Final Report RSC 3345

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DEMONSTRATION TO CHARACTERIZE WATERSHED RUNOFF POTENTIAL BY MICROWAVE TECHNIQUES

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by

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TEXAS A&M UNIVERSITY
REMOTE SENSING CENTER
COLLEGE STATION, TEXAS

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DEMONSTRATION TO CHARACTERIZE WATERSHED RUNOFF POTENTIAL BY MICROWAVE TECHNIQUES

BACKGROUND AND OBJECTIVES

Background

Microwave systems have the unique capability to sense conditions to some depth near the surface when appropriate longer wavelengths are used. Shorter wavelengths in the microwave region are sensitive to vegetation and surface roughness. The wavelength used by the Passive Microwave Imaging System (PMIS) is 2.8 centimeters which is in an intermediate area with regard to penetration ability and vegetation sensitivity. This system cannot be expected to sense conditions in bare soil to depths greater than one to two centimeters and should be sensitive to any significant vegetative cover or roughness of the surface.

The near surface characteristics of drainage areas have a major influence on the proportion of rainfall that runs off from the surface. These characteristics such as storage capacity of the soil, volume of storage in vegetative matter and volume of storage available in local depressions are expressed in empirical watershed runoff equations as one or more coefficients. Conventional techniques for estimating coefficients representing the spatial distribution of these characteristics over a watershed drainage area are subjective and produce significant error in estimates of flood volumes. Poor estimates of flood flows in turn lead to inefficient design of flood control structures and indirectly result in reduced water quality in the regions where evaporation is high.

The most common empirical watershed storm runoff equation (Eq.1) was developed by the Soil Conservation Service (SCS) [1]. The SCS runoff equation can be written:

$$Q = \frac{\left(P - \frac{200}{CN} + 2\right)^2}{\left(P + \frac{800}{CN} - 8\right)} \qquad (1)$$

where

Q = runoff in inches (cm/2.54)

P = precipitation in inches (cm/2.54)

CN = dimensionless coefficient representing the composite of surface-storage characteristics

The characteristics of the near surface are described in this equation as a single coefficient called the curve number (CN). The conventional technique for selection of the appropriate CN value for a watershed involves selection of curve numbers from a series of tables that relate soil type, cover type and condition, tillage practices and antecedent rainfall to estimates of a curve number. When a curve number is needed for a non-homogeneous drainage area, the area is subdivided into relatively homogeneous areas and curve numbers for each are weighted to produce an estimated curve number for the composite area. Obviously, the selection of accurate classes for each sub-area and the validity of the table values provide complex opportunities for inaccurate estimations of curve numbers.

Average curve numbers from highly instrumented watersheds in central Oklahoma have been related to linear combinations of reflectance from Landsat data [2] when dormant and extremely dry soils conditions existed. The technique proved repeatable under the same restricted conditions on the same watersheds. Dry and dormant conditions are seldom found over large areas at the same time; thus, the Landsat technique is limited severely. The analysis did provide some insight into the fact that sensing of the soil differences was an essential requirement of any remote measurement related to the curve number. Longer wavelengths (microwave region) will be required to provide some response to soils differences when soils cannot be seen with visible light due to cloud cover and moderate amounts of vegetation covering the surface.

A preliminary study of the feasibility of measuring average curve numbers with the PMIS microwave imager was made in 1974 [3]. In that study, eight small watersheds within the same area as the Landsat study were imaged during dormant and growing seasons. The resulting data indicated that even though the PMIS imager cannot effectively penetrate vegetation, it provided an average horizontal antenna temperature that correlated well with average runoff curve numbers. Satisfactory results could be obtained by imaging the watersheds when vegetation was dormant; however, the extremely dry conditions required for the Landsat technique were not necessary for the microwave system. The relation between average horizontal polarized antenna temperature and average SCS curve numbers determined in the previous study is illustrated in Figure 1.

Objectives

This study was directed toward the testing of the PMIS as a source of microwave data that could be used to predict curve numbers for watersheds ranging from two to twenty square kilometers in area. Two groups of ten or more watersheds were to be selected where PMIS-microwave, photographic and thermal data were available over relatively small watersheds. One group of these watersheds was to be used for development of a prediction scheme while the remaining group would serve to test predictions. The origi-

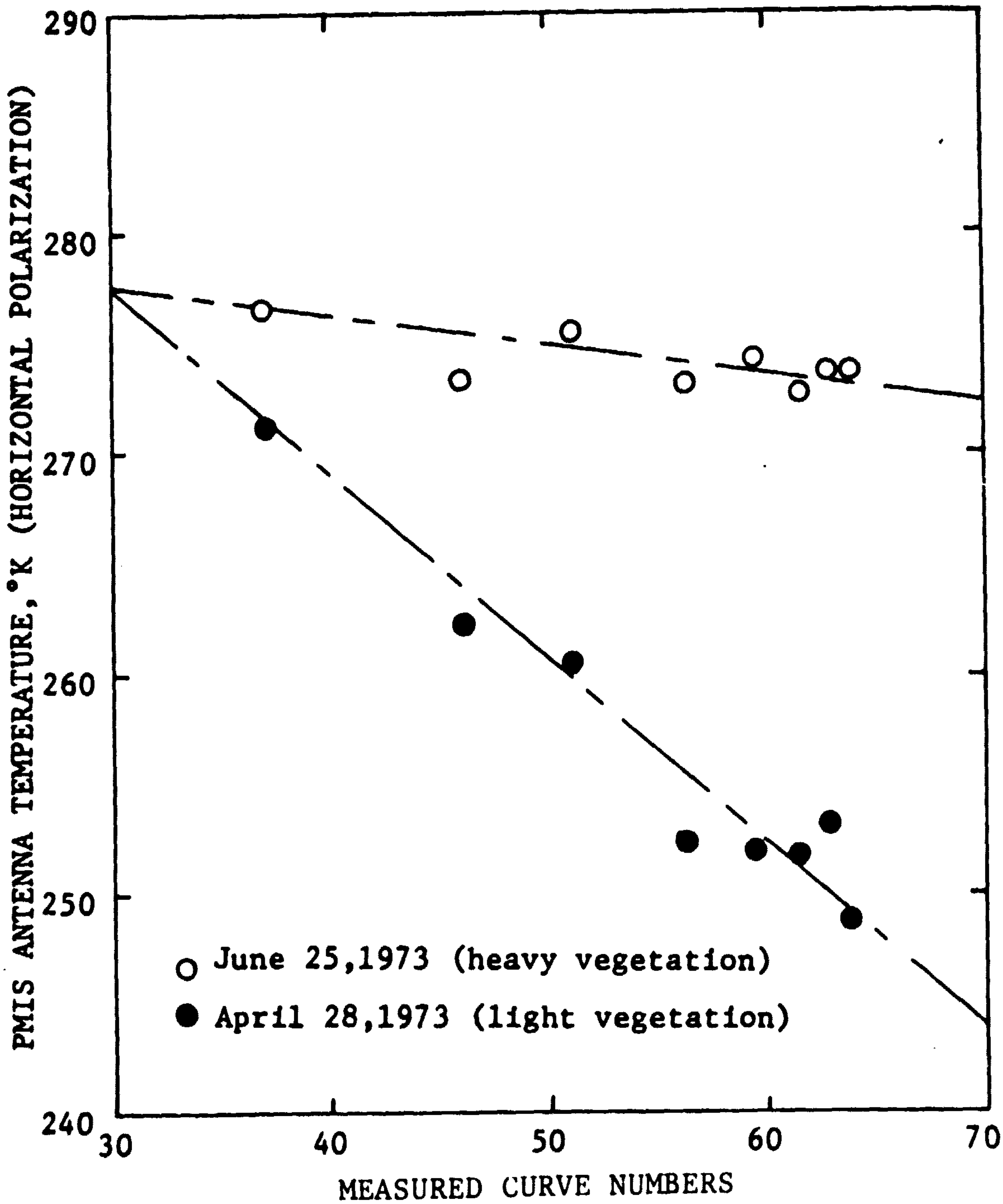

Figure 1. The relation between average horizontal polarized microwave temperature and average storm runoff curve numbers.

nal proposal stated in part that the watersheds would be selected "where reliable measurement of rainfall and runoff are available."

The objective of this work was to demonstrate that watershed runoff coefficients can be effectively predicted using microwave techniques for ungauged watersheds when a small number of gauged watersheds are available for calibration.

DATA SOURCES AND PROCESSING

Aircraft Sensor Data

As a portion of aircraft mission 295, May 3, 1975, flights were made over numerous small watersheds located in south central Texas, north central Texas and north central Oklahoma (Figure 2). Sensors used on the aircraft included the PMIS, the M^2S thermal band scanner, the PRT-5 thermal sensor and one nine inch format, six inch focal length camera with color infrared film. Data were supplied by NASA/Johnson Space Center in the form of nine track tapes for microwave and thermal data and photographic data were supplied as color transparencies.

The data quality for each of the sensors used appears to be good. Digital data for the PMIS were available as output from the "revised" data analysis system

Figure 2. Geographical Location of Watersheds

after corrections had been made to software in 1976. The data, therefore, should not have geometric and cross polarization problems that were present in previous missions.

Watershed Data

Adequate long term data on small watersheds in Texas and Oklahoma are almost non-existent. Watersheds used in this study have, in general, two types of data. The majority have only one measurement set collected by SCS personnel as part of their evaluation of the effects of one major storm event. Ten of the watersheds used were sub-watersheds located in tributary watersheds that had been instrumented with rain gauges and water state recorders by the United States Geological Survey (USGS). These areas were part of a long term cooperative study by the USGS and SCS to determine the effects of flood detention reservoirs on the stream flow. The records on this limited set of watersheds are of good quality; however, the period of record for each watershed does not exceed twelve years.

Thiessen-weighted rainfall was calculated for all rainfall events and compiled with the appropriate storm runoff in inches. For the watersheds with single events, compilation of raw data was made by SCS hydrologists from Temple, Texas and Stillwater, Oklahoma state offices. Weighted rainfall and storm runoff for the remaining watersheds was available from publications provided by the USGS. Each watershed used in the study discharged into an SCS flood detention reservoir for which a curve number had been estimated by the conventional SCS method. The conventional curve numbers were supplied by SCS hydrologists for comparison to curve numbers calculated from measurements.

Aircraft Data Processing

Photo mosaics of the positive transparencies along each flight line were prepared as a base map. Watershed boundaries were then outlined on the transparencies to define the drainage area of interest on each flight line.

The nine track tapes of PMIS data were then mapped using programs recently developed in another study. The mapping technique allows adjustment of scale such that maps of the PMIS data can be matched to wet areas of water bodies in the mosaic. A direct overlay for each mosaic was prepared and the drainage area boundaries were transferred to the PMIS map. Beam positions falling within the drainage area can then be readily identified. Using scan line numbers and beam positions

Using scan line numbers and beam positions to identify boundaries on the PMIS data, a secondary computer program was used to compute average vertical and horizontal polarized antenna temperatures from the tapes. The technique for mapping the PMIS data is described in greater detail in a previous report [4].

A similar technique was used to identify the M^2S thermal data that represented surface temperature for each watershed. Average surface temperatures were calculated for each drainage area in order to normalize the microwave data taken at different times of the day over a relatively large geographical area.

Watershed Data Processing

With the rainfall and runoff known for a storm event over a watershed, Eq. 1 can be solved to determine the effective curve number.

$$CN = 1000/10 + \left\{5\left[(P + 2Q) - \sqrt{4Q^2 + 5PQ}\right]\right\} \qquad (2)$$

A curve number determined for a single storm using Eq. 2 is a unique value representing the response of the watershed surface during that particular storm.

Average watershed runoff curve numbers were used in the prior study [3] of PMIS response over watershed surfaces. Obviously, when only one storm event was available for a watershed, the average value has little significance. Averages over the ten watersheds which had a ten to twelve year period of record with twenty to thirty storm events are comparable to data used in the previous study. For these reasons, there are only ten watersheds considered in this study where valid averages can be calculated.

Studies by Hawkins have shown the SCS runoff equation does not fully describe the effect of storm rainfall [5]. His results can be verified to some extent with data collected for this study. Generally, curve numbers calculated from measured rainfall and runoff tend to be smaller for larger storms. There is, however, some scatter from a mean curve through the points. This scatter was attributed to variations in storm characteristics, intensity, duration, etc. or seasonal differences in the watershed vegetative cover.

Even with the evident scatter in the data, the Hawkins approach appears to offer a means for normalizing data between watersheds with adequate and inadequate numbers of measured storms. Therefore, a curve number designated CN_7 was calculated by Hawkins techniques for a design storm of seven inches rainfall by using the following equations:

$$CN_7 = 100\left(\frac{2 + 7k}{9}\right)$$

where

$$k = \left(\sum_{i=1}^{i=n} \frac{CN_i - CN_{oi}}{100 - CN_{oi}}\right) / n$$

$$CN_i = 1000/(10 + 5[(P_i + 2Q_i) - \sqrt{4Q_i^2 + 5P_iQ_i}\,])$$

$$CN_{oi} = 200/(P_i - 2)$$

P_i = measured precipitation (cm/2.54)

Q_i = measured runoff (cm/2.54)

Composite Data Sets

Average surface temperatures and average antenna temperatures are shown in Table 1. The original average antenna temperatures have been normalized for surface temperature differences to an arbitrary 300 degree Kelvin level in order that bias due to climatic differences in the watershed locations would be reduced. The resultant temperatures in the last columns can then be related to differences in surface conditions.

Data compiled in Table 2 represent the curve numbers derived from three approaches. For the watersheds having adequate records, an average of curve numbers computed from actual measurements are shown in the first column. The second column of curve numbers were calculated from one or more measurements by using Hawkins technique. The third column of curve numbers were acquired from the SCS hydrologist and from published watershed work plans.

Table 3 contains aircraft data for three watersheds that were imaged twice in different flight lines. Only one of the repeated lines over each site was used in Table 2. Generally,the flight line that centered best over the watershed and was flown in an upstream direction was used.

Table 1

No.	Name	Thermal & Microwave Temperatures T_q	T_h	T_v	Normalized Antenna Temperature T_h	T_v
1	Cow Bayou 2	299.3	268.4	278.1	268.5	278.1
2	Escondido 11	293.6	271.7	279.9	277.2	285.6
3	Deep 3	293.5	272.8	280.0	278.4	285.9
4	Deep 8	302.9	273.3	282.1	270.0	278.7
5	Mukewater 9	301.2	269.1	280.9	267.3	279.3
6	Green 1	303.6	275.8	282.2	271.8	278.4
7	Honey 12	303.6	268.0	279.6	264.0	275.7
8	Honey 11	302.4	263.8	276.9	260.7	274.2
9	Little Elm 10	300.4	269.6	280.8	268.5	279.9
10	Elm Fork 20	301.0	254.5	273.7	252.6	272.1
11	Nolan 14	292.4	272.2	273.2	278.7	279.9
12	Nolan 15	292.6	266.3	274.6	272.4	281.1
13	Nolan 12	293.0	272.7	274.6	278.7	280.8
14	Nolan 13	294.0	272.0	274.7	277.2	279.9
15	Nolan 10	294.1	264.0	272.0	268.5	276.9
16	Nolan 9	294.0	266.9	276.4	271.8	281.7
17	Nolan 1	300.3	262.9	280.5	261.6	279.6
18	Nolan 3	295.6	269.4	277.3	272.7	281.1
19	Red Rock 14	296.3	256.5	273.3	258.6	276.0
20	Red Rock 40	294.5	256.3	271.4	260.1	276.0
21	Red Rock 18	294.0	262.1	277.3	266.7	282.6
22	Red Rock 37	293.5	261.7	274.1	266.7	279.6
23	Red Rock 22	294.9	259.5	271.3	263.1	275.4
24	Red Rock 24	293.1	259.9	273.8	265.2	279.9
25	Red Rock 25	293.2	262.6	273.0	267.9	278.7
26	Red Rock 33	294.0	254.9	274.0	259.2	279.0

Table 2

WATERSHED			CURVE NUMBER		
No.	Name	Area (km^2)	Average	Hawkins (CN_7)	Conventional SCS
1	Cow Bayou 2	13.6	73.3	50.9	80
2	Escondido 11	21.8	68.0	50.9	80
3	Deep 3	8.8	69.2	51.2	83
4	Deep 8	14.1	71.0	54.2	83
5	Mukewater 9	10.4	74.5	57.4	77
6	Green 1	8.7	72.8	56.6	76
7	Honey 12	3.3	84.9	77.8	83
8	Honey 11	5.6	81.0	72.7	69
9	Little Elm 10	5.5	87.0	81.6	83
10	Elm Fork 20	2.0	86.1	76.2	83
11	Nolan 14	2.3		69.7	81
12	Nolan 15	3.5		71.5	82
13	Nolan 12	4.2		72.9	82
14	Nolan 13	2.9		71.9	82
15	Nolan 10	9.6		69.2	82
16	Nolan 9	9.3		77.6	81
17	Nolan 1	14.3		90.8	82
18	Nolan 3	22.8		78.9	81
19	Red Rock 14	3.8		87.1	80
20	Red Rock 40	9.8		61.7	80
21	Red Rock 18	7.4		67.2	80
22	Red Rock 37	3.0		72.4	80
23	Red Rock 22	13.3		93.7	80
24	Red Rock 24	16.3		53.3	80
25	Red Rock 25	8.4		47.9	80
26	Red Rock 33	5.9		72.0	80

Table 3

Thermal and microwave data processed from different flight lines over the same watershed areas.

	Flight Lines			Thermal & Microwave Temperatures		
No.	Line	Run	Watershed	T_q	T_h	T_v
1	3	1	Nolan 14	292.2	266.4	274.2
2*	4	1	Nolan 14	292.4	272.2	273.2
3*	5	1	Nolan 10	294.1	264.0	272.0
4	6	1	Nolan 10	294.7	264.9	277.4
5	23	1	Red Rock 40	295.4	256.2	272.1
6*	24	1	Red Rock 40	294.5	256.3	271.4

* used in plots

Antecedent precipitation index as an indicator of probable moisture conditions on each watershed are listed in Table 4. These values were calculated from rainfall in the preceeding month before the aircraft data were acquired and are based on data available from the National Weather Service for gauges near each study watershed.

ANALYSIS OF DATA

Horizontal Polarized Antenna Temperature

Considering the results of the previous study [3], average curve numbers available were plotted versus horizontal antenna temperatures that had been normalized for surface temperature differences (Figure 3). The data are comparable in quality to the data from the Chickasha, Oklahoma watersheds in regard to the amount of storms available, length of record and quality of records. Therefore, both the Oklahoma and Texas instrumented watersheds are included in Figure 2.

A similar trend in the data for the Texas watershed is evident, however, the two data sets are offset and the Texas data exhibits more scatter. A regression line was calculated for both sets of data. These regression lines have R^2 values of .937 for the

Table 4

NO.	WATERSHED NAME	RAINFALL STATIONS AND API	WEIGHTED API
1	Cou Bayou 2	McGregor, .268; Waco, .216	.216
2	Escondido 11	Kennedy, .000	.000
3	Deep 3	Fife, .051; Brady, .055	.052
4	Deep 1	Fife, .051, Brady, .055	.052
5	Mukewater 9	Brownwood, .147	.147
6	Green 1	Dublin, .192	.192
7	Honey 12	Gunter, .877; McKinney, .646; Anne, .560	.690
8	Honey 11	Gunter, .877; McKinney, .646; Anne, .560	.690
9	Little Elm 10	Gunter, .877; Pilot Point, 1.256; Celino, .718	1.256
10	Elm Fork 20	Meunster, 1.256	1.256
11-18	Nolan Creek	Stillhouse, H., .276; Killeen, .289; Belton, .230	.289
19-26	Red Rock	Garber, 574; Enid, .544	.574

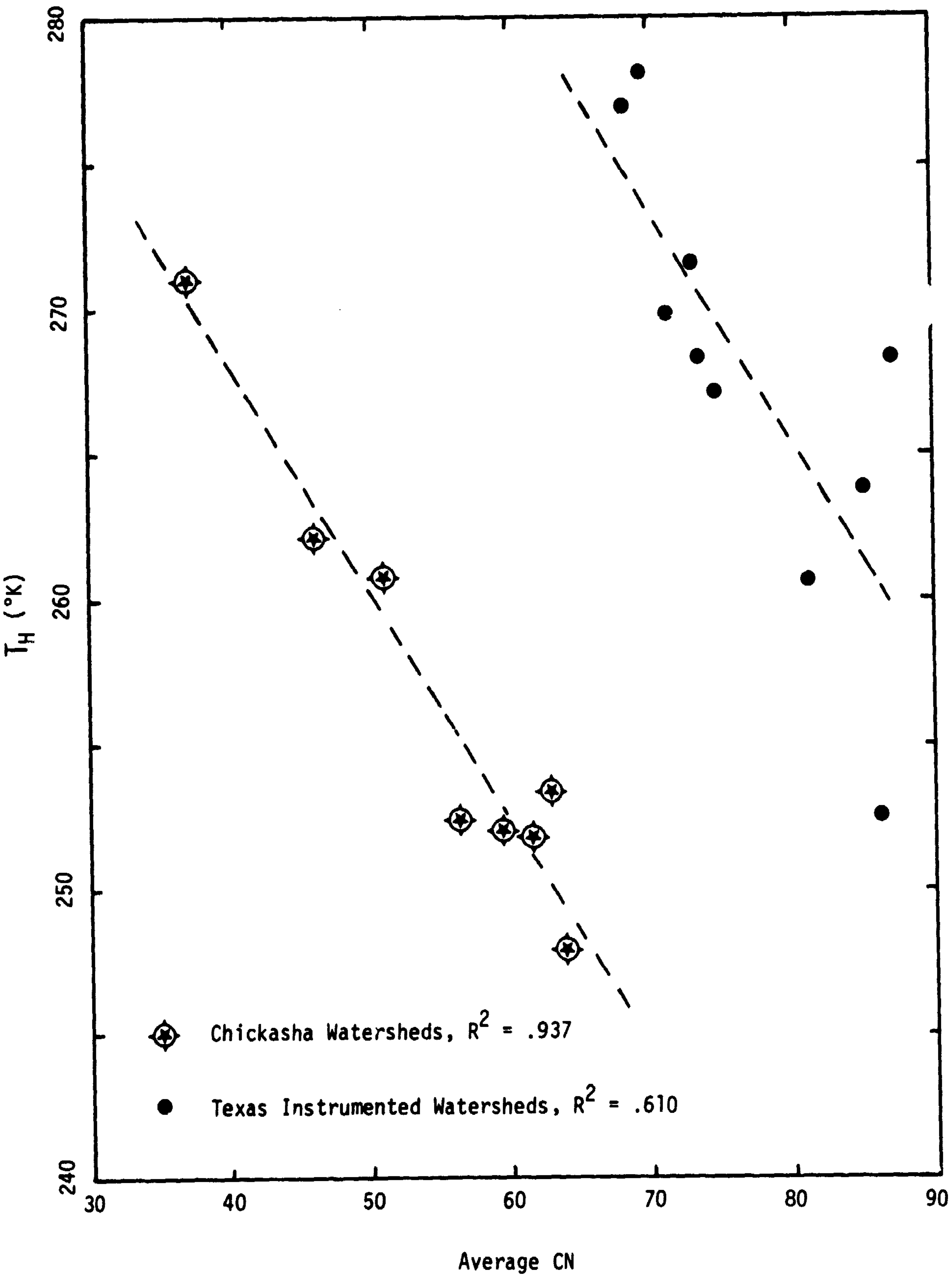

Figure 3. Comparison of horizontal polarized antenna temperatures from well instrumented watersheds in Texas with prior data for well instrumented watersheds at Chickasha, Oklahoma.

Chickasha data and .610 for the Texas data. This figure illustrates that with similar quality data the trend toward higher curve numbers is indicated by a lowering of the horizontal polarized antenna temperatures.

The increased scatter and lower R^2 value for the ten Texas watersheds might be expected as a result of the wide geographic distribution of the watersheds. No attempt was made to select uniform land use in the set of watersheds and over such a wide area there is considerable difference in vegetation. The antecedent precipitation index varied from nearly .05 to 1.2 over this set of watersheds. Although moderate moisture seemed to have little effect on the results of the prior study, the wide range of antecedent moisture evident in Table 4 could cause some of the scatter.

The shift in these data sets is most likely due to two major factors. First, major changes in both hardware and software components of the PMIS system were made between the times that these two data sets were collected. Most changes made were concerned with the calibration and apparently the system now produces higher final values for antenna temperature. The temperatures for the watersheds in this study do appear to be extremely high for agricultural watersheds in a moderate climate. Secondly, green vegetation seemed to produce higher temperatures in the earlier study and since the Texas watersheds were not truly dormant in the spring of 1975, the condition of the vegitation may have added to the displacement between the two sets of data.

Curve numbers derived from the Hawkins technique (CN_7) were compared with the same horizontal temperatures for the ten well instrumented watersheds (Figure 4). A straight line fit through these data results in an R^2 value of .494.

When the basis of the average curve number and the basis for a Hawkins curve number are considered, it becomes evident the numbers are not directly related unless the watersheds are all from the same geological climatic area. The average curve number is highly dependent on the mean storm precipitation or in other words, the climatic region. Both numbers are also dependent on the numbers of storms for which records are available. At best we can only consider the Hawkins curve number as good for the ten instrumented watersheds.

With these considerations in mind, the trend illustrated in Figure 4 is encouraging. Most of the increase in scatter can be attributed to climatic differences at the widespread locations of the watersheds areas.

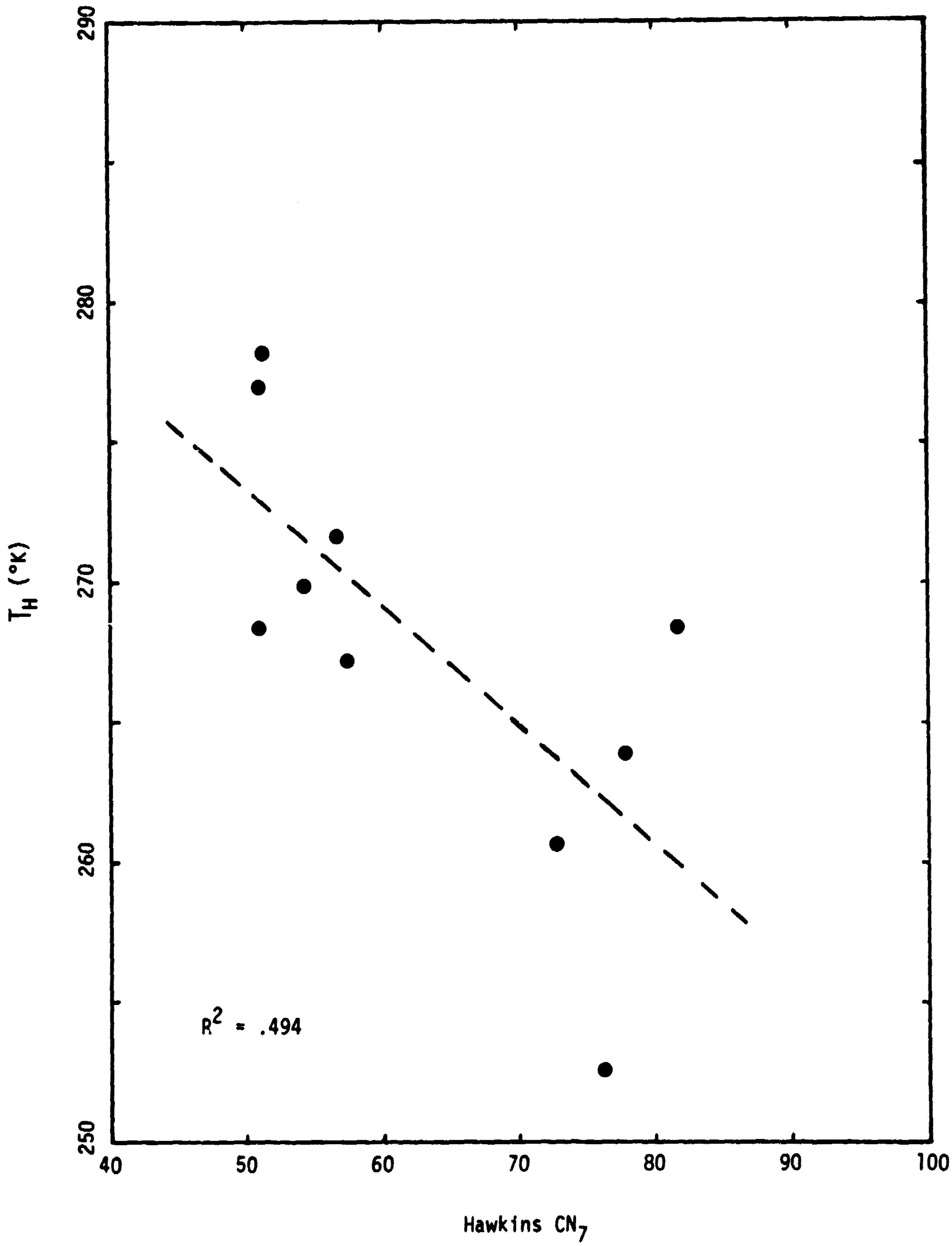

Figure 4. Relation between normalized horizontal polarized PMIS antenna temperature T_H and Hawkins curve number for well instrumented Texas Watersheds.

Other Texas Watersheds are used in Figure 5 to indicate that a trend in Hawkins curve number in relation to antenna temperature is apparent. The data for estimating the Hawkins curve number for these watersheds came from a single large storm and are less reliable than data for the ten instrumented watersheds.

Figure 6 illustrates the wide distribution of temperatures experienced for any one Hawkins curve number when all watersheds flown the same day are considered. Regression lines are shown in this figure to illustrate the disagreement between Figure 4 and Figure 5.

Quality of Data for Nolan and Red Rock Creeks

There is a possibility that curve numbers in Figure 5 are high due to over estimation of runoff volume. When calculating a curve number from a single storm with Eq. 2, either a low precipitation estimate of a high runoff estimate will produce higher curve numbers. All of the watersheds in Figure 5 were located in Nolan Creek drainage basin and curve numbers were estimated for the one storm and by one individual, therefore, these values are subjective. Precipitation data are usually of better quality than the runoff data, thus the shift is more likely to be due to poor runoff data.

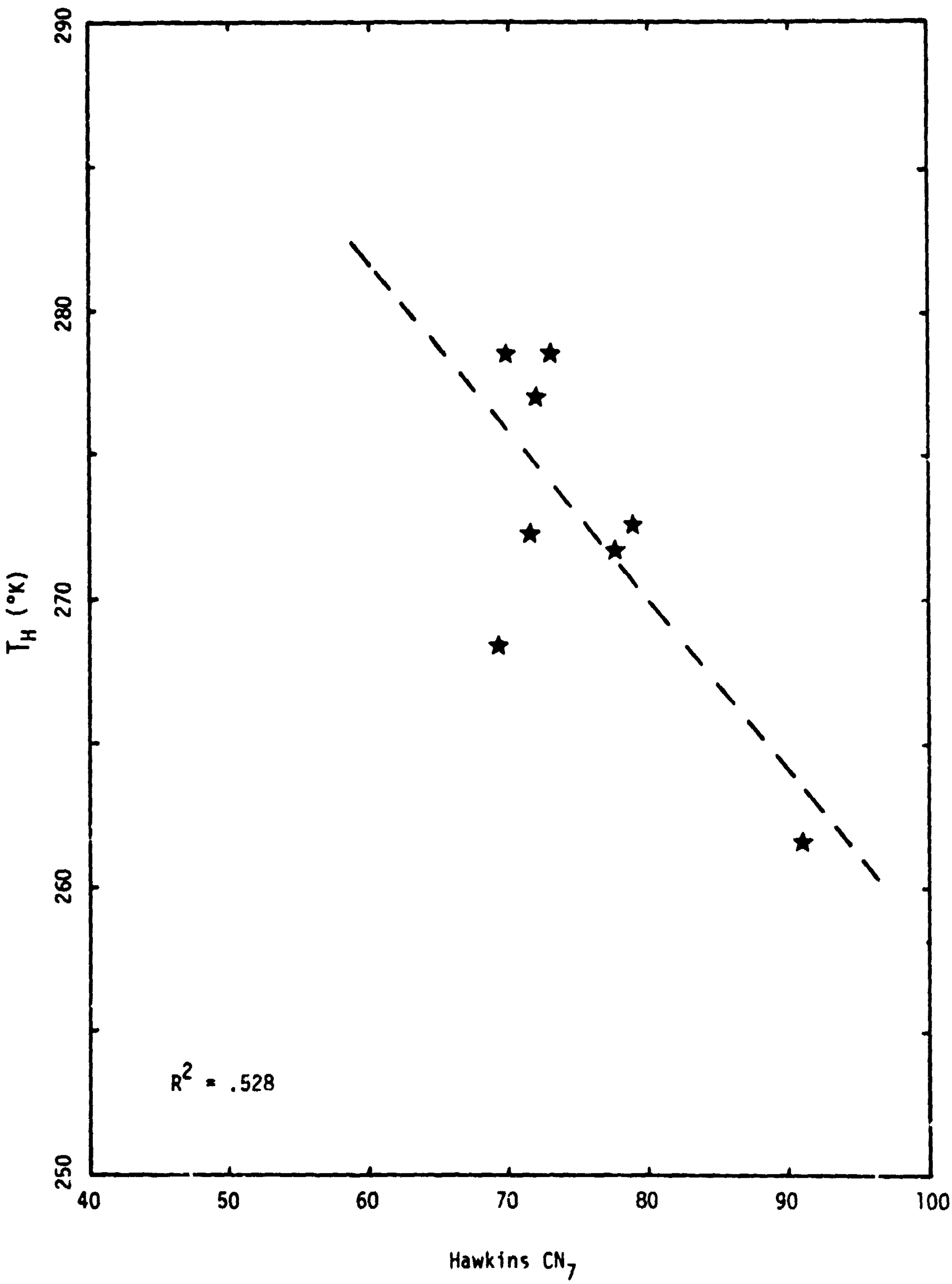

Figure 5. Relation between normalized horizontal polarized PMIS antenna temperature T_H and Hawkins curve number for Nolan Creek watersheds.

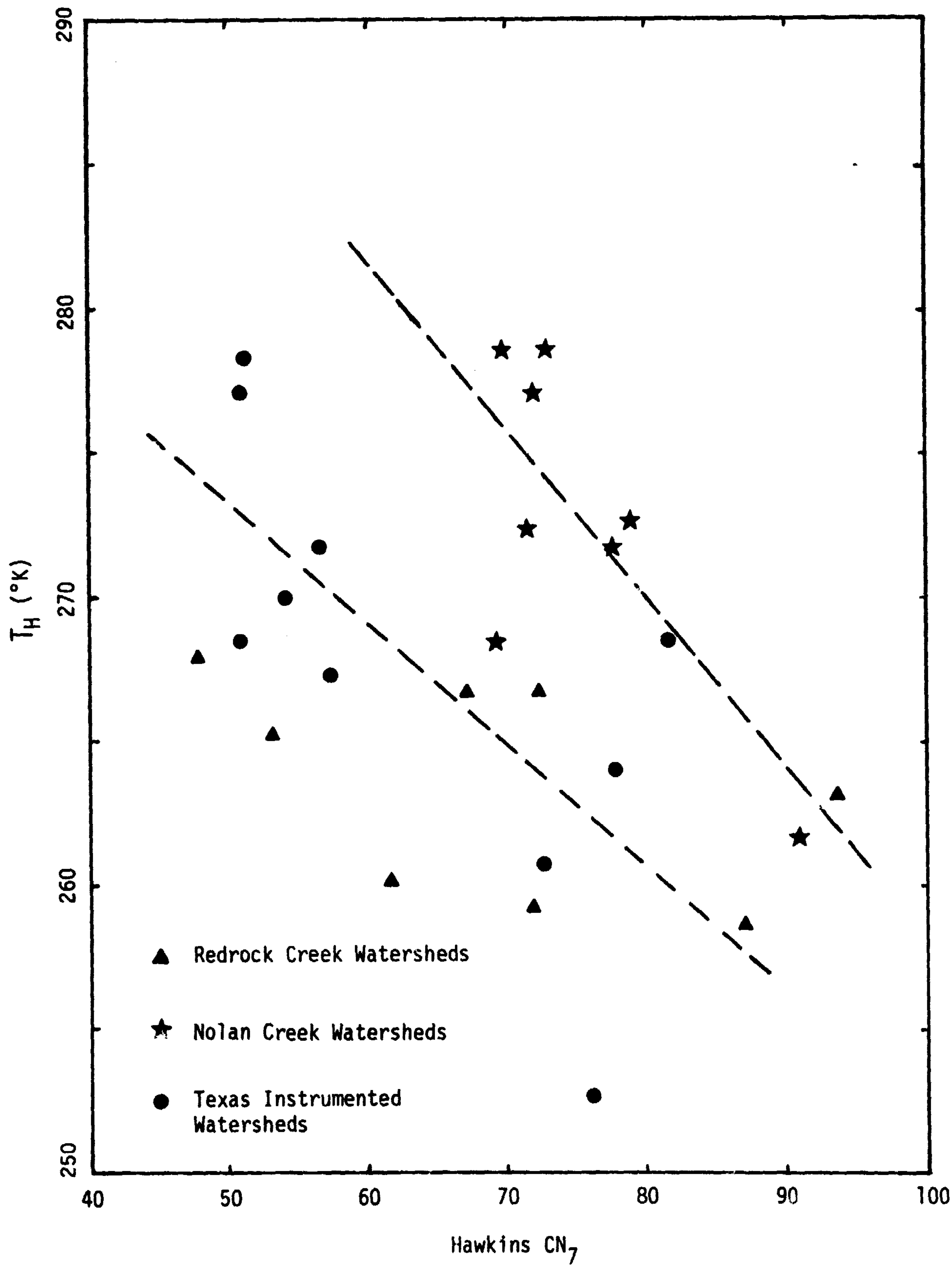

Figure 6. Relation between normalized horizontal polarized PMIS antenna temperature T_H and Hawkins curve number for all watersheds imaged in this study.

Data points shown for Red Rock Creek were derived from a massive storm where estimated rainfall on individual watersheds ranged from 5 cm to 42 cm. The wide range of rainfall and the difficulty of estimating runoff volume from watersheds where flood volumes exceeded the structure storage capacity makes the quality of the single curve numbers even more suspect than those on Nolan Creek. Data for Red Rock Creek are illustrated in Figure 7 merely to illustrate the downward trend of antenna temperatures with increases in Hawkins curve number.

Vertical Polarized Antenna Averages

Little value was found in vertical polarized PMIS antenna temperature in the previous study. Figure 8 illustrates that when all data in the current study are considered there is little if any sensitivity in PMIS vertical polarized temperatures with regard to runoff potential of watershed surfaces.

Effects of Look Angle in PMIS Images

Table 3 illustrates some variations that can be expected if care is not taken in planning the orientation of the flight line or viewing angle of the PMIS relative to the drainage pattern. The Nolan 14 Site was flown off-side the centerline of the drainage pattern in Line 3 and

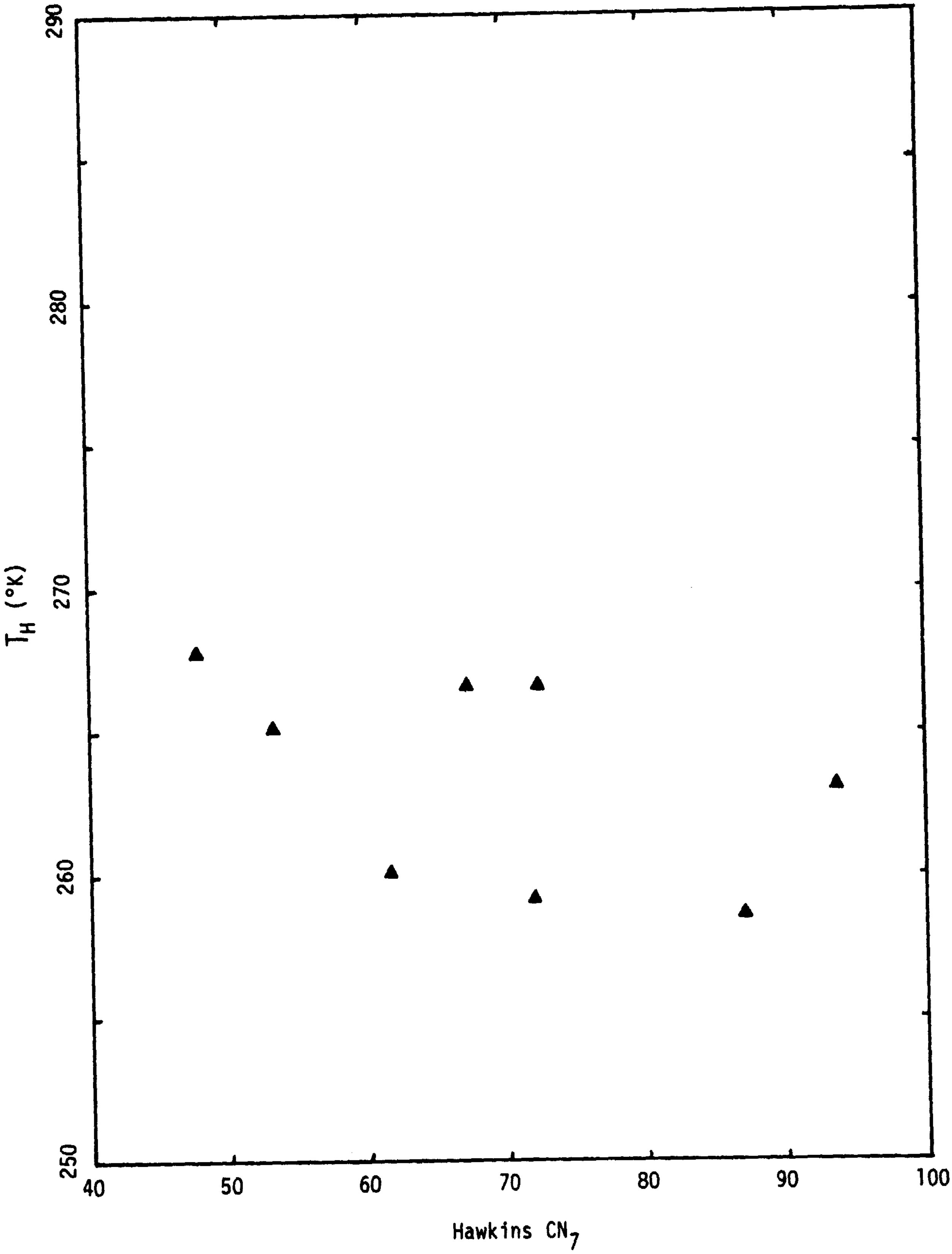

Figure 7. Relation between normalized horizontal polarized PMIS antenna temperature T_H and Hawkins curve number for Red Rock Creek watershed.

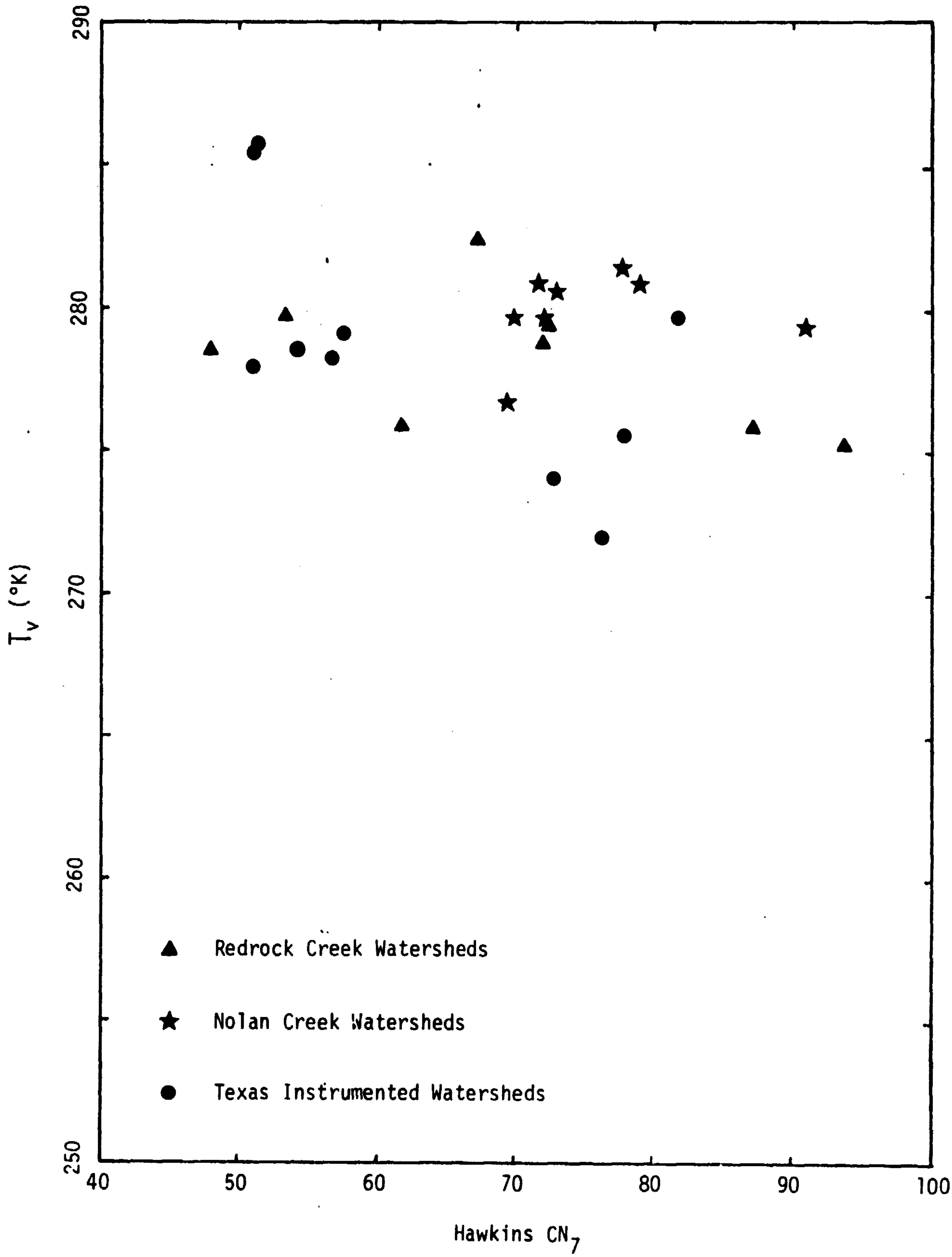

Figure 8. Illustration of the relative insensitivity of vertical polarized PMIS antenna temperature T_V to differences in Hawkins curve number.

across the drainage pattern in Line 4. Horizontal temperatures were six degrees higher for the line across the drainage pattern. Vertical polarized temperature remained constant. For the Nolan 10 watershed, Line 5 was centered with the drainage pattern and flown upstream while Line 6 was flown across the drainage pattern. In this instance the vertical polarized antenna temperature increased approximately five degrees while the horizontal antenna temperature was only increased .9 degrees when the flight line was crosswise with the drainage pattern. For the Red Rock 40 site, both lines were parallel with the drainage, however, Line 23 was off side and both polarizations produces essentially the same data.

These observations indicate that it is important to fly parallel to the drainage pattern. If this is not done, the differences in look angle with the watersheds surface can produce significant differences in antenna temperatures. It should also be noted that the downward looking cross track scan of the multispectral scanner showed no difference in average surface temperature regardless of flight direction.

Magnitude of Error in Curve Number Estimates

Examination of the conventional SCS curve numbers used on the design of flood detention structures as compared to estimates of runoff curve numbers from one or more measurements indicates the magnitude of error in design flood volume that is possible. Differences between the conventional design curve number and the relatively reliable Hawkins curve number based on a large number of storms for the instrumented Texas watersheds run as high as 29 units.

For Cow Bayou 2 or Escodido 11 a design storm, precipitation can be as high as a 25.4 cm or 10 inches. Using Equation 1 to calculate the volume of storm runoff produces 19.1 cm for the conventional method and 9.4 for the actual runoff. This would indicate the flood storage volumes used for design was 2.04 times larger than necessary. If the difference in curve number estimates from the actual curve number can be reduced to 10 units, the volume of storage could be reduced to 1.36 times the true required volume. Even a relatively poor measure may therefore produce significant reduction in construction costs.

The specific objective of this study was to test the prediction of watershed runoff curve numbers by use of the PMIS data. The amount and quality of watershed runoff data available limited the number of runoff curve numbers that can legitimately be compared. The study of these data does indicate that some reliable conclusions can be made that will benefit future use of the techniques for microwave sensing of surface conditions. It is obvious that the question arises from Figure 3 as to the present calibration of the PMIS. The question might be resolved by flying the sensor over both the well instrumented watershed in Texas and those used in the prior study in Oklahoma.

The overall implication when considering the entire set of data is that good to excellent sets of watershed data can be related to horizontal polarized bond passive microwave antenna temperatures. Good quality long term records are not available in adequate number within a single geologic and climatic domain; thus,it is difficult to calibrate the system within a hydrologic region. The quality of results from this study appear to have a direct relation to the quality watershed data available. It also became apparent in the study of these data that results could be improved if longer wavelength images were available to improve penetration through vegetation thus making the application of the technique more sensitive to soil differences and therefore more universal.

CONCLUSIONS

When good records of precipitation and runoff are available there is a relatively good linear relation between average SCS run off curve numbers and the horizontal polarized antenna temperature of the PMIS.

When only one major runoff event is available to quantify the runoff characteristics of sample watersheds, it is unliekly the PMIS data can reliably be calibrated. The relationship between curve numbers derived from Hawkins technique are more related to major storm events and are not as well correlated as average curve numbers to the X-band PMIS data.

Reduction of error in selection of design curve numbers can be relatively small yet provide significant improvement in predicting storm runoff volume.

It is apparent that care should be taken to operate the PMIS along flight lines parallel to the drainage pattern to minimize look angle effects.

Differences between this antenna temperatures for different dates indicate that the well instrumented sites in Texas and the Chickasha, Oklahoma sites should be re-flown at the same time to determine if sensor hardware and software changes are responsible for the shift in the antenna temperatures illustrated in Figure 2.

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