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ABSTRACT: Traditionally in the application of hydrologic/water quality (H/WQ) models, rainfall is assumed to be spatially homogeneous and is considered not to contribute to output uncertainty. The objective of this study was to assess the uncertainty induced in model outputs solely due to rainfall spatial variability. The study was conducted using the AGNPS model and the rainfall pattern captured by a network of 17 rain gauges. For each rainfall event, the model was run using the rainfall captured by each rain gauge, one at a time, under the assumption of rainfall spatial homogeneity. A large uncertainty in the modeled outputs resulted from the rainfall spatial variability. The uncertainty in the modeled outputs exceeded the input rainfall uncertainty. Results of this study indicate that spatial variability of rainfall should be captured and used in H/WQ models in order to accurately assess the release and transport of pollutants. A large uncertainty in the model outputs can be expected if this rainfall property is not taken into account.
(KEY TERMS: agricultural hydrology; water quality; modeling; output uncertainty; spatial variability; AGNPS.)

INTRODUCTION

Rainfall is a key input for all hydrologic/water quality (H/WQ) models because it activates flow and mass transport. Accurate input of rainfall in time and space is crucial for modeling runoff and transport of non-point source pollutants using H/WQ models. Even though the importance of spatial variability of rainfall in simulating runoff was recognized more than three decades ago (Osborn and Reynolds, 1963; Osborn and Keppel, 1966; Rodda, 1967; Dawdy and Bergman, 1969), the assumption of uniform rainfall is still applied in modeling the hydrologic behavior of watersheds (Goodrich et *al.*, 1995). Consequently, a single rainfall depth either measured at one gauge location, or averaged from a few gauges is input in the models. Troutman (1983) suggested that, in rainfall-runoff modeling, an input error is present when measurement from only a small number of gauges are used when a more extensive network might be necessary to accurately describe rainfall pattern. Rudra et *al*. (1993) noted that failure to consider the spatial variability of rainfall may lead to serious errors in predicted results.

A hydrologic model can be mathematically represented as

$$\underline{O} = \underline{f}(\underline{I}, \underline{P}, t) + \underline{e} \qquad (1)$$

where $\underline{O}$ is an n x k matrix of hydrologic responses to be modeled, $\underline{f}$ is a collection of functional relationships, $\underline{I}$ is an n x m matrix of inputs, $\underline{P}$ is a vector of p parameters, t is time, $\underline{e}$, is an n x k matrix of errors, n is the number of data points, k is the number of responses, and m is the number of inputs (Haan, 1989). Errors in modeling results obtained from Equation (1) can be classified into two groups (Troutman, 1983): (a) errors within the model structure with correct inputs and parameters, and (b) errors due to erroneous inputs and/or parameters. This research focuses on the input errors. The input of interest is rainfall depth. The outputs considered are runoff volume, total sediment yield, sediment-attached N, and sediment-attached P transport. A correct input means that the true rainfall pattern is known at every point within the watershed. A rainfall event observed by only one gauge or a few gauges gives an input error when a dense network of rain gauges are needed to

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give an adequate representation of rainfall over the watershed (Troutman, 1983).

With increasing environmental problems, the objectives are also changing from mainly quantitative to qualitative aspects. Hence, the requirements and purposes of runoff calculations and the necessary rainfall input are also changing (Berndtsson and Niemczynowicz, 1988). In H/WQ modeling, we are not solely interested in the peak flow and runoff volume. In order to increase the prediction accuracy of models, it becomes very important that the spatial variability of rainfall and its effect on runoff as well as water quality parameters are studied.

The overall objective of this research was to study the uncertainty induced in H/WQ model outputs solely due to spatial variability of rainfall. This will help isolate this source of model output uncertainty from other sources.

Most of the studies conducted to examine the effect of spatial variability of rainfall on H/WQ processes have focused primarily on runoff volume, time to peak runoff, and peak runoff rate predictions (e.g., Dawdy and Bergman, 1969; Wilson *et al.*, 1979; Seliga *et aL,* 1992; Corradini and Singh, 1985; Obled *et al., 1994;* Troutman, 1983; Hamlin, 1983; Faures *et al.,* 1995; Shah *et al.,* 1996). Information on the effect of rainfall spatial variability on transport of sediment and nutrients is limited. Young *et al.* (1992) reported a first approximation of the deviations of runoff volume and sediment load caused by varying the spatial distribution of rainfall input to the AGricultural Non-Point Source (AGNPS) pollution model. They found that in one case total N loss was four times more and the total P loss and sediment yield were five times greater than the estimates obtained from an average uniform rainfall. This study was limited by the fact that the authors had captured spatial rainfall variability using a synthetic storm. Hamlin (1983) mentioned that the synthetic storm may not model the patterns and amount of real rainfall adequately. In a similar study, Luzio and Lenzi (1995) applied the AGNPS model to a watershed in Northem Italy. Rainfall erosion index and sediment yield were increased by more than 20 percent and total N and total P loads were increased by more than 17 percent when a spatially variable rainfall was used.

Another important issue in the study of rainfall spatial variability is the size of watershed under consideration. Even though the importance of spatial rainfall pattern on runoff generation has been reported at various spatial scales ranging from less than a hectare to tens of square kilometers for urban and rural watersheds (Dawdy and Bergman, 1969; Jaco i and Dawdy, 1973; Osborn *et al.,* 1979; Beven and Hornberger, 1982; Troutman, 1983; Berndtsson and Niemczynowicz, 1988; Michaud and Sorooshian, 1992; Faures *et al.,* 1995; Goodrich *et al.,* 1995), information about the effect of rainfall spatial variability on predicted runoff and water quality is limited for relatively larger watersheds. A limited number of gauges were used to capture rainfall spatial variability in these studies. Since rainfall spatial variability can be expected to increase with an increase in the watershed size, the results reported in the literature may not be applied to larger watersheds where a large number of gauges may be available to measure rainfall patterns. This study attempts to quantify the uncertainty in the predicted water quantity and quality due to rainfall spatial variability when applied to a relatively larger watershed (159 km2) with a dense network of rain gauges (17).

METHODS

Site Description

This study was conducted on Little Washita basin having a total area of 610 kM2. This basin is located in Southwest Oklahoma and is a tributary to the Washita River (Figure 1). The watershed has a typical continental climate, characterized as moist subhumid with average annual precipitation of 750 mm. The Natural Resources Conservation Service (NRCS) has extensively surveyed the soils in the watershed and have classified 64 different soil series. Within the soil series, 162 different soil phases have been mapped to reflect differences in the characteristics that affect land uses. Land cover is primarily rangeland, winter wheat, woodland and summer crops each accounting for 63, 20, 12, and *4* percent of the area, respectively. Impervious areas and water bodies each, comprise less than one percent of the total area. A detailed description of the soils, topography, geology, and climate of the watershed can be found in ARS (1991). The U.S. Department of Agriculture, Agricultural Research Services (USDA-ARS) operates a network of 48 recording rain gauges, known as Micronet. A subwatershed, known as Cement watershed, was delineated from the Little Washita basin and was used in this study. A network of 17 Micronet rain gauges located within and around the Cement watershed was used to capture the rainfall. The location of the Cement watershed and the Micronet Stations used are shown in Figure 1. The total area of the Cement watershed is 159 km2.

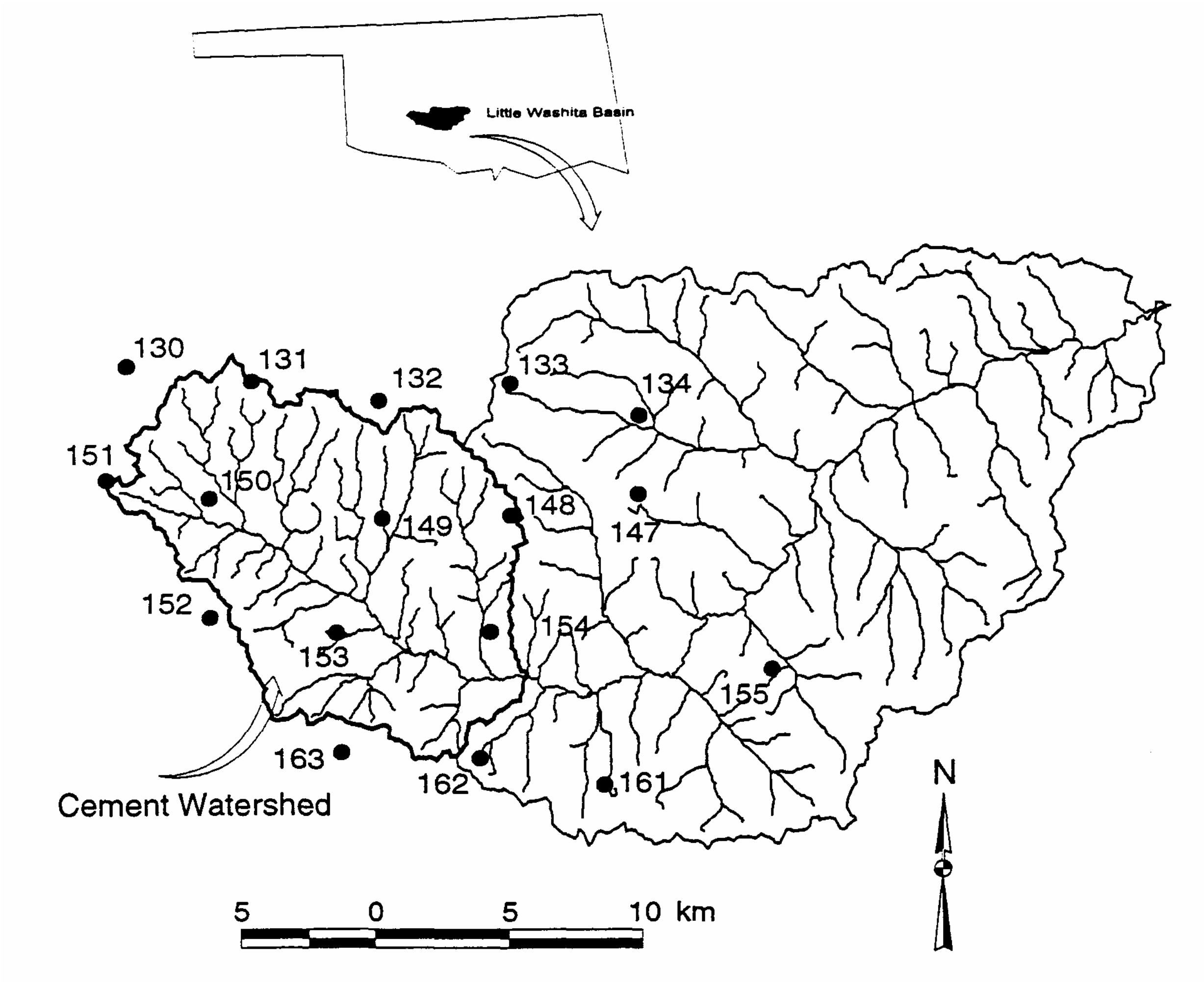

Figure 1. Location of Little Washita Basin, Cement Watershed
and the Macronet Stations Used in this Study.

Model Description

The AGNPS model was used to assess the effect of spatial variability of rainfall on model outputs. The model simulates surface runoff, sediment and nutrient transport from a single rainfall event. Basic model components include hydrology, erosion, and sediment and chemical transport. The nutrients considered are nitrogen (N) and phosphorus (P). In addition, transport of chemical oxygen demand (COD) and pesticides are also considered. Pollutant transport is subdivided into soluble pollutants and sediment-attached pollutants. Point sources of water, sediment, nutrients, and COD from animal feedlots and springs also are considered. The model can generate water quality characteristics at intermediate points throughout the watershed network.

The model operates on a geographic cell basis that is used to represent upland and channel conditions. The entire watershed of interest is divided into square cells having homogeneous soil and land use conditions. All watershed characteristics and inputs are specified at the cell level. Surface runoff and potential pollutants are routed through cells from watershed divide to the outlet in a stepwise manner and model output at any point between cells can be examined. Generally, the model requires 20 different input informations for each cell. Output includes watershed area and cell size, storm precipitation and erosivity, runoff volume and peak flow rate at the watershed outlet, and area-weighted erosion, both upland and channel. The model also estimates sediment delivery ratio, mean sediment concentration, and total sediment yield for each of five sediment particle size classes. More details about the model can be found in Young *et al. (1987, 1989).*

One of the limitations of the AGNPS model, like most HIWQ models, is that it does not allow the input of spatially variable rainfall depths. The model was modified to input rainfall and energy intensity at the cell level. The modifications were based on the work done by Grunwald and Frede (1997) at the USDAARS National Soil Erosion Research Laboratory, West Lafayette, **Indiana.** The input files for AGNPS were prepared using a GIS-based WATERSHEDSS, a GRASS-AGNPS modeling tool developed by Osmond *et* al. (1997). **Input GIS layers required** by the modeling tool were prepared in a raster format using a 30m cell resolution. The cell size used in AGNPS modeling was 200 in.

Description of the Rainfall Events and Data Set

Rainfall data for the Micronet stations at five minute intervals were obtained from USDA- ARS. Daily stream flow data, in cubic feet per second, were obtained from US Geological Survey. A total of nine rainfall dates (March 27, 1996; March 28, 1996; April 21, 1996, April 23, 1996; May 31, 1996; June 1, 1996; July 9, 1996; July 10, 1996; and October 27, 1996) were selected for the study. The criteria used in selecting rainfall dates was the magnitude of the rainfall. Only relatively larger rainfall events were selected because of their importance in erosion and transport of sediment and nutrients from agricultural watersheds. The surface runoff volume for each rainfall event was obtained by separating base flow from total flow using the method outlined by Kim and Hawkins (1993). It was not possible to separate the base flow from total flow for the following rainfall on each day because several days elapsed as the runoff volume was occurring- March 27 and 28, 1996; April 21 and 23, 1996; May 31, 1996, and June 1, 1996; and July 9 and 10, 1996. The total rainfall for the two days was considered as one rainfall event and was used in the analysis. Thus, the total number of rainfall events considered was five. The events are indicated by the first day of the event. Antecedent moisture conditions used in CN calculations were characterized by considering rainfall preceding five days to each event and the method described by Haan *et* al. (1993).

The outputs considered were runoff volume, total sediment, sediment-attached N and sedimentattached P transport at the watershed outlet. The model parameters were- calibrated before the model was run to assess output uncertainty due to the spatial variability of rainfall. Grid-based rainfall depths were captured using 17 Micronet rain gauges and the Thiessen polygon method. This spatially variable rainfall, for each event, was considered as the 'true' rainfall pattern. AGNPS was calibrated for CN using the observed 'true' rainfall and runoff volume by adjusting the individual cell curve numbers either all upward or downward by a constant percentage until predicted runoff volume equaled observed runoff volume. All other parameters were calibrated based on the observed watershed characteristics.

The only observed data were the rainfall and runoff volume. No measured water quality or sediment data were available for this watershed. Total sediment, sediment-attached N, and sediment-attached P were obtained by running the model using calibrated parameters and the 'true' rainfall pattern for each event. These outputs were considered as the 'observed' values for further analysis. Characteristics of the rainfall, runoff, sediment, and nutrient data for all events are shown in Table 1.

AGNPS was run using the rainfall measured at each gauge location, one at a time, assuming that the rainfall depth was uniform across the watershed. The calibrated parameters were fixed for each event. This gave 17 sets of output for each rainfall event. The variability in the model outputs induced by the spatial variability of rainfall, for each event, was termed the output uncertainty. It was quantitatively described using Average Error (AE), Relative Error (RE), Standard Error (SE), and Coefficient of Variation (CV). These error statistics can be defined as

TABLE 1. Observed Rainfall, Runoff and Simulated Sediment, and Nutrient Values.

Rainfall Date	**Rainfall** (mm)	Runoff (mm)	Total **Sediment*** (Mg)	Sediment-N* ft/ha)	**Sediment-P*** (kg/ha)
March 27, 1996	33	0.5	242	0.07	0.03
April 21, 1996	25	0.8	443	0.10	0.06
May 31, 1996	83	3.0	3395	0.53	0.27
July 9, 1996	64	1.5	2367	0.39	0.20
October 27, 1996	23	0.3	68	0.02	0.01

*Simulated using spatially variable 'true' rainfall pattern and calibrated parameters.

$$AE = \frac{1}{n}\sum_{i}^{n} \left(|P_i - O|\right) \quad (2)$$

$$RE = \frac{AE}{\overline{O}} \quad (3)$$

$$SE = \sqrt{\frac{1}{n}\sum_{i}^{n}(P_i - O)^2} \quad (4)$$

$$CV = \frac{SE}{\overline{O}} \quad (5)$$

where P_i is the predicted value, O is an observed parameter value, $\overline{o}$ is the mean of the observed data, and n (i = 1,2,3, - . .,n) is the number of data pairs. In this case, since the observed value of parameter is fixed for each event, O is equal to $\overline{o}$. The average error quantifies parameter variability in the units of O and P (e.g., kg, m/m, mg(L). In order to compare the parameters having different units, RE was used. The standard error, SE, and the coefficient of variation, CV, are numerical indicators of the variability in predicted data.

The variability in the rainfall amounts observed by 17 rain gauges for each event was quantified using Equations (2) through (5). Here Pi is the rainfall observed at the gauge i, $\overline{o}$ is the average rainfall for the area, and n is the number of gauges used to capture the rainfall spatial variability.

RESULTS AND DISCUSSION

Rainfall Spatial Variability

The characteristics of the rainfall observed by 17 Micronet rain gauges are shown in Table 2. The average rainfall ranged from 19 to 78 mm for the five events. The CV ranged from 0. 11 to 0.64. The smallest and largest CV and RE were observed for the rainfall on May 31, 1996, and October 27, 1996, respectively. The SE was smallest for the rainfall on March 27, 1996. For the watershed, 13 rain gauges were used in the Thiessen polygon method to capture the 'true' rainfall pattern. The area-weighted rainfall in Table 2 is based on the Thiessen polygon method. The average rainfall was obtained from all of the 17 gauges. The average rainfall and the area-weighted rainfall were different for all events. Inclusion of additional gauges that were in the vicinity of the watershed but not a part of the Thiessen polygon network introduced a bias in the average rainfall estimates. In actual conditions, it is not uncommon to have a rain gauge located outside the watershed of interest. As the number of rain gauges available to estimate the areaweighted rainfall increases, this bias can be expected to decrease.

The isohyetal map of map of rainfall depth for the storm on October 27, 1996, over the Little Washita basin as recorded at 42 Micronet stations is presented in Figure 2. The rainfall depth varied from zero to 45 mm. The rainfall pattern observed over Cement watershed for the events on May 31, 1996, and October 27, 1996, are shown in Figure 3. Note that the rainfall, when measured as CV and RE was least and most heterogeneous in nature on these two dates,

TABLE 2. Spatial Variability of Rainfall.

Statistic	March **27,1996**	**April 21, 1996**	Rainfall Date may **31, 1996**	**July 9, 1996**	October **27, 1996**
Average (mm)	32	26	78	69	19
AX Avg.a (mm)	33	25	83	64	23
Range (mm)	18-41	17-50	57-95	31-137	0-45
Avg. Errorb (mm)	6.35	7.15	6.47	27	9.34
Rel. Errorc	0.2	0.27	0.08	0.39	0.51
Std. Errord (mm)	7.95	9.08	8.87	31.6	11.7
CV	0.25	0.35	0.11	0.46	0.64
Number of Gauges	13	16	17	17	17

aArea weighted average.
bAverage error.
cRelative error.
dStandard error.

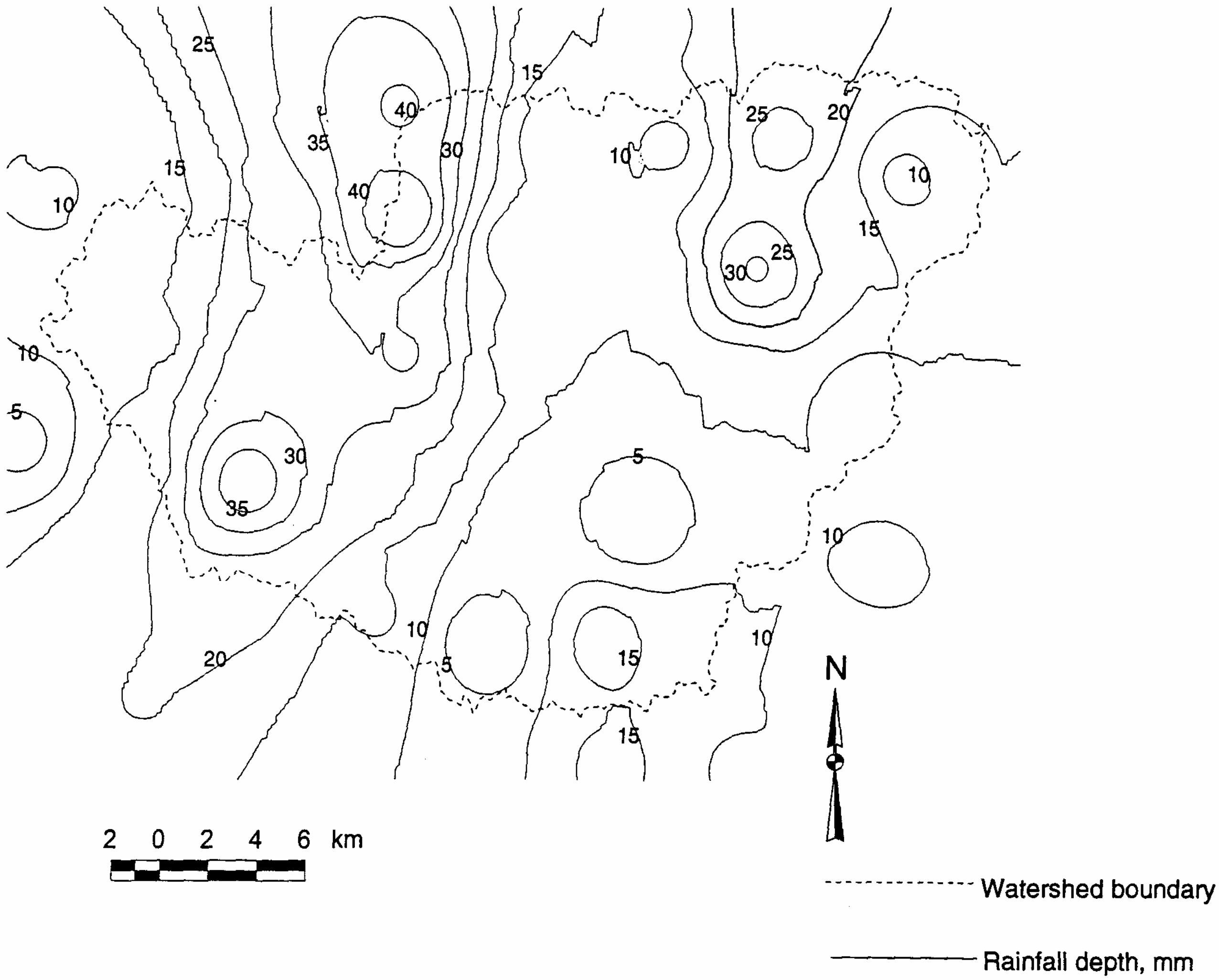

Figure 2. Isohyetal Map of Rainfall Depth that Occurred on October 27, 1996, Over Little Washita Basin.

respectively (Table 2). A large variation in the cumulative rainfall depth over the area is evident for the two watersheds on both dates. For the Cement watershed, the rainfall spatial variability, and the direction of the rainfall depth gradient is different for the two events. Traditionally, rainfall is measured at a few gauges (possibly only one). Often, these gauges are not located within the basin of interest. In an ideal condition, where the density and distribution of gauges are adequate, rainfall depth can be estimated with sufficient accuracy at any point in the basin by using a spatial interpolation technique. Unfortunately, this ideal condition rarely exists. Depending upon the location of the gauge within the watershed, a large variability in the observed rainfall depth can be expected (Figures 2 and 3). This will result in a large output variability.

Model Output Uncertainty

The effect of rainfall spatial variability on model outputs is shown in Table 3. For all rainfall events, variability in the measured rainfall resulted in variability in the model outputs based on a fixed set of parameters. Four of the five events analyzed had rainfall at some of the gauge locations too small to predict any significant runoff, sediment, and nutrient transport at the watershed outlet (Table 3). The range in CV in estimated runoff volume, total sediment, sediment-attached N, and sediment-attached P was 0.52-.29, 0.43-2.4, 0.36-2.15, and 0.37-2.17, respectively. The smallest CV in the modeled outputs was obtained for rainfall on May 31, 1996 (Table 3), which was most uniform in nature. The largest CV in output resulted on October 27, 1996 (Table 3), from the most heterogeneous rainfall. The range of SE for runoff volume,

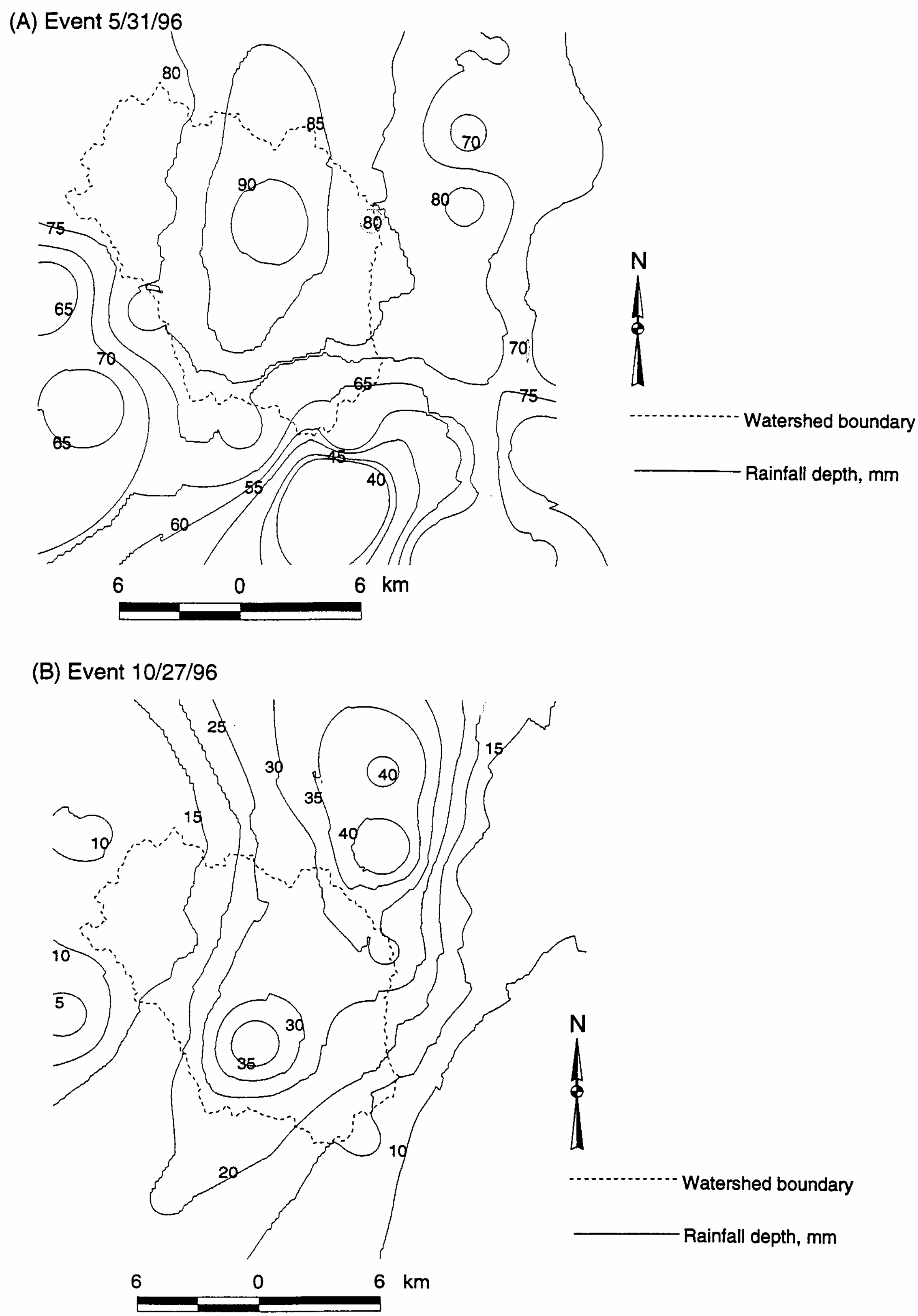

Figure 3. Isohyetal Map of Rainfall Depth that Occurred on May 31, 1996, and October 27, 1996, Over Cement Watershed.

TABLE 3. Output Uncertainty Induced by the Spatial Variability of Rainfall.

		Output Values for Rainfall Dates				
output	**Statistic**	**March 27,1996**	**April 21, 1996**	May **31, 1996**	**July 9,1996**	Oct r **27, 1996**
Runoff Volume (mm)	Observed	0.51	0.76	3.05	1.52	0.25
	Average	0.51	1.02	2.03	1.52	0.25
	Range	0-1.27	0-6.1	0.25-4.32	0-9.14	0-1.52
	CV	0.75	1.56	0.5	1.84	2.29
	SE	0.51	1.52	1.52	2.54	0.51
	RE	0.67	1.15	0.41	1.27	1.09
Total Sediment (Mg)	Simulated*	242	443	3390	2370	68
	Average	282	267	2760	2450	93.4
	Range	0-621	9-1610	398-5420	0-13580	0-802
	CV	0.76	1.54	0.43	1.65	2.4
	SE	211	436	1320	3930	219
	RE	0.75	0.82	0.3	1.23	1.82
Sediment-N (kg1ha)	Simulated*	0.07	0.1	0.53	0.39	0.02
	Average	0.07	0.067	0.44	0.34	0.02
	Range	0-0.13	0-0.29	0.1-0.75	0-1.60	0-0.17
	CV	0.71	1.29	0.36	1.47	2.15
	SE	0.04	0.09	0.18	0.48	0.04
	RE	0.59	0.73	0.25	1.01	1.4
Sediment-P (kglha)	Simulated*	0.03	0.06	0.27	0.2	0.01
	Average	0.03	0.03	0.22	0.17	0.01
	Range	0-0.07	0-0.15	0.04-0.37	0-0.81	0-0.08
	CV	0.7	1.24	0.37	1.47	2.17
	SE	0.02	0.04	0.09	0.25	0.02
	RE	0.61	0.72	0.26	1	1.36

*Simulated using spatially variable 'true rainfall pattern and calibrated parameters.

total sediment, sediment-attached N, and sediment-attached P was 0.51-2.54 mm, 211-3930 Mg, 0.04-0.48 kg/ha, and 0.02-0.25 kg/ha, respectively. For all outputs the smallest SE in rainfall resulted in the smallest SE in outputs. The SE in estimated output increased with an increase in rainfall SE. The same result is evident with RE. The smallest RE in output occurred on May 31, 1996, and was associated with the rainfall having the smallest RE.

Coefficient of variation and RE in estimated outputs were larger than the corresponding CV and RE in rainfall for all events. This shows that the uncertainty in estimated runoff, total sediment, sediment-attached N, and sediment-attached P using a single rainfall depth, as measured by CV and RE, can be expected to exceed the input rainfall uncertainty. A similar result was reported by Faures *et al.* (1995) on a small watershed (< 5 ha). This has an important implication for parameter estimation during model calibration if a single rain gauge is used to measure input rainfall. If the spatial homogeneity of rainfall is assumed during the parameter estimation process, the variation in the modeled outputs could be mistakenly attributed to the model shortcomings. The results of this study show that even for physically based distributed parameter models, an output uncertainty will result if the spatial variability of rainfall is not taken into account.

In general, a larger range in input rainfall values in a single event resulted in a larger range in modeled runoff volume, total sediment, sediment-attached N, and sediment-attached P transport. When compared with the observed output values, a large variability in the estimated output is evident for all events for both watersheds. All of the events, except on May 31, 1996, had rainfall measured by at least one gauge which was too small to produce any significant output. Rainfall input error, measured as CV and RE resulted in magnified output errors with a fixed set of parameters. Estimated output varied from few folds to several orders of magnitude when compared with the observed outputs.

Bias in Modeled Output due to Rainfall Spatial Variability

Biases in the modeled runoff volume, total sediment, sediment-attached N, and sediment- attached P are shown in Table 4. The bias is represented as a percent deviation of average output from the observed output. The modeled average outputs are the average of 17 outputs, each corresponding to one rainfall at a time. The positive values of the bias represent the underestimation and negative values represent overestimation of the modeled output compared to the observed outputs.

TA13LE 4. Bias in Modeled Outputs Due to Rainfall Spatial Variability.

Rainfall Date	Runoff	Total Sediment	Sediment-N	Sediment-P
Mar. 27, 1996	0	-16	0	0
Apr. 21, 1996	-31	40	40	33
May 31,1996	34	19	17	15
July 9, 1996	0	-4	15	15
Oct. 27, 1996	0	-37	0	0

In general, a bias in input rainfall resulted in a bias in modeled outputs. The biases in modeled runoff volume, sediment-attached N, and sediment-attached P were significant for all outputs for at least one event and ranged from 0 to 40 percent. The bias in the predicted results can be expected to decrease with an increase in the number of rain gauges to capture the rainfall pattern.

Relative Errors in Modeled Outputs due to Rainfall Spatial Variability

Relative errors in modeled outputs are shown in Table 5. For each event, the maximum and minimum relative errors represent a set of 17 outputs, each corresponding to the rainfall observed at one of the Micronet stations. The maximum relative errors in predicted runoff volume, total sediment, sedimentattached N, and sediment-attached P were 6.74, 10-74, 6.5, and 6.2, respectively, for all events analyzed. The maximum relative error in runoff volume occurred at gauge location 163 on April 21, 1996. The rainfall relative error was maximum at this site for all events analyzed. The maximum relative error in total sediment, sediment-attached N, and sediment-attached P occurred at the gauge 133 on October 27 1996. This gauge also observed the maximum rainfall relative error and the maximum rainfall depth for this event.

TABLE 5. Relative Errors in Modeled Outputs Due to Spatial Variability of Rainfall.

Rainfall Date	output	Relative Error Maximum	**Minimum**
March 27, 1996	Runoff Volume	1.42	0.16
	Total Sediment	1.57	0.15
	Sediment-N	1	0.17
	Sediment-P	1.13	0.12
April 21, 1996	Runoff Volume	6.74	0.04
	Total Sediment	2.64	0.07
	Sediment-N	1.89	0
	Sediment-P	1.81	0.06
May 31,1996	Runoff Volume	0.91	0.03
	Total Sediment	0.88	0.07
	Sediment-N	0.81	0.04
	Sediment-P	0.82	0.05
July 9, 1996	Runoff Volume	5.39	0.16
	Total Sediment	4.73	0.17
	Sediment-N	3.09	0.14
	Sediment-P	3.05	0.13
October 27, 1996	Runoff Volume	3.47	0.38
	Total Sediment	10.74	0.29
	Sediment-N	6.5	0
	Sediment-P	6.2	0.24

The smallest relative errors in runoff volume, total sediment, sediment-attached N, and sediment-attached P were 0.03, 0.07, 0, and 0.05, respectively. The corresponding rainfall relative errors were 0.03, 0.29, 0.29, and 0.29, respectively. The minimum relative error in runoff volume occurred on May 31, 1996, at gauge 153. The rainfall relative error at this gauge location was not minimum for the event. The smallest relative error in total sediment, sediment-attached N, and sediment-attached P occurred at gauge 155 on April 21, 1996. Here again the rainfall relative error at this gauge location was not minimum. For this watershed, the minimum rainfall relative error did not result in the minimum output relative error. For example, a rainfall relative error very close to zero was observed at gauge 154 on April 21, 1996. However, this rainfall did not produce the minimum output relative error. A gauge-observed rainfall greater than the area-weighted rainfall was needed to get the minimum output relative error. This may have been due to the non- linearity of the model under consideration. Assuming that the output modeled by Equation (1) is non-linear in terms of input I, and parameters P, the average response of the non linear systems will not be equal to the average of the responses evaluated at average input and parameter values. Mathematically it can be represented as

$$\underline{O*} \neq f(\underline{I*}, \underline{P*}, t) \quad (6)$$

where $\underline{Q*}$ is the modeled average output, $I*$ is the average input values, and $\underline{P*}$ is the average parameter values. In other words, the expected value of the output is not equal to the functional relationship of the expected values of the input variables.

Similar relative errors in the model outputs are reported in a limited number of studies conducted using spatially variable rainfall inputs. Faures *et al.* *(1995)* reported that even for a very small watershed *(< 5* ha), spatial variability in input rainfall could translate into a large variation in the modeled runoff. The CV in runoff rate was found to range from 0.02 to *0.65* when five model outputs were obtained using input from one of the five recording gauges, one at a time. Goodrich *et al. (1995)* reported a relative variation in modeled runoff volume up to 0.43 when two gauges were used independently as input for a runoff model in three small catchments 0.4 to 4.4 ha in size. Shah *et al. (1996)* found the relative errors in runoff volume to range from 0.01 to *0.16* for a *10.6* km2 catchment in the United Kingdom. The errors were observed to increase with an increase in the rainfall spatial variability.

Young *et al. (1992)* applied a spatially variable modeled storm on a *6500* ha watershed. The maximum relative errors in runoff volume, sediment yield, total N, and total P transport predicted by AGNPS were found to be *0.85, 3.26, 3.29,* and *5.15,* respectively. Luzio and Lenzi *(1995)* applied grid-based rainfall values on a 77 km2 watershed in Italy. The true rainfall pattern was captured using five rain gauges and a spline method of interpolation. The authors reported maximum relative errors in predicted runoff volume, total sediment, total N, and total P as *0.08,* 0.17, *0.21,* and *0.19*, respectively, using the AGNPS model. The main difference between our study and the research reported by Young *et al.* (1992) and Luzio and Lenzi *(1995) is* the size of the watershed and number of gauges available to capture the rainfall spatial variability. The results reported by Young *et al. (1992)* were based on modeled rainfall data. A modeled rainfall may not describe the patterns and amounts of real rainfall adequately. The study of Luzio and Lenzi was based on a small watershed with a small number of gauges available to measure the true rainfall pattern. In our study a larger number of rain gauges were available to measure the true rainfall pattern.

The variability in the modeled runoff volume, total sediment, sediment-attached N, and sedimentattached P obtained in this study was significantly larger than the variability reported by Faures *et al.* *(1995),* Luzio and Lenzi *(1995),* and Shah *et al. (1996).* This could have come from the larger size of the watershed studied in this research. This variability can be expected to increase with an increase in the watershed size because the rainfall variability increases with watershed size and the rainfall input error is magnified in the modeled outputs.

CONCLUSIONS

The variability induced in H/WQ model outputs solely due to spatial variability of rainfall was assessed using the AGNPS model and rainfall data measured by 17 rain gauges in a rural watershed in Oklahoma. The following conclusions were drawn from the study:

1. In the application of H/WQ models, the assumption of the spatial homogeneity of the rainfall may not be valid.
2. Spatial variability of rainfall introduces uncertainty into model outputs when uniformity of rainfall is assumed.
3. Spatial variability of rainfall should be captured and used in H/WQ models in order to accurately assess the release and transport of pollutants. Since rainfall is a driving force behind many kind of pollutant release and subsequent transport mechanisms, ignoring this property of rainfall in the application of H/WQ models will put a limit on the accuracy of the model results.

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