HYDROLOGIC RESPONSE OF A SMALL WATERSHED MODEL TO GENERATED PRECIPITATION

R. D. Harmel, C. W. Richardson, K. W. King

ABSTRACT. *Watershed models such as SWAT (Soil and Water Assessment Tool) simulate water quality impacts of land and water resource management alternatives. To simulate these impacts, long-term daily rainfall data are necessary. In the absence of measured rainfall data, watershed models use weather generators to simulate rainfall events. The objective of this study is to examine several daily precipitation generators in terms of the hydrologic response of SWAT. SWAT is generally applied to large river basins but has been validated and applied on the small watershed scale as well. Daily rainfall inputs included a 60-year measured rainfall record from 1939 to 1998 for Riesel, Texas, in the heart of the Blackland Prairie, and data generated with the precipitation components of three weather generation programs: WGEN, WXGEN, and USCLIMATE. Measured and generated rainfall were input into SWAT and run for a 53 ha watershed near Riesel, Texas. Rainfall totals, extreme rainfall events, and the resulting hydrologic responses of runoff volume and peak flows were then examined. For this study scenario, WXGEN was able to more closely match observed rainfall than WGEN and USCLIMATE. In terms of resulting SWAT hydrologic response, WXGEN rainfall best reproduced runoff volumes simulated with measured rainfall, and USCLIMATE performed better in reproducing peak runoff rates. These are important results as probabilities of exceeding runoff volume or peak flow thresholds are often questions of interest in watershed projects.*

Keywords. *Weather generation, Watershed modeling, Hydrology.*

In water quality models such as EPIC (Erosion Productivity Impact Calculator) and SWAT (Soil and Water Assessment Tool), long-term rainfall data are necessary for continuous, long-term simulation (Williams et al., 1984; Arnold et al., 1998). In the absence of actual long-term rainfall data, many water quality models use weather generators to simulate rainfall events for the location of interest. Rainfall generators are also useful because examination of the hydrologic response to observed weather alone is seldom sufficient for hydrologic or water quality modeling studies (Richardson, 1981). Generated precipitation allows examination of numerous scenarios that could occur with other equally likely future rainfall sequences. Appropriate generated weather sequences, which match the stochastic structure of actual weather data, allow analysis of questions such as: What are the ranges of runoff volumes and peak runoff rates that could be expected under increased urbanization of a forested watershed and at what frequency can these volumes and peaks be expected to occur?

The objective of this article is to examine the hydrologic response of SWAT to precipitation generated with WGEN, WXGEN, and USCLIMATE. Because of the natural interactions between rainfall, soil moisture, landuse, etc., properties of rainfall and resulting simulated runoff need to be examined. This study provides needed information on the hydrologic impacts of using various rainfall generators in watershed models, which are important tools in assessing hydrologic and water quality impacts of land and water resource management alternatives.

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DAILY PRECIPITATION GENERATORS

Models commonly used to generate daily precipitation for input into water quality models include WGEN (Richardson and Wright, 1984), WXGEN (Nicks, 1974) and USCLIMATE (Hanson et al., 1994). Each of these weather generators uses a first-order, two-state Markov chain model to generate the occurrence of wet and dry days. Given the previous day's wet or dry state, the model stochastically determines whether precipitation occurs on that day. Each model, however, uses a different distribution to determine daily rainfall on wet days (table 1).

QUALITY OF GENERATED RAINFALL

Since rainfall is a major determinant of hydrologic response, the quality of generated rainfall is important in watershed modeling. The difficulty in generating realistic rainfall data arises from the difficulty in capturing the statistical properties of natural events. Natural rainfall

Table 1. Models used to generate daily precipitation records for this study

Generator	Distribution to Determine Daily Amount
WGEN	Gamma distribution (two parameters)
WXGEN	Skewed normal distribution (three parameters)
USCLIMATE	Mixed exponential distribution (three parameters)

varies in amount, duration, and extreme events. Generated rainfall data need not match natural rainfall point by point; but to be considered useful, generated rainfall should approximate the amount, variability, periodicity, and extreme values of observed rainfall. That is, observed rainfall should have its important stochastic components preserved.

Several studies including Richardson (1982), Johnson et al. (1996), and Wilks (1999) have investigated the ability of rainfall models to appropriately represent actual rainfall. Richardson (1982) compared exponential, gamma, and mixed exponential distributions and concluded that each can reproduce observed monthly and annual rainfall totals, but that the mixed exponential distribution provided a better fit to daily precipitation totals for most locations. Wilks (1999) found that the gamma distribution under predicts observed extreme events and that the mixed exponential distribution better represents extremes. Wilks (1999) also found that the first-order Markov model for occurrence of wet and dry days is adequate for several central and eastern U.S. sites but underestimates length of dry periods for western U.S. sites. Johnson et al. (1996) concluded that the skewed normal and mixed exponential distributions adequately replicate measured monthly and annual rainfall totals but that extreme daily amounts were not satisfactorily reproduced by either distribution.

Additional studies, such as Haan et al. (1976) and Favis-Mortlock (1995), are needed to determine how rainfall generators affect hydrologic outputs of watershed models. Haan et al. (1976) used a simple hydrologic model to evaluate a daily rainfall generator they developed. To analyze the precipitation differences, the authors compared several properties of measured and generated rainfall records and also compared runoff simulated from the actual rainfall record and from the generated record. Generated rainfall exceeded measured rainfall by 27 mm/year on average, and this translated into approximately a 25 mm difference in simulated annual runoff.

Favis-Mortlock (1995) studied the influence of using actual and generated daily rainfall to model soil erosion with EPIC. He concluded that the skewed normal distribution was able to reproduce mean monthly rainfall values for the study areas; however, mean monthly standard deviations were significantly different. The model also under predicted the occurrence of infrequent large daily rainfall events, which was an important result in the erosion study.

PROCEDURES

STUDY SITE

Watershed Y2 (lat 31°28′30″ long 96°52′46″) at the USDA-ARS Grassland Soil and Water Research Laboratory, Riesel, Texas, was used as the study site (fig. 1). Watershed Y2 includes sub-watersheds Y6 (6.6 ha), Y8 (8.4 ha), and Y10 (7.5 ha), and drains an area of 53.4 ha. The watercourse through Y2 is a small ephemeral stream, which receives runoff from upstream waterways in Y6, Y8, and Y10. According to data taken onsite, the average annual precipitation is 877 mm, and average daily high temperatures range from a minimum of 15°C in January to a maximum of 35°C in July and August.

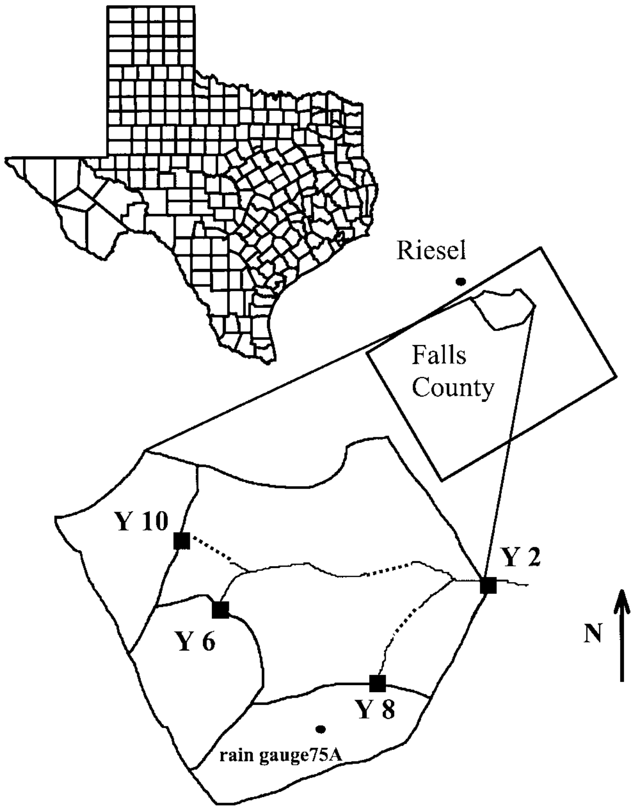

Figure 1-The USDA-ARS Riesel watershed Y2 study site.

The Riesel research center is located in the heart of the Blackland Prairie in Texas, a region of fertile agricultural land extending from San Antonio north to the Red River. Houston Black Clay soils (fine, smectitic, thermic, *Udic Haplustert*) with strong shrink/swell potential dominate the region. Slopes generally range from 1 to 3% and are classified as gently rolling. Present day agricultural land use in the region consists of pasture and rangeland, and corn, grain sorghum, and oat production under a wide range of tillage and management operations.

DAILY RAINFALL MODELS

Each of the daily rainfall generators requires measured data to calculate the Markov chain parameters (occurrences of wet and dry days) and daily rainfall distribution parameters. These parameters were calculated from the daily rainfall record for 1939 to 1998 obtained from Riesel rain gauge 75A (lat 31°28′14″ long 96°53′00″) located within watershed Y2 (fig. 1). WGEN and WXGEN utilize monthly varying Markov chain and distribution parameters. However, USCLIMATE produces parameters for 14-day periods and uses a Fourier series to fit the parameters and vary them for each day of the year.

WATERSHED MODEL

SWAT is a physically based, continuous model that simulates the impacts of land management activities on water, sediment, pesticide, and nutrient yields. SWAT is generally applied to large river basins but has been validated both on the river basin and small watershed scale in terms of annual water and sediment yield (Arnold et al., 1996; Arnold et al., 1999; Arnold and Williams, 1987). In fact, Riesel watershed G (17 km^2), which includes watershed Y2, was used for the small watershed validation. Daily values of precipitation, minimum temperature, and maximum temperature can either be input or generated by SWAT, but solar radiation, wind speed, and relative humidity must be generated within SWAT.

Four, 60-year daily precipitation records (the actual rainfall record and rainfall generated by WGEN, WXGEN, and USCLIMATE) and the measured daily maximum and minimum temperature record from 1939 to 1998 were input into SWAT. Measured temperatures were input to limit the confounding influence of generating temperature data with SWAT. A typical three-year crop rotation for this area (corn, winter wheat, grain sorghum) was created. Four, 60-year SWAT runs were then made for watershed Y2.

Analysis

Selected properties of the four rainfall sets and SWAT hydrologic outputs (runoff volumes and peaks) were examined. For the three generated rainfall sets, monthly and annual rain totals and variability, and recurrence intervals of annual rainfall totals and maximum daily rain per year were compared to measured data. Statistical differences between measured and generated means were evaluated using t-tests, and differences in medians were evaluated using the Mann-Whitney test, both at $\alpha = 0.05$ (Helsel and Hirsch, 1993). Standard deviations were compared with Levene's test at $\alpha = 0.05$ (Helsel and Hirsch, 1993).

Corresponding SWAT surface water hydrology outputs (runoff volumes and peak flow rates) were also analyzed. Differences in means, medians, and variability between runoff modeled with measured and generated rainfall data were tested for significant differences. Return periods of annual runoff volume and annual peak flows were also evaluated.

Results and Discussion

Monthly and Annual Rainfall Totals

For each of the generated rainfall sets, means and medians of monthly and annual rainfall totals were not significantly different than measured data (table 2). This result was anticipated as each of the generators is able to approximate monthly and annual rain totals in most cases. WGEN and USCLIMATE produced monthly rainfall variability that was generally less than measured variability, and annual rainfall variability was significantly lower than measured variability (table 3). In contrast to the other generators, WXGEN produced variability that exceeded or was less than measured variability depending on the month. In a frequency analysis, annual rainfall totals generated with WXGEN matched measured rainfall most closely for commonly analyzed return periods of 1, 2, 5, 10, 25, and 50 years (fig. 2).

Table 2. Mean monthly and annual rain totals (mm)

	Monthly Means			
Month	Measured	WGEN	WXGEN	USCLIMATE
January	54	50	55	60
February	72	60	75	59
March	75	69	88	79
April	93	96	100	104
May	119	112	123	108
June	92	92	82	88
July	47	47	45	48
August	55	60	62	57
September	67	67	66	70
October	87	81	90	86
November	76	81	68	74
December	72	71	75	75
Annual total (mean*)	909	885	930	907
Annual total (median†)	924	873	918	896

* No significant differences between measured and generated monthly and annual means were determined (t-test, $\alpha = 0.05$).

† No significant differences between measured and generated monthly and annual medians were determined (Mann-Whitney test, $\alpha = 0.05$).

Table 3. Standard deviations of monthly and annual rainfall (mm)

Month	Measured	WGEN	WXGEN	USCLIMATE
January	38	33	38	37
February	41	40	70	30
March	46	39	71	40
April	64	51	80	64
May	71	69	66	63
June	63	57	56	54
July	50	39	34	45
August	55	53	55	52
September	49	50	54	52
October	72	46*	48*	64
November	50	55	55	56
December	51	48	54	42
Annual total	232	147*	210	165*

* Significant differences between variability of measured and generated rainfall (determined with Levene's test, $\alpha = 0.05$).

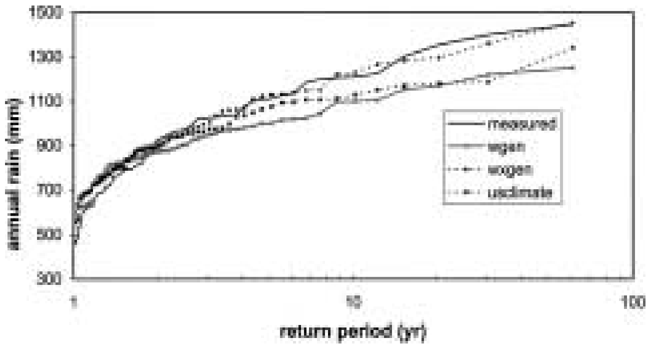

Figure 2–Return periods of annual rain total.

Maximum Daily Rainfall

Although precipitation generators are usually able to approximate monthly and annual rain totals, extreme events are more difficult to reproduce. Figure 3 shows that WXGEN produced a similar number of large rainfall events as were measured from 1939 to 1998 and that WGEN and USCLIMATE were not able to reproduce the observed number of extreme rainfall events. The maximum daily rainfall observed during the 60-year period (203 mm) was adequately reproduced by WXGEN (224 mm) and USCLIMATE (201 mm) but not by WGEN (118 mm).

When the return periods of maximum daily rainfall for each year were analyzed for each rainfall set, each generator best reproduced measured daily maximums for certain return period ranges (fig. 4). For frequent return periods (1.0 to 1.5 year), WGEN best reproduced measured maximum daily rainfall totals; for 1.5 to 2.0-year and 4.0 to

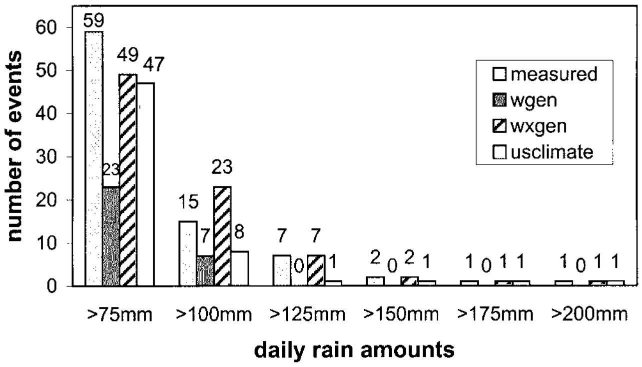

Figure 3–Comparison of the frequency of extreme rain events.

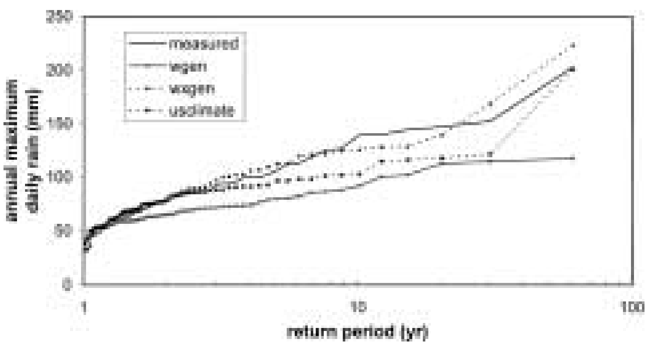

Figure 4–Return periods of annual maximum daily rain.

60-year return periods, WXGEN generally performed better; and for 2.0 to 4.0-year return periods, USCLIMATE performed better. Based on this result, WXGEN and USCLIMATE seem more applicable for modeling nonpoint source pollution processes, which are driven by less frequent, higher magnitude rainfall events.

Monthly and Annual Runoff Volume

Although no significant differences were found between measured and generated rainfall totals (table 2), several

Table 4. Mean monthly and annual runoff volume (mm)

	Monthly Means			
Month	Measured	WGEN	WXGEN	USCLIMATE
January	11	7	11	11
February	18	10*	21	8*
March	17	10*	25	14
April	17	11	19	19
May	25	20	25	19
June	24	20	17	21
July	10	7	6	7
August	11	12	14	10
September	14	10	13	13
October	27	20	24	22
November	18	20	18	19
December	20	18	20	19
Annual total (mean)	211	165*	212	184
Annual total (median †)	180	162	211	200

* Significant differences between measured and generated monthly and annual means (determined with t-test, $\alpha = 0.05$).

† Only one significant difference (February measured vs WGEN) between measured and generated monthly and annual medians was determined (Mann-Whitney test, $\alpha = 0.05$).

Table 5. Standard deviations of monthly and annual runoff volume (mm)

Month	Measured	WGEN	WXGEN	USCLIMATE
January	17	11	17	16
February	26	16	50	10*
March	25	16*	46	17
April	31	15	38	25
May	34	28	34	23
June	31	24	25	27
July	19	13	12	16
August	23	21	29	19
September	23	15	22	20
October	37	23	24	33
November	20	26	29	30
December	28	23	31	22
Annual total	127	77*	123	101

* Significant differences between variability of measured and generated runoff volume (determined with Levene's test, $\alpha = 0.05$).

significant differences existed between runoff volumes simulated from measured and generated rainfall (table 4). WXGEN and USCLIMATE were able to best reproduce monthly runoff volumes, and WXGEN was able to best reproduce annual runoff volume.

Similar to rainfall variability, runoff produced with WGEN and USCLIMATE rainfall inputs was less variable than with measured rainfall (table 5). In contrast, WXGEN runoff exceeded measured variability in several months and was less than measured variability for other months.

When return periods of annual runoff volumes were analyzed, SWAT simulated runoff from WXGEN and WGEN rainfall inputs most closely matched runoff from measured rainfall (fig. 5). WXGEN was commonly better for years with higher runoff (return periods greater than two years). However, for less than two-year return periods WGEN was generally best.

Peak Flows

Simulation of extreme flow events is also important in many watershed studies. Figure 6 shows that the number of extreme events (runoff peaks) from USCLIMATE input closely matched the number of extreme events simulated from measured rainfall. The maximum peak runoff of 4.7 m^3/s simulated with measured rainfall was exceeded twice with WGEN rainfall input, five times with WXGEN, and once with USCLIMATE over the 60-year model run. This is an interesting and important result since: (1) the measured daily maximum rainfall from 1939 to 1998 was only exceeded once by WXGEN and never by WGEN or USCLIMATE; and (2) extreme events are major

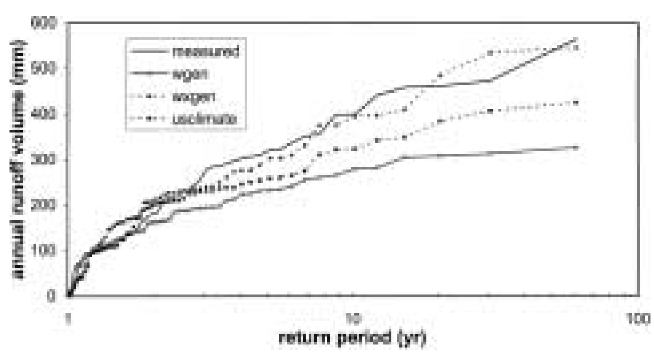

Figure 5–Return periods of annual runoff volume.

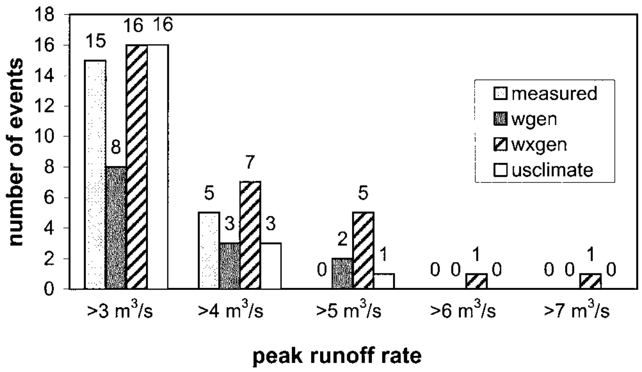

Figure 6–Comparison of the frequency of extreme flow events.

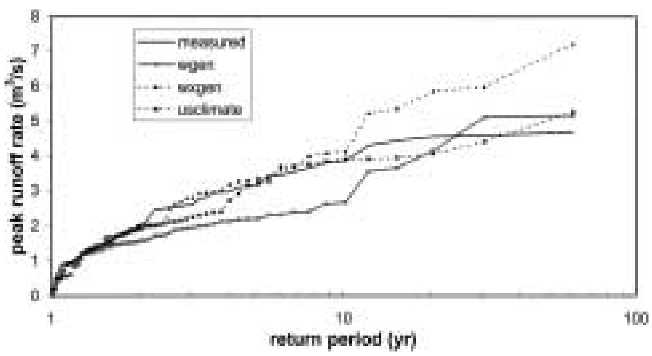

Figure 7–Return periods of annual peak runoff rate.

determinants of erosion rates, nonpoint source pollutant loads, and flood levels.

Annual peak runoffs simulated with USCLIMATE rainfall input generally matched return periods from measured rainfall most closely (fig. 7). At return periods of 2, 5, 10, and 50 years, annual peak runoff was best reproduced by USCLIMATE. However, WGEN and WXGEN more closely matched measured peaks for other return periods.

Conclusions

Our purpose in this study was to examine the effects of various precipitation generation models on the hydrologic outputs of SWAT on a small watershed scale. To accomplish this purpose, we analyzed properties of the four rainfall sets (rainfall amounts and extreme rainfall events) and corresponding SWAT hydrologic outputs (runoff volumes and peak flow rates). Three-parameter precipitation models are more capable of fitting measured rainfall than two-parameter models, but how this affected simulated runoff was not known. We found that WXGEN and USCLIMATE were able to more closely match measured rainfall, especially extreme events, and also more closely match hydrologic response modeled with SWAT.

In comparing the rainfall records, generated monthly and annual rainfall totals were not significantly different than measured data. The variability of rainfall generated with WGEN and USCLIMATE, however, was generally less than measured variability. WXGEN rainfall most closely matched the return periods of measured annual rainfall totals. For extreme events, WXGEN and USCLIMATE were able to best reproduce the number of extreme events and return periods of measured maximum daily rainfall.

In comparing runoff simulated by SWAT, monthly and annual runoff volumes from generated rainfall records were generally similar to runoff simulated with measured rainfall data. However, runoff volumes simulated with WGEN and USCLIMATE rainfall did exhibit several significant differences when compared to runoff simulated with measured rainfall. For less frequent, high runoff years, annual runoff volume generated with WXGEN rainfall input most closely matched runoff simulated with measured rainfall. For extreme flow events, USCLIMATE resulted in peak rates that best matched the number of extreme events and return periods of peak flows simulated from measured rainfall.

For this study scenario, WXGEN was able to more closely match observed rainfall than the other generators studied, especially in a frequency analysis. In terms of resulting SWAT outputs, WXGEN best reproduced runoff volumes simulated with measured rainfall, and USCLIMATE performed better in reproducing peak runoff rates. These are important results as probabilities of exceeding runoff volume or peak flow thresholds are often questions of interest in small watershed projects such as Total Maximum Daily Load (TMDL) studies and environmental impact analyses of urban expansion. However, other precipitation generators may perform better in other regions or within other watershed models.

In any long-term watershed study, it should be remembered that it is very difficult for generated rainfall to match the extreme variability of natural rainfall events. As a result, caution should be used when using generated data to predict extreme rainfall events (floods and droughts); but caution should also be used when using observed data to predict future extreme events. Each year nature produces events of “never before seen” magnitude and emphasizes the extreme variability of rainfall. Therefore, whenever measured or simulated rainfall data are used to model future water quantity or quality, the variability and uncertainty of future rainfall events must be considered.

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