))$, where cell_surf_res is the AnnAGNPS parameter associated with the mass of residue in a cell for the day in kg/ha. The α parameter will reflect the last crop grown even during the non-growing period until a new crop is called. If pools of residue can be associated with each type of residue added, then the α parameter would be assigned to each associated residue when added to the soil. Currently, AnnAGNPS may not track the associated residues during the simulation, but accumulates them all together. Although, for the determination of the RUSLE surface-cover subfactor in the C-factor, the associated residues are separated during the preprocessing stages of AnnAGNPS.

- c. The fraction of the surface covered by rock, f_{rr} . Use the AnnAGNPS Management Field data section parameter, percent rock cover/100, as entered by the user and associated with a cell. This user may want to consider this parameter for use in all conditions that would inhibit evaporation, such as impermeable membranes placed on the surface.
- 2). The fraction of the surface wetted by irrigation or precipitation, f_w (Table 20, Assume 1.0 for all days on the precipitation event and those following, for irrigation events assume 1.0 except for furrow irrigation = 0.5, and sprinkler irrigation = 0.4);
- 3). The fraction of surface from which most evaporation occurs, f_{ew} or exposed and wetted soil fraction (FAO, Equation 75, Range 0.01 – 1.0.

$$f_{ew} = \min((1 - f_c), f_w)$$

(FAO, Equation 75)

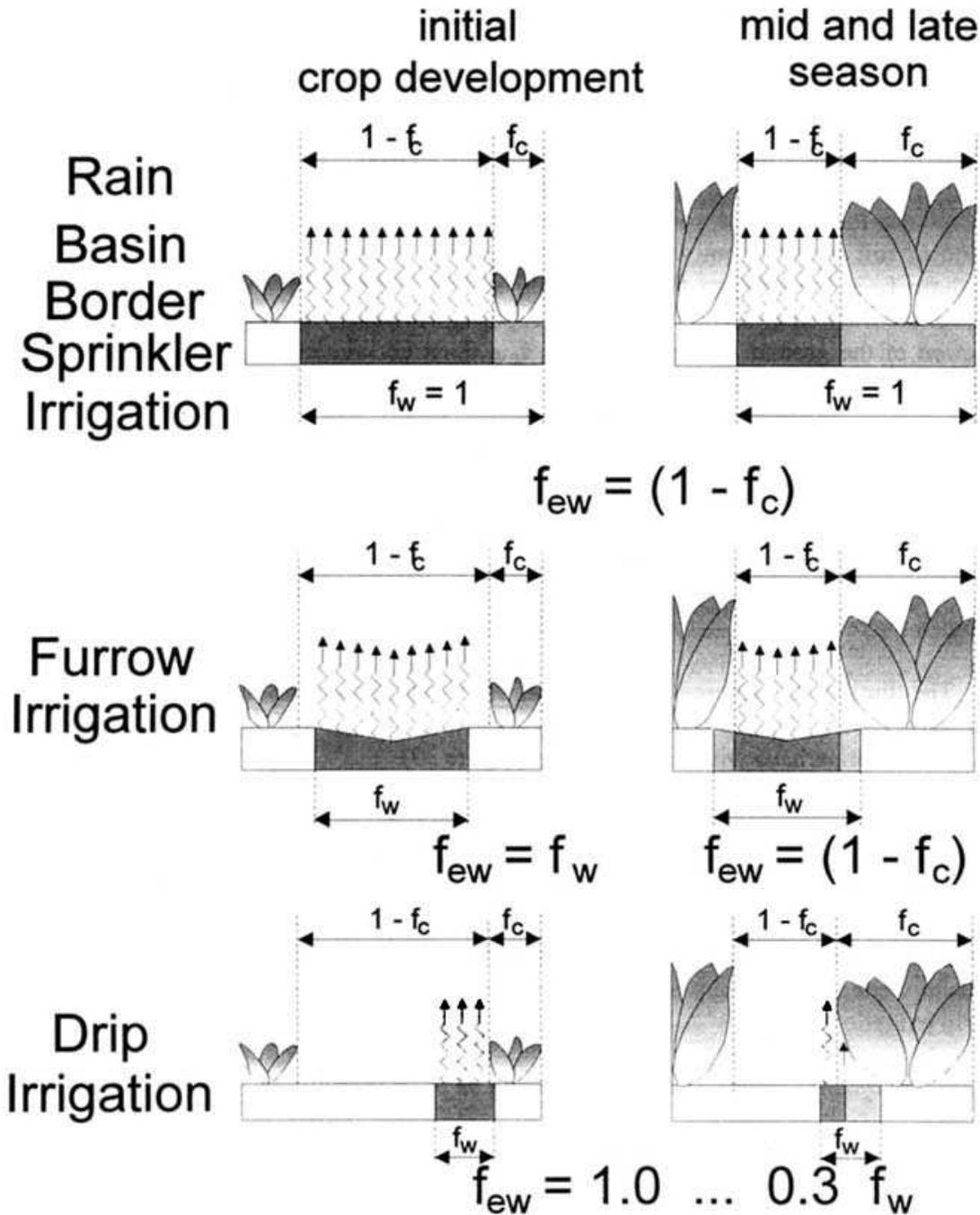


Figure 6-3. The fraction of surface from which most evaporation occurs, f_{ew} , comprised of the exposed and wetted soil fractions of a field.

- 4). The cumulative depletion from the evaporating soil layer, D_e in mm, determined by means of a daily soil water balance of the top soil layer of the previous day (calculate via the AnnAGNPS using the amount of total soil moisture (amount of water at full porosity) minus the amount of soil moisture in the soil for the previous day times the first soil layer thickness);

AnnAGNPS: Technical Descriptions

5). The corresponding evaporation reduction coefficient, K_r (FAO, Equation 74).

Soil evaporation from the exposed soil can be assumed to take place in two stages: an energy limiting stage, and a falling rate stage. When the soil surface is wet, K_r is 1. When the water content in the upper soil becomes limiting, K_r decreases and becomes zero, as a result of the depletion of the total amount of water that can be evaporated from the topsoil.

At the start of a drying cycle, following heavy rain or irrigation, the soil water content in the topsoil can be completely saturated and the amount of water depleted by evaporation, D_e , is zero. During stage 1 of the drying process, the energy limiting stage, the soil surface remains wet and evaporation is assumed to occur from the soil exposed to the atmosphere and will occur at the maximum rate limited only by energy availability at the soil surface. This stage holds until the cumulative depth of evaporation, D_e , is such that the hydraulic properties of the upper soil become limiting and water cannot be transported to the soil surface at a rate that can supply the potential demand. During stage 1, the energy limiting stage, $K_r = 1$.

The second stage (where the evaporation rate is reducing) is termed the 'falling rate stage' evaporation and starts when D_e exceeds REW. At this point, the soil surface is visibly dry, and the evaporation from the exposed soil decreases in proportion to the amount of water remaining in the surface soil layer:

$$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} \text{ for } D_{e,i-1} > REW \quad (\text{FAO, Equation 74})$$

where

K_r - dimensionless evaporation reduction coefficient dependent on the soil water depletion (cumulative depth of evaporation) from the topsoil layer ($K_r = 1$ when $D_{e,i-1} \leq REW$),

$D_{e,i-1}$ - cumulative depth of depletion from the soil surface layer at the end of day $i-1$ (the previous day) or root zone depletion. Within AnnAGNPS this is the amount of soil moisture depletion from field capacity (amount of water at field capacity minus the amount of water at the previous day's soil moisture level. [mm],

TEW - maximum cumulative depth of evaporation (depletion) from the soil surface layer when $K_r = 0$ or total available water (TEW = total evaporable water) [mm], (For AnnAGNPS, use FAO Equation 73 that assumes that the soil can dry to a soil water content level halfway between oven dry (no water left) and wilting point).

$$TEW = (FC - 0.5 * WP) * \text{Depth of the 1st soil layer} \quad (\text{FAO, Equation 73})$$

REW - cumulative depth of evaporation (depletion) at the end of stage 1 (REW = readily evaporable water) [mm]. (For AnnAGNPS, assume this falls halfway between field capacity and the wilting point (50% of the field capacity minus 50% of the wilting point times the depth of the first soil layer, see K_r versus D_e figure.)

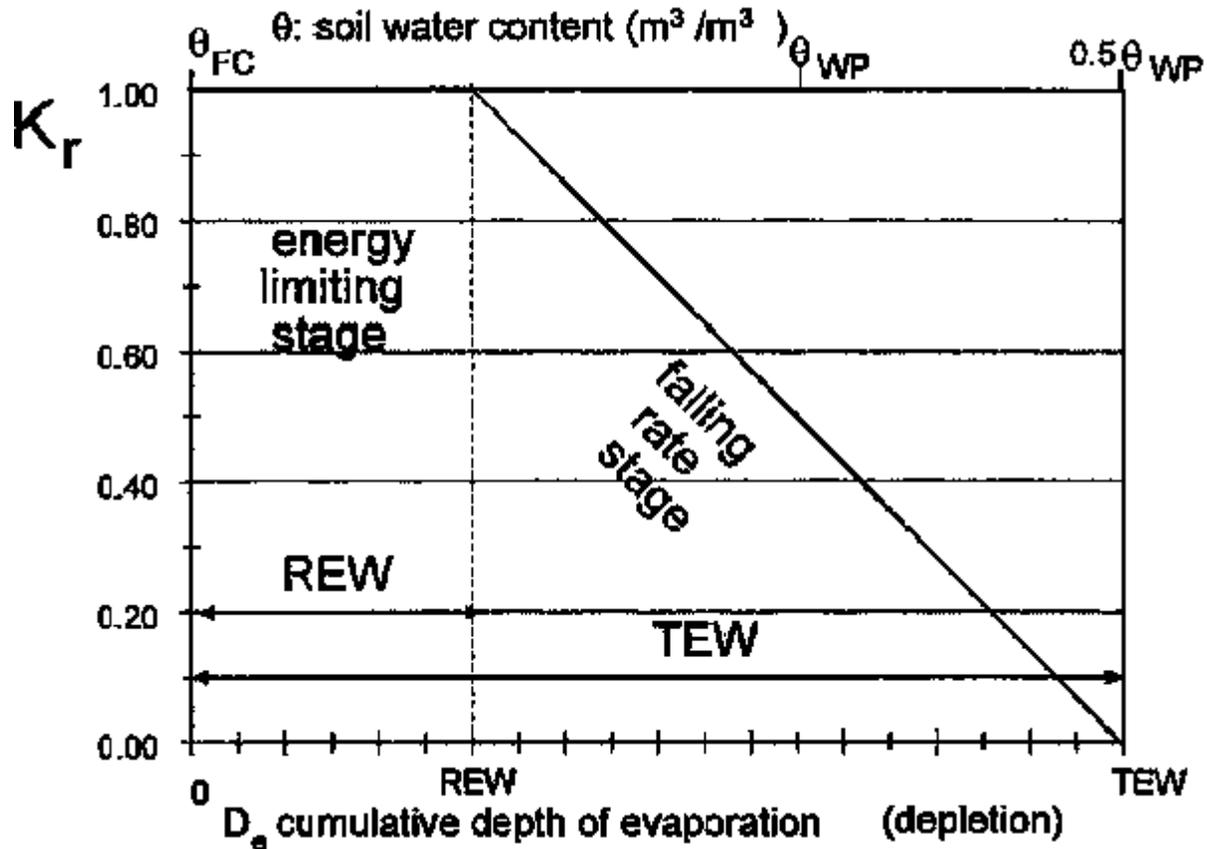


Figure 6-4. Energy limiting and falling rate stages of the evaporation reduction coefficient, K_r .

6). The soil evaporation coefficient, K_e (FAO Equation 71).

Where the soil is wet, evaporation from the soil occurs at the maximum rate. However, the crop coefficient ($K_c = K_{cb} + K_e$) can never exceed a maximum value, $K_{c\ max}$. This value is determined by the energy available for evapotranspiration at the soil surface ($K_{cb} + K_e \leq K_{c\ max}$) or $K_e \leq (K_{c\ max} - K_{cb})$.

When the topsoil dries out, less water is available for evaporation and a reduction in evaporation begins to occur in proportion to the amount of water remaining in the surface soil layer, or:

$$K_e = K_r * (K_{c\ max} - K_{cb}) \leq f_{ew} * K_{c\ max} \quad \text{(FAO, Equation 71)}$$

Where,

K_e - soil evaporation coefficient,

K_{cb} - basal crop coefficient,

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$K_{c \text{ max}}$ - maximum value of K_c following rain or irrigation,

K_r - dimensionless evaporation reduction coefficient dependent on the cumulative depth of water depleted (evaporated) from the topsoil,

f_{ew} - fraction of the soil that is both exposed and wetted, i.e., the fraction of soil surface from which most evaporation occurs.

In computer programming terminology, FAO Equation 71 can be expressed as $K_e = \min (K_r * (K_{c \text{ max}} - K_{cb}), f_{ew} * K_{c \text{ max}})$.

6.3.5 Crop evapotranspiration, ET_c :

To determine ET_c , the solution consists of splitting K_c into two separate coefficients, one for crop transpiration, i.e., the basal crop coefficient (K_{cb}), and one for soil evaporation (K_e). The total of K_{cb} and K_e must not exceed $K_{c \text{ max}}$.

$$ET_c = (K_{cb} + K_e) * ET_o \quad (\text{FAO, Equation 69})$$

6.3.6 Actual Crop evapotranspiration, ET_a :

The actual crop evapotranspiration, ET_a , within AnnAGNPS is based on the root mass within the first and second soil layers to allocate the amount of ET that occurs between the top and bottom soil layers. ET is adjusted for each soil moisture time step in the top soil layer based on FAO Equation 100.

$$ET_a = ET_c * (0.25 + (0.75 * ((\text{live root mass in top layer}) / (\text{accumulated live root mass in all layers})))) \quad (\text{FAO, 100})$$

The ET_a in the second layer $ET_c * (\text{one} - (0.25 + (0.75 * ((\text{live root mass in top layer}) / (\text{accumulated live root mass in all layers}))))$.

If there are no roots then all of the ET will occur in the top layer.

If the available soil moisture is not at the level required to meet the evapotranspiration in either soil layer then evapotranspiration will be limited to the amount of soil moisture in each soil layer.

6.4 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

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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.

6.4.1 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.

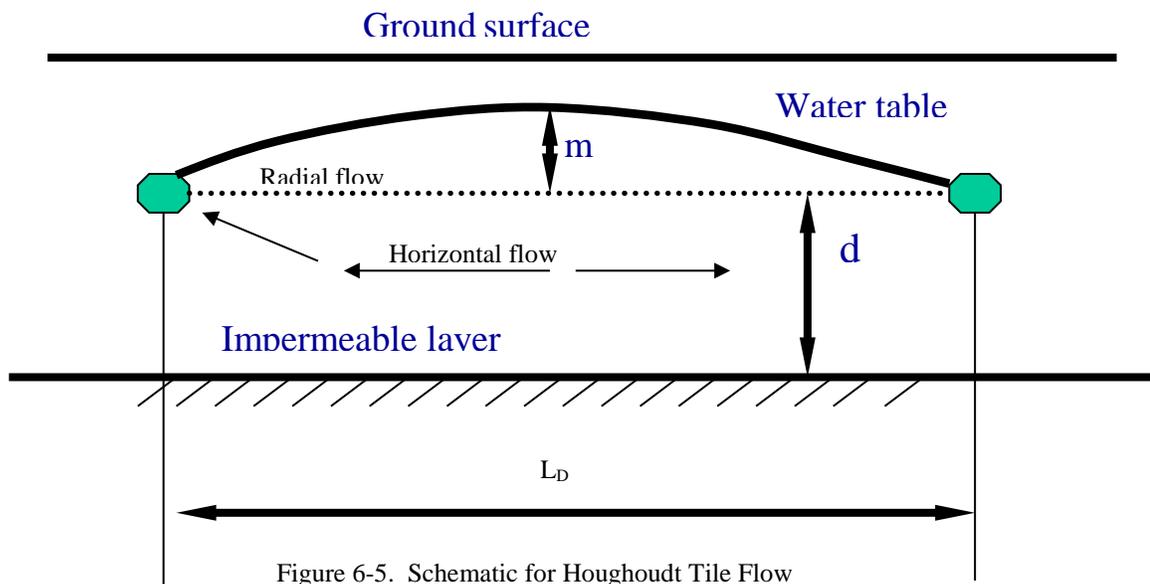


Figure 6-5. Schematic for Houghoudt Tile Flow

The water table above parallel drains is often approximated using an elliptical shape, as shown in Figure 6-5. Schematic for Houghoudt Tile Flow. The streamlines for the drainage flow towards two parallel pipes typically show a pattern as in Figure 6-5. Schematic for Houghoudt Tile Flow. 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:

$$q_{\text{drain}} = \frac{8K_s d_e m + 4K_s m^2}{L_D^2} \quad \text{Equation 6-61}$$

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

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

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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).

$$d_e = \frac{d}{1 + \frac{d}{L_D} \left[\frac{8}{\pi} \ln\left(\frac{d}{r}\right) - \alpha_c \right]} \quad \text{Equation 6-62}$$

r = radius of the drain tube (m)

α_c = a constant defined by:

$$\alpha_c = 3.55 - \frac{1.6d}{L_D} + 2\left(\frac{d}{L_D}\right)^2 \quad \text{Equation 6-63}$$

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

$$d_e = \frac{L_D \pi}{8 \left[\ln\left(\frac{L_D}{r}\right) - 1.15 \right]} \quad \text{Equation 6-64}$$

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:

$$SM_{t+1} = SM_t + \frac{WI_t - PERC_t - ET_t}{Z} \quad \text{Equation 6-65}$$

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:

$$h = \frac{(SM_{t+1} - FC) * Z}{(PO - FC)} \quad \text{Equation 6-66}$$

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:

$$Q_{Tile} = \frac{q_{drain} * A_{cell}}{1000} \quad \text{Equation 6-67}$$

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

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A_{cell} = Cell area (m²)

6.4.2 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.

$$q_{\text{lat}} = -K_s \frac{dh}{dl} \quad \text{Equation 6-68}$$

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.

$$Q_{\text{lat}} = \frac{q_{\text{lat}} * A_{\text{across}}}{1000} \quad \text{Equation 6-69}$$

$$A_{\text{across}} = \frac{h * L_{\text{Reach}}}{1000} \quad \text{Equation 6-70}$$

Q_{lat} = total volume of lateral flow out of cell each time step (m³)

A_{across} = Lateral flow across area (m²)

h = Saturated depth from the imperious layer (mm)

L_{reach} = Reach length (m)

6.5 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.

6.5.1 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

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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.

6.5.1.1 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 6-6 is a diagram of the trapezoidal cross-section dimensions used to define the generalized in-cell concentrated flow channel hydraulic geometry.

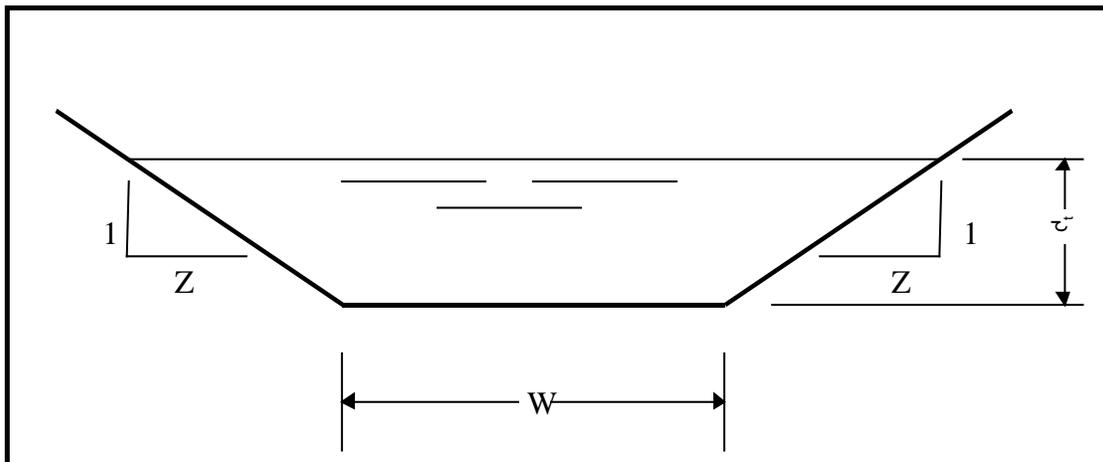


Figure 6-6. Generalized In-Cell Channel Shape--trapezoid

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

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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

6-71

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 6-72

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 6-73

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:

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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 6-74

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 6-75

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 6-76

where:

- d_t = total depth of flow, ft;
- Q_t = total discharge, m³/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 6-77

For a rectangle

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

Equation 6-78

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 6-79

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:

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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 6-80

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 6-81

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 6-82

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 6-83

where:

- d_t = total depth of flow, ft;
- n = Manning's roughness (n_{ch}), non-dimensional;
- Q_t = total discharge, m³/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:

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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 6-84

For a rectangle

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

Equation 6-85

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 6-86

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 6-87

For a rectangle

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

Equation 6-88

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 6-89

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.

6.5.1.2 In-Stream Channel Compound Cross-sections

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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 6-7 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 $W_f = W_v - W_b$.

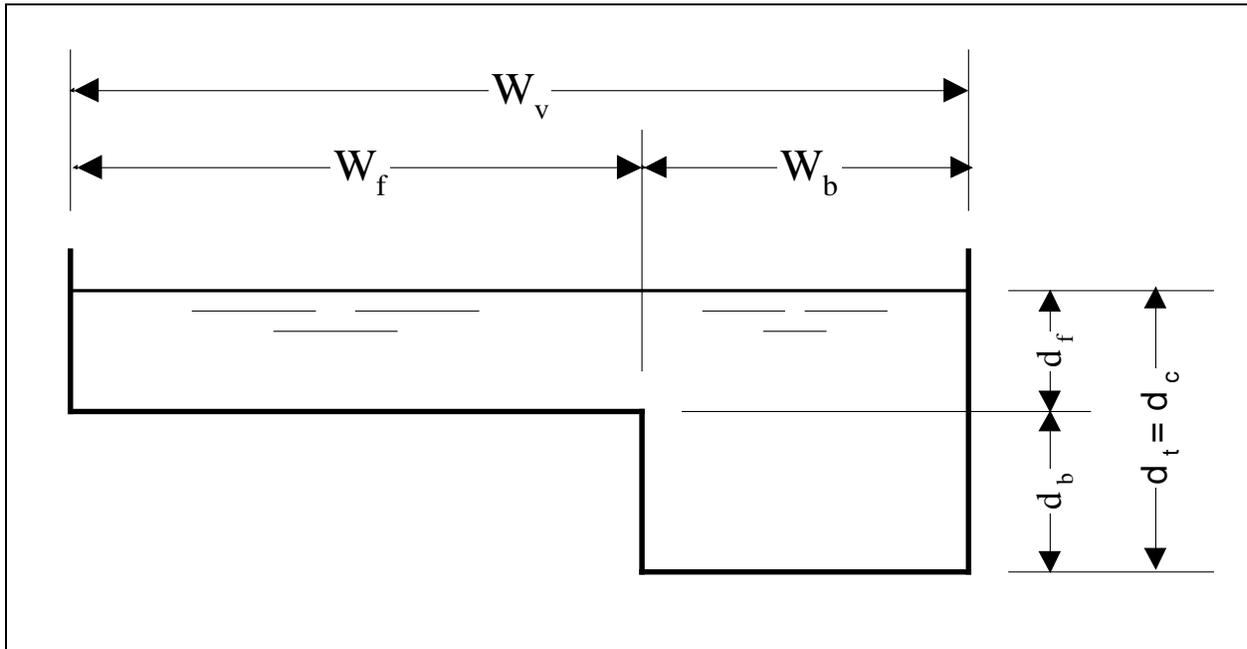


Figure 6-7. Generalized In-Stream Channel Shape--Compound X-Section

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 6-90

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:

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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 6-91

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 6-92

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, m³/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:

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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 6-93

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 6-94

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, m³/sec;
- Q_f = floodplain discharge, m³/sec;
- Q_t = total discharge, m³/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, m³/sec;
- Q_c = channel section discharge, m³/sec;
- Q_f = floodplain discharge, m³/sec;
- Q_t = total discharge, m³/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:

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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 6-95

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 6-96

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, m³/sec;
- Q_f = floodplain discharge, m³/sec;
- Q_t = total discharge, m³/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 6-97

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 6-98

where:

- d_b = bankfull depth of flow, ft;
- d_t = total depth of flow, ft;

AnnAGNPS: Technical Descriptions

- 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, m³/sec/m;
 q_f = floodplain unit discharge, m³/sec/m;
 q_t = total unit discharge, m³/sec/m;
 Q_c = channel section discharge, m³/sec;
 Q_f = floodplain discharge, m³/sec;
 Q_t = total discharge, m³/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 6-99

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 6-100

where:

- q_c = channel section unit discharge, m³/sec/m;
 q_f = floodplain unit discharge, m³/sec/m;
 q_t = total unit discharge, m³/sec/m;
 Q_c = channel section discharge, m³/sec;
 Q_f = floodplain discharge, m³/sec;
 Q_t = total discharge, m³/sec;
 W_b = bankfull top width, m; and
 W_f = floodplain width, m.

6.5.1.3 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 6-101

where: d_w = hydraulic depth, m;
 R = hydraulic radius, m;
 A_H = flow area, m²; and
 W_H = flow width, m.

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

AnnAGNPS: Technical Descriptions

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

Equation 6-102

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 6-103

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, m³/s;
 $q_w = Q_w / W$, unit-width water discharge, m³/s/m; and
 S_o = channel slope, m/m.

And the term, d_w , derived from Equation 6-104, will be used in subsequent formulas:

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

Equation 6-104

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, m³/s/m; and
 S_o = channel slope, m/m.

6.5.1.4 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:

$$T_{c,in_cell} = T_{t,ov} + T_{t,scf} + T_{t,cf}$$

Equation 6-105

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.

AnnAGNPS: Technical Descriptions

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:

$$L_{ov_max} = 50$$

$$L_{ov} = MIN(L_{ov_max}, L)$$

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

Equation 6-106

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_2 .

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 6-107

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_{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;
- S_{ov} = overland flow land slope, m/m;
- $T_{t,scf}$ = travel time for the shallow concentrated flow period, hr; and

AnnAGNPS: Technical Descriptions

V_{scf} = 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 6-108

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_{cf} = flow path length for the concentrated flow segment, 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;
- L_{scf} = flow path length for the shallow concentrated flow segment, m;
- $T_{t,scf}$ = 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 (ΔL) 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 6-109

where:

- $T_{t,reach}$ = travel time through the reach segment, hr;
- V_{reach} = velocity of flow through the reach, m/s; and
- ΔL = 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:

AnnAGNPS: Technical Descriptions

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 6-110

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.

6.5.2 Channel Hydrology**6.5.2.1 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:

$$Q_{24} \equiv (P_{24} - I_a)^2 / (P_{24} + 4 I_a) \quad \text{Equation 6-111}$$

Algebraic manipulation gives:

$$I_a^2 + (-2P_{24} + 4Q_{24}) I_a + (P_{24}^2 - Q_{24}P_{24}) = 0 \quad \text{Equation 6-112}$$

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

$$I_a = (P_{24} + 2Q_{24}) - (5Q_{24}P_{24} + 4Q_{24}^2)^{0.5} \quad \text{Equation 6-113}$$

To calculate the I_a / P_{24} ratio use:

$$(I_a / P_{24}) \equiv [(P_{24} + 2Q_{24}) - (5Q_{24}P_{24} + 4Q_{24}^2)^{0.5}] / P_{24} \quad \text{Equation 6-114}$$

6.5.2.2 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 IIa60, IIa65, IIa70, & IIa75.

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

AnnAGNPS: Technical Descriptions

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:

$$Q_p = 2.777777778 \cdot 10^{-3} \cdot P_{24} \cdot D_a \cdot \left[\frac{a + (c \cdot T_c) + (e \cdot T_c^2)}{1 + (b \cdot T_c) + (d \cdot T_c^2) + (f \cdot T_c^3)} \right]$$

Equation 6-115

where: 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; 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 6-1: Unit Peak Discharge 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 6-2: Unit Peak Discharge 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

AnnAGNPS: Technical Descriptions

I_a/P_{24}	a	b	c	d	e	f
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 6-3: Unit Peak Discharge 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 6-4: Unit Peak Discharge 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

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I_a/P_{24}	a	b	c	d	e	f
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 6-5: Unit Peak Discharge 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 6-6: Unit Peak Discharge 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

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I_a/P_{24}	a	b	c	d	e	f
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 6-7: Unit Peak Discharge 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 6-8: Unit Peak Discharge 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

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I _a /P ₂₄	a	b	c	d	e	f
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 6-9: Unit Peak Discharge Regression Coefficients—Type 9 (IIa75)

I _a /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:

$$t_b = 20 \cdot (R_Q \cdot D_a / Q_p)$$

Equation 6-116

where: Q_p = peak discharge, m³/s;
 D_a = total drainage area, hectares;

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R_0 = surface runoff volume from upstream drainage area, mm;
and
 t_b = time to base, s.

The hydrograph as a function of time is:

$$Q_w = (Q_p/t_b) \cdot t, \quad 0 \leq t \leq t_b \quad \text{Equation 6-117}$$

where: Q_w = discharge as a function of time, m³/s;
 Q_p = peak discharge, m³/s;
 t_b = time to base, s; and
 t = time from beginning of runoff, s.

And the unit-width peak discharge is:

$$q_p = Q_p/W \quad \text{Equation 6-118}$$

where: q_p = unit-width peak discharge, m³/s/m;
 Q_p = peak discharge, m³/s; and
 W = flow width, m.

6.5.3 RCN Calibration

The streamflow may be automatically calibrated, but there are nuances which can greatly affect the results. Streamflow is the total water flowing in the stream at a specified location; e.g., at a USGS gauging station. The sources for this streamflow is groundwater-fed baseflow and runoff from any storm events. The runoff is comprised of surface runoff plus any quick return flow; and quick return flow is a comprised of any lateral flow through the root zone that ends up in the eventually stream plus any tile drain flow if tile drains exist. Baseflow resulting from bank storage is included in the runoff since it goes into the bank during the rising limb of the hydrograph and drains out of the bank during the falling limb.

Two parameters are necessary to calibrate the SCS runoff curve numbers and they are the average annual values for: (1) streamflow; and (2) runoff. It is necessary to know the average annual runoff to be able to calibrate. If the average annual streamflow is also known, then the daily baseflow (groundwater-fed) can also be estimated, but currently AnnAGNPS assumes it to be constant. When the groundwater feature is developed, the groundwater-fed baseflow will be automatically included.

The actual RCN calibration procedure adjusts the maximum potential retention variable that is at the heart of the runoff curve number; in fact, there is a one-to-one hyperbolic relationship between the two parameters as can be seen in Equation 6-119.

$$C_n = \frac{1000}{S_{\max} - 10} \quad \text{Equation 6-119}$$

where: C_n = SCS runoff curve number;
 S_{\max} = maximum potential retention variable, in.

Note that the units for the maximum potential retention variable is always in inches.

7. SEDIMENT

7.1 Erosion

7.1.1 Sheet & Rill

7.1.1.1 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

AnnAGNPS: Technical Descriptions

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

AnnAGNPS: Technical Descriptions

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 7-1.

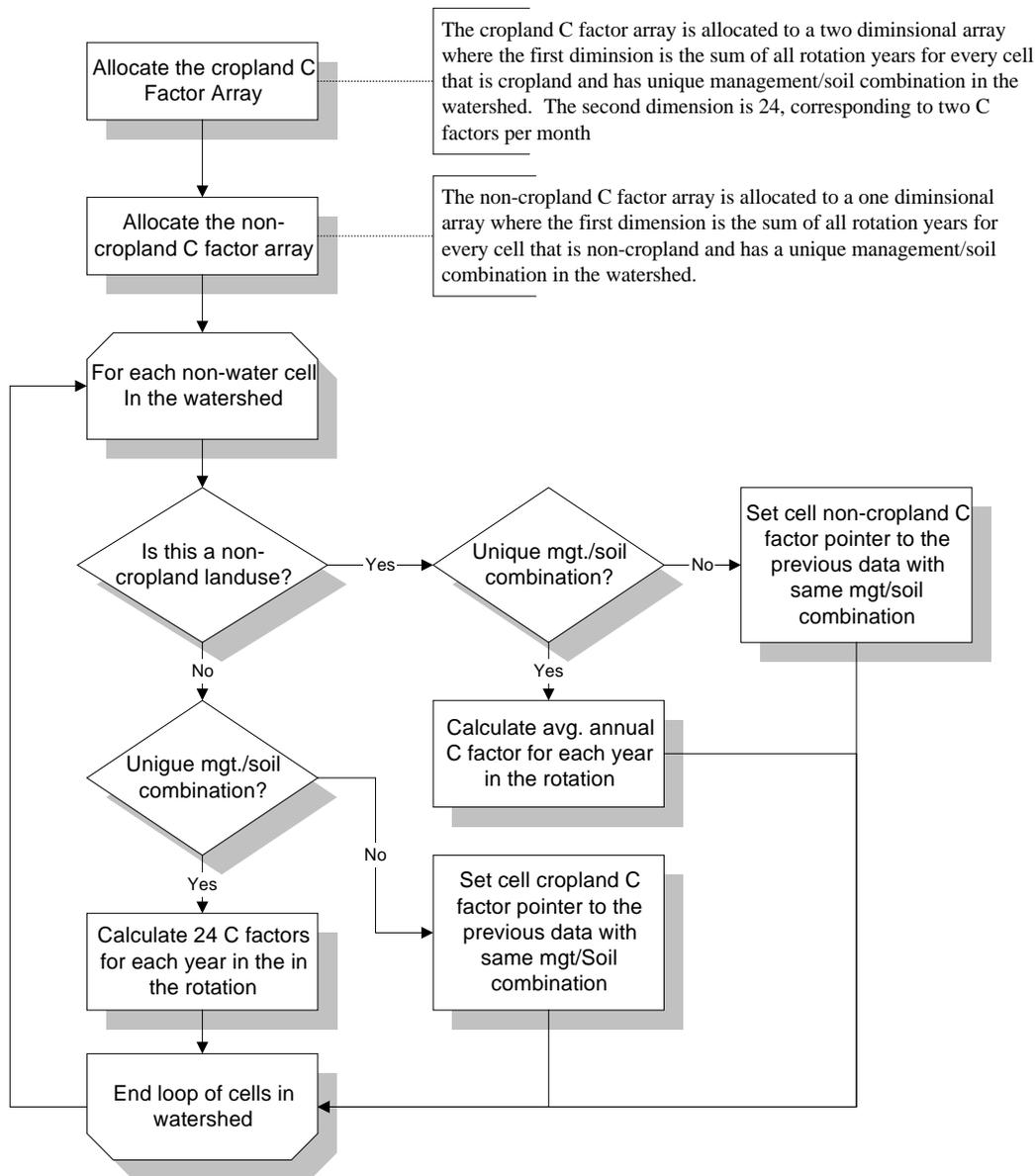


Figure 7-1. Flow chart of the AnnAGNPS C-factor calculation.

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.

AnnAGNPS: Technical Descriptions

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 7-1.

Table 7-1. 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 7-2. illustrates the high level structure of the K factor routines used in AnnAGNPS.

AnnAGNPS: Technical Descriptions

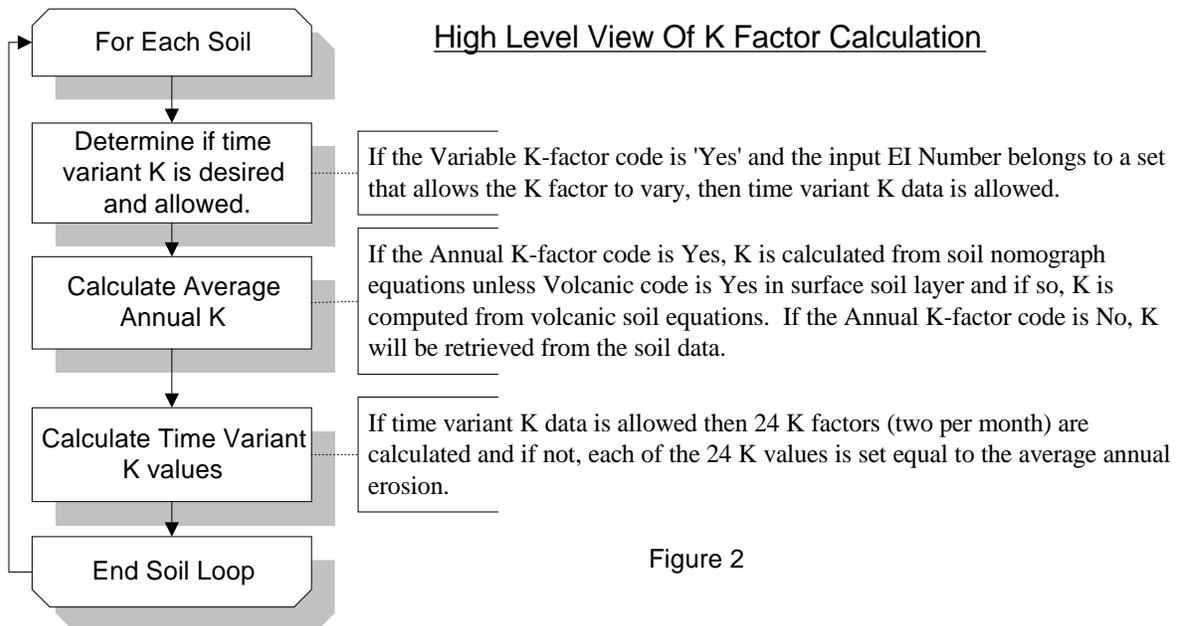


Figure 7-2. Flow chart of AnnAGNPS K factor calculation.

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

AnnAGNPS: Technical Descriptions

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 7-1 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).

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 7-2. 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 7-2 assigns a RUSLE predefined cover code to each cell based on the type of landuse specified in the field data as shown in Table 7-2. 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 7-2. 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

AnnAGNPS: Technical Descriptions

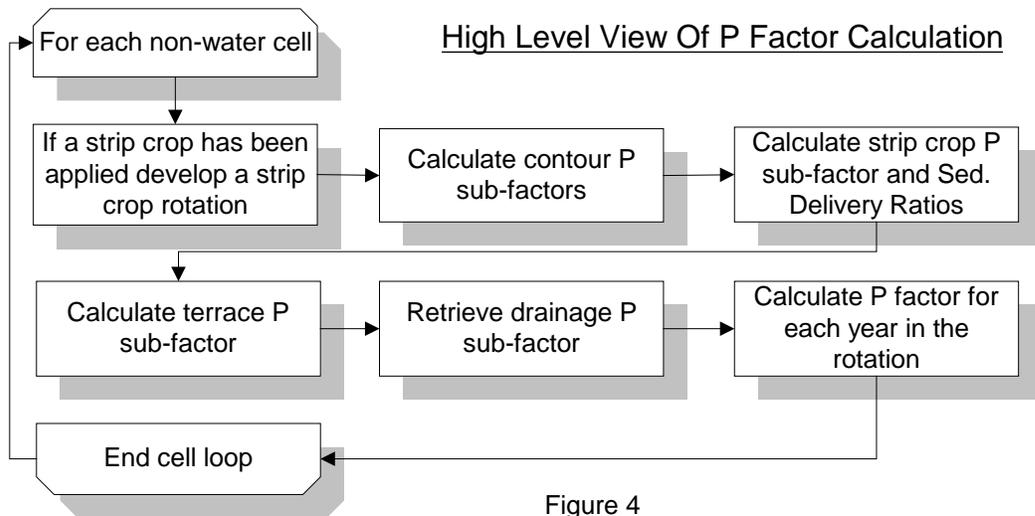


Figure 4

Figure 7-3. A high level view of the process used in AnnAGNPS to calculate P factors.

RUSLE EI Parameter:

The EI value is used to determine the sheet & rill erosion within a cell using RUSLE technology (Renard et al, 1997) and is calculated given the rainfall distribution (storm type) and the RUSLE procedures for the value of EI as a product of total storm energy and the maximum 30-minute intensity. A unit rainfall event distribution is used within AnnAGNPS with the event rainfall to determine a 30 minute intensity for the storm event and the storm event energy is determined from Brown and Foster (1987), as also described in RUSLE (Renard et al, 1997), to determine the storm event erosivity. The user provides the rainfall distribution either by entering user-defined storm types or by selecting preset storm types within AnnAGNPS.

For snowmelt and irrigation, a uniform rainfall distribution is automatically assumed. If precipitation and snowmelt and/or irrigation occur on the same day, a uniform distribution is assumed if the combined runoff from snowmelt and/or irrigation is greater than 50%; otherwise the rainfall distribution associated with the daily storm type is used.

RUSLE K Parameter:

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,:

$$K = K * (1 + 14 * (1 - \exp(-4 * (M - 0.5)))) \quad \text{Equation 7-1}$$

where: K = 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.

7.1.1.2 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.

AnnAGNPS: Technical Descriptions

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:

$$S_y = 0.22 * Q^{0.68} * q_p^{0.95} * KLSCP \quad \text{Equation 7-2}$$

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:

$$D_r = S_{y2}/S_{y1} = (q_{p2} / q_{p1})^{0.95} \quad \text{Equation 7-3}$$

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.

AnnAGNPS: Technical Descriptions

Table 7-3: Sediment Particle-Size Class Static Parameters

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 7-3 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

Sediment Particle Class	Particle Density	Particle Fall Velocity	Deposition Mass Rate	Deposition Rate Ratio	Deposition Ratio Mass Rate
	(Mg/m ³)	(mm/s)	(g/m ² /s)	(-)	(Mg-particle / Mg-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	

(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 6-6 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 7-4. The non-italicized fields are to be calculated within the RUSLE_Delivery_Ratio subprogram.

Table 7-4 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 7-3. Column 2 (Sediment Distribution) is a required input and is available as output from the RUSLE subprogram.

AnnAGNPS: Technical Descriptions

Column 3 (Sediment Settling Ratio) is product of Column 5 (Deposition Rate Ratio) from Table 7-3 and Column 2 (Sediment Distribution) from Table 7-4 divided by the Sediment Settling Ration Normalizing Ratio which is the sum of the cross products of Column 5 (Deposition Rate Ratio) from Table 7-3 and Column 2 (Sediment Distribution) from Table 7-4. 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 7-4. Column 5 (Particle Delivery Ratio) is 1 minus Column 4 (Particle Deposition Ratio) from Table 7-4.

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.

AnnAGNPS: Technical Descriptions

Table 7-4: 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)
HUSLE Delivery Ratio (-) = 0.200000				RUSLE Erosion (g) = 1000000		
Initial Estimate						
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		
1st Correction						
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		
2nd Correction						
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		
3rd Correction						
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		
4th Correction						
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

AnnAGNPS: Technical Descriptions

7.1.2 Tillage-Induced Ephemeral Gully Erosion

7.1.2.1 Introduction

The National Resources Inventory (NRI), conducted by the U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS), in cooperation with Iowa State University's Center for Survey Statistics and Methodology, reported that there has been a 42% decrease in sheet and rill erosion in the U.S. between 1982 and 2003. Erosion control practices within agricultural watersheds have a significant impact on reducing the sheet and rill source of sediment to the streams. While these practices have significantly affected sheet and rill erosion, they do not appreciably affect ephemeral gully erosion. Ephemeral gully erosion is becoming a dominant source of cropland erosion simply because sheet and rill erosion is decreasing.

Most ephemeral gullies that develop within croplands are tillage-induced; i.e., certain tillage operations weaken the top layer down to the maximum depth disturbed by this mechanical process during a rotation. What makes a tillage-induced ephemeral gully different from other gullies is the assumption that a non-erosive layer develops at the maximum tillage depth from operations during the management rotation cycle. Ephemeral gullies may form into the soil profile that are greater than tillage depths if the tractive stresses exceed the critical tractive stress of the more resistant bottom layer below the tillage layer. A management operation in the rotation cycle may also remove the gully, by filling in the gully through mechanical soil disturbance, but the gully may reform when conditions are again sufficient to produce ephemeral gully erosion.

Sheet and rill erosion conservation management technologies, such as the Revised Universal Soil Loss Equation (RUSLE, Renard et al, 1997), have provided valuable tools in reducing cropland erosion, but have not considered the impact of ephemeral gully erosion. NRCS has requested improvements in USDA Agricultural Research Service (ARS) technologies to account for watershed sources of sediment from ephemeral gully erosion through the USDA Annualized Agricultural Non-Point Source model (AnnAGNPS, Bingner and Theurer, 2001). AnnAGNPS has been developed to determine the effects of conservation management plans and provide sediment tracking from all sources within the watershed. Technology is also needed to identify where ephemeral gullies may form in the watershed using geographic information system (GIS) technology.

7.1.2.1.1 AnnAGNPS Ephemeral Gully Model Enhancements

Although not satisfactorily achieved, the only USDA technology available to assess ephemeral gully erosion on an agricultural field for many years has been the Ephemeral Gully Erosion Model (EGEM, Woodward, 1999). Gordon et al. (2007) has extended the capabilities of EGEM through the Revised EGEM (REGEM) as a stand-alone program, by: (1) adding a new algorithm which estimates the migration rate of the headcut; (2) adding an algorithm which creates the initial headcut's knickpoint; (3) refining some of the existing EGEM components; and (4) developing additional components into a revised and further enhanced algorithm.

The integration of REGEM technology into AnnAGNPS led to other additions to simulate tillage-induced ephemeral gully erosion including: the capability to repair gullies through tillage that defines when an ephemeral gully can again initially form; the influence of prior landuse as defined from RUSLE-technology; utilization of HUSLE (Theurer and Clarke, 1991) components for sediment transport determination; enhanced gully width calculations; and the determination of the amount of scour hole erosion. These enhancements and the inclusion of REGEM-technology have led to the Tillage-Induced Ephemeral Gully Erosion Model (TIEGEM) within AnnAGNPS to provide a watershed-scale assessment of management practice effects on sediment production from ephemeral gully erosion within croplands.

This technology provides an integrated approach in simulating ephemeral gully erosion as the headcut is induced and moves up the length of the pathway with varying widths, depths and migration rates as a result of management practices, watershed characteristics, and climatic effects. Examples of sheet and rill erosion and ephemeral gully erosion control conservation practice assessments include simulations from the conversion of cultivated fields to the Conservation Reserve Program (CRP), from conventional-till to no-till farming practices, or from the use of grassed waterways for ephemeral gully erosion control. Sediment from ephemeral gully erosion, as well as from sheet and rill erosion, that eventually reaches the edge of a field (sediment yield), can then be separately tracked as sediment moves further downstream from the utilization of AnnAGNPS.

A gully is either cell-located or reach-located. The gully is cell-located if the gully is wholly contained within just a single AnnAGNPS cell; the gully is reach-located if the gully is located within the thalweg of a reach. A cell-located gully is affected by only one AnnAGNPS cell; a reach-located gully is affected by more than just one AnnAGNPS

AnnAGNPS: Technical Descriptions

cell. A gully's delivery ratio to its receiving stream is defined to be the gully yield divided by the gully's sediment passing the gully mouth.

If the gully is cell-located, the single AnnAGNPS cell is the "Primary Cell". The single cell's drainage area that affects the gully erosion may be only a portion or all of the cell's total drainage area. The drainage area affecting the cell-located gully is the "Primary Drainage Area". A cell-located gully does not have an associated "Secondary Cell". The delivery ratio to the Primary Cell's receiving stream is also a function of the drainage area of the subarea, within which the gully is located, to the Primary Cell's receiving stream. This drainage area of the Primary Cell's subarea is described as the "Primary Cell's Subarea". A Primary Cell may be composed entirely of just one subarea, where the gully's subarea would be equal to the Primary Cell's total drainage area, or many subareas, where the gully may be located in only one of these subareas.

If the gully is reach-located, the drainage area affecting the gully is all or part of each of the reach's local-contributing AnnAGNPS cells—both the reach's left-bank cell, which is the Primary Cell and the reach's right-bank cell, which is the Secondary Cell—and all of the drainage area above the upstream end of the reach. For a reach-located gully, the "Primary Drainage Area" is the portion of the primary cell (reach's left-bank cell) that drains into the reach upstream of the gully mouth; and the "Secondary Drainage Area" is the portion of the secondary cell (reach's right-bank cell) that drains into the reach upstream of the gully mouth. Since the reach-located gully is located within the reach, at the gully's mouth the gully's sediment yield is equal to the gully's sediment load and the subsequent delivery ratio to its receiving stream results in unity. Therefore, no subarea information is required, but both the primary & secondary cell IDs & drainage areas are necessary.

7.1.2.1.2 Current Model Limitations

The integration and transformation of EGEM to REGEM into TIEGEM within AnnAGNPS has identified several model limitations because little is known about several critical components. Some of the more important limiting components are the identification of and relationships for: (1) ephemeral gully width; (2) soil resistance to gully erosion including a definition for non-erosive layers; (3) the effect of root mass and above ground vegetation on erosion resistance; (4) ephemeral gully networks; and (5) the effect of subsurface flow on ephemeral gullies. Currently, these components are represented through widely divergent to non-existent algorithms, which at best have a heuristic basis.

7.1.2.2 Soil Properties

7.1.2.2.1 Critical shear

7.1.2.2.1.1 RUSLE Prior Landuse

The RUSLE prior landuse subfactor is determined according to RUSLE procedures (see Renard et al, 1997) for the semi-monthly time period in which the event occurs.

7.1.2.2.1.2 Critical Shear

The soils critical shear was taken from EGEM (USDA 1992) and modified for prior landuse conditions.

$$\tau_c = (17.9 \cdot C_c) + e^{[1.97 - (9.98 \cdot P_u)]} \quad \text{Equation 7-4}$$

where: C_c \equiv clay content [g-clay/g-soil];

τ_c \equiv critical shear [N/m²]; and

P_u \equiv RUSLE prior landuse subfactor from [-].

7.1.2.2.2 Nickpoint Erodibility Coefficient

$$k_n = 29.1 \cdot 10^{-6} \cdot e^{(-0.224 \cdot \tau_c)} \quad \text{Equation 7-5}$$

where: τ_c \equiv critical shear [N/m²]; and

AnnAGNPS: Technical Descriptions

k_n \equiv nickpoint erodibility rate coefficient for the erosive soil layer [Mg/N/s].

7.1.2.2.3 Headcut Migration Erodibility Coefficient

The headcut migration erodibility coefficient was developed by Hanson and Simon (2001) as Equation 7-6. Alonso et al. (2002) validated this equation with their results.

$$k_h = 0.0000002 / \sqrt{\tau_c} \quad \text{Equation 7-6}$$

where: τ_c \equiv critical shear [N/m²]; and

k_h \equiv headcut migration rate coefficient for the erosive soil layer [m³/s/N].

7.1.2.3 Hydrograph Development

Simplifying assumptions are made to make the solutions tractable. It is not the objective to predict what is happening during an event, just what the results after the event is past. Therefore, a unit slice assumption is satisfactory throughout all analyses.

7.1.2.3.1 Minimum Gully Width

Several algorithms may be available to determine the minimum gully width for each event. They are: (1) previously determined width by a prior event; (2) Nachtergaele et al's (2002) equation 10; (3) the hydraulic geometry relationship for concentrated flow in which the gully is located; and (4) non-submerging tailwater depth which is just at the crest of the headcut; (5) Woodward's (1999) equilibrium gully width; and (6) Woodward's (1999) ultimate gully width. The maximum width of these the flag designated algorithms will be selected. These algorithms are:

7.1.2.3.1.1 Nachtergaele et al's (2002) Equation 10

The Nachtergaele et al's (2002) peak discharge versus gully-width relationship from equation 10 is the first algorithm to be considered:

$$W_n = 2.51 \cdot Q_p^{0.412} \quad \text{Equation 7-7}$$

where: Q_p \equiv peak discharge at gully station [cms]; and

W_n \equiv Nachtergaele et al's minimum width [m].

7.1.2.3.1.2 Gully-Located Hydraulic Geometry

The hydraulic geometry for concentrated flow can be related specifically to each cell/reach in which the gully mouth is located. All hydraulic geometry relationships are of the following form:

$$\begin{aligned} W_h &= a \cdot D_a^b \\ D_h &= c \cdot D_a^d \\ A_h &= W_h \cdot D_h \\ V_h &= \left(D_h^{2/3} \cdot \sqrt{S_0} \right) / n \\ Q &= A_h \cdot V_h \end{aligned} \quad \text{Equation 7-8}$$

where: D_a \equiv drainage area at gully station [cms];

a \equiv hydraulic geometry's width regression coefficient;

b \equiv hydraulic geometry's width regression exponent;

c \equiv hydraulic geometry's depth regression coefficient;

AnnAGNPS: Technical Descriptions

- d \equiv hydraulic geometry's depth regression exponent;
 D_h \equiv hydraulic geometry's depth [m];
 W_h \equiv hydraulic geometry's width [m];
 A_h \equiv hydraulic geometry's flow area [m²];
 V_h \equiv hydraulic geometry's flow velocity [m/sec]; and
 Q \equiv discharge [m³/sec].

Solving the above system of equations for the hydraulic geometry's minimum gully width as a function of discharge when given the hydraulic geometry coefficients and exponents as well as Manning's "n" and gully slope results in:

$$W_h = \left\{ \left(\frac{a^{(d/b)}}{c} \right)^{5/3} \cdot \left(\frac{n \cdot Q}{\sqrt{S_0}} \right) \right\}^{\left(\frac{1}{1 + [(5/3) \cdot (d/b)]} \right)}$$

Equation 7-9

- where: W_h \equiv hydraulic geometry's minimum gully width [m];
 a \equiv hydraulic geometry's width regression coefficient;
 b \equiv hydraulic geometry's width regression exponent;
 c \equiv hydraulic geometry's depth regression coefficient;
 d \equiv hydraulic geometry's depth regression exponent;
 n \equiv Manning's "n" value [?];
 S_0 \equiv gully bed slope [m/m]; and
 Q \equiv discharge [m³/sec].

7.1.2.3.1.3 [Non-submerging Tailwater](#)

The non-submerging tailwater whose depth is just at the crest of the headcut is:

$$W_s = Q_p / \left[\left(d_t^{5/3} \cdot \sqrt{S_0} \right) / n \right]$$

Equation 7-10

- Q_p \equiv peak discharge at gully station [cms];
 d_t \equiv tailwater depth;
 n \equiv Manning's "n" value [s/m^{1/3}];
 S_0 \equiv average bed slope above the nickpoint [m/m]; and
 W_s \equiv incipient submerged flow's minimum width [m].

The minimum width along the gully as the headcut migrates is the maximum of these three relationships associated with either the peak discharge of all hydrographs or the drainage area at the downstream end of the gully section which contains the headcut.

7.1.2.3.1.4 [Woodward's \(1999\) Equilibrium Gully Width](#)

In EGEM, the equilibrium width is the gully width while the headcut is deepening to its non-erosive layer.

AnnAGNPS: Technical Descriptions

$$W_e = 2.66 \cdot Q_p^{0.396} \cdot n^{0.387} \cdot S_0^{-0.160} \cdot \tau_c^{-0.240}$$

Equation 7-11

where: Q_p \equiv peak discharge at gully station [cms];

τ_c \equiv critical shear [N/m²];

n \equiv Manning's "n" value [s/m^{1/3}];

S_0 \equiv average bed slope above the nickpoint [m/m]; and

W_e \equiv equilibrium minimum gully width [m].

7.1.2.3.1.5 [Woodward's \(1999\) Ultimate Gully Width](#)

In EGEM, the ultimate width is the width at which the shear stress is equal to the critical shear stress.

$$W_u = 179.0 \cdot Q_p^{0.552} \cdot n^{0.556} \cdot S_0^{0.199} \cdot \tau_c^{-0.476}$$

Equation 7-12

where: Q_p \equiv peak discharge at gully station [cms];

τ_c \equiv critical shear [N/m²];

n \equiv Manning's "n" value [s/m^{1/3}];

S_0 \equiv average bed slope above the nickpoint [m/m]; and

W_u \equiv ultimate minimum gully width [m].

7.1.2.3.2 [Gully Mouth \(Nickpoint\)](#)

To make the solution tractable, assume that the shape of the hydrograph is triangular.

Assume a triangular hydrograph (t vs Q_n) where the time to peak (t_p) may be anywhere between zero and the time to base (t_b) (See Figure 1.).

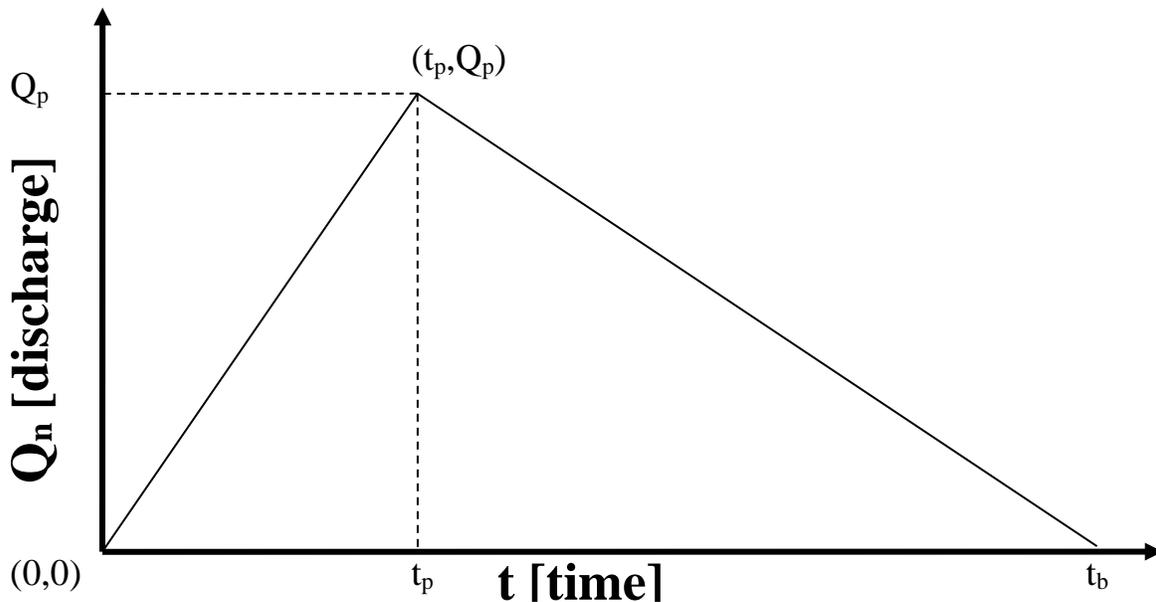


Figure 7-4: Triangular hydrograph showing the key variables.

The volume of runoff at time to base is V_b ; and the volume of runoff at the time to peak is V_p , then:

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$$V_{p,n} = \int_{t=0}^{t=t_p} Q_n dt \quad \text{Equation 7-13}$$

$$V_{b,n} = \int_{t=0}^{t=t_b} Q_n dt \quad \text{Equation 7-14}$$

where: Q_n \equiv nickpoint discharge as a function of time “t” [cms];

t_p \equiv time to peak [sec];

t_b \equiv time to base [sec];

$V_{p,n}$ \equiv volume of gully mouth (nickpoint) runoff at time to peak [m³]; and

$V_{b,n}$ \equiv total volume of gully mouth (nickpoint) runoff at time to base as determined by the effective rainfall and the SCS runoff curve number [m³].

Using the previously defined relationships, then:

$$t_{b,n} = 2 \cdot V_{b,n} / Q_{p,n} \quad \text{Equation 7-15}$$

where: $t_{b,n}$ \equiv gully mouth (nickpoint) time to base of hydrograph [sec];

$V_{b,n}$ \equiv volume of gully mouth (nickpoint) runoff at time to base “t_b” [m³]; and

$Q_{p,n}$ \equiv gully mouth (nickpoint) peak discharge at time “t_p” which is a function of the time of concentration, effective rainfall, storm type, & SCS runoff curve number and can be determined by the extended TR-55 procedure [cms].

$$t_{p,n} = 2 \cdot V_{p,n} / Q_{p,n} \quad \text{Equation 7-16}$$

where: $t_{p,n}$ \equiv gully mouth (nickpoint) time to peak of hydrograph [sec];

$V_{p,n}$ \equiv volume of gully mouth (nickpoint) runoff at time to peak “t_p” [m³]; and

$Q_{p,n}$ \equiv gully mouth (nickpoint) peak discharge at time “t_p” as determined by extended TR-55 [cms].

7.1.2.3.2.1 [Discharge as a Function of Time \(Q_n vs t\)](#)

The nickpoint discharge at anytime “t” is:

when $0 \leq t < t_p$:

$$Q_n = (t/t_p) \cdot Q_p \quad \text{Equation 7-17}$$

and when $t_p \leq t \leq t_b$:

$$Q_n = [(t_b - t)/(t_b - t_p)] \cdot Q_p \quad \text{Equation 7-18}$$

where: t \equiv the independent integration variable time during the hydrograph [sec];

t_p \equiv time to peak [sec];

AnnAGNPS: Technical Descriptions

$t_b \equiv$ time to base [sec];

$Q_n \equiv$ nickpoint discharge as a function of time “t” [cms]; and

$Q_p \equiv$ peak discharge at time “ t_p ” [cms].

7.1.2.3.2.2 [Normalization of \$Q_n\$ vs t](#)

To optimize the solution, normalize the independent integration variable “t” with respect to the time to base “ t_b ”; therefore let:

$$t' = t / t_b \quad \text{Equation 7-19}$$

then:

$$dt = t_b dt' \quad \text{Equation 7-20}$$

where: $t \equiv$ the independent integration variable time [sec];

$t' \equiv$ normalized independent integration variable time corresponding to time t with respect to time to base [non-dimensional]; and

$t_b \equiv$ time to base [sec].

To allow the time to peak be a function of an arbitrary constant “ r_p ” with respect to the time to base “ t_b ”, let:

$$r_p = V_p / V_b = t_p / t_b \quad \text{Equation 7-21}$$

where: $r_p \equiv$ ratio of time to peak (t_p) to time to base (t_b) which is equal to the ratio of the volume of runoff at t_p to the volume of runoff at t_b [non-dimensional];

$V_p \equiv$ volume of runoff at time to peak [m^3];

$V_b \equiv$ volume of runoff at time to base [m^3];

$t_p \equiv$ time to peak [sec]; and

$t_b \equiv$ time to base [sec].

Substituting Equation 7-21 into Equation 6-18 and Equation 6-19, results in the following normalized equations where only “ t' ” is a variable, the other parameters on the right-hand sides are constant:

when $0 \leq t' < r_p$:

$$Q_n = (t' / r_p) \cdot Q_p \quad \text{Equation 7-22}$$

and when $r_p \leq t' \leq 1$:

$$Q_n = [(1 - t') / (1 - r_p)] \cdot Q_p \quad \text{Equation 7-23}$$

where: $Q_n \equiv$ nickpoint discharge as a function of time “t” [cms];

$r_p \equiv$ ratio of time to peak (t_p) to time to base (t_b) which is equal to the ratio of the volume of runoff at t_p to the volume of runoff at t_b [non-dimensional]

AnnAGNPS: Technical Descriptions

t' \equiv normalized independent integration variable [[non-dimensional]]; and

Q_p \equiv peak discharge at time “ t_p ” [cms].

7.1.2.3.3 Upstream Stations

As the headcut advances upstream, its drainage area decreases. Hydraulic geometry relationships will be used to reflect this phenomenon. Power curve equations of the form $X = a \cdot Q^b$ are standard. Leopold, Maddox, and Wolman found the following relationship fits small to large watersheds throughout the world:

$$l = 80.23 \cdot D_a^{0.6} \quad \text{Equation 7-24}$$

where: l \equiv hydraulically most distant point from the gully station to the watershed divide [m]; and

D_a \equiv drainage area to the gully station [ha].

Assuming that the time of concentration to each station is a linear function of its hydraulically most distant point to the watershed divide, then:

$$t_{c,s} = t_{c,n} \cdot (l_s / l_n) = t_{c,n} \cdot (D_{a,s} / D_{a,n})^{0.6} \quad \text{Equation 7-25}$$

where: l_n \equiv hydraulically most distant point from the gully mouth (nickpoint) to the watershed divide [m];

l_s \equiv hydraulically most distant point from the gully station to the watershed divide [m];

$D_{a,n}$ \equiv drainage area to the gully mouth (nickpoint) [ha];

$D_{a,s}$ \equiv drainage area to the gully station [ha];

$t_{c,n}$ \equiv time of concentration to the gully mouth (nickpoint) [sec]; and

$t_{c,s}$ \equiv time of concentration to the gully station [sec].

The total runoff volume at each station is:

$$V_{b,s} = V_{b,n} \cdot (D_{a,s} / D_{a,n})^{0.6} \quad \text{Equation 7-26}$$

where: $D_{a,n}$ \equiv drainage area to the gully mouth (nickpoint) [ha];

$D_{a,s}$ \equiv drainage area to the gully station [ha];

$V_{b,s}$ \equiv total volume of station runoff at time to base [m³]; and

$V_{b,n}$ \equiv total volume of gully mouth (nickpoint) runoff at time to [m³].

The time to peak and time to base at each station is:

$$t_{b,s} = 2 \cdot V_{b,s} / Q_{p,s} \quad \text{Equation 7-27}$$

where: $t_{b,s}$ \equiv gully station time to base of hydrograph [sec];

$V_{b,s}$ \equiv volume of gully station runoff at time to base “ t_b ” [m³]; and

$Q_{p,s}$ \equiv gully station peak discharge at time “ t_p ” as determined by extended TR-55 [cms].

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$$t_{p,n} = 2 \cdot V_{p,n} / Q_{p,n} \quad \text{Equation 7-28}$$

where: $t_{p,n}$ \equiv gully station time to peak of hydrograph [sec];

$V_{p,n}$ \equiv volume of gully station runoff at time to peak “ t_p ” [m³]; and

$Q_{p,n}$ \equiv gully station peak discharge at time “ t_p ” as determined by extended TR-55 [cms].

The hydrographs at each station can be determined by the same procedures as at the nickpoint.

7.1.2.4 Plunge Pool Development at the Nickpoint

A nickpoint is at fixed point in the landscape and is referred to as the gully’s mouth. It is the downstream most point of an ephemeral gully. The nickpoint plunge pool, which is below the gully’s mouth, develops before the headcut begins to advance upstream.

7.1.2.4.1 Gully Width, Flow Depth, & Bed Shear

The ephemeral gully width is a function of the maximum discharge that occurs sometime during its development (Nachtergaele et al, 2001). Several different gully width relationships have been offered; e.g., Nachtergaele et al gave the following regression equation for this relationship:

$$W_n = 2.51 \cdot Q_{n,p}^{0.412} \quad \text{Equation 7-29}$$

where: W_n \equiv nickpoint gully width which is assumed to also be the flow width [m]; and

$Q_{n,p}$ \equiv nickpoint peak discharge at time “ t_p ” as determined by extended TR-55 [cms].

While the gully width relationship is extremely important to be able to quantify gully erosion, none of the current suggestions appear to be satisfactory for general usage yet. This relationship is a high priority research-need item.

Assuming uniform flow above the mouth of the gully, the flow depth upstream from the nickpoint varies with the discharge “ $Q_{n,t}$ ”, and is:

$$d_{n,t} = \left\{ \left[(n \cdot Q_{n,t}) \right] / W_n \sqrt{S_0} \right\}^{(0.6)} \quad \text{Equation 7-30}$$

where: $d_{n,t}$ \equiv depth of flow upstream of the nickpoint [m];

n \equiv Manning’s “ n ” value [s/m^{1/3}];

$Q_{n,t}$ \equiv nickpoint discharge at anytime “ t ” [cms];

W_n \equiv nickpoint flow width immediately above nickpoint [m]; and

S_0 \equiv average bed slope upstream of the nickpoint [m/m].

The average bed shear stress is:

$$\tau_{b,t} = \gamma_w \cdot d_{n,t} \cdot S_0 \quad \text{Equation 7-31}$$

where: $\tau_{b,t}$ \equiv average bed shear upstream of the nickpoint for a given discharge “ $Q_{n,t}$ ” [N/m²];

γ_w \equiv unit weight of water (9802.26) [N/m³];

$d_{n,t}$ \equiv depth of flow upstream of nickpoint at anytime “ t ” [m]; and

AnnAGNPS: Technical Descriptions

S_0 \equiv average bed slope upstream of the nickpoint [m/m].

Substituting Equation 6-31 for “ d_n ” into Equation 6-32 and normalizing the discharge with respect to the peak discharge “ $Q_{n,p}$ ”, the critical bed shear is:

$$\tau_{n,c} = (\gamma_w \cdot S_0) \cdot \left(\frac{n \cdot Q_{n,p}}{W_n \cdot \sqrt{S_0}} \right)^{0.6} \cdot \left(\frac{Q_{n,c}}{Q_{n,p}} \right)^{0.6} = \tau_{n,p} \cdot (Q_{n,c} / Q_{n,p})^{0.6} \quad \text{Equation 7-32}$$

where: $\tau_{n,c}$ \equiv nickpoint critical bed shear [N/m²];

$\tau_{n,p}$ \equiv maximum nickpoint transverse bed shear for the peak discharge [N/m²];

γ_w \equiv unit weight of water (9802.26) [N/m³];

n \equiv Manning’s “n” value [s/m^{1/3}];

$Q_{n,c}$ \equiv nickpoint discharge when the maximum transverse bed shear is equal to the critical shear [cms];

$Q_{n,p}$ \equiv nickpoint peak discharge at time “ t_p ” as determined by extended TR-55 [cms];

W_n \equiv nickpoint flow width immediately above nickpoint [m]; and

S_0 \equiv average bed slope upstream of the nickpoint [m/m].

The maximum transverse bed shear along the cross-section upstream of the nickpoint for a given uniform flow depth & bed slope is a function of the discharge “ $Q_{n,t}$ ” at anytime “ t ” and is the only parameter that is a variable. The rest of the parameters are arbitrary constants with respect to the integration. The result is:

$$\tau_{n,c} = 1.35 \cdot \tau_{b,c} = 1.35 \cdot \left[\gamma_w \cdot S_0 \cdot \left(\frac{n \cdot Q_{n,p}}{W_n \cdot \sqrt{S_0}} \right)^{0.6} \right] \cdot \left(\frac{Q_{n,c}}{Q_{n,p}} \right)^{0.6} = \tau_{n,p} \cdot \left(\frac{Q_{n,c}}{Q_{n,p}} \right)^{0.6} \quad \text{Equation 7-33}$$

where: n \equiv Manning’s “n” value [s/m^{1/3}];

$Q_{n,c}$ \equiv nickpoint discharge when the maximum transverse bed shear is equal to the critical shear [cms];

$Q_{n,p}$ \equiv nickpoint peak discharge at time “ t_p ” as determined by extended TR-55 [cms];

W_n \equiv nickpoint flow width immediately above nickpoint [m]; and

S_0 \equiv average bed slope upstream of the nickpoint [m/m];

γ_w \equiv unit weight of water (9802.26) [N/m³];

$\tau_{b,c}$ \equiv average bed shear associated with maximum nickpoint transverse bed shear r [N/m²];

$\tau_{n,c}$ \equiv maximum nickpoint transverse bed shear associated with average bed shear [N/m²];

$\tau_{n,p}$ \equiv maximum nickpoint transverse bed shear for the peak discharge [N/m²]; and

Substituting Equation 6-31 for d_n into Equation 6-32 and normalizing the discharge with respect to the peak discharge, the average bed shear stress is:

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$$\tau_{b,t} = (\gamma_w \cdot S_0) \cdot \left(\frac{n \cdot Q_{n,p}}{W_n \cdot \sqrt{S_0}} \right)^{0.6} \cdot \left(\frac{Q_{n,t}}{Q_{n,p}} \right)^{0.6}$$

Equation 7-34

where: $\tau_{b,t}$ \equiv average nickpoint bed shear at anytime “t” [N/m²];

γ_w \equiv unit weight of water (9802.26) [N/m³];

n \equiv Manning’s “n” value [s/m^{1/3}];

$Q_{n,t}$ \equiv nickpoint discharge at anytime “t” [cms];

$Q_{n,p}$ \equiv nickpoint peak discharge at time “t_p” as determined by extended TR-55 [cms];

W_n \equiv nickpoint flow width immediately above nickpoint [m]; and

S_0 \equiv average bed slope upstream of the nickpoint [m/m].

The maximum transverse bed shear along the cross-section at the nickpoint for a given flow depth & bed slope— a function of the discharge “Q_n” at anytime “t” which is the only parameter that is a variable. The rest of the parameters are arbitrary constants with respect to the integration. The result is:

$$\tau_{x,t} = 1.35 \cdot \tau_{b,t} = 1.35 \cdot \left[\gamma_w \cdot S_0 \cdot \left(\frac{n \cdot Q_{n,p}}{W_n \cdot \sqrt{S_0}} \right)^{0.6} \right] \cdot \left(\frac{Q_{n,t}}{Q_{n,p}} \right)^{0.6} = \tau_{x,p} \cdot \left(\frac{Q_{n,t}}{Q_{n,p}} \right)^{0.6}$$

Equation 7-35

where: n \equiv Manning’s “n” value [s/m^{1/3}];

$Q_{n,t}$ \equiv nickpoint discharge at anytime “t” [cms];

$Q_{n,p}$ \equiv nickpoint peak discharge at time “t_p” as determined by extended TR-55 [cms];

W_n \equiv nickpoint flow width immediately above nickpoint [m]; and

S_0 \equiv average bed slope upstream of the nickpoint [m/m];

γ_w \equiv unit weight of water (9802.26) [N/m³];

$\tau_{b,t}$ \equiv average bed shear at anytime “t” [N/m²];

$\tau_{x,t}$ \equiv maximum nickpoint transverse bed shear corresponding to the average bed shear at anytime “t” [N/m²]; and

$\tau_{n,p}$ \equiv maximum nickpoint transverse bed shear for the peak discharge [N/m²]; and

7.1.2.4.2 Rate of Nickpoint Development

The rate of development of the depth of the nickpoint’s headcut is:

$$\text{When } D_{n,t} < D_{n,x}: dD_{n,t} / dt = \left[(k_n / \gamma_s) \cdot (\tau_{n,t} - \tau_{n,c}) \right]; \text{ and}$$

$$\text{when } D_{n,t} = D_{n,x}: dD_{n,t} / dt = 0$$

Equation 7-36

where: $D_{n,t}$ \equiv nickpoint headcut depth at anytime “t” [m];

$D_{n,x}$ \equiv maximum nickpoint headcut depth to non-erosive soil layer [m];

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- k_n \equiv nickpoint erodibility rate coefficient for the erosive soil layer [Mg/N/s];
 t \equiv anytime during the hydrograph [sec];
 $\tau_{n,t}$ \equiv maximum nickpoint transverse bed shear for a discharge “ $Q_{n,t}$ ” at anytime “ t ” [N/m²];
 $\tau_{n,c}$ \equiv critical shear stress of the soil below which there is no erosion [N/m²]; and
 γ_s \equiv bulk density of the *insitu* soil [Mg/m³].

7.1.2.4.2.1 [Integration for rate of Development](#)

So, using separation of variables, the headcut development at the nickpoint can be determined by integrating Equation 6-37 over the proper limits:

$$\int_{D_{n1}}^{D_{n2}} dD_{n,t} = \int_{t_{c1}}^{t_2 \leq t_{c2}} \left[(k_n / \gamma_s) \cdot (\tau_{x,t} - \tau_{n,c}) \right] dt \quad \text{Equation 7-37}$$

- where: $D_{n,t}$ \equiv nickpoint headcut depth at anytime “ t ” [m];
- D_{n1} \equiv depth of headcut at the beginning of the nickpoint development for this hydrograph (t_1) [m];
- D_{n2} \equiv depth of headcut at the end of the nickpoint development for this hydrograph (t_2) [m];
- k_n \equiv nickpoint erodibility rate coefficient [Mg/N/s];
- t \equiv anytime during the hydrograph [sec];
- t_{c1} \equiv time at which the discharge along the ascending limb of the hydrograph’s maximum transverse bed shear reaches critical stress ($\tau_x = \tau_c$) [sec];
- t_{c2} \equiv time at which the discharge along the descending limb of the hydrograph’s maximum transverse bed shear reaches critical stress ($\tau_x = \tau_c$) [sec];
- t_2 \equiv time at which the discharge along the descending limb of the hydrograph’s maximum transverse bed shear reaches depth stress ($\tau_x = \tau_c$) or the headcut depth reaches the non-erosive soil layer ($D_{n,t} = D_{n,x}$), whichever occurs first [sec];
- $\tau_{n,c}$ \equiv critical shear stress of the soil below which there is no erosion [N/m²];
- $\tau_{x,t}$ \equiv maximum transverse bed shear along at the nickpoint [N/m²]; and
- γ_s \equiv bulk density of the *insitu* soil [Mg/m³].

The left-hand side of Equation 6-38 can easily be integrated as:

$$\int_{D_{n1}}^{D_{n2}} dD_{n,t} = D_{n2} - D_{n1} = \Delta D_{n,t} \quad \text{Equation 7-38}$$

- where: $D_{n,t}$ \equiv nickpoint headcut depth at anytime “ t ” [m];
- $\Delta D_{n,t}$ \equiv incremental depth of headcut at ant time “ t ” [m];
- D_{n1} \equiv depth of headcut at the beginning of the nickpoint development for this hydrograph (t_1) [m]; and
- D_{n2} \equiv depth of headcut at the end of the nickpoint development for this hydrograph (t_2) [m].

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Since only the average bed shear (τ_b) varies as a function of time (t) and the rest of the parameters are constants, the right-hand side of Equation 6-38 can be integrated easily using separation of variables with the appropriate substitutions including the normalization for time. Extracting the arbitrary constants from within the integration and normalizing the right-hand side of Equation 6-38 by dividing all time variables by the time to base results in:

$$\int_{t_{c1}}^{t_2 \leq t_{c2}} \left[(k_n / \gamma_s) \cdot (\tau_{x,t} - \tau_{n,c}) \right] dt = \left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \int_{t'_{c1}}^{t'_2 \leq t'_{c2}} (\tau_{x,t} - \tau_{n,c}) dt' \quad \text{Equation 7-39}$$

- where: k_n \equiv nickpoint erodibility rate coefficient [Mg/N/s];
 t \equiv anytime during the hydrograph [sec];
 t_2 \equiv time at which the discharge along the descending limb of the hydrograph's maximum transverse bed shear reaches critical shear ($\tau_x = \tau_c$) or the headcut depth reaches the non-erosive soil layer ($D_{n,t} = D_{n,x}$) whichever occurs first [sec];
 t_b \equiv time to base [sec];
 t_{c1} \equiv time at which the discharge along the ascending limb of the hydrograph's maximum transverse bed shear reaches critical stress ($\tau_x = \tau_c$) [sec];
 t_{c2} \equiv time at which the discharge along the descending limb of the hydrograph's maximum transverse bed shear reaches critical stress ($\tau_x = \tau_c$) [sec];
 $t' = t / t_b$ \equiv normalized time during the hydrograph [[non-dimensional];
 $t'_2 = t_2 / t_b$ \equiv normalized time at which the discharge along the descending limb of the hydrograph's maximum transverse bed shear reaches critical stress ($\tau_x = \tau_c$) or the headcut reaches the non-erosive soil layer ($D_{n,t} = D_{n,x}$), whichever occurs first [non-dimensional];
 $t'_{c1} = t_{c1} / t_b$ \equiv normalized time at which the discharge along the ascending limb of the hydrograph's maximum transverse bed shear reaches critical stress ($\tau_x = \tau_c$) [non-dimensional];
 $t'_{c2} = t_{c2} / t_b$ \equiv normalized time at which the discharge along the descending limb of the hydrograph's maximum transverse bed shear reaches critical stress ($\tau_x = \tau_c$) [sec];
 $\tau_{n,c}$ \equiv critical shear stress of the soil below which there is no erosion [N/m²];
 $\tau_{x,t}$ \equiv maximum nickpoint transverse bed shear along [N/m²]; and
 γ_s \equiv bulk density of the *insitu* soil [Mg/m³].

The resulting equations after appropriate substitutions into Equation 6-40 for the maximum nickpoint transverse bed shear and before integration are:

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$$\text{If } 0 \leq t'_2 < t'_p, \text{ then: } D_{n2} - D_{n1} = \left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \left\{ \int_{t'_{c1}}^{t'_2} \left[\tau_{n,p} \cdot (t'/r_p)^{0.6} \right] dt' - \int_{t'_{c1}}^{t'_2} \left[\tau_{n,c} \right] dt' \right\}$$

If $t'_p \leq t'_2 \leq 1$, then:

$$D_{n2} - D_{n1} = \left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \left\{ \left[\int_{t'_{c1}}^{t'_p} \left[\tau_{n,p} \cdot (t'/r_p)^{0.6} \right] dt' + \int_{t'_p}^{t'_2} \left[\tau_{n,p} \cdot \left(\frac{1-t'}{1-r_p} \right)^{0.6} \right] dt' \right] - \left[\int_{t'_{c1}}^{t'_2} \left[\tau_{n,p} \cdot \left(\frac{Q_{n,c}}{Q_{n,p}} \right)^{0.6} \right] dt' \right] \right\}$$

Equation 7-40

- where: $D_{n1} \equiv$ depth of headcut at the beginning of the nickpoint development for this hydrograph (t_1) [m]; and
- $D_{n2} \equiv$ depth of headcut at the end of the nickpoint development for this hydrograph (t_2) [m];
- $k_n \equiv$ nickpoint erodibility rate coefficient [Mg/N/s];
- $Q_{n,c} \equiv$ nickpoint discharge when the maximum transverse bed shear is equal to the critical shear [cms];
- $Q_{n,p} \equiv$ nickpoint peak discharge at time “ t_p ” as determined by extended TR-55 [cms];
- $r_p \equiv$ ratio of time to peak (t_p) to time to base (t_b) which is equal to the ratio of the volume of runoff at t_p to the volume of runoff at t_b [non-dimensional]
- $t_b \equiv$ time to base [sec];
- $t' = t/t_b \equiv$ normalized time during the hydrograph [[non-dimensional];
- $t'_{c1} = t_{c1}/t_b \equiv$ normalized time at which the discharge along the ascending limb of the hydrograph’s maximum transverse bed shear reaches critical stress ($\tau_x = \tau_c$) [non-dimensional];
- $t'_2 = t_2/t_b \equiv$ normalized time at which the discharge along the descending limb of the hydrograph’s maximum transverse bed shear reaches critical stress ($\tau_x = \tau_c$) or the headcut reaches the non-erosive soil layer ($D_{n,t} = D_{n,x}$), whichever occurs first [non-dimensional];
- $t'_p = t_p/t_b \equiv$ normalized time to peak [non-dimensional];
- $\tau_{n,c} \equiv$ critical shear stress of the soil below which there is no erosion [N/m²];
- $\tau_{n,p} \equiv$ maximum nickpoint transverse bed shear for the peak discharge [N/m²]; and
- $\gamma_s \equiv$ bulk density of the *insitu* soil [Mg/m³].

The normalized integrals in Equation 6-41 can easily be solved. Remembering that $t'_p = r_p$, then when $0 < t'_2 < t'_p$:

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$$\left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_{c1}}^{t'_2} (t'/t_p)^{0.6} dt' \right] = \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[(t_2^{1.6} - t_{c1}^{1.6}) / (1.6 \cdot t_p^{0.6}) \right];$$

$$\text{let, } n_c = \left(\frac{k_n \cdot t_b \cdot \tau_{n,p}}{\gamma_s} \right);$$

$$\text{then, } \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_{c1}}^{t'_2} (t'/t_p)^{0.6} dt' \right] = n_c \cdot \left[(t_2^{1.6} - t_{c1}^{1.6}) / (1.6 \cdot t_p^{0.6}) \right]; \quad \text{Equation 7-41}$$

$$\text{and then let, } a = n_c / (1.6 \cdot t_p^{0.6});$$

$$\text{results in, } \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_{c1}}^{t'_2} (t'/t_p)^{0.6} dt' \right] = a \cdot (t_2^{1.6} - t_{c1}^{1.6})$$

And when $t'_p \leq t'_2 \leq t'_b$, then Equation 6-41 must be solved in two parts as :

$$\left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_{c1}}^{t'_2} (t'/t_p)^{0.6} dt' \right] = \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left\{ \left[\int_{t'_{c1}}^{t'_p} (t'/t_p)^{0.6} dt' \right] + \left[\int_{t'_p}^{t'_2} \left[\frac{(1-t')}{(1-t_p)} \right]^{0.6} dt' \right] \right\}$$

Equation 7-42

The first part is where $t'_{c1} \leq t' < t'_p$ and $t'_p = r_p$:

$$\left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_{c1}}^{t'_p} (t'/t_p)^{0.6} dt' \right] = \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[(t_p^{1.6} - t_{c1}^{1.6}) / (1.6 \cdot t_p^{0.6}) \right];$$

$$\text{let, } n_c = \left(\frac{k_n \cdot t_b \cdot \tau_{n,p}}{\gamma_s} \right);$$

Equation 7-43

$$\text{then, } \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_{c1}}^{t'_p} (t'/t_p)^{0.6} dt' \right] = n_c \cdot \left[(t_p^{1.6} - t_{c1}^{1.6}) / (1.6 \cdot t_p^{0.6}) \right]$$

$$\text{and then again let } a = n_c / (1.6 \cdot t_p^{0.6});$$

$$\text{results in } \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_{c1}}^{t'_p} (t'/t_p)^{0.6} dt' \right] = a \cdot (t_p^{1.6} - t_{c1}^{1.6})$$

Equation 7-44

And the second part is where $t'_p \leq t' \leq t'_b$ and $t'_p = r_p$:

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$$\left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_p}^{t'_2} \left[(1-t') / (1-t'_p) \right]^{0.6} dt' \right] = \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\frac{(1-t_p)^{1.6} - (1-t'_2)^{1.6}}{1.6 \cdot (1-t'_p)^{0.6}} \right]$$

$$\text{let, } n_c = \left(\frac{k_n \cdot t_b \cdot \tau_{n,p}}{\gamma_s} \right);$$

$$\text{then, } \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_p}^{t'_2} \left[(1-t') / (1-t'_p) \right]^{0.6} dt' \right] = n_c \cdot \left\{ \frac{\left[(1-t'_p)^{1.6} - (1-t'_2)^{1.6} \right]}{\left[1.6 \cdot (1-t'_p)^{0.6} \right]} \right\}$$

Equation 7-45

$$\text{and then let, } b = n_c / \left[1.6 \cdot (1-t'_p)^{0.6} \right]$$

$$\text{results in, } \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,p} \right] \cdot \left[\int_{t'_p}^{t'_2} \left[(1-t') / (1-t'_p) \right]^{0.6} dt' \right] = b \cdot \left[(1-t'_p)^{1.6} - (1-t'_2)^{1.6} \right]$$

Equation 7-46

The critical shear term is:

$$\left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,c} \right] \cdot \left[\int_{t'_{c1}}^{t'_2} dt' \right] = \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,c} \right] \cdot (t'_2 - t'_{c1})$$

$$\text{let, } n_c = \left(\frac{k_n \cdot t_b \cdot \tau_{n,p}}{\gamma_s} \right) \text{ and } c = n_c \cdot \left(\frac{Q_{n,c}}{Q_{n,p}} \right)^{0.6}$$

$$\text{then, } \left[\left(\frac{k_n \cdot t_b}{\gamma_s} \right) \cdot \tau_{n,c} \right] \cdot \left[\int_{t'_{c1}}^{t'_2} dt' \right] = c \cdot (t'_2 - t'_{c1})$$

Equation 7-47

where: $a, b, c, \& n_c \equiv$ constants as defined above where n_c is a normalization & simplification constant [m];

$k_n \equiv$ nickpoint erodibility rate coefficient for erosive soil layer [Mg/N/s];

$Q_{n,c} \equiv$ nickpoint discharge when the maximum transverse bed shear is equal to the critical shear [cms];

$Q_{n,p} \equiv$ nickpoint peak discharge at time “ t_p ” as determined by extended TR-55 [cms];

$r_p \equiv$ ratio of time to peak (t_p) to time to base (t_b) which is equal to the ratio of the volumes of runoff at the respect times [non-dimensional];

$t' = t / t_b \equiv$ normalized time during the hydrograph [[non-dimensional];

$t'_{c1} = t_{c1} / t_b \equiv$ normalized time at which the discharge along the ascending limb of the hydrograph's maximum transverse bed shear reaches critical stress ($\tau_x = \tau_c$) [non-dimensional];

$t'_2 = t_2 / t_b \equiv$ normalized time at which the discharge along the descending limb of the hydrograph's maximum transverse bed shear reaches critical stress ($\tau_x = \tau_c$) or the headcut reaches the non-erosive soil layer ($D_{n,t} = D_{n,x}$), whichever occurs first [non-dimensional];

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$t'_p = t_p / t_b \equiv$ normalized time to peak [non-dimensional];

$\tau_{n,c} \equiv$ critical shear stress of the soil below which there is no erosion [N/m²];

$\tau_{n,p} \equiv$ maximum nickpoint transverse bed shear for the peak discharge [N/m²]; and

$\gamma_s \equiv$ bulk density of the insitu soil [Mg/m³].

7.1.2.4.2.2 Integration Limits

The integration limits can be directly determined at the point when the hydrograph's discharge causes the maximum transverse bed shear to be equal to the critical shear for the soil.

$$d_{n,c} = \tau_{n,c} / (1.35 \cdot \gamma_w \cdot S_0) \quad \text{Equation 7-48}$$

where: $d_{n,c} \equiv$ nickpoint flow depth for the discharge when maximum transverse bed shear stress is critical [m];

$S_0 \equiv$ average bed slope above the nickpoint [m/m];

$\tau_{n,c} \equiv$ critical shear stress of the soil below which there is no erosion [N/m²]; and

$\gamma_w \equiv$ unit weight of water (9802.26) [N/m³].

Then the discharge at critical bed shear is:

$$Q_{n,c} = \left[(W_n \cdot \sqrt{S_0}) / n \right] \cdot d_{n,c}^{5/3} \quad \text{Equation 7-49}$$

where: $d_{n,c} \equiv$ nickpoint flow depth for the discharge when maximum transverse bed shear stress is critical [m];

$n \equiv$ Manning's "n" value [s/m^{1/3}];

$S_0 \equiv$ average bed slope above the nickpoint [m/m];

$Q_{n,c} \equiv$ discharge when maximum transverse bed shear is critical [cms]; and

$W_n \equiv$ nickpoint gully width [m].

Along the ascending limb:

$$t'_{c1} = r_p \cdot (Q_{n,c} / Q_{n,p}) = t'_p \cdot (Q_{n,c} / Q_{n,p});$$

let, $Q'_c = Q_{n,c} / Q_{n,p}$; then

$$t'_{c1} = t'_p \cdot Q'_c \quad \text{Equation 7-50}$$

and when $r_p = t_p > 0$, then

$$Q_{n,c} / Q_{n,p} = t'_{c1} / t'_p \quad \text{Equation 7-51}$$

and along the descending limb

$$t'_{c2} = 1 - \left[(1 - r_p) \cdot (Q_{n,c} / Q_{n,p}) \right] = 1 - \left[(1 - t'_p) \cdot (Q_{n,c} / Q_{n,p}) \right] \quad \text{Equation 7-52}$$

and when $r_p = t_p < 1$, then

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$$Q'_c = (1 - t'_{c2}) / (1 - t'_p)$$

Equation 7-53

where: $Q_{n,c}$ \equiv discharge when maximum transverse bed shear is critical [cms];

$Q_{n,p}$ \equiv peak discharge at time “tp” [cms].

Q'_c \equiv relative critical shear discharge—ratio of critical shear discharge to peak discharge [-].

r_p \equiv ratio of time to peak (tp) to time to base (tb) which is equal to the ratio of the volume of runoff at tp to the volume of runoff at tb [non-dimensional];

$t'_{c1} = t_{c1} / t_b$ \equiv normalized time at which the discharge along the ascending limb of the hydrograph’s maximum transverse bed shear reaches critical stress ($\tau_x = \tau_c$) [non-dimensional];

$t'_{c2} = t_{c2} / t_b$ \equiv normalized time at which the discharge along the descending limb of the hydrograph’s maximum transverse bed shear reaches critical stress ($\tau_x = \tau_c$) [sec];

$t'_p = t_p / t_b$ \equiv normalized time to peak [non-dimensional];

NICKPOINT DEVELOPMENT

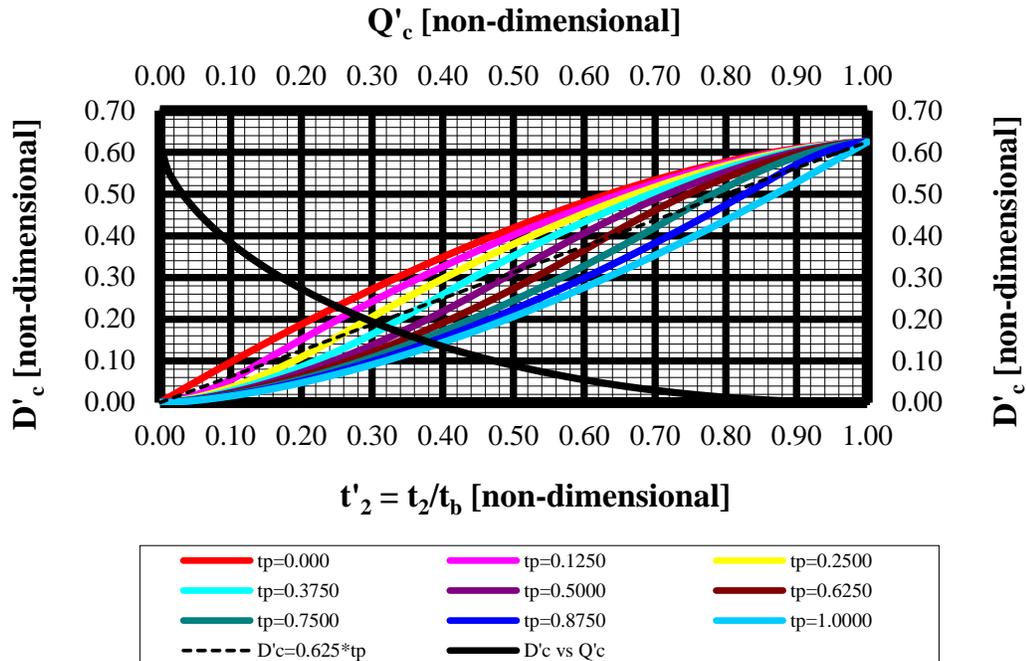


Figure 7-5. Normalized times versus nickpoint depth development showing erosivity (D'_c) versus critical shear discharge ratio (Q'_c) and erosivity (D'_2) versus relative times (t'_2) for time to peaks (t'_p) ranging from 0 to time to base ($t'_b=1$) when critical shear (τ_c) is equal to 0.

7.1.2.5 Headcut Migration (advancement)

The migration rate of the gully headcut (M , m s^{-1}) is determined as described by Alonso et al. (2002) and restated by Gordon et al. (2007). Headcut migration rate (M , m s^{-1}) is determined by:

$$M = V \sqrt{\frac{\mu q}{S_D - h}}$$

where V is the jet entry velocity (m s^{-1}), q is unit discharge (m^2s^{-1}), S_D is the scour depth, which is assumed equal to the tillage depth (m) or as defined by the user, h is vertical distance from the brink to the pool surface(m).

$$\mu = 0.5\rho_w k_d \sin^2\left(\frac{\theta}{2}\right)$$

θ is jet entry angle (radians),

$$h = S_D - d$$

d is the flow depth(m),

B_{ij} is the flow depth at the headcut brinkpoint (m), Fr is Froude number upstream of the brinkpoint ($Fr_{ij} = u_{ij}/[gd_{ij}]^{0.5}$), T_e is the arc tangent of the jet entry angle for gravitational ventilated jets, and α and β are calibrating pressure-gradient and suction-head coefficients (Alonso et al., 2002), herein taken as 2 and 0.3, respectively.

7.1.2.5.1 Headcut Dimensions

The brink point parameters are based upon the dimensions shown in Figure 7-6. Assumptions are: (1) unit slice; (2) ventilated overfall; and (3) free overfall (no significant back pressure of the downstream flow on the flow at the headcut).

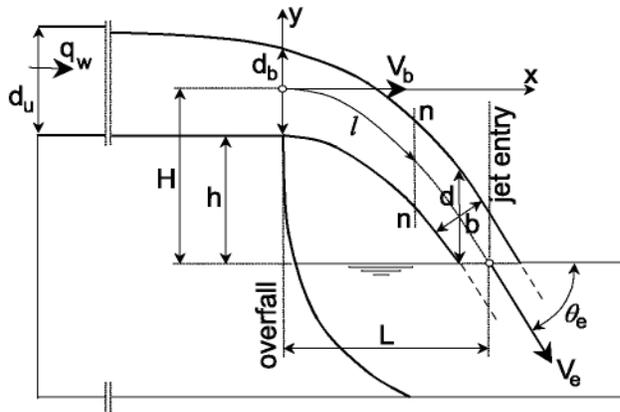


Figure 7-6. Definition sketch of a flow profile over a ventilated overfall (after Alonso & Bennett, 2002).

The unit slice discharge is:

$$q_w = Q/W$$

Equation 7-54

The upstream depth of flow is assumed to be normal, therefore:

$$d_u = \left[(n \cdot q) / \sqrt{S_0} \right]^{3/5}$$

Equation 7-55

And the upstream flow's Froude number is:

$$F_u = (q_w / d_u) / \sqrt{(g \cdot d_u)}$$

Equation 7-56

Critical depth, assuming minimum specific energy, is:

$$d_c = \left[q_w^2 / (2 \cdot g) \right]^{1/3}$$

Equation 7-57

The depth of flow at the brink will always be less than critical depth, therefore:

$$\text{If } F_u > 1, \text{ then: } d_b = \left[F_u^2 / (F_u^2 + 0.4) \right] \cdot d_u;$$

$$\text{If } F_u \leq 1, \text{ then: } d_b = \text{MIN} \left[(d_u / 1.4), (C_c \cdot d_c) \right]$$

Equation 7-58

7.1.2.5.2 Headcut Scour Pool

A headcut scour pool forms initially at the nickpoint (gully mouth) before migrating upstream; then the scour pool advances upstream along with the headcut.

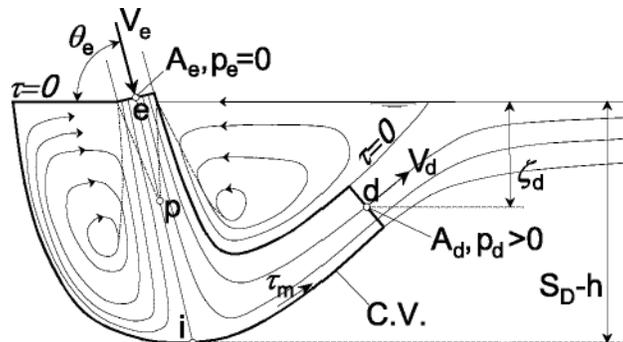


Figure 7-7: Definition sketch of flow pattern in the pool region showing impinging and wall jets, confined eddies, and control volume used in energy balance analysis. It should be noted that shear friction is neglected along the interface between the downstream wall jet and captive eddy. (after Alonso & Bennett, 2002).

7.1.2.5.3 Gully Width Adjustment

Of the three space dimensions which define an ephemeral gully, possibly the most sensitive one is the width because there are many, widely divergent empirical relationships offered resulting in large variations in estimated gully erosion. Until research offers better science, the following algorithm is used.

By default, five different relationships are available. The user can select any combination; i.e., the user can eliminate up to any four of the five ephemeral gully width relationships. The five are:

1. Nachtergaele et al— $W = 2.51 * (Q^{0.412})$;
2. Hydraulic Geometry— $W = a * (D_a^b)$;
3. Tailwater non-submergence— $W = Q / \{[(D^{5/3}) * (S^{1/2})] / n\}$;

AnnAGNPS: Technical Descriptions

4. Woodward's equilibrium width— $W = 2.66 * (Q^{0.396}) * (n^{0.387}) / [(s^{0.16}) * \tau_c^{0.24}]$; and

5. Woodward's ultimate width— $W = 179.0 * (Q^{0.552}) * (n^{0.556}) * [(s^{0.199}) / \tau_c^{0.476}]$.

Where: $a \equiv$ default or user-supplied hydraulic geometry coefficient for width versus drainage area [m];

$b \equiv$ default or user-supplied hydraulic geometry exponent for width versus drainage area [-];

$D \equiv$ headcut depth [m];

$D_a \equiv$ drainage area to headcut [ha];

$N \equiv$ manning's "n" value for ephemeral gully; [?];

$Q \equiv$ discharge [m^3/s];

$S \equiv$ ephemeral gully thalweg slope [m/m];

$W \equiv$ ephemeral gully width [m];

$\tau_c \equiv$ critical shear of soil being eroded [N/m^2]

AnnAGNPS select's the greatest of the allowable ephemeral gully widths where the allowable which, either by default or by user choice, may be any combination of the five. Once the gully has a fully developed nickpoint at the mouth of the ephemeral gully, a sixth candidate width is added unless the ephemeral gully is repaired. This already formed gully width is subject to the previous calculated gully width; i.e., the gully width formed during previous events. This condition must be checked to make certain that the gully width narrows as the headcut migrates upstream resulting in a reduction in drainage area.

AnnAGNPS allows for ephemeral gully repairs where tillage operations (or deliberate repairs) fill the gully so that the ephemeral gully formation must begin with the formation of the nickpoint all over again.

7.1.2.6 [Sediment Transport of Deposition](#)

The HUSLE (Theurer and Clarke, 1991) components are utilized for sediment transport determination from the ephemeral gully.

7.2 Channel Sediment Processes

7.2.1 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_{s1}) 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})

AnnAGNPS: Technical Descriptions

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:

$$C_s = S_m/W \quad \text{Equation 7-59}$$

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:

$$q_s = c_s q_w \quad \text{Equation 7-60}$$

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:

$$U_* = [g \cdot d_w \cdot S_o]^{1/2} = g^{0.5} \cdot n^{0.3} \cdot S_o^{0.35} \cdot q_w^{0.3} \quad \text{Equation 7-61}$$

where: d_w = hydraulic depth at x_2 , m;
 g = gravitational constant, 9.81 m/sec²;
 q_w = unit-width water discharge, m³/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:

$$q_{sc} = \eta \cdot k \cdot \tau \cdot v_w^2 / v_f \quad \text{Equation 7-62}$$

where: q_{sc} = unit-width sediment transport capacity, Mg/s/m;
 η = effective transport factor, non-dimensional;
 k = transport capacity factor (see Table 7-5), non-dimensional;
 τ = bed shear stress; Mg/m²
 v_w = flow velocity of water, m/s; and
 v_f = particle fall velocity (see Table 7-5), m/s.

The effective transport factor currently estimated as:

$$\eta = 0.322 \cdot [(\gamma_p - \gamma_w) / (\tau / D_p)]^{1.626} \leq 1 \quad \text{Equation 7-63}$$

where: η = effective transport factor, non-dimensional;
 τ = bed shear stress; Mg/m²;
 γ_w = 1.00, water density, Mg/m³;
 γ_p = particle density, (see Table 7-5), Mg/m³; and

AnnAGNPS: Technical Descriptions

D_p = equivalent sand size particle diameter (see Table 7-5),
m.

The bed shear stress can be computed as follows:

$$\tau = \gamma_w \cdot d_w \cdot S \quad \text{Equation 7-64}$$

where: τ = bed shear stress; Mg/m²
 $\gamma_w = 1.00$, water density, Mg/m³;
 d_w = hydraulic depth, m; and
 S_o = channel slope, m/m.

**Table 7-5. Particle-size Class Physical Properties
(after Young et al 1987)**

Particle-size Class	Particle Size Range (mm)	γ_p Particle Density (Mg/m ³)	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	$1.65 \cdot 10^{+1}$	$16.631 \cdot 10^{-3}$	$5.00 \cdot 10^{-1}$

Table 7-5 contains the physical properties for each particle-size class (note D_p is in millimeters and v_f is in millimeters per second).

Substituting **Equation 7-64** into **Equation 7-63** and using Equation 6-103 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:

$$\eta = [C_1 / (n^{0.6} \cdot S_o^{0.7} \cdot q_w^{0.6})]^{1.626} \leq 1, \text{ and}$$

$$C_1 = \{[D_p/2004] \cdot [(\gamma_p - \gamma_w) / \gamma_w]\} \quad \text{Equation 7-65}$$

where: η = effective transport factor, non-dimensional;
 $\gamma_w = 1.00$, water density, Mg/m³;
 γ_p = particle density, (see Table 7-6), Mg/m³;
 C_1 = particle-size class constant for the effective transport factor (see Table 7-6), m;
 D_p = particle diameter (see Table 7-6), mm;
 n = Manning's retardance;
 q_w = unit-width water discharge, m³/s/m; and
 S_o = channel slope, m/m.

The effective transport factor (η) is equal to 1 when $S_o \cdot d_w = C_1$. Therefore, using Equation 6-104 in Equation 7-65, results in:

AnnAGNPS: Technical Descriptions

$$q_{\eta} = [C_1 / (n^{0.6} \cdot S_0^{0.7})]^{5/3} \quad \text{Equation 7-66}$$

where: q_{η} = critical unit-width water discharge below which effective transport factor (η) is 1 and above which it is calculated according to **Equation 7-65**, $m^3/s/m$;
 C_1 = particle-size class constant for the effective transport factor (see Table 7-6), m ;
 n = Manning's retardance; and
 S_0 = channel slope, m/m .

And the critical unit-width water discharge (q_{η}) occurs at the critical transport factor time (t_{η}). When $0 \geq t < t_{\eta}$, $\eta = 1$; and when $t \geq t_{\eta}$, η is solved according to Equation 7-65.

$$t_{\eta} = t_b \cdot (q_{\eta} / q_p) \quad \text{Equation 7-67}$$

where: t_{η} = critical effective transport factor time, when $t < t_{\eta}$ $\eta = 1$, s ;
 q_{η} = critical unit-width water discharge below which effective transport factor (η) is 1 and above which it is calculated according to **Equation 7-65**, $m^3/s/m$;
 q_p = unit-width peak discharge, $m^3/s/m$; and
 t_b = time to base, s .

Combining Equation 7-62 and Equation 7-65, correcting for v_f in millimeters per second to meters per second, and using Equation 7-66 results in:

For $0 \leq t \leq t_{\eta}$:

$$C_2 = 322 \cdot k \cdot \gamma_w / v_f, \text{ and}$$

$$q_{sc} = C_2 \cdot n^{-0.6} \cdot S_0^{1.3} \cdot q_w^{1.4}$$

For $t \geq t_{\eta}$:

$$C_3 = C_{11.626} \cdot C_2, \text{ and}$$

$$q_{sc} = C_3 \cdot n^{-1.5756} \cdot S_0^{0.1618} \cdot q_w^{0.4244} \quad \text{Equation 7-68}$$

where: q_{sc} = unit-width sediment transport capacity, $Mg/s/m$;
 C_1 = particle-size class constant for the effective transport factor (see Table 7-6), m ;
 C_2 = particle-size class constant for the sediment transport capacity for $\eta = 1$ (see Table 7-6), $Mg-s/m^4$;
 C_3 = particle-size class constant for the sediment transport capacity for $\eta < 1$ (see Table 7-6), $Mg-s/m^{2.374}$;
 k = transport capacity factor (see Table 7-5), 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_{η} = critical effective transport factor time, s ;
 t_b = time to base of hydrograph, s ;
 v_f = particle fall velocity (see Table 7-5), mm/s ; and
 $\gamma_w = 1.00$, water density, Mg/m^3 .

Using $0 \leq t \leq t_b$ Equation 6-117 and Equation 6-118 in Equation 7-68, the total sediment transport capacity for the hydrograph is:

When $t_{\eta} \geq t_b$ is:

AnnAGNPS: Technical Descriptions

$$S_{sc} = \int_0^{t_b} (W \cdot q_{sc}) dt = W \cdot C_2 \cdot n^{-0.6} \cdot S_0^{1.3} \cdot q_p^{1.4} \cdot t_b / 2.4$$

Equation 7-69

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 7-70

where:

- C_2 = particle-size class constant for the sediment transport capacity for $\eta = 1$ (see Table 7-6), Mg-s/m⁴;
- C_3 = particle-size class constant for the sediment transport capacity for $\eta < 1$ (see Table 7-6), Mg-s/m^{2.374};
- n = Manning's retardance;
- q_p = unit-width peak discharge, m³/s/m;
- q_{sc} = unit-width sediment transport capacity, Mg/s/m;
- q_η = critical unit-width water discharge below which effective transport factor (η) is 1 and above which it is calculated according to **Equation 7-65**, m³/s/m;
- S_{sc} = total sediment transport capacity mass, Mg.
- S_0 = channel slope, m/m.
- t = time from beginning of runoff, s;
- t_η = critical effective transport factor time, s;
- t_b = time to base, s; and
- W = flow width, m.

Table 7-6 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 7-6: Sediment Particle-size Class Sediment Transport Capacity Values

Sediment Class	D_p (mm)	γ_p (Mg/m ³)	v_f (mm/s)	k (-)	C_1 (m)	C_2 (Mg-s/m ⁴)	C_3 (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. For AnnAGNPS cells that represent the only source to a reach, the upstream sediment discharges (q_{s1}) of that reach will consist only of local loadings since there is no incoming sediment from upstream reaches to a AnnAGNPS cell.

AnnAGNPS: Technical Descriptions

$$q_{s2} = q_{sc} + [(q_{s1} - q_{sc}) \cdot \exp(-N_d)] \quad \text{Equation 7-71}$$

where: N_d = deposition number, non-dimensional;
 q_{sc} = unit-width sediment transport capacity, 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;

The determination of the deposition number, N_d , is performed using the following equation:

$$N_d = (A_E \cdot v_f \cdot L_2) / q_w \quad \text{Equation 7-72}$$

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 7-73**);
 v_f = particle fall velocity, m/s.
 L_2 = distance from x_1 to x_2 , m; and
 q_w = unit-width water discharge, m³/s/m.

For clay, silt, and small aggregates, $A_E = 1$; for sand and large aggregates, use:

$$A_E = [(6 \cdot v_f) / (\kappa \cdot U^*)] / \{1 - \exp[-(6 \cdot v_f) / (\kappa \cdot U^*)]\} \quad \text{Equation 7-73}$$

where: κ = von Karman's turbulent-flow mixing-length constant (assume 0.4), non-dimensional;
 U^* = shear velocity at x_1 (see **Equation 7-61**), m/s; and
 vf = 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 reaches with only AnnAGNPS source 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 other AnnAGNPS 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 (ω_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 7-7.

Table 7-7: 15-Point Gaussian-Legendre Quadrature for Numerical Integration

Point No.	t_i/t_b	ω_i
1	.006003741	.015376621
2	.031363304	.035183024
3	.075896109	.053579610
4	.137791135	.069785339
5	.214513914	.083134603
6	.302924330	.093080500

AnnAGNPS: Technical Descriptions

Point No.	t_i/t_b	ω_i
7	.399402954	.099215743
8	.500000000	.101289120
9	.600597047	.099215743
10	.697075674	.093080500
11	.785486087	.083134603
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 7-74

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.

7.2.2 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 7-8 contains the default conditions regarding the availability of a particle-size class in the channel bed.

Table 7-8: 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 7-9 is the decision table for all possible combinations of scour indicators for the five particle-size classes.

AnnAGNPS: Technical Descriptions

Table 7-9: Bed & 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

AnnAGNPS: Technical Descriptions

8. 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 8-1;
- 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_0); (4) runoff event water volume (V_I); 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:

$$\text{sediment_out} = \left\{ \left[\frac{\text{total_inflow}}{\text{total_inflow} + (\text{mixing_coef} * \text{permanent_storage})} \right] * \text{sediment_in} \right\} + \left\{ \left[\frac{(\text{detention_depth} - \text{settling_depth})}{\text{detention_depth}} \right] * [\text{detention_storage}] \right\} \quad \text{Equation 8-1}$$

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;

AnnAGNPS: Technical Descriptions

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 8-1: 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 8-1 shows the fall velocities (v_f) for each of the sediment particle size classes. They are taken from Table 7-6. 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

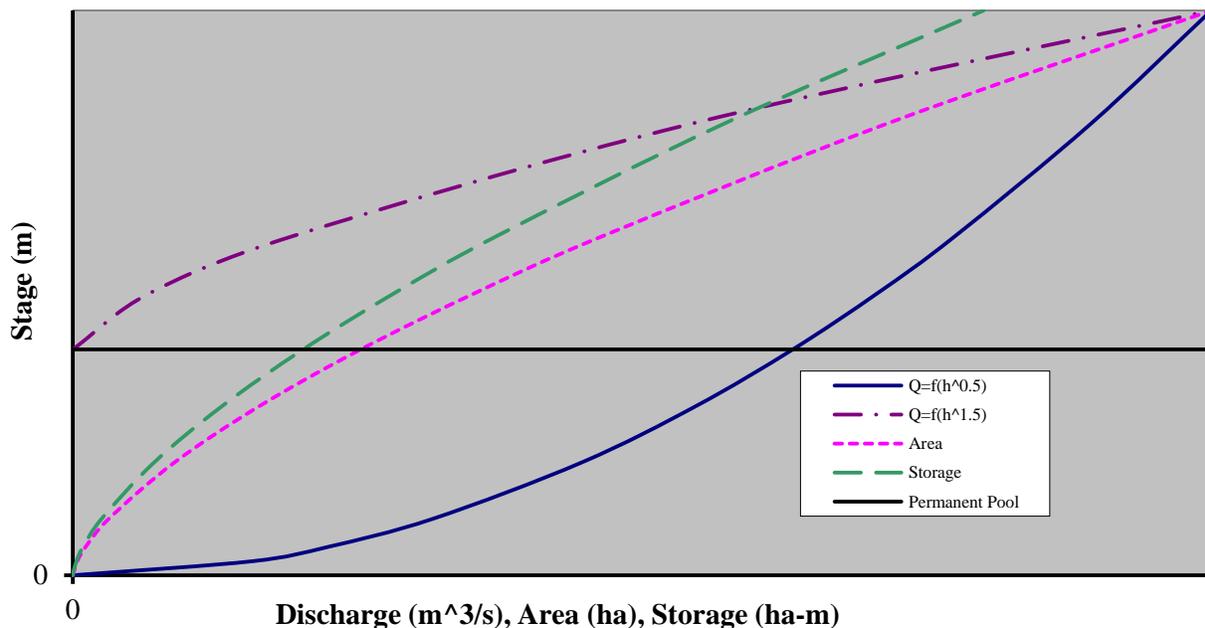


Figure 8-1. Elevation-Discharge-Area-Storage Relationships shows the elevation-discharge (both pressure flow and weir flow control), elevation-area, and elevation-storage relationships for impoundments.

The impoundment permanent pool storage is:

$$V_p = a \cdot h_o^b \tag{Equation 8-2}$$

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.

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The average event outflow discharge under pressure flow control ($d = 0.5$) is:

$$Q_o = c \cdot \{[(V_p + V_I/2) / a]^{1/b}\}^{0.5} \quad \text{Equation 8-3}$$

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:

$$Q_o = c \cdot \{[(V_p + V_I/2) / a]^{1/b} - h_o\}^{1.5} \quad \text{Equation 8-4}$$

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:

$$A_s = a \cdot b \cdot [(V_p + V_I/2) / a]^{[(b-1)/b]} \quad \text{Equation 8-5}$$

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.

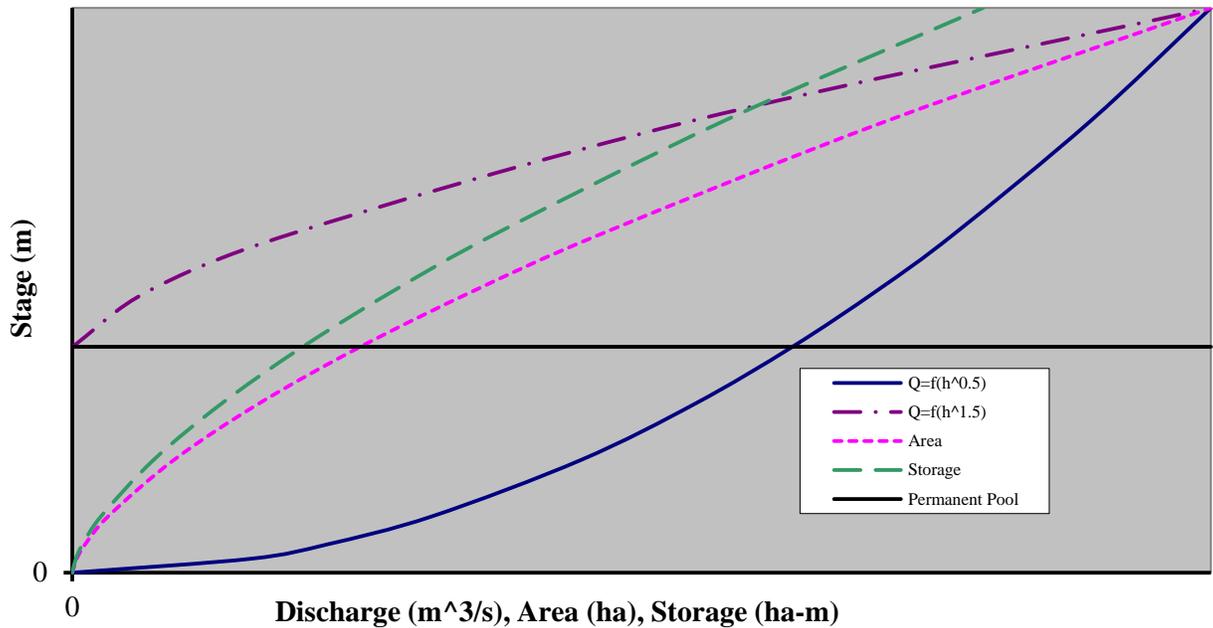


Figure 8-1. Elevation-Discharge-Area-Storage Relationships

8.1.1 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 8-2. 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.

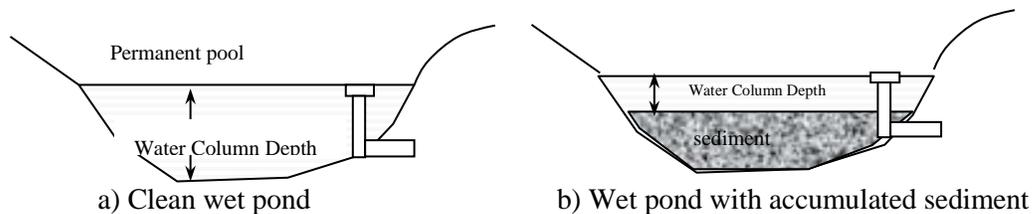


Figure 8-2. Schematic diagram showing the effect of sediment accumulation (wet ponds)

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 8-2. 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 8-3. 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

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sediment trap efficiency. In addition, with sediment exposed at the bottom, sediment re-suspension during storms can potentially impair pond performance.



Figure 8-3. 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 8-2. 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 8-2. Bulk density of sediment by particle size

Particle Size	Bulk Density (lb/ft ³)	
	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

AnnAGNPS: Technical Descriptions

9. 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.

Equilibration: A simple first order equilibration model for equilibration is used:

$$M_s = M_c / (1 + K_d) \quad \text{Equation 9-1}$$

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.

10. NITROGEN

10.1 GENERAL INTRODUCTION

American agriculture is very important to the national economy. Sixteen percent of the gross national product of the United States is from agricultural commodities sales (Novotny and Olem, 1994). Agrichemicals such as fertilizers and pesticides have made a significant contribution in the production of agriculture. Nitrogen is one of the most important fertilizers used for agricultural production. Plants require nitrogen more than any other essential element, excluding carbon, oxygen and hydrogen.

10.1.1 Nitrogen Cycle

Nitrogen has the most complex nutrient cycle of all the mineral nutrients because nitrogen can exist as a gas in ammonia or nitrogen (Jones and Jacobson, 2002). Nitrogen dynamics in agricultural soils are very complicated biological and chemical processes. To understand nitrogen loss mechanisms and develop a nitrogen loading model, an understanding of nitrogen transformation in the soil and nitrogen cycle is necessary.

The general nitrogen processes in soil is illustrated in Figure 9-1. Generally, major forms of nitrogen in soils are organic N associated with humus (active and stable in organic pool), soluble forms of mineral N (mainly NO_3^- and NH_4^+ , with low concentration of NO_2^-). Nitrogen cycling consists of nine major processes: plant uptake, nitrification, denitrification, volatilization, mineralization, immobilization, nitrogen fixation from the atmosphere, leaching, and decomposition of fresh residue (Figure 9-1).

Figure 10-1. A simplification of nitrogen processes (Havlin et al., 1999)

Total nitrogen content in the natural soil top one foot ranges from 0.03% to 0.4% (Tisdale et al., 1985). The primary sources of soil nitrogen are from fertilizer application (46%), manure application (7%), N fixation from the atmosphere by symbiotic or nonsymbiotic soil bacteria (20%), plant residue (17%) and precipitation (10%) (Novotny and Olem, 1994). Most soil nitrogen is in soil organic matter which is derived from biological materials such as roots, microflora, fauna, leaf litter and humification processes (Stevenson, 1982). Organic nitrogen and ammonium nitrogen are mostly absorbed by clays. In such forms, it can be considered immobile and not available to plants. But those immobile forms can be transformed into nitrate, which is highly mobile. Mobile nitrogen can be used by plants, transported by

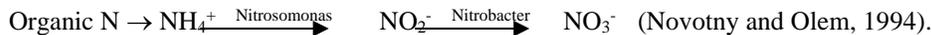
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soil water and infiltrated into ground water. Nitrogen is removed from the soil by plant uptake, surface runoff and subsurface flow (leaching), volatilization, denitrification and erosion.

Mineralization is the process that breaks down organic nitrogen compounds in the soil to release ammonium ions, NH_4^+ , with the concurrent release of carbon as CO_2 in most cases (Vinten and Smith, 1993). The reverse process of mineralization is **immobilization** by which ammonium NH_4^+ is transformed into organic forms. Cropping residues, soil moisture content, soil temperature, and pH are the main factors affecting mineralization and immobilization (Stanford and Epstein, 1974; Haynes, 1986). Immobilization occurs more easily at high C:N ratios (above 30:1). In addition, nitrogen fertilizer application stimulates the mineralization process (Haynes, 1986). The promotion of mineralization of soil organic nitrogen increases the crop uptake of nitrogen (Stevenson, 1982).

The release of nitrogen from organic matter is critical to the nitrogen cycle and to nitrate leaching in particular. A study done in England (Vinten and Smith, 1993) showed as high as 71 kg/ha/year nitrogen released from organic nitrogen in a field with no manure or N fertilizer application (Burt et al., 1993).

More than 90% of the nitrogen fertilizer used in the United States is ammonium salts (Novotny and Olem, 1994). Manure applied to the soil and septic tank sludge applied to the soil can be quickly decomposed into ammonium. Mineralization converts organic nitrogen into NH_4^+ . In an aerated, microorganism-rich soil such as farmland, **nitrification** occurs which converts NH_4^+ to NO_3^- as follows:



The reaction from NO_2^- to NO_3^- is much faster than the conversion of NH_4^+ to NO_2^- . Therefore, little nitrite remains in soils. Nitrate is highly soluble and can readily move with soil water. Nitrification occurs between temperatures of 10°C to 45°C with the optimum temperature at 22°C (Stanford and Smith, 1972). Nitrification is also dependent on the soil pH value, which occurs between pH 6 to 10 with the optimum at 8.5. Additionally, nitrification depends on soil moisture content; the nitrification rate decreases with decreasing moisture content (Novotny and Olem, 1994).

However, if the soil is saturated for a long period and oxygen is absent or depleted to a point below the oxygen demand, **denitrification** occurs. In this process, NO_3^- is converted to NO_2 , NO , N_2O and N_2 (gaseous nitrogenous forms which return to the atmosphere). This process usually occurs in subsoil with low permeability, and in soils saturated with water for a long period, such as a wetland (Carter and Allison, 1960; Firestone, 1982; Havlin et al., 1999).

The phenomenon of denitrification in soils, resulting in a loss of available nitrate has been considered a benign process in reducing the quantities of nitrate loss in surface runoff and subsurface flow such as in tile drainage or aquifers. Therefore, wetland and field ponds and control of drainage in the winter may be useful in reducing leached nitrate in tile drain systems. However, if the nitrate reduction does not go entirely to N_2 and N_2O is emitted, another environment problem is raised because N_2O is a factor in the depletion of the Earth's stratospheric ozone layer and contributes to global warming (Vinten and Smith, 1993).

Volatilization (NH_3) refers to the loss of ammonia as a gas into the atmosphere. Because NH_4^+ will more easily convert to NH_3 at high PH, the process is increased at high PH. Volatilization also increases with increase wind and temperature (Havlin et al., 1999). Since the nitrification as talked above transforms NH_4^+ to NO_3^- in hours to weeks, volatilization usually happens during a short period after ammonia-based fertilizer application. Once it becomes nitrate, it can no longer volatilize. Incorporating fertilizers, applying it right before rainstorm would push ammonia fertilizer further into soil profile where it is less available for volatilization (Reddy et al., 1979; Jones and Jacobson, 2002). In addition, applying the ammonia fertilizer in a calm day would help reduce the volatilization too.

Nitrogen fixation is the processes through which convert nitrogen gas into available forms of nitrogen. Nitrogen fixation is affected by many factors, nitrogen content, soil PH, soil moisture and plant conditions are major factors. Nitrogen fixation supplies nitrogen to microorganism and plant, increases available nitrogen level in the soil. In the United States, Nitrogen fixation produces about one third of the amount of fertilizer applied (Havlin et al., 1999).

Decomposition is the breakdown of fresh organic residue into simpler organic components and adds organic nitrogen to the soil. Factors affect mineralization as talked above and the residue characteristics would affect the decomposition.

10.1.2 Nitrate Leaching and Runoff Losses

There are several combined forms of nitrogen, including fertilizer added in soils as introduced above, but only the nitrate ion is leached out of soils in appreciable amounts by water passing through the soil profile (Vinten and Smith,

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1993). The movement of nitrate in the field is a complex process, and is mainly affected by the water content of the soil during leaching. Given a quantity of rainfall, the depth of water movement is different for different kinds of soils. Thus, soil structure, pore size, the spatial distribution of pores and their continuity all contribute to the irregular movement of water down the soil profile which causes the irregular movement of nitrate. The soil moisture front affects the diffusive dispersion of nitrate in the soil solution. The diffusive dispersion of nitrate in the soil solution is the nitrate movement due to the differences in nitrate concentration. Several studies have been done in modeling nitrate transport in the soil (Barraclough, 1989; Addiscott and Whitmore, 1991). The difficulties in modeling nitrate transport are in defining the highly transient nature of compounds in the nitrogen cycle. Time steps during simulation should be one hour or less; however, such data are often lacking (Vinten and Smith, 1993).

Many factors, such as fertilization, soil texture, land use, crop rotation, and cultivation can have an effect on the quantity of nitrate leached from a soil. The amount of fertilizer, the timing of fertilizer and the particular type of fertilizer used can affect the fertilizer available for crop uptake and leaching.

Bergstrom and Brink (1986) provided a general relationship between nitrogen fertilizer application and leaching losses. They conducted ten years of research on a clay soil in Sweden. They concluded that leaching of nitrate was moderate up to a rate of application of 100 kg N ha⁻¹ annual⁻¹, increased rapidly thereafter, and reached a rate of 91 kg ha⁻¹ for an application of 200 kg ha⁻¹ in a year in which rainfall was 638 mm.

A similar study was conducted on a Minnesota silt loam soil (Randall et al., 1993a). Anhydrous ammonia was applied at rates of 0 to 252-kg ha⁻¹ to different plots; they found the nitrate-nitrogen concentration in soil water increased with increasing application rates. When application rate was above 84-kg ha⁻¹, the nitrate-nitrogen concentration was above 10 mg/L. The optimum application rate for corn production was 168-kg ha⁻¹. They also concluded that fall application of fertilizer resulted in higher nitrate leaching losses than that of spring application.

Harris et al. (1984) compared the timing of fertilization on nitrogen leaching losses. They found that half of the nitrogen was lost from autumn applied nitrogen and up to 15% of nitrogen was lost from spring applied nitrogen.

Kanwar and Baker (1993) investigated the use of a single application and split applications of nitrogen fertilizer on leaching losses. The nitrate concentration in drainage water was less from split application plots.

On freely drained soils, nitrate leaching can be estimated by an estimation of water flux associated with the soil solution concentration measured. Kolenbrander (1981) found that for arable soils the leaching of nitrogen depends on soil texture, with clay soils losing about half the nitrate than from sandy soils as long as application rate did not exceed 100-200 kg/ha. Once the application rate exceeds this range, leaching losses increased rapidly and became less dependent on soil texture. The leaching of nitrogen from artificially drained soils is much larger than from freely drained soils depending on the drainage system. For a given site, nitrate leaching was proportional to drain flow.

Several studies showed that arable land was more prone to leaching than grass land (Kolenbrander, 1981; Barraclough et al., 1983). However, nitrate leaching losses from grazed systems is much higher than mowed grassland and arable land (Ryden, 1984).

The nature of the crop dictates the nitrogen requirement and, thus, the nitrate available for leaching. Randall et al. (1993b) investigated the effects of cropping system on nitrate leaching from tile drainage in a Minnesota clay loam soil. They concluded that the nitrogen losses from continuous corn systems were much higher than that from corn-soybean rotation systems under the fertilizer management treatment recommended to optimize yield. Kanwar and Baker (1993) conducted a similar investigation in Iowa clay soil. They also found that nitrogen losses from continuous corn systems were much higher than that from corn-soybean rotation systems. However, Melvin et al. (1993) pointed out that the corn-soybean rotation system required less fertilizer application than a continuous corn system; thus, the effects on the quality of tile drainage is from fertilizer application amount, not the crop.

Dowdell et al. (1987) compared leaching losses of nitrogen from direct drilled plots and plowed plots over four years. They found that nitrogen losses from direct drilled plots were only 48-49% of losses from plowed plots. Vinten et al. (1991) also reported greater leaching losses from plots that have been cultivated (chisel plowed and subsoiled) than from plots left stubble over the winter. The probable reason is that cultivation promotes aeration and, consequently, higher mineralization and lower denitrification losses. However, Harris et al. (1993) observed greater levels of nitrate from no-tillage plots, but they suggested that more nitrogen was lost by way of denitrification with conventional tillage.

Kanwar and Baker (1993) compared nitrate losses from tile drainage on no-tillage, chisel plow, ridge tillage and moldboard plow. They found that the greatest concentrations were measured in the drainage from moldboard plowed

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plots. However, the total mass of nitrate in the drainage effluent from moldboard plow was less than that from no-tillage because a larger proportion of water drains through the undisturbed soil, through fairly continuous micropores.

Naveen et al. (1996) compared the effect of no-tillage and conventional tillage on tile drain flow, nitrate concentration and loss in tile effluent in loam soil. They found that flow was significantly higher from no-tillage treatment than that from conventional tillage treatment. The flow-averaged nitrate-nitrogen concentrations in tile flow were greater from conventional tillage than that from no-tillage, but the total loss from these two treatments was not significantly different over the 40-month study period.

Mitchell et al. (1998) analyzed five years of nitrate-nitrogen data from the Little Vermilion River watershed and found that the leaching nitrate-nitrogen concentrations follow a seasonal cycle. Nitrate-nitrogen concentrations varied considerably from the tile drains between fields depending on the management system. The total loss from the grass field is 3.8kg/ha/year, 15 kg/ha/year with no-tillage corn-soybeans rotation and corn silage, and 41 kg/ha/year and 38 kg/ha/year from reduced-tillage white corn-soybeans and reduced tillage corn-soybeans respectively.

10.1.3 Nitrogen Balance

An available nitrogen mass balance could be established through summarizing the nitrogen gains (mineralization, fixation, fertilization) and losses (plant uptake, denitrification, volatilization, and immobilization). Nitrogen could be gain or loss through exchanging with soil as absorption and desorption. However, this process usually is not simulated in nitrogen models. In addition, precipitation represents other input to the nitrogen pool. The final potential loss is nitrate leaching or through surface runoff. Factors affect nitrate leaching affect surface runoff loss too.

Because of the complex mechanisms of the nitrogen cycle in agricultural soils, long term studies of nitrogen balance in agricultural soils are very important to determine the effects of agricultural management practices on leaching of nitrate from agricultural land to groundwater and surface water. Such studies are essential for testing the long-term predictive power of models of the agricultural soil-plant nitrogen cycle, which should include calculations of mineralization, immobilization, nitrification, denitrification, crop uptake and nitrate leaching. Such models are becoming increasingly important in helping policy makers and land use managers make policy decisions. However, because of the initial condition of the soil organic matter, uncertainties in measuring mineralization and denitrification rates which cause inaccurate estimates of change in organic matter content as well as difficulties in quantifying other nitrogen processes, it is very difficult to predict nitrogen losses.

10.2 ANNAGNPS NITROGEN PROCESSES

The nitrogen cycle represented in AnnAGNPS is a simplified version of nitrogen cycle introduced in above section. AnnAGNPS tracks only major nitrogen transformations of mineralization from humified soil organic matter and plant residues, crop residue decay, fertilizer inputs, and plant uptake. Three pools of soil nitrogen are considered, stable organic N, active organic N (mineralizable N), and inorganic N. Losses (cell output pathways) include soluble inorganic N in runoff, leaching, denitrification, and sediment-bound organic N from soil erosion (Figure 9-2). The nitrogen mineralization equation is adapted from the EPIC model (Sharpley and Williams, 1990). Plant uptake of N is modeled with a simple crop growth stage index with adaptations for soil profile nutrient uptake from the TETRANS model (Corwin, 1995). Residue return and decomposition uses equations from RUSLE (Renard, et al., 1997).

Figure 10-2. Nitrogen processes simulated in AnnAGNPS

10.2.1 Soil Initial Nitrogen Contents and Conversion Factor

Users can define the amount of inorganic and organic nitrogen contained in soil layers. If such information is not available, users can use default values for inorganic and organic nitrogen concentration (mg/kg or ppm). The default value for organic N is assumed as 9% of the soil organic matter; and inorganic N is assumed as 0.27% of the soil organic matter (Stevenson, 1994). Soil organic matter is usually available from national soil database such as NASIS.

The input of amount of nitrogen levels in the soil profile are as concentrations, but AnnAGNPS performs calculations on a mass basis. To convert a concentration to a mass, AnnAGNPS uses a conversion factor (conv). Conversion factor represents a weight of soil in that it is a volume of soil times bulk density. It is used to convert nutrient concentration in soil to kilograms used to do mass balances.

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$$conv = D * 10 * 1000 * \rho_b * A_{cell} \quad \text{Equation 10-1}$$

Where:

conv = intensive unit to extensive unit conversion factor (kg)
 D = thickness for soil layer (mm)
 ρ_b = bulk density of composite soil layer (g/cc or Metric tons/ m3)
 Acell = AnnAGNPS cell_area (hectares)

10.2.2 Organic Nitrogen Simulation Processes

All AnnAGNPS mass balance is based on AnnAGNPS cells and maintained for both composite soil layers.

The mass balance equation for organic nitrogen simulation processes is as followings:

$$orgN_t = orgN_{t-1} + \frac{(resN + fer_orgN - hmnN - sedN) * 1000000}{conv} \quad \text{Equation 10-2}$$

Where:

orgN_t = Concentration of organic_N in the total composite soil layer for current day (ppm)
 orgN_{t-1} = Concentration of organic_N in the total composite soil layer for previous day (ppm)
 resN = organic N addition from decomposition of crop and noncrop residue laying on the soil surface to cell soil layer 1 on current day, (kg). Noncrop residue refers to nitrogen from litter dry biomass for noncropland surface residue that is subject to decomposition. Upon decomposition byproducts are considered mixed uniformly in soil layer 1.
 fer_orgN = organic N from fertilizer application such as manure or other sources (kg)
 hmnN = N mineralized from organic N in soil layer on current day (actual argument passed to inorg_N_mass_bal subroutine (kg)
 sedN = current days mass of nitrogen attached to sediment (kg)

10.2.2.1 Cell Residue Nitrogen Calculations

a) Crop land

The cell residue nitrogen from decomposition is calculated only for the top soil layer for crop land. It is calculated using following equations:

$$resN = \frac{(res_decomp) * 0.5}{CNR_{harvest}} \quad \text{Equation 10-3}$$

Where:

resN = organic N addition from decomposition of crop residue (kg)
 res_decomp = crop residue mass decomposition for current day (kg)
 CNR_{harvest} = ratio of carbon to nitrogen for crop at harvest

Crop residue mass decomposition is calculated as:

$$res_decomp = (surf_res) * (1 - \exp(-temp_f * (decomp_coeff))) * A_{cell} \quad \text{Equation 10-4}$$

Where:

surf_res = surface residue for a cell which is computed from RUSLE module (kg/ha)
 temp_f = RUSLE temperature correction factor (unitless)
 decomp_coeff = crop surface residue decomposition coefficient (unitless)

Temperature correction factor is calculated using following equation:

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$$temp_f = \frac{3200 * ((T_{soil} + 8) ** 2) - (T_{soil} + 8) ** 4}{2560000}, \quad 0 < T_{soil} < 32$$

$$temp_f = 0, \quad T_{soil} < 0$$

$$temp_f = 1, \quad T_{soil} > 32$$

Equation 10-5

Where:

Tsoil = the average cell soil temperature (oC).

Above equation is a simplification of temperature correction factor from RUSLE (Page 152, equation 5-7). The 32.0 in temp_f equation is the RUSLE (To) value (°C) which is 90 (°F), and the 8.0 is the A value, in deg. C. The equation assumes residue, irrespective of crop, is 50% organic carbon. The detail of this part is described in the cell residue calculation document.

b) Non-crop land

The cell residue nitrogen from decomposition for non-crop land is calculated for both top soil layer and bottom soil layer. It is calculated using following equations:

$$resN = (res_decomp) * NF \quad \text{Equation 10-6}$$

Where:

resN = organic N addition from decomposition of noncrop residue (kg)

NF = nitrogen fraction of dry total biomass for non-crop field (weight of N/weight of biomass)

res_decomp = crop residue mass decomposition for current day (kg)

FN is assumed to be 1% N in dry biomass for grassland, 0.4% for forest systems, and zero for urban or mixed land.

Non-crop residue mass decomposition is calculated the same as crop residue decomposition:

c) Subsurface residue nitrogen calculation for non-crop land

$$res_subsN = (res_decomp) * NF \quad \text{Equation 10-7}$$

Where:

res_subsN = noncrop organic N addition from decomposed subsurface (below ground) residue

res_decomp = crop residue mass decomposition for current day (kg)

NF = nitrogen fraction of dry total biomass for non-crop field (weight of N/weight of biomass)

$$res_decomp = (sub_res) * (1 - \exp(-temp_f * (decomp_coeff))) * A_{cell} \quad \text{Equation 10-8}$$

Where:

sub_res = noncrop subsurface residue for a cell which is computed from RUSLE module (kg/ha),

10.2.2.2 Cell Organic Nitrogen from Fertilizer Application

Cell organic nitrogen from fertilizer application is calculated using the rate of fertilizer applied for current day operation times the fertilizer fraction which is organic nitrogen (from fertilizer reference database weight/weight).

$$fer_orgN = (fer_app) * (frac_orgN) * A_{cell} \quad \text{Equation 10-9}$$

Where:

fer_orgN = organic nitrogen from fertilizer application on current day (kg)

fer_app = the rate of fertilizer applied for current day operation (kg/ha)

frac_orgN = fertilizer fraction which is organic N, from fertilizer reference database (Weight/Weight)

10.2.2.3 Mineralized Nitrogen from Organic Nitrogen on Current Day

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Mineralization equations are adapted from the EPIC model (Sharpley and Williams, 1990). This epic mineralization model is a modification of the PAPRAN mineralization model (Seligman and van Keulen, 1981). The model considers two sources of mineralization: the fresh organic N pool associated with crop residue and microbial biomass and the active organic N pool associated with soil humus.

Temperature, soil moisture, aeration, and PH affect N mineralization (Sharpley and Williams, 1990). Mineralization is allowed to occur only if the temperature of the soil layer is above 0°C. Mineralization is also dependent on water availability. A correction factor is used in the mineralization equations to account for the impact of temperature and water on these processes.

Mineralization from organic N pool associated with crop residue and microbial biomass is estimated for each soil layer with the equation.

$$hmnN = CMN * frac * orgN * corr * \frac{conv}{1000000} \quad \text{Equation 10-10}$$

Where:

hmnN = the mineralization rate from the humus active organic N pool (kg/d);

CMN = the humus rate constant which is approximately 0.0003 (d-1), From EPIC;

frac = fraction of active organic N pool;

orgN = amount of organic N in the cell soil composite layers (g/Mg);

corr = corr_fact computes moisture/temperature correction factor used in N and P mineralization equations (From EPIC, Sharpley and Williams,1990) non-dimensional; and

conv = intensive unit to extensive unit conversion factor

The active pool fraction is calculated based on following equation:

$$frac = 0.4 * \exp(-0.0277 * YC) + 0.1 \quad \text{Equation 10-11}$$

Where YC is the period of cultivation before the simulation starts (year), the concepts expressed in above equation are based on work of Hobbs and Thompson (1971). For crop land, year of cultivation is set to 50, otherwise, it is set to zero. Below the plow layer, the active pool fraction is set to 40% of plow layer value. This is based on work of Cassman and Munns (1980).

The water, temperature correction factor varies between 0 to 1.0. The calculation of correction factor is based on the temperature correction factor (F_t) and water correction factor (F_w) and is calculated the same as in EPIC. The temperature correction factor (F_t) for N mineralization is the same as in EPIC and it is calculated based on following equations:

$$F_t = \frac{T_i}{T_i + \exp(9.93 - 0.312 * T_i)} \quad 0 < T_i < 100 \quad \text{Equation 10-12}$$

$$F_t = 0 \quad T_i \leq 0$$

In order to ensure temperature correction does not fall below 0.1,

$$F_t = \text{MAX}(F_t, 0.1) \quad \text{Equation 10-13}$$

Water correction factor (F_w) for N mineralization is calculated as

$$F_w = \frac{SW}{f} \quad \text{Equation 10-14}$$

Where:

Tl = the average cell soil temperature (oC)

SW= the water content of soil layer on a given day (mm H2O)

f = the water content at saturation

The correction factor (corr) is calculated as:

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$$corr = \text{sqrt}(F_t * F_w) \quad \text{Equation 10-15}$$

10.2.2.4 Calculation of Mass of Nitrogen Attached to Sediment

Assumption:

- it is the organic nitrogen makes up cell_sed_n because total nitrogen is predominantly organic nitrogen in soils.
- the organic nitrogen is associated with clay fraction. This eliminates the need for separate nutrient enrichment ratio (Menzel; 1980 from GLEAM documentation)

$$\text{sedN} = \text{frac_orgN_clay} * (\text{sed_part}(1,1) + \text{sed_part}(1,2)) * 1000 \quad \text{Equation 10-16}$$

Where:

sedN = mass of nitrogen attached to sediment (kg). Sed_part is metric tons, so multiply by 1000.
 frac_orgN_clay = decimal fraction of organic N in clay in soil layer (g/g)

$$\text{frac_orgN_clay} = \frac{\text{orgN}}{(\text{frac_clay}) * 1000000} \quad \text{Equation 10-17}$$

Where:

orgN = Concentration of organic_N in the total composite soil layer for current day (ppm).
 frac_clay = fraction of clay to total composite soil.
 sed_part(1,1) and sed_part(1,2) = Current day's mass of sediment (by particle size and source) at edge of cell.

Array subscript are: Particle Size (first): 1 - clay 2 - silt 3 - sand 4 - small aggregate 5 - large aggregate Source (second): 1 - irrigation 2 - other than irrigation.

Organic nitrogen mass balance is maintained for the second soil layer which is the bottom soil layer. For second soil layer, there is not much to talk about because AnnAGNPS assumes that fertilizer application, rainfall caused runoff and sediment loss are only associated with the top soil layer. In other word, fertilizer application, rainfall does not interact with the bottom soil layer.

$$\text{orgN}_t = \text{orgN}_{t-1} - \frac{\text{hmnN} * 1000000}{\text{conv}} \quad \text{Equation 10-18}$$

Where:

orgN_t = Concentration of organic_N in the total composite soil layer for current day (ppm)
 orgN_{t-1} = Concentration of organic_N in the total composite soil layer for previous day (ppm)
 hmnN = N mineralized from organic N in soil layer on current day (actual argument passed to inorg_N_mass_bal subroutine (kg). N mineralization is only calculated for noncrop for the second layer.

10.2.3 Inorganic Nitrogen Simulation Processes

For inorganic nitrogen, addition from fertilizer application is calculated first, followed by the losses from runoff, denitrification and plant uptake. Then, mass balance was updated for inorganic nitrogen that incorporates mineralization of organic N. In other word, mineralization of organic N is not used to calculate losses from runoff, denitrification and plant uptake. At the end of the day, leaching loss is calculated and inorganic N is updated to reflect the leaching loss.

10.2.3.1 Calculation of Inorganic N Additions to a Cell

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Added fertilizers are considered either well mixed with the top soil layer which is 200 mm or stay on soil surface based on the operation effect which is supplied by the user through operation data section. If a soil disturbance exceeds 50 percent, any fertilizer operations are considered as mixed. Otherwise, it assumes the applied fertilizer stays on soil surface. In addition, when the soil disturbance exceeds 50 percent, it not only incorporates the applied fertilizer from current operation into soil, but also incorporates any fertilizer left on the soil surface from previous fertilization.

When a soil disturbance exceeds 50 percent, fertilizers on soil surface mix with soil. The amount of fertilizer mixed with soil and the amount of fertilizer left on the soil surface after a soil disturbance is determined by the depth to the impervious layer. If the soil depth to imperious layer is greater than 200 mm (AnnAGNPS set this layer as the top soil layer, it is also called tillage layer), take all surface fertilizer and incorporate it into soil. For this case:

$$mnaN = surf_inorgN \quad \text{Equation 10-19}$$

$$surf_inorgN = 0 \quad \text{Equation 10-20}$$

Where:

$mnaN$ = mass of inorganic N added to a cell from incorporated inorganic additions such as fertilizers and is assumed well mixed with soil(kg); and

$surf_inorgN$ = surface inorganic N for a cell, added through fertilization at the soil surface (kg).

Otherwise, if the soil depth to imperious layer is less than 200 mm (not many this kind of cases), to prevent the concentration of fertilizer in the top layer to skyrocket, AnnAGNPS incorporates only the pre-rated fraction of fertilizer application into the top soil layer. For this case,

$$mnaN = \frac{D}{200} * surf_inorgN \quad \text{Equation 10-21}$$

$$surf_inorgN = surf_inorgN - mnaN \quad \text{Equation 10-22}$$

Fertilizer inorganic N added to a cell

Inorganic N from fertilizer application is calculated using the rate of fertilizer applied for current day operation times the fertilizer inorganic N fraction (from fertilizer reference database weight/weight).

$$inorgN_applied = (fer_app) * (frac_inorgN) * A_{cell} \quad \text{Equation 10-23}$$

Where:

$inorgN_applied$ = inorganic N from fertilizer application on current day (kg);

fer_app = the rate of fertilizer applied for current day operation (kg/ha); and

$frac_inorgN$ = fertilizer inorganic N fraction, from fertilizer reference database (mass/mass).

After a fertilizer application, the model updates the inorganic N mass balance.

a). When a soil disturbance exceeds 50 percent, for soils which the depth to imperious layer is greater or equal to 200 mm

$$mnaN = mnaN + inorgN_applied \quad \text{Equation 10-24}$$

For soils which the depth to imperious layer is less than 200 mm

$$mnaN = mnaN + \frac{D}{200} * inorgN_applied \quad \text{Equation 10-25}$$

$$surf_inorgN = surf_inorgN + (1 - \frac{D}{200}) * inorgN_applied \quad \text{Equation 10-26}$$

b). When a soil disturbance is less than 50 percent:

AnnAGNPS: Technical Descriptions

$$surf_inorgN = surf_inorgN + inorgN_applied \quad \text{Equation 10-27}$$

Additions added to soil profile from rainfall processes

When rainfall occurs, it dissolves the inorganic N on the soil surface.

Case 1. When the rainfall event is bigger enough to generate runoff, runoff carries the dissolved inorganic N away from the field. In this situation, AnnANPS assumes that inorganic N on the soil surface is totally dissolved in the water and either carried away with runoff or carried into soil profile with infiltration. The amount of dissolved inorganic N carried away with runoff or carried into soil profile with infiltration is determined as following:

If the infiltration is greater than 1.0 mm, the total soluble inorganic N lost to surface runoff is calculated as:

$$surf_sol_N = \frac{runoff}{(runoff + inf)} * surf_inorgN \quad \text{Equation 10-28}$$

Inorganic N lost to infiltration is calculated as

$$inf_sol_N = surf_inorgN - surf_sol_N \quad \text{Equation 10-29}$$

However, when the top soil layer is less than 200 mm, pro-rate the lost to infiltration, which partition part of lost to infiltration back to lost to surface runoff. This prevents mathematical problems later when the concentration is calculated based on the layer thickness.

$$surf_sol_N = surf_sol_N + (1.0 - \frac{D}{200}) * (inf_sol_N) \quad \text{Equation 10-30}$$

$$inf_sol_N = \frac{D}{200} * (inf_sol_N) \quad \text{Equation 10-31}$$

If the infiltration is less than 1.0 mm, the total soluble inorganic N lost to surface runoff is calculated as:

$$surf_sol_N = surf_sol_N \quad \text{Equation 10-32}$$

$$inf_sol_N = 0 \quad \text{Equation 10-33}$$

Where:

surf_sol_N= mass of inorganic N in runoff from fertilizer applied on soil surface (kg)

Then, AGNPS resets mnaN and surf_inorg N values to reflect the impact of current rainfall event.

$$mnaN = mnaN + inf_sol_N \quad \text{Equation 10-34}$$

$$surf_inorgN = 0 \quad \text{Equation 10-35}$$

Case 2. When rainfall is not bigger enough to generate runoff, there is no loss to surface runoff. For this situation, AnnANPS assumes that inorganic N on the soil surface either stay in place or carried into soil profile with infiltration. The amount of surface inorganic N stay on soil surface or carried into soil profile with infiltration is determined as following:

If the infiltration is greater than 1.0 mm, the surface soluble inorganic N carried into soil profile with infiltration is calculated as:

$$inf_sol_N = surf_inorgN \quad \text{Equation 10-36}$$

However, when the top soil layer is less than 200 mm, pro-rate lost to infiltration, which partition part of infiltration back to soil surface. This prevents mathematical problems later when the concentration is calculated based on the layer thickness.

AnnAGNPS: Technical Descriptions

$$\text{inf_sol_N} = \frac{D}{200} * (\text{inf_sol_N}) \quad \text{Equation 10-37}$$

Then, AGNPS resets mnaN and surf_inorg N values to reflect the impact of current rainfall event.

$$\text{mnaN} = \text{mnaN} + \text{inf_sol_N} \quad \text{Equation 10-38}$$

$$\text{surf_inorgN} = \text{surf_inorgN} - \text{inf_sol_N} \quad \text{Equation 10-39}$$

If the infiltration is less than 1.0 mm, surface inorganic N remains in place.

10.2.3.2 Calculation of Intermediate Inorganic N Mass Balance

The intermediate inorganic N mass balance refers to N pools which includes N additions but prior to N losses as soluble N, sediment N, and plant uptake. Bottom soil layer inorganic N does not change with this operation.

$$\text{inorgN}_i = \text{inorgN}_{i-1} + \frac{\text{mnaN} * 1000000}{\text{conv}} \quad \text{Equation 10-40}$$

Where:

inorgNi = Intermediate concentration of organic_N in the total composite soil layer for current day (ppm)

inorgNt-1 = Concentration of organic_N in the total composite soil layer for previous day (ppm)

mnaN = inorganic N addition to the soil profile. From above calculation (kg)

10.2.3.3 Calculation of Inorganic N Losses From a Cell

This calculation will include sequential adjustments to N pool size to reflect losses.

Loss through surface runoff

When rainfall occurs, runoff interacts with soil and carries soluble inorganic N in the soil profile away from fields. AnnAGNPS assumes the effective depth of runoff interaction is 10 mm. This lost is different from surface inorg N loss which has been introduced in previous section.

Incorporated inorganic N from manure or other fertilizer (mnaN) is added into the inorganic fertilizer, thus fertilizer's impact on soluble N losses is reflected in elevated inorganic N level.

1). Calculate soluble inorganic N removed from soil top layer by runoff, this refers to only that which is incorporated in top soil layer

$$\text{cell_soil_sol_N} = \text{edi} * \frac{\text{inorgN} * \text{conv}}{D * 1000000} \quad \text{Equation 10-41}$$

Where:

cell_soil_sol_N = mass of inorganic N removed from top soil layer through runoff (kg); and

edi = effective depth of interaction factor, AnnAGNPS uses 10 mm

Denitrification Loss

Denitrification occurs only when soil moisture content is above the 90% of porosity.

$$DN = \frac{\text{inorgN} * \text{conv}}{1000000} * (1 - \exp(-1.4 * F_t * \text{orgC})), \quad F_w > 0.9 \quad \text{Equation 10-42}$$

$$DN = 0, \quad F_w < 0.9$$

Where:

DN = denitrification rate (kg);

inorgN = amount of nitrate nitrogen in the soil (ppm);

AnnAGNPS: Technical Descriptions

conv = conversion factor;

Ft = nutrient cycling temperature factor, temperature correction factor as used for mineralization;

orgC = organic carbon content (%); and

Fw = nutrient cycling water factor, as used for mineralization.

Loss through plant uptake of inorganic nitrogen

In AnnAGNPS, the amount of crop nutrient uptake is calculated in a crop growth stage subroutine. This subroutine determines the crop growth stage based on crop data a user supplied. Amount of nutrient uptake was calculated based on the crop growth stage. Four growth stages are simulated by AnnAGNPS. There are initial; development; mature; senescence. The length of each growth stage can be specified by a user or use the RUSLE (Renard et al., 1997) crop database information. At different growth stage, crop nutrient uptake is different. The crop nutrient uptake is also limited by available nutrients in the composite soil layer. The calculated crop uptake N in the crop growth stage subroutine passes to inorganic N mass balance. Nitrogen uptake on current day is calculated as follow:

$$uptN = \frac{growth_N_uptake * (yield_wt) * N_uptake_harvest}{stage_length} * A_{cell} \quad \text{Equation 10-43}$$

Where:

uptN = mass of inorganic nitrogen taken up by the plant on current day (kg/d);

growth_N_uptake = Fraction of N uptake for current growth stage. Growth stages are initial, development, mature, and senescence;

yield_wt = yield at harvest (Kg/ha);

N_uptake_harvest = N uptake per yield unit at harvest (wt-N / wt-harvest unit, dimensionless); and

stage length = the number of growing days for current growth stage (days).

Plant nitrogen uptake is adjusted based on the availability of nutrient in the soil. If uptN calculated above is greater than the available inorganic N in the soil layer, then a limited crop N uptake is calculated as:

$$limited_uptN = 0.99 * \frac{inorgN * conv}{1000000} \quad \text{Equation 10-44}$$

Where:

limited_uptN = mass of inorganic nitrogen taken up by the plant on current day (kg/d);

inorgN = amount of nitrate nitrogen in the soil (ppm); and

conv = conversion factor.

10.2.3.4 Reconcile Inorganic N Mass Balance

Inorganic mass balance is updated. Mineralized N is added.

$$inorgN_{i+1} = inorgN_i + \frac{(hmnN - uptN - cell_soil_sol_N - DN) * 1000000}{conv} \quad \text{Equation 10-45}$$

Where:

inorgNi+1 = Concentration of inorganic_N in the total composite soil layer for current day (ppm);

inorgNi = Concentration of organic_N in the total composite soil layer for previous day (ppm);

hmnN = inorganic N mineralized from organic matter (kg). In the inorganic forms of nitrogen, it simulates amount of nitrogen generated through nitrogen mineralization on a daily basis;

uptN = from growth_stage subroutine. Call cell_growth stage subroutine to get this value;

cell_soil_sol_N = soil incorporated inorganic N lost to runoff, kilograms (kg); and

DN = denitrification rate (kg),

10.2.4 Total Inorganic Nitrogen Losses to Surface Runoff

Total mass of inorganic N lost in surface runoff includes soil incorporated and surface applied N lost.

AnnAGNPS: Technical Descriptions

$$sol_N = cell_soil_sol_N + surf_sol_N \quad \text{Equation 10-46}$$

Where:

cell_soil_sol_N = nitrogen losses to runoff from composite soil layer (kg)
 surf_sol_N = nitrogen losses to runoff from soil surface (kg)
 sol_N = total mass of inorganic N lost in surface runoff.

10.2.5 Leaching

Leaching losses is calculated using the updated inorganic nitrogen level in the soil.

$$N_Leaching = \frac{perc_loss}{SW - Wilting} * \frac{inorgN * conv}{1000000}, \quad perc_loss > 0 \quad \text{Equation 10-47}$$

$$N_Leaching = 0, \quad perc_loss \leq 0$$

Where:

N_leaching = leaching loss from soil layer (kg);
 Perc_loss = percolation loss for current day (mm);
 SW = soil water content (mm);
 Wilting = wilting point (mm);
 inorgN = amount of nitrate nitrogen in the soil (ppm); and
 conv = conversion factor.

Then, the inorganic nitrogen content shall be recalculated to reflect the leaching losses at the end of the day.

$$inorgN_t = inorgN_{t+1} - \frac{(N_Leaching) * 1000000}{conv} \quad \text{Equation 10-48}$$

Where:

inorgNt = Concentration of inorganic_N in the total composite soil layer for current day (ppm)

Inorganic nitrogen mass balance is maintained for the second soil layer the same way as the top layer except that fertilizer application, rainfall caused runoff and sediment loss are not considered. The leaching from first layer is added to the second layer and leaching from second layer is lost to the groundwater system.

10.2.6 Losses to Subsurface Flow

Losses to subsurface flow is considered as two parts: loss to subsurface drainage flow (tile flow) and loss to subsurface lateral flow.

10.2.6.1 Calculation of Inorganic N Loss Through Subsurface Drainage (Tile Drain) Systems

Loss to subsurface drainage flow (tile flow) is calculated using the updated inorganic nitrogen level in the second soil layer.

$$N_subsurface_drain = \frac{drain_outflow}{SW(2) - Wilting(2)} * \frac{inorgN(2) * conv(2)}{1000000}, \quad drain_outflow > 0$$

$$N_subsurface_drain = 0, \quad drain_outflow \leq 0 \quad \text{Equation 10-49}$$

Where:

N_subsurface_Drain = amount of nitrogen lost to subsurface drainage on current day (kg);
 drain_outflow = amount of water drained through subsurface drainage system on current day (mm);
 SW (2) = soil water content of the second soil layer (mm);
 Wilting (2) = wilting point of the second soil layer (mm);
 inorgN (2) = amount of nitrate nitrogen in the second soil layer (ppm); and
 conv = conversion factor.

AnnAGNPS: Technical Descriptions

10.2.6.2 Calculation of Inorganic N Loss to Subsurface Lateral Flow

Loss to subsurface lateral flow is calculated as follow:

$$N_Lateral_Flow = \frac{Lateral_flow}{SW(2) - Wilting(2)} * \frac{inorgN(2) * conv(2)}{1000000}, \quad Lateral_flow > 0$$

$$N_Lateral_Flow = 0, \quad Lateral_flow \leq 0 \quad \text{Equation 10-50}$$

Where:

N_Lateral_Flow = amount of nitrogen lost to subsurface lateral flow on current day (kg);

Lateral_flow = amount of subsurface lateral flow out of the second soil layer on current day (mm);

SW (2)= soil water content of the second soil layer (mm);

Wilting (2) = wilting point of the second soil layer (mm);

inorgN (2) = amount of nitrate nitrogen in the second soil layer (ppm); and

conv = conversion factor.

The total loss to subsurface flow is the sum of above two. At the end of the day, the inorganic nitrogen content shall be recalculated to reflect the losses to subsurface flow.

11. PHOSPHORUS

11.1 GENERAL INTRODUCTION

Phosphorus is an essential nutrient for all life forms and it is required for many essential functions. Research has shown that a deficiency of phosphorus in soils could limit crop production (Maples and Keogh, 1973). A deficiency of phosphorus in fresh water could limit production of fresh water organisms; wherea an abundance of phosphorus in fresh water will lead to algal blooms. Algae blooms have many detrimental effects on natural ecosystems. Odors and discoloration caused by decay of algae clumps will interfere with recreational and aesthetic water use; algae blooms shade submerged aquatic vegetation, reducing or eliminating photosynthesis and productivity; and algae may clog water treatment plant filters (Sharpley et al., 1994).

Phosphorus is not as mobile as nitrogen, it is generally strongly absorbed by soil. The phosphorus absorbed by sediment particles may be transported in overland flow. Orthophosphate can be dissolved in the water and be transported by surface and sub-surface flow (Smith, 1990). Sharpley and Syers (1979) observed that surface runoff is the primary mechanism by which phosphorus is exported from most catchments.

Agricultural conservation practices which control erosion and runoff will definitely control the load of phosphorus and orthophosphate to surface water bodies. However, reducing sediment transport will not reduce the phosphorus transport by the same magnitude.

11.1.1 Phosphorus Cycle

Phosphorus does not occur as abundantly as nitrogen in soil. Total P in surface soils ranges from 0.005% to 0.15% (Halvin et al., 1999). A complete understanding of the relationship and chemical, physical and biological interactions of various phosphorous forms in the soil profile is essential for a full description of phosphorous cycle in soils and plants (Jones et al, 1984). A model based on mathematical descriptions of fundamental chemical, physical and biological mechanisms of the soil phosphorus behavior would be ideal for phosphorous modeling. However, complex physiochemical mechanisms of phosphorus have not been fully described (Havlin et al., 1999). Therefore, all available phosphorus models are simplification of real world and are more empirical approach.

The general phosphorus processes in soil is illustrated in Figure 10-1. Generally, there are six forms (six pools) of phosphorus available in the soil profile. Of those six forms, three major forms of phosphorus in soils are organic phosphorus associated with humus (active and stable in organic pool), insoluble forms of mineral phosphorus (stable in inorganic pool), and plant-available phosphorus in soil solution (labile in solution). Phosphorus may be added to the soil by fertilizer, manure or residue application (both organic and inorganic). Phosphorus is removed from the soil by plant uptake, runoff, soil erosion and leaching. The pool of solution inorganic phosphorus supplies the plant, which can be divided into root, shoot and grain. The root and shoot (plant residue) or manure residue add to the fresh organic pool (Jones et al, 1984). Transformation of crop residue to other forms are very complicated and limited by many factors in soil. For soil inorganic phosphorus, the labile pool (solution) is in rapid (several days or week) equilibrium with the active pool; but the active pool is in slow equilibrium with the stable pool (Jones et al, 1984).

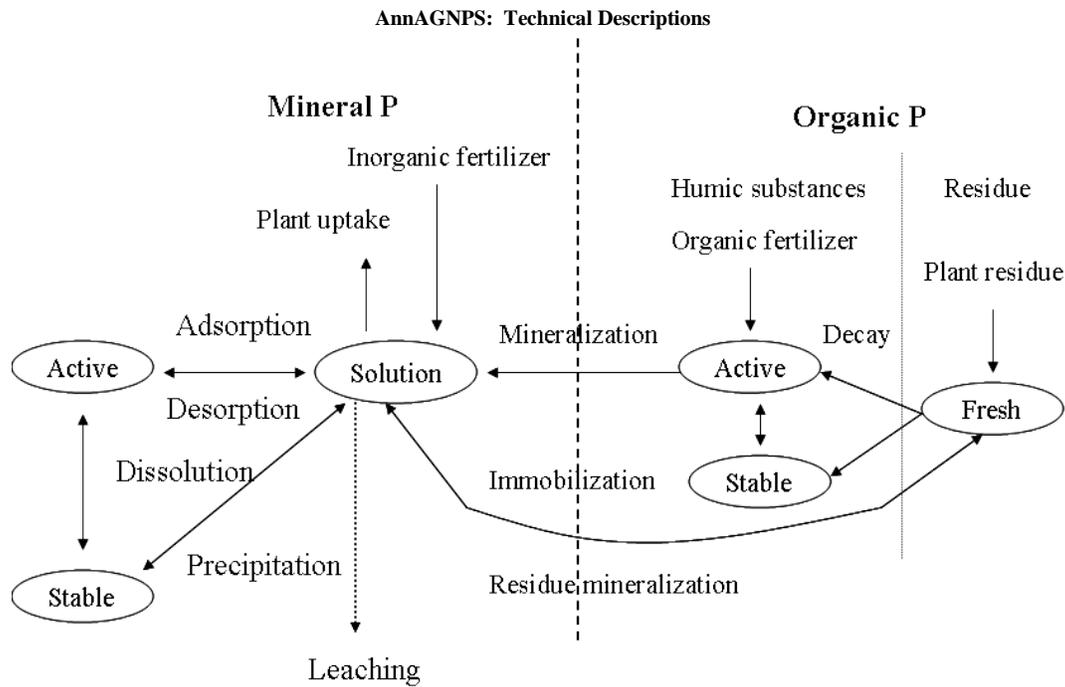


Figure 11-1. A simplification of phosphorus processes (Havlin et al., 1999)

Decomposition is the breakdown of fresh organic residue into simpler organic components. **Mineralization** is the microbial conversion of organic, plant unavailable phosphorus to inorganic, plant-available phosphorus. **Immobilization** is the microbial conversion of plant-available inorganic soil phosphorus to plant unavailable organic phosphorus (Figure 10-1). Approximately 4 to 22 lb P₂O₅/ac has been mineralized each year in the United States (Jones and Jacobson, 2002). The decomposition and mineralization processes is controlled by the decay rate constant which is a function of Carbon-Nitrogen (C: N) ratio (CNR) and Carbon- Phosphorus (C:P) ratio (CPR) in the residue, temperature, soil water content, PH values, cultivation intensity, P fertilization and composition of crop residue. Studies (Havlin et al., 1999) show that mineralization occurs most readily when the C:P ratio is less than 200:1, and immobilization occurs when that ratio is greater than 300:1. Mineralization is increased with the total organic P content. With continued cultivation, the P mineralization decreases because the organic P decrease.

Absorption refers to the binding of P to soil particles. Absorbed P is bound only to the outside of minerals. The solution P is usually in a form of HPO₄²⁻ or H₂PO₄⁻, so it is strongly attached to positive charged minerals. Because minerals become more positively charged at lower PH, more phosphate is absorbed at lower soil PH values; whereas more phosphate is available for plant uptake at higher soil PH values (Havlin et al., 1999). In addition, as more P fertilizer is added, more P is available for plant uptake. P absorption is generally increased with increased temperature (Jones and Jacobson, 2002). **Desorption** is the opposite of absorption. Factors that affect absorption affect desorption too.

Precipitation is the processes through which soluble P is converted to part of mineral. The solubility of P minerals controls the available P concentrations. Calcium phosphate is the dominant minerals in neutral to high PH soils. There are numerous forms of calcium phosphate in soil, ranging from very soluble to very insoluble. Usually, after fertilizing with P in a neutral or high PH soil, calcium phosphate forms in order from high to low solubility, and the time for each mineral to form is highly dependent on temperature (Jones and Jacobson, 2002).

Al phosphate and Fe phosphate are the dominant minerals in soils with PH levels below 6.5 (Havlin et al., 1999). Opposite to the calcium phosphate, the solubility of these minerals decreases at lower PH. Therefore, P is most available around PH 6.5 (Havlin et al., 1999).

11.2 ANNAGNPS PHOSPHORUS PROCESSES

The purpose of the P module in AnnAGNPS is to extract P into surface runoff and output it from a cell (a *transport* process). In doing so an appropriate soil mass balance of phosphorus (P) in a cell must be maintained on a daily basis by horizon or computational layer. It is not a detailed chemical model of P in the soil, but simulates the effect of P

AnnAGNPS: Technical Descriptions

adsorption that control P availability and partitioning into runoff. The mass balance portion of the model is a simplification of the EPIC (Sharpley and Williams, 1990) P model (Sharpley, et al., 1984). In this model, P is partitioned into organic P and mineral P. Mineral P is further broken down into: 1) labile P (that P readily available for plant uptake, for example fertilizer P); 2) active mineral P (P that is more or less reversibly absorbed to the soil), and stable mineral P (absorbed P that is “fixed” or relatively irreversibly chemisorbed to the soil adsorption complex or as discrete insoluble P minerals). An empirical distribution coefficient, K_d , is used to partition P between the soluble and absorbed phases, thus dictating the amount of P available for extraction into runoff. Sediment-bound P is estimated from soil erosion and is assumed associated with the clay-size fraction of the soil and consists of the organic, active and stable mineral P. Figure 10-2 shows the P processes simulated in AGNPS.

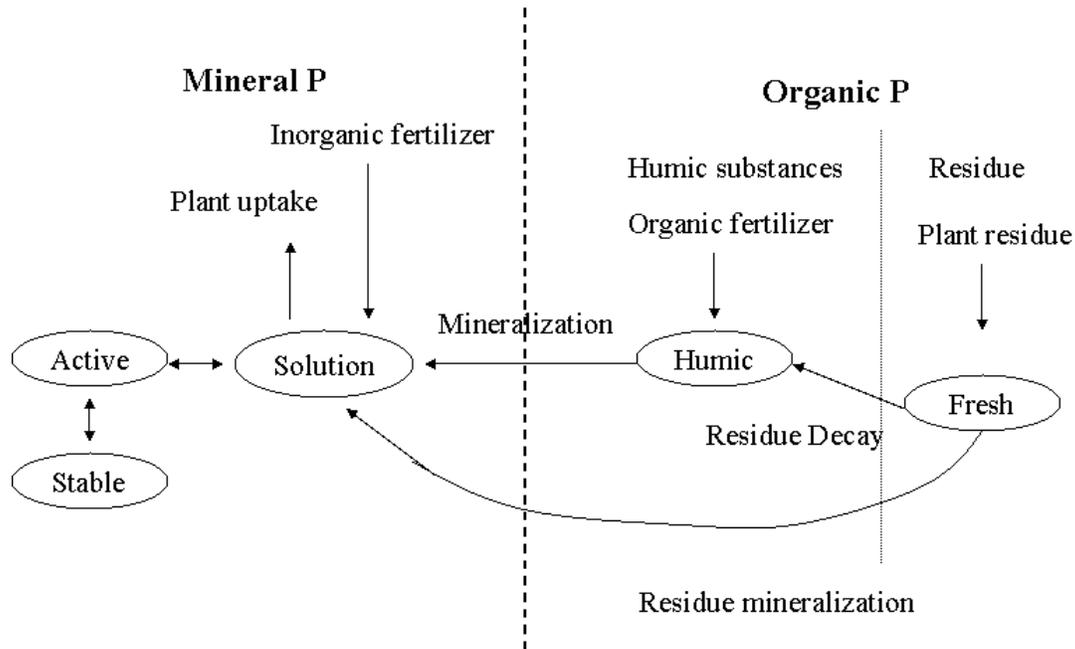


Figure 11-2. Processes simulated in AnnAGNPS

11.2.1 Initial Soil Phosphorus—Contents and Conversion Factors

Users can define the amount of inorganic and organic P contained in soil layers. If such information is not available, users can use default values for inorganic and organic phosphorus concentration (mg/kg or ppm). The default value for organic P is assumed as 1.5% of the soil organic matter; and inorganic P is assumed as 0.75% of the soil organic matter (Stevenson, 1994). Soil organic matter is usually available from national soil database such as NASIS.

The input phosphorus levels in the soil profile are as concentrations, but AnnAGNPS performs calculations on a mass basis. To convert a concentration to a mass, AnnAGNPS uses a conversion factor ($conv$). Conversion factor represents a weight of soil in that it is a volume of soil times bulk density. It is used to convert nutrient concentration in soil to kilograms used to do mass balances.

The concentration of inorganic phosphorus and organic phosphorus in top soil layer is initially set to 500 mg/kg (ppm) soil, 250 mg/kg (ppm) soil in the bottom soil layer.

$$conv = D * 10 * 1000 * \rho_b * A_{cell} \quad \text{Equation 11-1}$$

Where:

- $conv$ = intensive unit to extensive unit conversion factor (kg);
- D = thickness of soil layer (mm);
- ρ_b = bulk density of composite soil layer (g/cc or Metric tons/ m³); and
- A_{cell} = AnnAGNPS cell area (hectares).

AnnAGNPS: Technical Descriptions

11.2.2 Organic Phosphorus Simulation Processes

All AnnAGNPS mass balances were based on AnnAGNPS cells and maintained for two composite soil layers.

The mass balance equation for organic P simulation processes is as followings:

For Soil Layer 1

$$orgP_t = orgP_{t-1} - \frac{(resP + fer_orgP - hmnP - sed_orgP) * 1000000}{conv} \quad \text{Equation 11-2}$$

Where:

- orgP_t = Concentration of organic_P in the total composite soil layer for current day (ppm)
- orgP_{t-1} = Concentration of organic_P in the total composite soil layer for previous day (ppm)
- resP = organic P addition to cell soil layer 1 from decomposed fresh crop residue on current day (kg)
- fer_orgP = organic P from fertilizer application such as manure or other sources (kg)
- hmnP = The mineralization rate from the humus active organic P pool on current day (kg)
- sed_orgP = current days mass of P attached to sediment (kg)

11.2.2.1 Cell Residue P Calculations

Decomposition is the breakdown of fresh organic residue into simpler organic components. It is calculated once a day. Equations for residue decomposition were adapted from RUSLE (Renard et al., 1997). The decomposition calculations are different from crop land to noncrop land. For crop land, only surface decomposition is calculated. For noncrop land, both surface decomposition and subsurface decomposition are calculated. Crop residue mass decomposition is not corrected for moisture, but is corrected for temperature by the factor temp_f.

a. Crop land

The cell residue P is calculated using following equations:

$$resP = \frac{(res_decomp) * 0.5}{CPR_{harvest}} \quad \text{Equation 11-3}$$

Where:

- resP = organic P addition from decomposition of crop residue laying on the soil surface on current day (kg)
- res_decomp = crop residue mass decomposition for current day (kg)
- CPR_{harvest} = Ratio of Carbon to phosphorus for crop at harvest

$$res_decomp = (surf_res) * (1 - \exp(-temp_f * (decomp_coeff))) * A_{cell} \quad \text{Equation 11-4}$$

Where:

- surf_res = surface residue for a cell which is computed from RUSLE module (kg/ha)
- temp_f = RUSLE temperature correction factor (unitless)
- decomp_coeff = crop surface residue decomposition coefficient, user input, the default value is 0.016.

Temperature correction factor is calculated using following equation:

$$temp_f = \frac{3200 * ((T_{soil} + 8) ** 2) - (T_{soil} + 8) ** 4}{2560000}, \quad 0 < T_{soil} < 32$$

$$temp_f = 1$$

$$temp_f = 0 \quad \text{Equation 11-5}$$

Where:

- T_{soil} = the average cell soil temperature (oC).

AnnAGNPS: Technical Descriptions

Above equation is a simplification of temperature correction factor from RUSLE (Page 152, equation 5-7). The 32.0 in temp_f equation is the RUSLE (To) value (°C) which is 90 (°F), and the 8.0 is the A value, in deg. C. The equation assumes residue, irrespective of crop, is 50% organic carbon. The detail of this part is described in the cell residue calculation document.

b. Non-crop land

For non-crop land, both surface layer and subsurface layer were considered for decomposition.

For surface layer

The cell residue P is calculated using following equations:

$$resP = \frac{(Res_decomp) * 0.5}{CPR} \quad \text{Equation 11-6}$$

Where:

resP = organic phosphorus addition from decomposition of noncrop residue (kg).

CPR = carbon to phosphorus ratio for dry total biomass for noncrop fields (weight of carbon/weight of phosphorus).

res_decomp = noncrop residue mass decomposition for current day (kg).

$$res_decomp = (surf_res) * (1 - \exp(-temp_f * (nonc_decomp_coeff))) * A_{cell} \quad \text{Equation 11-7}$$

Where:

surf_res = surface residue for a cell which is computed from RUSLE module (kg/ha)

temp_f = RUSLE temperature correction factor, for noncrop res decomp, used to adjust the calculation of residue decomposition based on a first order rate, constant (unitless)

nonc_decomp_coeff = noncrop surface residue decomposition coefficient (nonc_decomp_coeff is hard-coded to 0.016 (see init_parm subroutine))

CPR is assumed 3000 for grassland (which means the Carbon to Phosphorus ratio in dry biomass is 3000), 1500 for forest systems, and zero for urban or mixed land.

(Hingston and Raison, 1982; Odum, 1971; Prescott, et al, 1989)

c. Subsurface residue P calculation for non-crop land

$$res_subsP = \frac{(Res_decomp) * 0.5}{CPR} \quad \text{Equation 11-8}$$

Where:

res_subsP = noncrop organic phosphorus addition from decomposed subsurface (below ground) residue (kg);

CPR = carbon to phosphorus ratio for dry total biomass for noncrop fields (weight of carbon/weight of phosphorus),

res_decomp = crop residue mass decomposition for current day (kg).

$$res_decomp = (sub_res) * (1 - \exp(-temp_f * (nonc_decomp_coeff))) * A_{cell} \quad \text{Equation 11-9}$$

Where:

sub_res = noncrop subsurface residue for a cell which is computed from RUSLE module (kg/ha)

temp_f = RUSLE temperature correction factor for noncrop subsurface residue decomposition.

nonc_decomp_coeff = noncrop surface residue decomposition coefficient (nonc_decomp_coeff is hard-coded to 0.016.

11.2.2.2 Cell Organic P From Fertilizer Application

AnnAGNPS: Technical Descriptions

Cell organic P from fertilizer application is calculated using the rate of fertilizer applied for current day operation times the fertilizer fraction which is organic P (from fertilizer reference database weight/weight).

$$fer_orgP = (fer_app) * (frac_orgP) * A_{cell} \quad \text{Equation 11-10}$$

Where:

- fer_organicP = organic P from fertilizer application on current day (kg)
- fer_app = the rate of fertilizer applied for current day operation (kg/ha)
- frac_organicP = fertilizer fraction which is organic P, from fertilizer reference database (Weight/Weight)

11.2.2.3 Mineralized P From Organic P on Current Day

Mineralization is a microbial process which converts organic, plant unavailable phosphorus to inorganic, plant-available phosphorus (phosphate). Immobilization is the microbial conversion of plant-available inorganic soil phosphorus to plant unavailable organic phosphorus. In the United States, approximately 4 to 22 lb P₂O₅/acre has been generated by phosphorus mineralization each year (Jones and Jacobsen, 2002). Jones and Jacobsen (2002) also reported that: "Mineralization occurs most readily when the C:P ratio is less than 200:1, and immobilization occurs when that ratio is greater than 300:1". Temperature, soil moisture, aeration, and PH affect phosphorus mineralization as they affect the N Mineralization (Sharpley and Williams, 1990). The phosphorus mineralization algorithms in AnnAGNPS are net mineralization algorithms which incorporate immobilization into the equations.

The P mineralization equation in AGNPS is adapted from the EPIC model (Sharpley and Williams, 1990). This epic mineralization model is similar in structure to the N mineralization model developed by Jones et al. (1984). Mineralization and decomposition are dependent on water availability and temperature. Mineralization from the fresh organic p pool associated with crop residue and microbial biomass is estimated for each soil layer with the equation.

$$hmnP = CMN * frac * orgP * corr * \frac{conv}{1000000} \quad \text{Equation 11-11}$$

Where:

- hmnP = the mineralization rate (kg/ha/d) from the humus active organic P pool in soil layer. It is the P mineralized from active organic P in soil layer on current day (actual argument passed to inorg_P_mass_bal subroutine (kg/d)
- CMN = The humus rate constant, in EPIC it is approximately 0.0003 (d-1),
- Frac_actP = fraction of active P,
- orgP = amount of organic P in the cell soil composite layers (g/Mg)
- corr = correction factor which computes moisture/temperature correction used in N and

P mineralization equations (From EPIC, Sharpley and Williams,1990) non-dimensional

The tillage impact on mineralization is not considered in AnnAGNPS. In this way, it reduces the need for calculating the ratio of bulk density to settled bulk density. In addition, conservation tillage such as no-tillage as recommended by the NRCS, the ratio of bulk density to settled bulk density is one.

The way to calculate the fraction of active P pool in AnnAGNPS is different from SWAT. The fraction is calculated based on the cultivation history.

The active pool fraction is calculated based on following equation:

$$frac = 0.4 * \exp(-0.0277 * YC) + 0.1 \quad \text{Equation 11-12}$$

Where YC is the period of cultivation before the simulation starts (year), the concepts expressed in above equation are based on work of Hobbs and Thompson (1971). For crop land, year of cultivation is set to 50, otherwise, it is set to zero. Below the plow layer, the active pool fraction is set to 40% of plow layer value. This is based on work of Cassman and Munns (1980).

The water, temperature correction factor varies between 0 to 1.0. The calculation of correction factor is based on the temperature correction factor (F_t) and water correction factor (F_w). It is calculated the same way as in EPIC. The temperature correction factor (F_t) for P mineralization is calculated based on following equations:

AnnAGNPS: Technical Descriptions

$$F_t = \frac{T_l}{T_l + \exp(9.93 - 0.312 * T_l)}, \quad 0 < T_l < 100$$

$$F_t = 0, \quad T_l \leq 0$$

Equation 11-13

In order to ensure temperature correction does not fall below 0.1,

$$F_t = \text{MAX}(F_t, 0.1)$$

Equation 11-14

Water correction factor (F_w) for P mineralization is calculated as

$$F_w = \frac{SW}{f}$$

Equation 11-15

Where:

SW= the water content of soil layer on a given day (mm H2O)

f = the water content at saturation (mm H2O)

Tsoil = the average cell soil temperature (oC).

The correction factor (corr) is calculated as:

$$\text{corr} = \text{sqrt}(F_t * F_w)$$

Equation 11-16

11.2.2.4 Calculation of Mass of P Attached to Sediment**Assumption:**

The organic phosphate is associated with clay fraction. This eliminates the need for separate nutrient enrichment ratio (Menzel; 1980 from GLEAM documentation).

The cell_sed_P is in kg, cell_sed_part is metric tons, so multiply by 1000.

$$\text{sed_orgP} = \text{frac_orgP_clay} * (\text{sed_part}(1,1) + \text{sed_part}(1,2)) * 1000$$

Equation 11-17

Where:

sed_orgP = mass of phosphorus attached to sediment (kg). Sed_part is metric tons, so multiply by 1000.

frac_orgP_clay = decimal fraction of organic P in clay in soil layer (g/g)

sed_part(1,1) and sed_part(1,2) = Current day's mass of sediment (by particle size and source) at edge of cell.

Array subscript are: Particle Size (first): 1 - clay 2 - silt 3 - sand 4 - small aggregate 5 - large aggregate
Source (second): 1 - irrigation 2 - other than irrigation.

$$\text{frac_orgP_clay} = \frac{\text{orgP}}{(\text{frac_clay}) * 1000000}$$

Equation 11-18

Where:

orgP = Concentration of organic_P in the total composite soil layer (1) for current day (ppm)

frac_clay = Ratio of clay mass to sum total mass of mineral soil (sand, silt, clay) excluding rock in the soil layer.

Organic P mass balance is maintained for the second soil layer which is the bottom soil layer. For second soil layer, there is not much to talk about because AnnAGNPS assumes that fertilizer application, rainfall caused runoff and sediment loss are only associated with the top soil layer. In other word, fertilizer application, rainfall does not interact in the bottom soil layer.

$$\text{orgP}_t = \text{orgP}_{t-1} - \frac{\text{hmnP} * 1000000}{\text{conv}}$$

Equation 11-19

Where:

orgPt = Concentration of organic_P in the total composite soil layer (for current day(ppm)

orgPt-1= Concentration of organic_P in the total composite soil layer for previous day(ppm)

AnnAGNPS: Technical Descriptions

hmnP = P mineralized from organic P in soil layer on current day (actual argument passed to inorg_P_mass_bal subroutine (kg). The calculation of P mineralized is the same as the first layer.

11.2.3 Inorganic P Simulation Processes

AnnAGNPS monitors three different pools of inorganic phosphorus in the soil as mentioned before. It adapts the mineral P model developed by Jones et al (1984). Mineral P is transferred among three forms: labile P in solution (available for plant use), the active P and stable P. AnnAGNPS assumes that inorganic P added from manures or other fertilizers goes initially to the labile P (available for plant use) pool and the active P pool, based on value of the P sorption coefficient. Fertilizer P which is labile at application may be quickly transferred to the active mineral pool. Flow between the active and stable mineral pools is governed by a P flow rate.

Within each inorganic P pool, additions from fertilizer application, mineralization of organic P is calculated first, followed by the losses from runoff, sediment and plant uptake. At the end of the day, mass balance was updated for each P pool. The simulation is in a sequence of calculation.

11.2.3.1 Calculation of Inorganic P Additions to a Cell

Added fertilizers are considered either well mixed with the top soil layer which is 200 mm or stay on soil surface based on the operation effect which is supplied by the user through operation data section. If a soil disturbance exceeds 50 percent, any fertilizer operations are considered as mixed. Otherwise, it assumes the applied fertilizer stays on soil surface. In addition, when the soil disturbance exceeds 50 percent, it not only incorporates the applied fertilizer from current operation into soil, but also incorporates any fertilizer left on the soil surface from previous fertilization into soil.

When a soil disturbance exceeds 50 percent, fertilizers on soil surface mix with soil. The amount of fertilizer mixed with soil and the amount of fertilizer left on the soil surface after a soil disturbance is determined by the depth to the impervious layer. If the soil depth to imperious layer is greater than 200 mm (AnnAGNPS set this layer as the top soil layer, it is also called tillage layer), take all surface fertilizer and incorporate it into soil. For this case:

$$mnaP = surf_inorgP \quad \text{Equation 11-20}$$

$$surf_inorgP = 0 \quad \text{Equation 11-21}$$

Where:

mnaP = mass of inorganic P added to a cell from incorporated inorganic additions such as fertilizers (kg). It is assumed well mixed with soil.

surf_inorgP = surface inorganic phosphate for a cell, added through fertilization at the soil surface (kg).

Otherwise, if the soil depth to imperious layer is less than 200 mm (not many this kind of cases), to prevent the concentration of fertilizer in the top layer to skyrocket, AnnAGNPS incorporates only the pre-rated fraction of fertilizer application into the top soil layer. For this case,

$$mnaP = \frac{D}{200} * surf_inorgP \quad \text{Equation 11-22}$$

$$surf_inorgP = surf_inorgP - mnaP \quad \text{Equation 11-23}$$

D is the depth to the impervious layer and it is less than 200 mm for this case.

Fertilizer inorganic P added to a cell

Inorganic P from fertilizer application is calculated using the rate of fertilizer applied for current day operation times the fertilizer inorganic P fraction (from fertilizer reference database weight/weight).

$$inorgP_applied = (fer_app) * (frac_inorgP) * A_{cell} \quad \text{Equation 11-24}$$

Where:

AnnAGNPS: Technical Descriptions

$inorgP_applied$ = inorganic P from fertilizer application on current day (kg)

fer_app = the rate of fertilizer applied for current day operation (kg/ha)

$frac_inorgP$ = fertilizer inorganic P fraction, from fertilizer reference database (Weight/Weight).

After a fertilizer application, the model updates the inorganic P mass balance.

a). When a soil disturbance exceeds 50 percent, for soils which the depth to imperious layer is greater or equal to 200 mm

$$mnaP = mnaP + inorgP_applied \quad \text{Equation 11-25}$$

For soils which the depth to imperious layer is less than 200 mm:

$$mnaP = mnaP + \frac{D}{200} * inorgP_applied \quad \text{Equation 11-26}$$

$$surf_inorgP = surf_inorgP + (1 - \frac{D}{200}) * inorgP_applied \quad \text{Equation 11-27}$$

b). When a soil disturbance is less than 50 percent:

$$surf_inorgP = surf_inorgP + inorgP_applied \quad \text{Equation 11-28}$$

Additions added to soil profile from rainfall processes

When rainfall occurs, it dissolves the inorganic P on the soil surface.

Case 1. When the rainfall event is bigger enough to generate runoff, runoff carries the dissolved inorganic P away from the field. In this situation, AnnANPS assumes that inorganic P on the soil surface is totally dissolved in the water and either carried away with runoff or carried into soil profile with infiltration. The amount of dissolved inorganic P carried away with runoff or carried into soil profile with infiltration is determined as following:

If the infiltration is greater than 1.0 mm, the total soluble inorganic P lost to surface runoff is calculated as:

$$surf_sol_P = \frac{Q}{(Q + inf)} * surf_inorgP \quad \text{Equation 11-29}$$

Inorganic P lost to infiltration is calculated as

$$inf_sol_P = surf_inorgP - surf_sol_P \quad \text{Equation 11-30}$$

However, when the top soil layer is less than 200 mm, pro-rate the lost to infiltration, which partition part of lost to infiltration back to lost to surface runoff. This prevents mathematical problems later when the concentration is calculated based on the layer thickness.

$$surf_sol_P = surf_sol_P + (1.0 - \frac{D}{200}) * (inf_sol_P) \quad \text{Equation 11-31}$$

$$inf_sol_P = \frac{D}{200} * (inf_sol_P) \quad \text{Equation 11-32}$$

If the infiltration is less than 1.0 mm, the total soluble inorganic P lost to surface runoff is calculated as:

$$surf_sol_P = surf_inorgP \quad \text{Equation 11-33}$$

$$inf_sol_P = 0 \quad \text{Equation 11-34}$$

Where:

$surf_sol_P$ = mass of inorganic P in runoff from fertilizer applied on soil surface (kg),

AnnAGNPS: Technical Descriptions

inf_sol_P = mass of inorganic P infiltrated into soil layer from fertilizer applied on soil surface during rainfall event. (kg) ,
 D = Thickness for soil layer (mm),
 Q = runoff volume (mm),
 Inf = amount of infiltration (mm).

Then, AGNPS resets $mnaP$ and $surf_inorg P$ values to reflect the impact of current rainfall event.

$$mnaP = mnaP + inf_sol_P \quad \text{Equation 11-35}$$

$$surf_inorgP = 0 \quad \text{Equation 11-36}$$

Case 2. When rainfall is not bigger enough to generate runoff, there is no loss to surface runoff. For this situation, AnnANPS assumes that inorganic P on the soil surface either stay in place or carried into soil profile with infiltration. The amount of surface inorganic P stay on soil surface or carried into soil profile with infiltration is determined as following:

If the infiltration is greater than 1.0 mm, the surface soluble inorganic P carried into soil profile with infiltration is calculated as:

$$inf_sol_P = surf_inorgP \quad \text{Equation 11-37}$$

However, when the top soil layer is less than 200 mm, pro-rate lost to infiltration, which partition part of infiltration back to soil surface. This prevents mathematical problems later when the concentration is calculated based on the layer thickness.

$$inf_sol_P = \frac{D}{200} * (inf_sol_P) \quad \text{Equation 11-38}$$

Then, AGNPS resets $mnaP$ and $surf_inorg P$ values to reflect the impact of current rainfall event.

$$mnaP = mnaP + inf_sol_P \quad \text{Equation 11-39}$$

$$surf_inorgP = surf_inorgP - inf_sol_P \quad \text{Equation 11-40}$$

If the infiltration is less than 1.0 mm, surface inorganic P remains in place.

11.2.3.2 Calculation of Intermediate Inorganic P Mass Balance

The intermediate inorganic P mass balance refers to P pools which includes P additions but prior to P losses as soluble P, sediment P, and plant uptake. Inorganic P added from manures or other fertilizers goes initially to the labile P pool and the active P pool, based on value of the P sorption coefficient. Units in following equation are ppm.

11.2.3.2.1 Calculation of Flow Rate between Labile P and Active P

Many studies have shown that after an application of inorganic P fertilizer, solution P concentration decreases rapidly with time due to reaction with the soil. This initial “fast” reaction is followed by a much slower decrease in solution P that may continue for several years (Barrow and Shaw, 1975; Munns and Fox, 1976; Rajan and Fox, 1972; Sharpley, 1982).

Equilibration between the solution and active mineral pool is governed by following equation:

Flow between labile P pool and active pool occurs only when soil temperature is above zero. It is calculated as:

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$$mpr = 0.1 * \frac{SW}{f} * \exp(0.115 * T_{soil} - 2.88) *$$

$$(start_labP - start_actP * \frac{Psp}{1 - Psp})$$

Equation 11-41

Where:

mpr = flow rate of P between labile and active P pools for soil layer on current day (+ implies flow from labile to active pool, - in opposite direction) (g/Mg/d) (Sharpley and Williams, 1990);
 $start_labP$ = starting day's soil layers' labile pool of inorganic phosphorous (ppm);
 $start_actP$ = starting day's soil layers' active pool of inorganic phosphorous (ppm); and
 Psp = P absorption coefficient for soil layer on current day (dimensionless) (Sharpley and Williams, 1990)

The actual value of mpr is restricted to the sign of mpr , values of labile and active pools. Positive sign implies flow from labile to active pool, negative sign implies the opposite direction. The daily amount of P computed with above equation flows to the active mineral P and is, therefore, added to that pool and subtracted from the labile pool. To prevent oscillation of active and labile pools, only allow no more than half the difference between active and labile pools to move.

P sorption coefficient is defined as the fraction of fertilizer P remaining in the labile pool after the initial rapid phase of P sorption is complete. The P sorption coefficient is a function of chemical and physical soil properties as described by the following equations (Jones et al., 1984).

1. When soil PH value is greater than 7.8 or the concentration of $CaCO_3$ is greater than zero.

P sorption coefficient is calculated as

$$Psp = 0.58 - 0.61 * CaCO_3$$

Equation 11-42

Where:

Psp = P absorption coefficient for soil layer
 $CaCO_3$ = Concentration of $CaCO_3$ (fraction).

The same as EPIC. However, in EPIC, $CaCO_3$ is in percent, so 0.0061 is used in above equation.

2. When soil PH value is less than 5.0 or base saturation is less than 35,

For clay content is greater than zero to prevent log zero

$$Psp = -0.047 * \ln(frac_clay * 100) + 0.0045 * start_labP - 5.3 * orgC + 0.39$$

Equation 11-43

For clay content is zero

$$Psp = 0.0045 * start_labP - 5.3 * orgC + 0.39$$

Equation 11-44

3. for all the other cases:

$$Psp = 0.0043 * sat + 0.0034 * start_labP + 0.11 * PH - 0.7$$

Equation 11-45

Psp has the limits of 0.05 and 0.75. Psp value is checked after calculations. If Psp is less than 0.05, 0.05 is set for this value; and if Psp is greater than 0.75, set Psp equals to 0.75.

Where:

$Frac_caly$ = fraction of clay content,
 Sat = base saturation (%),
 PH = PH value,
 $orgC$ = Organic carbon content (%)

Calculation of flow rate between active P and stable P

Flow rate of P between active and stable are calculated as follow:

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$$aspr = flow * (4 * start_actP - start_stbP) \quad \text{Equation 11-46}$$

1. When soil PH value is greater than 7.8 or the concentration of CaCO₃ is greater than zero.

The soil type dependent P flow coefficient is:

$$flow = 0.00076 \quad \text{Equation 11-47}$$

Otherwise, the soil type dependent P flow coefficient is calculated as

$$flow = \exp(-1.77 * Psp - 7.05) \quad \text{Equation 11-48}$$

Where:

flow = soil type-dependent P flow coefficient for soil layer on current day (dimensionless) (Sharpley and Williams, 1990; Jones, et al., 1984). It can be estimated based on following equations:

The value of aspr is restricted based on value of active P and stable P pools, and sign of aspr.

1). If aspr is positive sign and aspr is greater than start_actP, then set aspr equal to start_actP

$$aspr = start_actP \quad \text{Equation 11-49}$$

2). If aspr is negative and the absolute value of aspr is great than start_stbP, then set aspr equal to minus start_stbP.

$$aspr = (-1) * start_stbP \quad \text{Equation 11-50}$$

Compute new values for labile, active and stable P in soil layer 1 and 2 in ppm

a). Portion of incorporated inorganic P is added into labile P pool

$$labP = start_labP - mpr + \frac{Psp * mnaP * 1000000}{conv} \quad \text{Equation 11-51}$$

Where:

labP = Amount of labile pool inorganic phosphorus in the composite cell's soil layer. Top layer is the first layer (g/Mg);

start_labP = starting day's soil layers' labile pool of inorganic phosphorous;

start_labP = comp_layer_labP;

mpr = flow rate of P between labile and active P pools for soil layer j on current day (+ implies flow from labile to active pool, - in opposite direction) (g/Mg/d) (Sharpley and Williams, 1990);

Psp = soil type-dependent P sorption coefficient for soil layer j on current day, it is dimensionless (Sharpley and Williams, 1990); and

mnaP = mass of inorganic (mineral) P added to a cell from incorporated inorganic additions such as fertilizers (kg). It is calculated in fertilizer section.

b). The rest of incorporated inorganic P is added into active P pool

$$actP = start_actP + mpr + \frac{(1 - Psp) * mnaP * 1000000}{conv} - aspr \quad \text{Equation 11-52}$$

Where:

aspr = flow rate of phosphorus between active and stable phosphorus pools for soil layer j on current day (a "+" implies flow from active to stable pool, a "-" implies flow in opposite direction); (g/Mg/d);

The following section introduces the calculation of aspr, if the actP is less than zero, then readjust the aspr value as follow:

AnnAGNPS: Technical Descriptions

$$aspr = start_actP + mpr + \frac{(1 - Psp) * mnaP * 1000000}{conv} \quad \text{Equation 11-53}$$

And set the actP as zero

c) Compute stable P pool size

$$stbP = start_stbP + aspr \quad \text{Equation 11-54}$$

Where:

start_stbP = starting day's soil layers' stable pool of inorganic phosphorous; and
stbP = stable phosphorous.

11.2.3.3 Calculation of Additions From P Mineralization

$$total_inorgP = labP + actP + stbP \quad \text{Equation 11-55}$$

$$frac_labP = \frac{labP}{total_inorgP} \quad \text{Equation 11-56}$$

$$frac_actP = \frac{actP}{total_inorgP} \quad \text{Equation 11-57}$$

$$frac_stbP = \frac{stbP}{total_inorgP} \quad \text{Equation 11-58}$$

$$labP = labP + \frac{hmnP * frac_labP * 1000000}{conv} \quad \text{Equation 11-59}$$

$$actP = actP + \frac{hmnP * frac_actP * 1000000}{conv} \quad \text{Equation 11-60}$$

$$stbP = stbP + \frac{hmnP * frac_stbP * 1000000}{conv} \quad \text{Equation 11-61}$$

Where:

hmnP = is from the organic phosphorus mass balance and is the mineralization rate (kg/d) from the humus active organic phosphorus pool in soil layer. It is the phosphorus mineralized from active organic phosphorus in soil layer on current day (actual argument passed to inorg_P_mass_bal subroutine (kg/d));

frac_labP = fraction labile phosphorus;

frac_actP = fraction active; and

frac_stbP = fraction stable.

Compute mass (tons) of each pool

$$mplab = \frac{labP * conv}{1000000} \quad \text{Equation 11-62}$$

$$mpact = \frac{actP * conv}{1000000} \quad \text{Equation 11-63}$$

$$mpatb = \frac{stbP * conv}{1000000} \quad \text{Equation 11-64}$$

Where:

mplab = mass of labile P in cell soil layer (kg);

mpact = mass of active P in cell soil layer (kg);

mpatb = mass of stable P in cell soil layer (kg);

AnnAGNPS: Technical Descriptions

actP = active P (kg); and
 stbP = stable P (kg).

11.2.3.4 Calculation of Inorganic P Losses From a Cell

This calculation will include sequential adjustments to P pool size to reflect losses.

Loss through surface runoff

When rainfall occurs, runoff interacts with soil and carries soluble inorganic P in the soil profile away from fields. AnnAGNPS assumes the effective depth of runoff interaction is 1 mm. This loss is different from surface inorg P loss which has been introduced in previous section.

Incorporated inorganic P from manure or other fertilizer (mnaP) is added into the labile and active P pools (previous section), thus fertilizer's impact on soluble P losses is reflected in elevated labile P pool levels.

1). Calculate soil soluble inorganic P, this refers to only that which is incorporated in top soil layer

$$soil_sol_P = \frac{labP}{(1. + Kd_inorgP)} \quad \text{Equation 11-65}$$

Where:

soil_sol_P = concentration of soluble P in cell soil layer on current day, reflects inorganic P additions that are incorporated in top soil layer (intensive, units, g/Mg)

Kd_inorgP = Linear partitioning coefficient for inorganic Phosphorus. It is the ratio of the mass of absorbed P to the mass of P in solution. Kd_inorgP = 0.175 ,

labP = Amount of labile pool inorganic phosphorous in the composite cell's soil layer (g/Mg).

2). Calculate soluble inorganic P removed from soil top layer by runoff, this refers to only that which is incorporated in top soil layer

$$cell_soil_sol_P = edi * \frac{soil_sol_P * conv}{D * 1000000} \quad \text{Equation 11-66}$$

Where:

cell_soil_sol_P = mass of inorganic P removed from top soil layer through runoff (kg); and

edi = effective depth of interaction factor, AnnAGNPS uses 1 mm

3). Compute new value for labile P (in ppm) in soil top layer (reflects loss of soil soluble P)

$$labP = labP - \frac{cell_soil_sol_P * 1000000}{conv} \quad \text{Equation 11-67}$$

Loss through sediment (clay-bound) inorganic P that leaves cell soil layer

When rainfall occurs, soil erosion carries inorganic P away from fields. This is calculated in the following equations. When there is no rainfall, this is not calculated.

1). Calculation of the concentration of inorganic P in clay fraction:

$$cell_clay_p_w = \frac{labP + actP + stbP}{(frac_clay) * 1000000} \quad \text{Equation 11-68}$$

Where:

cell_clay_p_w = concentration of inorganic P in clay fraction of cell soil layer (intensive units, g/g)

2). Total loss of inorganic P through soil erosion is calculated as:

AnnAGNPS: Technical Descriptions

$$sed_inorgP = cell_clay_p_w * (sed_part(1,1) + sed_part(1,2)) * 1000 \quad \text{Equation 11-69}$$

Where:

sed_inorgP = current days mass of inorganic P attached to sediment (kg).

sed_part(1,1) and sed_part(1,2) = Current day's mass of sediment (by particle size and source) at edge of cell.

Array subscript are: Particle Size (first): 1) – clay; 2) silt; 3) sand; 4) small aggregate; and 5) large aggregate. Source (second): 1) irrigation; 2) other than irrigation.

sed_part is metric tons, sed_inorgP is kilograms. This is done in the same as organic P loss through soil erosion.

3). Adjust P pool values of soil layer 1 based on what was lost with sediment followed by the readjustment of fractions of each P pool.

$$labP = labP - \frac{sed_inorgP * frac_labP * 1000000}{conv} \quad \text{Equation 11-70}$$

$$actP = actP - \frac{sed_inorgP * frac_actP * 1000000}{conv} \quad \text{Equation 11-71}$$

$$stbP = stbP - \frac{sed_inorgP * frac_stbP * 1000000}{conv} \quad \text{Equation 11-72}$$

Loss through plant uptake of inorganic phosphate

Amount of crop uptake P is taken off from labile P pool at the end of day.

$$labP = labP - \frac{uptP * 1000000}{conv} \quad \text{Equation 11-73}$$

Where:

uptP = mass of inorganic P taken up by the plant on current day (kg)

$$mplab = \frac{labP * conv}{1000000} \quad \text{Equation 11-74}$$

Crop uptake P is calculated in a crop growth stage subroutine and passes to inorganic P balance. The crop P uptake is limited by the inorganic P available in the composite soil layer. For detail algorithms, see crop uptake section.

11.2.4 Total Inorganic P Losses to Surface Runoff

Total mass of inorganic P lost in surface runoff includes soil incorporated and surface applied P lost.

$$sol_P = cell_soil_sol_P + surf_sol_P \quad \text{Equation 11-75}$$

Where:

cell_soil_sol_P = nitrogen losses to runoff from composite soil layer (kg)

surf_sol_P = nitrogen losses to runoff from soil surface (kg)

sol_P = soluble P (kg).

11.2.5 Leaching

Due to the low mobility of phosphorus, AnnAGNPS does not simulate leaching of soluble P.

12. CARBON

12.1 GENERAL INTRODUCTION

A growing concern of global warming necessitates a growing demand to reduce atmospheric CO₂ level. Removing carbon from the atmosphere by sequestration in the biosphere is one of two ways that scientists have been exploring. Understanding the carbon sequestration in soil is vital important to achieve the goal of carbon removal by biosphere.

The most stable long-term surface reservoir for carbon is the soil. Thus, changes in agriculture and forestry can potentially increase soil-carbon storage and reduce atmospheric carbon dioxide (CO₂) that is, in part, contributing to global warming. Models are valuable tools in guiding policy-makers in land-use management which potentially change terrestrial carbon sequestration. Understanding how carbon is cycled and distributed on the landscape is essential in simulating terrestrial carbon sequestration.

12.2 ANNAGNPS CARBON PROCESSES

The carbon cycle represented in AnnAGNPS is a simplified version of carbon cycle in soil. In general, the carbon exists in soil in many different ways: dissolved (solution) in the surface runoff and attached (adsorbed) to clay-size particles resulting from sheet and rill erosion. To simulate Carbon (C) processes, daily soil mass balances of C in a cell are maintained for each computational layer whose maximum value can be two (*). The computational layer 1 would be the top soil with a depth of 200 mm while the layer 2 is the remaining soil profile indicated in Soil Initial Conditions of Input Editor. In the layer 2, only a simple mass balance where the differences between C input and mineralization affecting the relationship C:N in the layer 2 are calculated. In the Figure 12-1, a simple scheme about the processes considered and the abbreviations is presented. The soil processes determine only **organic carbon attached to loaded clay sediments (*Att_C*)**. The rate of equilibration between total mass of organic carbon in solution and the total mass (adsorbed & in solution) of organic carbon must be extremely slow with respect to travel time through the catchment due to clay-size particles are not expected to be deposited within the stream reach. The **dissolved fraction of the OC** in the runoff from cell soil is equal to 0 as a result of considering a very low partition coefficient of chemical, K_d . However, organic carbon in solution (*Sol_C*) can be computed from other sources such as point sources, gullies, ponds, irrigation and lateral flow in channels where organic carbon in solution can be exported. Finally, in order to consider the decay process in the reaches, a factor depending on the reach organic carbon half-life and the travel times to compute a exponential losses associated to chemical, biological degradation is applied to the organic carbon load.

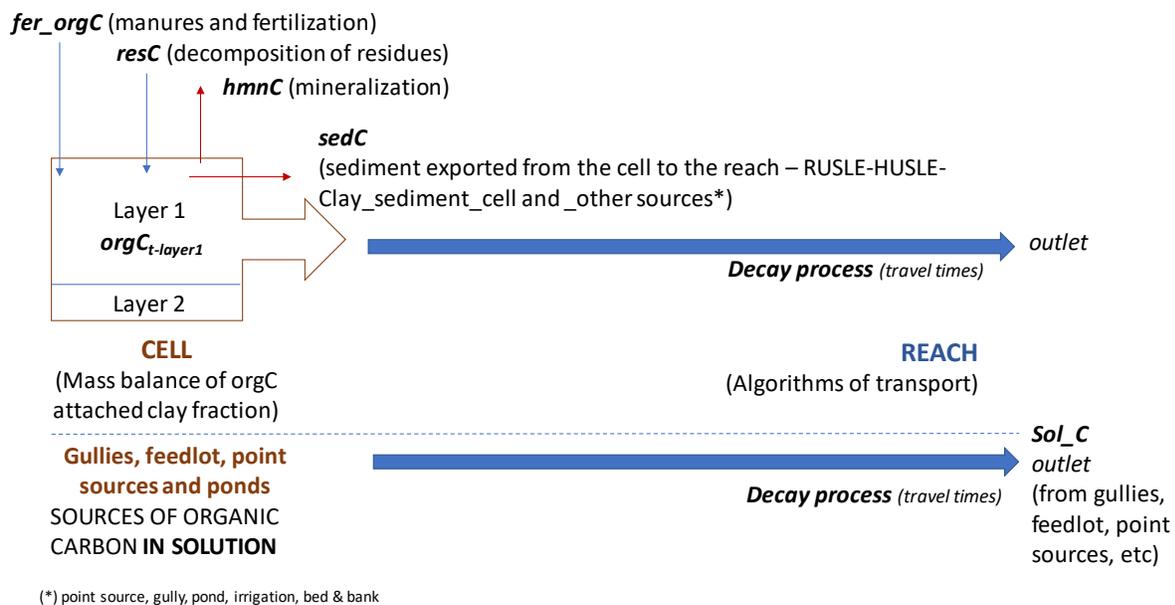


Figure 12-1. Representation of the organic carbon dynamics processes. In the cells the *orgC* is updated in the layer 1 each day. The depth of the layer 1 is 200 mm (8 in) whereas the layer 2 the remaining soil profile. Inflows due to

AnnAGNPS: Technical Descriptions

fertilization and residue decomposition can be considered whereas outflows are associated to the mineralization and eroded sediments. The current *OrgC_{layer1}* in the cells and the sediment dynamics derived from RUSLE, the sediment delivery ratio (HUSLE) and the algorithms of transport in reaches determine the organic carbon fraction attached to the clay fraction of sediment load. Total sediment load computes all multiple sources of attached OC to clay sediments (e.g. gullies) as well as considering the decay process associated to travel times in reaches (*Att_C*). Carbon in solution is computed through the concentration values provided by the user for point sources (gullies, feedlot, point sources and ponds). Decay processes in the reaches are also computed (*Sol_C*).

(*) In the code, the organic C content in each layer would be: $cv(c)\%lyr_C_org_nd(1)$ and $cv(c)\%lyr_C_org_nd(2)$. Between the layers 1 and 2, there is no vertical Carbon exchange which could be thought to simulate in the future.

(**) In the code, $ptrv\%dn_sol_C = ptrv\%up_sol_C * EXP (meta_factor * exp_half_life_const * ptrs\%trvl_time / rch_hflife_C)$

12.2.1 Soil Initial Carbon Contents and Conversion Factor

In the soil data section of input data, Organic Matter Ratio (mass_organic matter/mass_ratio) of each soil layer needs to be defined by a user. If such information is not defined by a user, default values are used during the simulation. The default value for Organic Matter Ratio is initially set to 3%.

The content of organic C is calculated based on the Organic Matter Ratio (OMR) in the following equation:

$$orgC = 0.58 * OMR \quad \text{Equation 12-1}$$

Where:

orgC = Organic C content in fraction; and
OMR = Organic Matter Ratio in fraction.

The input of amount of nutrient levels in the soil profile are as concentrations, but AnnAGNPS performs calculations on a mass basis. To convert a concentration to a mass, AnnAGNPS uses a conversion factor (conv). Conversion factor represents a weight of soil in that it is a volume of soil times bulk density. It is used to convert nutrient concentration in soil to kilograms used to do mass balances.

$$conv = D * 10 * 1000 * \rho_b * A_{cell} \quad \text{Equation 12-2}$$

Where:

conv = intensive unit to extensive unit conversion factor (kg)
D = thickness for soil layer (mm)
pb = bulk density of composite soil layer (g/cc or Metric tons/ m3)
Acell = AnnAGNPS cell_area (hectares)

12.2.2 Organic Carbon Simulation Processes

The organic carbon exported from the cells "*sedC*" depends on the clay fraction of the soil layer 1 and on the organic carbon mass balance in the layer 1 (top soil) in *t-1* (*orgC_{t-1}*) following the equation 12-3 and Figure 12-1

All AnnAGNPS mass balance is based on AnnAGNPS cells and maintained for both composite soil layers, although in the layer 2 only the loss due to mineralization are considered and its calculations are associated to N and P dynamics.

The mass balance equation for organic carbon processes is as followings:

$$orgC_t = orgC_{t-1} + \frac{(resC + fer_orgC - hmnC - sedC)}{conv} \quad \text{Equation 12-3}$$

Where:

orgC_t = Organic C in the total composite soil layer for current day in fraction (-)
orgC_{t-1} = Organic C in the total composite soil layer for previous day (-)

AnnAGNPS: Technical Descriptions

$resC$ = organic C addition from decomposition of crop and noncrop residue (kg)
 fer_orgC = organic C from fertilizer application such as manure or other sources (kg)
 $hmnC$ = C mineralized from organic C in soil layer on current day (kg)
 $sedC$ = mass of C attached to sediment (kg) to loaded clay from the previous day

In the layer 2, the mass balance is simplified, Eq. 12-3A:

$$orgC_{t-layer2} = orgC_{t-1-layer2} - hmnC_{layer2}/conv \quad \text{Equation 12-3A (****)}$$

Where:

$orgC_{t-layer2}$ = Organic C in the total composite soil layer for current day in fraction (-)
 $orgC_{t-1-layer2}$ = Organic C in the total composite soil layer for previous day (-)
 $hmnC_{layer2}$ = C mineralized from organic C in soil layer on current day (kg)

(***) In the code, the equation 12-3 is written as :

$$cv(c)\%lyr_C_org_nd(1) = cv(c)\%lyr_C_org_nd(1) + (C_decmp_sur + cell_C - cell_snr_rnof_att_C - C_humus(1)) / soil_mass_kg(1)$$

Where:

$orgC_i / orgC_{t-i} = cv(c)\%lyr_C_org_nd(1)$
 $resC = C_decmp_sur$
 $fer_orgC = cell_C$
 $hmnC = C_humus(1)$

$$sedC = cell_snr_rnof_att_C = 1000. * cv(c)\%lyr_C_org_nd(1) / cs(c)\%pt_soil\%cly_nd(1) * cell_clay_rnof_snr * cs(c)\%clb_fct_C;$$

($cs(c)\%clb_fct_C$ is a calibration factor to weight the carbon source; for all sources such as gullies, irrigation, feedlot, etc can be adjunsted; default is 1).

(****)In the code, the equation 12-3A is written as :

$$cv(c)\%lyr_C_org_nd(2) = cv(c)\%lyr_C_org_nd(2) - C_humus(2)/soil-mass_kg(2)$$

12.2.2.1 Carbon/Nitrogen Ratio (C:N) and C Mineralization

In the Equation 12-4, the calculations worked out to update C:N in each layer and each day is shown

$$\frac{C}{N_{layer-i}} = \frac{orgC_{layer-i} * 1000000}{orgN_{layer-i}} \quad \text{Equation 12-4}$$

Where:

$C/N_{layer-i}$ = C:N ratio corresponding with the layer 1 or 2;
 $orgC_{layer-i}$ = Concentration of organic_C in the total composite soil layer i for current day (%); and
 $orgN$ = Concentration of organic_N in the total composite soil layer i for current day (ppm).

The organic N is in ppm and organic C is a ratio (mass organic matter/mass soil).

Then, the carbon mineralization is calculated as:

$$hmnC_{layer-i} = \frac{C}{N_{layer-i}} * hmnN_{layer-i} * 0.5 \quad \text{Equation 12-5}$$

Where:

$hmnC$ = the mineralization rate of C on a given day (kg/d) for the layer i

AnnAGNPS: Technical Descriptions

hmnN = the mineralization rate of N from the humus active organic N pool (kg/d) for the layer i

(+) In the code, the Eq. 12-4 and 12-5 are written as:

C/N_layer-I, Eq. 12-4=> $C_N_soil_ratio(i) = (nd_to_ppm * cv(c)\%lyr_C_org_nd(i)) / cv(c)\%N_org_ppm(i)$
 hmnC_layer-I, eq. 12-5 => $C_humus(i) = C_N_soil_ratio(i) * N_mineral_humus(i) * 0.5$

12.2.2.2 Cell Residue Decomposition

Plant residue decomposition is a microbial process and associated with a loss of CO₂ as a result of microbial respiration (Parton et al., 1987). The loss of CO₂ on decomposition increases with increasing soil sand content. Decomposition from crop residues is added to the SOM or carbon pool. The potential decomposition rate is reduced by the function of soil moisture and soil temperature and may be increased as an effect of cultivation (Parton et al., 1987). In AnnAGNPS, residue decomposition is adjusted based on the average soil temperature (average daily temperature), not soil moisture. It is assumed that about 50% of carbon decomposed is lost as gas (CO₂) to the atmosphere in the decomposition processes.

It is reported that total carbon concentration in plant tissue is close to 40% (Honeycutt et al., 1993; Kuo et al., 1997; Chesson, 1997). However, the difference in nitrogen (N) concentration produced variation of C/N ratio among plant residue. The C/N ratio is about 17 for winter wheat cover crop (Kuo and Sainju, 1998) and it can be varied from 11-300.

a. Crop land

The cell residue carbon from decomposition is calculated for the layer 1 (top soil layer) for “crop land use” (**cropland**) in order to apply Eq. 12-3. If soil surface is disturbed due to some operations, the total residue remains the same. If some is actually incorporated in the top soil layer, it does not affect in decomposition calculations. The following equations assume 50% of residue decomposed (approximately the half) is lost as CO₂ (Eq. 12-6).

$$resC = (res_decomp) * 0.5 * 0.5 \quad \text{Equation 12-6}$$

Where:

resC = organic C addition from decomposition of crop residue (kg) (C_decmp_sur in the code)
 res_decomp = crop residue mass decomposition for current day (kg) (cell_res_day_decomp in the code where $cv(c)\%cell_surf_res$ is expressed in mass for each day. In organic N mass balance, the routine cell_surf_res is used to estimate daily decomposition)

Crop residue mass decomposition is calculated as:

$$res_decomp = (surf_res) * (1 - temp) * A_{cell} \quad \text{Equation 12-7}$$

Where:

surf_res = surface residue for a cell which is computed from RUSLE module (kg/ha)
 temp = RUSLE temperature correction factor depending on $tempf$ (Eq. 12-7A-8: (unitless) tmpr_fctr; see ISM_Nitrogen_Organic)

$$temp = -temp_f * surface_decomposition \quad \text{Equation 12-7A (++)}$$

Where:

surface-decomposition ($cv(c)\%pt_crp_surf_decomp$) is the surface residue coefficient (See Crop Data, 0.016 default)
 $temp_f$ is the temperature correction factor calculated by using the following equation 12-8. Its maximum value is 1.0 and is equal to 0.0 under extreme cold (<0.0 °C) and hold conditions (32 °C<):

AnnAGNPS: Technical Descriptions

$$temp_f = \frac{3200 * ((T_{soil} + 8) ** 2) - (T_{soil} + 8) ** 4}{2560000}, 0 < T_{soil} < 32$$

$$temp_f = 0, T_{soil} < 0$$

$$temp_f = 1, T_{soil} > 32$$

Equation 12-8

Where:

Tsoil = the average cell soil temperature (oC).

Above equation is a simplification of temperature correction factor from RUSLE (Page 152, equation 5-7). The 32.0 in temp_f equation is the RUSLE (To) value (°C) which is 90 (°F), and the 8.0 is the A value, in deg. C. The equation assumes residue, irrespective of crop, is 50% organic carbon. The detail of this part is described in the cell residue calculation document.

(++)In the code, Eq. 12- 7-8 are the following:

(Eq. 12-7) `cell_res_day_decomp = cv(c)%cell_surf_res * ((1-temp) * cs(c)%da_tot)`

(Eq. 12-7A) `temp = -tmpr_fctr * cv(c)%pt_crp%surf_decomp`

(Eq. 12-8) `tmpr_fctr = MIN(1., MAX(0., (((2.*((cell_tmpr_ave + 7.78)**2) *1600.)) - ((cell_tmpr_ave + 7.78)**4))) / 2560000.))`

b. Non-crop land

For different land uses to croplands (non-croplands), where there is no specific operations to incorporate residues, the rate of decomposition compute surface residue added to soil surface litter in the soil layers 1 and 2 (used for simulating the inorganic N-dynamics and P-dynamics). The Eq. 12-9 is used for determining resC in both layers.

$$resC = (res_decomp) * 0.5 * 0.5$$

Equation 12-9

Where:

resC = organic C addition from decomposition of noncrop residue (kg); and

res_decomp = noncrop residue mass decomposition for current day (kg).

For the term *resdecomp* the following consideration must be taken into account:

- 1) If “growing season” is active in Input Editor for the land use considered, an increase of rate of residue *resdecomp* (`cell_res_day_decomp`) in the layers 1 and 2 is calculated derived from the development of vegetation. For the layer 1, it is equivalent to 0.02% of the net production whereas for the layer 2, 0.13% (+++).
- 2) For the rest of conditions, the term *resdecomp* (`cell_res_day_decomp`) is calculated for the layers 1 and 2 following the Eq. 12-9:

Non-crop residue mass decomposition is calculated as:

$$res_decomp = (surf_res) * (1 - exp(temp)) * A_{cell}$$

Equation 12-10

Where:

surf_res = surface residue for a cell which is computed from RUSLE module (kg/ha); and

temp= RUSLE temperature correction factor depending on *tempf* (Eq. 12-7A-8: (unitless). `tmpr_fctr`; see `ISM_Nitrogen_Organic`), `temp=temp_f * 0.016`. **Where:** `cs(c)_nonc_surf_decomp` is the fraction of the surface of the cell (noncropland) where the residue decomposition is considered. *temp_f* is the temperature

AnnAGNPS: Technical Descriptions

correction factor calculated by using the following equation 12-8. Its maximum value is 1.0 and is equal to 0.0 under extreme cold (<0.0 °C) and hold conditions (32 °C<):

```
(+++)
```

$$cv(c)\%cell_surf_res = cv(c)\%cell_surf_res + (cs(c)\%sur_net_prod * 0.0002)$$

$$cv(c)\%cell_subs_res(1) = cv(c)\%cell_subs_res(1) + (cs(c)\%subsur_net_prod(1) * 0.0013)$$

```
(++++)
```

(In the code Eq. 12-9 is written as: $cell_res_day_decomp = cv(c)\%cell_surf_res * (1 - EXP(-tmpr_fctr * cs(c)\%nonc_surf_decomp)) * cs(c)\%da_tot$; $cs(c)\%nonc_surf_decomp=0.016$)

12.2.2.3 Cell Organic Carbon Addition from Manures or Other Sources

Cell organic C from manure application is calculated using the rate of application times the fraction which is organic C (from manure reference database weight/weight). It is associated to fertilization operations included into Input Editor.

$$fer_orgC = (fer_app) * (frac_orgC) * A_{cell} \quad \text{Equation 12-11}$$

Where:

fer_orgC = organic carbon from manure application on current day (kg);
 fer_app = the rate of fertilizer applied for current day operation (kg/ha); and
 $frac_orgC$ = fertilizer fraction which is organic C, from fertilizer reference database (mass/mass).

(/) In the code the Eq. 12-11 is written:

```
cell_C=cell_C+((cop(i)%pt_mse%pt_app_fert%fert_rate*  
cop(i)%pt_mse%pt_app_fert%frt_ref_pt%C_org_nd) * cs(c)%da_tot)
```

12.2.2.4 Calculation of Mass of Carbon Attached to Sediment (sedC)

The organic carbon exported from the cells “ $sedC$ ” depends on the clay fraction of the soil layer 1 and on the organic carbon mass balance in the layer 1 (top soil) in $t-1$ ($orgC_{t-1}$) following the equation 12-3. It is assumed that is the organic C makes up $cell_sed_C$ because total C is predominantly organic C in soils.

$$sedC = 1000 * (orgC_{layer1t-1}) * clay_soil_{layer1} * clay_eroded \quad \text{Equation 12-12}$$

Where:

$sedC$ = mass of C attached to sediment (kg). Sed_part is metric tons, so multiply by 1000;
 $orgC_{layer1-t-1}/clay_soil_{layer1}$ = decimal fraction of organic C per unit of clay in soil layer 1 (g/g) for the precious day;
 $clay_eroded$ = clay sediment associated to erosion in the cell (tons).

Following the catchment topology of cells and reaches, the exported organic carbon attached to clay fraction in the outlet will be determined by the travel times and the reach organic carbon half-life time (see also Figure 12-1).

```
(//) In the code, the Eq. 12-12 is written:  $sedC = cell\_snr\_rnof\_att\_C = 1000. *  
cv(c)\%lyr\_C\_org\_nd(1) / cs(c)\%pt\_soil\%cly\_nd(1) * cell\_clay\_rnof\_snr * cs(c)\%clb\_fct\_C$ 
```

AnnAGNPS: Technical Descriptions

12.2.3 AnnAGNPS CARBON PROCESSES: Input Parameterization

In the Table12-1, the list of the required parameters and the potential variation sources for a sensitivity analysis:

Component	Adjustment factors (in bold, "adjustable")	Where to change?	Variation ranges based on usual values and the potential catchment features
$conv$ = intensive unit to extensive unit conversion factor (kg)	D = thickness for soil layer 1 (mm)	Menu "Soil Data" in Input Editor /4_Editor_DataSets_CSV_Input_Files/general/	ρ_b (1.1-1.7 g/cm ³) It should be agreed with textures -sandy soils (1.3–1.7 g/cm ³); fine silts and clays (1.1 – 1.6 g/cm ³)
	ρ_b = bulk density of composite soil layer 1 (g/cc or Metric tons/ m ³)	AnnAGNPS_Combined_Group_1_Soil_Layer_Data.csv	
$hmnC_{layer-1}$	$(C/N)_{layer-1}$ =relation organic Carbon/Nitrogen in the computational layer 1 $hmnN_{layer-1}$ = mineralization rate of N from the humus active organic N pool (kg/d) for the layer 1	Internal Calculations Menus "Soil Data" or "Soil Initial Conditions" in Input Editor for initial Organic Carbon and Organic Nitrogen in layers 1 and 2. Soil Initial Conditions are only needed if the global defaults are not sufficient for the initialization. Optional file "Soil Initial Conditions Data" File/4_Editor_DataSets_CSV_Input_Files/general/ Soil-Initial_Conditions.csv	Complete the analysis with the parametrization of the nitrogen algorithms
$resC$ = organic C addition from decomposition of crop residue (kg)	$surf_{res}$ = surface residue for a cell which is computed from RUSLE module (kg/ha)	Menus "Crop Data" in Input Editor (kg/ha corresponding with 30%, 60% and 90% of cover) /4_Editor_DataSets_CSV_Input_Files/general/ cropdata.csv and /manoper.csv	0-15.000 kg/ha (Define type of residue and to prepare in agreement with roughness and n-Manning)
	surface-decomposition = is the surface residue coefficient (See Crop Data, 0.016 default)	Menu "Crop Data" in Input Editor, Surface Decomposition /4_Editor_DataSets_CSV_Input_Files/general/ cropdata.csv and /manoper.csv	0-1
	T_{soil} = the average cell temperature (°C; cell_tmpr_avg= average air temperature)	Menu "Climate Data" in Input Editor /4_Editor_DataSets_CSV_Input_Files/climate/ Climate_daily.csv	What to do? Between -10 and +10°C summed to the collected data? For climate change, the predictions is +/-3°C
fer_{org}	fer_{app} = the rate of fertilizer applied for current day operation (kg/ha); and $frac_{orgC}$ = fertilizer fraction which is organic C, from fertilizer reference database (mass/mass).	Menu "Fertilizer>Fertilizer Application Data" Fertilizer>Fertilizer Reference Data" in Input Editor /4_Editor_DataSets_CSV_Input_Files/general/ fertapp.csv /4_Editor_DataSets_CSV_Input_Files/general/ fertref.csv	All combinations N-P-K (from 5-5-5 until 12-52-0) Rates of application 50 kg/ha-500 kg/ha
$sedC$	Clay_soil K-factor (texture, initial organic matter)	Menu "Soil Data" in Input Editor /4_Editor_DataSets_CSV_Input_Files/general/ AnnAGNPS_Combined_Group_1_Soil_Layer_Data.csv	5-80% of clay fraction (adjusted with bulk density and the rest of fractions) 0.1-4%
Hydrology and Erosive dynamics	C-factor (Subfactor Roughness management, subfactor residue was previously included)	Menu "Management Operation Data" in Input Editor /4_Editor_DataSets_CSV_Input_Files/general/ manfield.csv and /manoper.csv	0.00001-50 mm (in agreement with the rater of residues and n-Manning in cells)

AnnAGNPS: Technical Descriptions

	<i>CN</i>	Menu “Runoff Curve Number Data” in Input Editor 4_Editor_DataSets_CSV_Input_Files/general/rocurve.csv and /manoper.csv	60-100
	<i>Storm type</i>	Menu “Storm Type Data” in Input Editor _Editor_DataSets_CSV_Input_Files/climate / Storm type input data (optional)	All types – Would it be suitable to adjust the observed pattern in the catchment also?
	<i>n Manning</i>	Menu “Cell Data” and “Reach Data” in Input Editor /4_Editor_DataSets_CSV_Input_Files/watershed/celldata.csv and rchdata/manoper.csv	0.01-0.45

13. WETLAND NITROGEN REMOVAL COMPONENT

13.1 WETLAND COMPONENTS

Conceptualizing wetland processes into an AnnAGNPS module (wetland feature) requires (1) identifying critical physical and chemical processes, (2) developing appropriate algorithms for simulating these processes, and (3) defining needed parameters for model simulation. Physical and chemical processes of interest include water inflow to the wetland and outflow from the wetland and water associated pollutant concentrations; and how nutrient changes in the wetland. A mass balance approach is used to simulate hydrologic and water quality processes in the wetland. Specific parameters considered in these simulations were determined based on the review of the current wetland researches on nitrogen removal (Crumpton et al., 1997; Crumpton and Goldsborough, 1998; Crumpton and Kadlec, 1997) and are presented in table 1.

The principal of mass conservation for a fixed control volume can be stated as,

[rate of mass inflow] - [rate of mass outflow] ± [rate of mass transfer through a source or sink] = [rate of change of mass within the control volume]. This principal is applied for both hydrology and pollutant mass balances in the wetland feature. The hydrology mass balance is maintained as:

$$V_i = V_{(i-1)} + Q_{inflow} - Q_{outflow} + P - ET - I \quad \text{Equation 13-1}$$

Where:

V_i = volume of the water per unit area of wetland at the end of the day, [mm];

$V_{(i-1)}$ = volume of the water per unit area of wetland at the beginning of the day, [mm];

Q_{inflow} = volume of the water added to the wetland during the day per unit area of wetland, [mm];

$Q_{outflow}$ = volume of the water released from the wetland per unit area of wetland, [mm];

P = precipitation, from climate data information a user supplied, [mm];

ET = daily evaporation or evapotranspiration, daily evaporation or evapotranspiration is calculated internally based on the climate data and vegetation a user supplied, [mm]; and

I = daily infiltration, daily infiltration is calculated internally based on the soil properties a user supplied at the time when a wetland created, a constant daily seepage rate to the local groundwater beneath the inundated area is calculated after inundation [mm].

AnnAGNPS: Technical Descriptions

In equation 13–1, all water measurements are in equivalent water depth, which is the quotient of volume and area. The wetland area is assumed to be constant during the simulation period. At the end of a day, the wetland volume is adjusted to reflect the inflows and outflows that occurred during the day.

Wetlands are located on the reach to intercept upland flow; and wetland can also be used in conjunction with controlled subsurface drainage in which the drainage water is retained for denitrification before it is released to the main stream. Q_{inflow} are calculated by AnnAGNPS after each rainfall event and $Q_{outflow}$ are calculated based on wetland characteristics and can be controlled by the user.

$$Q_{inflow} = \frac{1000 * Q_{volume_inflow}}{A_{wetland}} \quad \text{Equation 13-2}$$

Where:

Q_{inflow} = volume of the water added to the wetland during the day per unit area of wetland, [mm];

Q_{volume_inflow} = total volume of the water added to the wetland, [m³];

$A_{wetland}$ = wetland surface area, [m²].

Total volume of water added to the wetland (Q_{volume_inflow}) on a given day is from AnnAGNPS simulation. AnnAGNPS can provide results for any given point a user selects within the watershed.

If a wetland outflow is controlled by a weir and H is greater than zero based on equation 13–5, total amount of water flow out of the wetland is calculated as:

$$Q_{volume_outflow} = B * L * H^a \quad \text{Equation 13-3}$$

Where:

$Q_{volume_outflow}$ = total volume of the water flow out of the wetland on a given day, [m³];

B = the weir coefficient and it is determined by a user;

L = width of the weir opening, [m];

a = the weir exponent as determined by the user or default as 1.5; and

H = head (m).

$$Q_{outflow} = \frac{1000 * Q_{volume_outflow}}{A_{wetland}} \quad \text{Equation 13-4}$$

Where:

$Q_{outflow}$ = volume of the water released from the wetland per unit area of wetland, [mm];

$Q_{volume_outflow}$ = total volume of the water released from the wetland on a given day, [m³];

$A_{wetland}$ = wetland surface area, [m²].

The hydraulic head is a function of the water in the wetland and can be calculated as:

AnnAGNPS: Technical Descriptions

$$H = \frac{V}{1000} - H_{weir}$$

Equation 13-5

Where:

H = hydraulic head on a given day, [m];

V = volume of the water per unit area in the wetland on a given day, [mm]; and

H_{weir} = the distance of the bottom of the weir above the bottom soil surface of the wetland, [m].

The height of the weir is a user input with a default value of 1-m above the ground surface (bottom of the wetland).

The pollutant mass balance is maintained as:

$$M_i = M_{(i-1)} + M_{inflow} - M_{outflow} - S$$

Equation 13-6

Where:

M_i = mass of the pollutant in the wetland at the end of the day, [kg];

$M_{(i-1)}$ = mass of the pollutant in the wetland at the beginning of the day, [kg];

M_{inflow} = mass of the pollutant added to the wetland in the day, [kg];

$M_{outflow}$ = mass of the pollutant released from the wetland in the day, [kg]; and

S = source or sink term (which includes the crop decay, pollutant transformation, and any chemical reactions caused by the change of the mass of the pollutant in the wetland), [kg]. This term is calculated only for nitrogen removal at this stage of model development.

Total amount of nitrogen added to the wetland (M_{inflow}) on a given day is from AnnAGNPS simulation. AnnAGNPS can provide results for any given point a user selects within the watershed.

$M_{outflow}$ is calculated using:

$$M_{outflow} = \frac{C_{outflow} * Q_{volume_outflow}}{1000}$$

Equation 13-7

Where:

$M_{outflow}$ = mass of the pollutant released from the wetland during a day, [kg];

$C_{outflow}$ = pollutant concentration of the released water, which is internally determined, [mg/L or g/m³];

$Q_{volume_outflow}$ = total volume of the water released from the wetland, [m³].

The pollutant concentration of released water ($C_{outflow}$) is assumed the same as the pollutant concentration in the wetland (C) at the beginning of the day which is calculated as:

AnnAGNPS: Technical Descriptions

$$C = \frac{10^6 * M_{i-1}}{V_{i-1} * A_{wetland}} \quad \text{Equation 13-8}$$

Where:

C = the concentration of nitrate-N in wetland, [mg/L or g/m³];

M_{i-1} = mass of the pollutant at the beginning of the day, [kg];

V_{i-1} = volume of the water per unit area of wetland at the beginning of the day, [mm];

A_{wetland} = wetland surface area, [m²].

Nitrate transformations in wetlands involve complex spatial and temporal patterns, and the efficiency of wetland on nitrate removal differs greatly. In this study, the nitrogen loss rate described by a temperature dependent first-order model (Crumpton et al., 1997; Crumpton and Goldsborough, 1998; Crumpton and Kadlec, 1997) was used to calculate S. Therefore, the sink term S is calculated as:

$$S = \frac{J * A_{wetland}}{1000} \quad \text{Equation 13-9}$$

Where:

S = the sink term, [kg];

J = Nitrate-N loss rate, [g m⁻² day⁻¹];

A_{wetland} = wetland surface area, [m²].

The nitrate-N loss rate J is calculated as:

$$J = k_{20} * C * \theta^{(T-20)} \quad \text{Equation 13-10}$$

Where:

J = Nitrate-N loss rate, [g m⁻² day⁻¹];

K₂₀ = the area based first order loss rate coefficient for nitrate-N at 20 °C, [m/day];

C = the concentration of nitrate-N in wetland, [mg/L or g/m³];

θ = the temperature coefficient for nitrate-N loss; and

T = water temperature, (°C).

The area based first order loss rate coefficient (K₂₀) can be estimated based on field measurement and is a user input with a default value of 0.15 (Crumpton et al., 1997; Crumpton and Goldsborough, 1998; Crumpton and Kadlec, 1997). The temperature coefficient for nitrate-N loss (θ) is also a user input with a default value of 1.09 (Crumpton et al., 1997; Crumpton and Goldsborough, 1998; Crumpton and Kadlec, 1997). Water temperature (T) on a given day is assumed as the average air temperature; and average air temperature is calculated as the average of maximum and minimum air temperature (maximum and minimum air temperature is available from AnnAGNPS climate file).

Using equations (13–5), (13–6), (13–7), (13–8), (13–9) and (13–10), temporal variations of water quality in the wetland can be determined. In the presently developed stage, pollutant mass balances are maintained for nitrogen only.

AnnAGNPS: Technical Descriptions

13.2 IMPLEMENTATION OF THE WETLAND FEATURE IN ANNAGNPS

On a given day, the following calculation is performed in a sequence:

- 1) Wetland N concentration (C) is calculated using equation 13–8; the amount of water and pollutant in the wetland at the beginning of a day is the same as the amount of water and pollutant in the wetland at the end of the previous day.
- 2) the N loss (S) during the day is calculated based on equations 13–9 & 13–10;
- 3) the hydraulic head (H) is calculated using equation 13–5. The amount of water per unit area in the wetland is assumed the same as the amount of water per unit area in the wetland at the beginning of the day which is the amount of water per unit area in the wetland at the end of the previous day. If H is greater than zero, the amount of flow out of the wetland (Q_{outflow}) is calculated based on equations 13–3 & 13–4; and the amount of N released with water is calculated using equation 13–7.
- 4) Runoff and pollutant loading to the wetland are supplied by AnnAGNPS through parameter passing. the amount of water in the wetland is updated using AnnAGNPS produced precipitation, evapotranspiration, seepage and runoff based on equation 13–1; and the amount of N in the wetland is updated using equation 13–6.
- 5) The processes are repeated for next day.

A wetland is assumed to be established on an AnnAGNPS reach (fig. 13–1). The wetland area is determined based on the DEM and wetland design criteria. When a wetland is established, separate calculations are performed for the wetland (equations 13–1 through 13–10). The flow and pollutant loading to the wetland are equal to AnnAGNPS output for the inlet point of the wetland. Precipitation, infiltration or seepage, and evaporation or evapotranspiration are calculated for the wetland. Precipitation is considered as water input to the wetland and no runoff (no soil erosion) is calculated for the wetland. The percolation from a wetland is calculated the same as for a cell at the time when a wetland is initially inundated, and after inundation a constant daily seepage rate to the local groundwater beneath the inundated area is user-supplied, with a default value equal to the saturated hydraulic conductivity of the soil beneath the wetland. Nitrate-N mass balances for a wetland are maintained based on the inflows and loss.

The outflow from the wetland is added to the same reach where the wetland is constructed. AnnAGNPS routes water and pollutant loadings from the wetland into the stream network and finally to the watershed outlet and has the ability to track pollutant sources as they move through the watershed system. Thus, the impact of wetland can be tracked down to any specified point in the watershed and to the watershed outlet.

13.3 USER INTERFACE

A user interface should be designed to facilitate the application of the wetland feature. This interface provides a user the flexibility of controlling the characteristics of the wetland. User supplied information overwrites internal calculations and defaults as described in Table 13–1.

AnnAGNPS: Technical Descriptions

Table 13-1. Input parameters needed to describe the wetland feature and user guidance associated with various parameters. Input parameters are required for each wetland to be simulated.

Parameter	Comments
Wetland identifier	The identifier of a wetland
Wetland reach ID	The reach where a wetland exists
Wetland area (m ²)	The area of a wetland
Minimum depth (mm)	The minimum water depth in the wetland
Maximum depth (mm)	The maximum water depth in the wetland
Seepage rate (mm/day)	Daily water loss due to seepage
V (mm)	Volume of the water per unit area of in the wetland (it is updated every day based on equation 1)
Q _{inflow} (mm)	The amount of water flow to the wetland on current day
Q _{volume_inflow} (m ³)	total volume of the water flow to the wetland on a given day
Q _{outflow} (mm)	The amount of water released from the wetland on current day
Q _{volume_outflow} (m ³)	total volume of the water flow out of the wetland on a given day
B	weir coefficient and it is determined by a user
L (m)	width of the weir opening
H _{weir} (m)	the height of a wetland weir (user input with a default value of 1 m above the ground surface which is the bottom of the wetland)
H (m)	Hydraulic head (it is calculated based on equation
M _{inflow} (kg)	The amount of nitrogen added to the wetland on current day
M _{outflow} (kg)	The amount of nitrogen added released from the wetland on current day
C (mg/L or g/m ³)	Nitrogen concentration in the wetland
S (kg)	nitrogen loss on a given day from the wetland
J (g m ⁻² day ⁻¹)	Nitrate nitrogen loss rate on a given (calculated based on equation 9)
K ₂₀	The area based first order loss rate coefficient for nitrate-N at 20 °C (user input with a default value Of 0.15)
θ	the temperature coefficient for nitrate-N loss (user input with a default value Of 1.09)
T (°C)	Wetland water temperature on a given day (average air temperature on a given day)

AnnAGNPS: Technical Descriptions

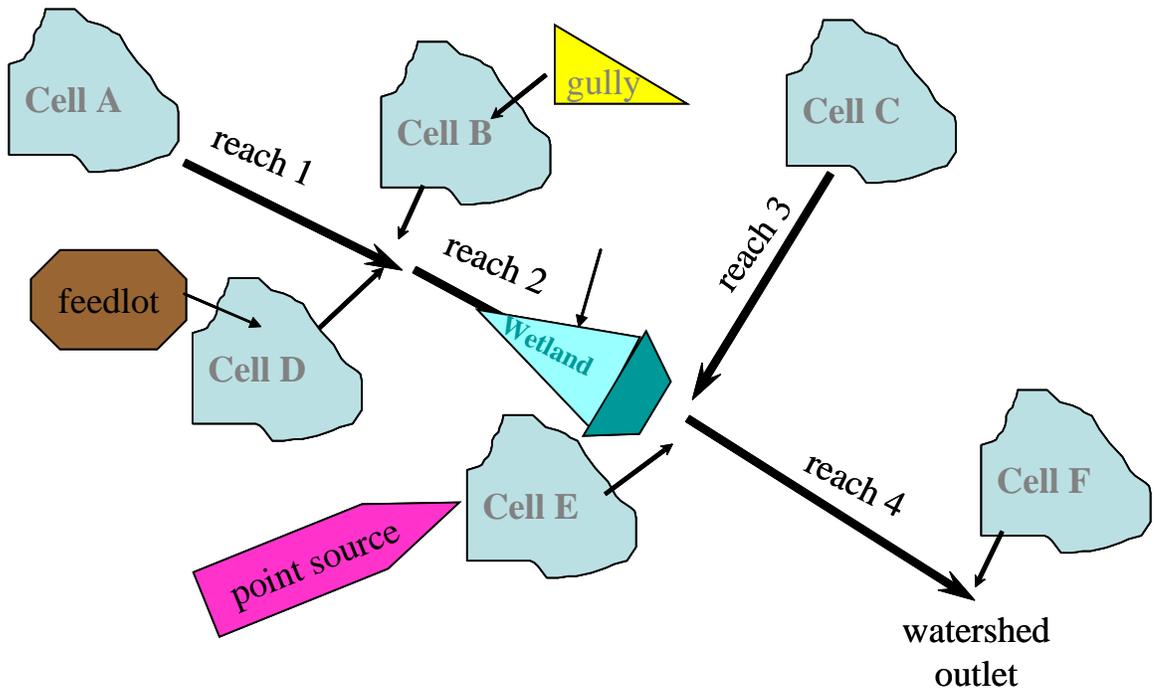


Figure 13-1. Processes simulated in AnnAGNPS. Wetlands are located on AnnAGNPS reaches, and the effluent from wetland goes back to the same AnnAGNPS reach where the wetland is constructed. As shown in this figure, a wetland is located on reach 2, more wetlands can be constructed on other reaches such as reach 1 and 3.

14. RIPARIAN BUFFER COMPONENT

Riparian buffers or buffers are defined as edge of field or in-stream conditions that reduce the sediment delivered to a reach from an AnnAGNPS cell or within an AnnAGNPS reach. Buffers can be comprised of vegetation, berms, drop pips, furrows, or any other condition that traps sediment delivered from the cell and before entering a reach. A simple view of a buffer is that the trapping efficiency is dependent on buffer slope, width and type of vegetation (Yuan et al, 2009).

Sediment trapping efficiency is one parameter that can be used to calculate the effectiveness of a riparian buffer to filter out sediment and is:

$$TE = (M_i - M_o) / M_i = 1 - \frac{M_o}{M_i} = 1 - SDR \quad \text{Equation 14-1}$$

Where:

TE = Trapping efficiency.

SDR = sediment delivery ratio.

M_i = total mass flowing onto the buffer zone (Tons/ha.).

M_o = total mass flowing out of the buffer zone (Tons/ha.).

As Meyer et al. (1995) and Dabney et al. (1995) observed, sediment trapping by a narrow stiff-grass hedge is primarily from settling in the backwater upslope of the hedge. Sediment characteristics greatly affected sediment trapping, flow rate had some effect, but sediment concentration had little effect (figure 5 in Meyer et al., 1995). As shown in tables 2 & 3 in Meyer et al. (1995), among the different switchgrass arrangements, the wide 760-mm hedge of Kanlow was considerably more effective than the 140-mm Kanlow hedge, but the combination of fescue before wild switchgrass (350-mm) was as effective as the wider Kanlow hedge (760-mm). It was found that the major effect of the type of grass was on flow ponding which was directly linked with the stem characteristics as they affected ponded depth. As the depth of ponding increased, the trapping efficiency increased and the resulting longer and deeper pool also increased the volume of sediment that could be stored before the delta of deposited sediment reached the hedge (Dabney et al., 1995). Also, as shown in tables 2 & 3 in Meyer et al. (1995), trapping efficiency of these hedges decreased less as flow increased than did the effectiveness of the other hedges; and the fraction trapped decreased only a few percent as flow doubled from 1.3 to 2.6 m³/min-m. A higher trapping efficiency of switchgrass and vetiver for the Dubbs II sediment than for the finer Dubbs I and Grenada sediments was observed. It was determined that nearly all of the sand-size sediment was trapped by the hedges, and the outflow from the hedges is dominated by silt and clay-size sediment. The trapped portion of sediment decreased as flow rate increased.

The following flow and trapping effectiveness relationship was suggested by Meyer et al. (1995):

$$TE_{ps} = 1 - aQ^b \quad \text{Equation 14-2}$$

Where: TE_{ps} = fraction trapped (decimal);

Q = peak flow rate (m³/min-m);

a = coefficient; and

b = exponent

a and b are functions of the sediment size and particle distribution trapped before the buffer because of ponding. The following coefficients and exponents were obtained from Dubbs II sediment during Meyer et al. (1995) experiments for the first three sizes down to < 32 μm . Q is the flow per meter length of buffer, where the length of the buffer

AnnAGNPS: Technical Descriptions

within AnnAGNPS would represent the effective width of the concentrated flow through the buffer (l_j) in meters.

$$Q = Q_p * 60 / l_j \quad \text{Equation 14-3}$$

Where Q_p is the peak flow rate (m^3/s) from AnnAGNPS for the AnnAGNPS cell or the downstream end of the reach that are adjusted based on the total drainage area contributing to the flow entering the upstream portion of the buffer, A_c , and the total area of the AnnAGNPS cell, $Q_p = A_c/\text{Cell Area}$ or the drainage area to the downstream end of the reach, $Q_p = A_c/\text{Area}$ to the downstream end of the reach. Peak flow is used assuming that most of the sediment is eroded early in the hydrograph and before the peak and that the peak will transport the sediment at the buffer that has arrived before the peak. Flow after the peak will be assumed to not be as significant.

The dimension of the width of the buffer flow can be estimated from topographic information or hydraulic geometry and determined as:

$$l_j = \text{hydraulic geometry width coefficient} * A_c^{**} \text{hydraulic geometry width exponent}$$

Table 14-1. Associated AnnAGNPS particle sizes with the Meyer et al. (1995) coefficients and illustrated in Figure 14-1.

Sediment size	a	b	Associated AnnAGNPS Particle Size Diameter (μm)
> 125 μm	0.025	2	Sand (200), Large Aggregate (500)
32- 125 μm	0.39	0.5	Small Aggregate (35.1)
< 32 μm	0.78	0.08	Clay (2), Silt (10),

Based on their relationship and a and b obtained from Meyer et al. (1995), sediment that can be trapped by various hedges for a wide range of sediment and flow conditions can be estimated. The flow is based on the flow entering a grass hedge so most of the sediment is trapped before entering the buffer. Meyer et al. (1995) suggested that in the absence of sediment-size distributions, particle size distributions can be estimated from analysis of bulk soil samples for the sediment resulting from interrill erosion. Foster et al. (1985) describe a method for evaluating sediment-size distributions of five broad size density classes using a soil's primary particle size distribution.

AnnAGNPS: Technical Descriptions

Table 14-2. Sediment Particle-Size Class Static Parameters

Sediment Particle Class	Particle Density (Mg/m ³)	Particle Fall Velocity (mm/s)	Deposition Mass Rate (g/m ² /s)	Deposition Rate Ratio (-)	Deposition Ratio Mass Rate (Mg-particle / Mg-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	

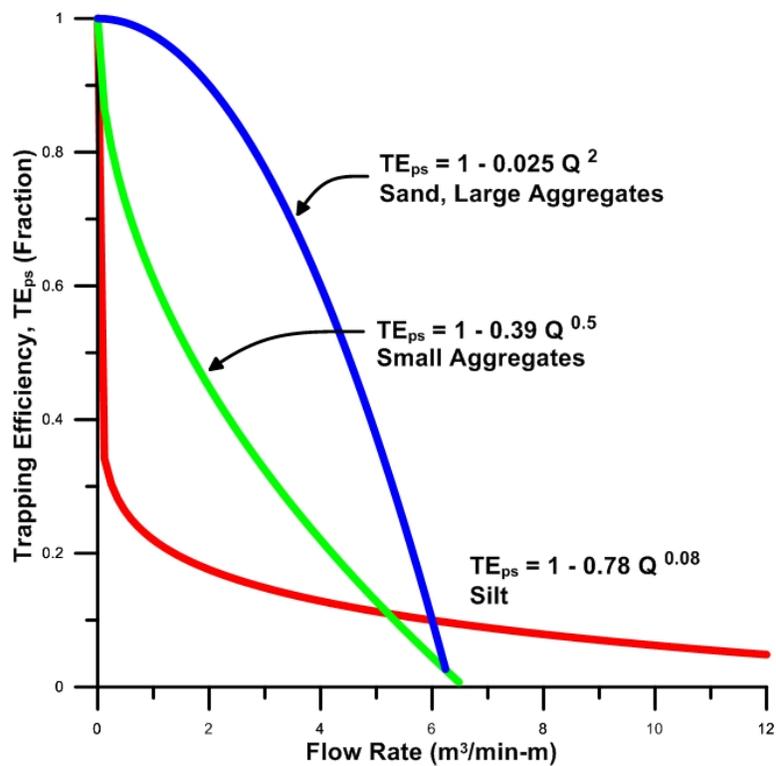


Figure 14-1. Sediment trapping efficiency defined by Meyer et al. (1995) and applied to the particle sizes utilized within AnnAGNPS.

The assumption is that the trapping efficiency is based on the fall velocities of the particle density of the particle classes. According to Meyer et al (1995) the five particle sizes used within AnnAGNPS can be assigned as shown in

AnnAGNPS: Technical Descriptions

Table 14–1 based on the corresponding fall velocities. Although, clay size particles are assumed to never deposit from the flow through buffers. Clay can be deposited as part of the small and large aggregate deposition. The various sources of sediment: sheet & rill (SR), gully, pond and irrigation, can be accounted for separately as their sediment enters a buffer. SR and gully sediment will have a peak flow associated with the transport of sediment. Ponds and irrigation sediment will only have a total flow determined within AnnAGNPS, so the assumption can be that the total flow is as if there is uniform flow entering the buffer for the trapping efficiency or that the Meyer et al. (1995) equation does not apply and that only the efficiency from the buffer will apply.

TE_m is the local trapping efficiency applied for all of the sediment going through a vegetative buffer strip. This can be described as the maximum trapping efficiency that can be attained within the buffer. This is determined based on Yuan et al (2009) relating TE_m with buffer width and slope. Vegetative type can also be a factor, but there is limited research to indicate a relationship. This also assumes that all sediment from each source is transported independently of all other sources. Within AnnAGNPS only width, slope, and vegetative type will be utilized based on:

- For vegetation = grass-type AND buffer slope ≤ 0.05 m/m (Figure 14–2):

$$TE_m = 0.6261 * (w_j) ** 0.127 \quad \text{Equation 14-4}$$

- For vegetation = grass-type AND buffer slope > 0.05 m/m (Figure 14–3):

$$TE_m = 0.6747 * (w_j) ** 0.06 \quad \text{Equation 14-5}$$

- For vegetation = bush and forest (Figure 14–4):

$$TE_m = 0.5957 * (w_j) ** 0.1527 \quad \text{Equation 14-6}$$

Where, TE_m is the local trapping efficiency, decimal;

w_j is the effective buffer width associated with the length of the flow path through the buffer, m.

14.1 CELL-LOCATED BUFFERS

If the effective buffer width is not provided then a default of 10 meters will be used. Each flow path will have a single vegetation type (predominant vegetation type). The buffer slope is the average slope of the flow path through the buffer with a default as the cell slope (cell_slp). An assumption for clay size particles is that clay will not deposit as a result of the buffer resulting in TE_m for clay to be equal to 0. The assumption for silt is that there will not be deposition of TE_{ps} above a Q of 3.0 m³/min-m. A further assumption is that concentrated flow will impact the effectiveness of the buffer to trap sediment, but not all of the flow upstream of the buffer will enter the buffer as concentrated flow. Combining the additive effect of concentrated flow based on TE_{ps} and uniform flow effects using TE_m will provide an impact from multiple uniform flow paths and also from concentrated flow that may reduce the effects of trapping sediment in the buffer.

The user can enter a value for TE_m or TE_{ps} or both, but if left blank then the internal calculations will be used.

The effect of TE_{ps} on sediment yield at the upstream edge of the buffer, src_yld_bfr is:

AnnAGNPS: Technical Descriptions

$$src_yld_aft(\cdot) = src_yld_bfr(\cdot) * (1.0 - TE_{ps}(\cdot)) \quad \text{Equation 14-7}$$

The effect of the flow through the buffer is then related to TE_m to produce the total effect on the sediment from the buffer as:

$$src_yld_aft(\cdot) = src_yld_aft(\cdot) * (1.0 - TE_m) \quad \text{Equation 14-8}$$

The actual trapping efficiency, TE_a , of the particle sizes of the sediment in the flow deposited throughout the entire buffer is then related to:

$$TE_a(\cdot) = 1 - src_yld_aft(\cdot) / src_yld_bfr(\cdot) \quad \text{Equation 14-9}$$

Users can also enter a value for TE_a , but then the $TE_m * TE_{ps}$ are ignored. Then the sediment yield for sheet and rill, gullies, irrigation, and ponds is determined as:

$$src_yld_aft(\cdot) = src_yld_bfr(\cdot) * (1.0 - TE_a(\cdot)) \quad \text{Equation 14-10}$$

Where for each particle size,

$$TE_{ps}(1) = 0 \text{ (clay)}$$

$$TE_{ps}(2) = 1 - 0.78 * (Q)^{0.08} \text{ for } Q \leq 3.0, TE_{ps}(2) = 0 \text{ for } Q > 3.0 \text{ (silt)}$$

$$TE_{ps}(3) = 1 - 0.025 * (Q)^{2.0} \text{ (sand)}$$

$$TE_{ps}(4) = 1 - 0.39 * (Q)^{0.5} \text{ (small aggregates)}$$

$$TE_{ps}(5) = 1 - 0.025 * (Q)^{2.0} \text{ (large aggregates)}$$

AnnAGNPS Inputs

TE_a is the actual trapping efficiency for each particle size, decimal, default is to use equations, if the user enter a value for this then all other parameters are ignored;

TE_m is the maximum buffer trapping efficiency, decimal, default is to use equations, if the user enters a value for this then values for buffer width and slope are ignored;

w_j is the effective buffer width associated with the length of the flow path through the buffer, m, default is 10 m;

TE_{ps} is the fraction trapped for each AnnAGNPS particle size (decimal), default is to use equations;

Buffer slope (m/m), default is the slope of the cell;

Buffer vegetative type (forest or grass), default is grass;

l_j is the concentrated flow width through the buffer, m, default is the hydraulic geometry width of concentrated flow in the cell;

A_c is the total drainage area contributing to the flow entering the upstream portion of the buffer, ha. Blank defaults to the cell's entire drainage area.

AnnAGNPS: Technical Descriptions

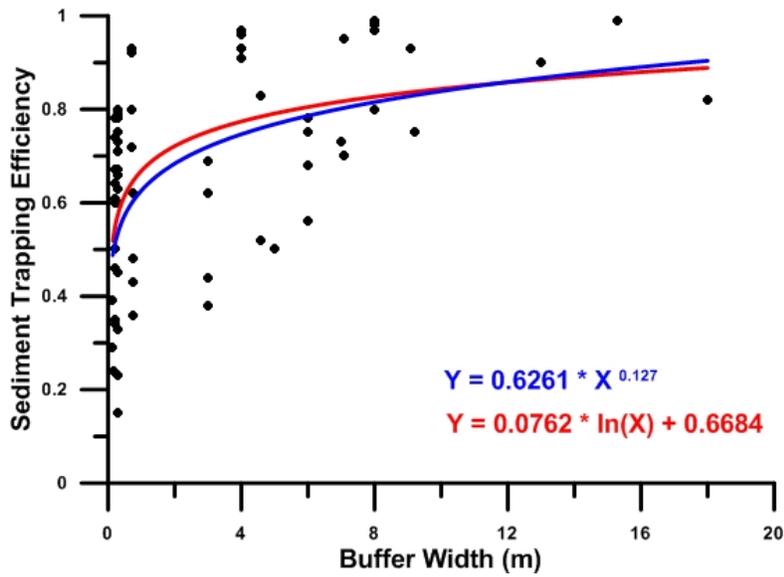


Figure 14-2. Buffer width and sediment trapping efficiency for predominant grass-like vegetation and local slope values smaller than or equal to 5%.

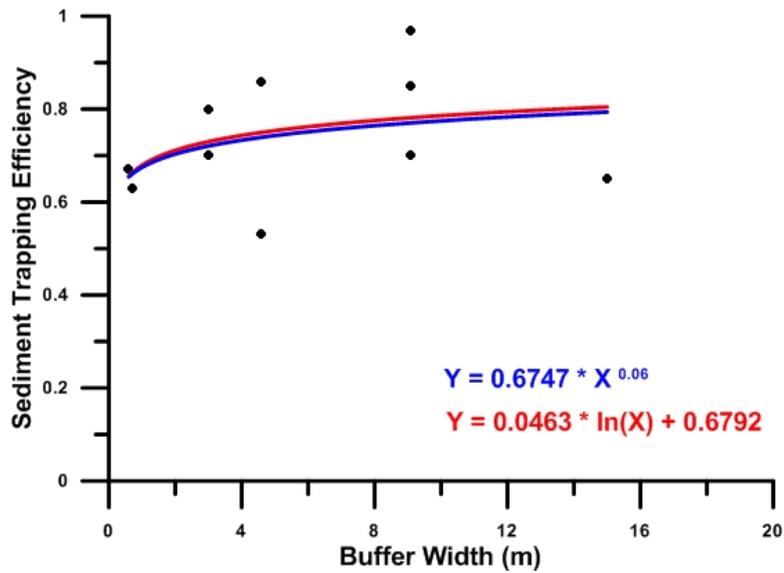


Figure 14-3. Buffer width and sediment trapping efficiency for predominant grass-like vegetation and local slope values greater than 5%.

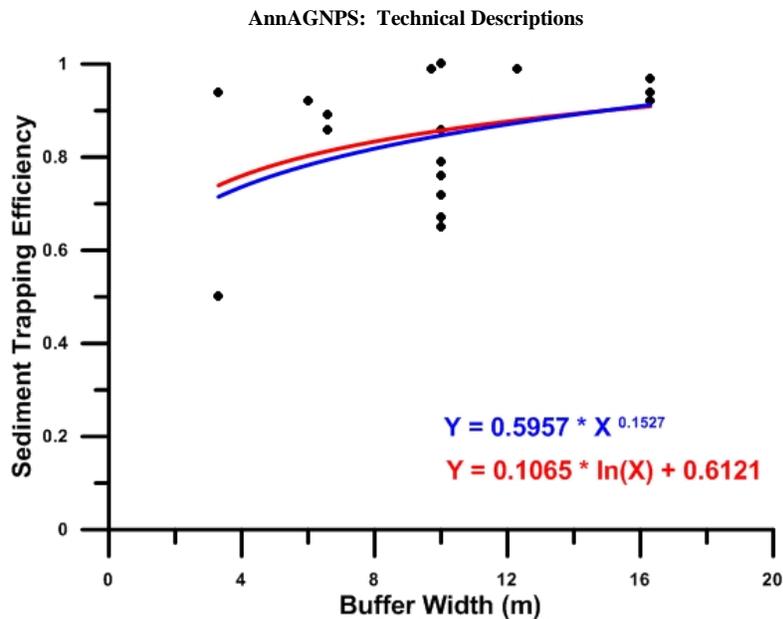


Figure 14-4. Buffer width and sediment trapping efficiency for bush-like and/or forest-like vegetation types.

14.2 REACH-LOCATED BUFFERS

Buffers that are within an AnnAGNPS reach will affect the sediment load transported within the reach. Multiple buffers can occur within a reach, with each described with a width, drainage area to the upstream end of the reach, and trapping efficiency. Unlike cell located buffer, reach located buffers will contain a single concentrated flow path with no other flow paths considered, such as for uniform flow. The effect of the most upstream buffer in the reach is determined first based on TE_m and TE_{ps} or a user enter actual trapping efficiency. Additionally, only clay, silt, and sand size particles are considered within a reach, as all aggregates are assumed to be broken up (disaggregated) instantly within a reach. If the buffer width is not provided then a default of 10 meters will be used. Each reach flow path will have a single vegetation type (predominant vegetation type). The buffer slope is the average slope of the flow path through the buffer with a default as the reach slope. An assumption for clay size particle is that they will not deposit as a result of the buffer. The assumption for silt is that there will not be deposition above a Q of $3.0 \text{ m}^3/\text{min-m}$.

The user can enter a value for TE_m or TE_{ps} or both, but if left blank then the internal calculations will be used.

The actual trapping efficiency for each particle size, TE_a , is then the combination of TE_m and TE_{ps}

$$TE_a = TE_m * TE_{ps} \quad \text{Equation 14-11}$$

Instead of adding the effects as performed in cell located buffers, the trapping efficiencies are multiplied together since the assumption is that once the concentrated flow is impacted by the buffer through any ponding effect then the maximum trapping efficiency will also be impacted by the concentrated flow through the buffer. Since there are no other flow paths through the reach located buffer except for the single AnnAGNPS reach concentrated flow path, any

AnnAGNPS: Technical Descriptions

other uniform flow path effects are not considered as assumed in the cell located buffers. Then the sediment load for sediment transported in a reach is determined as:

$$Reach_Load(:) = Reach_Load(:) * (1.0 - TEa (:)) \quad \text{Equation 14-12}$$

Where for each particle size,

$$TE_{ps}(1) = 0 \text{ (clay)}$$

$$TE_{ps}(2) = 1 - 0.78 * (Q)^{0.08} \text{ for } Q \leq 3.0, TE_{ps}(2) = 0 \text{ for } Q > 3.0 \text{ (silt)}$$

$$TE_{ps}(3) = 1 - 0.025 * (Q)^{2.0} \text{ (sand)}$$

AnnAGNPS Inputs

TE_a is the actual trapping efficiency for each particle size, decimal, default is to use equations, if the user enters a value for this then all other parameters are ignored;

TE_m is the maximum buffer trapping efficiency, decimal, default is to use equations, if the user enters a value for this then values for buffer width and slope are ignored;

w_j is the effective buffer width associated with the length of the flow path through the buffer, m, default is 10 m;

TE_{ps} is the fraction trapped for each AnnAGNPS particle size (decimal), default is to use equations;

Buffer slope (m/m), default is the slope of the reach;

Buffer vegetative type (forest or grass), default is grass.

l_j is the concentrated flow width through the buffer, m, default is the reach width as defined in the Reach Data section;

14.3 RIPARIAN BUFFER EFFECTS ON EPHEMERAL GULLIES

The effect of buffers on concentrated flow paths is also included within AnnAGNPS, especially for flow paths that contain ephemeral gullies. A riparian buffer trapping efficiency parameter has been added to the AnnAGNPS Ephemeral Gully data section that can be determined using the AGBUF utility or entered by the user. This will provide a way to define a trapping efficiency from a buffer targeted to a specific gully flow path instead of the entire trapping efficiency of a buffer assigned to a gully. If this parameter is blank then the trapping efficiency determined for the entire buffer would be applied to the gully, if a buffer is present in the cell or reach that contains the gully. Additionally, if a gully knickpoint or mouth is located within a buffer then the user can enter a keyword of "Buffer" within the Management Field ID parameter within the Ephemeral Gully data section to allow for no erosion from the gully, since the assumption is that the headcut will not form within the buffer without any surface disturbance within a buffer. The trapping efficiency from a buffer on a gully is assumed to have no effect on clay sizes, since clay will not deposit unless the water is very slow or still.

Additionally, the particle size trapping efficiency for gully sediment flowing through the buffer is determined by AnnAGNPS for where the gully flow path enters the buffer. AGBUF will determine the drainage area to this point and revise the Cell's Drainage Subcell parameter to be the drainage area of the gully flow path at the entry into a buffer. Currently, AnnAGNPS defines the Cell's Drainage Subcell as:

AnnAGNPS: Technical Descriptions

If the gully is cell-located (i.e.; the gully's drainage area is located wholly within one AnnAGNPS cell), the cell's total drainage area for local subareas that are created as left- & right-bank cells may actually be comprised of many subcells that drain separately into and along the receiving reach such as likely to be the case for either the left- or right-bank cells, even though the cell's entire drainage is designated to only enter either the upstream or downstream end of the reach. Then the gully may be located in one of these cell's subcells, requiring a designation of the drainage area of the subcell containing the gully to the receiving reach as the Cell's Drainage Subcell. A blank means that cell's drainage subcell is composed of the entire cell's drainage area (such as a source cell with the gully mouth located at the downstream end of the cell), resulting in the cell containing the gully to be equal to the cell's total drainage area. A blank is required if the gully is reach-located.

The approach uses a new definition to describe the AnnAGNPS Cell's Drainage Subcell parameter for gullies in riparian buffers as:

If the gully is cell-located (i.e.; the gully's drainage area is located wholly within one AnnAGNPS cell), the cell's total drainage area for local subareas that are created as left- & right-bank cells may actually be comprised of many subcells that drain separately into and along the receiving reach or riparian buffer such as likely to be the case for either the left- or right-bank cells, even though the cell's entire drainage is designated to only enter either the upstream or downstream end of the reach. Then the gully may be located in one of these cell's subcells, requiring a designation of the drainage area of the subcell containing the gully to the receiving reach or to the location where the flow path enters the riparian buffer, if present. A blank means that cell's drainage subcell is composed of the entire cell's drainage area (such as a source cell with the gully mouth located at the downstream end of the cell), resulting in the cell containing the gully to be equal to the cell's total drainage area. A blank is required if the gully is reach-located.

AnnAGNPS would then use this information to determine the peak discharge and flow width based on hydraulic geometry defined for the gully using the Cell's Drainage Subcell value at this point for drainage area where the gully flow path enters the buffer to determine the particle size trapping efficiency for the gully sediment passing through the buffer. The flow rate for the gully flow path at the buffer the model uses the approach similar to flow in riparian buffers, but revised specific for the gully flow path. The peak discharge for the gully flow path entering the buffer uses the approach similar to that in gullies, but revised for Cell's drainage area of the subcell for the gully.

For reach located gullies, the volume of flow and peak discharge of the reach that the gully is in will be used to determine the particle size trapping efficiency of the buffer on gully sediment. The reach-located buffer procedure for including the effects of trapping efficiency is assumed to apply for gully flow paths whether the gully is reach or cell-located.

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