E82-10107
NASA-CR-167454

AgRISTARS

FC-J1-04176
JSC-17435

A Joint Program for Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing

Foreign Commodity Production Forecasting

August 1981

A GRADIENT MODEL OF VEGETATION AND CLIMATE UTILIZING NOAA SATELLITE IMAGERY

PHASE I: TEXAS TRANSECT

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(E82-10107) A GRADIENT MODEL OF VEGETATION AND CLIMATE UTILIZING NOAA SATELLITE IMAGERY. PHASE 1: TEXAS TRANSECT (Nebraska Univ.) 65 p HC A04/MF A01 CSCL 02C

N82-21648

Unclas
G3/43 00107

Lyndon B. Johnson Space Center
Houston, Texas 77058

1. Report No. JSC-17435; FC-J1-04176	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Gradient Model of Vegetation and Climate Utilizing NOAA Satellite Imagery - Phase I: Texas Transect		5. Report Date August 1981
		6. Performing Organization Code
7. Author(s) D. H. Greegor and J. Norwine		8. Performing Organization Report No.
9. Performing Organization Name and Address		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address AgRISTARS Program at Johnson Space Center NASA Houston, TX 77058		13. Type of Report and Period Covered Technical Report
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A new experimental climatological model/variable termed the sponge -- a measure of moisture availability based on daily temperature maxima and minima, and precipitation -- is tested for potential biogeographic, ecological, and agro-climatological applications. Mean monthly and annual sponge values are calculated for 75 Texas locations for the "normal" period of 1941-1970. Similar values are also computed for approximately 25 stations along an east-west transect across the State for 1979 and 1980. Results, depicted in tabular and graphic form, suggest that, as a generalized climatic index, sponge's simplicity and sensitivity make it particularly appropriate for trans-regional biogeographic studies (e.g., large-area and global vegetation monitoring.

A significant amount of research has investigated the validity of using Landsat data for remote vegetation analysis but there has been little similar use of NOAA/AVHRR meteorological satellite data. The feasibility of utilizing NOAA/AVHRR data for vegetation classification has been investigated and a vegetation gradient model that utilizes sponge and AVHRR data has been initiated. Along an east-west Texas gradient, vegetation, sponge, and AVHRR pixel data (channels 1 and 2) were obtained for 12 locations. The normalized difference (ND) values for the AVHRR data when plotted against vegetation characteristics (biomass, net productivity, leaf area) and sponge values along the Texas gradient suggest that a multivariate gradient model incorporating AVHRR and sponge data may indeed be useful in global vegetation stratification and monitoring.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Vegetation, Climate, Gradient Model, Surveys, Texas, Moisture, NOAA Satellites, Remote Sensing, Normalized Difference	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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October 1981

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I. OVERVIEW

Phase 1 of this investigation has several objectives: (1) to test a new experimental climatological model/variable termed the sponge for potential biogeographical, ecological, and climatological applications (the sponge is a measure of moisture availability based on daily temperature maxima and minima, and precipitation); (2) to investigate the feasibility of utilizing NOAA/AVHRR meteorological satellite data for vegetation classification; and (3) to initiate a vegetation gradient model that utilizes climatological (i.e., sponge), biological, and NOAA data that is ultimately applicable to global vegetation stratification and monitoring.

To accomplish the initial objective, mean monthly and annual sponge values are calculated for 75 Texas locations for the "normal" period of 1941-70. Similar values are also computed for approximately 25 stations along an east-west transect across Texas for 1979 and 1980. Results suggest that as a generalized climatic index, sponge's simplicity and sensitivity make it particularly appropriate for trans-regional biogeographic studies.

The latter two objectives were approached by acquiring vegetation, climatological (sponge), and AVHRR pixel data (channels 1 and 2) for 12 locations along the east-west Texas gradient. The normalized difference (ND) values for the AVHRR data when plotted against the vegetation characteristics (biomass, net productivity, leaf area) and the sponge values suggest that a multivariate gradient model incorporating AVHRR and sponge data may indeed be useful in global vegetation analysis.

II. THE SPONGE: A NEW ECO-CLIMATOLOGICAL VARIABLE

The planetary distribution of types of natural vegetation is largely a function of climate, most especially of spatial variations in energy and moisture budgets. As a general rule, climate is recognized as the pre-eminent control of natural vegetation at subcontinental-to global-scales. For small areas, geologic, pedologic and other local factors may dominate for long, even indefinite, periods of time.

Natural scientists such as ecologists and biogeographers have attempted to utilize climatic measures and indices in surveys, stratifications and classifications of natural vegetation. Typically, it is assumed that most major ecoregion and native vegetation-region "boundaries" actually represent climatic discontinuities or "breaks". This assumption, while not entirely valid, probably is reasonably accurate.

A key problem for such scholars has been the determination of a simple but accurate climatic "index" (or indices) which would reflect the primary spatial variations in moisture and energy balances and, hence, could be applied to the classification of native vegetation. Climate itself, a complexly synergistic synthesis of many variables, does not readily succumb to quantitative classification. [For example, what is the "real" boundary between a desert and a (semi-arid) steppe? In fact, of course, there is no abrupt statistical limit but rather a gradual transition from one type into another.]

Identifying and quantifying climatic factors which explain the distribution of natural vegetation is even more challenging. Temperature and precipitation by themselves are poor descriptions of climate and, hence, explainers of vegetation distributions (Mather and Yoshioka, 1968).

It is therefore essential to select and/or develop climatic indices which influence vegetation growth and development. Most recent approaches to this problem emphasize the importance of moisture availability (e.g., surpluses versus deficits) and, more specifically, evapotranspiration. Unfortunately, evapotranspiration is measured at very few places, and even evaporation itself is not widely monitored. Numerous models have been developed which estimate evaporation from measurements of air temperature, average wind speed, and net radiation (Penman, 1948; Jensen et al, 1970), but their usefulness is constrained by the sparcity of stations which record solar radiation and wind speed.

Simpler evapotranspiration schemes which require only air temperature and precipitation -- both commonly measured around the world -- have been devised (e.g., Thornthwaite, 1948; Griffiths, 1964; Moe, 1965; Trenchard, 1976). Thornthwaite's classification made use of mean monthly temperature and precipitation values to generate a moisture index. Because of its relative simplicity and accuracy, Thornthwaite's approach has been widely adopted (e.g., it is used to calculate the USDA's Crop Moisture Index). However, its use of average monthly temperatures somewhat limits its sensitivity to variations in continentality and altitude.

An alternate method of relating climate to vegetation is that of multivariate discriminant analysis of climatic variables to determine their relative influence in a particular ecoregion (e.g., Biogeoclimatic Units of Vancouver Island, Klinka and Nuszdorfer, 1979). While very accurate for detailed, site-specific studies, the resulting multiple regression equations tend to be (a) cumbersome and lengthy, and (b) less applicable to regional and global-scale vegetation classifications.

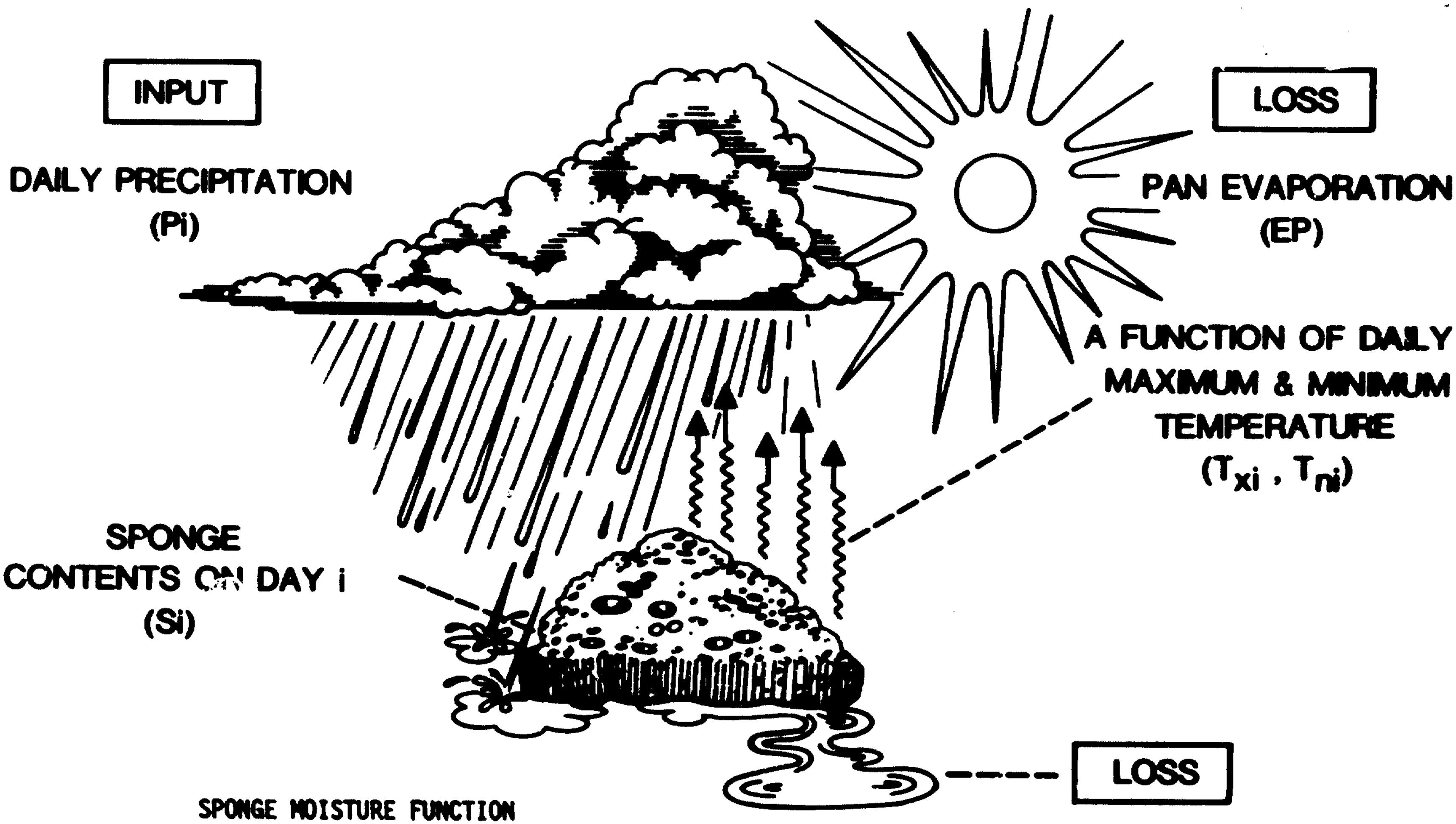
Thus climatologists, geographers, and ecologists interested in large-area comparisons have found themselves forced to choose between an approach which stratifies climate somewhat too broadly (e.g., Thornthwaite's) and another which "hides the forest in the trees", viz., too much emphasis on detail (e.g., Klinka and Nuszdorfer).

Recently, Trenchard and Artley (1981) developed a new climatological/meteorological variable whose simple form, minimal data requirements and accuracy make it an ideal candidate for application to meso- and macro-scale biogeographical, agroclimatological, and ecological investigations.

This hypothetical medium is termed the sponge (see Figure 1). Sponge's rationale is summarized as follows (Trenchard and Artley):

> We desired a simple moisture variable with a sound physical basis that used common meteorological variables, was suitable over a broad range of climates, and applicable to a single station. The result was named sponge.
>
> Sponge is described as a simple medium with 8 inches of water holding capacity which is initialized half-full of water on 1 January.* Each day, in accordance with the hydrologic cycle, water is added to the medium from precipitation and lost through evaporation. Precipitation (both liquid and frozen) is added at the full amount until the layer is saturated. It is this sponge like behavior which gives the variable its name. Any additional precipitation is assumed to be lost as run-off or drainage. Evaporation occurs at a fraction of the Class A Pan rate, the exact proportion being the ratio of the current contents to the total capacity of the sponge. Either actual or estimated evaporation pan values may be used. The daily contents of the sponge are defined as:
>
> $$S_i = S_{i-1} + P_i - (E_i * S_{i-1}/CAP)$$
>
> Where:
>
> S_i = Sponge contents on day i, in inches.
>
> P_i = Precipitation on day i, in inches.
>
> E = Actual or estimated pan evaporation in inches on day i.
>
> CAP = Sponge capacity in inches
>
> and $0 \leq S_i \leq CAP$
>
> When evaporation pan measurements are not available, they may be estimated with a divisor of 30 days to convert the evaporation function to a daily value.
>
> $$S_i = S_{i-1} + P_i - EP(TX_i, TN_i)*S_{i-1}/CAP*30$$

*Alternatively, the final value of the previous year may be used as an initial value, and the capacity may be varied for a particular region.



SPONGE MOISTURE FUNCTION

$$S_i = S_{i-1} + P_i - EP(T_{xi}, T_{ni}) * S_{i-1}/CAP$$

WHERE $0 \leq S_i \leq CAP$

RUNOFF

(PRECIPITATION > CAPACITY)

(CAP)

Figure 1.- Sponge moisture variables

Where:

EP = Pan evaporation function

TX_i = Maximum temperature on day i.

TN_i = Minimum temperature on day i.

Because of its simple data requirements (daily precipitation and evaporation estimated from maximum and minimum temperatures), the sponge can be calculated at any temperature precipitation observation station.

Long-term (1941-1970) sponge "normals" (average values) were recently calculated for all first-order meteorological stations in the counterminous USA (Trenchard, 1981). Some representative values are presented in Table 1. It is interesting to note that mean annual sponge values were found to range between Yuma, Arizona (0.20") and Mt. Washington, New Hampshire (8.00", or absolute sponge capacity).

Sponge is concluded to present a meaningful measure of areal "environmental moistness". As a generalized climatic index, sponge's simplicity and sensitivity make it particularly appropriate for transregional biogeographical studies (e.g., a large-area vegetation classification).

TABLE I. SELECTED USA 8-INCH SPONGE NORMALS: 1941-1970[1]

Station	Latitude (°N)	Longitude (°W)	Mean January Sponge Value (")	Mean July Sponge Value (")	Mean Annual Sponge Value (")
Mt. Washington, N.H.	44.27	71.30	8.00	8.00	8.00
Stampede Pass, Wash.	47.28	121.33	8.00	6.78	7.49
Caribou, ME.	46.87	68.02	8.00	5.47	6.89
Duluth, Minn.	46.83	92.18	7.97	6.01	6.73
Pensacola, Fla.	30.47	87.20	6.98	6.11	6.41
Seattle, Wash.	47.45	122.30	8.00	2.98	5.67
Cincinnati, Ohio	39.05	84.67	6.89	4.00	5.24
Chicago, Ill.	41.98	87.90	5.85	4.32	5.04
Key West, Fla.	24.55	81.75	3.77	4.66	4.50
Houston, TX.	29.97	95.35	5.56	3.39	4.27
San Francisco, Cal.	37.62	122.38	6.17	1.24	3.35
Dallas, TX.	32.90	97.03	3.26	2.13	3.06
Walla Walla, Wash.	46.03	118.33	4.65	1.14	2.79
Salt Lake City, UT.	40.78	111.95	3.03	0.99	2.14
Goodland, Kan.	39.37	101.70	1.24	2.15	1.60
San Diego, Cal.	32.73	117.17	2.29	0.60	1.37
El Paso, TX.	31.80	106.40	0.76	0.67	0.64
Yuma, Ariz.	32.67	114.60	0.42	0.04	0.20

[1] Calculations by M. Trenchard (Lockheed), NASA-JSC, Houston, TX., July, 1981.

III. THE SPONGE VARIABLE AS APPLIED TO MOISTURE AND VEGETATION GRADIENTS IN TEXAS

There exists in Texas the most pronounced continuous, non-orographic, intrastate climatological gradient found anywhere in the United States. At least four distinct, first-order climatic types occur within the state (humid subtropical, tropical steppe, tropical desert, and mid-latitude steppe), with many more important subtypes (e.g., subtropical subhumid). In particular, there is an extraordinarily steep east-west moisture gradient, ranging from very humid in southeastern Texas (mean annual precipitation $>$ 50") to true desert in far western Texas (average yearly precipitation $<$ 8.0"). This gradient strongly influences ecological patterns, and virtually controls the regional distribution of natural vegetation.

Texas is, then, an excellent natural "laboratory" to test the responsiveness and usefulness of the sponge variable (e.g., with respect to the classification of natural vegetation utilizing satellite data). With this in mind, mean sponge values were calculated for various Texas locations in order to address these questions:

1. Does use of the sponge portray the distribution of climates (especially moisture regions) in Texas better than, say, precipitation alone?
2. If sponge accurately reflects the climates of Texas, can these values be meaningfully correlated with vegetation-index ("greenness") values as measured from space by NOAA meteorological satellites (see the discussion of these indices later in this report)?
3. If the answer to question (2) is affirmative, can a combination of sponge and satellite-derived greenness indices be used to classify the major natural vegetation regions/types of the state? If so, it might well prove feasible to utilize this methodology for other large-area and even global-scale vegetation surveys and classifications.

Climatic Strata And Gradients in Texas Using The Sponge: Long-Term "Normals".

In order to assess sponge's potential usefulness as a climatic index in Texas, long-term annual and monthly sponge "normal" (1941-1970 mean) values were computed for 75 locations widely distributed throughout the state (see Map 1). Sponge values were obtained by utilizing (1) the formula presented in section 1 of this report, and (2) mean monthly temperature maxima and minima, and precipitation, as compiled by the U.S. National Weather Service (NOAA)*.

The results of these computations are illustrated in Maps 2-6, while Tables AI (2) - (f) (pages 48-53) present average normal (1941-70) monthly and annual precipitation and sponge values for each of the 75 locations. They are largely self-evident, but several of the more intriguing aspects should be briefly addressed.

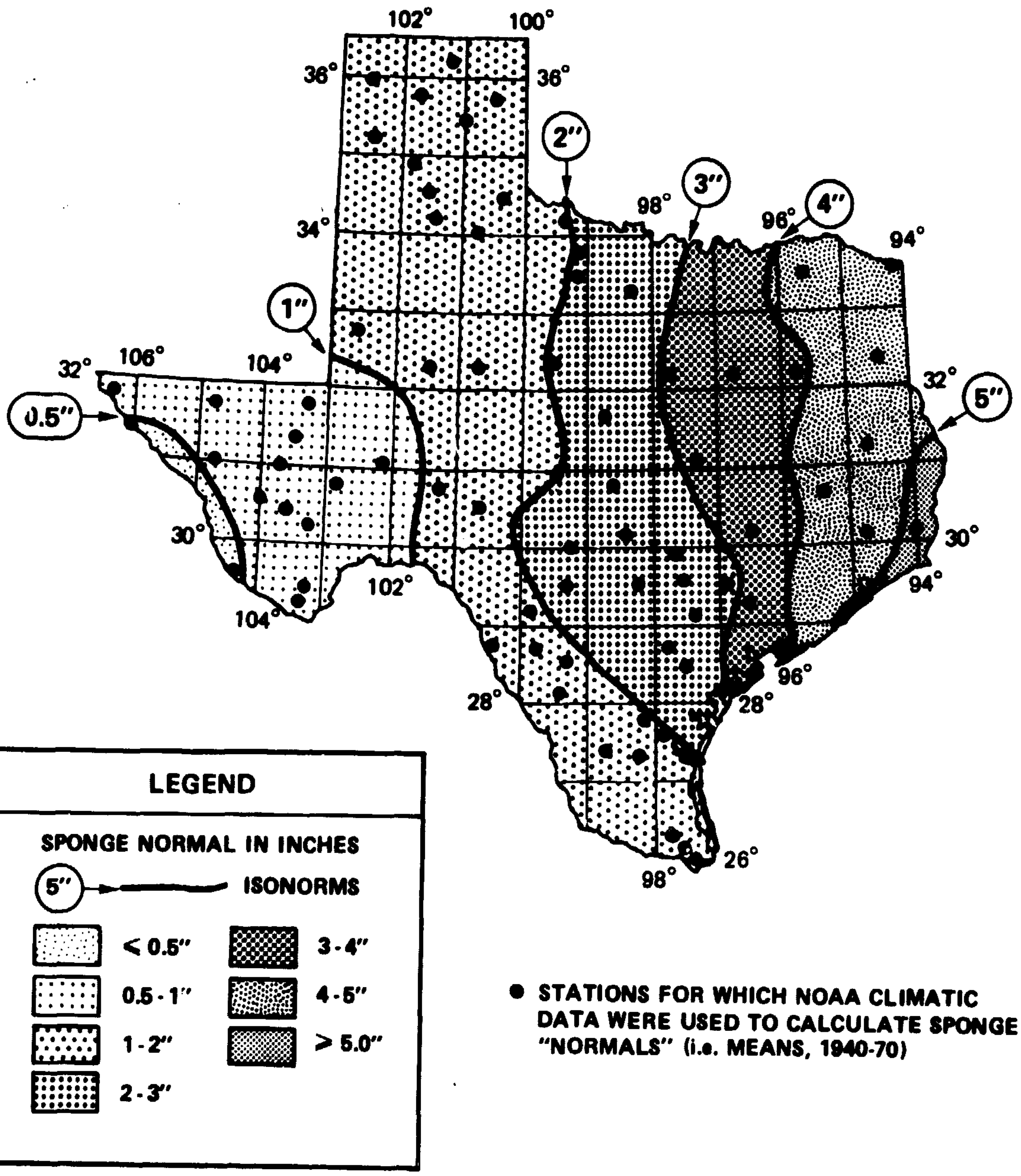
Mean annual sponge values are greatest in the southeast (e.g., 5.2" at Beaumont) and decrease continuously to lows in the westernmost quadrant (0.49") at Presidio in the Chihuahuan Desert). This is virtually identical to the pattern of average annual precipitation. However, sponge appears to more accurately portray (1) seasonal moisture changes across the state, and (2) the magnitude of differences in the relative moistness of the varous parts of Texas than does either precipitation or potential evapotranspiration (estimated by Thornthwaite's method; see Table 3).

With respect to season, Figures A1 - A4 (pages 55-58) and Tables AI (a) - (f) and AII (page 54) clearly indicate that, for vegetative activity, winter and spring are the wet seasons in East Texas while summer and fall are the moist periods in West Texas -- quite unlike the seasonal distribution of precipitation alone, which is greatest in the summer throughout the state. (Thornthwaite's "Index of Moisture" would also reveal this aspect but, because of its reliance on mean monthly temperatures, with less spatial sensitivity than sponge; Carter and Mather, 1966).

*Daily data were simulated from monthly mean temperature maxima, minima, and precipitation for each station for 1941-70 using a series of harmonic transformations. For 1979 and 1980, actual daily data were used.

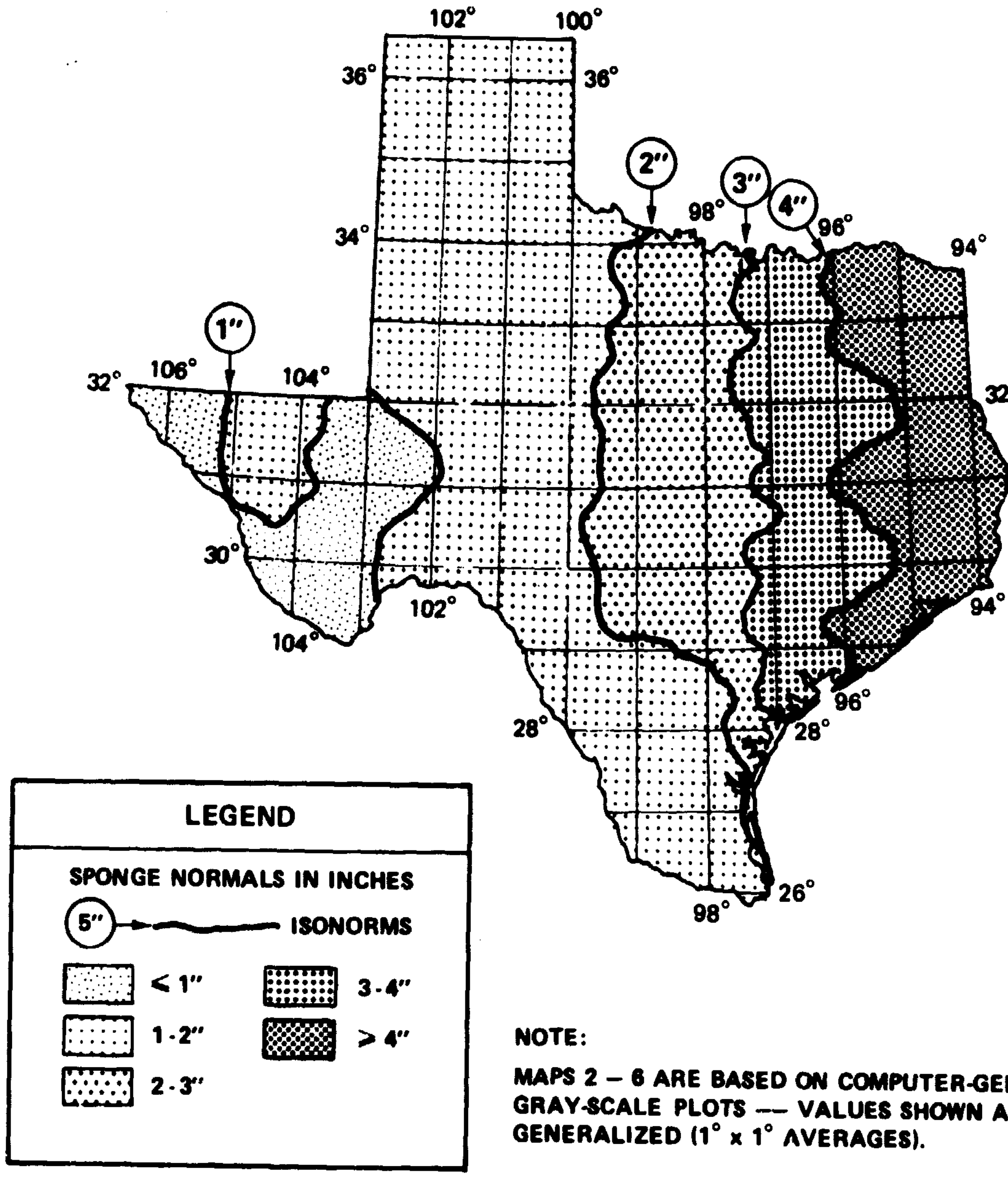
MAP 1. 8-INCH SPONGE NORMALS FOR TEXAS

(PERIOD 1941-70, EXCEPT AS NOTED IN TABLES AI (a) - (f))



MAP 2. NORMAL ANNUAL AVERAGE OF 8-INCH SPONGE - STATE OF TEXAS

(PERIOD 1941-70, EXCEPT AS NOTED IN TABLES AI (a) - (f))

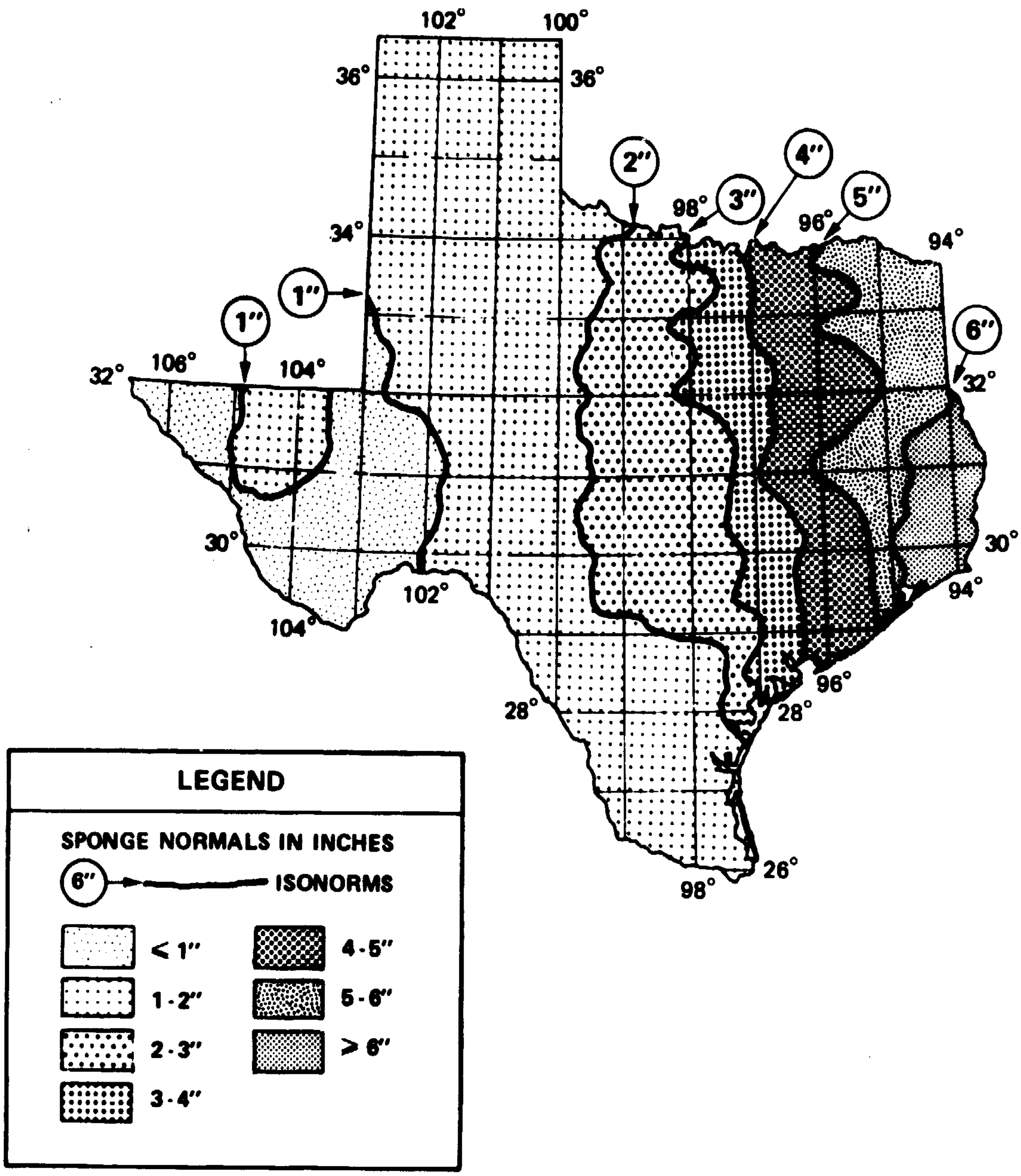


NOTE:

MAPS 2 – 6 ARE BASED ON COMPUTER-GENERATED GRAY-SCALE PLOTS — VALUES SHOWN ARE GENERALIZED (1° x 1° AVERAGES).

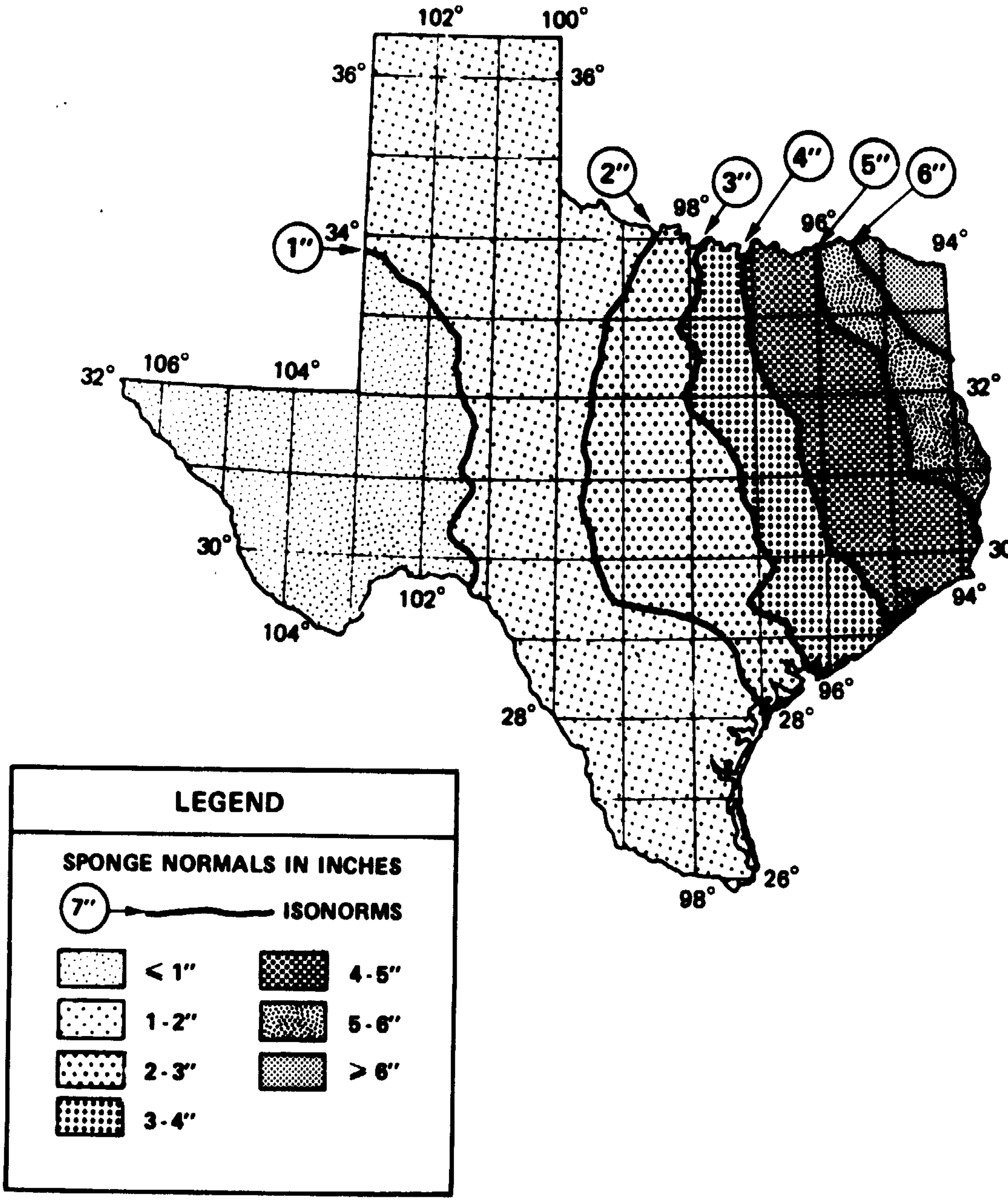
MAP 3. NORMAL JANUARY AVERAGE 8-INCH SPONGE - STATE OF TEXAS

(PERIOD 1941-70, EXCEPT AS NOTED IN TABLES AI (a) - (f))



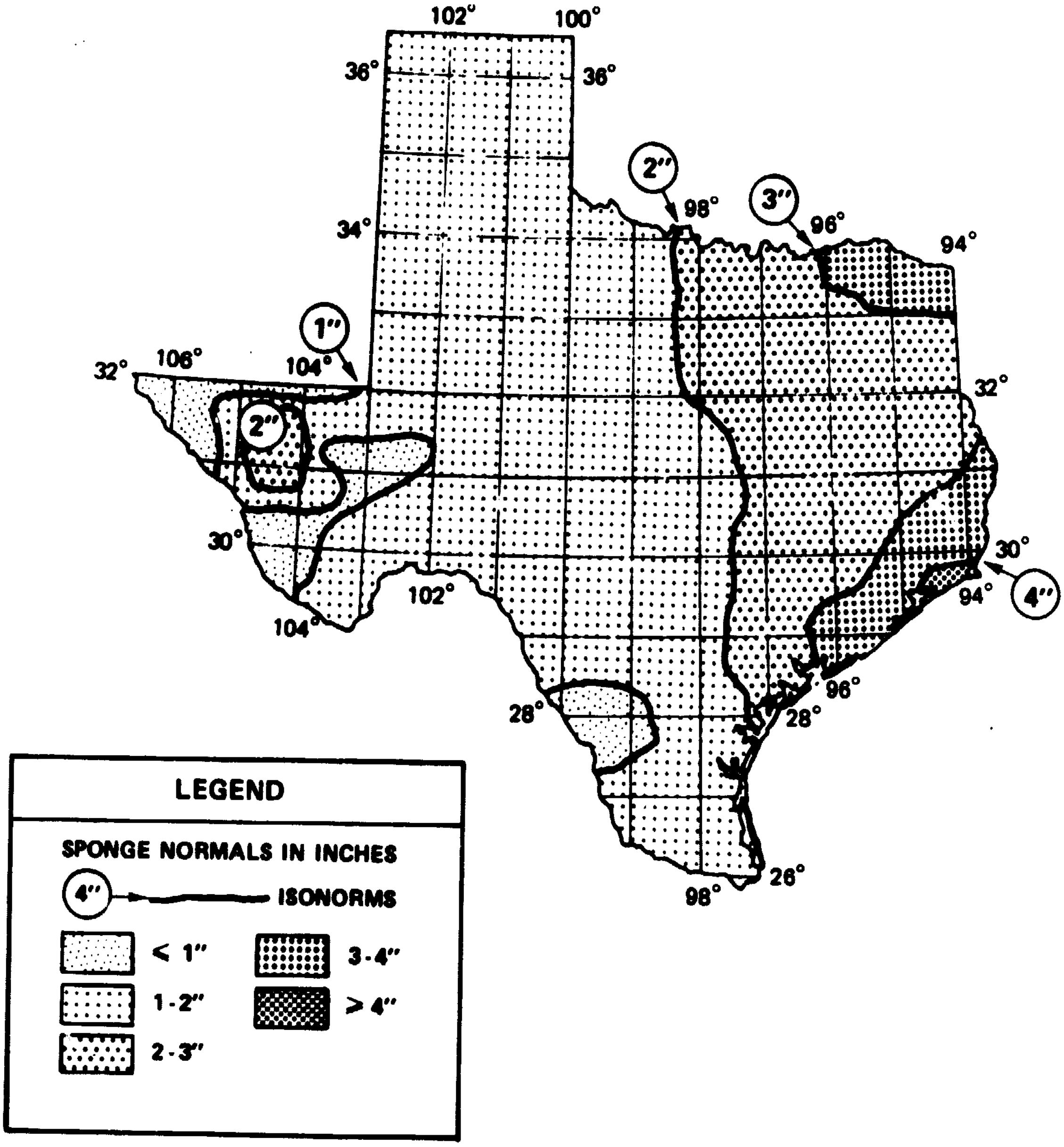
MAP 4. NORMAL AVERAGE APRIL 8-INCH SPONGE - STATE OF TEXAS

(PERIOD 1941-70, EXCEPT AS NOTED IN TABLES AI (a) - (f))



MAP 5. NORMAL JULY AVERAGE 8-INCH SPONGE - STATE OF TEXAS

(PERIOD 1941-70, EXCEPT AS NOTED IN TABLES AI (a) - (f))



MAP 6. NORMAL OCTOBER AVERAGE 8-INCH SPONGE - STATE OF TEXAS

(PERIOD 1941-70, EXCEPT AS NOTED IN TABLES AI (a) - (f))

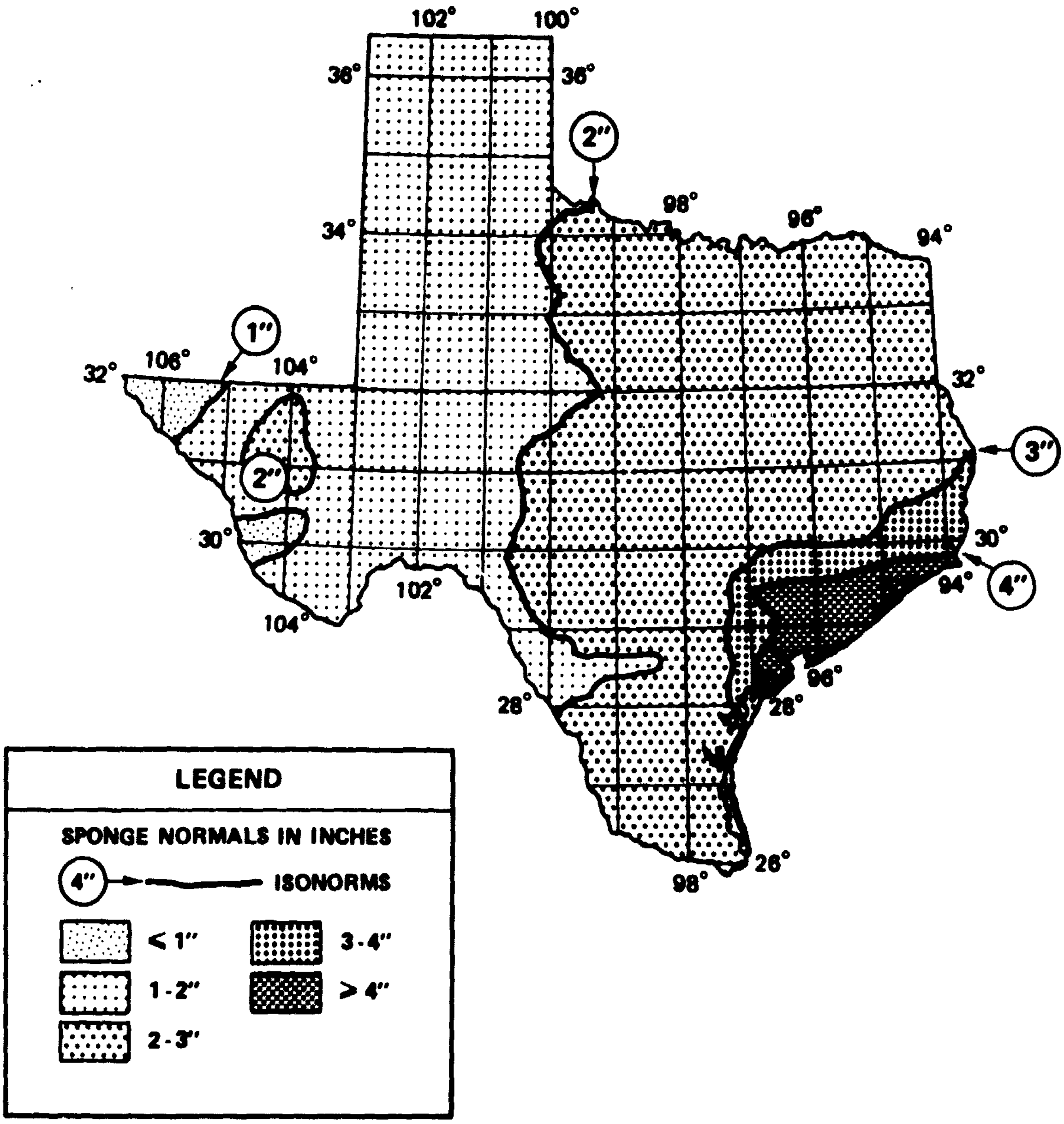


TABLE II. COMPARISON OF NORMAL AVERAGE SPONGE, POTENTIAL EVAPOTRANSPIRATION[1], ACTUAL EVAPOTRANSPIRATION[1], AND PRECIPITATION AT FOUR TEXAS STATION[2]

Station	Period	Precipitation	Potential Evapotranspiration	Actual Evapotranspiration	Sponge
El Paso/La Tuna	Annual	8.06	38.40	8.72	0.59
El Paso/La Tuna	January	0.41	0.4[illegible]	0.44	0.71
El Paso/La Tuna	April	0.15	2.72	0.32	0.35
El Paso/La Tuna	July	1.61	6.96	1.76	0.66
El Paso/La Tuna	October	0.70	2.60	0.84	0.73
McCamey	Annual	12.75	42.72	14.28	0.94
McCamey	January	0.64	0.32	0.32	0.98
McCamey	April	0.77	3.24	0.88	0.61
McCamey	July	1.64	7.48	1.60	0.99
McCamey	October	1.39	3.04	1.20	1.14
Temple	Annual	33.87	41.20	33.68	3.03
Temple	January	2.35	0.44	0.44	4.08
Temple	April	3.67	2.92	2.92	3.50
Temple	July	1.96	7.40	5.20	2.03
Temple	October	2.73	2.92	2.92	2.24
Port Arthur/Beaumont	Annual	54.77	43.44	42.44	5.20
Port Arthur/Beaumont	January	4.57	0.76	0.76	7.00
Port Arthur/Beaumont	April	4.43	3.12	3.12	5.33
Port Arthur/Beaumont	July	5.71	7.20	7.08	4.30
Port Arthur/Beaumont	October	3.19	3.40	3.36	3.85

[1]P. E. and A. E. values extracted from: Average Climatic Water Balance Data of the Continents, Part VII, United States, 1964, C. W. Thornthwaite Assoc Laboratory of Climatology, Pub. in Clim. Vol. 17, No.3, Centerton, N. J.

[2]All values in inches.

Regarding differences in the absolute magnitude of available moisture from place to place (i.e., how much wetter is site "x" than site "Y"?), sponge also proves highly effective. For example, note that Beaumont's mean precipitation is 6.4 times that of Presidio annually and, in April, Beaumont's average rainfall is 21 times that of Presidio. Sponge shows that the moisture gradient between these locations is actually much steeper: Beaumont's mean annual sponge value is 10.6 times greater than that of Presidio and, in April, Presidio's average sponge value of 0.15" is only 3% of Beaumont (5.33"), a difference of 35.5X. In other words, West Texas is nearly twice as dry -- compared with the humid eastern part of the state -- as precipitation averages alone would suggest. Considering that moisture availability is the primary limiting factor with respect to ecoregions and natural vegetation communities in Texas, it may be concluded that the sponge variable is an effective tool for analyzing climate-vegetation relationships.

Recent Sponge Conditions in Texas: 1979 and 1980. Mean monthly and annual sponge values for the 75 test stations, as well as an additional number of locations along the "Texas Transect" (see next section) were calculated for 1979 and 1980 to assess sponge's responsiveness to inter-annual moisture variability. (Only briefly examined here, these variations, and their associations with satellite-measured vegetative index values, will be more intensively studied in a later phase of this research effort.) Refer to Tables AI and AII and Figures A1 - A4 (pages 48-58).

It is evident that 1979 was wetter than normal in East Texas (e.g., 1979 $\overline{X}_{Sp}$ at Liberty = 5.31" compared with normal annual $\overline{X}_{Sp}$ of 4.41"), while it was dry in central Texas (e.g., at Brady, in 1979 $\overline{X}_{Sp}$ = 2.09"; $\overline{X}_{Sp}$normal = 1.96") and near-normal in West Texas (e.g., at Balmorhea, 1979, $\overline{X}_{Sp}$ = 0.87"; $\overline{X}_{Sp}$normal = 0.81").

Intrastate moisture conditions in 1980 were quite different than those of 1979. East Texas was unusually dry in 1980: For example, Huntsville's mean annual sponge was 2.67", only 61% of the long-term normal value. The difference was especially pronounced in mid-summer, when this area experienced drought conditions (see Figure A3, page 57).

By contrast, 1980 was a relatively moist year in West Texas: Pecos and Balmorhea, for instance, had annual sponge values nearly 100% above their 30-year normals (see Table AII, page 54).

Preliminary Assessment of Sponge

Based on these early results, it may be concluded that the sponge is a useful new climatic variable for purposes of identifying and interpreting trans-regional moisture (and, therefore, ecological) gradients and strata. In fact, it may well prove to be, on balance, the best such measure yet devised for practical large-area analysis. Accordingly, sponge is utilized in the following sections of this report as a generalized climatic index, one which is correlated with vegetative indices derived from NOAA meteorological satellite imagery, as part of a gradient study of natural vegetation along a hypothetical east-west "Texas Transect".

IV. THE VEGETATION GRADIENT UTILIZING NOAA SATELLITE IMAGERY

Historically, two broadly conceived research methods have evolved to allow stratification and abstraction of plant communities, classification and gradient analysis (Kessell, 1979). Classification involves grouping samples together on the basis of shared characteristics into an abstract class of plant communities. Such a grouping of communities by any definition of shared characteristics is referred to as a community-type (Whittaker, 1975). The second method, gradient analysis, deals not with discontinuous classes but with continuity and gradient relationships. When the arrangement is along a predetermined environmental gradient, i.e. moisture, the method is termed direct gradient analysis. Indirect gradient analysis is the arrangement of samples along abstract axes that may or may not correspond to environmental gradients. The process of arranging samples along one or more environmental gradients is called ordination (Goodall, 1954 cited in Kessell, 1979). Since vegetation varies continuously along a moisture gradient, samples can indeed be ordinated.

Frequently, the development of a useful classification system requires the use of ordination methods. Discontinuities in the natural vegetation are sought for the purpose of determining the boundaries of the community types recognized. These are often best determined objectively by employing the methods of gradient analysis and ordination. The development of a Montana habitat-type system (Phister et al., 1977, cited in Kessell, 1979) is a good example of the successful use of ordination in developing a classification system.

Gradient modeling has been the first extensive application of gradient analysis to the needs of resource management information systems (Kessell, 1979). Gradient modeling involves the linkage of a multidimensional gradient analysis with a remote site-specific inventory and appropriate computer software. Once the gradient model is complete, it can provide quantitative community inferences (i.e., biomass, cover) if the location of each site within the gradient matrix is known (geographic coordinates, elevation, aspect, etc.).

The initial step is to obtain information about the vegetation. Data on the vegetation can be obtained by field samples ("ground truth" studies) and remote methods (aerial photography and satellite imagery). Most systems use both. Detailed ground truth data are used to derive community-types, whereas aerial photographs and imagery are generally used to infer the vegetation of unsampled areas.

To date, a considerable number of vegetation investigations have been carried out using Landsat MSS imagery but very little has been attempted with the meteorological satellite systems, particularly the NOAA/AVHRR. Gray and McCrary (1980, cited in Gray and McCrary, 1981) obtained a high correlation for detection of vegetation greenness between the NOAA-6 AVHRR Large Area Coverage (LAC) data sets and Landsat MSS data within identical target areas. This finding led Gray and McCrary (1981) to suggest the NOAA satellite systems should be used for monitoring global vegetation. One major advantage of NOAA over Landsat is the tremendous increase in frequency of data collection. Gray and McCrary (1981) anticipated that variations in the AVHRR responses will provide information about reactions of vegetation to moisture availability and thermal effects. They have demonstrated this for croplands in southern Texas before and after Hurricane Allen in April 1980. Since vegetation, particularly in regions arid and semi-arid is very responsive to moisture patterns, it is well worthwhile to investigate temporal changes in natural vegetation and how closely these relate to shifts in the AVHRR vegetation index.

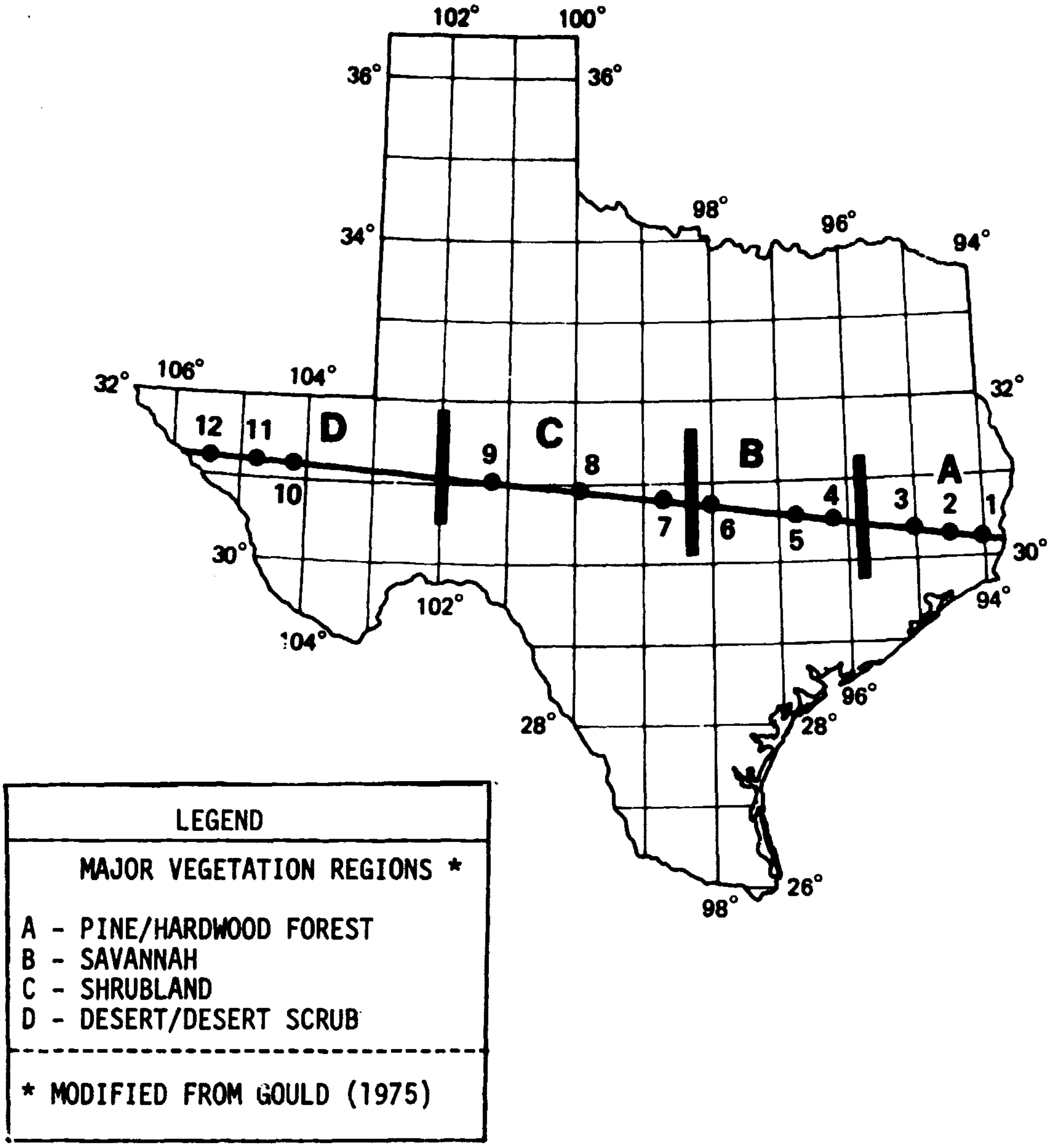
Quite likely, we shall ultimately discover that the success of stratifying different vegetation types from AVHRR vegetation indices will depend not on spatial distinctions but on temporal distinctions, i.e., the rate and magnitude of the spectral shift during a single season. Eventually, vegetation indices can be ordinated (indirect gradient analysis) and correlated to ground truth vegetation and climatological gradients (direct gradient analysis). The ultimate gradient model, incorporating both field and satellite data, may permit vegetation classification and monitoring of changes with minimal ground truthing.

Data Acquisition and Processing

The vegetation gradient model initially necessitated establishing a sample series along an environmental gradient. At NASA/JSC, we were geographically sitting at the eastern edge of perhaps one of the best natural east-west gradients in North America: Trans-Texas, along approximately 30 (^{o}N) latitude. As one moves from Beaumont to El Paso, Texas, one passes through four major natural vegetation regions: (a) mixed pine-hardwood forest, (b) savannah, (c) shrubland, and (d) desert/desert scrub (Map 7). Precipitation exhibits a continuum that has an annual mean > 50" (east Texas) to < 8" (west Texas). The elevation is 0.0' at the Gulf, 5000' just east of El Paso. It would be difficult to identify a better east-west continuum anywhere that changes gradually, yet dramatically and without any obvious disjunctures over a distance of approximately 750 miles. While the soil and geology definitely change across Texas, we do not intend to include a discussion of those variables at this time.

Our main objective has been to design a model that may ultimately allow vegetation classification on a global scale utilizing satellite imagery. We initially expected to use Landsat data. By a stroke of good fortune, we discovered that NOAA/AVHRR "Metsat" data was not only being archived locally by NOAA personnel (T. Gray, D. McCrary) in a readily useable form but it fit our specifications perfectly. The appropriate software had been written by Lockheed, Inc., to be able to retrieve raw pixel data for AVHRR - channels 1 and 2 along specific scanlines or bands of scanlines across the entire state of Texas. In addition, the software provided geographic coordinates for each pixel. In order to obtain a specific scanline, it was really only necessary to provide the specific coordinates at the beginning and end of our trans-Texas transect. Since the NOAA - n series of satellites orbit is near-polar, sun-synchronous, and twice daily, it crosses a given longitude at an angle and at varying places. Consequently, since scanlines are perpendicular to the orbit, it was impossible to select scanlines that remained "isolatitude" or were exactly superimposed from one date to the next. It is also important to remember that NOAA scenes cover such an expanse that related angles to each pixel vary greatly. To permit comparisons, the pixel radiance values have been normalized to an overhead sun.

MAP 7. 12 SAMPLE LOCATIONS ON TEXAS TRANSECT



It has been our intention to acquire scanlines for four cloud-free days during 1980 - one from each season. At this point we have only been able to process 3 dates (April 19, July 10, October 9); winter has been excluded for lack of data. We requested and received bands of 5 adjacent scanlines, extending essentially from El Paso to Beaumont (Figure 2). At predetermined locations which corresponded to our ground truth sites along the strip, we sampled a 25 pixel grid (5 x 5), obtaining an average grid value of pixel counts for each two channels. The selection of the 25 pixel sample grids was somewhat difficult because it was not possible to accurately ground-truth the transect line. The intention has been to select 12 sites, approximately 3 sites in each of the four major vegetation regions bisected (Map 7). Using Texas vegetation-type maps (Texas Parks and Wildlife Department - based on Landsat data), original Landsat MSS scenes, aerial photos, Aeronautical Navigation maps (1:1,000,000), and selected vegetation references (Gould, 1975; see Smeins, 1978), an effort was made to choose "homogeneous" natural vegetation sites, devoid of water, urbanization, and cultivation. The site locations were shifted slightly between sampling dates because the scanlines could not be superimposed.

It was difficult deciding just how to initially treat the satellite data. Gray and McCrary (1981) have devised their own vegetation index, that they now rather appropriately call the Gray-McCrary Index (GMI). The GMI is simply the difference between the solar-zenith corrected albedo value for the two channels. At least initially, we are using the Landsat-derived normalized difference (ND) equation of Rouse, et al. (1973) and Deering, et al. (1975) where:

$$ND = \frac{\text{Channel 2} - \text{Channel 1}}{\text{Channel 2} + \text{Channel 1}}$$

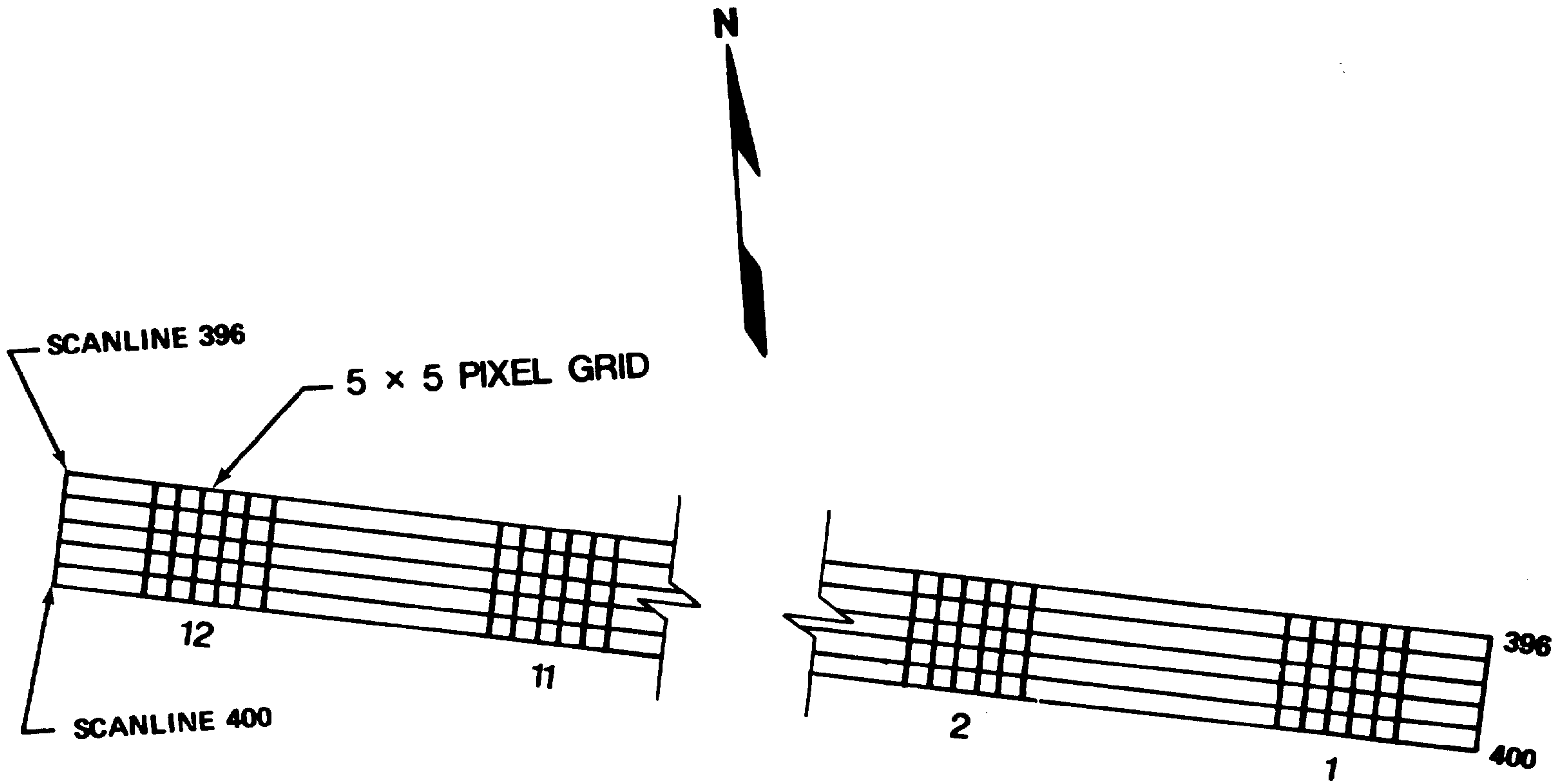


Figure 2.- Example of a band of 5 NOAA/AVHRR scanlines and the 5x5 sampling grids along the Texas transect.

Normalized difference values were obtained for each of the twelve (12) sites on the three (3) dates. The next step was to decide how to best statistically treat the ND values. At this stage we have simply been able to do some preliminary analysis of variance. Normalized difference values were plotted as a function of longitude, sponge and certain vegetation characteristics (i.e., biomass, net productivity, leaf area).

Vegetation Regions on the Texas Transect

The Texas transect selected for our model essentially runs from Beaumont (94°W) to El Paso (106°) and the 12 sample sites have been numbered east to west (see Map 7). Since it was not feasible to visit the transect for optimal site selection, it was necessary to utilize vegetation maps. At this level of our investigation, the ground-truth precision was not terribly critical since our initial concern has been to get a general feeling for the potential of NOAA imagery for global vegetation stratification.

Gould's (1975) vegetation map and discussion of the vegetation regions of the state is large-scale but is the best complete map available. The Texas Parks and Wildlife Department is in the process of completing a state-wide series of land-use classification maps based on Landsat data. Utilizing primarily those two sources, it appears as though our transect bisects four major vegetation regions. Table III enumerates those four regions from east to west, their approximate longitudinal boundaries on the transect, and document vegetation. For a more complete vegetation description, see Gould (1975), Texas Parks and Wildlife vegetation-type maps, and Smeins (1978).

TABLE III. THE VEGETATION REGIONS, THEIR APPROXIMATE LONGITUDINAL BOUNDARIES, AND DOMINANT VEGETATION ALONG THE TEXAS TRANSECT.

VEGETATION REGION	GOULD (1975) NOMENCLATURE	LONGITUDE(^{o}W) LIMITS	DOMINANT VEGETATION
Pine-Hardwood Forest	Pineywoods	93.45^{o}-95.45^{o}	loblolly pine, slash pine, sweetgum, oak, elm, pecan, blackgum
Savannah	Post oak savannah, Blackland prairies	95.45^{o}-98.30^{o}	grasses, oak, elm, hackberry, (cropland)
Shrubland	Edwards Plateau	98.30^{o}-102^{o}	oaks, ash, juniper, mesquite, (rangeland)
Desert/Desert-scrub	Trans Pecos Mountains & basins	102^{o}-106^{o}	creosote, tarbush, yucca, (rangeland)

Results and Discussion

1. Normalized difference (ND) as a function of longitude. As previously mentioned it was impossible to insure superimposition of pixel sampling locations between dates because the satellite orbit fluctuates. For example, while still in pine-hardwood forest, site 1 on April 19 is not geographically identical to site 1 on October 9. The tabular and graphic summaries when the three sample dates were individually plotted as a function of longitude are presented below (Table IV, Figures 3, 4).

There is generally a high correlation between ND and longitude (mean r^2 = .756); ND decreases from east to west.

The sample size of 12 is not sufficiently large enough to merit serious discussion as to significant differences among the three sampling periods. Neither can we eliminate the real possibility of cloud cover affecting reflectance values. We definitely know that there was some cloud cover in West Texas on October 9. What the regressions do suggest is what one would expect knowing the phenological nature of the vegetation regions on the transect. April and July values are high in the mixed forest because the deciduous trees have leafed out. By October, they have dropped their leaves, reducing their "greenness". Progressing westward across the state, a greater percentage of the perennials are non-deciduous but the vegetation becomes less dense and more dependent on infrequent precipitation. In addition, the amount of exposed ground in the desert scrub poses problems of separating soil spectra from vegetation spectroreflectance (Miller, Lee D., pers. comm.).

The variation between seasons appears to diminish going from east to west. The mean regression for all three dates (Figure 4) indicates not only that the greater between-date variation is in the pine-hardwood forest but also that April, and to a lesser extent July are well above the line for the three dates. We would have expected much higher values during the annual blooms in April in the Trans-Pecos but more extensive sampling may clarify this.

TABLE IV. INDIVIDUAL NORMALIZED DIFFERENCE (ND) VALUES, MEANS, REGRESSION EQUATIONS, AND r^2 FOR 3 DATES IN 1980 ALONG TEXAS TRANSECT.

Site	April 19	July 10	October 9	Combined
1.	.258	.238	.161	
2.	.289	.229	.171	
3.	.286	.231	.215	
4.	.259	.136	.147	
5.	.224	.205	.151	
6.	.126	.137	.090	
7.	.138	.125	.033	
8.	.062	.141	.101	
9.	.038	.159	.112	
10.	.044	.029	.051	
11.	.046	.005	.044	
12.	.035	.001	.063	
X	.159	.128	.112	.130
$\hat{Y}$	2.526 - .024X	2.268 - .022X	1.23 - .011X	2.00 - .019X
r^2	.752	.934	.636	.756

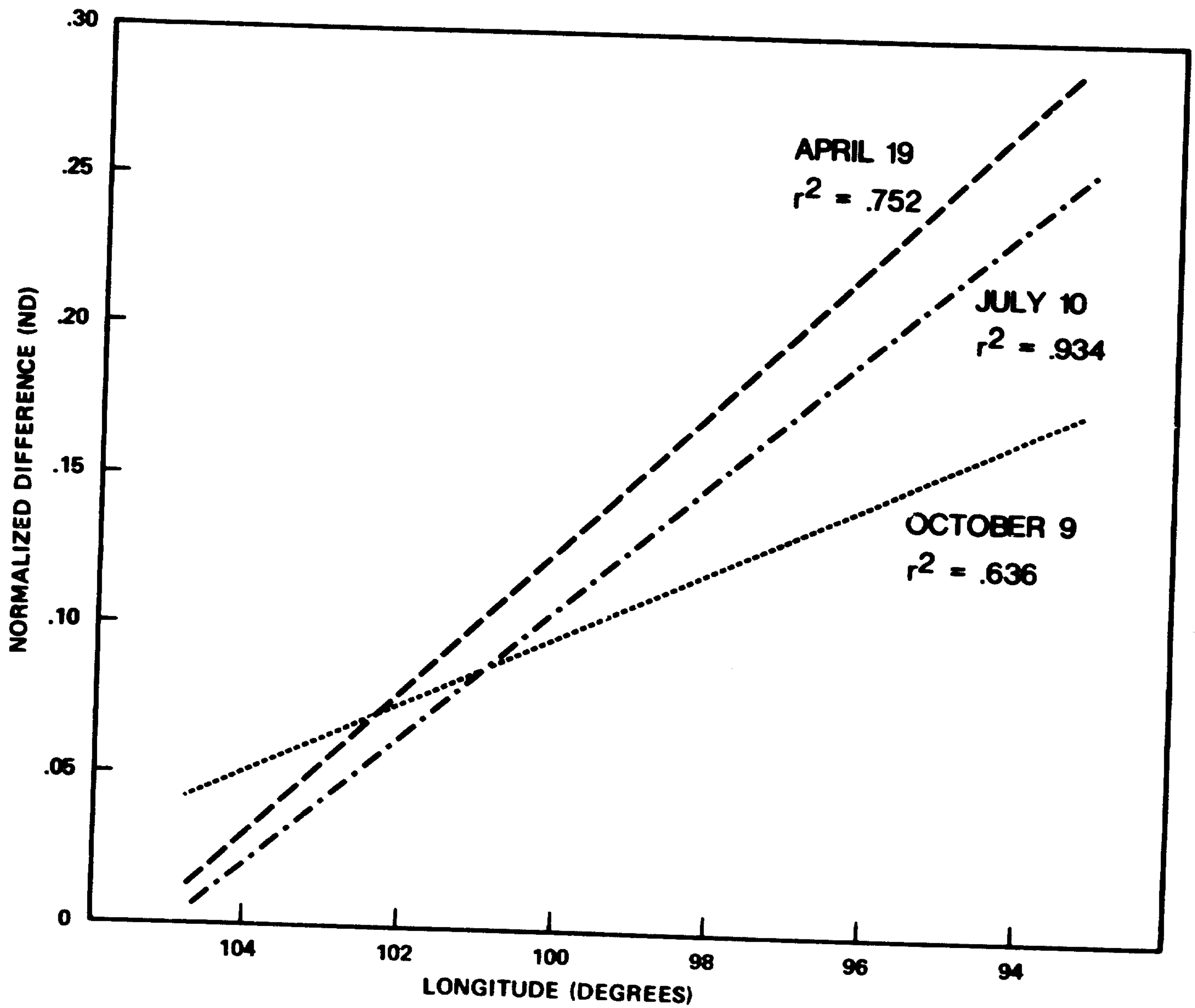


Figure 3.- Vegetation index regression lines for 3 days in 1980 - Texas transect.

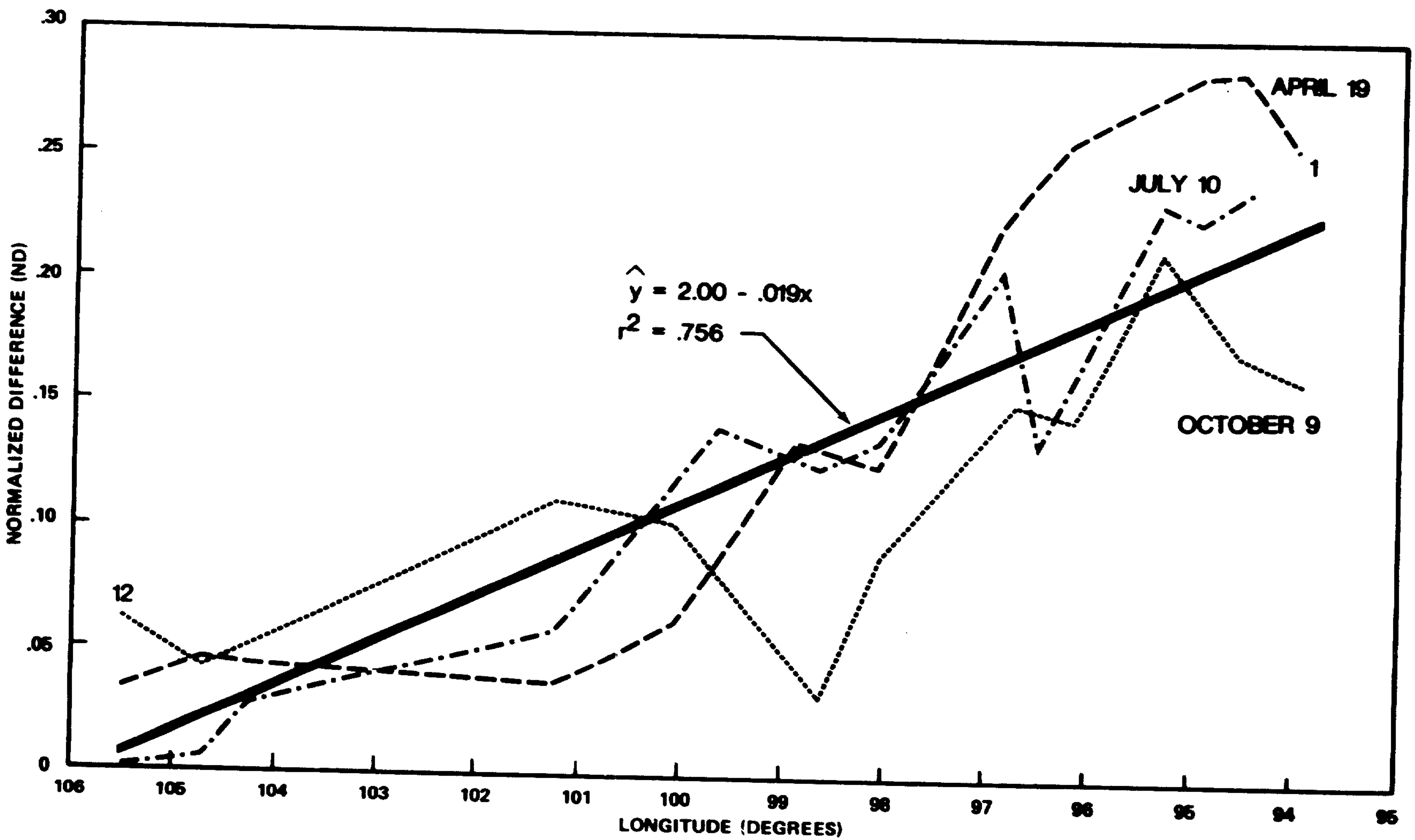


Figure 4.- 1980 Vegetation indices and mean regression line - Texas transect.

2. Sponge index as a function of longitude. For a discussion of a new moisture variable, the sponge, we refer you to earlier sections II, III of this report. Long-term annual "normals" (1941-70) were calculated for 26 stations along or near the Texas transect. These values were plotted as a function of longitude (Figure 5). The results indicate an extremely high correlation ($r^2 = .911$) between sponge and longitude; sponge increases (as does precipitation) from west to east.

3. Normalized difference (ND) as function of sponge. Since both the vegetation index, ND, and sponge showed similar positive correlation with geographic position on the transect, it seemed appropriate to interpolate sponge values from the 26 stations (see Table A**, page 54; Maps 8,9) along the transect for each of 36 ND values (3 values for each of the 12 sites). When ND was plotted against sponge, there was a good correlation ($r^2 = .777$) (Figure 6). Regressing the two regressions, (ND (Figure 4) vs. Sponge (Figure 5), the result is a very pleasing (r^2 - 1.001) but transect-limited, prediction model that permits estimating longitude, sponge index, and ND value, requiring input of only one of the 3 variables (Figure 7). This model serves to illustrate the very high correlation between the vegetation index and the sponge. To further establish this correlation, if one plots the highest ND value of the three dates at each 12 stations against the long-term sponge value for that particular month, $r^2 = .946$.

4. Normalized difference (ND) as a function of vegetation. As earlier mentioned, it was not feasible to actually ground truth the transect to verify and quantify the vegetation. No doubt this should be done at some later stage. In lieu of a better alternative, biomass, net productivity, and leaf area estimates from Whittaker and Likens (1973) were used (see Table V). Since the predominant vegetation limiting factor along the Texas gradient is moisture, these vegetation parameters predictably decline from east to west. It has been previously demonstrated that all of these parameters have been correlated with spectral data (see introduction to Tucker, et al. 1981 for literature review). While general, when ND means for each site are plotted against biomass, net productivity, and leaf area mean values, the results are prophetic as to which vegetation characteristic has the highest correlation with the satellite data (Table VI).

TABLE V. MEAN VALUES FOR WORLD-WIDE ESTIMATES OF NET PRODUCTIVITY BIOMASS AND LEAF AREA INDEX (WHITTAKER AND LIKENS, 1973)

	NET PRODUCTIVITY $gm/M^2/Yr$	BIOMASS Kg/M^2	LAI M^2/M^2
Temperate Evergreen/Deciduous Forest	1250	32.5	8.5
Savannah	900	4.0	4.0
Shrubland	700	6.0	4.0
Desert/Desert	90	0.7	1.0

TABLE VI.- COEFFICIENTS OF DETERMINATION (r^2) WHEN MEAN ND VALUES FOR THE 12 TEXAS TRANSECT SITES ARE PLOTTED AGAINST NET PRODUCTIVITY, LEAF AREA, AND BIOMASS

	r^2
Net primary productivity (g/m^2yr)	.895
Leaf area (M^2/M^2)	.815
Biomass (Kg/M^2)	.650

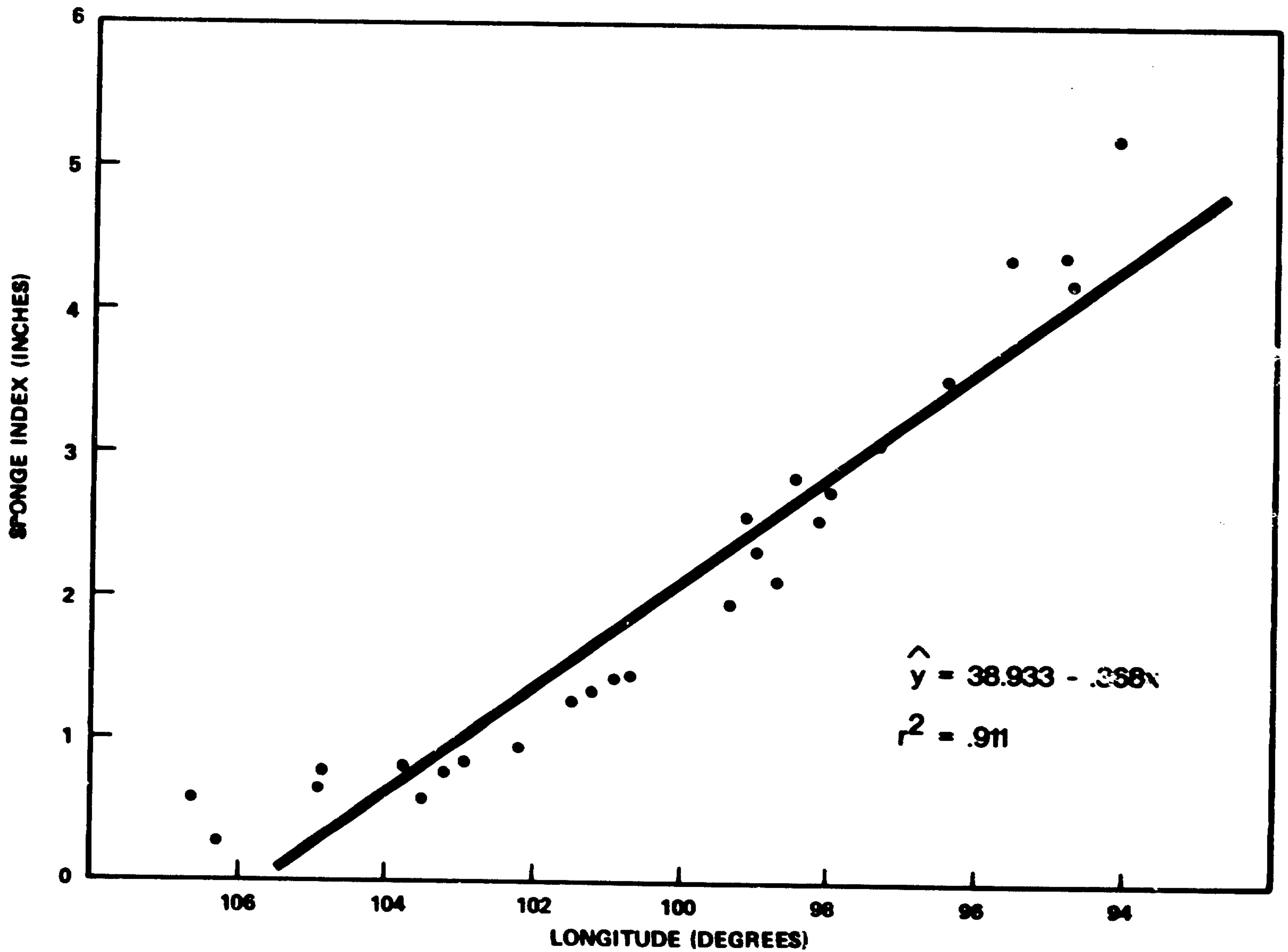


Figure 5.- Long term (1941-70) sponge normals from 26 stations - Texas transect.

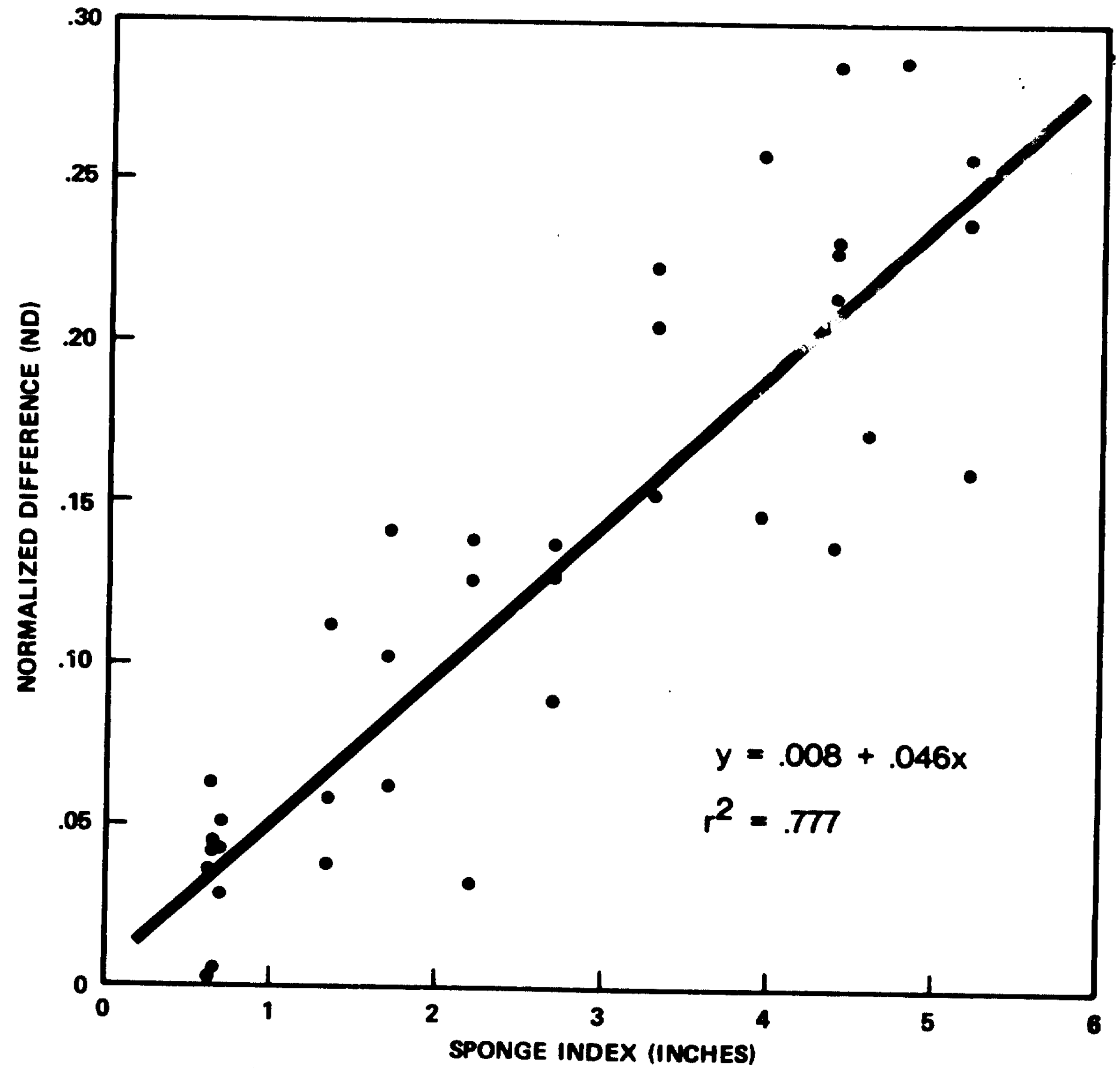


Figure 6.- Vegetation and sponge indices from 12 sites (3 dates) - Texas transect.

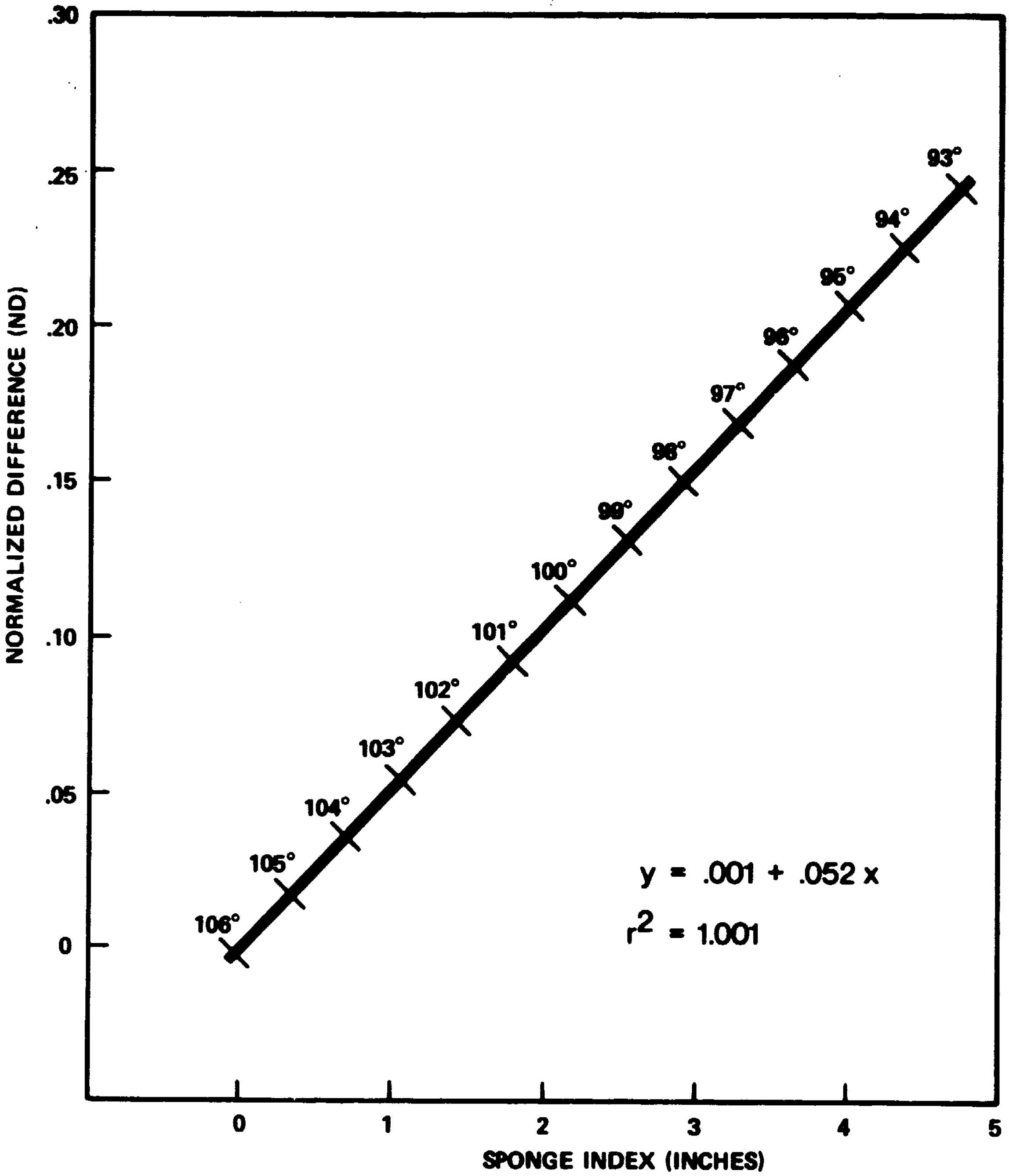
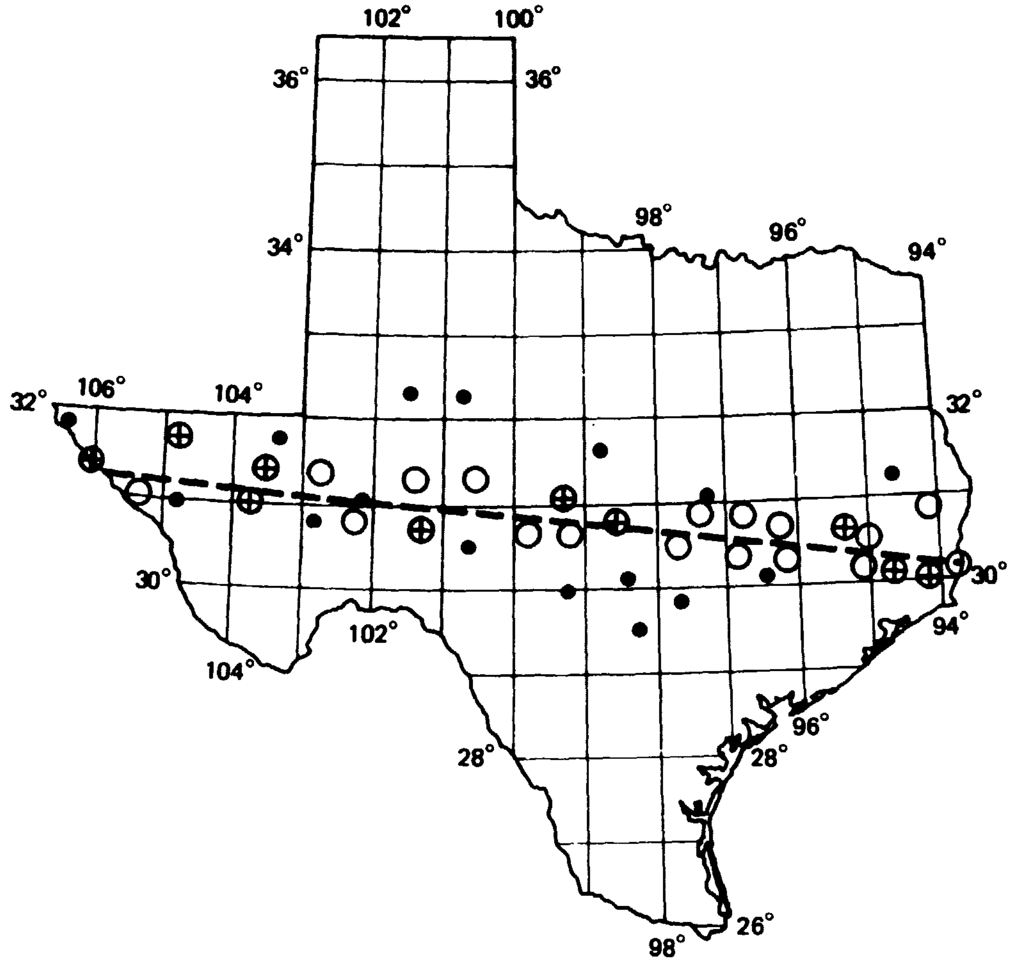


Figure 7.- Vegetation-Sponge prediction model - Texas transect.

MAP 8. STATION LOCATIONS FOR SPONGE CALCULATIONS ALONG TEXAS TRANSECT

(PERIOD 1941-70 AND 1980, EXCEPT AS NOTED IN TABLES AI (a) - (f))



LEGEND

○ – STATIONS (17) USED TO CALCULATE MEAN SPONGE VALUE ALONG TRANSECT IN 1980

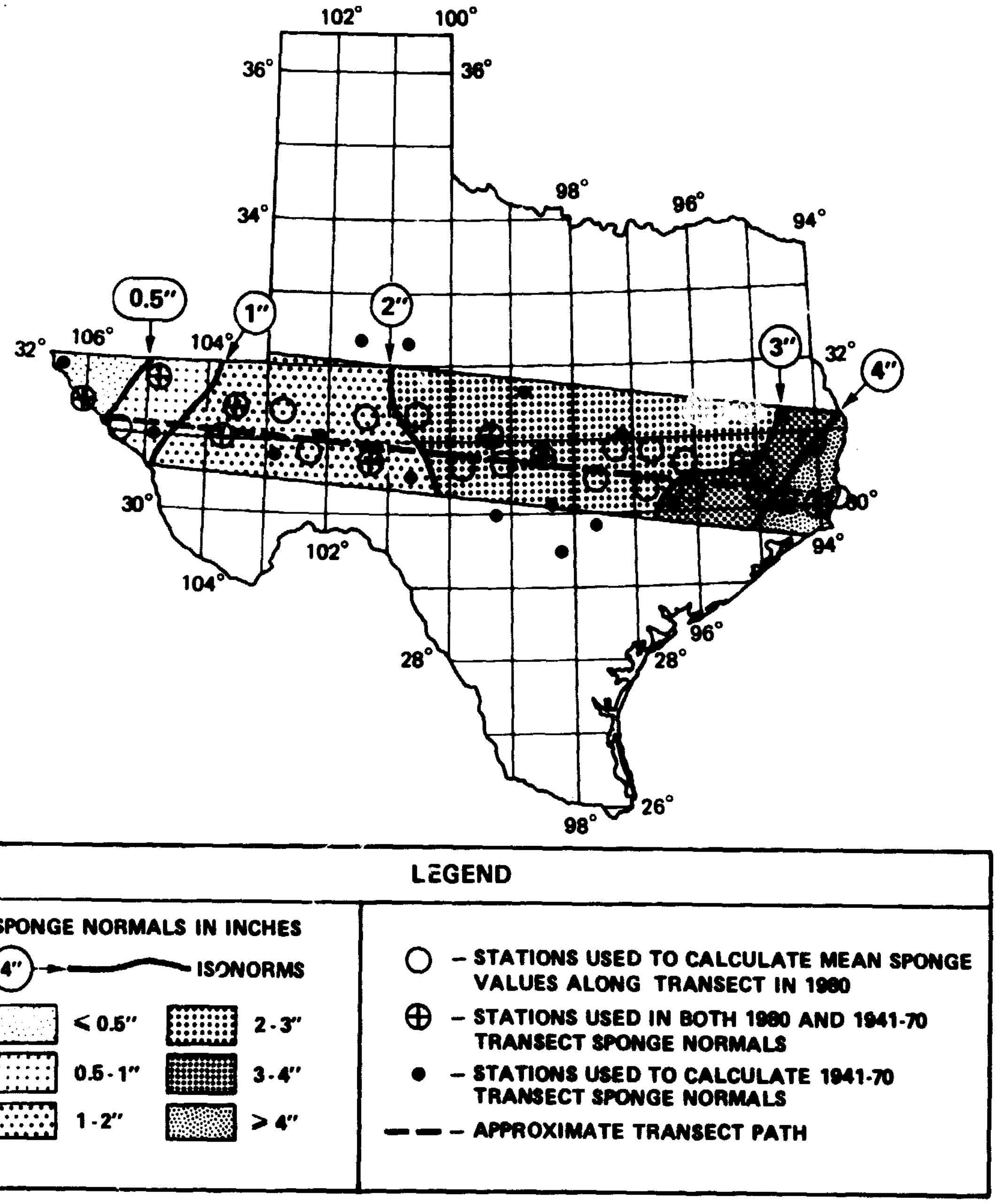
⊕ – STATIONS (10) USED FOR BOTH 1980 AND 1941-70 TRANSECT SPONGE NORMALS

● – STATIONS (16) USED TO CALCULATE 1941-70 TRANSECT SPONGE NORMALS

— — – APPROXIMATE TRANSECT PATH

MAP 9. MEAN 8-INCH SPONGE VALUES ALONG TEXAS TRANSECT 7

(1980)



The inference is that net productivity has the highest correlation to the vegetation index, biomass the lowest. Several studies have recently shown that currently used remote sensing techniques are not sensitive to non-green-leaf components of the phytomass. However, there appears to be a high correlation of spectral data with green-leaf area (biomass) and net production of certain vegetation types (see Introduction, Tucker, et al. 1981). Our selection of ND as a vegetation index was largely founded on Deering and Haas' (1977) high correlation between Landsat-derived ND and rangeland biomass.

In Table V, it is noted that of the three parameters of vegetation, biomass is the only one that doesn't consistently decline from east to west along the transect. Shrubland, consisting largely of woody perennials, does not produce the annual net production that a savannah, containing more herbaceous annuals would, but its accumulative biomass would be greater. The ND does not respond to the increase in biomass from savannah to shrubland because much of that biomass is tied up in non-green components in shrubland which is not as true in the savannah. Because net productivity and leaf area more closely reflect the actual spectral component of those vegetation regions on our transect, we would anticipate their higher correlation with ND.

5. Vegetation-Sponge Index (VSI). Having previously established a high correlation between ND and sponge, we would like to propose a new index that represents the multiplicative of the two variables: the Vegetation - Sponge Index (VSI).

$$ND \times SPONGE = VSI$$

The mean VSI values for the 12 sample sites are presented below in tabular and graphic form (Table VII, Figure 8).

TABLE VII. SPONGE, ND, AND VSI MEAN VALUES FOR DATES IN 1980 (APRIL 19, JULY 10, OCTOBER 9) FOR 12 SITES ALONG TEXAS TRANSECT.

SITE	VEGETATION REGIONS	SPONGE	ND *	VEGETATION-SPONGE INDEX (VIS)
1.	Pine-hardwood forest	5.20	.2192	1.13
2.	"	4.61	.2298	1.06
3.	"	4.40	.2440	1.07
4.	Savannah/cropland	4.10	.1806	0.74
5.	"	3.31	.1935	0.64
6.	Shrubland	2.70	.1176	0.32
7.	"	2.12	.0989	0.21
8.	"	1.71	.1012	0.17
9.	"	1.36	.0695	0.10
10.	Desert/desert scrub	0.70	.0414	0.03
11.	"	0.67	.0315	0.02
12.	"	0.63	.0333	0.02

* ND - NORMALIZED DIFFERENCE

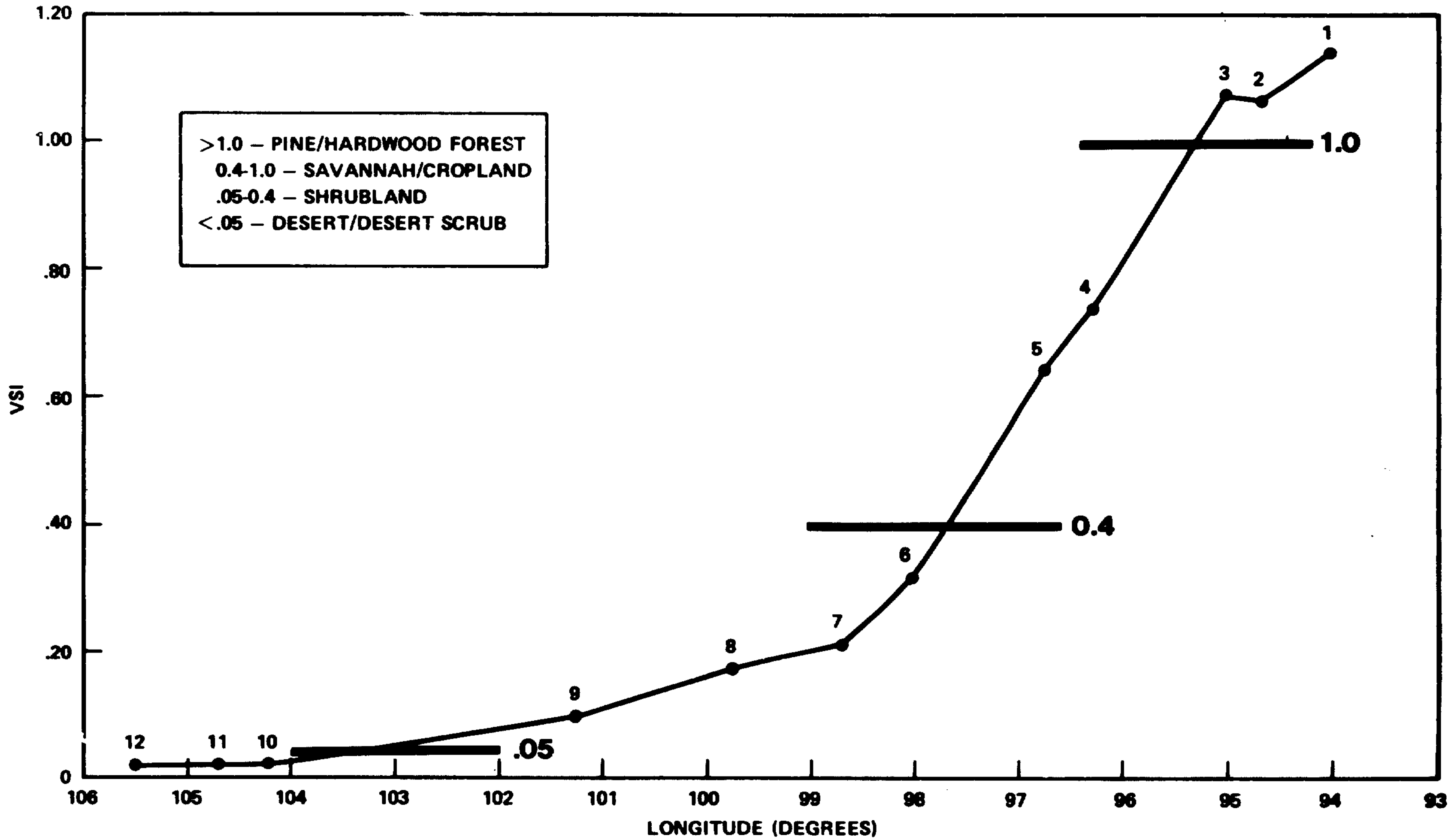


Figure 8.- Vegetation-Sponge index (VSI) - Texas transect.

When VSI is plotted as a function of longitude, the separation of the four major vegetation regions becomes much more apparent (Figure 8). It is ever possible to suggest boundaries for the four classes:

>1.0	pine-hardwood forest
0.4-1.0	savannah/cropland
.05-0.4	shrubland
<.05	desert/desert scrub

Using these suggested limits, it becomes readily apparent that the least within-class variation occurs in desert and forest; the greatest variation is in the shrubland and savannah/cropland classes. This seems consistent with what we would expect. The desert and mixed forest would be more homogeneous in the sense that desert has extensive bare soil during much of the year while the forest would have relatively little. The shrubland and savannah would be considerably more heterogeneous.

V. THE TEXAS MODEL: CONCLUSIONS AND PROJECTIONS

It has been demonstrated that the sponge variable is a superior tool for the analysis of climate/vegetation relationships. Furthermore, NOAA/AVHRR satellite data proved useful for vegetation stratification. Finally, a preliminary multivariate model of vegetation distribution, the VSI, was developed based on an experimental east-west Texas gradient. The next stage of this research effort will involve a more extensive analysis of the application of the model to the Texas transect (e.g., increasing the sample size), to be followed later by refinement of the model which will then be tested against other natural vegetation regions across North America. It is anticipated that ultimately such a model may be utilized for global vegetation surveys, and as a means of remotely monitoring vegetation region dynamics (e.g., desertification).

VI. ACKNOWLEDGEMENTS:

That this report was carried forth to completion owes in large measure to the assistance of certain key individuals. The authors are particularly indebted to K. Demel and R. Hill (NASA) for support, encouragement and substantive suggestions; M. Helfert (NOAA), M. Trenchard, and Ken Oney (Lockheed) were also quite helpful. Special appreciation is extended to Jimmy Gilbert (NASA) and Tom Gray and Dee McCrary (NOAA) for essential data-acquisition and -analysis. The manuscript was expertly prepared by C. M. Graham, M. B. Wiggins, and N. Maxey; graphics and publication were handled by S. B. Allbritton and R. Eason. Finally, the support of the ASEE/NASA Summer Faculty Fellowship Program is greatly acknowledged. Any remaining errors and shortcomings in this report are, of course, solely the responsibility of the authors, to whom they should be reported.

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VIII. APPENDIX

TABLE AI(a). MEAN TEXAS PRECIPITATION AND 8-INCH SPONGE NORMAL VALUES: 1941-1970*. NORTH TEXAS GROUP

STATION	(°N) LATITUDE	(°W) LONGITUDE	JAN. P	JAN. Sp	FEB. P	FEB. Sp	MARCH P	MARCH Sp	APRIL P	APRIL Sp	MAY P	MAY Sp	JUNE P	JUNE Sp	JULY P	JULY Sp	AUG. P	AUG. Sp	SEPT. P	SEPT. Sp	OCT. P	OCT. Sp	NOV. P	NOV. Sp	DEC. P	DEC. Sp	YEAR P	YEAR Sp
Canadian[6]	35.92	100.37	0.53	1.43	0.72	1.37	0.83	1.41	1.45	1.33	3.94	2.30	3.07	2.73	2.30	1.88	2.32	1.54	2.04	1.55	1.75	1.70	0.64	1.54	0.71	1.39	20.30	1.67
Canyon[13]	34.98	101.92	0.57	1.38	0.51	1.20	0.67	1.07	1.41	1.16	2.60	1.65	3.38	2.19	2.97	2.15	2.74	2.03	1.82	1.73	2.00	1.78	0.61	1.62	0.79	1.39	20.07	1.61
Childress[13]	34.43	100.28	0.80	1.75	0.87	1.74	0.94	1.65	2.00	1.72	3.53	2.39	3.08	2.56	1.79	1.69	2.07	1.29	2.21	1.48	2.07	1.86	0.78	1.77	0.89	1.64	21.03	1.79
Dalhart[26]	36.02	102.55	0.38	0.95	0.51	0.90	0.74	1.07	0.89	1.01	2.69	1.63	2.27	1.88	3.32	1.97	2.19	1.91	1.35	1.43	1.14	1.30	0.35	1.09	0.42	0.92	16.25	1.33
Dumas[7]	35.87	101.97	0.60	1.37	0.61	1.35	0.93	1.45	1.22	1.43	2.56	1.80	2.88	2.09	3.56	2.23	2.45	2.02	1.57	1.55	1.34	1.45	0.48	1.29	0.75	1.20	18.9[illegible]	1.60
Matador[21]	34.02	100.83	0.67	1.48	0.64	1.36	0.71	1.25	1.56	1.25	3.20	1.94	3.05	2.27	2.67	1.95	2.04	1.54	2.03	1.43	2.10	1.78	0.77	1.69	0.78	1.47	20.22	1.62
Pampa[6]	35.57	100.97	0.52	1.49	0.70	1.45	0.81	1.49	1.31	1.45	3.35	2.16	3.34	2.79	2.33	2.17	2.51	1.85	1.91	1.76	1.88	1.92	0.54	1.78	0.60	1.49	19.80	1.82
Plainview[9]	34.18	101.70	0.76	1.40	0.65	1.37	0.62	1.21	1.40	1.16	3.04	1.83	3.11	2.19	2.67	1.97	1.86	1.55	1.97	1.43	1.62	1.61	0.55	1.37	0.76	1.24	19.01	1.53
Quanah[6]	34.25	99.68	0.79	1.94	0.96	1.87	1.33	1.90	2.31	2.02	3.87	2.68	3.10	2.62	1.98	1.68	2.08	1.23	3.06	1.69	2.57	2.27	1.13	2.17	0.93	1.98	24.11	2.00
Seminole[26]	32.72	102.67	0.55	0.90	0.58	0.89	0.58	0.86	1.08	0.82	2.25	1.29	1.67	1.27	2.30	1.25	2.05	1.34	2.07	1.38	1.64	1.52	0.50	1.25	0.37	0.92	15.64	1.14
Seymour[10]	33.58	99.27	1.16	2.16	1.25	2.21	1.32	2.10	2.40	2.05	3.95	2.66	3.49	2.69	2.63	1.94	2.15	1.34	2.77	1.51	2.50	1.97	1.37	1.99	1.21	2.01	26.21	2.05
Spearman[7]	36.18	101.20	0.67	1.67	0.81	1.64	1.18	1.78	1.59	1.79	3.47	2.38	3.28	2.67	3.17	2.20	2.76	1.93	1.96	1.67	1.79	1.70	0.84	1.68	0.76	1.59	22.29	1.89
Tulia[24]	34.53	101.77	0.53	1.12	0.37	1.02	0.54	0.88	1.16	0.98	2.49	1.49	3.68	2.23	2.46	2.10	1.70	1.46	1.77	1.35	1.50	1.47	0.53	1.29	0.51	1.10	17.24	1.37
Vega[7]	35.25	102.43	0.58	1.55	0.66	1.46	0.80	1.43	1.25	1.38	2.62	1.79	3.04	2.20	2.99	2.08	2.84	2.04	1.74	0.75	1.59	1.65	0.67	1.55	0.79	1.48	19.53	1.70
Vernon[9]	34.17	99.30	0.99	2.03	1.31	2.08	1.29	2.04	2.43	1.97	4.63	2.83	3.33	2.81	1.84	1.64	1.74	1.09	2.51	1.32	2.90	2.09	1.28	2.15	1.08	1.98	25.33	2.00

*Except as noted. All values in inches. Data from Climatological Summaries for Texas, National Weather Service, NOAA.

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TABLE AI(b). MEAN TEXAS PRECIPITATION AND 8-INCH SPONGE NORMAL VALUES: 1941-1970*. CENTRAL TEXAS GROUP

STATION	(°N) LATITUDE	(°W) LONGITUDE	JAN. P	JAN. Sp	FEB. P	FEB. Sp	MARCH P	MARCH Sp	APRIL P	APRIL Sp	MAY P	MAY Sp	JUNE P	JUNE Sp	JULY P	JULY Sp	AUG. P	AUG. Sp	SEPT. P	SEPT. Sp	OCT. P	OCT. Sp	NOV. P	NOV. Sp	DEC. P	DEC. Sp	YEAR P	YEAR Sp
Albany[9]	32.73	99.30	1.17	2.03	1.38	2.13	1.18	1.95	2.79	1.99	4.21	2.85	2.71	2.53	2.41	1.70	2.27	1.33	2.96	1.61	2.52	2.03	1.49	2.03	1.16	1.99	26.25	2.01
Big Spring[5]	32.25	101.45	0.63	1.30	0.57	1.16	0.72	1.10	1.08	0.96	2.68	1.55	1.67	1.54	1.97	1.28	1.64	1.22	1.82	1.27	1.45	1.43	0.78	1.35	0.71	1.27	15.72	1.28
Blanco	30.10	98.42	2.12	3.23	3.00	3.76	2.10	3.59	3.54	3.22	3.98	3.47	2.92	2.78	1.98	1.79	2.21	1.30	4.65	2.25	3.60	3.12	2.90	2.89	2.20	3.01	34.39	2.86
Brady[10]	31.12	99.35	1.52	2.16	1.41	2.35	1.10	2.00	2.58	1.98	3.50	2.64	2.32	2.34	1.34	1.41	1.61	0.99	3.05	1.63	2.28	2.12	1.36	2.00	1.20	1.95	23.27	1.96
Brownwood[7]	31.72	98.98	1.72	2.63	1.77	2.88	1.46	2.59	3.03	2.53	4.22	3.18	3.40	3.02	1.85	1.92	1.46	1.11	2.60	1.39	2.66	2.07	1.51	2.22	1.52	2.30	27.20	2.32
Colorado City[11]	32.38	100.87	0.82	1.46	0.78	1.32	0.86	1.17	1.82	1.20	3.19	1.86	2.17	1.77	2.14	1.39	1.76	1.19	2.24	1.32	1.96	1.62	1.11	1.56	0.95	1.48	19.80	1.44
Jacksboro[14]	33.23	98.15	1.48	2.68	1.39	2.63	1.70	2.39	3.88	2.84	4.34	3.57	3.16	3.01	2.43	2.04	1.96	1.37	3.05	1.67	2.96	2.35	2.03	2.61	1.43	2.65	29.81	2.48
Kerrville[2]	30.05	99.15	1.86	2.86	2.16	3.06	1.93	2.93	2.95	2.71	4.00	3.20	2.86	2.83	2.10	1.96	1.92	1.34	4.27	2.14	3.12	2.88	1.63	2.57	1.95	2.61	30.75	2.59
Llano	30.75	98.68	1.37	2.16	1.92	2.46	1.47	2.37	3.16	2.42	3.80	3.04	2.14	2.37	1.20	1.22	1.87	0.93	3.79	1.85	2.57	2.41	1.50	2.15	1.37	2.12	26.16	2.12
New Braunfels[9]	29.70	98.12	1.88	2.92	2.66	3.23	1.92	2.90	3.24	2.65	3.73	2.94	3.32	2.67	1.83	1.78	2.40	1.34	3.75	2.00	3.43	2.67	2.30	2.73	2.15	2.87	32.61	2.56
Ozona[32]	30.72	101.20	0.81	1.21	1.19	1.47	0.69	1.34	1.65	1.24	2.20	1.52	2.45	1.68	1.30	1.19	1.62	0.90	2.17	1.22	2.06	1.64	0.91	1.60	0.54	1.30	17.59	1.36
San Marcos[10]	29.88	97.95	2.06	3.08	2.85	3.58	1.86	3.21	3.28	2.88	3.27	2.90	3.86	2.77	1.89	2.04	2.24	1.32	4.57	2.27	3.53	2.97	2.36	2.88	2.09	3.02	33.86	2.74
Sonora[27]	30.57	100.65	0.82	1.28	1.19	1.41	0.75	1.26	2.07	1.31	2.95	1.95	2.19	1.88	1.61	1.33	1.47	1.02	2.23	1.25	2.33	1.81	0.95	1.71	0.72	1.38	19.28	1.46
Temple[4]	31.10	97.35	2.35	4.08	2.62	4.35	2.01	3.88	3.67	3.50	4.65	3.96	3.17	3.32	1.96	2.03	1.97	1.32	3.15	1.73	2.73	2.24	2.93	2.82	2.66	3.07	33.87	3.08
Weatherford[9]	32.75	97.80	1.89	3.40	2.35	3.85	1.97	3.71	4.12	3.76	5.07	4.54	3.10	3.70	2.06	2.10	1.88	1.35	2.92	1.55	2.88	2.27	1.99	2.67	1.82	3.03	23.05	3.08

*Except as noted. All values in inches. Data from Climatological Summaries for Texas, National Weather Service, NOAA.

TABLE AI(c). MEAN TEXAS PRECIPITATION AND 8-INCH SPONGE NORMAL VALUES: 1941-1970*. EAST TEXAS GROUP

STATION	LATI-TUDE (°N)	LONGI-TUDE (°W)	JAN. P	JAN. Sp	FEB. P	FEB. Sp	MARCH P	MARCH Sp	APRIL P	APRIL Sp	MAY P	MAY Sp	JUNE P	JUNE Sp	JULY P	JULY Sp	AUG. P	AUG. Sp	SEPT. P	SEPT. Sp	OCT. P	OCT. Sp	NOV. P	NOV. Sp	DEC. P	DEC. Sp	YEAR P	YEAR Sp
Athens[30]	32.20	95.85	2.51	4.80	3.30	5.10	2.58	4.79	4.64	4.51	5.17	4.81	3.14	3.77	1.41	1.96	2.04	1.24	3.82	2.02	3.45	2.88	3.38	3.48	3.26	4.43	38.70	3.64
Beaumont[7]	30.08	94.10	4.57	7.00	4.38	7.47	2.82	6.41	4.43	5.33	4.79	5.10	4.75	4.33	5.71	4.30	5.34	4.23	5.30	4.35	3.19	3.85	4.54	4.19	4.95	5.93	54.77	5.20
Brenham[16]	30.15	96.40	2.78	4.84	3.12	5.06	2.46	4.53	3.71	3.97	4.43	4.01	3.24	3.29	1.90	2.01	3.09	1.68	3.97	2.43	3.17	2.79	3.72	3.38	3.37	4.41	38.96	3.53
Cuero[16]	29.08	97.25	2.03	2.88	2.41	3.18	1.41	2.71	2.95	2.41	3.79	2.91	3.18	2.64	2.22	1.89	2.75	1.52	4.69	2.44	3.27	2.88	2.35	2.64	2.12	2.77	33.17	2.57
Freeport[11]	28.98	95.38	3.41	6.08	3.43	6.31	2.23	5.55	3.25	4.68	3.29	4.36	4.17	3.99	5.46	4.53	4.98	4.57	6.56	5.21	3.78	5.08	4.10	4.78	4.07	5.64	43.83	5.06
Hallettsville[16]	29.45	96.93	2.25	3.36	2.70	3.58	2.08	3.29	3.01	2.86	4.65	3.39	3.53	3.18	2.22	2.09	3.08	1.68	4.37	2.48	2.72	2.61	2.71	2.58	2.60	3.13	35.92	2.35
Huntsville[7]	30.72	95.57	3.80	6.25	3.76	6.65	2.98	5.85	4.34	5.13	4.35	4.70	4.57	3.97	3.28	3.10	3.05	2.23	4.05	2.62	3.27	2.94	4.39	3.89	4.11	5.44	45.95	4.39
Liberty[8]	30.05	94.82	4.21	6.21	4.18	6.58	2.77	5.67	4.16	4.73	4.50	4.51	4.33	3.82	4.65	3.49	3.90	3.04	4.23	2.99	3.69	3.13	4.07	3.82	4.92	5.15	43.61	4.41
Lufkin[7]	31.23	94.75	4.29	6.32	3.83	6.70	3.49	5.96	4.38	5.16	4.81	4.73	3.48	3.75	2.83	2.63	2.81	1.96	3.22	2.18	2.07	2.40	4.60	3.63	4.22	5.26	44.93	4.22
Marshall[7]	32.53	94.35	4.40	7.06	3.85	7.62	4.08	7.14	5.02	6.42	4.78	5.52	3.45	3.94	2.97	2.67	2.81	2.05	3.09	2.18	2.86	2.44	4.20	3.62	4.41	5.50	45.92	4.68
Palacios[9]	28.63	96.63	2.10	3.70	2.96	4.10	1.61	3.69	2.80	3.29	3.21	3.23	5.34	3.90	1.85	3.05	4.16	2.48	5.60	3.77	3.94	4.15	2.42	3.64	2.59	3.70	38.56	3.56
Paris[15]	33.67	95.57	2.59	5.49	3.52	6.04	3.49	6.12	5.59	6.19	5.42	6.27	4.46	5.01	3.76	3.63	3.05	2.53	3.68	2.57	3.10	2.93	2.62	3.68	3.06	4.96	45.32	4.61
Seguin[9]	29.57	97.95	1.72	2.67	2.34	3.00	1.75	2.71	3.27	2.67	3.18	2.87	3.17	2.53	1.89	1.85	1.98	1.27	3.80	1.97	3.35	2.73	2.05	2.69	1.73	2.68	30.23	2.49
Texarkana[20]	33.30	94.17	4.09	6.51	4.05	7.43	4.04	7.33	5.91	7.15	4.81	6.24	3.54	4.35	3.16	3.03	2.71	2.16	4.03	2.66	2.75	2.99	3.53	3.47	3.88	5.02	46.50	4.86
Waxahachie[9]	32.38	96.85	2.19	4.04	2.98	4.59	2.19	4.34	4.51	4.09	4.87	4.57	3.60	3.87	2.21	2.44	2.03	1.55	3.05	1.78	2.90	2.39	2.73	2.94	2.47	3.69	35.73	3.36

* Except as noted. All values in inches. Data from <u>Climatological Summaries</u> for Texas, National Weather Service, NOAA.

TABLE AI(d). MEAN TEXAS PRECIPITATION AND 8-INCH SPONGE NORMAL VALUES: 1941-1970*. WEST TEXAS GROUP

STATION	(°N) LATITUDE	(°W) LONGITUDE	JAN. P	JAN. Sp	FEB. P	FEB. Sp	MARCH P	MARCH Sp	APRIL P	APRIL Sp	MAY P	MAY Sp	JUNE P	JUNE Sp	JULY P	JULY Sp	AUG. P	AUG. Sp	SEPT. P	SEPT. Sp	OCT. P	OCT. Sp	NOV. P	NOV. Sp	DEC. P	DEC. Sp	YEAR P	YEAR Sp
Alpine[9]	30.37	103.65	0.85	1.18	0.36	1.12	0.26	0.76	0.47	0.56	1.24	0.70	2.56	1.31	2.73	1.85	2.43	1.95	1.99	1.86	1.36	1.68	0.41	1.30	0.55	1.01	15.21	1.27
Balmorhea	30.98	103.75	0.64	0.86	0.49	0.79	0.44	0.64	0.59	0.48	1.50	0.71	1.48	0.85	1.56	0.86	1.41	0.86	1.69	0.99	1.28	1.09	0.55	0.91	0.54	0.76	12.12	0.81
Chisos Basin[18]	29.27	103.30	0.76	1.20	0.40	1.08	0.29	0.79	0.65	0.60	1.68	0.97	1.96	1.29	3.07	1.88	2.28	2.13	1.85	1.90	1.26	1.73	0.46	1.33	0.58	1.09	15.24	1.33
Fort Stockton[9]	30.87	102.92	0.83	0.98	0.52	0.97	0.42	0.73	0.62	0.54	1.67	0.80	1.78	1.05	1.44	0.95	1.27	0.82	1.29	0.83	1.29	0.99	0.51	0.91	0.59	0.78	12.23	0.86
La Tuna[17]	31.97	106.60	0.41	0.71	0.36	0.64	0.33	0.55	0.15	0.35	0.28	0.22	0.71	0.30	1.61	0.66	1.66	0.98	1.04	0.88	0.70	0.73	0.29	0.57	0.52	0.59	8.06	0.59
McCamey	31.13	102.20	0.64	0.98	0.51	0.90	0.48	0.76	0.77	0.61	1.91	0.98	1.49	1.09	1.64	0.99	1.42	0.95	1.39	0.94	1.39	1.14	0.53	1.05	0.58	0.89	12.75	0.94
Marathon[22]	30.20	103.23	0.51	0.75	0.41	0.70	0.36	0.57	0.65	0.49	1.36	0.74	1.70	0.96	1.78	1.14	1.72	1.12	2.51	1.52	1.02	1.43	0.56	0.98	0.41	0.81	12.99	0.93
Mount Locke	30.67	104.00	0.83	1.82	0.48	1.68	0.46	1.37	0.46	1.08	1.49	1.08	2.48	1.59	3.87	2.56	3.42	3.20	2.75	3.22	1.51	2.94	0.56	2.29	0.56	1.82	18.87	2.05
Panther Junction[33]	29.32	103.22	0.58	0.89	0.53	0.84	0.39	0.70	0.50	0.46	1.49	0.72	1.43	0.89	1.70	1.01	1.46	1.02	2.17	1.31	1.35	1.46	0.56	1.14	0.45	0.91	12.61	0.95
Pecos	31.42	103.50	0.34	0.57	0.31	0.51	0.32	0.43	0.60	0.39	1.07	0.56	1.07	0.57	1.35	0.66	0.90	0.56	1.37	0.68	0.96	0.82	0.39	0.66	0.37	0.57	9.05	0.58
Presidio	29.55	104.35	0.41	0.49	0.21	0.41	0.15	0.24	0.21	0.15	0.61	0.23	1.26	0.46	1.35	0.63	1.23	0.63	1.51	0.78	0.99	0.81	0.35	0.60	0.33	0.47	8.61	0.49
Salt Flat[34]	31.78	104.90	0.30	0.65	0.19	0.55	0.20	0.41	0.33	0.35	0.34	0.27	1.03	0.45	1.48	0.74	1.98	1.13	1.11	1.09	0.86	0.92	0.30	0.75	0.39	0.65	8.51	0.66
Van Horn	31.05	104.83	0.54	0.89	0.29	0.77	0.24	0.54	0.35	0.38	0.59	0.39	0.92	0.45	1.75	0.80	1.82	1.09	1.71	1.20	0.97	1.11	0.54	0.91	0.51	0.85	10.23	0.78
Wink[12]	31.78	103.20	0.59	0.79	0.31	0.72	0.31	0.55	0.75	0.52	1.44	0.79	1.26	0.83	1.64	0.86	1.52	0.96	1.19	0.86	1.41	1.04	0.30	0.93	0.39	0.66	11.11	0.79
Ysleta[19]	31.70	106.32	0.40	0.56	0.38	0.57	0.30	0.50	0.17	0.32	0.20	0.19	0.57	0.22	1.39	0.56	1.36	0.80	0.94	0.72	0.55	0.58	0.26	0.45	0.38	0.46	6.90	0.49

*Except as noted. All values in inches. Data from Climatological Summaries for Texas, National Weather Service, NOAA.

TABLE AI(e). MEAN TEXAS PRECIPITATION AND 8-INCH SPONGE NORMAL VALUES: 1941-1970*. SOUTH TEXAS GROUP.

STATION	(°N) LATI-TUDE	(°W) LONGI-TUDE	JAN. P	JAN. Sp	FEB. P	FEB. Sp	MARCH P	MARCH Sp	APRIL P	APRIL Sp	MAY P	MAY Sp	JUNE P	JUNE Sp	JULY P	JULY Sp	AUG. P	AUG. Sp	SEPT. P	SEPT. Sp	OCT. P	OCT. Sp	NOV. P	NOV. Sp	DEC. P	DEC. Sp	YEAR P	YEAR Sp
Alice[3]	27.73	98.07	1.37	2.00	1.48	1.98	1.10	1.68	1.80	1.45	2.93	1.91	2.96	2.11	1.96	1.70	2.28	1.28	4.90	2.41	2.69	2.77	1.41	2.03	1.55	1.97	26.43	1.94
Aransas County	28.27	96.80	2.18	3.86	2.45	3.88	1.61	3.40	2.43	2.97	3.17	3.16	3.52	3.40	2.26	2.80	4.49	2.89	5.82	4.19	3.97	4.54	2.11	3.72	2.80	3.67	35.81	3.54
Beeville[16]	28.45	97.70	1.61	2.32	2.06	2.58	1.37	2.34	2.38	2.06	3.35	2.54	2.69	2.40	2.14	1.81	2.58	1.53	4.68	2.51	2.94	2.95	1.70	2.41	1.59	2.28	29.09	2.31
Cotulla[28]	28.45	99.22	0.74	1.42	1.34	1.50	0.60	1.27	1.74	1.13	2.56	1.59	2.06	1.55	0.81	0.87	1.53	0.70	2.94	1.42	2.44	1.99	1.26	1.81	1.03	1.64	19.05	1.46
Crystal City[25]	28.68	99.83	0.79	1.32	1.28	1.41	0.75	1.28	1.59	1.09	3.23	1.77	2.27	1.88	1.37	1.14	2.23	1.14	2.69	1.57	2.51	2.03	0.87	1.79	0.82	1.42	20.40	1.48
Eagle Pass[10]	28.70	100.48	0.94	1.23	1.03	1.31	0.76	1.12	1.90	1.10	3.24	1.83	1.63	1.54	1.61	0.98	2.01	1.00	2.96	1.52	1.96	1.78	0.70	1.37	0.78	1.13	19.52	1.32
Encinal[13]	28.08	99.37	0.92	1.42	1.29	1.51	0.72	1.25	1.88	1.12	3.14	1.73	2.29	1.69	1.21	0.98	2.03	0.89	3.11	1.52	2.38	1.89	1.13	1.62	1.06	1.47	21.16	1.42
Falfurrias[13]	27.22	98.15	1.41	1.73	1.42	1.82	0.87	1.47	1.65	1.23	3.00	1.75	2.68	1.95	1.19	1.26	2.38	1.05	4.83	2.35	2.38	2.56	1.10	1.77	1.24	1.60	24.15	1.71
Harlingen[1]	26.22	97.68	1.43	1.96	1.22	1.80	0.95	1.47	1.47	1.22	3.18	1.83	2.49	2.07	1.71	1.52	3.04	1.54	4.80	2.68	2.56	2.77	1.43	2.03	1.57	1.89	25.86	1.89
Hebbronville[32]	27.30	98.67	1.15	1.32	1.44	1.74	0.55	1.39	1.55	1.14	1.64	1.21	2.13	1.29	0.64	0.90	1.54	0.62	4.05	1.88	2.11	2.23	1.20	1.68	0.66	1.37	18.66	1.39
Hondo	29.35	99.13	1.72	2.32	2.22	2.73	1.48	2.50	2.77	2.26	3.67	2.73	2.72	2.42	1.65	1.49	2.43	1.24	3.89	2.01	3.00	2.60	1.41	2.27	1.50	2.12	28.46	2.22
Kenedy[23]	28.82	97.85	1.54	2.34	2.39	2.64	0.99	2.19	2.70	1.93	3.50	2.52	2.98	2.38	1.48	1.49	2.28	1.16	3.64	1.86	3.03	2.35	2.19	2.31	1.83	2.47	28.55	2.13
Kingsville[29]	27.53	97.88	1.43	1.68	1.64	1.86	0.84	1.57	1.26	1.13	3.40	1.87	2.69	2.29	1.21	1.49	2.76	1.36	5.01	2.70	2.63	2.88	1.21	2.01	1.19	1.69	25.27	1.87
San Benito[31]	26.13	97.63	1.01	1.62	1.38	1.63	0.65	1.32	1.49	1.15	2.34	1.54	2.58	1.86	1.39	1.46	3.08	1.53	4.97	2.78	3.09	3.08	1.43	2.33	1.14	1.91	24.55	1.84
Uvalde	29.22	99.77	1.20	1.54	1.55	1.79	1.15	1.66	2.06	1.54	2.96	1.96	2.53	1.95	1.63	1.32	2.30	1.19	3.10	1.68	2.89	2.20	0.98	1.87	0.92	1.47	23.22	1.67

* Except as noted. All values in inches. Data from <u>Climatological Summaries</u> for Texas, National Weather Service, NOAA.

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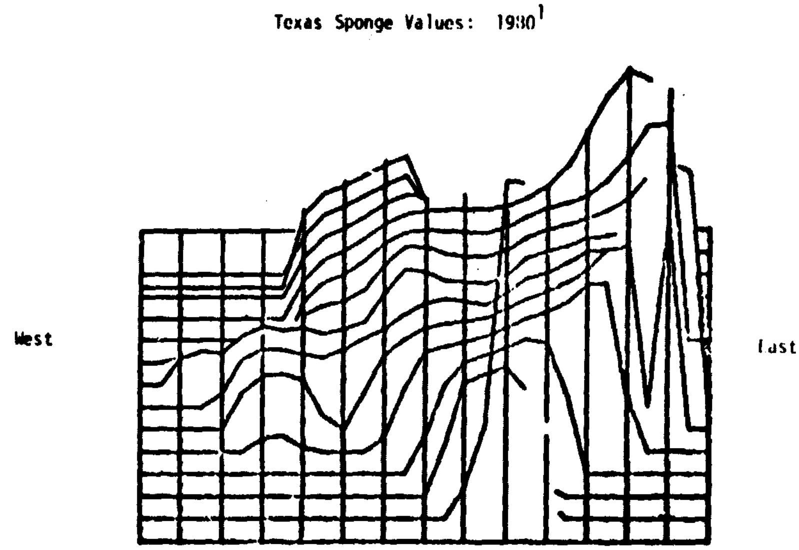
TABLE AI(f). PERIODS OF RECORD OTHER THAN 1941-1970: TABLES 2(a) - 2(e)

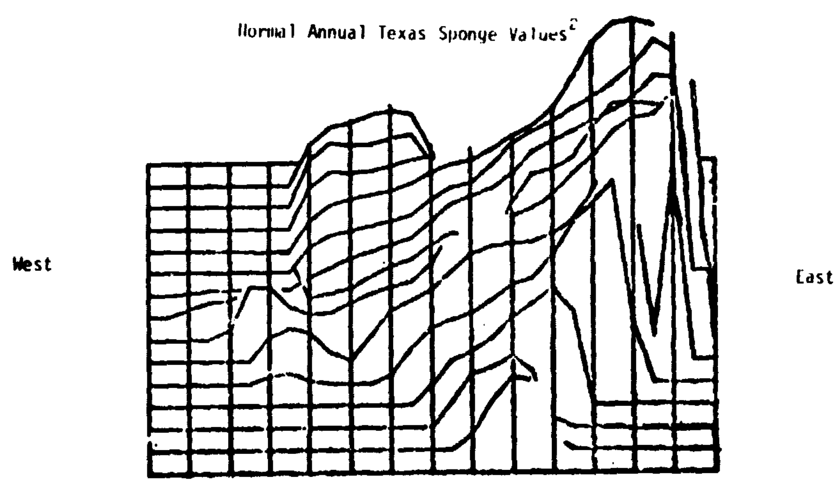
[1]1931 - 1969
[2]1931 - 1970
[3]1932 - 1969
[4]1933 - 1967
[5]1933 - 1968
[6]1934 - 1969
[7]1937 - 1966
[8]1937 - 1969
[9]1938 - 1967
[10]1939 - 1968
[11]1939 - 1969
[12]1940 - 1966
[13]1940 - 1969
[14]1941 - 1967
[15]1941 - 1968
[16]1942 - 1971
[17]1943 - 1970
[18]1947 - 1966
[19]1947 - 1970
[20]1948 - 1967
[21]1948 - 1969
[22]1948 - 1970
[23]1949 - 1966
[24]1949 - 1967
[25]1949 - 1968
[26]1949 - 1969
[27]1949 - 1970
[28]1950 - 1969
[29]1950 - 1971
[30]1951 - 1966
[31]1951 - 1967
[32]1953 - 1970
[33]1956 - 1970
[34]1959 - 1971

TABLE AII. PRECIPITATION AND 8-INCH SPONGE VALUES AT SELECTED STATIONS ALONG AN EAST-WEST TEXAS TRANSECT: BEAUMONT (30.08°N; 94.10°W)

Station	Sta. No.	Period	Latitude (°N)	Longitude (°W)	January Precip.	January Sponge	July Precip.	July Sponge	Year Precip.	Year Sponge
Beaumont	0613	1941-70	30.08	94.10	4.57	7.00	5.71	4.30	54.77	5.20
Beaumont	0613	1980	30.08	94.10	5.84	5.04	0.95	1.34	57.59	4.72
Beaumont	0613	1979	30.08	94.10	7.91	7.43	15.50	3.93	79.56	5.55
Lufkin	4524	1941-70	31.23	94.75	4.29	6.32	2.83	2.63	44.93	4.22
Liberty	5196	1941-70	30.05	94.82	4.21	6.21	4.65	3.49	49.61	4.41
Liberty	5196	1980	30.05	94.82	0.40	3.99	0.36	2.65	56.77	4.84
Liberty	5196	1979	30.05	94.82	8.91	7.49	7.61	4.08	70.11	5.31
Huntsville	4382	1941-70	30.72	95.57	3.80	6.25	3.28	3.10	45.95	4.39
Huntsville	4382	1980	30.72	95.57	0.94	2.61	0.05	0.78	28.30	2.67
Huntsville	4382	1979	30.72	95.57	7.65	7.64	5.90	3.20	64.07	5.31
Brenham	1048	1941-70	30.15	96.40	2.78	4.84	1.90	2.01	38.96	3.53
Temple	8910	1941-70	31.10	97.35	2.35	4.08	1.96	1.97	33.87	3.08
San Marcos	7983	1941-70	29.88	97.95	2.06	3.08	1.89	2.04	33.86	2.74
New Braunfels	0832	1941-70	30.10	98.42	2.12	3.23	1.98	1.79	34.39	2.86
Blanco	6276	1941-70	29.70	98.12	1.38	2.92	1.83	1.78	32.61	2.56
Llano	5272	1941-70	30.75	98.68	1.37	2.16	1.20	1.22	26.16	2.12
Brownwood	1138	1941-70	31.72	98.98	1.72	2.63	1.85	1.92	27.20	2.32
Kerrville	4782	1941-70	30.05	99.15	1.86	2.36	2.10	1.96	30.75	2.59
Brady	1017	1941-70	31.12	99.35	1.52	2.16	1.34	1.41	23.27	1.96
Brady	1017	1980	31.12	99.35	1.18	2.42	0.00	0.44	24.21	2.11
Brady	1017	1979	31.12	99.35	1.14	2.98	1.96	1.33	23.47	2.09
Sonora	8449	1941-70	30.57	100.65	0.82	1.28	1.61	1.33	19.28	1.46
Colorado City	4974	1941-70	32.38	100.87	0.82	1.46	2.14	1.39	19.80	1.44
Ozona	6734	1941-70	30.72	101.20	0.81	1.21	1.30	1.19	17.59	1.36
Ozona	6734	1980	30.72	101.20	0.08	2.52	0.00	0.87	17.10	1.61
Big Spring	0786	1941-70	32.25	101.45	0.63	1.30	1.97	1.28	15.72	1.28
McCamey	5707	1941-70	31.13	102.20	0.64	0.98	1.64	1.42	12.75	0.94
McCamey	5707	1979	31.13	102.20	0.08	0.67	1.01	0.58	[illegible]	0.57
Fort Stockton	3278	1941-70	30.87	102.92	0.83	0.98	1.44	0.95	12.23	0.86
Wink	9829	1941-70	31.78	103.20	0.59	0.79	1.64	0.86	11.11	0.79
Pecos	6892	1941-70	31.42	103.50	0.34	0.57	1.35	0.66	9.05	0.58
Pecos	6892	1980	31.42	103.50	0.04	1.46	0.09	1.44	15.78	1.12
Pecos	6892	1979	31.42	103.50	0.75	1.10	0.94	0.40	8.19	0.57
Balmorhea	0498	1941-70	30.98	103.75	0.64	0.86	1.56	0.86	12.12	0.81
Balmorhea	0498	1980	30.98	103.75	0.26	1.27	0.00	0.14	18.15	1.45
Balmorhea	0498	1979	30.98	103.75	1.43	1.51	1.89	0.68	12.78	0.87
Van Horn	9311	1941-70	31.05	104.83	0.54	0.89	1.75	0.80	10.23	0.78
Salt Flat	7920	1941-70	31.78	104.90	0.30	0.65	1.48	0.74	8.51	0.66
Salt Flat	7920	1980	31.78	104.90	0.11	0.56	0.16	0.10	7.08	0.56
Salt Flat	7920	1979	31.78	104.90	0.88	0.88	2.65	0.79	9.47	0.65
Ysleta	9966	1941-70	31.70	106.32	0.40	0.56	1.64	0.86	11.11	0.49
Ysleta	9966	1980	31.70	106.32	0.96	1.38	0.00	0.03	9.30	0.38
Ysleta	9966	1979	31.70	106.32	0.80	0.51	1.37	0.49	8.17	0.52
La Tuna	4931	1941-70	31.97	106.60	0.41	0.71	1.61	0.66	8.0[illegible]	0.59

[1] All precipitation and sponge values in inches. Data from National Climatic Center, NOAA, Asheville, N.C.





[1] Based on 28 stations along E-W "Texas Transect" from Beaumont to La Tuna.

[2] 1941-1970; 75 stations throughout Texas.

Note: 25% Vertical Exaggeration on all plots.

Figure A1.- Texas sponge values for 1980 compared to normal annual Texas sponge values.

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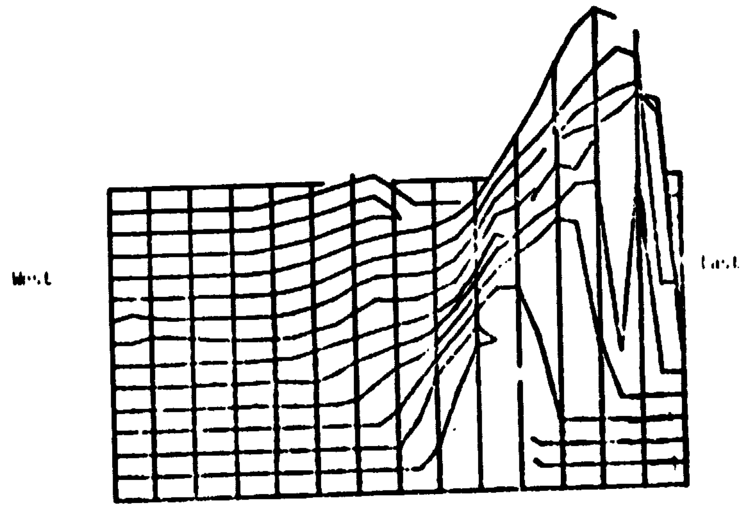
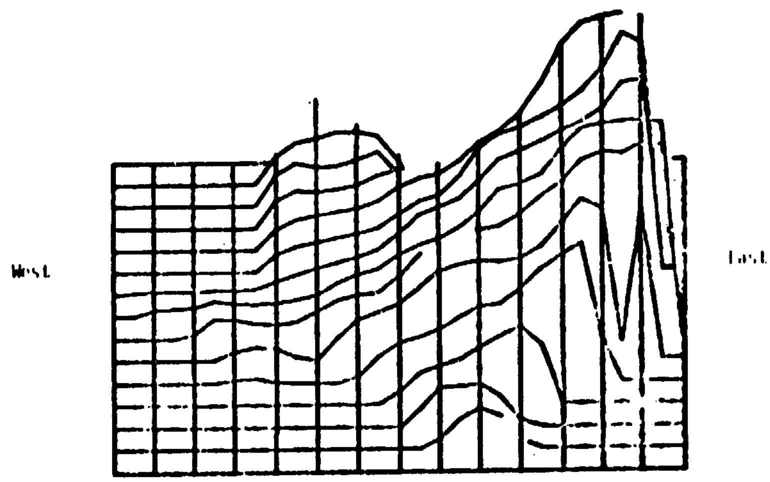
Texas Sponge Values: April, 1980[1]



Normal Texas Sponge Values: April[2]



[1]Based on 28 stations along E-W "Texas Transect" from Beaumont to La Tuna.

[2]1941-1970; 75 stations throughout Texas.

Note: 25X Vertical exaggeration on all plots.

Figure 42.- Texas sponge values for April 1980 compared to normal Texas sponge values for April.

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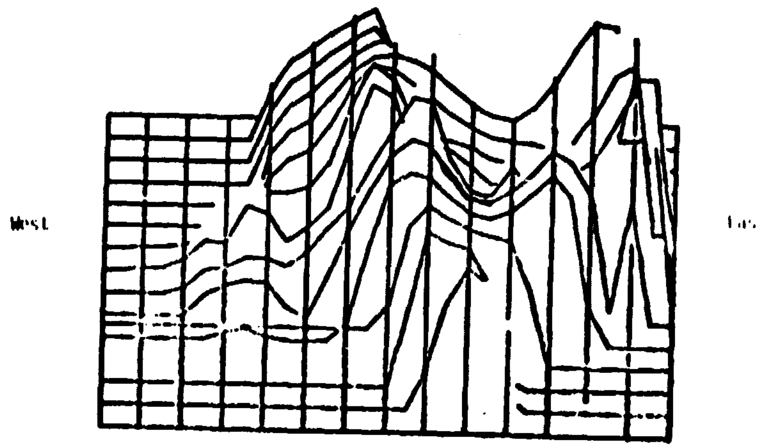
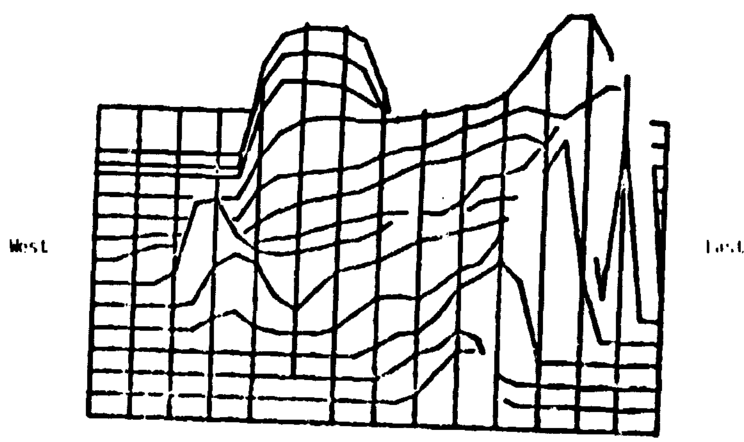
Texas Sponge Values: July, 1980[1]



Normal Texas Sponge Values: July[2]



[1]Based on 28 stations along E-W "Texas Transect" from Beaumont to La Pan..
[2]1941-1970; 75 stations throughout Texas.

Note: 25% Vertical Exaggeration on all plots.

Figure A3.- Texas sponge values for July 1980 compared to normal Texas sponge values for July.

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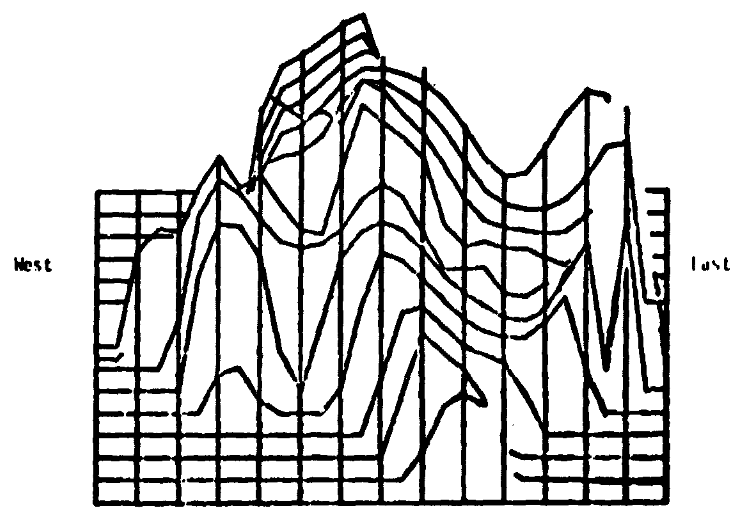
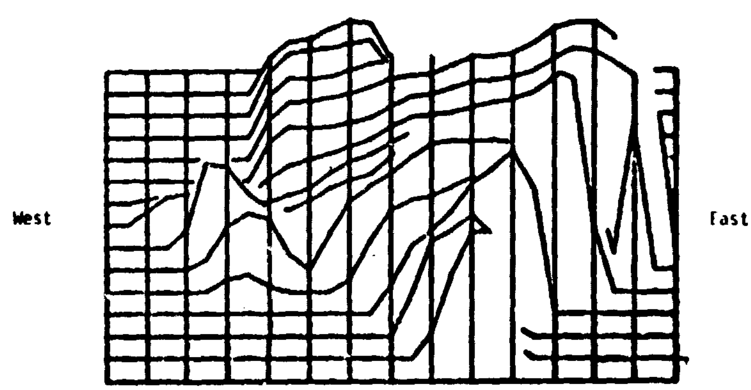
Texas Sponge Values: October, 19HO[1]



Normal Texas Sponge Values: October[2]



[1]Based on 28 stations along E-W "Texas Transect" from Beaumont to La Tuna.
[2]1941-1970; 75 stations throughout Texas.

Note: 25% Vertical Exaggeration on all plots.

Figure A4.- Texas sponge values for October 1980 compared to normal Texas sponge values for October.