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RESPONSE OF GREEN-AMPT MEIN-LARSEN SIMULATED RUNOFF VOLUMES TO TEMPORALLY AGGREGATED PRECIPITATION[1]

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ABSTRACT: Data collection frequency in automated systems is user determined and can range from seconds to hours or days. Currently, there is no standard or recommended frequency interval for collecting precipitation data from automated systems for input to event-based models such as Green-Ampt Mein-Larsen (GAML). Data from 47 storm events at seven locations were used to simulate the response of GAML excess rainfall to temporally aggregated precipitation data. No difference in model efficiency was recognized when comparing one-minute interval data (R^2 = 1.00) to five-minute data (R^2 = 1.00). Very little model efficiency was lost at a 10-minute (R^2 = 0.96) interval. After 10-minutes, decline in efficiency became more rapid with R^2 = 0.16 at one hour. The combined effect of time interval with respect to drainage area, hydraulic conductivity, maximum 30-minute intensity, and total precipitation also revealed similar results.
(KEY TERMS: precipitation; runoff; Green-Ampt; data collection; hydrologic instrumentation.)

INTRODUCTION

Automated digital data collection devices are becoming commonplace in the area of water resources. All facets of the hydrologic cycle are being monitored via automated data sampling. Automated data acquisition systems are being used to measure stage (Burcham *et al.*, 1998; Felton, 1994), meteorological data (Elliot *et al.*, 1991), soil moisture (Gray and Spies, 1995; van Grinsven *et al.*, 1988), evaporation (Van Haveren, 1982; Phene *et al.*, 1991), and ground water potentials (Booltink, 1995).

One of the most critical variables to be measured is precipitation, the driving force for the hydrologic cycle. A primary application of precipitation data is as input for simulation models. Most models operate on a daily time step. However, modeling is moving into an age of real-time or near real-time models. The use of Green-Ampt (Green and Ampt, 1911) or some similar (Smith-Parlange, 1978) excess rainfall models have been used to simulate excess rainfall. Various event-based models (Loague and Freeze, 1985), specific application models (Wilcox *et al.*, 1990; James *et al.*, 1992), field-scale models (Williams, 1995; Lane and Nearing, 1989), and basin-scale models (King *et al.*, 1999) use Green-Ampt or some similar version for estimating excess precipitation. These models require precipitation data at less than a daily time-step. The collection frequency in automated systems can range from seconds to hours or days and is user selected.

Precipitation data for time steps of less than a day are often reported at breakpoint intervals (generally intervals of equal intensity). With the onset of automated data collection devices, the time interval for collecting data is generally constant at a user determined value. The objective of this study was to identify the frequency at which precipitation data should be collected in order to preserve the simulation capabilities of the Green-Ampt (Green and Ampt, 1911) excess rainfall model, as modified by Mein and Larsen (1973) (GAML), and to examine the combined effect of time interval and selected physical properties of the system.

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MATERIALS AND METHODS

Experimental Data

Data from 47 precipitation events (Table 1) at seven locations were compiled for this study. Data from the selected sites consisted of precipitation data and corresponding runoff hydrographs. Rainfall data for the various locations were collected at an array of intervals (3, 5, 6, 10, and 15-minutes and breakpoint). The distribution of precipitation amounts varied from a minimum of 22.8 mm to a maximum of 137.2 mm. The median storm event analyzed was 50.8 mm. Maximum 30-minute intensities (Figure 1) for the events ranged from 8.7 $mm \cdot hr^{-1}$ to 132.0 $mm \cdot hr^{-1}$. Due to the magnitude of the events, initial abstractions (interception losses and depression storage) were assumed to be negligible. Precipitation was assumed uniform over the entire drainage area and the dominant soil was assumed homogeneous. On larger areas where soil, vegetation, and land use are not homogeneous and no routing is done, these assumptions could potentially lead to some error in assuming excess precipitation is equal to runoff.

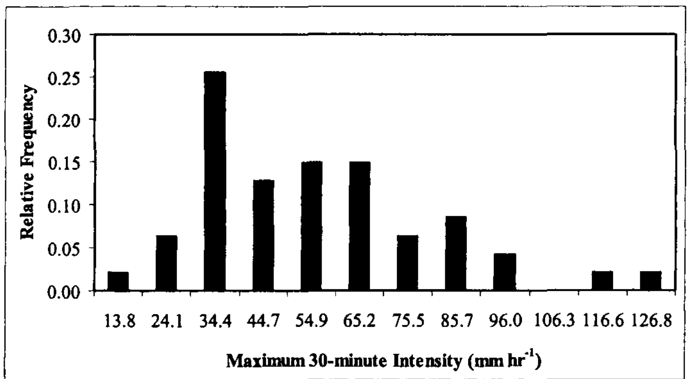

Figure 1. Frequency Distribution of Maximum 30-Minute Intensities for 47 Events.

Experimental Methods

To transform the data to uniform time intervals, the individual storm data were linearly disaggregated from the measured interval to one-minute intervals. Using one-minute interval data, antecedent soil moisture was estimated in an effort to force the GAML simulated runoff volumes to within 1 percent of measured volumes. Hydraulic conductivity and wetting front matric potential were calculated based on relationships developed by Rawls and Brakensiek (1985) and the dominant soil for the study location. Rawls and Brakensiek (1985) expressed wetting front matric potential, ψ (mm), as a function of porosity (POR), percent sand (PS), and percent clay (PC) where:

$$\psi = 10\exp\begin{pmatrix} 6.5209 - 7.32561\,POR + 0.0001583\,PC^2 + \\ 3.809479\,POR^2 + 0.000344\,PS\,PC - \\ 0.049837\,PS\,POR + 0.001608\,PS^2\,POR^2 + \\ 0.001602\,PC^2\,POR^2 - 0.0000136\,PS^2\,PC - \\ 0.003479\,PC^2\,POR - 0.000799\,PS^2\,POR \end{pmatrix}. \quad (1)$$

They developed a similar relationship for hydraulic conductivity, K (mm hr^{-1}), where:

$$K = 10\exp\begin{pmatrix} 19.52348\,POR - 8.96847 - 0.028212\,PC + \\ 0.00018107\,PS^2 - 0.0094125\,PC^2 - \\ 8.395215\,POR^2 + 0.077718\,PS\,POR - \\ 0.00298\,PS^2\,POR^2 - 0.09492\,PC^2\,POR^2 + \\ 0.0000173\,PS^2\,PC + 0.02733\,PC^2\,POR + \\ 0.001434\,PS^2\,POR - 0.0000035\,PC^2\,PS \end{pmatrix}. \quad (2)$$

Once K and ψ were calculated and antecedent soil moisture estimated, the one-minute event data were aggregated to intervals of 5, 10, 15, 20, 30, and 60 minutes. Excess precipitation volumes were estimated for each event at each time interval using the GAML infiltration equation. The GAML infiltration rate can be expressed as:

$$f(t) = K\left(\frac{\psi\Delta\theta}{F(t)} + 1\right) \quad (3)$$

where f(t) represents the infiltration rate ($mm \cdot hr^{-1}$), K is the hydraulic conductivity ($mm \cdot hr^{-1}$), ψ is the wetting front matric potential (mm), $\Delta\theta$ is the change in volumetric moisture content across the wetting front, F(t) is the cumulative infiltration (mm), and t is time (hrs). The cumulative infiltration can be represented by

$$F(t) = Kt + \psi\Delta\theta\ln\left(1 + \frac{F(t)}{\psi\Delta\theta}\right) \quad (4)$$

where all variables have been previously defined.

TABLE 1. Watershed Locations, Soil Characteristics, Total Precipitation, and Excess Rainfall.

Location	Watershed	Date of Storm	Area (ha)	Hydr. Cond.* (mm hr-1)	Wetting Front Matric Potential* (mm)	Dominant Soil	Silt (%)	Sand (%)	Clay (%)	Meas. Precip. (mm)	Meas. Runoff (mm)
Treynor, Iowa	W-3	3/17/79	2.3	0.4	380.6	Monona (fine-silty, mixed, mesic typic hapludolls)	68.7	4.3	27.0	34.5	12.6
Oxford, Mississippi	WP-4	8/9/60	1.3	2.7	416.0	Loring (fine-silty, mixed, thermic oxyaquic fragiudalfs)	72.7	14.3	13.0	26.7	7.1
	WC-3	7/8/65	0.8							31.0	15.1
										49.3	13.0
Hastings, Nebraska	3-H	5/21/65	1.6	2.5	570.5	Holdrege (fine-silty, mixed, mesic typic argiustolls)	68.6	11.4	20	85.3	57.3
	5-H	5/21/65	1.6							85.3	62.9
Coshocton, Ohio	135	10/12/78	1.0	2.2	549.2	Fitchville (fine-silty, mixed, mesic aeric endoaqualfs)	67.3	11.2	21.5	44.9	21.5
	182	10/12/78	28.2							29.7	14.1
	166	9/13/79	33.4							120.7	55.8
Chickasha, Oklahoma	C-7	8/28/65	10.6	4.5	411.4	Kingfisher (fine-silty, mixed, thermic udic argiustolls)	67.7	20.0	12.3	62.5	12.2
	C-3	8/29/66	17.9							50.8	29.1
	C-7	8/29/66	10.6							39.9	24.2
	C-7	6/15/68	10.6							41.7	21.6
	R-7	5/24/73	7.8							87.9	58.9
	R-5	6/4/73	9.6							32.8	15.0
	R-7	11/19/73	7.8							54.6	28.4
	C-5	6/23/76	5.2							46.7	6.4
	R-7	6/24/76	7.8							45.7	8.7
	C-4	8/5/76	12.2							37.3	11.7
	R-7	5/19/77	7.8							67.8	29.2
Stillwater, Oklahoma	W-3	5/28/60	0.8	6.5	92.4	Norge (fine-silty, mixed, thermic udic paleustolls)	41.1	44.9	14.0	63.8	42.3
	W-1	5/6/73	1.3							25.4	12.2
	W-3	10/11/73	0.8							38.1	18.6
Riesel, Texas	Y	5/11/57	125.1	3.3	287.5	Houston Black (fine,montmorillonitic, thermic udic haplusterts)	27.8	17.2	55.0	94.9	64.8
	W-1	3/29/65	71.2							127.2	83.0
	C	5/10/65	234.4							75.4	47.9
	W-1	5/10/65	71.2							52.8	23.2
	W-1	5/28/65	71.2							48.5	25.2
	W-1	2/9/66	71.2							51.3	23.4
	W-1	4/12/68	71.2							38.1	11.7
	Y	4/12/68	125.1							39.4	12.6
	P-4	5/17/68	0.1							41.1	18.8
	Y	5/17/68	125.1							35.3	16.4
	W-1	5/17/68	71.2							38.9	19.0
	Y	6/23/68	125.1							79.5	29.2
	W-1	6/23/68	71.2							76.2	31.8
	W-1	7/9/68	71.2							34.3	16.3
	Y	3/23/69	125.1							26.1	12.4
	W-1	3/23/69	71.2							22.8	10.6
	C	3/24/73	234.4							62.4	39.0
	C	4/24/73	234.4							59.6	47.5
	Y	4/24/73	125.1							51.9	35.1
	C	6/3/73	234.4							65.2	44.2
	Y	6/3/73	125.1							81.7	63.0
	W-1	6/3/73	71.2							88.6	67.1
	C	4/29/75	234.4							61.2	40.8
	Y-14	3/6/78	2.3							137.0	97.6

*Calculated from Rawls and Brakensiek (1985) equations.

When rainfall occurs, Equation (4) is solved iteratively until cumulative infiltration converges. Then, final cumulative infiltration is substituted in Equation (3) to solve for infiltration rate. The time step at which Equation (4) is solved is variable and equivalent to the time step associated with the breakpoint interval or, in this case, the collection frequency interval. If infiltration rate (Equation 1) is greater than rainfall intensity in that interval, 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 infiltration rate is assumed to runoff.

Comparison Methods

Simulated excess rainfall at each time interval was compared with measured excess rainfall using the Nash-Sutcliffe (1970) model efficiency statistic. Nash-Sutcliffe efficiency is an indicator of the model's ability to predict about the 1:1 line. The Nash-Sutcliffe coefficient is calculated as

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(x_i - y_i)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{5}$$

where y_i is the simulated value, x_i is the measured value, $\bar{x}$ is the mean of the measured values, n is the number of samples, and R^2 is the efficiency.

Surface plots were used to analyze the combined effect of physical properties and time intervals on total GAML predicted volumes. The kriging mechanism in the Surfer® (Golden Software, Inc, 1995) software was used to develop the surfaces.

RESULTS AND DISCUSSION

Collecting precipitation data at intervals less than five minutes had no impact on GAML model simulations (Figure 2) for the 47 storms used in this study. Very little model efficiency was lost at 10-minute (0.96 model efficiency) intervals. Once the time interval was greater than 10-minutes, preservation of the measured excess rainfall started to decrease more rapidly. At the one-hour interval, model efficiency dropped to 16 percent.

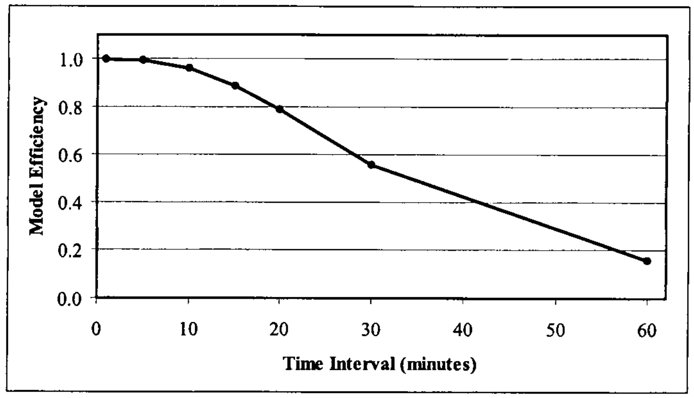

Figure 2. Relationship of Model Efficiency With Respect to Precipitation Collection Time Interval.

A general decline in model efficiency was evident with increases in hydraulic conductivity and time steps (Figure 3). Considerable prediction losses were noted with time steps above 10-minutes, regardless of hydraulic conductivity. After 20 minutes, the predictive capacity of the GAML model was decreased approximately 20 to 25 percent for every 2 mm hr^{-1} increase in hydraulic conductivity.

For drainage areas less than approximately 50 ha, time interval for precipitation collection is critical (Figure 4). A collection period of five to 10 minutes is needed to preserve the predictive capacity of the GAML model for scales less than 50 ha. Time interval is less significant for predicting GAML volumes for areas between 50 and 100 ha but becomes important again for areas larger than 100 ha. Generally time intervals of approximately 10 minutes are needed to retain the predictive capability of GAML regardless of drainage areas used in this study. With exception to the 50 to 100 ha range, greater time intervals are marked with considerable declines in prediction efficiency.

Regardless of maximum 30-minute intensity, the ability to simulate total runoff volumes decreased considerably for time intervals of more than 10-minutes (Figure 5). However, for maximum 30-minute intensities of less than approximately 20 $mm \cdot hr^{-1}$ the decline in prediction capability was not as rapid. In general, as maximum 30-minute rainfall intensity increased, a time step less than or equal to 10-minutes was needed to retain the predictive capacity of the GAML model. As total precipitation increased above 80 to 100 mm, time interval became less significant (Figure 6). For storms less than about 80 mm, a 10-minute to 15-minute time interval or less was needed to simulate the measured total volume. Similar to intensity, the smaller the storm magnitude the smaller time interval needed to maintain the predictive capacity of the GAML model.

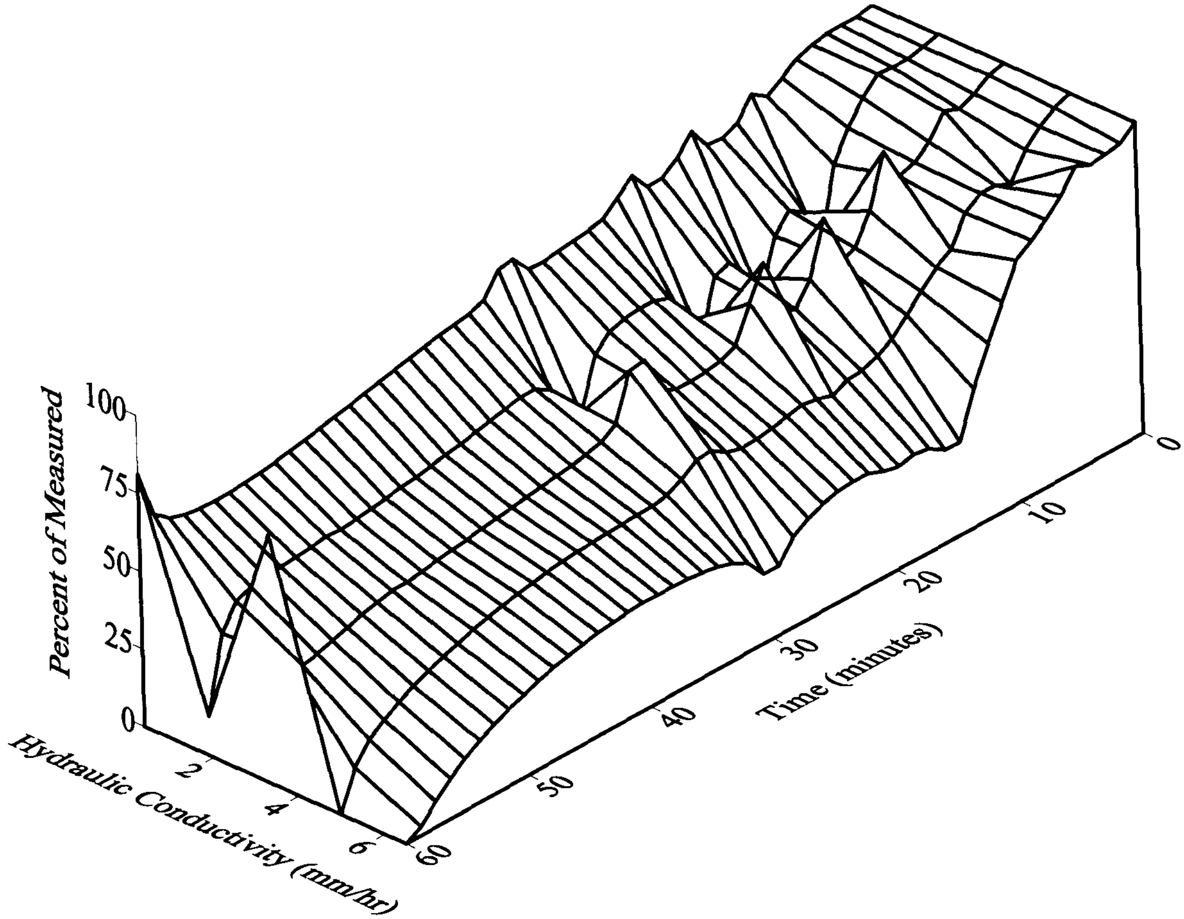

Figure 3. Predictive Capacity of Model With Respect to Time and Saturated Conductivity.

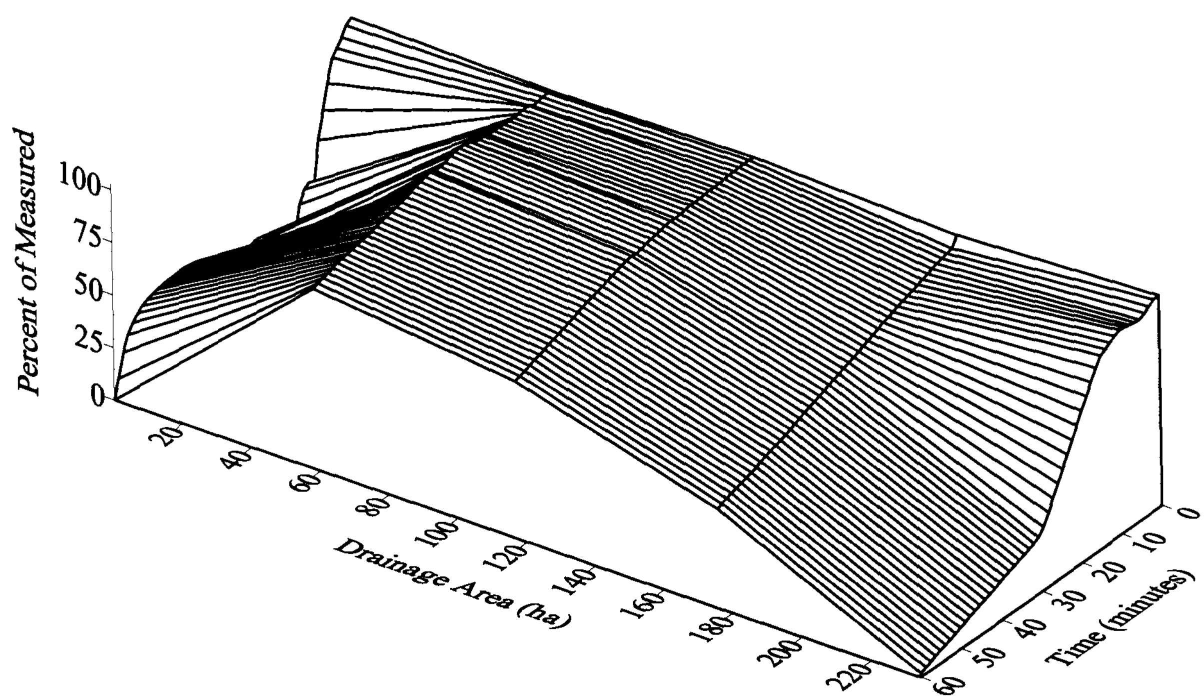

Figure 4. Relationship of Drainage Area and Data Time Interval on Total Volume Expressed as a Percent of Measured.

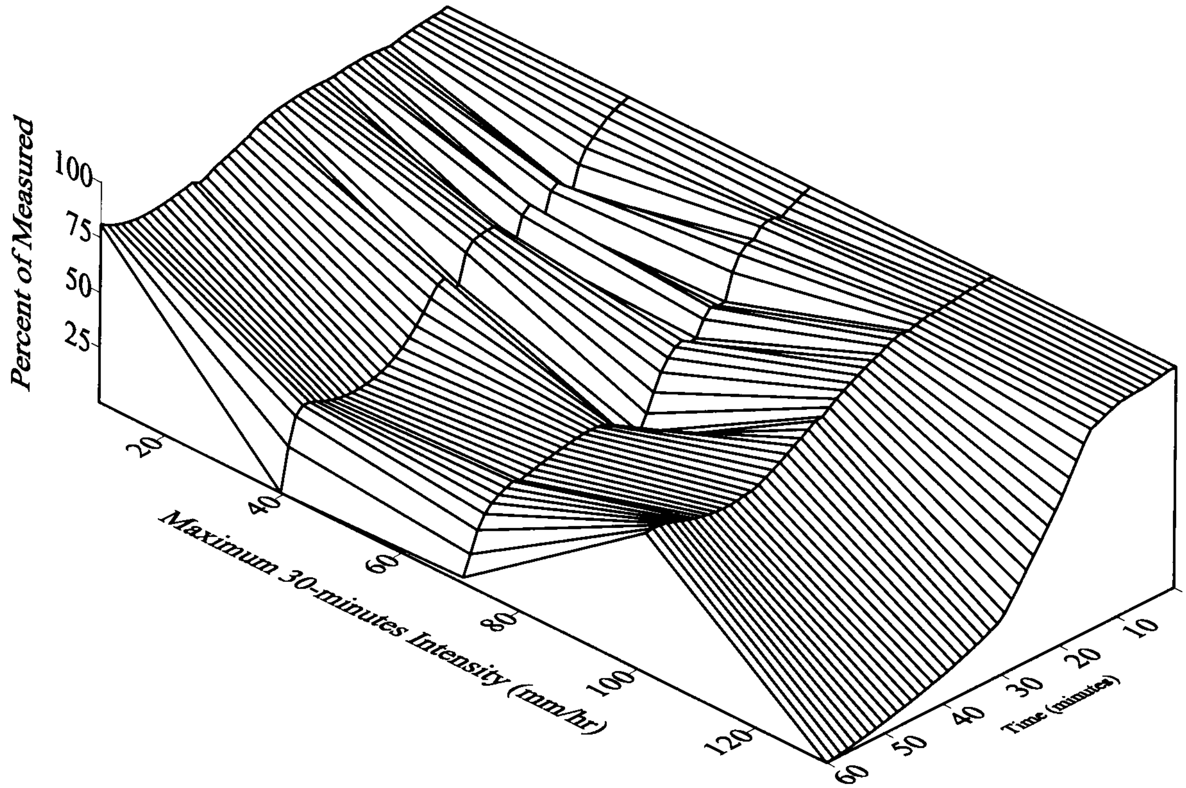

Figure 5. Combined Effect of Maximum 30-Minute Intensity ($mm{\cdot}hr^{-1}$) and Time Interval on Simulated Total Volume of Excess Rainfall Expressed as a Percent of Measured.

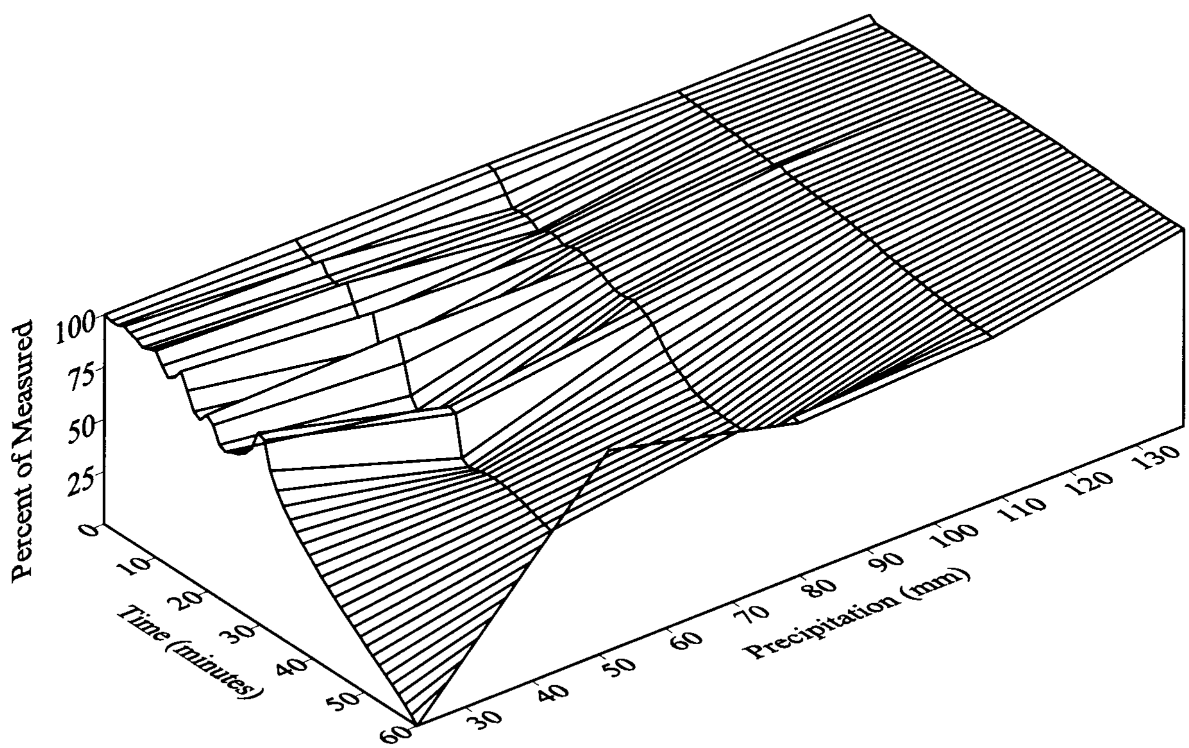

Figure 6. Effect of Precipitation Amount With Respect to Time on Total Excess Volume Expressed as a Percent of Measured.

SUMMARY AND CONCLUSIONS

Precipitation measurements are a key component of hydrologic studies. Currently no standard or recommendation exists for the time interval that should be used for collecting precipitation data. By using the GAML excess rainfall model on 47 storms, the following conclusions were made:

- A five-minute precipitation collection time interval resulted in a 100 percent model prediction efficiency.

- For the range of conductivities used in this study, for every 2 mm hr^{-1} increase in hydraulic conductivity an approximate 20 to 25 percent reduction of percent of measured excess precipitation volume was noted.

- For all drainage areas used in this study, a 10-minute time interval preserved the predictive capacity of the GAML model.

- For more intense precipitation, time steps less than or equal to 10-minutes were needed to maintain the predictive capacity of the GAML model.

- The smaller the storm magnitude the smaller the time interval needed to preserve the predictive capacity of GAML model.

This study highlights a tradeoff in selecting a time interval for precipitation collection. If the user is willing to sacrifice a minor loss in predictive capacity, considerable space and time for collecting data can be saved by collecting at 10-minute intervals. Furthermore, when using the data for model input, one-minute time intervals have no advantage over five-minute collection time intervals.

LITERATURE CITED

Booltink, H. W. G., 1995. Field Monitoring of Nitrate Leaching and Water Flow in a Structured Clay Soil. Agriculture, Ecosystems and Environment 52(2):251-261.

Burcham, T. N., D. G. Wren, J. R. Wooten, and J. J. Varco. 1998. Distributed Data Acquisition System for Runoff Monitoring and Automated Water Sample Control. Applied Engineering in Agriculture 14(6):591-597.

Elliott, R. L., F. Brock, S. J. Stadler, K. C. Crawford, G. W. Cuperus, H. L. Johnson, and C. A. Doswell III, 1991. MESONET: Oklahoma's Automated Weather Network. ASAE Paper No. 91-4071, St. Joseph, Michigan.

Felton, G. K., 1994. Hydrologic Response of a Karst Watershed. Trans. ASAE 37(1):143-150.

Golden Software, Inc., 1995. SURFER for Windows: Contouring and 3D Surface Mapping. Golden, Colorado.

Gray, A. N. and T. A. Spies, 1995. Water Content Measurement in Forest Soils and Decayed Wood Using Time Domain Reflectometry. Canadian Journal of Forest Research 25(3):376-385.

Green, W. H. and G. A. Amp, 1911. Studies on Soil Physics. J. Agric. Sci. 4(1):1-24.

James, W. P., J. Warinner, and M. Reedy, 1992. Application of the Green-Ampt Infiltration Equation to Watershed Modeling. Water Resources Bulletin 28(3):623-635.

King, K. W., J. G. Arnold, and R. L. Bingner, 1999. Comparison of Green-Ampt and Curve Number Methods on Goodwin Creek Watershed Using SWAT. Trans. ASAE 42(4):919-925.

Lane, L. J. and M. A. Nearing, 1989. USDA – Water Erosion Prediction Project: Hillslope Profile Model Documentation. NSERL Report No. 2, USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, Indiana.

Loague, K. M. and R. A. Freeze, 1985. A Comparison of Rainfall Runoff Modeling Techniques on Small Upland Catchments. Water Resources Research 21(2):229-248.

Mein, R. G. and C. L. Larsen, 1973. Modeling Infiltration During a Steady Rain. Water Resources Research 9(2):384-394.

Nash, J. E. and J. E. Sutcliffe, 1970. River Flow Forecasting Through Conceptual Models. Part 1-A: Discussion of Principles. J. Hydrology 10(3):282-290.

Phene, C. J., W. R. DeTar, and D. A. Clark, 1991. Real Time Irrigation Scheduling With Automated Evaporation Pans. ASAE Paper No. 91-2642, St. Joseph, Michigan.

Rawls, W. J. and D. L. Brakensiek, 1985. Simulation of Soil Water Properties for Hydrologic Modeling. *In:* Watershed Management in the 80s, E. B. Jones and T. J. Ward (Editors). ASCE, New York, New York, pp. 293-299.

Smith, R. E. and J. Y. Parlange, 1978. A Parameter-Efficient Hydrologic Infiltration Model. Water Resources Research 14(3): 533-538.

van Grinsven, J. J. M., H. W. G. Booltink, C. Dirksen, N. van Breemen, N. Bongers, and N. Waringa, 1988. Automated In Situ Measurement of Unsaturated Soil Water Flux. Soil Sci. Soc. of Am. J. 52(5):1215-1218.

Van Haveren, B. P., 1982. An Automated Recording System for Evaporation Pans: Water Reservoir to Water Supply. Water Resources Bulletin 18(3): 533-536.

Wilcox, B. P., W. J. Rawls, D. L Brakensiek, and J. R. Wight, 1990. Predicting Runoff From Rangeland Catchments: A Comparison of Two Models. Water Resources Research 26(10):2401-2410.

Williams, J. R, 1995. The EPIC Model. *In:* Computer Models of Watershed Hydrology, V. P. Singh (Editor). Water Resources Publications, Highlands Ranch, Colorado, pp. 909-1000.