COMPARISON OF GREEN-AMPT AND CURVE NUMBER METHODS ON GOODWIN CREEK WATERSHED USING SWAT

K. W. King, J. G. Arnold, R. L. Bingner

ABSTRACT. *Two methods of simulating excess rainfall were compared on a large basin with multiple rain gages. The SCS daily curve number method (CN) was compared with the Green-Ampt Mein-Larson (GAML) method on the Goodwin Creek Watershed (GCW). GCW is 21.3 km^2 in area and has 32 rain gages located within and surrounding the watershed. The model used was the Soil and Water Assessment Tool (SWAT). SWAT is a comprehensive watershed scale model developed to simulate management impacts on water, sediment, and chemical yields for ungaged basins. SWAT was modified to accept breakpoint rainfall data and route streamflow on a sub-daily time-step. Eight years of measured climatic data were used in the study. Simulated and measured streamflow at the watershed outlet were evaluated. Results were not calibrated. Monthly model efficiencies were 0.84 for CN and 0.69 for GAML. The use of a sub-daily routing technique allowed for very good correlation between measured and simulated hydrographs. Generally, CN undersimulated surface runoff while GAML had no pattern associated with events. Results suggest that no significant advantage was gained by using breakpoint rainfall and sub-daily time-steps when simulating the large basin used in this study.*

Keywords. *Rainfall, Runoff, Watershed, Infiltration, Modeling.*

Selection of a rainfall-runoff model is a compromise between model complexity and available input data. While more complex models should better represent the physical processes, the assumption that they lead to more reliable results has been questioned (Loague and Freeze, 1985). They have shown that simpler, less data-intensive models provided as good or better simulations than physically based models. An empirical model is a representation of data and has no real theoretical basis. A physically based model is one that has a theoretical basis and whose parameters and variables are measurable in the field (Beven, 1983). In reality, many empirical relationships are used for parameter estimation by the "physically based" models (Wilcox et al., 1990). The SCS runoff equation is basically an empirical model which came into common use in the 1950s. It is the product of more than 20 years of studies involving rainfall runoff relationships from small rural watersheds. The model was developed to provide a consistent basis for estimating the amounts of runoff under varying land use and soil types (Rallison and Miller, 1981). No other rainfall-runoff model has been used as successfully or as often on ungaged rangeland catchments as the CN (Graf, 1988). A major limitation of the curve number method is that rainfall intensity and duration are not considered, only total rainfall volume.

Time-based physical models such as Green-Ampt are thought to better mimic the impacts of land use on runoff, because infiltration parameters can be directly related to catchment characteristics (Wilcox et al., 1990). However, such models require disaggregated daily precipitation data which are difficult to obtain. Even though the Green-Ampt equation has a physical basis, much may be lost or diluted by the regression equations needed to parameterize the model (Wilcox et al., 1990). In a study of 585 storm events on 36 watersheds in six physiographic provinces of the Central and Eastern U.S., Bales and Betson (1981) concluded that the curve number appears to be a good numeric index of land use and is potentially a useful basin characteristic for use in hydrologic model regionalization. Studies by Wilcox et al. (1990) on six small catchments in Idaho, Arizona, Texas, Oklahoma, and Nebraska showed that the CN gave similar results to those obtained by the Green-Ampt model. More recent efforts have focussed on the relationships of curve numbers to Green-Ampt hydraulic conductivity (Risse et al., 1995; Zhang et al., 1995; Nearing et al., 1996). So while the CN is conceptually simple, it is regarded as an adequate procedure to use in estimates of runoff.

The major use and availability of Green-Ampt excess rainfall method in agricultural hydrologic models has been limited to event based models (Loague and Freeze, 1985), specific application models (Wilcox et al., 1990; James et al., 1992), and field-scale models (Williams, 1995; Lane and Nearing, 1989). The availability of Green-Ampt in a continuous-time agricultural watershed scale model has also been limited. The Water Erosion Prediction Project (WEPP) model (Lane and Nearing, 1989) has a watershed version that utilizes Green-Ampt, however WEPP was not designed for simulating large basins. KINEROS (Kinematic Runoff and Erosion Model) (Smith et al., 1995) is also a watershed scale model that uses the Smith-Parlange (1978) infiltration model which is very similar to

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Green-Ampt. The primary objective of this study was to apply and evaluate CN and Green-Ampt methods on the 21.3 km^2 Goodwin Creek Watershed using the basin scale SWAT (Soil and Water Assessment Tool) model (Arnold et al., 1998).

METHODS AND MATERIALS

SIMULATION MODEL

Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) is a deterministic continuous-time watershed scale model. SWAT was designed to assess the effect of long-term management decisions on ungaged basins. SWAT simulates biomass production, plant growth, and evapotranspiration (ET), and has the capability to deal with fertilization and management strategies on a daily time step. The SWAT/GIS (Geographic Information System) integrated system can address the effect of management scenarios on vegetation, crops, and hydrology. SWAT provides a reach-routing structure for simulating large basins (Arnold, 1992; Rosenthal et al., 1993). Water, sediment, and associated chemicals are routed through reaches and impoundments.

The hydrologic balance of SWAT is driven by several components. Precipitation, infiltration, surface runoff, lateral flow in the soil profile, ET, percolation from the soil profile, and transmission losses all serve as forces driving the hydrologic cycle. The system simulated by SWAT consists of four control volumes that include the: (1) surface, (2) soil profile or root zone, (3) shallow aquifer, and (4) deep aquifer. The percolate from the soil profile is assumed to recharge the shallow aquifer. Once the water percolates to the deep aquifer it is lost from the simulated system and cannot return. The model has been validated on several watersheds across the U.S. (Arnold et al., 1993; Srinivasan et al., 1993; Arnold and Allen, 1996).

EXPERIMENTAL DATA

The Goodwin Creek Watershed (GCW) is a 21.3 km^2 experimental watershed situated in north central Mississippi (fig. 1). Soils are generally silt loams with slopes ranging from 0 to 45% (table 1). Surface elevation varies from about 71 to 128 m above sea level with an average channel slope of 0.004. Land use across GCW can be summarized in four categories. The dominant land use is pasture (table 2). For this study the basin was divided into 48 subbasins (fig. 2). Soils layers were produced from the SCS soil survey maps of the area. Relational soil physical properties include texture, bulk density, available water capacity, saturated conductivity, soil albedo, and organic carbon. The condition II curve number was assigned to each subbasin based on the hydrologic soil group and land use (USDA-SCS, 1972). Land use was produced from a 1987 Landsat-5 thematic mapping image of the watershed. Curve numbers for the 48 subbasins ranged from a minimum of 55 to a maximum of 89 with a mean of 76 and a median of 79.

GCW is fully instrumented with 14 supercritical flow flumes and 32 rain gages located in and around the watershed (fig. 1). The 14 flumes are equipped to continuously monitor runoff and sediment yield. The 32 recording rain gages continuously record breakpoint rainfall data. Breakpoints are generally on the order of 5 to 15 min, however occurrences of 1 min to 2 h are not uncommon. Precipitation at GCW is generally greatest during the winter months (table 3).

Breakpoint rainfall data collected from 1982 to 1989 was used as input. Measured streamflow was filtered for baseflow using a method described by Arnold et al. (1995). Baseflow was estimated at 10% of total flow for the eight years of measured data. The filtering technique resulted in similar results reported by Bingner (1996) for the same watershed.

EXPERIMENTAL METHODS

The hydrologic component in SWAT was previously based solely on the SCS curve number method (USDA-SCS, 1972). The SCS curve number method is a rainfall-runoff model that was designed for computing excess rainfall (direct runoff). This method assumes an initial abstraction before ponding that is related to curve number. Curve numbers in SWAT were determined from USDA-*National Engineering Handbook* (USDA-SCS, 1972). The curve number method in SWAT relates runoff to soil type, land use, and management.

On the other hand, Green-Ampt (1911) is an infiltration equation. It assumes a homogeneous soil profile and antecedent soil moisture, total saturation above the wetting front, and a sharp break at the wetting front. Mein and Larson (1973) developed a methodology for determining ponding time with infiltration based on Green-Ampt (1911). The Green-Ampt Mein-Larson (GAML) excess rainfall method was incorporated and coupled with a user-supplied sub-daily routing step as an alternative option for determining excess rainfall and routing the excess to the outlet of the basin. The GAML infiltration rate can be expressed as:

$$f(t) = K\left[\frac{\psi\Delta\theta}{F(t)} + 1\right] \qquad (1)$$

where f(t) represents the infiltration rate (mm·h^{-1}), K is the hydraulic conductivity (mm·h^{-1}), ψ is the wetting front soil suction head (mm), $\Delta\theta$ is the change in moisture content, F(t) is the cumulative infiltration (mm), and t is time (h). The cumulative infiltration can be represented by:

$$F(t) = Kt + \psi\Delta\theta \ln\left[1 + \frac{F(t)}{\psi\Delta\theta}\right] \qquad (2)$$

where all variables have been previously defined. Soil properties were taken from the dominant soil type estimated by STATSGO map layers for each subbasin. Hydraulic conductivity was assumed equivalent to 50% saturated conductivity as suggested by Bouwer (1966). Wetting front suction head, ψ, was adapted from a regression analysis on several soils presented by Rawls and Brakensiek (1985). They expressed ψ as a function of porosity (POR), percent sand (PS) and percent clay (PC) where:

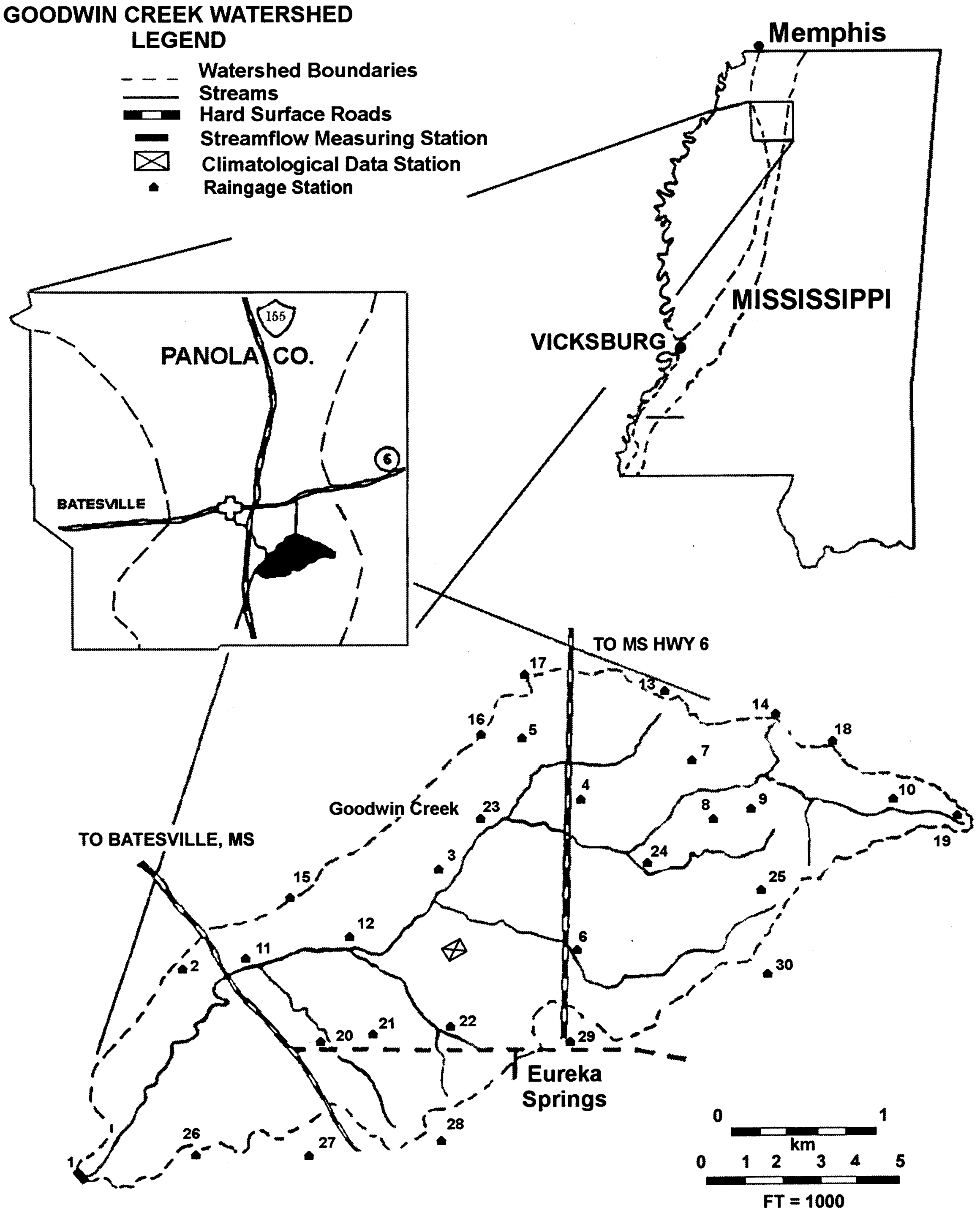

Figure 1–Location of Goodwin Creek Watershed (GCW) with stream gaging stations and rain gages (source: Bingner, 1996).

$$\psi = \exp(6.5309 - 7.3256\ \mathrm{POR} + 0.001583\ \mathrm{PC}^2 + 3.809479\ \mathrm{POR}^2 + 0.000344\ \mathrm{PS\ PC} - 0.049837\ \mathrm{PS\ POR} + 0.001608\ \mathrm{PS}^2\ \mathrm{POR}^2 + 0.001602\ \mathrm{PC}^2\ \mathrm{POR}^2 - 0.000014\ \mathrm{PS}^2\ \mathrm{PC} - 0.00348\ \mathrm{PC}^2\ \mathrm{POR} - 0.0008\ \mathrm{PS}^2\ \mathrm{POR}) \qquad (3)$$

When rainfall occurs, equation 2 is solved iteratively until cumulative infiltration converges. Once converged, final cumulative infiltration is substituted in equation 1 and infiltration rate is solved. The time step at which equation 2 is solved is variable and equivalent to the time step associated with the breakpoint interval. If infiltration rate is greater than rainfall intensity no excess rainfall is calculated (all rainfall in that time interval is infiltrated) and the model proceeds to the next time interval. If rainfall intensity exceeds the infiltration rate, rainfall in excess of

Table 1. Soil mapping units for Goodwin Creek Watershed

Soil Mapping Unit	Dominant Texture	NRCS Hydrologic Soil Group	Saturated Conductivity (mm h^{-1})	Extent of Unit (km^2)	Total Area (%)
Calloway 0 to 5% slope	Silt	C	0.6	0.4	2.4
Collins 0 to 2% slope	Silt	C	3.3	3.6	16.4
Falaya 0 to 2% slope	Silt	D	3.8	1.4	6.4
Grenada 0 to 12% slope	Silt	C	1.6	1.1	5.6
Gullied 8 to 40% slope	Sandy loam	B	5.0	3.3	16.1
Loring 0 to 20% slope	Silt	C	1.8	10.3	46.9
Memphis 0 to 45% slope	Silt	B	1.5	1.2	6.2

Table 2. Landuse mapping units for Goodwin Creek Watershed

Land Use	Extent of Unit (km^2)	Total Area (%)
Pasture	13.1	60.6
Forest	5.4	25.5
Cotton	2.7	13.5
Waterbodies	0.1	0.4

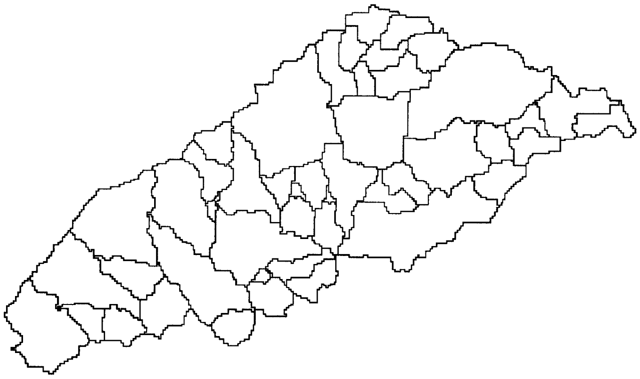

Figure 2–Discretization for 48 sub-basins at Goodwin Creek Watershed.

infiltration rate is assumed to runoff. The SWAT implementation of GAML assumes a small breakpoint rainfall interval. Thus, ponding during an interval is assumed negligible.

A canopy storage procedure was also added to account for interception losses. A user identified amount of canopy storage per vegetative cover is taken into account when precipitation occurs. Evaporation from the vegetation is estimated before soil evaporative losses.

The sub-daily routing technique was adapted from a variable storage coefficient method described by Williams (1969). This method is an intermediate solution between the simple storage methods and more complicated analytical techniques. Travel time is allowed to vary with stage and a corresponding coefficient is calculated to estimate outflow.

Table 3. Precipitation characteristics for eight-year period of record at GWC

Month	Eight-yr Average (mm)	Average Number of Events	Average Amount per Event (mm)	Maximum Event Amount (mm)	Average Duration per Event (min)
Jan	93.4	7.6	12.3	72.6	470
Feb	123.4	9.3	13.3	73.6	562
Mar	100.1	7.4	13.5	68.1	465
Apr	121.6	8.0	15.2	67.6	433
May	148.8	8.6	17.3	115.3	452
Jun	118.5	8.8	13.5	110.7	285
Jul	98.7	7.5	13.2	116.6	346
Aug	87.6	5.9	14.8	80.3	227
Sep	83.0	5.3	15.7	137.4	431
Oct	113.2	6.5	17.4	101.0	476
Nov	150.9	8.8	17.1	98.0	431
Dec	170.8	9.6	17.8	103.9	489

RESULTS AND DISCUSSION

ANNUAL COMPARISON

For the eight-year period of study, weighted mean annual rainfall for GCW was 1406 mm with measured runoff averaging 34% or 475 mm (table 4). Simulated runoff for individual years using CN was within 48% for all years and generally within 35% of observed. Simulated runoff with GAML was within 30% for all years and generally within 20% of measured surface runoff. Similar findings with respect to annual runoff have been documented by Wilcox et al. (1990).

In general, GAML better simulated total annual surface runoff when compared with CN (table 4). CN always undersimulated annual surface runoff. Neither model was able to simulate the large surface runoff recorded in 1982, 1983, and 1989. Model efficiencies (Nash and Sutcliffe, 1970) for annual simulations were 0.55 for CN and 0.81 for GAML. The low efficiency value for CN is a result of limited annual data points and an undersimulation using CN.

MONTHLY COMPARISON

For the eight-year period of record, monthly runoff was simulated with 84% efficiency using CN and 69% using GAML. Monthly results using CN were much better than annual results. Unlike Bingner's (1995) over estimated CN predictions, the CN results presented within were generally under simulated but had a much tighter fit. (fig. 3).

Table 4. Annual comparisons of Green-Ampt and CN simulated runoff at outlet of GCW

Year	Precipitation (mm)	Runoff* (mm)	Green-Ampt (mm)	Curve No. (mm)
1982	1694	660	580	417
1983	1659	778	584	561
1984	1457	496	485	420
1985	1209	278	326	202
1986	1236	288	372	183
1987	1162	286	322	255
1988	1055	255	241	134
1989	1781	762	646	616
Mean	1406	475	445	349

* Runoff has been adjusted for an estimated 10% baseflow.

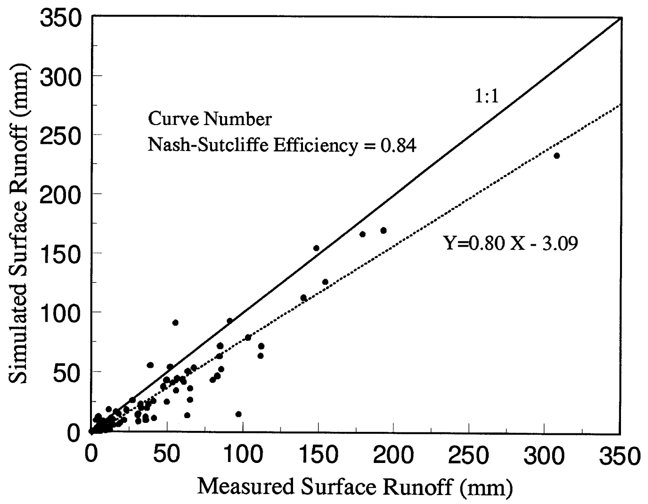

Figure 3–Simulated versus measured monthly runoff at the outlet of GCW using non-calibrated curve number methodology for eight-year period from 1982-1989.

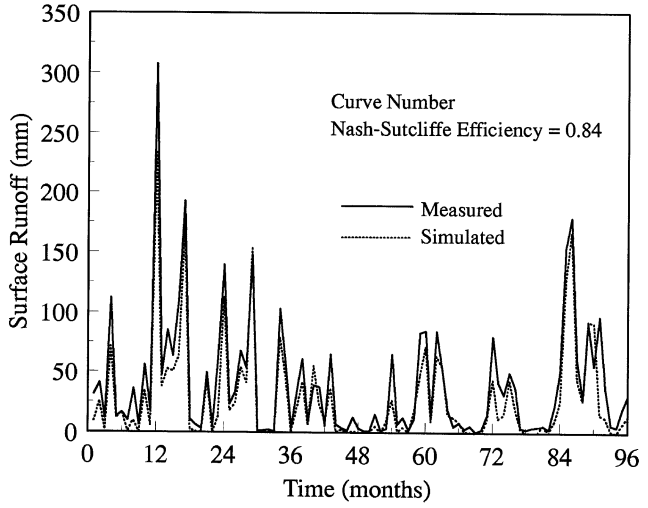

Figure 4–Observed and CN simulated monthly surface runoff time series at outlet of GCW for 1982-1989.

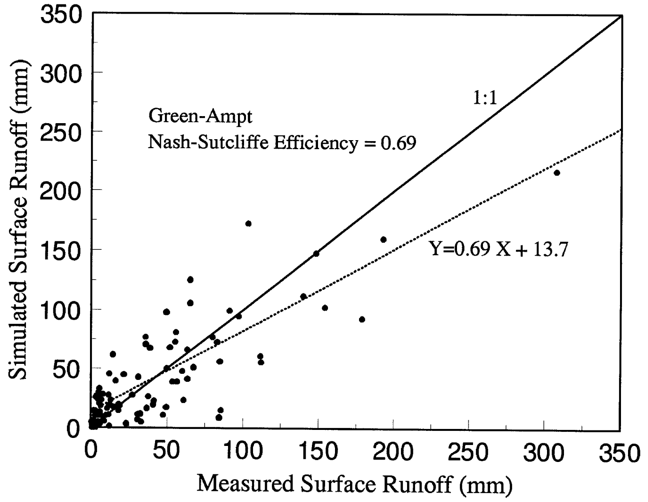

Figure 5–Simulated versus measured monthly runoff at the outlet of GCW using non-calibrated GAML methodology for eight-year period from 1982-1989.

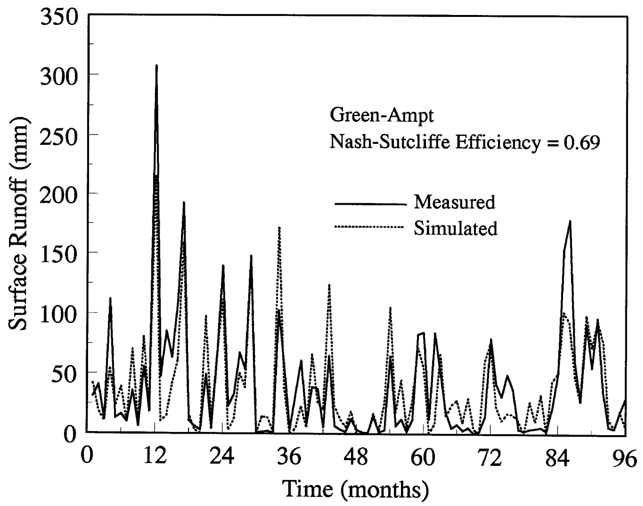

Figure 6–Observed and GAML simulated monthly surface runoff time series at outlet of GCW for 1982-1989.

Bingner's (1995) selection of CN was essentially calibrated where the CNs in this study were defaults from the SWAT/GIS database and not adjusted or calibrated. The underestimation of runoff using CN could be improved with a calibration procedure. Seasonal trends were present, but dampened (fig. 4). Unlike CN, GAML simulations showed considerable scatter (fig. 5). An inspection of GAML simulated and observed time series (fig. 6) indicates obvious seasonal trends in simulated surface runoff. GAML generally under-simulates in the winter and spring while over-simulating in the summer and fall. The use of a canopy storage function did not seem to alleviate the trend. This suggests possible limitations in soil moisture accounting with GAML that may be masked by the initial abstraction estimate when using CN. This could also be a reflection of errors in estimating effective hydraulic conductivity values (table 1) but since the results are well scattered about the 1:1 line this is doubtful. Perhaps using other methods of estimating hydraulic conductivities such as those of Risse et al. (1994) and Zhang et al. (1995a,b) may improve the fit about the 1:1 line. It appears that the depletion of soil water during the winter and spring may have occurred too rapidly while not fast enough in the summer and fall.

DAILY COMPARISON

Efficiencies for daily simulations were 0.53 for GAML and 0.43 for CN. Calendar year 1984 will be used as an in depth example of daily simulations. The daily application of GAML excess rainfall method was consistent with the monthly GAML performance. Model efficiencies were calculated at 0.63 for GAML and 0.78 for CN during calendar year 1984. Both models were able to simulate surface runoff at the outlet while preserving the first and second moments of distribution (table 5). Both models exhibited similar scatter patterns about a 1:1 line (fig. 7). Similar findings were reported by James et al. (1992) on an event basis.

A portion of May 1984 was selected to evaluate the sub-daily routing technique. During this period, three excess rainfall events (28.4, 37.5, and 70.3 mm) were simulated. Each event resulted in a well defined hydrograph. Using a

Table 5. Statistical parameters from measured versus simulated surface runoff for 1984 daily simulation using both Green-Ampt and curve number methodologies

	Measured	Green-Ampt	Curve No.
Mean (mm)	1.36	1.33	1.15
Standard deviation (mm)	5.20	5.73	5.74
Model efficiency		0.63	0.78
Slope, b*		0.92	1.00
Intercept, a*		0.08	–0.21
r^2		0.70	0.82

* Coefficients a and b follow from the expression Y = a + bX, where X is the measured (independent variable), and Y is the simulated (dependent variable): r^2 is the coefficient of determination.

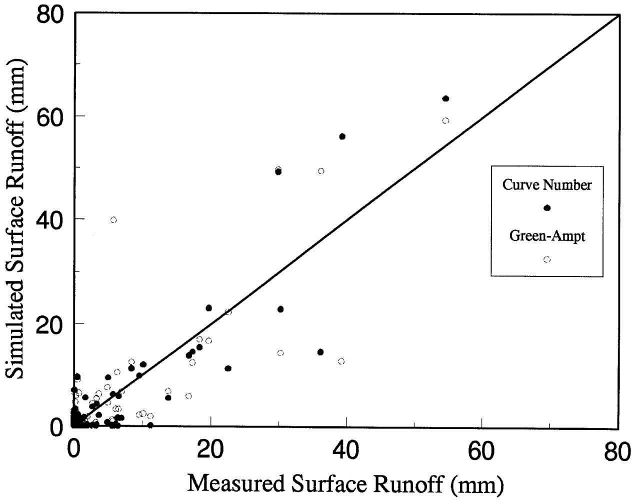

Figure 7–Simulated versus measured daily runoff for 1984 at outlet of GCW using both GAML and CN.

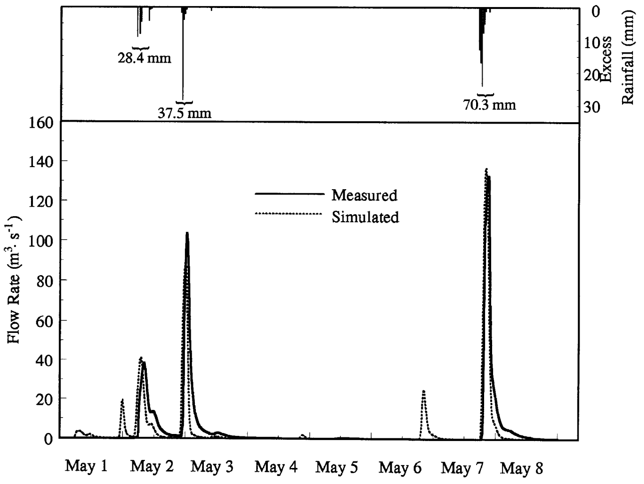

Figure 8–Measured and simulated hydrograph at outlet of GCW for 1-8 May 1984. Simulated hydrograph was obtained using a 20-min time step for routing.

20-min time step for routing allowed for preservation of the surface runoff hydrograph (fig. 8). The small simulated spikes in the hydrograph at the end of 1 May and 6 May were due to simulated excess rainfall on an upland catchment which was not measured. The recession time on all hydrographs during the 1-8 May period were somewhat rapid. Increasing the time-step may help retard the recession, however the peak runoff simulation will suffer.

ADVANTAGES AND DISADVANTAGES

When modeling hydrologic systems of large areas, one must consider the overall goal in selecting an excess rainfall procedure. As drainage area increases, stream flow peaks tend to smooth out and the use of GAML becomes ineffective. However, in this particular watershed, stream peaks respond quickly to excess rainfall and thus using GAML coupled with a sub-daily routing step becomes beneficial in estimating direct runoff hydrographs. As streams get larger, they do not respond as rapidly and CN should produce satisfactory results. A review of times of concentration and breakpoint rainfall data availability for the watershed should dictate the runoff procedure to use.

CN provides a simple, yet robust, means of estimating excess rainfall. The major limitation with CN is the inability to account for rainfall intensity/duration. GAML considers rainfall intensity/duration and is advantageous when flood routing and peak discharges are needed. The parameters required by GAML are physically measurable while CN is empirical. The drawbacks of GAML include the need for breakpoint rainfall data and the intensive and time consuming soil tests required for parameterization.

SUMMARY AND CONCLUSIONS

The GAML excess rainfall method was added to SWAT along with a sub-daily routing technique in an effort to facilitate the need for alternative excess rainfall methods in agricultural based watershed scale modeling. The time-step for routing is user defined. Non-calibrated GAML and CN models were evaluated on the 21.3 km^2 Goodwin Creek Watershed. Mean annual and monthly surface runoff was compared to observed values at the outlet of the watershed for an eight-year period. One selected year and series of events were also evaluated for daily and subdaily runoff.

General performance of GAML resulted in simulations being closer to the means but with more scatter while CN simulations had less scatter but were consistently under-simulated. CN model efficiency increased from daily to monthly simulations as expected but decreased from monthly to yearly simulations (fig. 9). This was attributed to a limited number of annual data points and consistent under simulation on a monthly basis. The monthly under simulation is compounded when aggregated to a yearly scale resulting in a low efficiency. GAML efficiency consistently increased with an aggregation in time scale. It was expected that on a daily application, GAML would perform better due to intensity and duration considerations. An evaluation of monthly trends suggests that GAML was limited in accounting for seasonal variations. Generally GAML over-simulated in the summer and fall while under-simulating in the winter and spring (fig. 6). This may be a limitation in model soil moisture accounting that is masked by initial abstraction estimates using CN or limitations in estimating effective hydraulic conductivities that could possibly be improved upon with another estimation method. As a result of over-simulating summer and fall amounts, GAML annual simulated amounts were simulated with a greater efficiency than with CN.

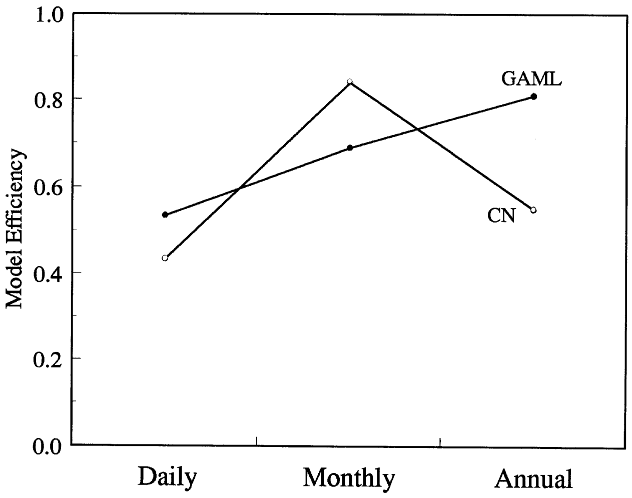

Figure 9–Relationship between model efficiency and simulation time scales for CN and GAML.

The primary conclusions can be summarized as:

1. GAML methodology was successfully incorporated into SWAT.
2. A sub-daily routing technique was also successfully included in SWAT.
3. Non-calibrated GAML and CN methods gave reasonable results for annual, monthly, and daily simulation times.
4. SWAT with GAML appeared to have more limitations in accounting for seasonal variability than did CN.
5. No significant advantage was obtained by using one method over the other for this particular application.

Overall, SWAT simulated annual, monthly, and daily surface runoff well using both GAML and CN excess rainfall methods. Possible enhancements in seasonal soil moisture accounting and a calibration procedure could have improved the simulation results.

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