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ABSTRACT

A region of low brightness temperature lying along the Mississippi River from Cairo, Illinois, to Morganza, Louisiana was observed in early Nimbus 5 Electrically Scanning Microwave Radiometer (ESMR) images. This region, which generally corresponds to an outwash aquifer in the Mississippi Valley, had brightness temperatures, at times as much as 40°K below the surrounding (drier) older uplands. Fluctuations of as much as 30°K were observed during the time interval 15 December 1972 to 28 February 1973. Comparison images taken from the Earth Resources Technology Satellite (ERTS-1) indicate that the study area is aligned with the Mississippi River floodplain, a region of potentially high soil moisture content. The brightness temperature fluctuations were compared with variations in precipitation and other hydrologic parameters in order to delineate the causative factors.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

HYDROLOGIC APPLICATIONS OF NIMBUS 5 ESMR DATA

INTRODUCTION

The Nimbus 5 satellite was launched on 11 December 1972 into a near polar orbit at an altitude of about 1100 km. One of the instruments aboard Nimbus 5 is the Electrically Scanning Microwave Radiometer (ESMR) which receives thermal radiation at a wavelength of 1.55 cm. The radiometer scans ±50° about the nadir with a spatial resolution of 25 km at the nadir. Because the ESMR is a scanning radiometer, it maps the radiation from a swath about 2500 km wide and thus can be displayed in an image format.

Experiments performed with a preliminary version of this radiometer on board an aircraft have indicated that the emission from soil is strongly dependent on the moisture content of the surface layer (Schmugge et al., 1974). Emissivities as low as 0.75 were observed for wet fields without vegetative cover; because of coarse satellite spatial resolution, the observation of emissivities this low is not expected from a space platform.

In early ESMR images of the United States, the Mississippi Valley was observed to have low brightness temperatures (T_B). An example of this response is shown in Figure 1, a black and white uncalibrated image for orbit 569 on 22 January 1973 in which the low T_B areas appear white. This region of low T_B approximately corresponds to an outwash aquifer as indicated on the right side of Figure 1, where unconsolidated sand and gravel deposits are capable of storing large amounts of groundwater. The 0.6-0.7 μm Earth Resources Technology Satellite (ERTS-1) composite image for this area taken on 1 and 2 October

1972 is presented in Figure 2 and shows these aquifer areas as having a higher reflectivity than the surrounding uplands. The upland areas possess predominantly hardwood forests whereas the outwash aquifer area is primarily agricultural. This man-affected vegetation distribution shown by ERTS-1 tends to highlight the Mississippi floodplain area which also corresponds to the highly reflective area. Similar anomalies have been observed by other satellite sensors such as the HRIR on Nimbus 3 (MacLeod, 1971) and the USAF Data Acquisition and Processing Program (DAPP) (Allison et al., 1974).

MICROWAVE OBSERVATIONS

The microwave data are shown more quantitatively in Figure 3, a T_B contour map of the lower Mississippi Valley for 22 January 1973. In this map the low T_B areas in the Mississippi Valley with T_B less than 240 K are shaded whereas the surrounding uplands are significantly warmer ($T_B \sim 250$-260 K). We believe that this lower emissivity is indicative of increased soil moisture following heavy rainfall. We base this belief on the response of T_B at this wavelength to variations in soil moisture as presented in Figures 4 and 5. These results were obtained with a preliminary version of the radiometer (1.55 cm) flown on board the NASA CV-990 over a Phoenix, Arizona test area. Figure 4, for lighter soils (sandy loam), shows that there is about a 70 K difference between the dry and wet fields for which surface temperature (T_S) are about 320 K. Considering that the lowest T_B observed is about 240 K, then the lowest emissivity observed was T_B/T_S = 240 K/320 K = 0.75. As a result, for the lower surface temperatures found in the Mississippi Valley, the lowest expected T_B would be about 200-210 K.

The soil moisture values in Figures 4 and 5 are for the average moisture content in the top centimeter of the soil. The curve shown in Figure 4 is a linear regression fit to the data with a correlation coefficient of 0.9. A similar response is observed for fields with heavier soils (clay loam) shown in Figure 5. The major difference is that the heavier soils can hold more water. Therefore, the same 70 K temperature difference between wet and dry fields is spread over a wider range of soil moisture. The correlation coefficient again is 0.9. Thus, the ESMR measurements provide a good estimate of the moisture in the top centimeter of the soil.

These Arizona results were obtained for bare fields; the effect of vegetation would be to moderate this positive correlation and a sufficiently thick layer of vegetation would obscure the effect markedly. We expect that the fields in the Mississippi Valley would be only partially covered with dead vegetation in January and thus should allow the effects of soil moisture variation on T_B to be observed. Also the instrument may be responding to variations in the amount of standing water within a resolution element. The uplands, contrastingly, have a greater amount of vegetation cover produced by the bare trees and would tend to mask similar changes in the soil moisture.

HYDROMETEOROLOGICAL OBSERVATIONS

From late fall through winter of 1972-73, the Mississippi Valley experienced well above average rainfall, in some cases in excess of 200% of normal. Figure 6 shows an example of the precipitation in the Eastern United States in December 1972 which indicates rainfall in excess of 8 inches in some portions of the Mississippi Valley (Weekly Weather and Crop Bulletin 1973). Figure 7 presents streamflow ranges in the Eastern U.S. for November and December 1972 which indicates flow much above normal in the Mississippi Valley (Water Resources Review, 1972). Subsequent flows in January and February 1973 were close to normal, but March 1973 flows markedly increased to abnormally high amounts. A more detailed presentation of streamflow on the Mississippi River for a number of different stations is in Figure 8. The streamflow levels are very high for this time of year, and, in fact, in March they rose to and above flood stage at many stations and remained that way well into May. For our interests in this paper, stream levels rose gradually in December and into January with a decrease in flow beginning about 10 January and increasing again around 20 January. This increase lasted until about 20 February when another decrease occurred. In addition to streamflow, groundwater conditions during the same period were examined and similar high moisture levels were noted. Figure 9 shows groundwater well data in the Missouri boot heel area of the Mississippi floodplain. The high groundwater levels of early 1973 are evident when compared to preceding years, but the most striking feature is the fact that the rise in levels, which usually reaches a peak in April or May, has occurred several months early in 1972-73. Piezometer data taken from the Low Sill Structure, Mississippi shown in Figure 10 shows groundwater variations similar to the streamflow variations presented in Figure 8. Two problems exist with these kinds of data. First, streamflow and groundwater observations possess too many lag properties to be easily referenced to T_B. Second, it would be difficult, if not impossible, to determine the average groundwater and soil moisture conditions over an area as large as the Mississippi Valley. As a result, it was decided to compare the average brightness temperature to daily rainfall averages for selected parts of the Mississippi Valley with the idea that this information would be indicative of surface soil moisture conditions. These comparison areas are shown in Figure 11 which is a map showing the principal rivers and the boundaries (shaded areas) between the uplands and the outwash aquifer area. The study area was divided in two: a northern region from the junction of the Ohio and Mississippi Rivers down to Memphis and westward from the Mississippi River to the western upland boundary; and a southern region from Memphis to Vicksburg extending from the Mississippi River to the eastern upland boundary.

RESULTS AND DISCUSSION

The T_B contours for these areas are shown in Figure 3, we note that the area inside the 240 K contour (shaded area) corresponds approximately to the aquifer area shown in Figure 11. The average T_B for the two regions of interests were calculated using these type of data on about an every other day basis and averaging resolution element by resolution element. The results for the northern region are shown in Figure 12 and compared with the average daily rainfall. The average rainfall over these areas was determined by averaging the rainfall data from 28 stations in the northern region and 20 stations in the southern region using their 0800 reports. In general low brightness temperatures were observed for the period immediately after a heavy rainfall, e.g. the sharp drop in T_B observed around 20 January. This was followed by a gradual warming trend as the area dries out. The anomalous values (e.g. the value on 7 January) are days on which it was precipitating during the satellite overpass. The effect of rain over oceans has been to raise observed T_B above the low value observed for water ($T_B \sim 130$). For example brightness temperatures as high as 260 K over the Indian Ocean were observed for the heavy rains in Hurricane Leila (Rogers, et. al., 1973). There would also be a rise in T_B over land when the T_B of the ground is less than the temperature of the cloud which would be the cause for wet ground. Estimates of rainfall from ESMR are not easy to obtain over land because the variable and unknown T_B of the ground make it difficult to determine the emission from the rain. Thus for our purposes the rain serves to obscure the surface and causes several of the anomalous values observed in Figures 12 and 13.

The results for the southern region are presented in Figure 13. Again there is the sharp drop in T_B observed after the heavy rains of 22 January 1973. This is followed by a gradual rise until 15 February during which there were several additional rains. For the last half of February, which was dry, there is a sharp rise in T_B, presumably due to the drying out of the surface layer of the soil. These results indicate that ESMR does respond to large soil moisture changes when they occur over a sufficiently wide area.

Although the T_B variations shown in Figures 12 and 13 cannot be easily related to the groundwater variations shown in Figures 9 and 10, there is a direct correlation with streamflow as shown in Figure 8. The decrease in streamflow in mid-January corresponds with a significant increase in T_B; the same is true of the streamflow decrease in late February. It is interesting to note that the heavy rains indicated for the southern region in early January produced neither a decrease in T_B nor an increase in the streamflow (Figure 8). This is perhaps an indication that the set of rainfall stations were not representative of the rainfall over the southern region for that particular storm. It appears then that ESMR T_B is closely related to rainfall totals and generally related to subsequent streamflow variations.

While ESMR is most sensitive to surface moisture variations it should be possible by following the time history of the T_B variations to make inferences about soil moisture at greater depths. Additional studies are necessary using multi-frequency microwave sensors, especially at longer wavelengths, flown over test areas in coordination with intensive ground truth efforts directed specifically to relating soil moisture variations to microwave data.

ACKNOWLEDGMENTS

The authors wish to thank Mr. Dale F. Fuller, Missouri Geological Survey and Water Resources, Rolla, Missouri, Mr. Robert L. Mitchell, NWS, Slidell, Louisiana, and Mr. L. E. Carroon, Water Resources Division, Geological Survey, Jackson, Mississippi, for providing piezometer well and river stage data used in this study.

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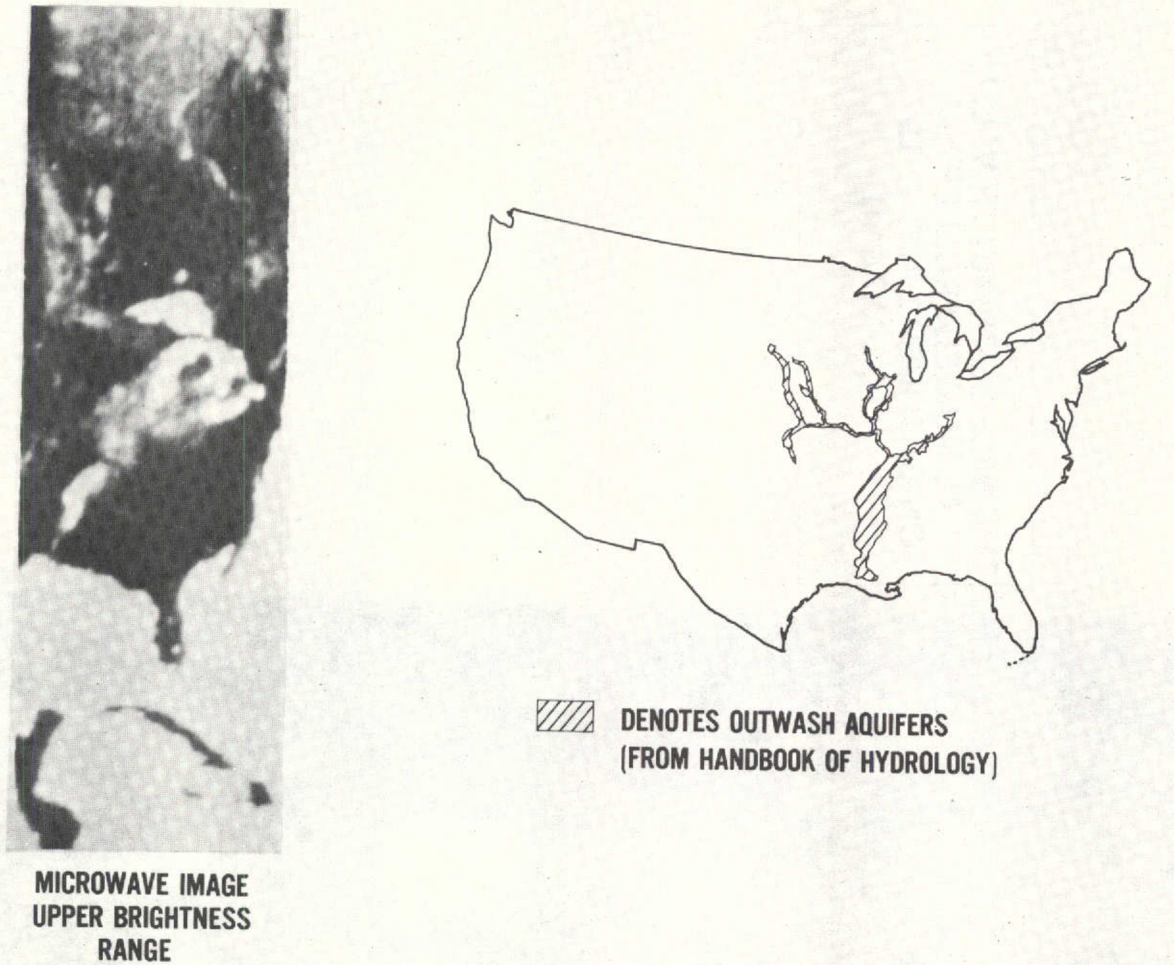

Figure 1. Microwave image of the Eastern portion of the U.S. for 22 January 1973. The white areas are those with brightness temperatures less than 250°K and black areas are those above 280°K. The outwash aquifer is indicated on the right side of the figure.

Figure 2. A Composite of Images from the 0.6–0.7 μm Band of ERTS-1 for 1 and 2 October, 1972

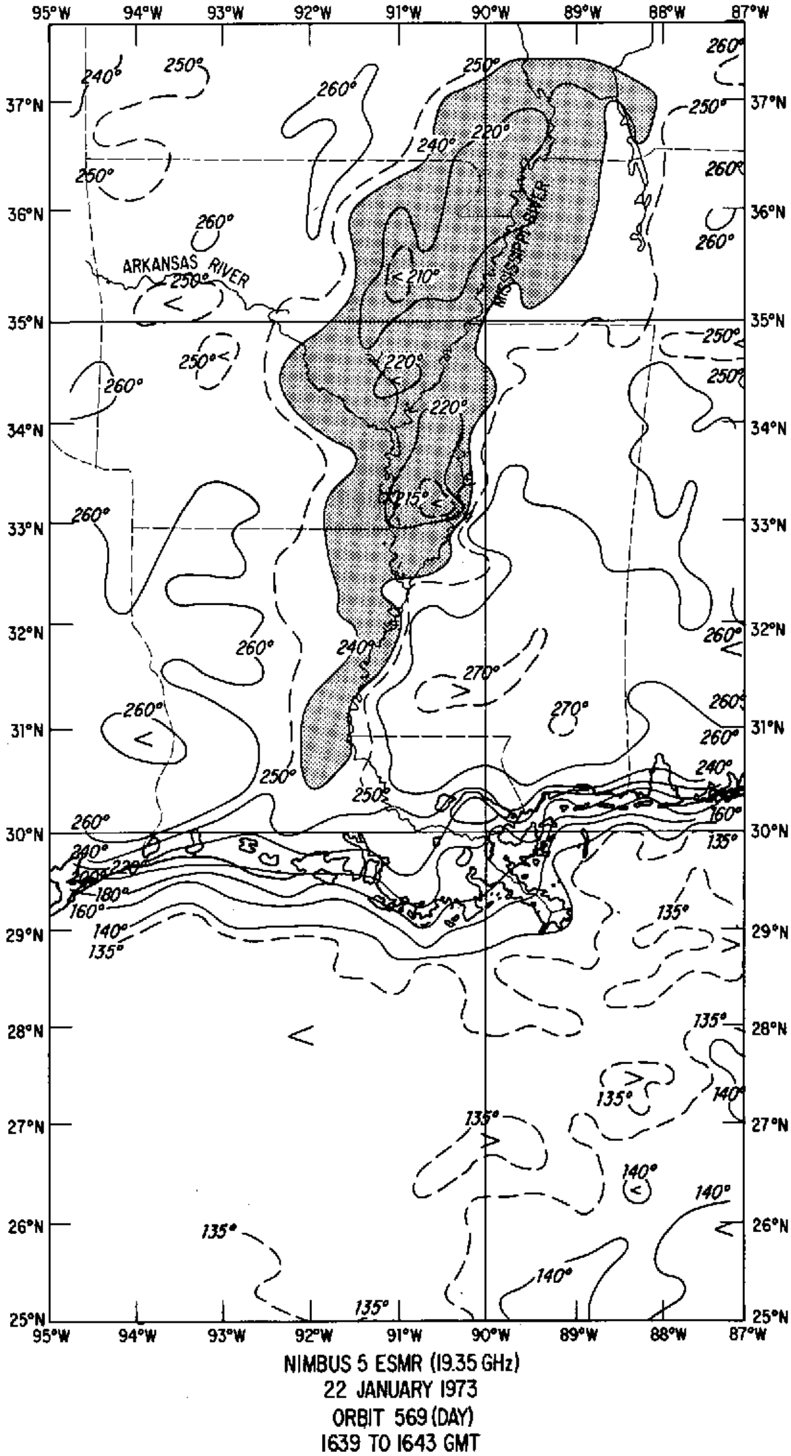

Figure 3. A brightness temperature contour map of the lower Mississippi Valley using the data of 22 January 1973. The contour interval is 10°K.

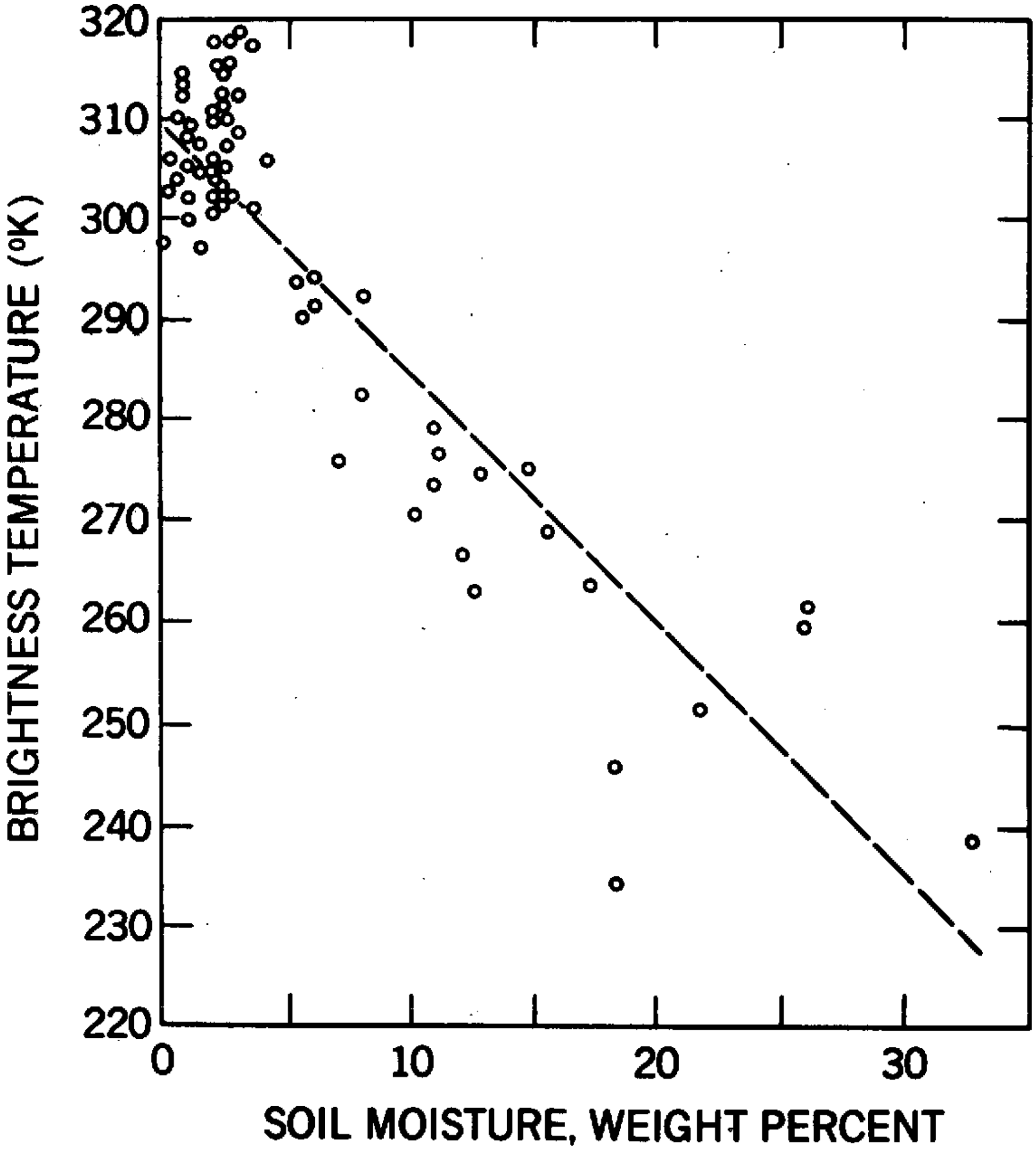

Figure 4. Plot of 1.55 cm Brightness Temperature Versus Soil Moisture for Fields with Sandy Loam Soils in the Phoenix, Arizona Test Area

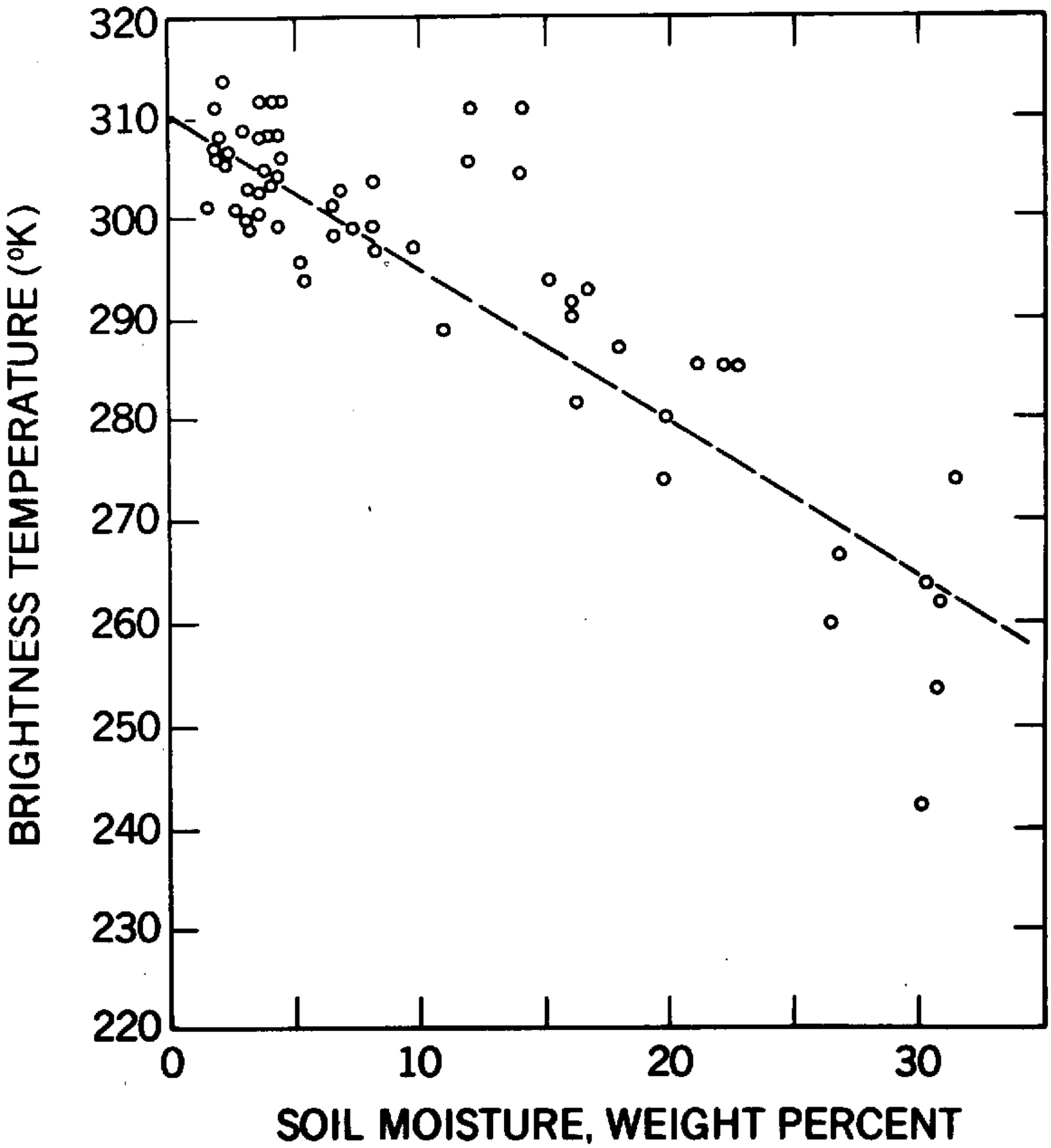

Figure 5. Plot of 1.55 cm Brightness Temperature Versus Soil Moisture for fields with Clay Loam Soils in the Phoenix, Arizona Test Area

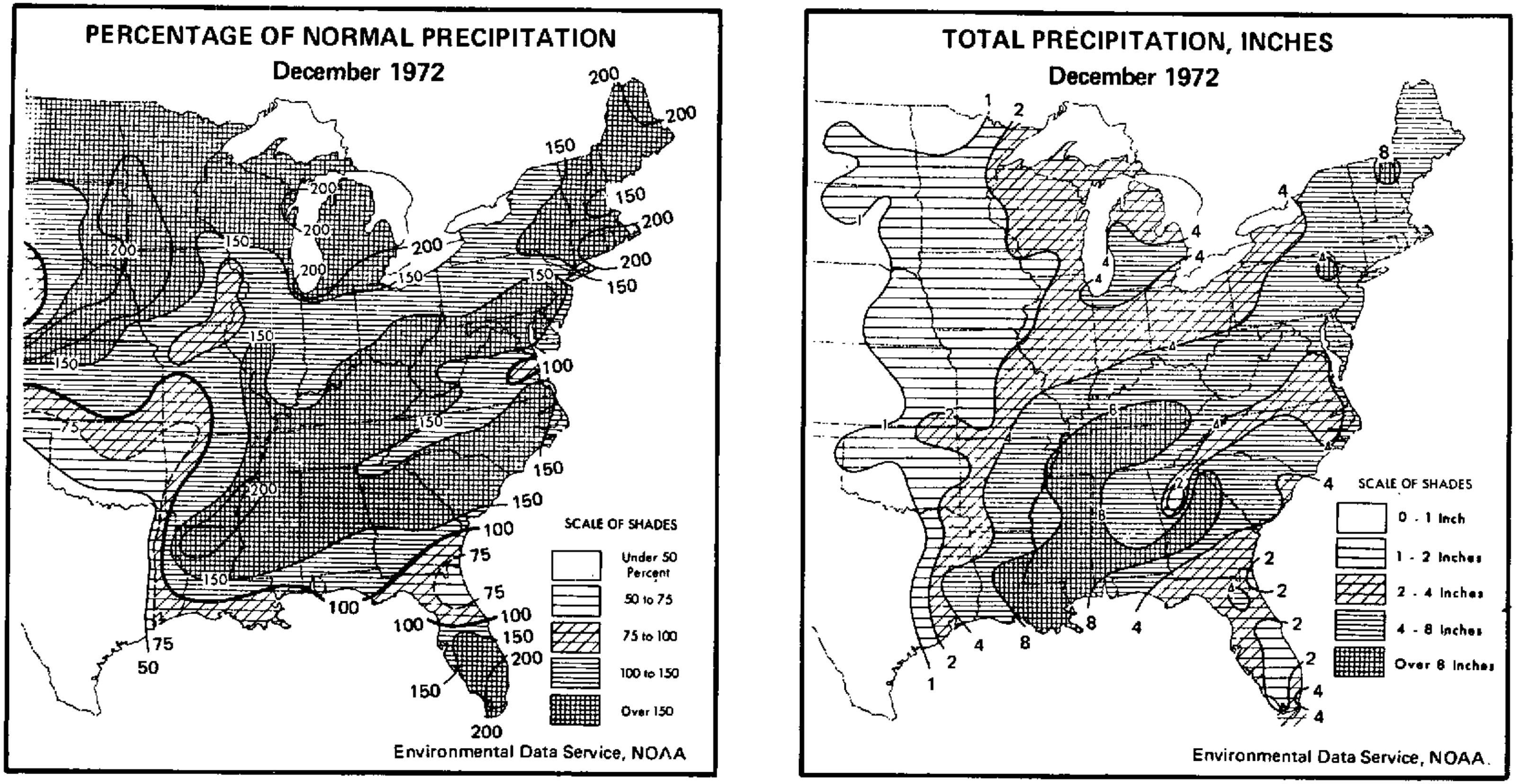

Figure 6. Precipitation Maps of the Eastern United States for December 1972 (Weekly Weather and Crop Bulletin, 1973)

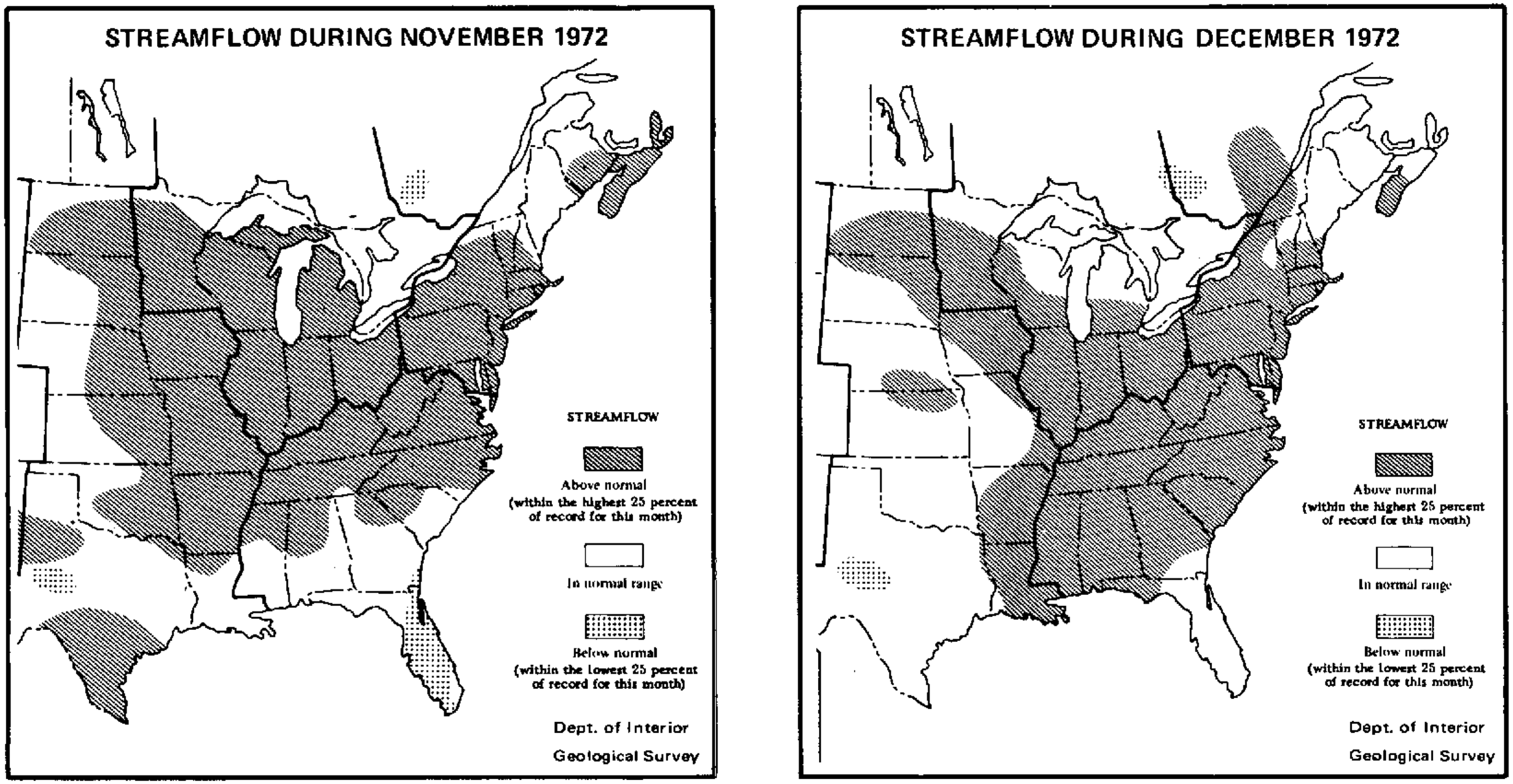

Figure 7. Streamflow Ranges in the Eastern United States for November and December 1972
(Water Resources Review, 1972)

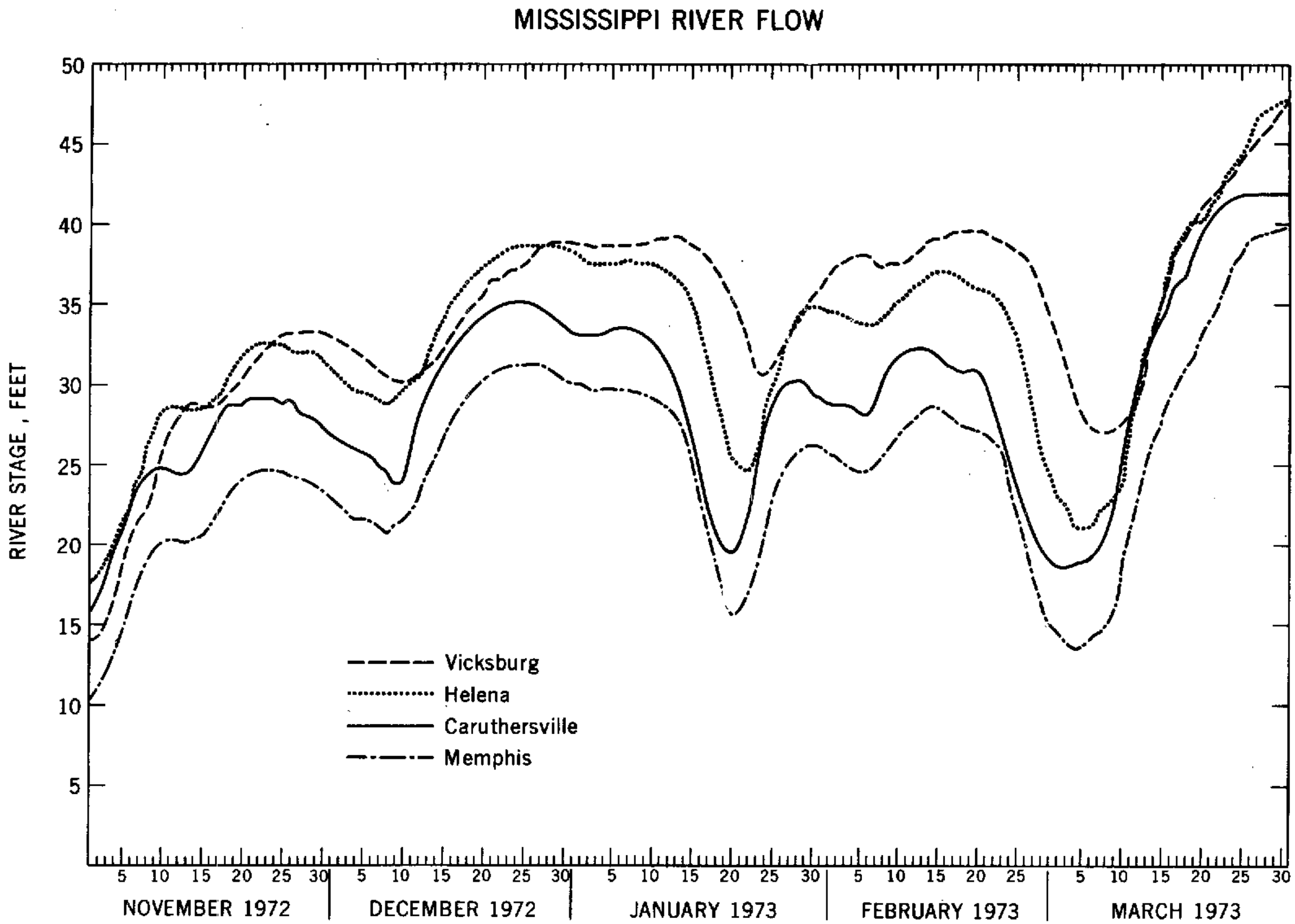

Figure 8. Streamflow Levels on the Mississippi River for the Period November 1972 through March 1973

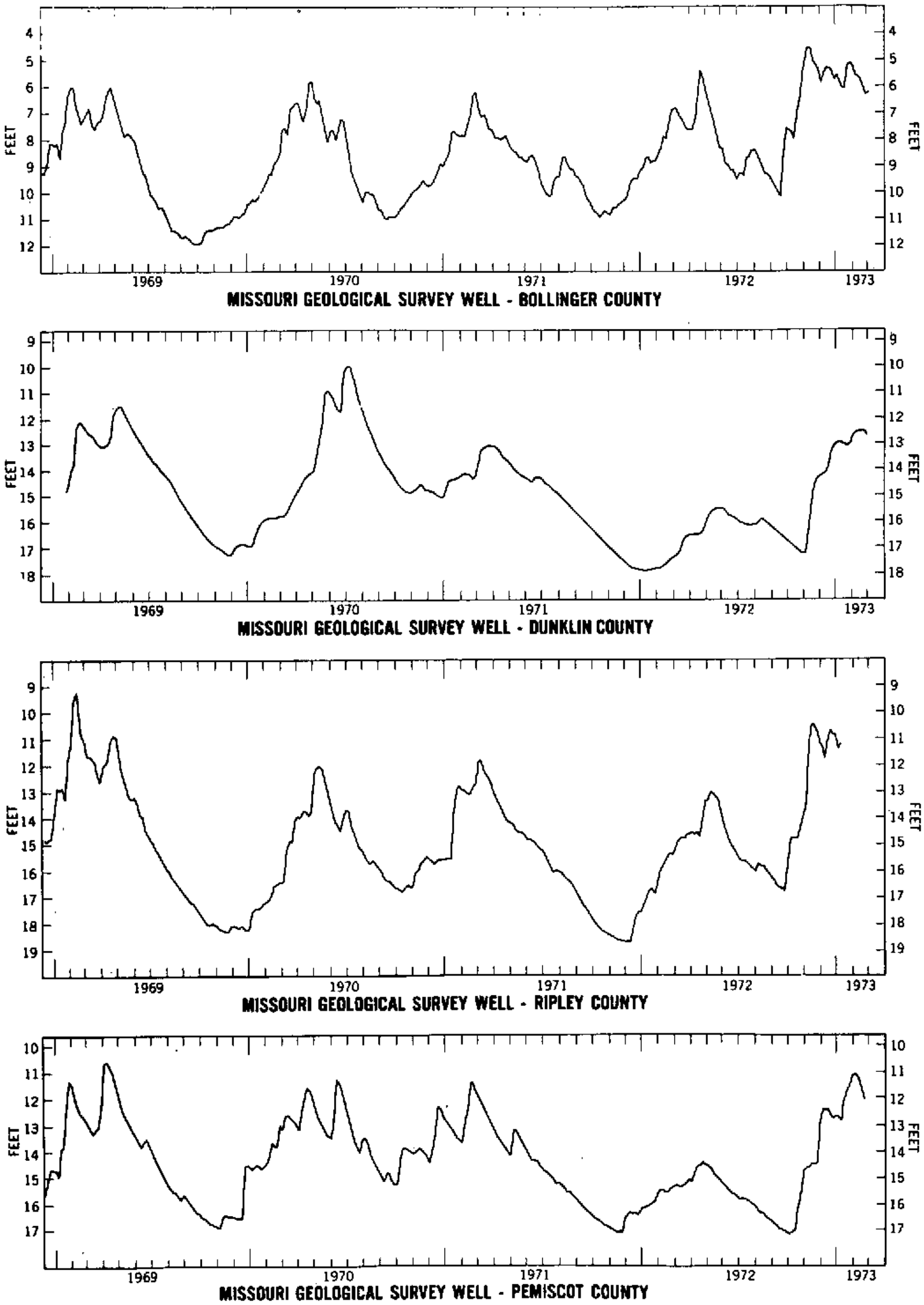

Figure 9. Groundwater well data from the southeastern corner of Missouri for 1969 through early 1973. Data from Missouri Geological Survey and Water Resources.

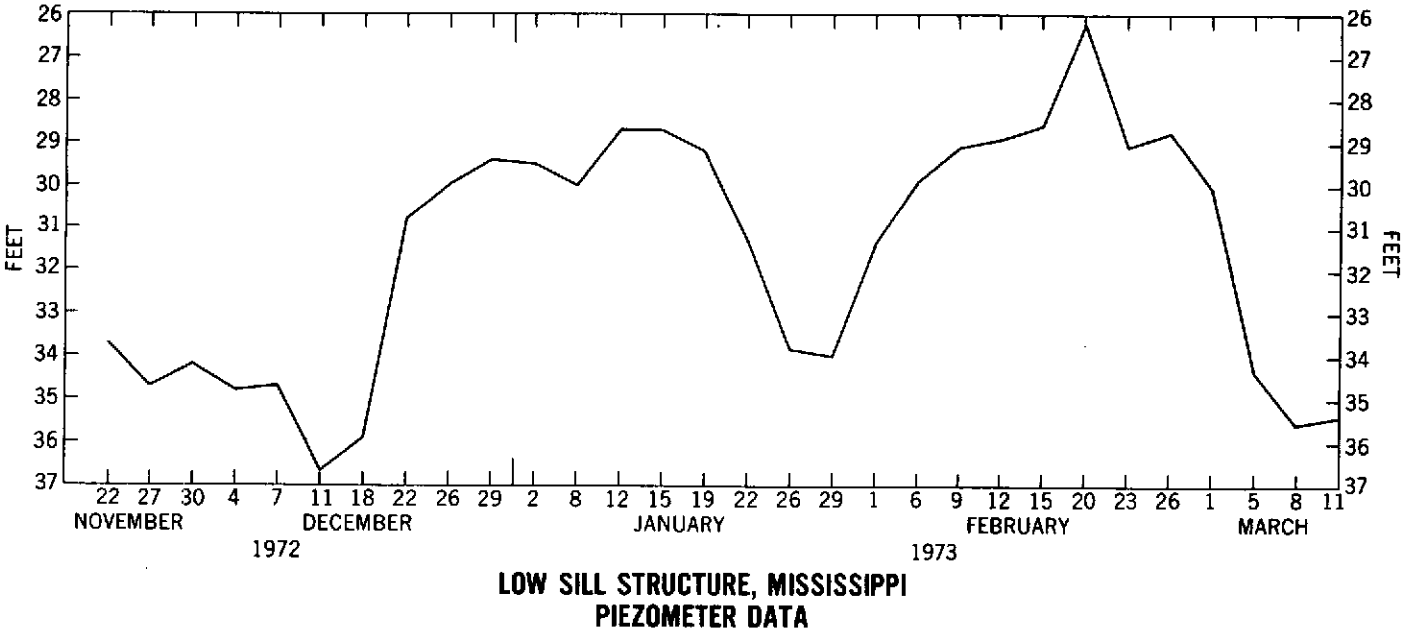

Figure 10. Piezometer Data from the Low Sill Structure Just South of Natchez, Mississippi

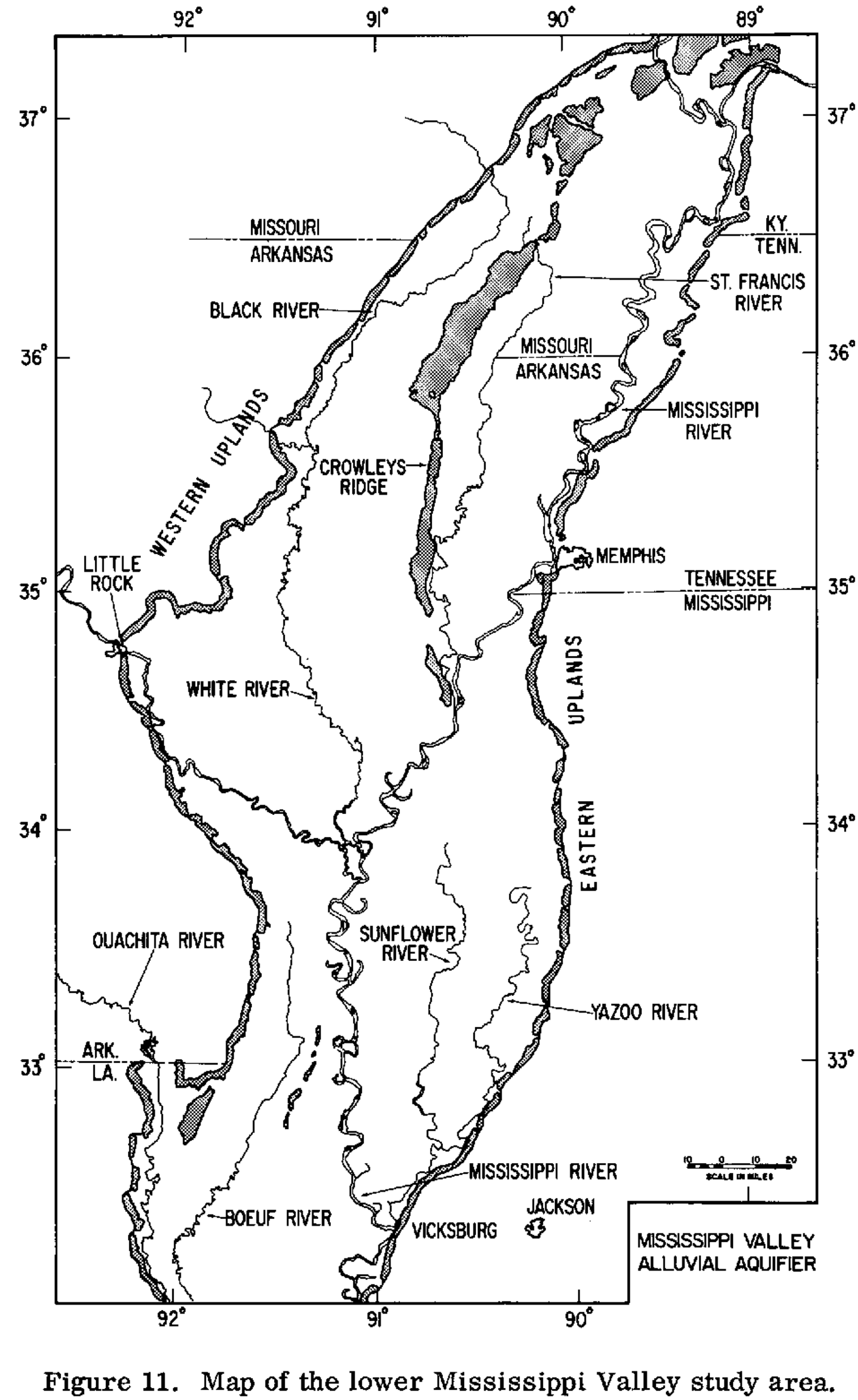

Figure 11. Map of the lower Mississippi Valley study area. The shaded areas delineate the boundaries between the alluvial aquifer and the surrounding uplands.

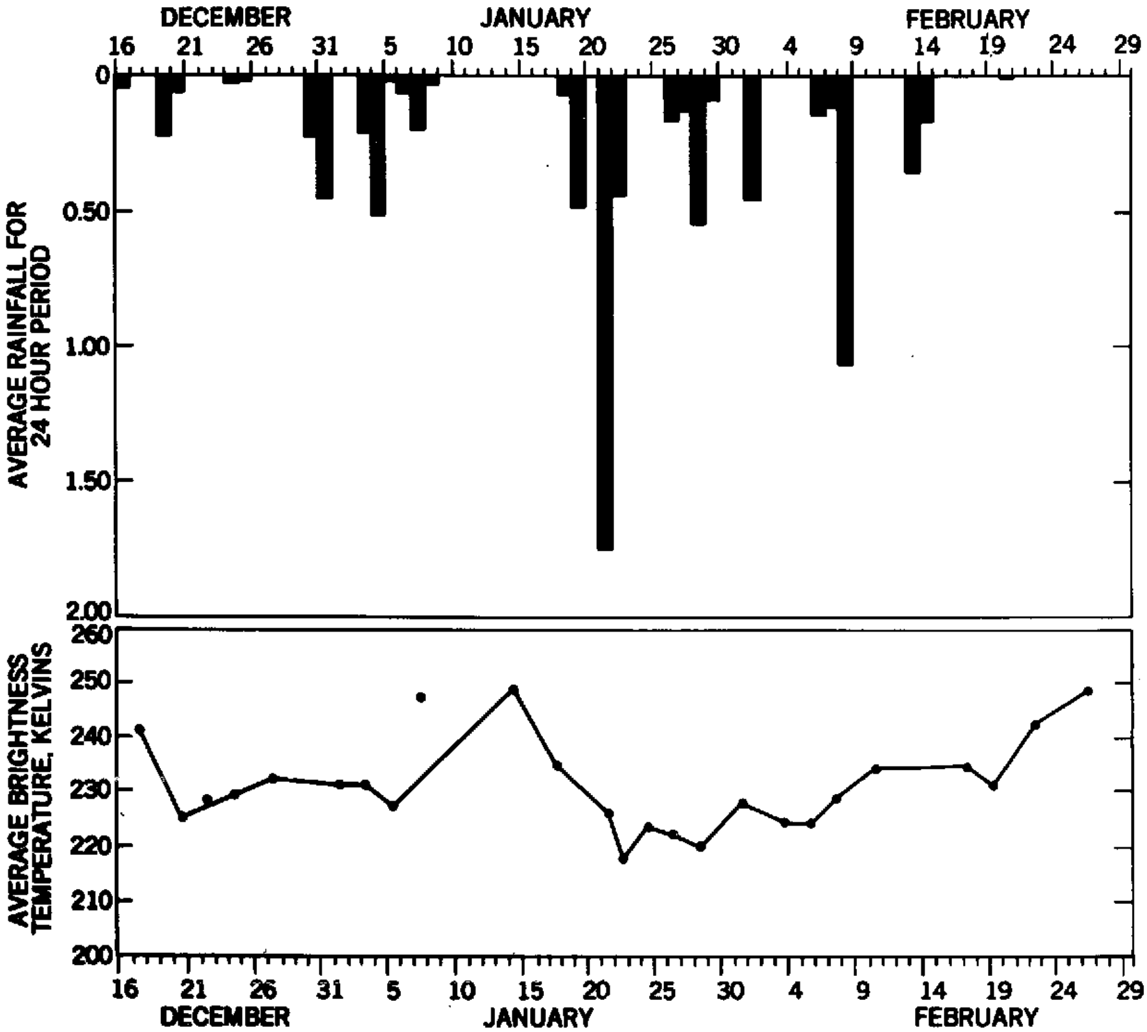

Figure 12. Comparison of ESMR brightness temperatures with average rainfall for northern test area. The latter is the average of the daily rainfall data from 28 stations.

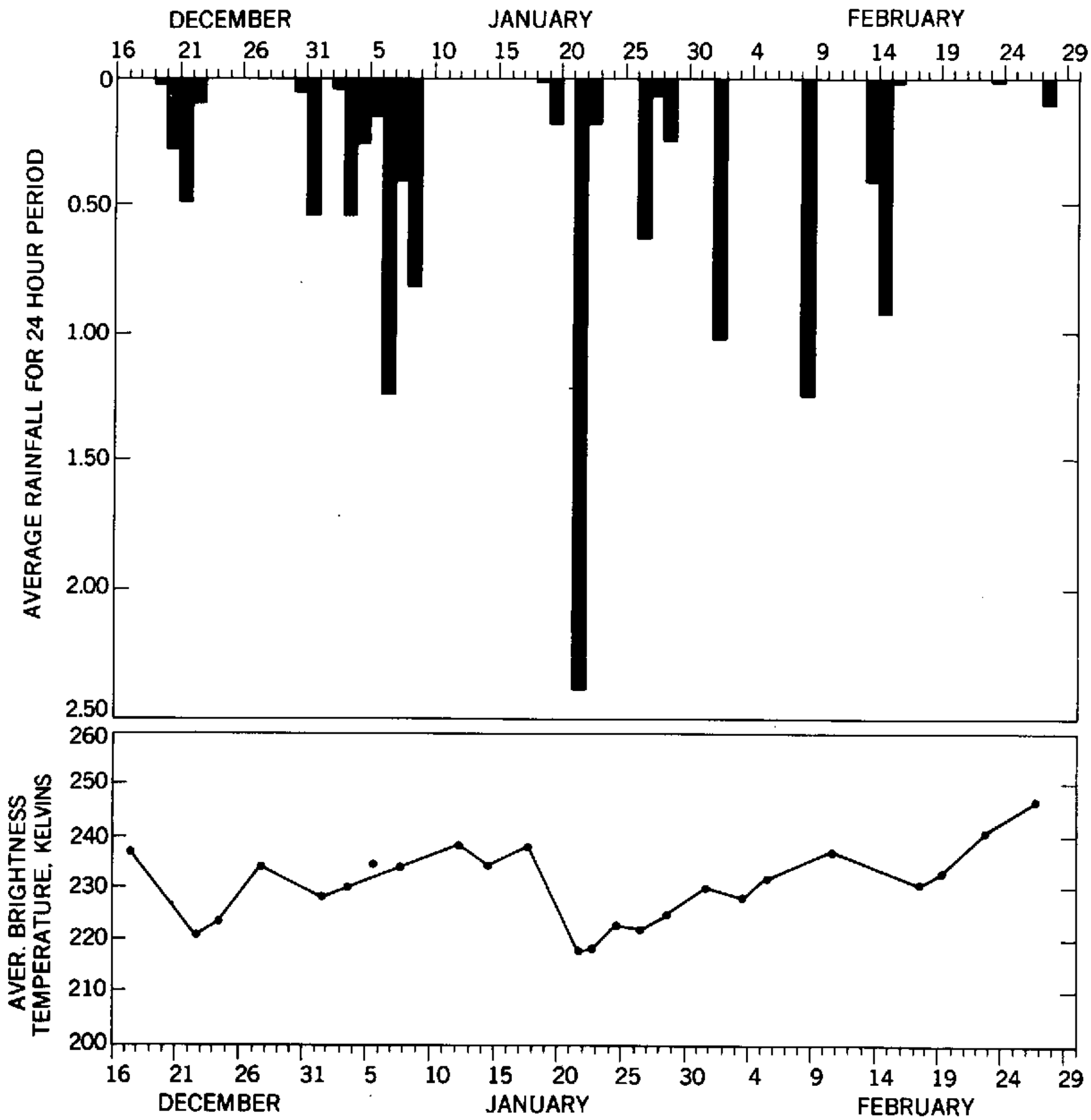

Figure 13. Comparison of ESMR brightness temperatures with average rainfall for southern test area. The latter is the average of the daily rainfall data from 20 stations.