ANNAGNPS: ACCOUNTING FOR SNOWPACK, SNOWMELT, AND SOIL FREEZE-THAW

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Abstract: The watershed model, AnnAGNPS (Annualized AGricultural Non-Point Source Pollution model) has been enhanced by incorporating winter climate algorithms that account for frozen soil conditions. The model includes snowpack accumulation and melt, and the freeze-thaw process in the soil. Three major improvements can be expected for watersheds with significant winter climates. First, the model will better account for the lag in runoff from precipitation held for months in snowpack. Second, the model will more accurately account for the movement of water through the soil layers and any resulting runoff. Third, the model will better account for the increase in sheet and rill erosion due to runoff over soil layers that have experienced the freeze-thaw process. These model improvements synthesize the science of the SHAW model (Simultaneous Heat and Water) by Gerald Flerchinger, Agricultural Research Service, Boise Idaho. SHAW, however, is a research model, while AnnAGNPS is a watershed model used by engineers and other practitioners for practical applications. In adapting SHAW, several modifications in computational procedures were made. For example, while the AnnAGNPS heat flux algorithm retains a simultaneous matrix solution of the temperature profile in soil and snow layers, the default timesteps and solution tolerances are larger than in SHAW. In addition, the first release of winter-enhanced AnnAGNPS will not include a full simultaneous matrix solution of soil moisture in thermal layers, as is done in SHAW. AnnAGNPS may adopt this in the future, but presently computes soil moisture in a more simplified manner. Also, SHAW includes a thermal layer for surface residue. This highly desired model component will be incorporated into AnnAGNPS in a future release. The AnnAGNPS winter enhancements improve modeling capability for many more geographic locations and will result in better sediment yield and pollutant loading estimates for water quality improvement in natural resources planning.

INTRODUCTION

The initial development and ongoing enhancement of water quality models is, of course, subject to considerable debate about appropriateness of scale, scope, complexity, and accuracy of results. Modeling the freeze-thaw process in the soil profile is inherently complex, and simplified procedures do not often produce meaningful results. The complexity of this natural process may be on a plane quite above the other modeled processes such as rainfall/runoff in many water quality models. The purpose of modeling the freeze-thaw process down into the soil profile, rather than merely at the surface, is that many watersheds, for example the Palouse area in the state of Washington, experience significant soil loss when a moderate rainfall event occurs on a thin layer of unfrozen soil, overlaying a deeper frozen layer. Other models similar to AnnAGNPS, such as SWAT, attempt to estimate soil surface temperature in an effort to better estimate winter runoff (Arnold and Fohrer, 2005). But sub-daily timesteps and an algorithm that takes into account heat and moisture fluxes in the soil profile are required for estimating the additional erosion off of frozen sublayers. It may be suggested that coupling a highly complex soil profile algorithm with a very simple soil loss methodology, such as RUSLE, is a mismatch. Many water quality models have been designed to model complex hydrologic processes using simplified methods that were developed for entirely different purposes, such as single-event flood peak models for engineering uses. Whether or not both the curve number method for runoff and RUSLE for erosion are appropriate is a matter of some debate (Garen and Moore, 2005). But ongoing enhancement of models naturally involves this kind of leap-frogging, and there is no reason that improvement in the snowpack accumulation and melt, soil freeze-thaw, and soil moisture accounting cannot be followed by improvements of these other processes.

Adapting SHAW: The winter enhancements to AnnAGNPS are based on an elaborate research model that can be calibrated and sufficiently tested only with large amounts of empirical data. The Simultaneous Heat and Water Transfer Model, by Gerald Flerchinger of the Agricultural Research Service in Boise, Idaho, is a physical process model that simulates the movement of heat, water, and solutes through the soil column. It accounts for all the relevant thermodynamic processes such as shortwave and longwave radiation, conductance, and latent heat transfer. It accounts for snowpack accumulation, compaction, and melt. It captures the soil/snow temperature and moisture profile by analyzing it as a matrix of thermal layers for which heat and moisture flux equations are written and solved simultaneously. The model was originally verified and calibrated using data from twelve field plots, seven meter by thirty meter each, in which different types of tillage and different amounts of crop residue were applied. Weather data, including precipitation, air temperature, relative humidity, wind speed, and solar radiation were collected, as well as soil temperature and moisture data in the soil profile. Some necessary equation parameters were not measured but assumed from the empirical investigations and testing of other researchers. Flerchinger and colleagues concluded that the model performed well and showed “excellent agreement between observed and measured snow and frost depths, soil temperatures, and moisture contents” which were also “obtained with minimal calibration” (Flerchinger, 1987).

Available for several years, AnnAGNPS has undergone continual update and improvement. See Bingner (2001). The winter options include a matrix of thermal layers with finite difference equations for each to balance the heat fluxes. Sub-daily timesteps of default three hours are employed and air temperature is varied in the 24 hour time period between high and low. Snowpack settles and compacts over time, as is done in SHAW, and snow releases melt-water only after the liquid-holding capacity of the pack is satisfied. Moisture is percolated through the soil layers using hydraulic conductivity, varying by soil type and moisture content. Runoff is generated by either saturation excess or freezing of the topmost thermal layer, or saturation at the soil surface due to high intensity rainfall or rapid melt.

The details of the SHAW adaptation are given below, with discussion of assumptions, simplifications, increased timestep length, and relaxed solution tolerances of the heat balance iterative solution. Intended future enhancements are also discussed..

SOIL PROPERTIES

AnnAGNPS currently accepts as input a very detailed and complete set of soil properties for any multi-layered soil. The use of GIS and soil databases such as SSURGO (USDA-NRCS 2005a) or STATSGO (USDA-NRCS 2005b) facilitate the differentiation of soil parameters spatially and depthwise in any watershed. For the soil temperature profile important parameters are thermal conductivity and heat capacity, both highly dependent on soil type and moisture content. To determine thermal conductivity AnnAGNPS employs the method of Johansen, generally accepted as best by several researchers, which takes into account soil grain size, quartz content, and moisture (Johansen, 1975, Andersland and Ladanyi, 1994). Soil heat capacity in AnnAGNPS is a function of silt, sand, clay, and organic content (Andersland and Ladanyi, 1994).

The temperature at the bottom of the soil column is considered constant and assumed to be the average annual air temperature at the watershed location. The depth at which the annual temperature variation decreases markedly (called the damping depth) is dependent on the amplitude of the temperature variation at the surface and the soil thermal diffusivity. Normally, damping depth refers to the depth at which the amplitude of temperature variation is about one third that at the surface, but it can be determined for any amplitude variation. Thus, for AnnAGNPS, the damping depth is determined for an amplitude of plus or minus 2.5º C at the bottom of the soil profile. The thermal layers may not extend to that depth, but the initial temperature of each thermal layer is determined from an elliptical curve between air temperature at the top and damping depth.

SNOWPACK PROPERTIES

Air and dewpoint temperatures are adjusted with elevation, and precipitation is considered snow when both the average temperature of the day and the dewpoint are below zero degrees C. The snow density at time of snowfall is dependent on air temperature (Marks, et al., 1999). Density of the snowpack is adjusted with time as settling and compaction occur, following SHAW, citing Anderson (1976). Snow albedo is determined, based on snow "optical" grain-size and solar azimuth (Marks, et al., 1999) following the procedure provided in the web-based image processing workshop, "Software Tools for Hydro-Climatic Modeling and Analysis", (Frew and Dozier, 1986). The snowpack thermal layers are at most two in number, with the top layer varying in thickness up to a maximum of 20cm and the lower layer varying up to the total remaining depth of the snowpack. The maximum thickness of the top snow layer was set at 20cm, as this is generally the thickness for which the layer temperature can be affected by aerodynamic variables such as radiation and convection (Marks, et al., 1999). When no lower snow layer exists some shortwave solar is considered to reach through to the soil layer, attenuated with greater depth or density. Of course, snowpacks may be quite deep in mountainous regions, and although it may be suggested that more thermal layers would be needed to properly delineate the temperature profile for such depths of snow, the agricultural watersheds generally modeled by AnnAGNPS tend to have shallower snowpacks. The model tracks the age, settling, and compacting of up to a week's new snowfall, as well as that of the remaining pack. The liquid water holding capacity of each snow layer is tracked, meltwater drained, and thickness adjusted on a timestep basis.

CLIMATE DATA INPUT

AnnAGNPS currently uses six major daily climate data variables: precipitation, max & min temperature, dewpoint temperature, solar radiation, and wind speed. The winter algorithms employ several techniques to distribute this data through the 24-hour day. Temperature is varied on a sine curve from the high, assumed to occur at 4pm, to the low, assumed to occur at 4am. Air and dewpoint temperatures are also varied with elevation. Daily precipitation can be varied during the day by storm type distributions. Solar radiation is varied based on latitude, date, and sun angle, as well as the slope and aspect of the ground for each "cell" or subwatershed unit. None of these data requirements are new with the winter enhancements.

THERMAL LAYERS

As discussed above, the snow thermal layers vary in thickness, with the top layer no thicker than 20 cm and the lower layer the remainder of the snowpack. The soil thermal layers are of pre-determined and unchanging thickness. As shown in Figure 1, below, a residue layer belongs between the two, and this is a feature of SHAW, not yet incorporated into AGNPS.

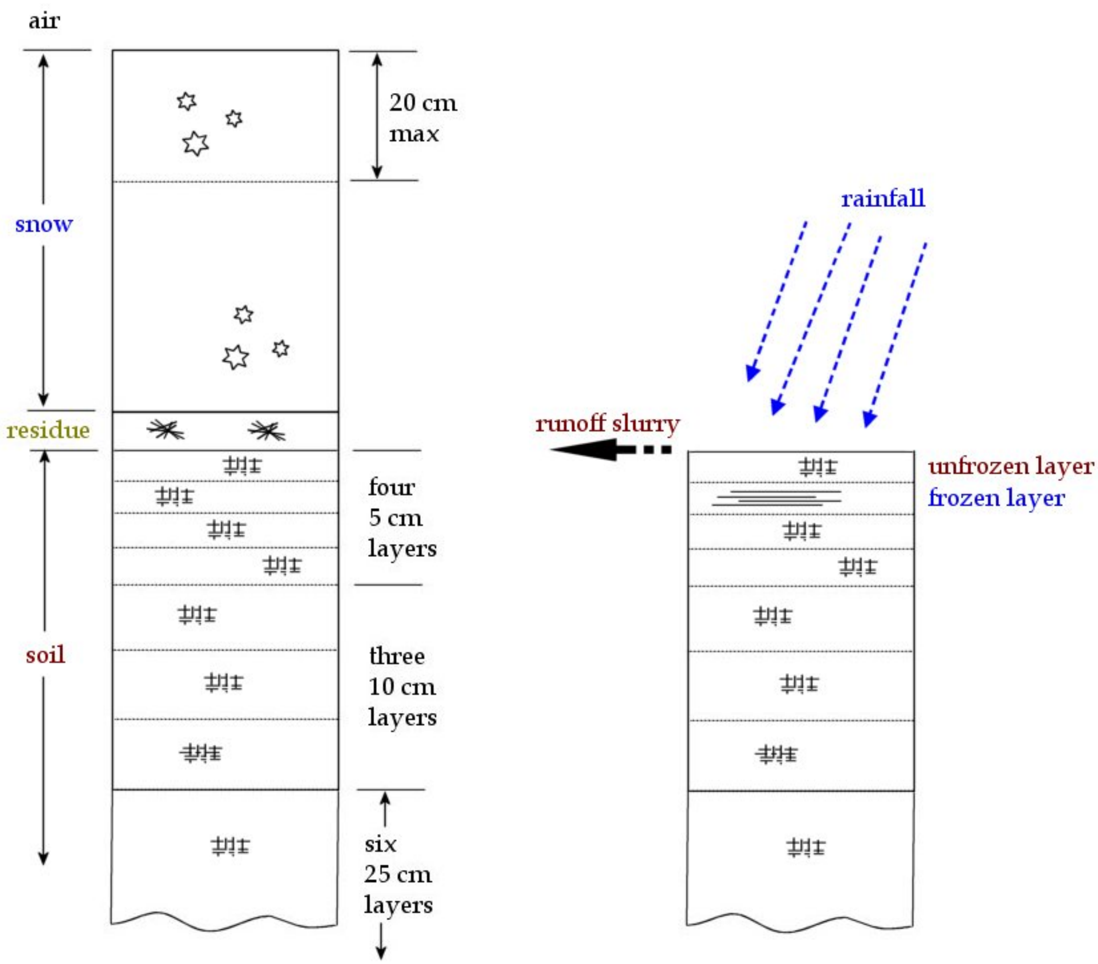

Figure 1 Snow-residue-soil thermal layers and an erosive runoff scenario.

The soil thermal layer thicknesses are thinner at the top and increasing down into the soil column because the upper layers experience more rapid temperature variation. In addition, thinner layers enable a more refined estimate of erosion over frozen soil. This latter scenario is also shown in Figure 1 above, in which the snowpack has melted or a significant rainfall is occurring while a thin top layer of soil is unfrozen, but a lower layer remains frozen. The frozen layer acts as something of a pavement, facilitating incorporation of soil from the unfrozen layer into the runoff stream. The deeper frozen layer, however, is not the only cause of the additional erodibility. As discussed in Gatto and Ferrick (2003), a good overall discussion of the phenomenon, the freeze-thaw process weakens the upper layers regardless of an underlying frozen layer.

For comparison, the center nodes of the soil layers used for the initial verification of SHAW were (in cm, not including a shallow top layer) 7.5, 15, 25, 38, 53, 68, 83, 107, 137, and 167. Many more recent articles exist concerning SHAW. See Flerchinger and Seyfried (1997) or Flerchinger, Hardegree, and Johnson (1998).

ENERGY BALANCE

Heat flow proceeds in the lower soil layers due to conduction between layers of different temperature, advection by moisture moving through the layers, and latent heat exchange due to phase change of the moisture. For the upper soil layer, or top snow layer, whichever is exposed to the atmosphere, additional significant heat flow is induced by radiation, convection due to wind, and advection from precipitation. As documented by Flerschinger (1987), second-order partial differential equations can be written for layers of infinitesimal thickness, with terms to represent each type of possible heat flux. To make practical application of these continuity equations, and apply them to thermal layers of finite thickness, they are reformulated as finite difference equations which approximate the partials. The solution of each layer's equation is dependent on the heat flux in neighboring layers, so the entire set of equations must be solved simultaneously.

A Key Assumption: Each thermal equation involves a number of unknowns related to either temperature or moisture content. Many references are available, for example, Marion (1995), which discuss the phenomenon of freezing point depression, and Flerchinger (1987) documents how the SHAW model takes into account the fact that the soil freezing temperature is dependent on, among other factors, solute concentration and matric potential. Freezing soil acts as a moisture sink, causing migration of water and solutes toward the freezing front. As the water freezes solutes are excluded and concentrate at the front. This phenomenon is not treated by the AnnAGNPS adaptation of SHAW. More significantly, neither is freezing point depression. By assuming a known temperature at which water freezes in the soil, the energy balance can compute ice content for layers in the process of freezing while simultaneously computing temperature for non-freezing layers. The AnnAGNPS winter algorithm could set this "known" phase change temperature at some subzero value, but currently it is assumed that soil water freezes at 0º C. Flerchinger indicated in conclusions from SHAW verification tests that "even very high concentrations of solutes seemingly have very little effect on soil freezing", while having a greater impact on salt redistribution.

Thus, if a soil layer contains no ice or is completely frozen then that layer's temperature is solved for. If the layer contains both ice and liquid, then the temperature of that layer is known (0º C) but the ice content of that layer becomes the unknown to solve for. For a snow layer, either the temperature is unknown or the layer contains meltwater and the temperature is known (zero), but the meltwater content becomes the unknown. Since each layer's equation also contains variables relating to its neighbors, the phase state of those layers also affects the given layer. The mechanics of the simultaneous solution of this matrix of equations is discussed in the Matrix Solution section below.

MOISTURE BALANCE

The percolation of moisture from one layer to another is dependent on hydraulic conductivity, matric potential, and moisture content of both layers, in addition to the moisture supply from above. Thus, a full moisture balance requires simultaneous solution of finite difference continuity equations written for the moisture flux of each layer. Keeping track of the moisture is a critical aspect of the energy balance, as well as for determining the instigation of runoff at the surface. Freezing and thawing involve the highly significant latent heat of fusion term. And the thermal conductivity of a soil layer depends on its moisture content. The SHAW model performs a full moisture balance of finite difference equations, solving either for matric potential, or ice content if the layer contains ice.

AnnAGNPS, however, simplifies the moisture accounting and avoids a simultaneous matrix solution. (A more complete moisture balance may be adopted in the future.) The simplified moisture accounting is accomplished as follows. Percolation through the thermal layers is computed by examining three layers at a time, starting at the bottom of the soil column at proceeding up, one layer at a time. Thus, the moisture content and percolation of two of the three layers can be adjusted twice, based on available incoming moisture from layers above. Percolation is assumed zero for layers more than 50% frozen and reduced for layers up to half frozen. This moisture accounting is computed at each timestep, but after the energy balance. For layers containing ice, liquid and ice content having been previously determined in each timestep by the energy balance, the liquid content only is adjusted for percolation into or out of that layer. Moisture loss due to evapotranspiration is accounted for in the top four thermal layers.

AnnAGNPS keeps track, on a timestep basis, of the infiltration or runoff of snowmelt or rainfall, accounting for a frozen or partially frozen top soil layer, and due to either saturation excess or infiltration excess. Surface saturation is computed by the Green-Ampt method, but should be coupled with the optional storm distribution capability which distributes daily rainfall into subdaily timesteps.

MATRIX SOLUTION

The equations for each thermal layer generally have three unknowns, relating to the given layer and its neighbors. A common method for solving indeterminate equations is the so-called Newton-Raphson method, a root-finding algorithm by which the first two terms (generally) of a Taylor Series expansion are used to continually improve on solution estimates until an acceptable tolerance range is achieved. As long as the first estimate is "reasonably close" to the correct solution the method converges rapidly. In addition, since each thermal layer and its neighbors are a successive trio through the soil/snow profile, the equation set forms a "tri-diagonal matrix" for which very efficient programming algorithms exist. It remains to be determined what tolerance range is acceptable for the solution.

AnnAGNPS timesteps, tolerances, and iteration limits: The SHAW initial verification employed one-hour timesteps. Solution tolerances were 0.0001º C for temperature and a maximum of ten iterations were attempted before non-convergence was assumed. (In that case, SHAW would automatically halve the timestep and try again.) The AnnAGNPS adaptation uses similar thermal layer thicknesses (as mentioned above), a default timestep of three hours, increases the temperature tolerance to ±0.1 º C, and assumes non-convergence after eight iterations. The algorithm allows a decreasing of timestep size to one-hour and a re-attempt at convergence, but only after performing a check of phase condition. In testing, the AnnAGNPS matrix solution scheme usually converges very rapidly, within one or two iterations, unless it is contemplating a phase change. If non-convergence seems to be as a result of phase change in the layer, the checking algorithm looks at how close the convergence came and whether freezing or thawing should be expected. If meeting relaxed criteria for just that particular timestep, the solution is accepted.

Other Assumptions: The SHAW model includes a term in the snowpack thermal layers for heat exchange due to vapor transfer, which also enables the computation of snowpack mass loss due to sublimation. It includes a similar term for the soil layers. Both of these are neglected in the AnnAGNPS adaptation. The loss of soil moisture mass due to evapotranspiration, however, is not neglected.

PLANNED ENHANCEMENTS

AnnAGNPS gives the modeler significant capability to account for the impact of agricultural management practices, and since a residue thermal layer can be expected to significantly affect the freeze-thaw process in the soil, adding this feature is planned. AnnAGNPS can also model watersheds of greatly varying size, with over 100 years of simulated climate data. Using a cpu intensive feature such as the winter algorithm may not be feasible for very large watersheds. The current winter algorithm includes some attention paid to computational efficiency, such as not running winter calculations out of season.. Future enhancements will include further attention to computational efficiency. At the same time, adding the option of a full moisture balance will be explored.

SUMMARY

The NRCS watershed model AnnAGNPS has many features that enable an accounting of the water quality impacts of agricultural practices including crop types, field management practices, fertilizers, irrigation, and soil erosion mitigation measures. The addition of a winter algorithm to account for the runoff lag due to snowpack water storage, as well as infiltration and runoff over frozen soil, and the additional erosion from freeze-thaw impacts provides important new modeling capability.

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