ANSWERS-2000

Areal **N**on-point **S**ource **W**atershed **E**nvironment **R**esponse **S**imulation

with **Questions** Graphical User Interface

Sandeep Dabral
Matthew Cohen
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Introduction

ANSWERS-2000 is a long-term, continuous simulation, physically based, distributed parameter watershed model for evaluating the effectiveness of select BMPs in reducing losses of sediment and nutrients from agricultural watersheds. It was designed for application in meso-scale heterogeneous systems where little empirical calibration information is available. The model was originally conceived as a hydrologic model only (Huggins and Monke, 1966) but sediment (Beasley et al. 1980) and nutrients (Dillaha et al. 1988, Bouraoui 1994) were added to make the model more appropriate for non-point source pollution concerns. Recent modifications of the model include the addition of more physically based sediment detachment algorithms, and the creation of a graphical user interface called Questions that allows less experienced users access to an extremely complex model.

The model has been found to perform well in hilly watersheds on the East Coast. It is predicted that the model will perform poorly under the proposed simulation scenario for a variety of reasons outlined in the summary section of this document. Cumulative predictions from the model for runoff, sediment yield, nitrate, ammonium, sediment bound TKN and orthophosphate were all within 40% of the observed values. However, it is argued that the true power of the model comes from exploring the role of spatial contingency on the application of BMPs. It has been shown using the model that targeting BMPs to critical source areas that have high sediment yields AND high sediment delivery functions can significantly lower NPS pollution levels over equal levels of untargeted management. The model shows that proximity to the stream network is as critical a factor as the sediment yield predicted on farm for assessing pollution risk.

Model Objectives

1) To serve as a continuous nonpoint source model to simulate runoff, erosion, transport of dissolved and sediment-bound nutrients, and nutrient transformations.

2) To serve as a tool for nonpoint source pollution managers to study the long term effectiveness of best management practices (BMPs) in reducing runoff, sediment, and nutrient losses from agricultural watersheds.
3) To simulate transformations and interactions between four nitrogen pools including stable organic N, active organic N, nitrate and ammonium. Transformations of nitrogen include mineralization simulated as a combination of ammonification and nitrification, denitrification, and plant uptake of ammonium and nitrate.
4) To model transformations and interactions between four phosphorous pools including stable mineral P, active mineral P, soil organic P and labile P.
5) To include both bed-load and suspended load simulation as a part of sediment transport in soil erosion. Further, to model sediment detachment using physical process models rather than empirical approaches such as USLE.

Model Structure

ANSWERS-2000 is a Fortran-77 model, with two main applications: *answers.for* and *answers-org.for*. In the pre-Questions versions of ANSWERS, a Fortran user-interface (Farmscale) was used to guide the user through the creation of the primary parameter input file *answers.inp*. Figure 1 shows the data layers that are required for the operation of the model in general form. A list of the parameters that are necessary to run the model is shown in Appendix 1. It is important to note that while there are considerable fewer model parameters for each cell than most NPS pollutions models, each parameter must be input for each cell, and each calculation presented below is done on a cell-by-cell basis. The model, therefore, can be limited in application by the computing power necessary to run simulations.

The new user interface, Questions, is written using the ArcView programming language Avenue (ESRI, 1996), Visual Basic and MapObjects. Screen captures of the interface windows are presented in Appendix 2. The user requires three spatial data layers to run the software. These include a raster-based DEM, a soil coverage with attribute data that includes the SSURGO nomenclature and a landuse cover map of the basin. These are manipulated for entry into the model within ArcView using an extension, *answers.avx*, which is provided with Questions. Additional data layers include the *comp* and *layer* files that provide standard soil information for each of the soil polygons, rotation information for the land-uses, and a variety of miscellaneous model parameters that are discussed further below. One severe drawback of the interface as it currently operates is the inability of the user to input measured climate data. Questions allows only Markov model random weather generation from the Cligen database for any given basin. Methods for overcoming this limitation are planned for future versions of the model.

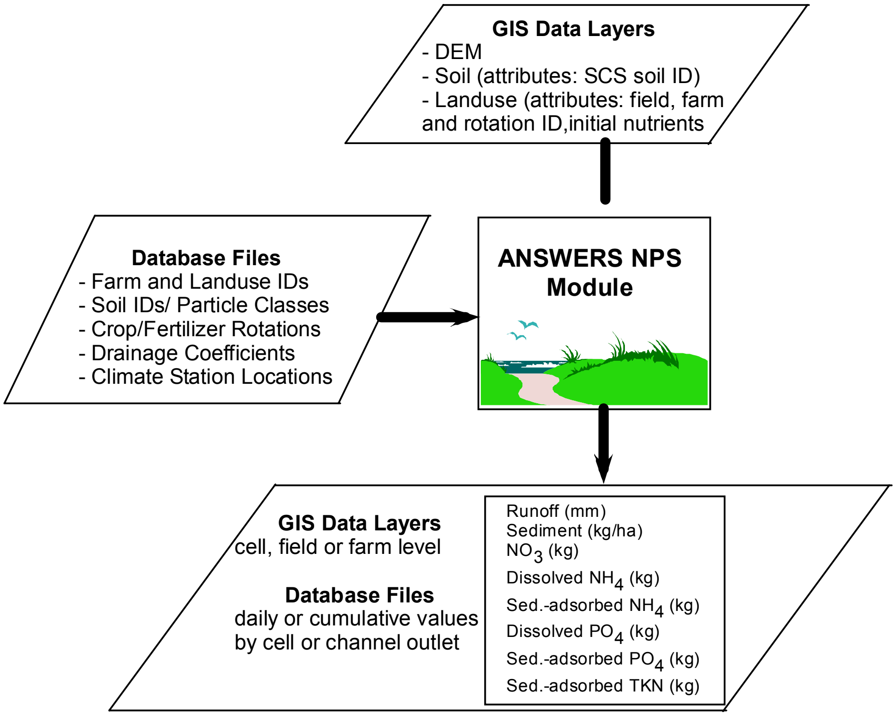


Figure 1: Schematic of data layer requirements for running ANSWERS-2000 through Questions.

Simulation Description

The ANSWERS model is based on the concept that "at every point within the watershed, relationship exists between water flow rates and those hydrologic parameters which govern them e.g., rainfall intensity, infiltration, topography, soil type etc." It uses the concept of watershed elements rather than the point concept and each element is assumed a homogeneous area within which all the hydrologic parameters are approximately uniform. Time steps in the model are daily for days without rain, and 30 seconds during days for which precipitation occurs. The overall dynamic structure of the model is presented in Figure 2.

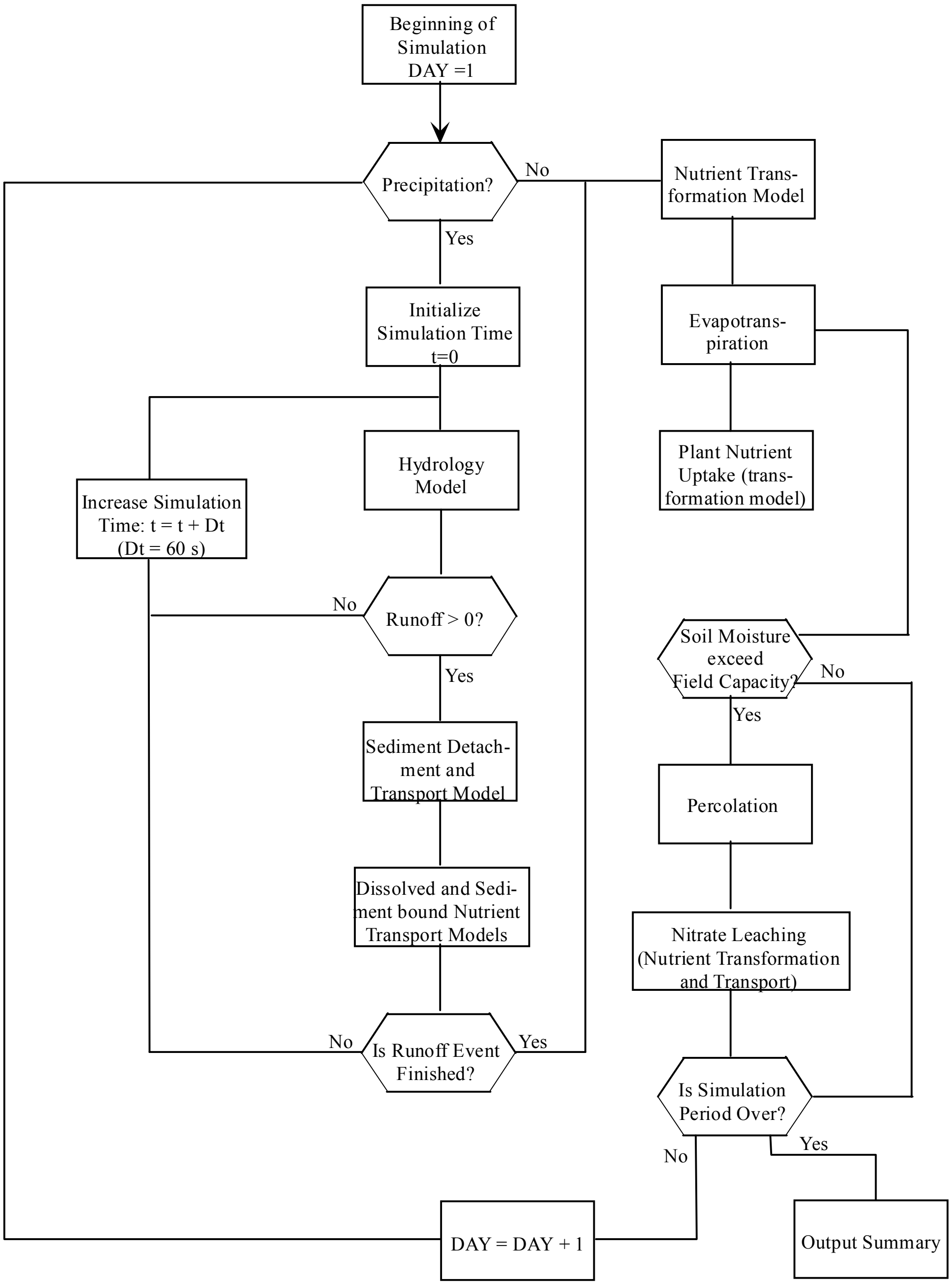


Figure 2: Overall dynamic structure of the model.

Hydrologic Model

Hydrologic processes represented in the ANSWERS model are shown in Figure 3. After rainfall begins, some precipitation is intercepted by the vegetal canopy until the interception storage potential is satisfied. As rainfall proceeds, infiltration decreases until it equals the rainfall rate. At this point water begins to accumulate on the surface in micro-depressions. Once the capacity of the micro-depressions is exceeded, runoff begins. The accumulated water in excess of surface retention capacity, surface detention, produces surface runoff. When rainfall ceases, the water in surface detention begins to dissipate until surface runoff ceases altogether. However, infiltration continues until all the depressional water has infiltrated. Infiltration is modeled using Green-Ampt equation. Water in the soil moisture control zone in excess of field capacity drains from the control zone.

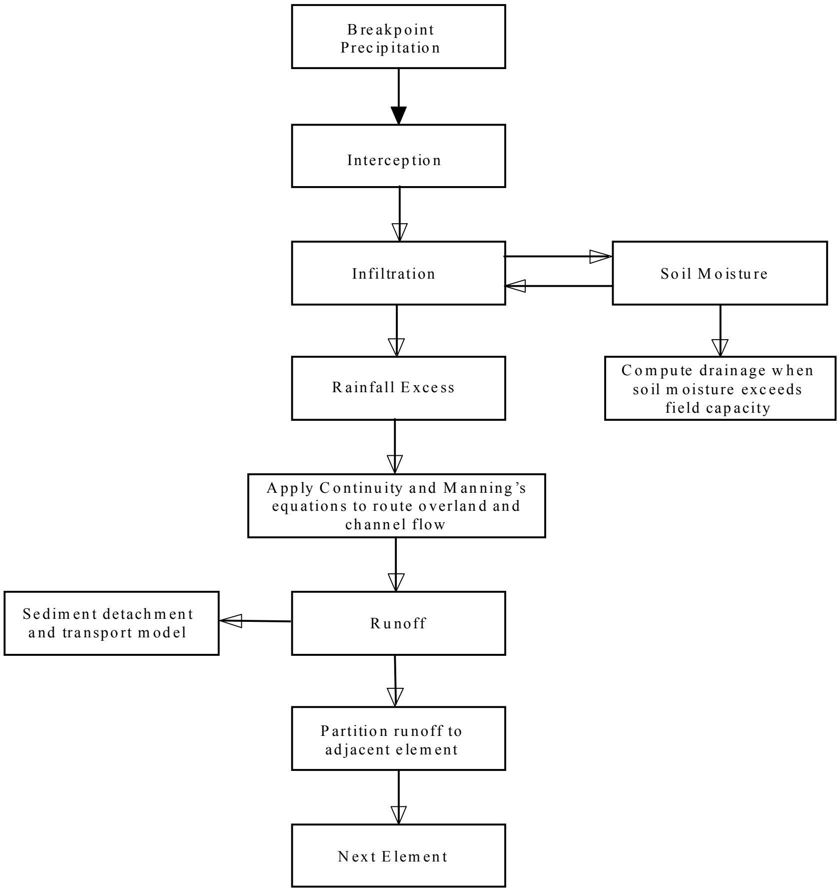


Figure 3: Flow chart for the hydrologic component of ANSWERS-2000.

Surface detention is the water volume, which must build up to sustain overland flow. Detention depth is calculated as the total volume of surface water in an element, minus the retention volume (which can only infiltrate), divided by the area of the element. The entire specified retention volume of an element must be filled before any water becomes available for surface detention and runoff. Manning's equation is used as the stage-discharge equation for both overland and channel flow routing. The hydraulic radius in Manning's equation is assumed equal to the average detention depth in the element.

Other assumptions included in the hydrologic model, infiltration model and evapotranspiration models are the same as inherent in the theories and the models that are used for predicting these parameters.

Evapotranspiration Model

The Ritchie method is used in the ANSWERS model due to its simplicity and because it is a combination method. The parameters used in this method are daily temperature, solar radiation, and leaf area index. The Ritchie method separates plant transpiration and soil evaporation. Potential soil evaporation is based on the leaf area index and is calculated by:

$E_0 = (0.0504\, H_0\, \Delta) / (0.68+\Delta)$
Where
E_0 = potential evapotranspiration (cm)
H_0 = net solar radiation
Δ = slope of the saturation vapor pressure curve at the mean air temperature:
$\Delta = 5304 / T^2\, EXP\,(21.55 - 5304/T)$
Where T is the daily temperature (^{0}K).

The net solar radiation is determined by:

$H_0 = (1 - \lambda)\, R$
Where,
R = daily solar radiation (l),
λ = albedo, and
c = 22.95

Soil evaporation is assumed to take place in two different stages. In the first or constant rate stage, soil evaporation is just limited by the amount of energy available.

Thus, the soil is evaporating at a rate equal to the potential evaporation rate. The potential soil evaporation is computed by:

$E_{s0} = E_0 \, e^{(-0.4\ LAI)}$

Where,

E_{s0} = potential soil evaporation (cm), and

LAI = leaf area index (ratio of plant leaf area and soil surface area).

The soil during the first stage evaporates at the potential rate. The upper limit of the first stage, U, is determined by:

$U = 0.9\ (\alpha_s - 3.0)^{0.42}$

where

U = first stage upper limit (cm), and

α_s = soil evaporation parameter (cm/day$^{0.5}$).

When the cumulative soil evaporation exceeds the upper limit of the first stage (U), the second stage begins. The second stage begins when the surface starts to dry, and water from within the soil starts to evaporate. During the second stage, also called the falling rate stage, the soil evaporation rate is given by:

$E_s = \alpha_s\ (t^{0.5}\ - (t-1)^{\ 0.5)}$

Where,

E_s = soil evaporation rate for day t (cm/day), and

t = number of days since sage two evaporation started (days).

The potential plant transpiration, EP_0 is given by:

$Ep0 = E_0\ LAI / 3 \qquad 0 \le LAI \ge 3$

And

$Ep0 = E_0 - E_S \qquad LAI \ge 3$

If soil moisture is a limiting factor, the plant transpiration is reduced to:

$E_p = (Ep0\ SW) / (0.25\ FC) \qquad SW \le 0.25FC$

Where,

E_p = plant transpiration (cm),

SW = current soil water in the root zone (cm), and
FC = field capacity of the soil (cm).

Infiltration Component

The Green-Ampt infiltration equation forms the basis of infiltration component in the ANSWERS model. It was selected as it is a physically based approach, computationally efficient and its' parameters can be easily determined from readily available soil and vegetal cover information. Furthermore, it has been tested for a wide variety of conditions, and it has successfully simulated the effects of different management practices on infiltration. The governing equations are as follows:

$$K_e\, t = F - N_s \ln (1 + F / N_s)$$

Where,
K_e = effective saturated hydraulic conductivity (cm / hr),
t= time (hr.),
F = cumulative infiltration (cm), and
N_s = effective matrix potential (cm).

The effective saturated hydraulic conductivity is a function of the saturated hydraulic conductivity. The saturated hydraulic conductivity can be estimated from field tests or values found in the literature. The equation that the model uses for estimating saturated hydraulic conductivity is given by (Rawls and Baumer, 1989):

$$K_S = 0.0002\, C^2 (CP - RW)^3 / (1-CP)^2 \, [\, BD / RW\,]^2$$

Where,
K_S = saturated hydraulic conductivity (cm/hr)
CP = effective porosity (cm),
BD = bulk density (g/cm^3),
RW = residual soil water (cm), and
C = soil texture coefficient.

The soil texture coefficient is determined using an equation developed by Rawls and Baumer (1989):

$$C = -0.17 + 0.181\, CL - 0.00000069 SA^2\, CL^2 - 0.00000041 SA^2\, SI^2 + 0.000118\, SA^2 BD^2 + 0.00069\, CL^2\, BD^2 + 0.000049\, SA^2\, CL^2 - 0.000085\, SI\, CL^2$$

Where,
CL = clay fraction (%),
SA = sand fraction (%),
SI = silt fraction (%)

The saturated hydraulic conductivity is adjusted to account for the influence of the vegetal cover that affects the speed and kinetic energy of impacting raindrops and surface crusting. The effective hydraulic conductivity for an area under canopy cover (K_C) is computed using the following equation (Rawls, et al., 1989):

$$K_c = K_S C_F [(B_c / A_c) C_r + MPF \{1 - (B_c / A_c)$$

Where,
MPF = macroporosity factor,
B_c = bare area under canopy (%),
A_c = canopy area (%),
$C_{r =}$ crust reduction factor, and
C_f = canopy factor.

The macroporosity factor is determined by:

$$MPF = \exp (0.96 - 0.032\ SA + 0.04\ CL - 0.032\ BD)$$

where all the parameters are as previously defined. The crust reduction factor is determined by (Brakensiek and Rawls, 1983):

$$C_r = L / [(L - Z_c)/S_c + Z_c /b]$$

Where,
L = average depth to wetting front (cm),
Z_c = crust thickness (assumed to be 1 cm),
S_c = correction factor for partial saturation of the subcrust soil, and
B = crust factor.

The average depth of the wetting front, L, is expressed as (Rawls et al., 1989):

$$L = 14.7 - 0.0015\ SA^2 - 0.3\ CL\ BD$$

The correction factor for partial saturation of the subcrust soil (SC) is determined by (Rawls et al., 1989):

$$SC = 0.736 + 0.0019\ SA$$

The crust factor, b, is computed by (Rawls et al., 1989):

$$B = 0.0099 + 0.0721Z_c + 0.0000068SA^2 + 0.000021SA^2Z_c - 0.000315SZ_c \text{ X } Z_c$$

The canopy factor used to determine the hydraulic conductivity in the area under canopy is defined as (Rawls et al., 1989):

$$C_f = 1 + [Ac / (A_0 + A_c)]$$

Where

A_0 = area outside the canopy in percent.

Subsurface Flow

The model does not address the dynamics of water in the subsurface zone particularly well. Specifically, there is no saturated soil overland flow, and flows from the subsurface contributing to channel output are assumed a linear function of the storage. The model does account for percolation out of the single soil layer that is used to model the profile, but again it is a simplified linear relationship. Since the original model was event-oriented, the focus has been on carefully simulating what happens when it rains, and little attention has been paid to the interim periods, except insofar as they provide the antecedent conditions for the next rainfall event. The model, therefore, is considered inappropriate for high-base flow conditions.

There is a coefficient in the model for dealing with tile drainage systems. This provides the model a constant rate of daily tile drain flow for all conditions.

Sediment

Erosion and sediment transport in the updated ANSWERS2000 model was revised from the ANSWERS2000 modules produced by Bouraoui and Dillaha (1996) to include channel scour. Furthermore, the subroutines governing rill and interrill erosion and transport were altered to include critical-shear subroutines. This approach is considered more consistent with current theory, and avoids the problems created by wide application of a model with considerable empirical content, such as the USLE. The modules are adapted from the WEPP model, and are considered sufficiently process based to be applicable to basins for which there is no calibration data.

The stated objectives of the updated sediment subroutines are (Byne 2000):

1. To develop and incorporate a new process-oriented sediment detachment submodel into ANSWERS-2000.
2. To develop and incorporate a process-oriented channel scour submodel into ANSWERS-2000.
3. To determine if the new process-based sediment detachment and channel scour submodels improve the ability of ANSWERS-2000 to predict sediment loss at the watershed scale.

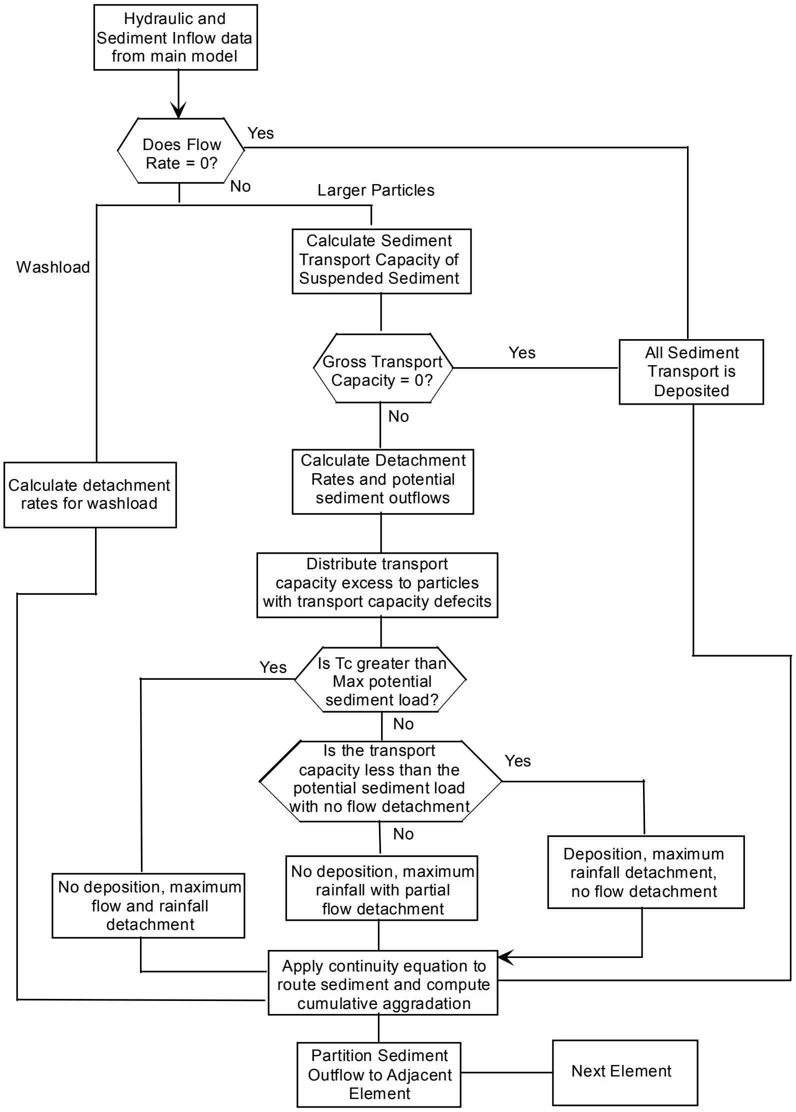


Figure 4: Sediment Detachment and Transport Flow Chart

Interrill Erosion

Raindrop impact is the primary detachment mechanism for soil erosion between rills, with overland flow playing a less significant role. When overland flow begins, however, there is a reduced effect of raindrop impact due to the energy absorbed by the surface water. Sediment delivery from interrill areas is presented as:

$$D_i = K_{iadj}*I_e*\sigma_{ir}*SDR_{rr}*(R_s/w)$$

where
D_i = sediment delivery
K_{iadj} = interrill erodibility adjusted for consolidating effects (kg/s/m^4)
I_e = effective rainfall intensity (m/s) (integral of rain over time, divided by time during which rain exceeds infiltration rate)
σ_{ir} = interrill runoff rate (m/s)
SDR_{rr} = sediment delivery ratio (a ratio of the random roughness of the soil surface and the particle size distribution of the eroding sediment)
R_s = rill spacing (m)
w = rill width (m)

This equation is relaxed somewhat in the actual model to:

$$DIINT = (K_{iadj}*XR*RNOFIR*SEDDR)/AREA$$

where
DIINT = interrill detachment
K_{iadj} = adjusted erodibility (see below)
XR = net rainfall rate (m/s)
SEDDR = sediment delivery ratio computed from tabular data of surface roughness and particle size
AREA = area of each cell (m^2)
RNOFIR = interrill runoff rate per rill contributing area
= QEFF/(DX*RILLSPC)
where
QEFF = flow rate per rill contributing area
DX = cell width
RILLSPC = spacing between rills (m) assumed generally to = 1 m

This value, DIINT, is adjusted to reflect the area of each cell that is interrill by subtracting the rill area.

Baseline erodibility (K) is determined based on soil texture and a suite of adjustment conditions:

$K_{adj} = K_{ib}(CK_{ican})(CK_{igc})(CK_{idr})(CK_{ilr})(CK_{isc})(CK_{isl})(CK_{ift})$
Where
K_{ib} = interrill erodibility
= 5,300,000 kg*s/m^4
= 2,728,000 + 19,210,000vfs when sand>0.3
= 10,412,000 when sand >0.3, vfs>0.4
= 6,054,000 – 5,513,000*clay when sand <0.3
= 5,502,700 when sand<0.3, clay <0.1
CK_{ican} = canopy height adjustment factor
CK_{igc} = ground cover adjustment factor
CK_{idr} = dead root cover adjustment factor
CK_{ilr} = live root cover adjustment factor
CK_{isc} = sealing and crusting factor

The revised version of ANSWERS2000 simplifies the necessary components of these adjustment factors (ground cover, canopy height, root density etc.) to ensure tractability and parameter identifiability.

Rill Erosion

Rill erosion is based on critical shear theory, which predicts the sediment detachment capacity of flowing water.

$D_c = K_r*(B*\tau-\tau_c)^a$
Where
D_c = detachment capacity of sediment (g/m^2/s)
K_r = sediment erodibility coefficient (g/m^2/s)
τ = hydraulic shear in the rill (Pa) – computed using the Darcy-Weisbach eq.
τ_c = critical shear (below this value no erosion occurs)
a, B = constants (usually taken to be 1)

When flowing water already carries sediment, the potential detachment rate is modified to an actual detachment rate by the following:

$(D_r/D_c) + (G_r/T_c) = 1$

where
D_r = adjusted detachment rate
G_r = sediment load in flow (kg/s)
T_c = transport capacity (kg/s)

Rill erodibility, K_r is determined according to the WEPP procedure, and modified by a series of adjustment factors for specific special case conditions.

$K_{radj} = K_{rb}(CK_{rbr}) (CK_{rdr}) (CK_{rlr}) (CK_{rsc}) (CK_{rft})$

Where

K_{radj} = adjusted rill erodibility (s/m)

K_{rb} = baseline rill erodibility (s/m)

= 0.00197 + 0.030*vfs + 0.03863*exp(-184*OM) sand>0.3
= 0.0069 + 0.134*exp (-20*clay) sand <. 3
vfs = fraction very fine sand
OM = organic matter fraction
Sand, clay = fraction of each in surface soil
CK_{rbr} = buried residue adjustment factor
CK_{rdr} = dead root adjustment factor
CK_{rlr} = live root adjustment factor
CK_{rsc} = surface crusting and sealing factor (a function of erodibility of the soil under consolidated conditions)

Rill width is modeled as a function of effective rill flow (total flow divided by the number of rills). Depth of flow in rills is computed using the Darcy-Weisbach friction equation. The effective shear stress that arises from that flow is then approximated using:

$TAUEFF = 9806.65*SL*HYDRAD*(MNSOIL^2/MNTOT^2)$
Where
TAUEFF = the effective shear stress
9806.65 = specific weight of water
MNSOIL = Manning's n for bare soil
MNTOT = Manning's n for vegetated cover
HYDRAD = the hydraulic radius
SL = element slope (1/10 percent)

Finally, the detachment capacity can be computed as discussed above, and adjusted based on the transport capacity to yield the actual detachment.

Channel Processes

Channels are modeled in much the same way as rills, with critical shear stress theory. Channel cells are assumed to have uniform geometry, with the channel bottom considered erodible (though a non-erodible layer can be input to the model). Armoring of the channel walls can occur. The scour component is presented as:

$DOWNRATE = K_{radj}*[(TAUEFF–TAUCADJ)/BULKDEN]*(1-ARMOR)$
Where

DOWNRATE = erosion rate of the channel
BULKDEN = soil bulk density
ARMOR = non-erodible fraction of the parent material
and others as in rill erodibility equation

When transport capacity is insufficient to transport the entire entering load, deposition occurs. Channel widening is another feature, which occurs with wall erosion, which augments when a non-erodible layer in the channel bottom is met.

Sediment Transport and Settling

The module for computing the capacity of overland flow to carry sediment is retained from the former ANSWERS2000 model. Transport is based on the equations of Yalin (1963) for each particle size class as follows:

$TF = P_s * S_g * \rho_w * g * dV$
Where
$P_s = 0.635 * \delta * [1 - \ln(1+\sigma)/\sigma]$
$\sigma = 2.45 S_g^{-0.4} * Y_{cr}^{0.5} * \delta$
$\delta = (Y/Y_{cr}) - 1$ if $Y < Y_{cr}$, $\delta = 0)$
$Y = V*^2/[(S_g - 1) * g * d]$
TF = transport capacity (kg/s)
P_s = number of particles in transport
ρ_w = mass density of fluid (kg m^3)
Y_{cr} = critical shear stress from Shield's diagram (Pa)
$V* = (g*R*S)^{0.5}$ = shear velocity (m/s)
S_g = particle specific gravity (kg/m^3)
S = slope of energy gradeline
R = hydraulic radius (assumed equal to flow depth)
d = diameter of particle (m)
g = acceleration due to gravity (m/s^2)

When transport capacity is met, no further entrainment occurs. When the sediment load exceeds the transport capacity, settling occurs according to particle size, with those particles less than 10 nm never settling unless flow rates drop to zero.

Model Assumptions (Byne 2000)

1. The particle size distribution of detached sediment is the same in the original soil mass (no enrichment during detachment).

2. Rainfall detachment is not limited by the transport capacity of the flow.
3. Flow detachment occurs only if there is excess transport capacity and can never exceed the transport capacity excess.
4. Deposition and flow detachment never occur at the same time for the same particle.
5. Washload transport is independent of the transport capacity of the flow and does not influence the transport of larger particles.
6. Deposited sediment requires the same amount of energy as in the original detachment to become redetached.
7. The deposition process controls enrichment.
8. The rate at which a particle will deposit is proportional to its fall velocity.
10. Subsurface or tile drainage produces no sediment.

Nutrients

In order for the ANSWERS2000 model to effectively capture the dynamics of nutrient cycling and movement in a distributed parameter setting at the watershed scale, detailed nutrient algorithms could not be included. Nutrient fate and transport dynamics were borrowed extensively from most recent version of GLEAMS, which was in turn based on the algorithms in the EPIC model.

ANSWERS2000 models only nitrogen and phosphorus dynamics because of the role that those nutrients typically play in aquatic eutrophication in freshwater systems. The transformation algorithms for each nutrient are presented below, along with a discussion of how dissolved and sediment-bound nutrient transport is handled for both.

Nutrient Transformations

Nitrogen

The major pools of nitrogen that are simulated are shown in Figure 5. They are active organic N, ammonium and nitrate. Plant bound N, N in plant residue and stable organic N are also included, and sources and sinks of N include fertilizer and atmospheric N. Nitrogen mineralization (organic N to nitrate) is modeled as a two-step process, via storage of ammonium, as in GLEAMS.

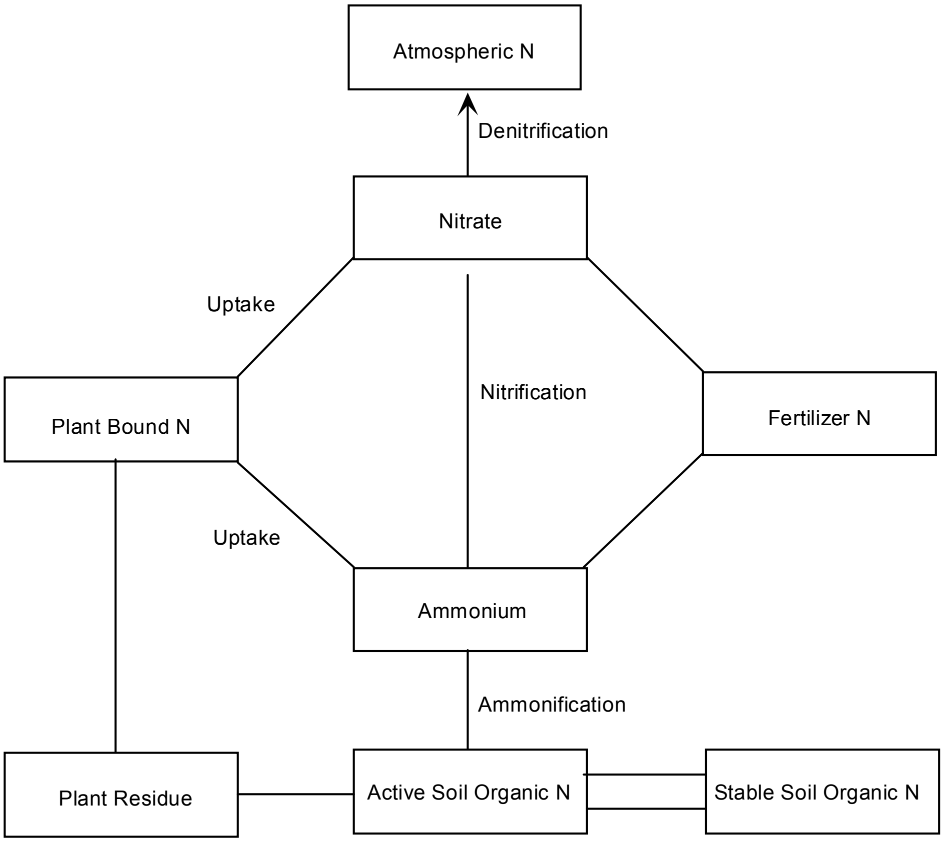


Figure 5: Flow chart for simulated nitrogen cycle.

The flow between the active and stable organic N pools is governed by the ratio of potentially mineralizable N to total soil N as follows:

$$RTN = POTMIN / (POTMIN + SOILN)$$

where
RTN = mineralizable fraction
POTMIN = potentially mineralizable N
SOILN = total soil N in stable pool.

The flux between the stable and active pools is given as:

$$POTSO = BKN\ [POTMIN*RTN - SOILN]$$

where
POTSO = daily flow between active and stable organic N pools (kg/ha/day)
BKN = a rate constant (E-5 kg/ha/day).

The sign of the output from the above equation indicates the direction of flow, with positive flows indicating movement from the active to the stable pool.

Mineralization to ammonia from the active organic N pool is governed by the following equation:

$$MIN = CMN*POTMIN*[SWFA*TEMPFA]^2$$

where
MIN = mineralization rate (kg/ha/day)
CMN = mineralization constant (0.0003 kg/ha/day)
SWFA = soil water factor for ammonification
TEMPFA = temperature factor for ammonification

This daily flux is added to the AMON pool, which represents the ammonium storage. In the above equation, the soil water factor is computed as:

$SWFA = (SW-WP)/(FC-WP)$ if $SW<FC$
where
SW = soil water
WP = wilting point (volumetric water content at 1500 Kpa)
FC = field capacity (volumetric water content at 33 Kpa).

If the SW is greater than the field capacity, then it is assumed that no ammonification occurs, and the SWFA is set to zero. TEMPFA, the temperature factor is modified by soil temperature, provided that temperature in non-negative as follows:

$TEMPFA = T / (T + \exp (9.93-0.312T)$
where
T = soil temperature in degrees centigrade.

As with SWFA, if the criteria of non-negative temperatures is violated, the factor value is set to zero, and no ammonification occurs.

After ammonification, the next transformation pathway is oxidation to nitrate, or nitrification. The intermediate stage of nitrite is not simulated because of the rapidity with which *Nitrobacter spp.* bacteria facilitate that reaction. Furthermore, ANSWERS2000 assumes that the rate of nitrification is constant, based on fertilizer application studies, and the rate is set at 0.005 mg-N/day/cm^2, which is depleted from the ammonium storage and added to the nitrate storage.

Denitrification, or the anaerobic use of nitrate as the terminal electron acceptor, occurs only when soil water exceeds field capacity. It is modeled with first order kinetics, and is dependant on the stock of soil organic carbon. The soil organic carbon pool is derived as follows:

SC = 18*POTMIN / SOILMA
where
SC = active carbon pool (mg/kg)
SOILMA = soil mass (kg/ha)

Denitrification is determined as follows, and subtracted from the nitrate pool:

DNI = exp (-DK*TEMPFD*SWFD)
where
DNI = denitrification rate (kg/ha/day)
DK = daily decay rate of SC = 0.0528*SC + 0.1008
SWFD = soil water factor for denitrification
= (SW – [FC + 0.1*(SAT-FC)])/(SAT – [FC + 0.1*(SAT-FC)])
TEMPFD = temp. factor for denitrification (computed the same as TEMPFA)

Ammonium can exist as sediment bound and dissolved fractions, the ratio of which is described by the following:

K_{am} = (ANSOIL/SOILMA)/(SZN4H/WATVOL)
Where
K_{am} = partition coefficient
ANSOIL = ammonia bound to the soil (kg)
SZNH4 = dissolved ammonium (kg)
WATVOL = water volume (kg/ha)

It follows that AMON, the ammonium storage, is the sum of ANSOIL and SZNH4, which can be calculated by solving the above equation when Kam is known.

The loss of N is modeled through erosion (runoff), percolation and denitrification. Also included is plant uptake. The last three are computed daily, while runoff losses occur only during storm events. Percolation losses are assumed proportional to water percolation rates and the concentration of the nitrogen species in the water. Potential plant uptake is modeled as proportional to transpiration rates and the concentration in the root zone for both ammonium (UPNH4) and nitrate (UPNO3). Total potential uptake TUPTN is then the sum of UPNH4 and UPNO3. The actual N demand is computed based on the growth status of the vegetation relative to some potential state. To arrive at the demand of the system, the N concentration in vegetative material is computed:

$$CN = c1*(SUMLAI/POTLAI)^{c2}$$

where
CN = concentration of N (% crop biomass)
c1 and c2 = plant (crop) dependant coefficients
SUMLAI = current leaf area index
POTLAI = potential leaf area index (i.e. max at time of harvest)
The total dry matter (DM - kg/ha) is then computed as:

$$DM = PGRT*YP*DMY$$

where
PGRT = plant growth ratio = (SUMLAI/POTLAI)
YP = yield potential
DMY = ratio of total dry matter to harvestable yield

Total N demand is then the difference between today's total dry matter N ($TMDN_i$) and yesterday's ($TMDN_{i-1}$), where TMDN = DM*CN/100. Finally, an N demand factor is computed as the ratio of the total demand to the total uptake or TDMN/TUPTN. The uptake rates are then both adjusted by this demand factor (DEMFAC) to represent the actual amounts removed from each of the storages in a given day.

Phosphorus

Phosphorus is modeled using five pools, as shown in Figure 6. They are active organic P, labile P, active mineral P, passive mineral P, and fresh organic P. The ratio of potentially mineralizable P to total organic P is assumed the same as for N, discussed above. Mineralization, or the transfer of P from the active organic pool to the active mineral or labile pools, is governed in the model by the following:

MINP = CMN*SORGP*(POTMIN/(POTMIN + SOILN))*SWFA *TEMPFA
where
MINP = mineralization rate (kg/ha/yr)
SORGP = soil organic P (kg/ha)
and CMN, POTMIN, SOILN, SWFA and TEMPFA are the same as defined for nitrogen mineralization.

For standard calibration purposes the stable mineral P pool is assumed to be in dynamic equilibrium with the active pool, which is four times smaller. The flows between stable and active pools is described as:

MPR = 0.1*SWF*(AP-MP*PSP/(1-PSP))*exp (0.115T – 2.88)
Where
MPR = mineral flow P (kg/ha/day)
T = soil temperature (deg. Centigrade)
MP = active mineral pool stock (kg/ha)
PSP = sorption coefficient from isotherm
AP = labile P (kg/ha)

Again, flow direction is determined by the sign of this calculation, with positive values representing flow from labile to active P. For each days calculation, labile P is partitioned into dissolved and sediment-bound fractions in a similar manner as nitrogen. Again, the dissolved fraction is available for percolation or plant uptake. The model, however, assumes that, due to the large adsorptivity of P (to clays, organic acids, free cations), percolation is negligible. The fractionation coefficient inputs to the following formula to provide the portion that is dissolved:

PSOL = PLAB / (1+(K_{phos}*WATVOL/SOILMA))
Where
PSOL = dissolved labile P (kg)
PLAB = labile P (kg)
K_{phos} = fractionation coefficient
WATVOL = water volume (kg/ha)
SOILMA = soil mass (kg)

Plant uptake of P is computed identically to the method shown for N above. Plant uptake is subtracted from the labile P pool.

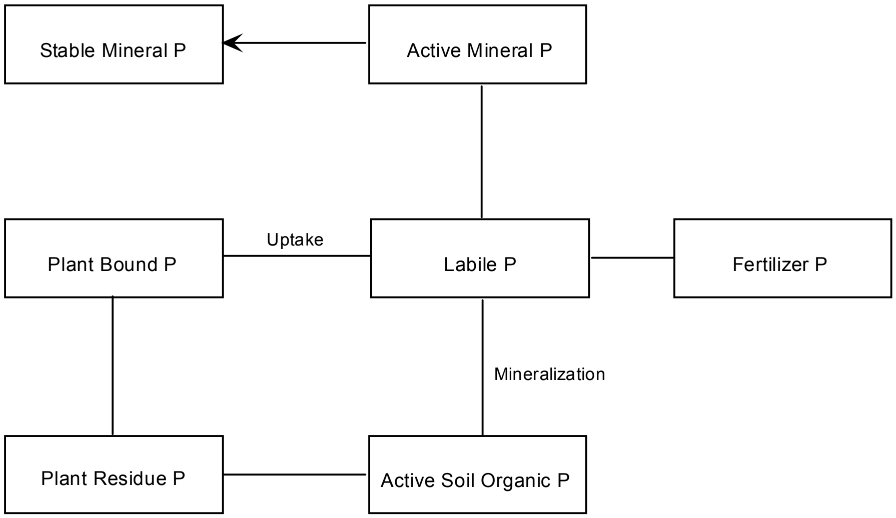


Figure 6: Flow chart for the simulated Phosphorus cycle

Nutrient Transport

Sediment Bound

Nutrients adsorbed or otherwise bound to the sediment were simulated identically. That is, there is no functional difference between the movement of N and the movement of P. Conservation of mass, in a discrete form, was used to compute the amount of material that is exported and imported each time step. If hydrologic flows are present, there is potential for nutrient outflow. The amount of newly entrained sediment-bound nutrients is proportional to the amount of sediment entrained. That is:

$$PCELL = P0*SEDNEW$$

Where

PCELL = locally entrained sediment-bound nutrients (kg/s)

P0 = concentration of nutrient in the soil (kg/kg)

SEDNEW = locally entrained sediment (kg/s)

Sediment flowing in carries some bound nutrient, which is added to the local cells storage, at which point outflow is computed proportional to the outflowing water volume. The inflow and outflow rates are computed for each sediment particle size class separately, with the sediment bound nutrient content distributed across the size class according to the specific area of the particles. Therefore, clays and silts, by virtue of their much higher specific area, bind most of the nutrient storage.

Basic assumptions of the sediment bound nutrient model are:

1) The sediment transport models assumptions are correct
2) The sediment-bound nutrients are distributed proportionally between the different soil particle size classes according to the specific surface area of the particle size classes, and
3) There is no transfer of sediment-bound nutrient between different particle size classes during a storm.

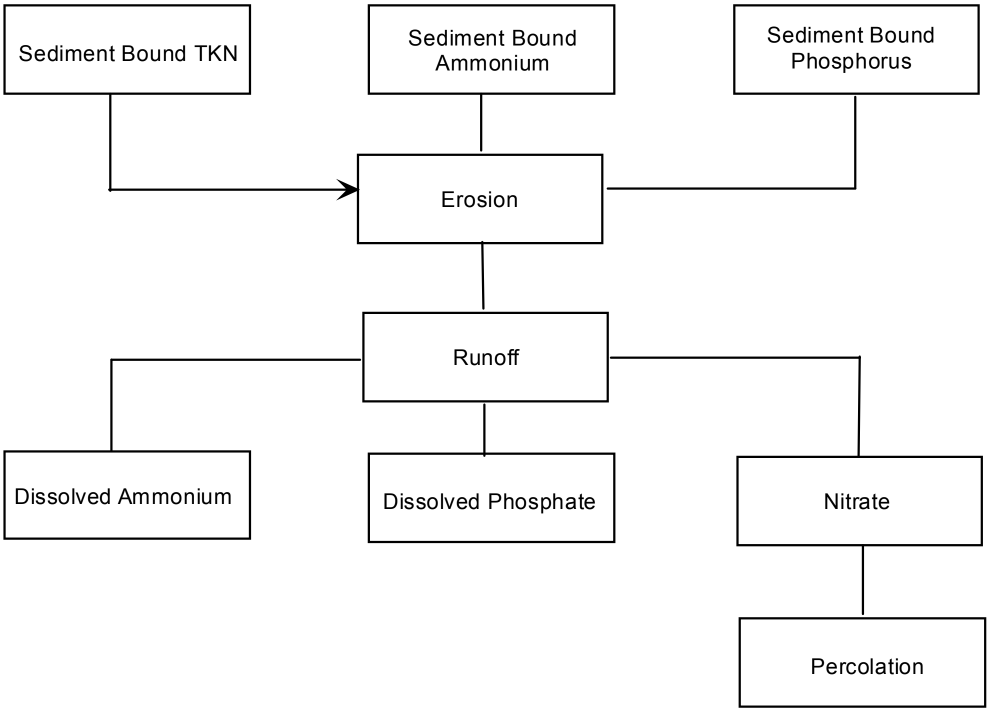


Figure 7: Flow chart showing nutrient loss pathways.

Dissolved Nutrients

The dynamics of how dissolved nutrients appear and are transported in the model are handled in a similar fashion to the sediment-bound fraction. Mass balance is the central concept. During a storm event, dynamic concentration equilibrium between the dissolved and sediment-bound labile fractions arises, and this is modeled as a linear isotherm. The nutrient available for dissolution is modeled as:

$$c_{av} = c^{*}\exp(-X1)$$
$$X1 = (Q + FIL + S)^{*}DT/(POR + 2.65(1-POR)^{*}K)$$

where

c_{av} = available nutrient in runoff (μg/g)

c = nutrient concentration in the surface layer (μg/g)
K = partition coefficient
Q = runoff rate (m^3/s)
FIL = infiltration rate (m^3/s)
S = storage rate (m^3/s)
POR = porosity of the surface layer (cm)
DT = time increment (sec)

The actual concentration of the nutrient in solution is then predicted as follows:

$c_s = c_{av}*\beta/(1+K*\beta)$
where
c_s = concentration in solution (μg/g)
β = extraction coefficient, a function of K as follows

= 0.5	$K<1$
= 0.598*exp (-0.179*K)	$1<K<10$
= 0.1	$K>10$

Transport of the dissolved nutrient is then addressed in a manner similar to the sediment-bound nutrient, adjusted for infiltration and change in storage. The movement of each dissolvable species is modeled like this, with a fractionation function that determines the quantity of the storage (e.g. of ammonium) that is available for dissolution. The exception is nitrate, which is entirely dissolved, so K above is set to 0 and β to 0.5 for assessing the available quantity.

Model limitations

1) ANSWERS is not well adapted for large watershed (>2000 ha) nor for extremely long simulations (> 10 years – due to computational requirements).
2) The nutrient transformations and transport simulation in ANSWERS relies on the empirical statistical equations. Thus, it works better for certain landuses and soil types than others.
3) Model simulation is time consuming and computationally intensive. In the development of the model, authors used a study area (1100 one-hectare cells) and a 5-month period, which required five hours of computer time.
4) ANSWERS is not well adapted to simulate a variety of landuses. It was not designed to simulate forested areas or urban areas.

5) It also poorly represents alternative fertilizer application methods.
6) It can't simulate animal waste application or management effects. This becomes important in watersheds where dairy operations are a large contribution to the total nutrient loading.

Summary

The ANSWERS-2000 model is a complex process based distributed parameter model for evaluating the spatial and temporal effects of BMPs on non-point source pollution for agricultural watersheds. The use of physical relationships for runoff computation and erosion/sediment transport allows the model to be applied without a great deal of calibration. However, several model assumptions will critically limit the ability of the model to perform under the conditions encountered in Florida systems. These are:

1) The oversimplification of groundwater effects and tile drainage will poorly represent the groundwater contributions in high-water table conditions.
2) The presence of only one soil layer in each cell will not capture the duplex nature of many flatwoods soils, where a confining layer often impedes infiltration.
3) The reliance on accurate Digital Elevation Models in areas where little topography exists and flow routing is not necessarily channelized may confound the accumulation algorithms in the model.
4) The model has no mechanism for modeling saturated overland flow, a condition which frequently occurs in high water-table systems.

References

Bouraoui, F. (1994); Development of a Continuous, Physically-Based, Distributed Parameter, Nonpoint Source Model (ANSWERS2000); PhD dissertation, Virginia Polytechnic Institute and State University, Blacksburg VA

Byne, W. F. (2000); Predicting Sediment Detachment and Channel Scour in the Process-Based Planning Model A NSWERS-2000; M.E. Thesis; Virginia Polytechnic Institute and State University, Blacksburg VA

Nordberg, T.M. and T.L. Veith (2001); Instructions for Running ANSWERS using QUESTIONS; ANSWERS2000 v.2.1 User-Documentation; http://dillaha.bse.vt.edu/answers/index.htm

Veith, T.L. and T.M. Nordberg (2001); ANSWERS2000 Input Data Guide; ANSWERS2000 v.2.1User-Documentation; http://dillaha.bse.vt.edu/answers/index.htm

Data Sources

In addition to the above references (within which there is considerable discussion of the theoretical model framework also), the following are data sources that can be used to gather some of the spatial data layers.

SSURGO Databases –

http://www.statlab.iastate.edu/cgi-bin/dmuir.cgi

The link above is for the tabular data.

The following link is to a database of shapefiles for various counties nationwide that have been digitized. - http://www.ftw.nrcs.usda.gov/ssur_data.html

DEMs -

www.gisdepot.com

These DEMs are extracted from USGS 1:24000 topographic maps. Cell resolution is 30 meters, which is adequate for larger basins, but may be insufficient for smaller field/farm level studies. Accurate topographic maps at this scale can only be achieved through a detailed field survey.

APPENDIX 1

Input Data File Considerations and Parameters

The configuration of an ANSWERS input data file allows the file to be constructed in two parts. All data except for the individual data can be contained in a separate file. This first or "predata" file contains all of the general information necessary to describe the various soils, land uses, and management systems in a given county, planning region, state etc. Once a pre-data file has been constructed for a given area, subsequent simulations, even on different watersheds, may be possible with very little or no additional general information collection.

Rainfall information

- Number of gauges used in the simulation (the maximum value is 40, with 200 values per gage. However, it has not yet been tested that ANSWERS-2000 runs properly using more than one gage)
- Two digit designator for each rain gage.
- Need breakpoint rainfall (time interval with rainfall intensity information).

Soils information

- Total porosity (soil surveys have information regarding bulk density of most of the soils from which total porosity can be estimated).
- Field capacity (can be known from the soil surveys or can be estimated from total porosity)
- Steady state infiltration rate
- Difference between steady state and maximum infiltration rate (can be estimated from the soil permeability values where the midpoint of the upper 2/3 of the range is assumed to be the maximum rate)
- Exponent in infiltration equation (charts are there to estimate the value of this exponent for different soil types).
- Antecedent soil moisture (percent saturation - dry or wet conditions, also the model calculates the actual value one month prior to the time to be simulated).
- USLE "K" (USDA soil survey).

Land Use and surface information

- Specific land use and management (tables are provided in ANSWERS-2000 for this)
- Potential interception volume (the volume of moisture that could be removed if the area were completely covered by that crop or land use. Some typical values are provided in the manual).
- Percentage of surface covered by specific land use (non-covered area has no interception can be estimated from the DEM).
- Roughness coefficient (a shape factor describes the frequency and severity of the roughness, tables are provided in ANSWERS-2000)

- Maximum roughness height (is used to establish the upper limits of the surface roughness and is physically measurable, tables are there for some typical values).
- Manning's n
- C (Relative erosivness of a particular land use (soil surveys)

Channel descriptions

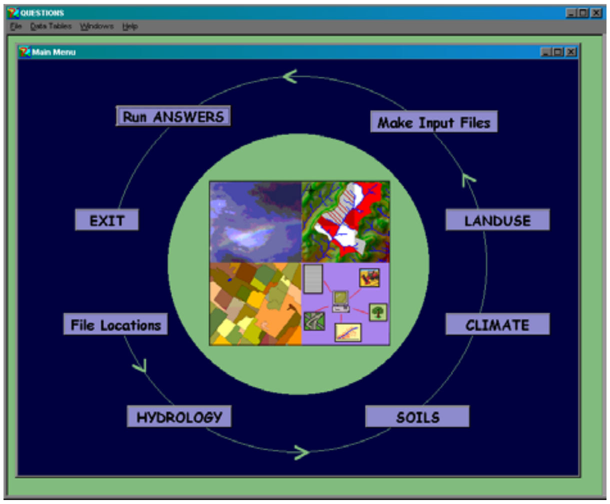
- Channel number
- Channel width
- Roughness coefficient

Individual element information

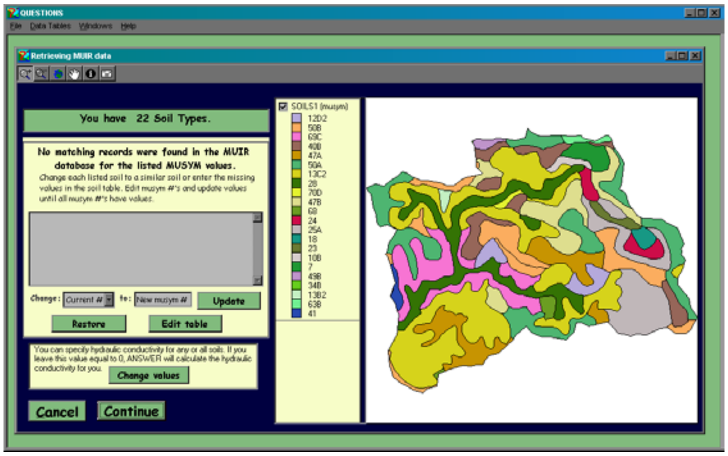
- Row number of element
- Column number of element
- Last element flag, this field should be blank except for the last watershed element: that element should have a value of 9 entered
- Slope steepness of the element, entered in tenths of a percent, e.g., an element with a slope of 2.9 percent would be entered as 29
- Direction of steepest slope, entered in degrees counterclockwise referenced to a horizontal line from the center of the element and directed to the right
- Channel size category, if this element has a well defined channel flowing through it, otherwise these columns should be blank
- Soil type number
- Crop/management type number
- Rain gage designator
- Tile flag; presence of the letters "TI" indicate tile drainage, anything else indicates no tile
- Channel slope steepness in tenths of a percent; when no value is present and a channel exists, the slope will be taken to be equal to the overland slope
- BMP identification number
- First BMP descriptor
- Second BMP descriptor
- Mean elevation of element (optional)

APPENDIX 2

Questions User Interface



Control window for the interface. Each button allow direct linkage with ArcView for input data layer processing.



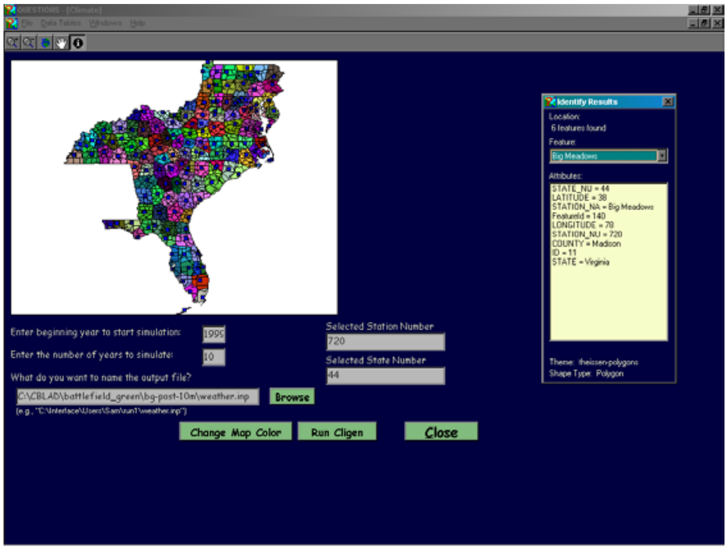
You have 22 Soil Types.

No matching records were found in the MUIR database for the listed MUSYM values.

Change each listed soil to a similar soil or enter the missing values in the soil table. Edit musym #'s and update values until all musym #'s have values.

You can specify hydraulic conductivity for any or all soils. If you leave this value equal to 0, ANSWER will calculate the hydraulic conductivity for you.

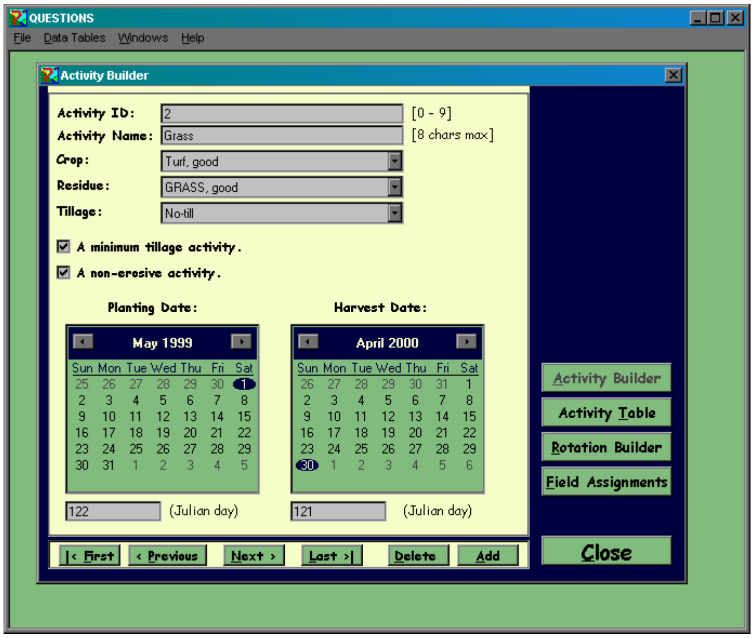
Soils module. This window links the GRID coverage produced in ArcView to the SSURGO soil files. Each soil parameter for each cell is recorded in the input file.



Location:
6 features found
Feature: Big Meadows
Attributes:
STATE_NU = 44
LATITUDE = 38
STATION_NA = Big Meadows
FeatureId = 140
LONGITUDE = 78
STATION_NU = 720
COUNTY = Madison
ID = 11
STATE = Virginia
Theme: theissen-polygons
Shape Type: Polygon

Enter beginning year to start simulation: 1999
Enter the number of years to simulate: 10
What do you want to name the output file? C:\CBLAD\battlefield_green\bg-post-10m\weather.inp
(e.g., "C:\Interface\Users\Sam\run1\weather.inp")
Selected Station Number 720
Selected State Number 44

Weather generation module. This window takes the spatial data within the Cligen database to allow the user to select the region from which weather data is required. Based on the station chosen, a Markov Model is used to produce weather. This is currently the only weather option in Questions. That is, there is no way to use measured climate data in the input files.

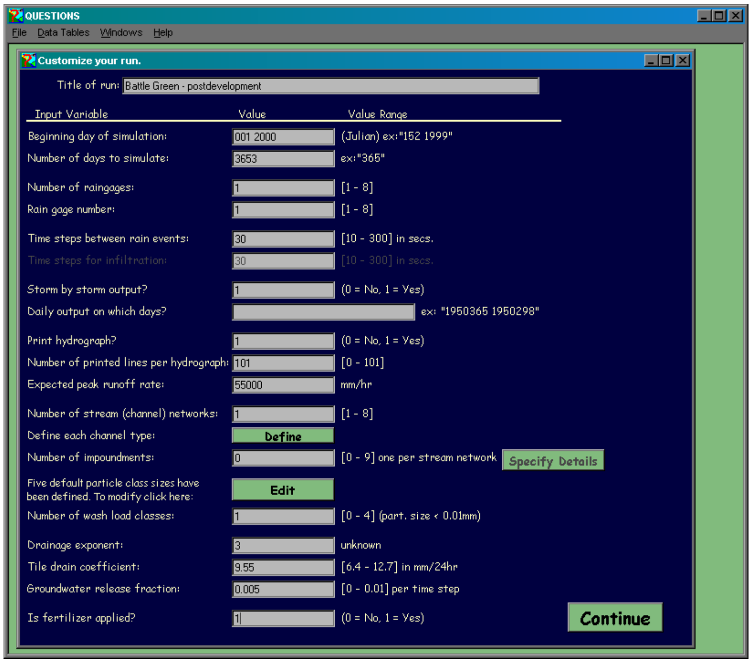


Activity ID: 2 [0 - 9]
Activity Name: Grass [8 chars max]
Crop: Turf, good
Residue: GRASS, good
Tillage: No-till

☑ A minimum tillage activity.
☑ A non-erosive activity.

Planting Date: May 1999 — 122 (Julian day)
Harvest Date: April 2000 — 121 (Julian day)

Activity Builder module. This allows the user to input the various landuses, planting and harvest dates, assign rotations, and link the land uses with tables that parametrize the model.



Title of run: Battle Green - postdevelopment

Input Variable	Value	Value Range
Beginning day of simulation:	001 2000	(Julian) ex:"152 1999"
Number of days to simulate:	3653	ex:"365"
Number of raingages:	1	[1 - 8]
Rain gage number:	1	[1 - 8]
Time steps between rain events:	30	[10 - 300] in secs.
Time steps for infiltration:	30	[10 - 300] in secs.
Storm by storm output?	1	(0 = No, 1 = Yes)
Daily output on which days?		ex: "1950365 1950298"
Print hydrograph?	1	(0 = No, 1 = Yes)
Number of printed lines per hydrograph:	101	[0 - 101]
Expected peak runoff rate:	55000	mm/hr
Number of stream (channel) networks:	1	[1 - 8]
Define each channel type:	Define	
Number of impoundments:	0	[0 - 9] one per stream network
Five default particle class sizes have been defined. To modify click here:	Edit	
Number of wash load classes:	1	[0 - 4] (part. size < 0.01mm)
Drainage exponent:	3	unknown
Tile drain coefficient:	9.55	[6.4 - 12.7] in mm/24hr
Groundwater release fraction:	0.005	[0 - 0.01] per time step
Is fertilizer applied?	1	(0 = No, 1 = Yes)

Additional data inputs. Sets the length of the simulation, channel and sediment particle classes, drainage coefficients, and data output formats.