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Development of a Simple Soil Moisture Model in the Hydrologic Simulator GSSHA

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PURPOSE: The purpose of this System-Wide Water Resources Program (SWWRP) technical note is to describe the development and application of simplified unsaturated zone modeling in the Gridded Surface Subsurface Hydrologic Analysis model (GSSHA) (Downer et al. 2005). This new method was developed to increase the applicability of the GSSHA model to high resolution coupled surface-water/groundwater simulations of large basins that may be limited by excessive simulation times or accuracy of methods of unsaturated zone computations previously available in the model.

BACKGROUND: The GSSHA model was developed to allow simulations of coupled surface-water/groundwater systems. The link between the surface-water zone and the saturated groundwater zone is the area between the two domains, referred to as the unsaturated zone, or the vadose zone. This area controls the important fluxes of infiltration, evapotranspiration (ET), and groundwater recharge. Movement of water in the unsaturated zone is largely vertical (Refsgard and Storm 1995) and GSSHA was developed with a one-dimensional (1-D) representation of the unsaturated zone. GSSHA simulates the unsaturated zone by solving the Richards equation (RE) (Richards 1931) which couples the equation of mass conservation with the equation describing unsaturated flow movement, the Darcy-Buckingham equation. Properly discretized, the RE can accurately simulate soil water movement and the associated fluxes critical to the coupling of the surface-water and groundwater systems (Downer and Ogden 2004).

However, the RE is highly nonlinear and time-consuming to solve. The computational burden can become a problem when there is a need for fine discretization of the overland flow plane in large watershed, as the RE must be solved in each coupled overland flow/groundwater cell. Therefore, alternatives to RE are desirable, especially when the thrust of the modeling is computation of surface-water flows.

Prior to the development of GSSHA, the Green and Ampt model (Green and Ampt 1911) with redistribution (GAR) had been developed in the CASC2D model (Ogden and Julien 2002) to allow simulations of infiltration during rainfall periods with redistribution of infiltrated water during rainfall hiatus (Ogden and Saghafian 1997). The GAR model was coupled to a simple "bucket" model of the unsaturated zone to allow for continuous simulations and improve model calibration (Senarath et. al. 2000). As described by Senarath et al., infiltrated water contained within a user-specified soil depth was uniformly distributed over that depth at the end of precipitation events and treated as a uniform bucket of water and soil. At that point, water was removed from the bucket due to ET until the next rainfall event. The resulting soil moisture in the bucket was then used as the initial condition for GAR simulations of infiltration during the next storm event, with the entire cycle repeating until the end of the simulation. Senarath et al. found that this method allowed for accurate simulations of surface-water discharge and led to improvements in calibration and verification. In comparing this simple method to simulations of Richards' equation in the Goodwin Creek Experimental Watershed (GCEW), Downer and Ogden (2003) found that for periods of Hortonian runoff, the GAR/bucket method produced comparable simulations of surface-water runoff. Modest improvements in surface-water predictions using RE were offset by the greatly increased simulation times.

As part of a study on the effects of wetland restoration on hydrology in a poorly characterized watershed, Downer et al. (2002) modified the GAR/bucket model and used the infiltration computed from the GAR model as an estimate of groundwater recharge. Downer et al. (2002) were able to closely reproduce the stream flow in the watershed, including the baseflow, and made qualitative estimates of wetland restoration effects on stream hydrology. While the model was clearly useful for simulating stream hydrology, it was not known how well the model actually reproduced groundwater recharge, as no estimates of groundwater recharge or groundwater level were available. Other concerns included:

- Because all infiltrated water is assumed to become groundwater recharge, water evaporated from the system results in mass balance errors.
- Infiltrated water immediately becomes recharge, so that timing errors in groundwater recharge are likely.
- Soil moisture in the bucket model was not subject to gravity drainage.
- As ET occurs only in the soil bucket, it was not possible to compute direct evaporation of ponded water, which could lead to errors in infiltration calculations.
- A mass balance could not be calculated for water in the unsaturated zone.

These limitations made the method most applicable for qualitative analysis and less applicable for design. The lack of mass balance essentially precluded the use of the method for water quality simulations.

METHODOLOGY: The original method of soil moisture simulations with GAR/bucket has been replaced with a two-layer unsaturated zone model that uses GAR to provide estimates of infiltration flux into the unsaturated zone. The intent is to improve estimates of soil moisture, groundwater recharge, ET, and to provide a mass balance of the unsaturated zone and the overall system. Although the concept is similar, the "bucket" has been replaced with a two-layer soil model (see Figure 1). A two-layer model was chosen after testing at GCEW indicated that a single layer model could not simultaneously reproduce discharge and soil moistures while maintaining a mass balance of water. The size of the top layer can equal the total soil depth, resulting in a single layer model. Water enters the soil as infiltration, and leaves the layer as ET and groundwater recharge.

Soil Moisture and Flux Computations. As previously described, infiltration into the soil layer is computed with the GAR method, but the method is general such that the method used to compute infiltration is irrelevant. Groundwater recharge is computed as the flux from the bottom of the unsaturated zone using Darcy's law. A unit head gradient is assumed, so that the recharge is equal to the unsaturated hydraulic conductivity of the soil, as computed by the Brooks and Corey (1964) method as shown in Equation 1. Recharge ceases at soil moistures at or below the field capacity, the point at which capillarity of the soil matrix prevents free drainage of the soil. The need for soil field capacity introduces an additional input to the GAR mapping table file. When simulating coupled surface water/groundwater systems the recharge from the bottom of the soil column is accumulated until the next groundwater update and then added to the groundwater cell as a source term.

$$K(\theta) = K_s\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{2+3/\lambda} \tag{1}$$

where

$K(\theta)$ = soil moisture dependent hydraulic conductivity of the soil (m/s)
K_s = saturated hydraulic conductivity of the soil (m/s)
θ - water content of the soil
θ_s = saturated water content of the soil
θ_r = residual water content of the soil
λ = soil distribution index.

Potential evaporation (PET) is computed hourly from hydrometeorological inputs using the Penman-Monteith (Monteith 1965, 1981) method for vegetated soils. PET is first subtracted from any water ponded on the cell surface. If there is no surface water or the amount of water ponded on the surface does not satisfy the PET demand, then actual ET (AET) taken from the soil layer is dependent on the soil moisture. For values of water content higher than the wilting point (θ_{wp}), the soil moisture below which plants cannot pull water from the soil matrix, the AET (m/s) is computed as (Dingman 1994):

$$AET = PET\left(\frac{\theta - \theta_{wp}}{\theta_s - \theta_{wp}}\right) \tag{2}$$

AET is computed separately for each layer. The *PET* is allocated to the two layers based on the relative size of the layers.

The volume of water in the soil layer is computed according to the following equation:

$$V^{n+1} = V^n + \Delta t A\left(I - R - AET\right) \tag{3}$$

where

V^{n+1} = updated volume of water in the soil layer (m^3)
V^n = volume of water in the soil layer at the time of the last update (m^3)
Δt = amount of time that has elapsed since the last update (s)
I = infiltration rate (m/s)
R = groundwater recharge rate (m/s)

A = is the surface area of the cell (m^2).

For the top layer R is the flux from the top layer to the second layer.

The soil moisture in each layer is computed as the volume of soil water in the layer divided by the layer depth, which can be a different value in each cell. The time-step (Δt) depends on the circumstances, being the infiltration time-step for periods when infiltration is occurring, or the *PET* time-step when no infiltration is occurring. The infiltration time-step is variable, but is typically 1 min. or less. The *PET* time-step is 1 hr.

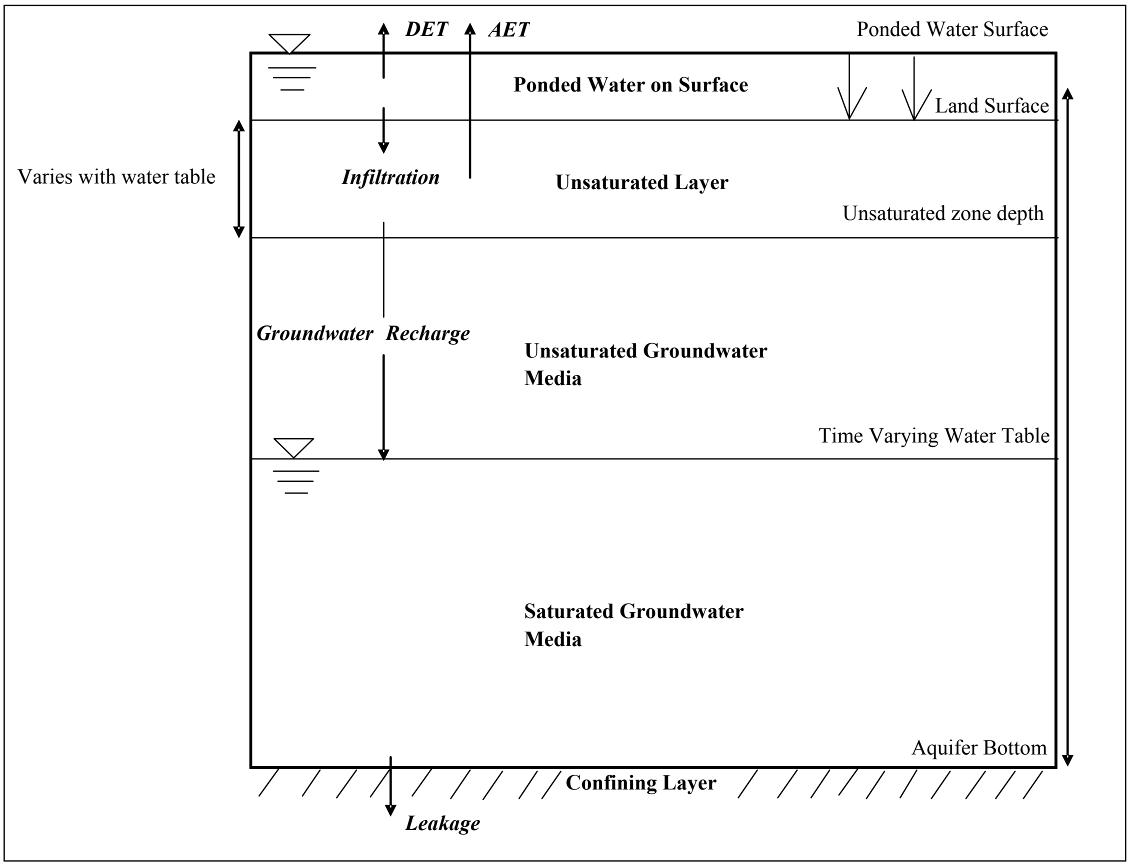

Figure 1. Conceptualization of a simple soil moisture model with linkages to surface water and groundwater

Coupling to Groundwater. Coupling the two-layer soil moisture model to the groundwater system introduces additional complexity. The groundwater table may be at, above, or below the specified soil layer depth. In addition, the groundwater level is time varying, so that this condition can change anytime during the simulation. The following conditions apply.

Condition 1 - Water table is below the soil column. The material between the soil and the water table is the same material specified for lateral groundwater movement. The soil moisture of the media in this zone is set to a user-specified fraction of the groundwater media porosity, with a default value of 0.75, roughly equal to field capacity. The volume of water in this zone is considered part of the unsaturated zone water but not as part of the soil layer, which is tracked separately. The storage term for groundwater simulations is the porosity of the groundwater media, fluxes are added to, or subtracted from, the groundwater to account for the water in the unsaturated portion of the groundwater media as the water table rises and falls, respectively.

Condition 2 - Water table is at or above the soil column. As the groundwater rises into the bottom of the soil column, the depth of the bottom soil layer changes to the depth of the water table. As the water table continues to rise, the bottom layer is reduced until it disappears. The same process is repeated as the water table rises into the top layer. If only one soil layer is specified, the process is the same. The storage capacity term for the groundwater is the porosity of the soil. The soil water volume in the soil layer remains the same as the groundwater level rises and falls, but the soil moisture increases and decreases, respectively. This can result in changes in ET and recharge, which are dependent on the soil moisture.

Condition 3 - Water table reaches the soil surface. The soil column disappears. The soil moisture in the cell is set to the saturated water content of the soil. Infiltration into the cell ceases and the groundwater storage term becomes unity. The surface water now interacts directly with the groundwater. If the surface-water elevation is higher than the groundwater elevation, the groundwater will be recharged at the aquifer leakage rate. If the groundwater elevation is higher than the surface-water elevation then groundwater will spill back onto the overland flow plane as exfiltration. Darcy's law is used to compute the flux from the groundwater across the soil layer onto the soil surface. PET is satisfied from either the surface water, or directly from the groundwater, depending on the availability of ponded water on the surface.

Condition 4 - Water table falls below land surface after condition 3 occurs. The soil layer reappears. The depth of the soil layer is equal to the depth of the water table below the land surface, up to the specified soil layer depth for each cell. The water content of the soil layer is set to the field capacity of the soil. The water for the soil layer moisture is taken from the groundwater. Infiltration, ET, recharge, and soil layer moisture calculations proceed as in condition 2. If the water table falls below the specified soil layer thickness, then the area between the soil layer and water table is treated as described in condition 1.

POTENTIAL ADVANTAGES, APPLICABILITY, and LIMITATIONS: The new method to simulate the unsaturated zone has many potential advantages over the current methodologies. The method may also expand the applicability of GSSHA to different classes of problems. However, as with all simulation techniques, the new unsaturated zone calculations have limitations that should be considered when deciding how to apply the model.

Advantages. The new method has the following potential advantages over the current methodologies.

Advantages over Richards' equation (RE). The primary advantage of the method over the RE is the savings in simulation time. Depending on the system, the difference is simulation time could be as great as an order of magnitude. Reduction of simulation times is significant when the simulation times become a limitation on applicability. Long simulation times can preclude the use of automated calibration methods, limit the practical simulation period, and limit the number of simulations, thus limiting the ability of the model to fully explore the possible range of solutions.

Advantages over the previous GAR/bucket method. One of the greatest advantages over the previous GAR/bucket method is that a water balance for the soil layer and the coupled groundwater/surface-water system is maintained. This allows the user to see how the water is partitioned, and assists in both calibration and in judging the adequacy of the model for the current application. Along the same lines, the soil layer model is now completely integrated into the GSSHA simulation model. Another significant advantage is that the soil layer is more realistically simulated. Soil moisture is continuously simulated; drainage is computed, and direct evapotranspiration (DET) is taken from surface waters. And although GAR is used to compute the infiltration flux into the single soil layer, any infiltration model in GSSHA could be used to provide this information. Another advantage is that the method works identical to the RE formulation in the model, with the exception of the complexity of the computations in the soil layer, providing consistency within the GSSHA model.

Applicability. The purpose for the addition of the new method is to increase the applicability of GSSHA to more problems and users. With the improvements as previously described, it is anticipated that the new single-layer model of the unsaturated zone can be used to make more quantitative assessments than was possible with the GAR/bucket model. This will allow the model to be applied to larger basins with greater resolution, due to the decrease in simulation times over the RE method. Given the method is mass conserving, it may also be applicable for water quality studies.

Limitations. While representing a significant improvement as compared to the previous GAR/bucket model for unsaturated zone and groundwater simulations, the model is still highly simplified when compared to the RE solution. The following limitations should be noted:

- Flux of water between the unsaturated zone and the saturated groundwater is limited to recharge. The soil layer model does not impose an upward demand on the groundwater due to ET. This may result in unrealistically low values of soil moisture in the soil column, as well as unrealistically high values of the groundwater table. However, errors should tend to be self limiting as demand on the water table will cause the water table to drop and, ultimately, for the soil moistures to fall.
- Recharge to the groundwater may be subject to significant errors in volume, and, especially, timing, due to the fact that the soil layer does not necessarily represent the full unsaturated depth, and the unsaturated soil moisture profile is highly simplified.
- Water in the soil layer is assumed to be uniformly distributed. This ignores the complex soil water profiles as seen in the field and reproducible with RE. This can result in errors in ET, recharge, and soil moisture. Soil moisture predictions will likely be inferior to those computed with RE.
- The representation of the soil as homogenous in the vertical may not prove adequate when layered soils are present, especially where layering may produce a perched water table.

SUMMARY: The previous GAR/bucket model of infiltration and soil moisture accounting in the GSSHA model has been replaced with a two-layer soil moisture model that uses GAR to compute the infiltration flux into the soil layer. The new method offers many advantages over the previous method while preserving its primary advantage over the RE solution, simulation speed. With the improvements, it is proposed that the method can be used to provide quantitative analysis of coupled surface water/groundwater systems, with accuracy of surface-water fluxes and groundwater heads comparable to solutions using RE to represent the unsaturated zone. The method increases the flexibility of the GSSHA model, and provides the user with more options in conceptualizing hydrologic systems. However, the method is simple when compared to the RE solution, and its applicability needs to be explored and verified before any definitive statements can be made.

ADDITIONAL INFORMATION: This technical note was prepared by Dr. Charles W. Downer, research hydraulic engineer, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center. The study was conducted as an activity of the Coastal Morphology Modeling and Management work unit of the System-Wide Water Resources Program (SWWRP). For information on SWWRP, please consult https://swwrp.usace.army.mil/ or contact the Program Manager, Dr. Steven L. Ashby at Steven.L.Ashby@erdc.usace.army.mil. This technical note should be cited as follows:

> Downer, C. W. 2007. *Development of a single layer unsaturated model in the hydrologic simulator GSSHA*. ERDC TN-SWWRP-07-8. Vicksburg, MS: U.S. Army Engineer Research and Development Center. https://swwrp.usace.army.mil/

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