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Demonstration of GSSHA Hydrology at Goodwin Creek Experimental Watershed

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PURPOSE: The purpose of this System-Wide Water Resources (SWWRP) technical note is to describe the application of the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model at the Goodwin Creek Experimental Watershed (GCEW). The purpose of applying the model at this site was to confirm that the hydrologic portions of the code were working properly and were able to achieve accurate results. Application of GSSHA at this site also allows the current model to be compared and contrasted with the performance of previous versions of the model.

BACKGROUND: GSSHA is a physics-based, distributed-parameter, hydrology and transport code. As part of SWWRP, the GSSHA model has undergone a series of major improvements and additions including changes to the stream hydraulics, soil moisture accounting, and sediment transport portions of the model. While these additions and improvements enhance the model's ability to perform additional analysis, it is essential that the new methods and enhanced model be tested to assure that the model is functioning as desired and that the model can reproduce historic results at an equal or superior level to previous versions of GSSHA.

The GCEW, a small (21.2-km^2) agricultural watershed located in northeast Mississippi, has been the test bed for many features of the GSSHA model. The watershed is instrumented to measure rainfall, hydrometeorological variables, soil moisture, and stream water and sediment discharge (Figure 1).

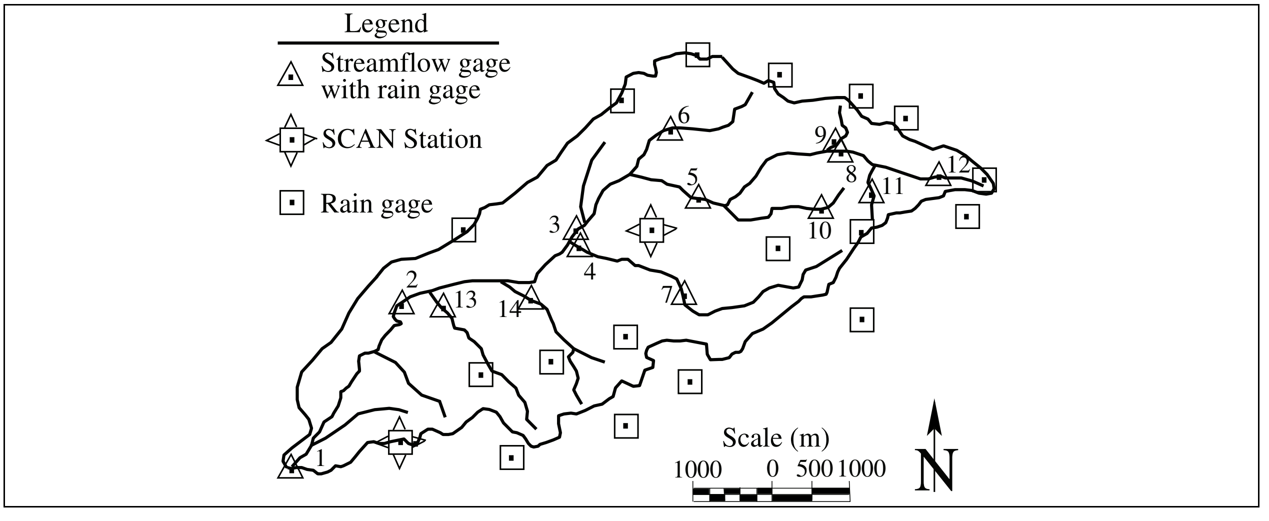

Figure 1. Location of sampling instruments at GCEW (after Downer and Ogden 2003).

Land use in the catchment consists of active cultivation (14 percent), pasture (44 percent), forest (27 percent), and, gullied land (15 percent) (Blackmarr 1995). Soil textures in the watershed consist of silt-loam (80 percent), clay-loam (19 percent), and sand (1 percent). The main channel of Goodwin Creek is incised 2-3 m and has an average slope of 0.004 (Bingner1996). The observed discharge measurements show that the base flow at the outlet of the catchment is typically less than 0.05 m^3 s^{-1}. Groundwater does not contribute significantly to runoff in the GCEW; streamflow is generated due to the Hortonian (infiltration excess) mechanism (Senarath et al. 2000).

MODEL APPLICATION: Topographic data for Goodwin Creek were obtained from a U.S. Geological Survey 30-m Digital Elevation Model (DEM). These data were spatially aggregated to 125-m resolution for use in GSSHA, resulting in a finite-difference overland flow grid with 1,357 cells. A stream network was developed using the nonorthogonal channels, as shown in Figure 1. The nonorthogonal channels allow a more accurate representation of the stream network, and should result in more representative values for channel roughness, length, and slope. Infiltration was simulated using the Green and Ampt with Redistribution (GAR) method (Ogden and Saghafian 1997) and soil moistures were simulated using the new soil moisture accounting method with two soil layers (Downer 2007).

Hydrologic Parameter Assignment. Hydrologic parameters were assigned based on soil textural classifications from U.S. Department of Agriculture-National Resource Conservation Service soil surveys, and satellite imagery and ground survey derived land use/ground cover from the National Sediment Laboratory (Blackmarr 1995). Not all soil textures occur within all land uses. Because of this, combining three soil textures, clay-loam, silt-loam, and sand, with five land use/ground cover classifications, soy/cotton production, pasture, forest, gully, and water, results in nine soil texture/land use (STLU) combinations used to assign and distribute all values of soil hydraulic, evapotranspiration (ET), and overland flow parameters. Initial estimates of soil hydraulic property values, namely: saturated hydraulic conductivity (K_s), Green and Ampt wetting front capillary head (S_f), effective porosity (e), residual water content (θ_r), wilting-point water content (θ_{wp}), and pore-size distribution index (λ). Model parameter values with unknown spatial distributions, such as the depth of the two soil layers, and channel roughness coefficients, were assumed spatially uniform over the entire catchment. Values of short-wave albedo, vegetation height, vegetation transmission coefficient, and canopy resistance were assigned based on land-use classification. Initial values for these and other parameters are available from a variety of published sources as provided in the GSSHA users manual (Downer and Ogden 2006).

Hydrologic Parameter Calibration. For the calibration, 18 parameters were adjusted: seven values of K_s, four values of overland roughness, n_{ov}, four values of overland retention depth, d_r, one value of channel roughness, n_{chan}, and the two soil layer depths. The model was calibrated using the Shuffled Complex Evolution (SCE) automated model calibration algorithm (Duan et al. 1992) to minimize the calibration error cost function. The cost function, a single numerical value of error, is a weighted sum of several streamflow statistics. The cost function for this study was the error from the event peaks discharge and discharge volume. Weight on the peaks was 60 percent; weight on the volumes was 40 percent. All significant events, those producing peak runoffs greater than 0.5 m^3 s^{-1} as described by Ogden et al. (2001) were weighted equally.

The initial calibration strategy was to follow previous studies and calibrate the model to the outlet discharge for the period of May 22, 1982, to July 2, 1982, and verify the model by extending the simulation until August 9, 1982. However, during the calibration the model was able to achieve an almost perfect fit to the observed data resulting in an inability to differentiate between parameter sets. To allow for a differentiation of model parameters, the calibration period was extended to include this entire split sample period, with the model being verified to data collected in 1999.

Hydrologic Calibration and Verification Results. For the nine events during the calibration period capable of producing significant runoff, the model was able to reproduce the peak discharge with a Mean Absolute Error (MAE) of 21 percent and the event volume with a MAE of 27 percent relative to the actual values. When applied to the 1999 verification period, the model was able to reproduce the peak discharge within 16 percent MAE and the event discharge volume within 19 percent MAE for the four significant events that occurred during the summer growing period. These results are comparable with previous versions of the model (Senarath et al. 2000; Downer and Ogden 2003). Observed and simulated discharge for the calibration period is shown in Figure 2.

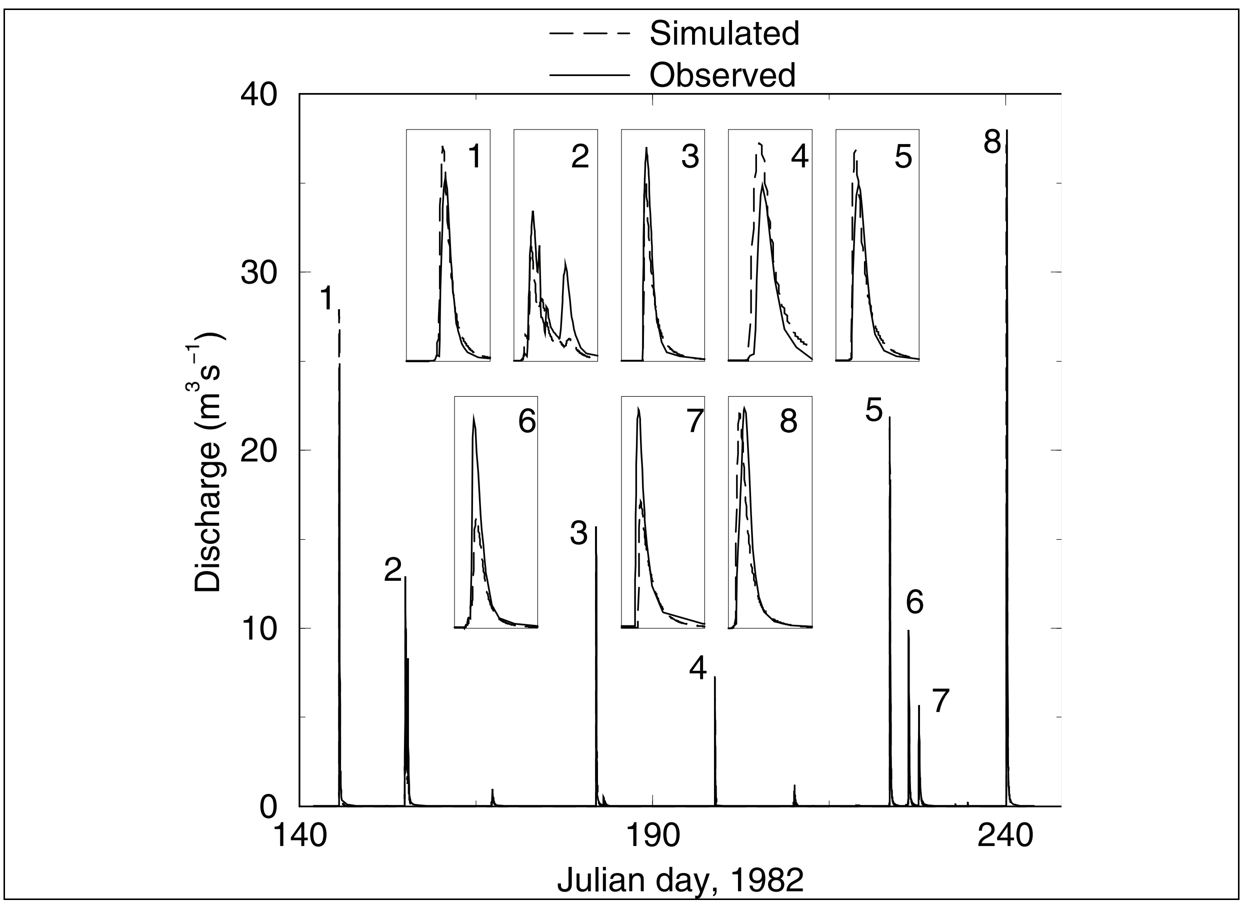

Figure 2. Observed and simulated discharges for the calibration period at GCEW outlet gage.

Parameter values. The parameter set determined for this study and the original parameter set determined by Senarath et al. (2000) are shown in Table 1.

Table 1
Calibrated Hydrologic Parameter Values

Parameter	Land Use	Soil Type	Senarath et al.	Current
Soil hydraulic conductivity (cm/hr)	gullied	silt loam	0.615	1.276
	pasture	clay loam	0.406	0.169
	cotton	clay loam	0.122	0.220
	forest	clay loam	0.341	0.162
	forest	silt loam	0.080	0.137
	cotton	silt loam	0.137	1.474
	pasture	silt loam	0.166	0.163
Overland retention depth (cm)	forest	all	1.132	0.465
	cotton	all	0.979	1.412
	pasture	all	1.018	1.214
	gullied land	all	1.653	1.683
Overland roughness	forest	all	0.198	0.180
	cotton	all	0.258	0.375
	pasture	all	0.235	0.253
	gullied	all	0.323	0.435
Soil layer depth (m)	all	all	0.58	0.627
Top layer depth (m)	all	all	na	0.201
Channel roughness	na	na	0.027	0.035

Overall, the parameter sets are similar. However, there are a few important changes. The soil hydraulic conductivities for silt loams for the current model seem to be in better proportion to the values for clay loams. For the previous model, values of K_s for silt loam were generally higher than those for clay loam, which was a criticism of the previous effort. In addition, the stream roughness value for the current effort was significantly higher than the previous version, likely a result of the new channel routing, which more accurately portrays stream lengths and slopes, and is more representative of actual roughness values in the stream. A comparison of the current nonorthogonal streams and the previous orthogonal streams are shown in Figure 3.

Water balance. While the parameter values and the observed streamflow values are similar between the previous and improved model formulations, the water balances are not. Table 2 shows the water balance components for the old and new formulations, together with the results of the GSSHA model used to simulate GCEW using the Richards equation Downer and Ogden (2003). The actual total discharge for the period is $1.71\text{x}10^6$ m^3, for a difference of 0.39 $\text{x}10^6$ m^3 between actual and observed. This amount is equal to the estimated baseflow of $0.39\text{x}10^6$ m^3, such that the surface runoff from both the current and Senarath et al. (2000) efforts is equal to the observed.

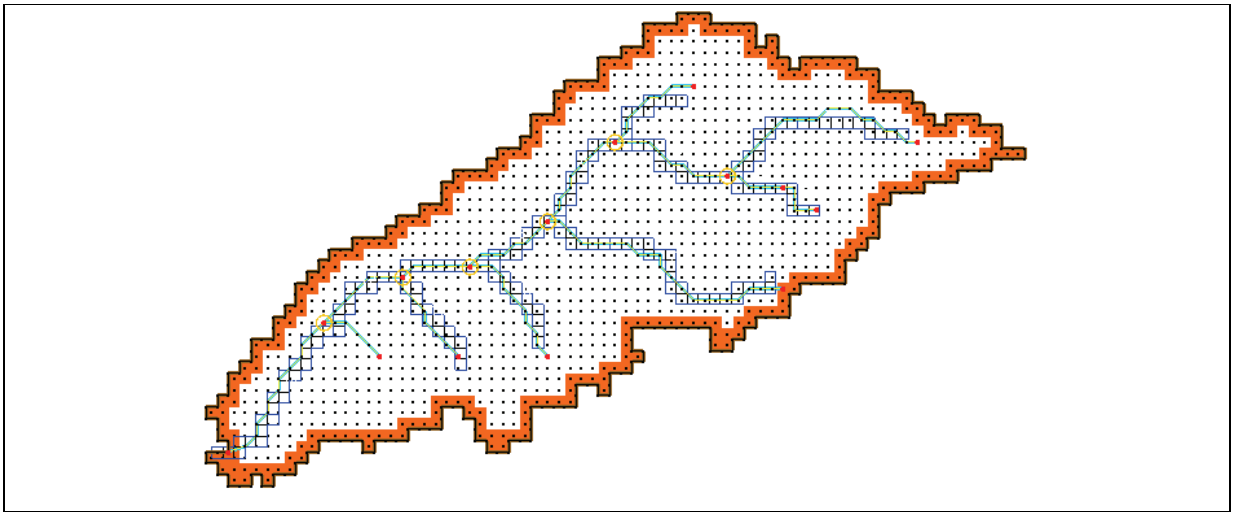

Figure 3. Comparison of orthogonal (squares) and nonorthogonal (lines) streams for GCEW.

As shown in the table, the amount of ET from the bucket approach used in the Senarath et al. (2000) is significantly higher than the ET from either the current two-layer model, or the previous Richards equation (RE) model (Downer and Ogden 2003). Also, for the bucket method, the amount of water needed to be added to the system to satisfy this ET demand and maintain the water balance in the 0.58-m soil column is 5 M m^3, which is an implied demand on the groundwater system (implied because there is no flux through the bottom of the bucket). This can occur because soil moisture in the bucket at the end of rainfall events is set based on values from the GAR infiltration model, regardless of the amount of water that may actually be available. So while the bucket model previously employed resulted in accurate predictions of discharge and likely surface soil moisture, it also produced less realistic values of ET, and did not maintain a soil water balance. In light of this, the two-layer model is a much more desirable solution because it produces similar discharge results, maintains mass balance in the soil column, and more closely mimics the ET results from the RE solution, without the addition of significant simulation time.

Table 2
GSSHA Water Balance 1982 Calibration/Verification Period

Water Balance Component	Current Volume (10^6 m^3)	Senarath Volume (10^6 m^3)	Richards Equation Volume (10^6 m^3)
Rainfall	9.24	9.24	9.24
Infiltration	7.84	7.83	7.50
Discharge	1.32	1.34	1.62
Evapotranspiration	8.38	13.45	9.19
Groundwater recharge	0.45	-5.07	2.68

Soil moisture. For the 1999 verification period, soil moistures were measured at two sites in the watershed, marked as the SCAN stations in Figure 1. At each of these sites, soil moistures were collected on an hourly basis at 5 cm, 10 cm, 20 cm, 51 cm, and 102 cm. GSSHA has the capability to output soil moisture at each grid cell, so that soil moisture for each of the two layers can be output for the grid cells where the SCAN stations are located. Downer and Ogden (2003) used these same data to demonstrate that the GSSHA model with the Richards equation solution for infiltration and ET could reproduce the soil moistures observed at these sites. The two-layer model does not allow division of the soil column into layers that represent the different SCAN measurement depths. For the calibrated two-layer model with a 21-cm top soil layer depth and 62-cm total soil layer depth, the 5-, 10-, and 20-cm measuring points all fall within layer 1; the 51-cm measuring point falls within layer 2, and the 102-cm measuring point falls outside of the modeled soil column. Comparisons for the two measuring points and the two soil layers are shown in Figures 4 and 5 for the pasture and forest sites, respectively. Observed data from the 5-, 10-, and 20-cm depths are shown with the model results from the top layer. For the second layer, observed data from the 51-cm depth site are graphed along with the model results.

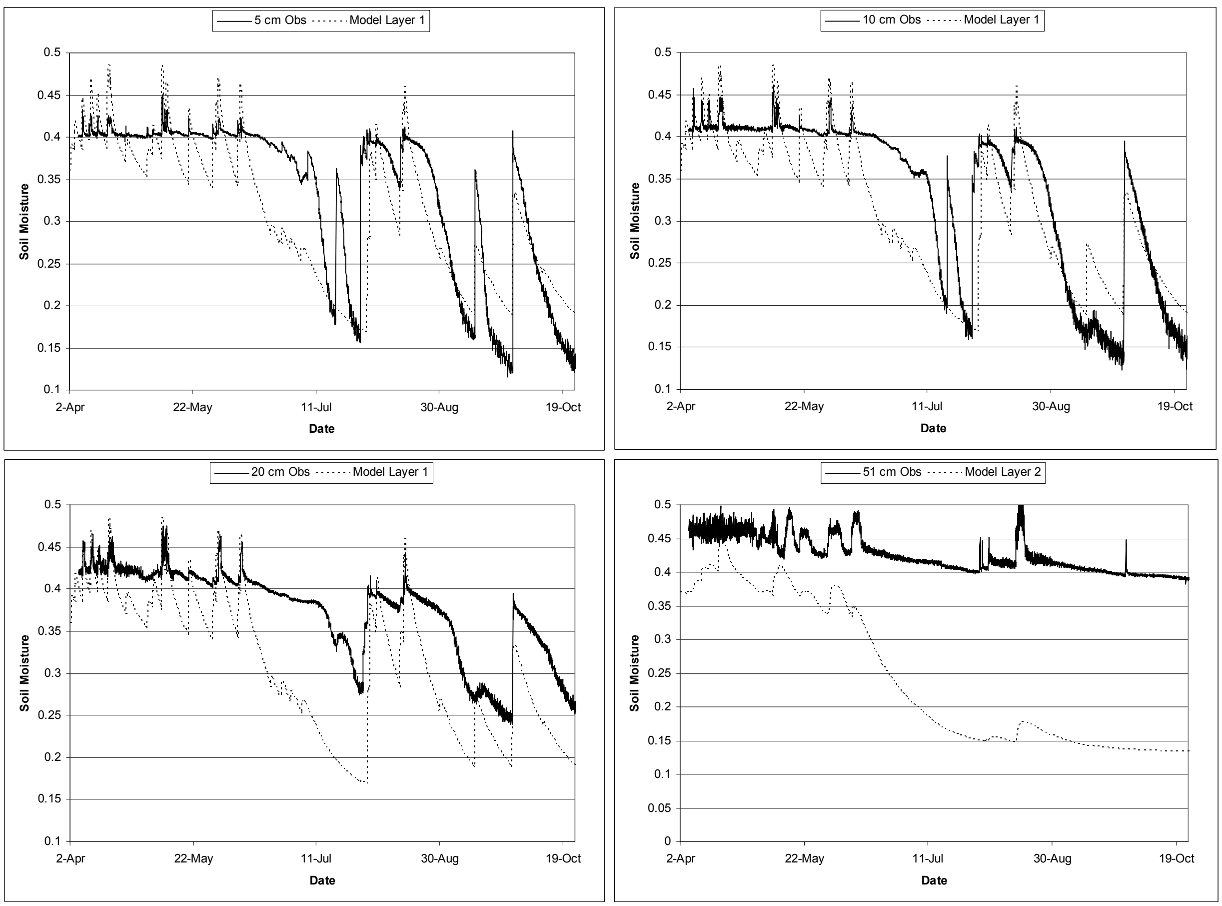

Figure 4. Comparison of observed soil moistures to model at SCAN station 2024, pasture.

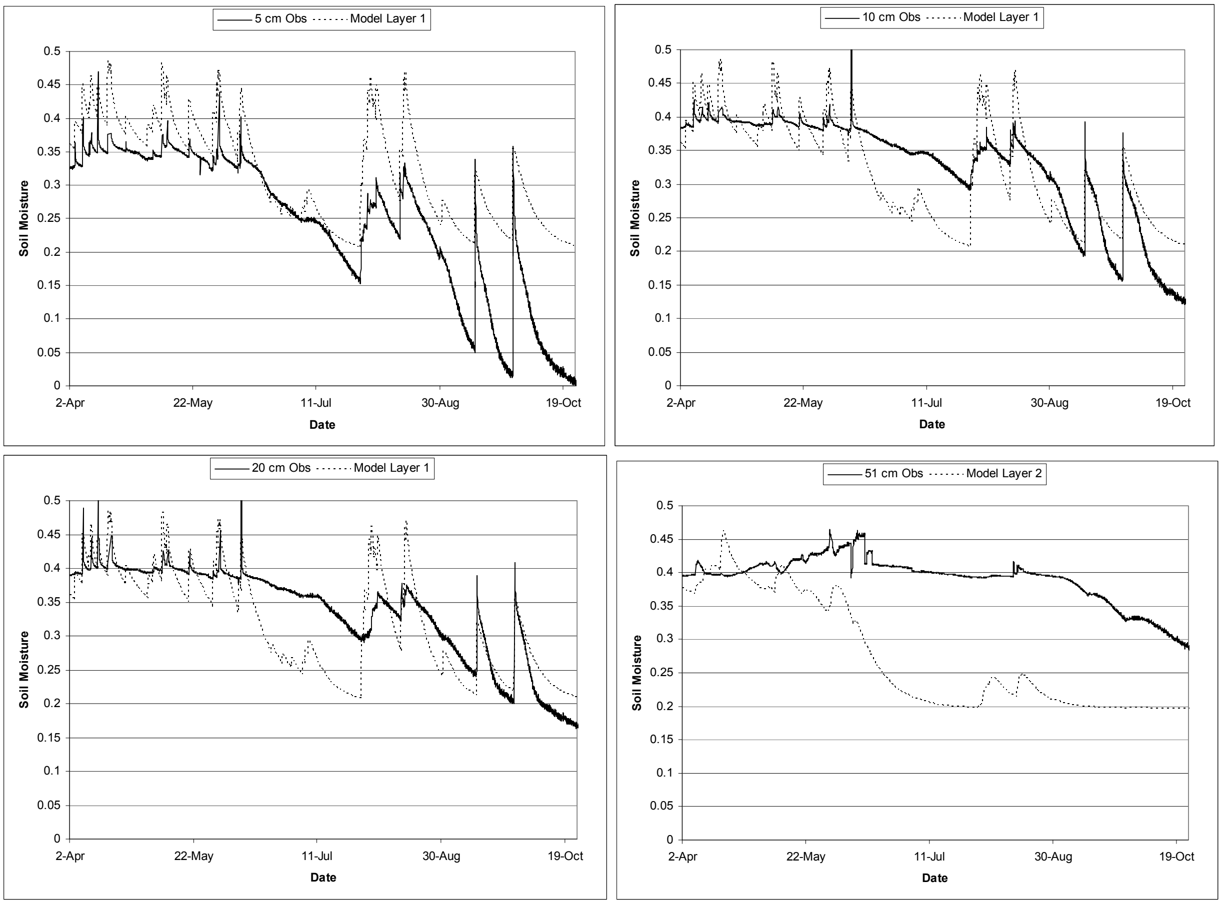

Figure 5. Comparison of observed soil moistures to model at SCAN station 2025, forest.

As seen in the figures, the two-layer model is capable of representing the soil moisture in the near surface layer, layer 1, corresponding to gages at the 5- 10-, and 20-cm depths. In general, the modeled soil moistures fall within the range of measured values at each site. As expected, as the modeled soil moistures are averaged over a larger depth, the modeled values tend to show less temporal variability than observed at the shallowest measured depth, 5 cm, and more temporal variability than observed at the deepest measurement point in the top layer, 20 cm. Differences in the maximum value of soil moisture can be explained by the fact that the porosities in the model are for a general soil texture only, and not tuned specifically to the measurement sites. The general trends in soil moisture are well simulated particularly during wetting. If the hourly soil moistures for the 5-cm, 10-cm, and 20-cm depths are averaged together, the Root Mean Square Error (RMSE) for the layer 1 soil moistures is 0.06 at both sites, which represents an error of only 12 percent of the soil porosity. These statistics compare well with previous estimates of point soil moisture generated by GSSHA using the Richards equation to estimate point soil moistures at each of the measurement points (Downer and Ogden 2003). While the two-layer model cannot simulate the soil profile to such detail, the model is producing comparable results for the top 20 cm taken as a whole.

As was the case with the previous study where the Richards equation was used to simulate soil moistures, the model significantly underpredicts the soil moisture at the deeper level. As was discussed in Downer and Ogden (2003), there is thought to be an impeding layer in the GCEW soils that prevents drainage of the soils as predicted. Still, the results are similar to those predicted by the Richards equation for the same locations, which is good performance for a much less computationally intensive method. In addition, the deep layer soil moistures are of little importance to modeling surface hydrology and sediments, as only the top layer soil moisture is used in infiltration calculations, and the top layer soil moisture is well represented by the model.

SUMMARY: The current version of GSSHA, version BlueMarlin20c, was applied at the GCEW to test the hydrologic performance of the model. The model was compared to observed flows and soil moistures as well as to results from previous studies published in peer review journals. The current version of GSSHA was able to satisfactorily simulate the hydrologic data at the GCEW. The model was also able to match or exceed the ability of previous versions to simulate discharge and was able to predict the average soil moisture in the top 20 cm of the soil column with similar skill as previous models that employed the Richards equation. In addition, the improvements to the model result in a better representation of the physical processes occurring at GCEW, as demonstrated by more realistic parameter values, and mass conservation of water and sediments.

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 GSSHA hydrologic 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, Steven.L.Ashby@usace.army.mil. This technical note should be cited as follows:

> Downer, C. W. 2008. *Demonstration of GSSHA hydrology at the Goodwin Creek Experimental Watershed.* ERDC TN-SWWRP-08-3, Vicksburg, MS: U.S. Army Engineer Research and Development Center. https://swwrp.usace.army.mil/

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